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Multiple Technologies Estimate Aerosol Effect on Surface and Atmosphere Radiation Budget

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Tropospheric aerosols are believed to play an important role in modulating the Earth's energy budget. Direct aerosol effects include the scattering and absorption of solar radiation: there is less (but still significant) scattering, absorption, and emission in the thermal infrared. In part, because aerosols vary widely in space, time, and composition, their radiative forcings have not been quantified with accuracy sufficient to allow a much-needed assessment of the effect of aerosols on global climate. Recent advances in space-based sensor capabilities (Visible Imaging spectRometer Suite [VIRS] and the Moderate Resolution Imaging Spectrometer [MODIS]) for retrieving aerosols and also improved aerosol transport and chemistry modeling capabilities (Model of Atmospheric Transport and Chemistry [MATCH]) have provided unprecedented information on aerosols. NASA's Cloud's and the Earth's Radiant Energy System project (CERES) has benefited from teaming with research groups performing space based aerosol retrievals and advanced aerosol chemistry and dispersion modeling. By coupling measurements of the aerosol forcing from space with specialized observations at the surface, top and bottom closure for aerosol forcing to the atmospheric column can be achieved. We present a recent history of CERES' progress in quantifying the aerosol forcing component of the energy budget by integrating satellite sensor observations with radiative transfer modeling. Data from surface observation sites and from CERES/Surface and Atmosphere Radiation Budget (SARB) edition 2A retrievals from the TERRA platform for the years 2000 and 2001 are presented. In these data, an error bias (satellite derived - surface measured) of surface downward diffuse shortwave irradiance shows a functional relationship with aerosol forcing. These results indicate additional progress in understanding the global aerosol's temporal, spatial, and compositional nature is needed to reduce the present uncertainty of direct aerosol forcing on the climate system. Progress in improved aerosol quantities by MODIS retrievals over an ocean observation site developed by CERES is demonstrated.

I. Introduction

Accounting for the radiative effects of aerosols within the atmosphere is required to give future global climate models more accurate predictive capabilities. Aerosols and clouds are similar because both are extremely small particulates in the atmosphere. They may be treated identically by radiative transfer models if the full detail of their locations within the atmosphere and their complete optical properties are known. These aerosols and clouds modulate the incoming and outgoing radiation of the planet in the shortwave and the longwave regimes. The suspended particles within the atmosphere interact with both the shortwave and longwave radiation in a size (of the aerosols) and wavelength (of the intervening radiation) dependent manner. The resulting primary and secondary scattering and absorption of the radiation increases the complexity of characterizing these radiative effects. NASA's CERES program was established to collect a multi-year dataset that could be used to develop methods that can

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accommodate the complex temporal and spatial variability of clouds (Wielicki et.al.,1996). The influence of the aerosols on radiative transfer within the atmosphere is important when clouds are either absent or present. When methods to better account for the distributions of aerosols within the atmosphere are completed, their inclusion into future global climate models (in theory) will give them improved predictive capabilities

We briefly review the history of aerosol technologies used since the inception of the CERES project but focus on the latest strategy. We limit the discussion to aerosols that primarily occupy the troposphere and most significantly effect the SW radiation. Only the direct aerosol forcing mechanism that takes into consideration radiation extinction due to scattering, multiple-scattering and absorption are considered. Indirect forcing, aerosol radiative effects which follow cloud formation when aerosols act as cloud condensation nuclei, is not considered.

A component of the CERES project, the Surface and Atmosphere Radiation Budget (SARB) working group, uses measurements from space-borne sensors aboard multiple Earth Observing System platforms (TRMM, TERRA, AQUA and future NPOESS) and fast radiative transfer model methods to estimate radiation parameters associated with the planets energy budget. The SARB methods use derived top-of-the-atmosphere (TOA) CERES irradiances and a highly modified version of the Fu-Liou (1993) radiative transfer model to produce all-sky and clear-sky estimates of upwelling and downwelling, column resolved (TOA, 70 hPa, 200 hPa, 500 hPa, and surface) broadband SW, broadband LW and an 8-15 micron band irradiances (Charlock et.at., 1997). Pristine sky fluxes are calculated so that direct aerosol forcing may be determined. These forcings are determined from the difference between clear sky irradiances and pristine (no aerosols) sky irradiances at various pressure altitudes.

