Comparisons of aerosol optical depth and surface shortwave irradiance and their effect on the aerosol surface radiative forcing estimation

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Received 6 May 2004; revised 6 December 2004; accepted 12 January 2005; published 6 April 2005.

[1] Column aerosol optical depth (AOD) and surface shortwave irradiance (SSI) measurements relevant to computation of the aerosol surface radiative forcing (ΔF) and forcing efficiency (β) were taken as part of Aerosol Characterization Experiment-Asia (ACE-Asia) at the Gosan surface site in Korea in April 2001. We compare the AOD and SSI derived from three different types of Sun photometers and three sets of radiometers. We also estimate the ΔF and β using two methods and quantify the observational uncertainties of these parameters. A comparison of the AOD at 500 nm shows that the three Sun photometers generally agreed within 0.014 (mean), 0.0142 (bias), and 0.0298 (root mean square) for coincident observations. Over the course of the comparison, the mean differences between the SSI measurements were 1.6, 11.7, and 10.1 Wm^{-2} for direct, diffuse and global irradiances, respectively. However, for both the AOD and the SSI comparisons, relatively high instantaneous differences between the instruments were apparent on days with heavy dust at the surface. The mean β and associated deviations, which were estimated by the combinations of different instrument-derived AODs and SSIs, for simultaneous observation data at a 60° solar zenith angle are -79.50 ± 3.92 and -82.57 ± 5.70 Wm^{-2}/τ_{500} for $global_{shaded}$ (sum of direct and diffuse irradiances) and $global_{unshaded}$ (measured by the unshaded pyranometer) irradiances, respectively. The uncertainties in β associated with uncertainties in the AOD and SSI (in parentheses) for $global_{shaded}$ and $global_{unshaded}$ irradiance are about 8.6% and 3.2% (10.7%), respectively. A 2% difference between the measured global irradiances for a given 9 days was translated into an uncertainty of 19% in ΔF. This difference in ΔF between instruments caused a 14% deviation in β.

Citation: Kim, S.-W., A. Jefferson, S.-C. Yoon, E. G. Dutton, J. A. Ogren, F. P. J. Valero, J. Kim, and B. N. Holben (2005), Comparisons of aerosol optical depth and surface shortwave irradiance and their effect on the aerosol surface radiative forcing estimation, *J. Geophys. Res.*, *110*, D07204, doi:10.1029/2004JD004989.

1. Introduction

[2] There is much interest in quantifying and reducing the uncertainties in calculations of the aerosol direct radiative forcing (ADRF), which is defined as the change in the global radiation balance attributable to changes in the amount of light scattered and absorbed by particles suspended in the atmosphere. Despite a good understanding of how atmospheric aerosols affect the Earth's radiation budget, the ADRF has larger uncertainties than those of greenhouse gases due to the relative short lifetime, nonuniform composition, size, spatial and temporal distributions of aerosols in the troposphere [*Charlson et al.*, 1992; *Schwartz and Andrea*, 1996]. Add to this that aerosol properties can be difficult to measure without instrumental offsets or bias and modeling the ADRF becomes difficult.

[3] Recently, more integrated studies of aerosols were performed to reduce the uncertainties of current estimates of the ADRF such as ACE-1 [*Bates et al.*, 1998], ACE-2 [*Raes et al.*, 2000], ACE-Asia [*Huebert et al.*, 2003], INDOEX [*Ramanathan et al.*, 2001] and TARFOX [*Russell et al.*, 1999]. In spite of numerous studies, there are substantial differences in ADRF estimates due to intrinsic errors in the observations and modeling. According to results from the Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia), which took place during the spring of 2001, the aerosol-induced radiative flux changes at the surface, in terms of aerosol surface radiative forcing (ΔF, defined as the difference between the net radiative flux calculated with and without aerosols) and forcing efficiency (β, defined as ΔF per unit aerosol optical depth), varied by tens of watts per square meter for the ACE-Asia region and were strongly perturbed by the varying aerosol loadings and types, surface albedo and relative humidity [*Huebert et al.*,

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0148-0227/05/2004JD004989$09.00

2003; *Markowicz et al.*, 2003]. Calculations of the daily mean ΔF with heavy dust loading differ by −58.1 W/m^2 and −52.1 W/m^2 on a day with heavy dust loading (DOY (day of year) 103, 2001), and, inversely, −29.0 W/m^2 and −34.0 W/m^2 on relatively clean day (DOY 105, 2001) by *Won et al.* [2004] and *Bush and Valero* [2003], respectively. In addition to the variability in the aerosol loadings, the estimated ΔF shows distinct differences due to different observational instruments, analytical periods and methods. For example, clear-sky shortwave ΔF at Gosan had a value of −30.5 W/m^2 from ground-based measurements from 25 March to 4 May 2001 [*Bush and Valero*, 2003], while an NCAR CRM simulation for April 2001 (16 days) estimated the value as −46.5 W/m^2 [*Won et al.*, 2004]. *Nakajima et al.* [2003] estimated a ΔF of −25.9 ± 8.3 W/m^2 from surface measurements, −30.7 ± 11.8 W/m^2 by satellite measurement, −19.8 ± 11.0 W/m^2 from the CFORS mesoscale chemical model and −21.6 ± 7.8 W/m^2 from the SPRINTARS model simulation for April 2001. These differences in the ΔF at Gosan site described in the above measurement and model studies stress the necessity of more accurate measurements of the aerosol optical properties (e.g., aerosol optical depth, single scattering albedo) and the surface solar irradiance before employing them in radiative transfer model simulations to reduce uncertainties in the ADRF.