To determine upwelling and downwelling fluxes within the atmospheric column over the entire planet, SARB methods use various parameter inputs for the Fu-Liou radiative transfer model. Time and space dependent realistic ancillary inputs to characterize the planet's atmosphere and surface are needed for meaningful radiative transfer predictions. These inputs include instantaneous scene identification, cloud properties from either VIRS (aboard TRMM) or MODIS (aboard TERRA and AQUA) , and gridded fields of temperature, humidity, wind and ozone. The meteorological data are provided by GEOS4 and the Stratospheric Monitoring group Ozone Blended Analysis (SMOBA). Ozone profiles are determined from an operational National Center for Environmental Predictions (NCEP) product.

Several types of aerosol information are needed to allow a thorough characterization of their effects on the SW radiation. A measure of optical thickness (quantity) and optical properties (quality) of the aerosols are needed to completely quantify their radiative effects. These fundamental parameters of aerosols change as a function of wavelength. Presently, only the aerosol quantity is sensed remotely from space-based sensors. The present state of the art is to estimate aerosol constituent types within the atmospheric column using models. The SARB presently uses seven aerosol types (1:small dust, 2:large dust, 3:soot, 4:soluble organics, 5:insoluble organics, 6:sulfates, and 7:sea salt). These constituent types are associated with specific optical properties that are used as inputs to the radiative transfer model. The optical properties for the dust aerosols follow the work of Tegen and Lacis (1996). Properties for the remaining constituents are from the Optical Properties of Aerosols and Clouds (OPAC, Hess et.at., 1998).

Estimation Method	Type	Time Resolution	Constituents	Includes Vertical Structure Information
None	-	-	-	-
Pinker/Stowe	Climatology	Static	N	N
GADS	Climatology	Seasonal	Y	N
GFDL	Climatology	Seasonal	Y	N
MATCH Only	Transport Model	Daily	Y	Y
MODIS Daily Gridded /MATCH	Satellite Sensor	Daily	Y	Y
MODIS/MATCH	Satellite Sensor + Transport Model	Minutes	Y	Y

Table 1. Aerosol source information used by the SARB working group to account for the radiative effects of aerosols. Aerosol characterization complexity increases from top (project beginning) to bottom (present). Shaded cells represent present SARB aerosol information strategy.

Aerosol information sources for input into the radiative transfer model of SARB have changed as information that is more accurate became available over the past decade (Table 1). Prior to CERES/SARB the Earth Radiation Budget Experiment (ERBE) project did not attempt detailed radiative transfer methods to augment the TOA measurements because of the unavailability of global aerosol data (top of Table 1). SARB used several global aerosol climatologies initially to provide the required aerosol information to the Fu-Liou model. The climatologies were global in coverage but offered only annual or seasonal temporal resolution. Constituent composition information of the aerosols was not well developed and consequently associations to optical properties could only be assumed. Information on the vertical distribution of aerosols within the atmosphere were also undefined for the climatologies.

II. Present Aerosol Technologies in CERES SARB

The MODIS instantaneous aerosol retrievals are the primary source for input into the radiative transfer model of the present SARB. Located on the same space platforms as CERES on AQUA and TERRA, MODIS offers simultaneous aerosol estimates from similar observation angles as the CERES instruments. Over-ocean and over-land retrieval methods for aerosols are operational by MODIS atmospheres (MOD04 products, Kaufman et.al., 1997). Cryosphere and desert land areas are not included in the MODIS products because their high surface albedo is problematic for the aerosol retrieval process. When instantaneous MODIS aerosols are not available, the SARB uses time interpolations of gridded daily aerosol products from MODIS (MOD08). Neither MODIS source provides altitude specific aerosol information so climatological vertical distributions are assigned.

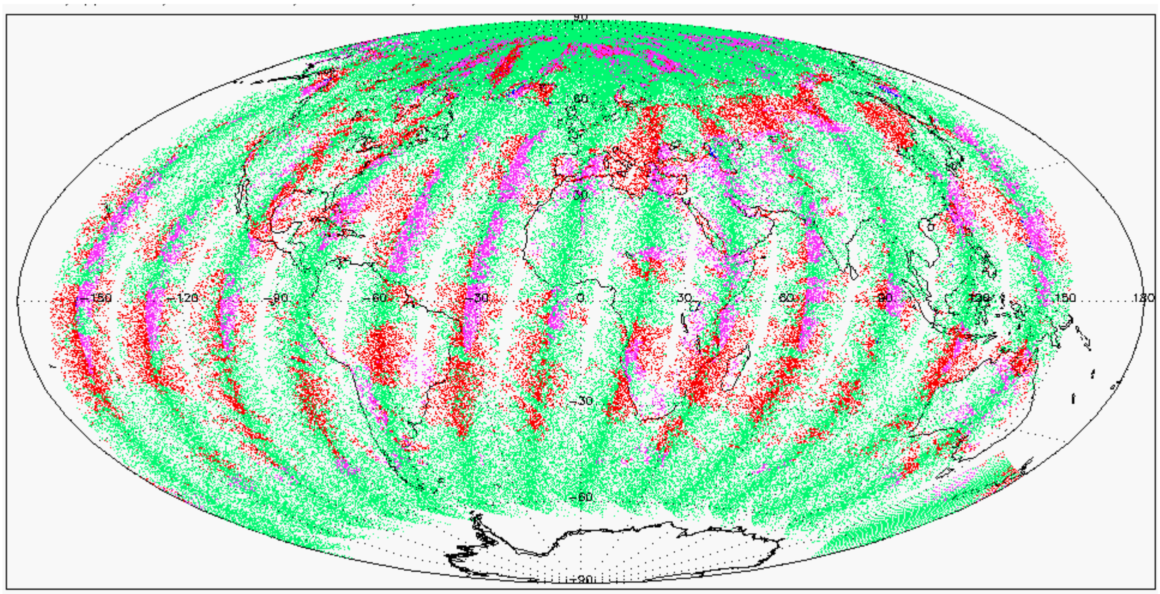

Figure 1. Spatial distribution of aerosol sources used in CRS edition 2a for June 23, 2000 from the CERES FM2 instrument aboard the TERRA satellite. Only 20% of footprints are displayed to enhance the graphical effect. Red pixels represent footprints which have aerosol information from instantaneous MODIS retrievals. Purple pixels represent footprints which have aerosols that are time interpolated from a MODIS daily gridded product. Green pixels represent footprints in which aerosols were obtained from MATCH .

When neither MODIS product is available, the CERES SARB uses the Model of Atmospheric Transport and Chemistry (MATCH) model aerosol information. Missing aerosol data is mostly due to intermittent or long duration cloudiness in the scene of view by the MODIS and CERES sensors.

The SARB operationally creates the CERES Surface and Radiation Budget product (CRS) that includes computed radiation and also the inputs to the radiative transfer model from the ancillary sources. Figure 1 displays CRS data for the entire planet demonstrating the spatial distribution of the aerosol sources required for processing a single day (June 23, 2003) of CERES/SARB data. All of the CRS footprints use the MATCH aerosol constituents information. The constituent types associate the optical property information (from OPAC or Tegin and Lacis) to the remotely sensed (spatially and vertically distributed) aerosols. In this way, optical properties of the aerosols (asymmetry factors and single scattering albedo) are available for the radiative transfer calculations.

III. Time Series of SW Irradiance from Surface and Space-borne Sensors

The SARB working group has established the CERES/ARM Validation Experiment (CAVE). This operational website (www-cave.larc.nasa.gov) avails high quality surface radiation observation data and CERES/SARB data products to the earth sciences research community. The CAVE archives data from several surface radiation observation networks (Baseline Surface Radiation Network / World Meteorological Organization, SURFRAD/NOAA's Surface Radiation Research Branch, SIROS/NOAA's Climate Monitoring and Diagnostics Laboratory and the Atmospheric Research Measurements program of the DOE). Forty-six surface observation sites are included in the CAVE. Since the SARB computes surface radiation parameters and the surface observation sites included in the CAVE make surface radiation measurements, a comparison of these two data sets can be instructive for validating the SARB products.

The inclusion of sites in this analysis resulted from a screening process imposed on the individual sites within the CAVE. Only sites with minimum of five coincident CRS radiation data and surface observations per month were included. Additionally, only sites represented by nine of the twelve months of the year were included. The MODIS cloud imager determined this data to be a clear-sky grouping. The screening resulted in a set of thirteen sites including ARM/DOE sites located in the Southern Great Plains region of the United States and two NOAA/SURFRAD sites (Fort Peck, MT and Desert Rock, NV).

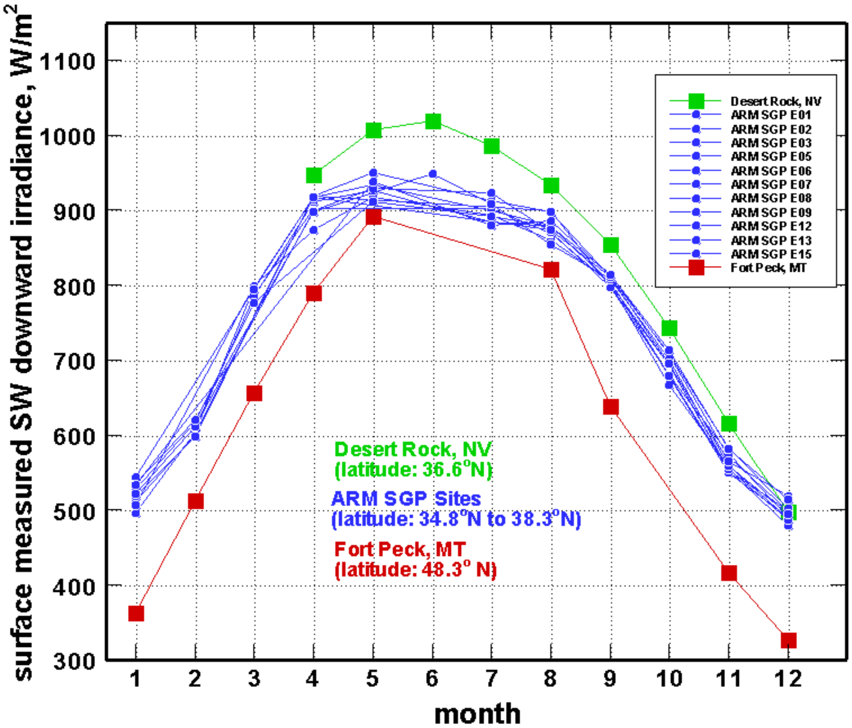

Figure 2. Clear-sky surface observations of downward global SW irradiance from thirteen US sites.

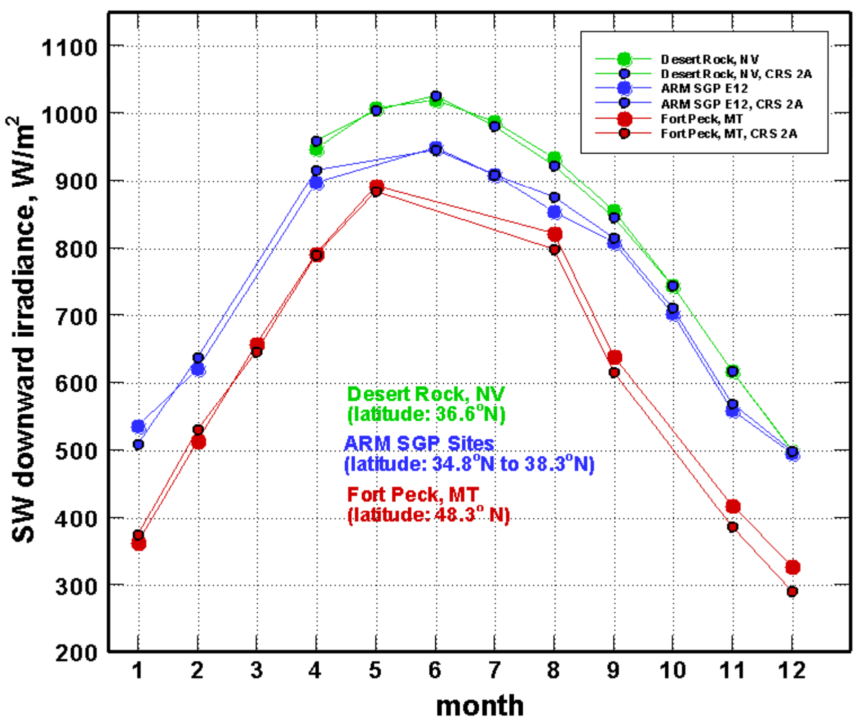

Figure 3. Clear-sky monthly mean surface observations and CERES/SARB CRS Edition 2A downward global SW irradiance

The time series of monthly means of SW downward surface measured solar flux for all thirteen sites (Figure 2) shows the annual cycle and a clear latitude effect. All of these sites are in the northern hemisphere so their annual downward SW irradiance peaks in the middle months of the year. The northern-most (red: Fort Peck) site shows the lowest annual variation. The sites associated with the ARM/SGP are dispersed in an area of approximately 143,000 km^2 centered over the state of Oklahoma. The observed downwelling SW radiation associated with this network of sites shows group self-similarity. The variability amongst the ARM/SGP sites is interpreted to represent the true variability of these parameters for this area (with the understanding that the surface instrumentation uncertainties are imposed on the measurements). The observations from the Desert Rock, NV site are the highest of the sites selected.

Example comparisons of SARB CRS radiation to surface observation radiation from three sites are shown in Figure 3. The annual variations of SW downward surface global irradiance are well mimicked by the SARB space-borne sensor/radiative modeling system. Random differences between the two measurement methods across months are generally observed except during months 5-12 of the Fort Peck comparisons. For this period, CERES/SARB surface SW systematically underestimates the surface observations made at the site. Monthly CERES/SARB edition 2A surface radiation results during clear-sky from all thirteen of the sites show strong positive correlation to the associated surface observations (Figure 4). The Fort Peck site presents the largest differences between SARB derived and surface measured.

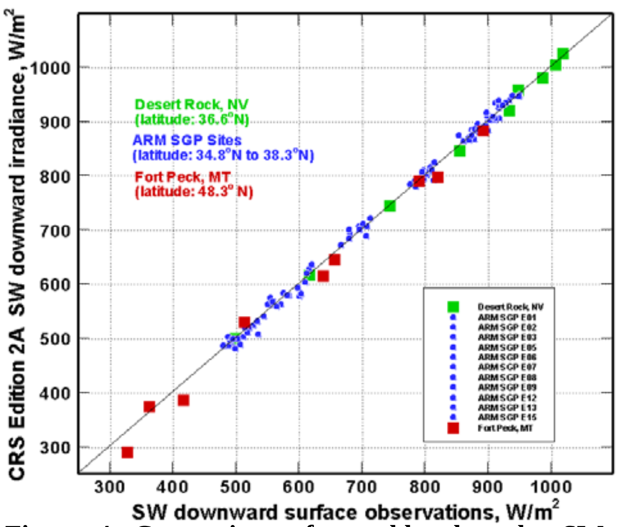

Figure 4. Comparison of monthly clear-sky SW downward irradiance at thirteen surface observation sites. Surface radiometer observations versus SARB derived SW downward irradiance.

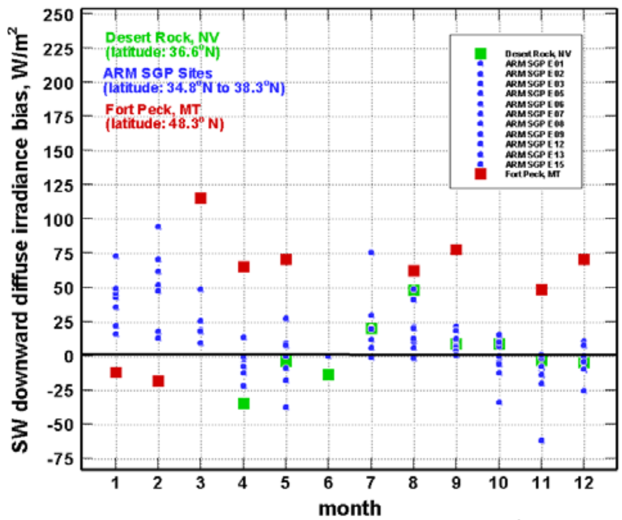

Figure 5. Monthly time series comparison of clear-sky SW downward diffuse irradiance bias at thirteen surface observation sites.

To focus on aerosol effects, reviewing a comparison of the diffuse component of the global radiation may be instructive. As the aerosol loads change so does the partitioning between the component quantities of global downwelling SW (direct component and diffuse component). The surface sites measure the radiation components separately using different instruments (direct: pyrheliometers and diffuse: shaded pyranometers). These quantities are specifically modeled in the Fu-Liou radiative transfer model and summed to produce the global downward SW.

The variation of the differences between the surface observations of diffuse flux and the CERES/SARB diffuse flux derived is presented as the diffuse bias (CRS – observed) in Figure 5. Trends in the diffuse bias as a function of month of the year suggest that no simple constant bias principle is operating at the ARM/SGP sites or the Desert Rock site. For these sites, a similar trend of bias for months 4 through 12 are observed. Generally, for these sites, a negative bias exists for April through June and from November to December. For these sites, a positive diffuse bias exists for the months from July through October. Negative bias is also observed for the ARM/SGP sites for the January through March period. Systematic positive biases for the Fort Peck site are observed for the periods of March through December.

IV. Diffuse Bias Effects on Surface Aerosol Forcing

The SARB CRS products include TOA and surface aerosol forcing estimates based on radiation computations for clear skies with aerosols minus pristine atmospheric conditions (no aerosols). The CRS derived forcings are considered here as they relate to the diffuse biases. For this analysis, the ARM/SGP site E01 was omitted from the analysis because it had extremely large outliers (diffuse biases greater than 375 W/m^2 ->physically impossible). The relationship between monthly averaged data for diffuse bias and surface aerosol forcing shows a weak but statistically significant negative slope (Figure 6). The monthly averaged diffuse biases from all the selected sites range from –60 to +112 W/m^2. The range of monthly aerosol forcing was –3 to –35 W/m^2. A majority of the Fort Peck data cluster in the region of high positive diffuse irradiance bias (50-112 W/m^2) and more negative aerosol forcing (-25 to –35 W/m^2). The regression line of figure 6 is statistically significant at the 99% confidence level (F-statistic: 52.64 on 1 and 111 degrees of freedom, p-value: 5.7e-11). The R^2 value is 0.352.

By omitting the influence of the Fort Peck data points, the resulting regression line (not shown) is still significant at the 99% confidence level. The associated R^2 for the remaining points after removing the Fort Peck data is 0.209.

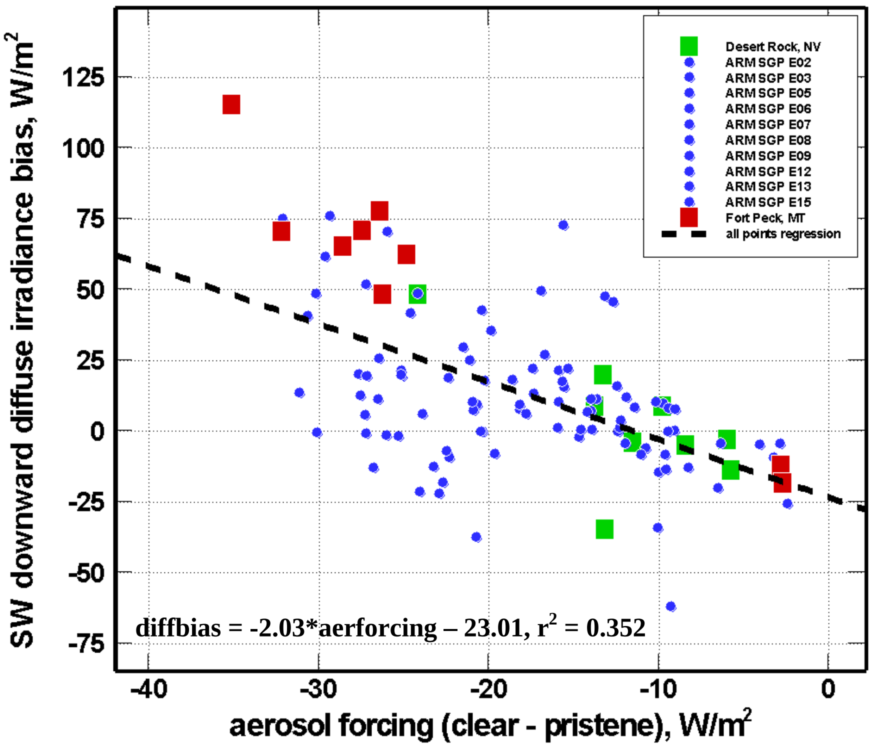

Figure 6. Relationship between diffuse irradiance bias and aerosol forcing associated with the SW downwelling at the surface for twelve selected observation sites.

Since the partitioning of the direct and diffuse components of the downwelling solar radiation systematically co-vary with the aerosol loading, the observed diffuse biases are problematic. This significant functional relationship suggests that the SARB aerosol information may not be sufficiently accurate to correctly partition the computed direct and diffuse radiation components. If this is the case, the estimated aerosol forcing appears to be effected by the aerosol inaccuracies. These data in themselves are not sufficient to identify the specific nature of the aerosol inaccuracies. The candidate reasons include: mismatched spatial or temporal sampling criteria between the SARB and the surface measurements, inappropriate aerosol quantities (optical depths) or qualities (constituents and associated optical properties) that ingested into the SARB radiative transfer algorithms, or interactions between these candidate reasons. It is also unrealistic to consider the surface measured radiation quantities, which are a component of the biases, as ideal observations. Any biases for the surface observations are also included in this summary.

V. Aerosol Retrieval Progress over the Oceans

Noticeably absent from the present analysis are surface measurement sites representing the surface area associated with the worlds oceans, the largest single surface type of the planet. Seven of the sites found in the CAVE represent the world's ocean areas but none were included in the previous analysis because of selection criteria used. The ocean sites in general produce precious few coincident SARB/CRS products and surface observations matches because of the high percentage of marine clouds at these sites. The CAVE includes island sites and an ocean platform-based site in the coastal zone region of the Atlantic Ocean off the coast of Virginia. The ocean sites hold potential for validation of aerosol retrieval algorithms because of the low surface albedo of the ocean in the SW wavelengths. With the low albedo surface of the ocean as a background, the contrast between radiation scattered by the aerosols and the surface is maximized. Because of the importance of accurate aerosol retrievals by satellites to the CERES/SARB project, CERES established the CERES Ocean Validation Experiment (COVE). A brief description of the COVE has been reported previously (Jin et.al., 2002).

We compare surface measured aerosol optical thickness by sunphotometer instruments to the MODIS retrieved product (MOD04_L2, Kaufman et.al., 1997) to determine the usefulness of over ocean measurements in understanding aerosol radiative effects on the radiation budget.. The surface measurements use sunphotometers associated with the Aerosol Robotic Network (AERONET) implemented by NASA Goddard (Holben et.al., 1999). The ARM/SGP CART site E13 and the COVE site are both members of the AERONET operational network.

The MODIS Atmospheres group uses different algorithms depending on whether the retrieval is over land or over ocean. There are large differences in the surface characteristics of the land versus those of the ocean sites. The important differences include: surface albedo, spatial heterogeneity, topographical relief, wind effects, and opacity of the scene (for example: the ocean surface may transmit radiation 100s of meters below the surface).

AERONET observations at the two sites were operational before the (TERRA and AQUA) MODIS sensors were deployed in space, consequently over four years of data for comparison are available (2000-2003). The 660/670 nm wavelengths were chosen from the MODIS sensor and the AERONET sensor respectively. The two filter functions for these wavelengths from these two instruments are different (full width half max (approx): MODIS-30nm, AERONET-10 nm). This results in the expectation that the two instruments would not theoretically produce identical optical depths from the same atmosphere scene. In practice, these differences should be quite small and they are not quantified here. The time synchronization between these two data sets has been set to +/- 5 minutes. This may be considered simultaneous for our purposes since most of the time, true aerosol properties change very little in five minutes.

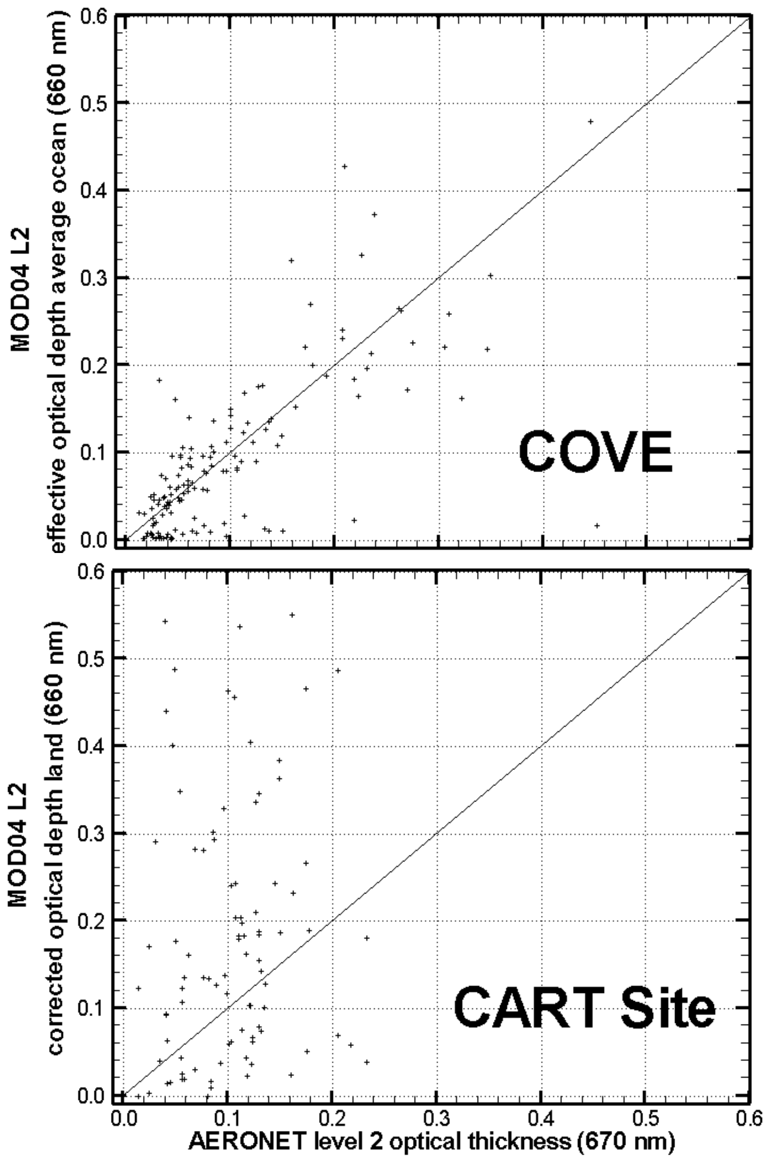

Figure 7. Comparisons of AERONET level 2 optical thickness surface observations (670 nm) to MODIS Atmospheres retrieved aerosol optical thickness (MOD04_L2, 660 nm) for the COVE site and for the ARM Central Facility site (E13). Data are from single 10X10 km pixels which cover the sites. Lines are 1:1 lines. All data from the MODIS validation archive for the years 2000 through and including 2003 are presented.

The comparison of surface measured to remotely sensed optical depth indicates that the MODIS Atmospheres retrieval over ocean (COVE) is performing appreciably better than over land (CART) as indicated by the grouping of the data relative to the 1:1 lines (figure 7, top). The COVE comparison presents a dataset where the bivariate points generally cluster along the 1:1 line with higher variability observed at optical depths greater than 0.15. A small grouping of points where the COVE MOD02_L2 optical depths are below 0.04 do not show high correlation with the AERONET data. The optical depth comparison over land (Figure 7 bottom, CART Site) shows a weak association of bivariate points grouping relative to the 1:1 comparison line. The variability of the MOD04_L2 data are observed to be high through out the entire range of AERONET optical depths measured at the CART site.

VI. Conclusions

The technologies associated with understanding the global distributions of aerosols within the atmosphere have improved significantly within the past eight to ten years. Earth radiation budget projects of the nineties were incapable of using remotely sensed aerosol information to infer the complex three-dimensional nature of the radiative processes within the atmosphere because the aerosol information did not exist. Significant advances in aerosol remote sensing (VIRS, MODIS), aerosol dispersion modeling and atmospheric chemistry (MATCH) have given the Earth sciences community new possibilities for quantifying the effects of aerosols on the Earth's energy budget. CERES/SARB has sequentially incorporated the new capabilities in aerosol sciences to improve their estimates of the instantaneous energy budgets within the atmospheric column of the planet. By using surface measurements of downwelling radiation and comparing it to estimates which use the aerosols as inputs, we have shown that still further improvements in aerosol information is required to more accurately understand aerosol effects on the SW radiation. Evidence of over-land versus over-ocean retrieved aerosols by the MODIS Atmospheres group compared to surface observations indicates the over-ocean method is superior.

Acknowledgements

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