[4] In this study, we present comparisons of the aerosol optical depth (AOD) and the surface solar irradiance (SSI) measured from three, independently calibrated, Sun photometers and sets of radiometers at Gosan during the ACE-Asia field campaign. From these measurements, we compute values of ΔF and β with two objectives: (1) to investigate how precisely we can measure the AOD and SSI from current radiometers over a broad range of aerosol loading conditions, and (2) to quantify how observational errors affect estimates of ΔF and β.

[5] Since the mid-1990s several networks for aerosol optical properties and solar radiation measurements have operated globally; e.g., respectively AERONET [*Holben et al.*, 1998] and Baseline Surface Radiation Network (BSRN) [*Ohmura et al.*, 1998]. To evaluate the quality of data from global networks a comparison across various atmospheric conditions is needed because the spatial and temporal distributions of aerosol loadings and compositions in the troposphere are highly varied. However, to date, most intercomparison studies of the AOD and SSI have been made under clean atmospheric conditions for accurate calibration [*McArthur et al.*, 2003; *Michalsky et al.*, 1999; *Mitchell and Forgan*, 2003; *Schmid et al.*, 1999]. Comparisons of the AOD and SSI under a broad range of aerosol loadings are needed to verify the consistency of data from the various instruments before employing them in an assessment of the observational uncertainties in the ADRF.

[6] This paper investigates the performance of current radiometric measurements at Gosan, South Korea, where AOD levels are 0.03–1.1 in the midvisible, and their effect on estimations of the ΔF and β. Section 2 gives brief descriptions of the instruments used in this study. In sections 3 and 4, we present comparisons of the AOD and SSI derived from independently calibrated Sun photometers and radiometers. We discuss the source of discrepancies and suggest what factors might help to reduce them. In section 5, we present calculations of the ΔF and β using two analytical methods, a direct approach using only measurements and a hybrid method which combines measurements and model calculations. We discuss the sensitivity of ΔF and β to the AOD and to the SSI. In the final section, we summarize and discuss how these results can be applied to minimize the observational errors to improve estimates of ΔF and β.

6. Summary and Conclusions

[42] We compared aerosol optical depths (AOD) and surface shortwave irradiances (SSI) measured from three Sun photometers and sets of radiometers at Gosan during the ACE-Asia field campaign in April 2001. We also quantified the effects of the uncertainties in the AOD and SSI estimates of aerosol surface radiative forcing (ΔF) and forcing efficiency (β). The principal findings of our analysis are summarized below:

[43] 1. The 500 nm AOD (τ_{500}) ranged from 0.05 to 1.0 at Gosan over the course of the ACE-Asia campaign. The mean (τ_{500}) shows a good agreement within 0.014 (3.6%). However, bias and root mean square differences of this study over a broad range of aerosol loadings are larger than previous comparison studies.

[44] 2. In spite of good statistical agreements, the CMDL Sun photometer showed lower AOD values under high AOD (>0.7) conditions, but higher values in clean conditions (<0.2) than that of other instruments. Instantaneous differences of τ_{500} between instruments were as large as 0.09 on a heavy dust day and may be due to differences in daily cleaning and tracking errors as well as measurement elevation of the instruments.

[45] 3. Over the course of the comparison, the mean difference of SSI was 1.6, 11.7 and 10.1 Wm^{-2} for direct, diffuse and global irradiance, respectively. However, an 8% difference on a heavy dust day (DOY 103) between direct radiometers was apparent. Distinct diurnal variations in the absolute differences of diffuse and global irradiances were prevalent on most days and is likely due to a difference in the cosine angular response of the instruments.

[46] 4. The mean βs and associated deviations, which were estimated by the combinations of different instrument-derived AODs and SSIs, for simultaneous observation data at 60° solar zenith angle over a 24 hour time period are −411.14 ± 10.6, 126.46 ± 5.68, −79.50 ± 3.92 and −82.57 ± 5.70 Wm^{-2}/τ_{500} for direct, diffuse, global$_{shaded}$ and global$_{unshaded}$ irradiances, respectively.

[47] 5. The effect of AOD and SSI (in parenthesis) on β, which was estimated by the direct method, relative to the mean value is about 4.3% (1.8%), 4.8% (2.7%), 8.6% and 3.2% (10.7%) for direct, diffuse, global$_{shaded}$ and global$_{unshaded}$ irradiance, respectively.

[48] 6. A 2.0% difference in the measured global irradiance for a given 9 days in this study caused differences of 16.8–19.0% in ΔF. Theses differences in ΔF between instruments caused about 4.5%–14.0% deviations in β.

[49] 7. The maximum deviation of β at 60° solar zenith angle due to a combined errors of AOD and SSI measurements is about 4.8%, 4.8% 6.5% and 10.8% for direct, diffuse, global$_{shaded}$ and global$_{unshaded}$, respectively.

[50] In this study, the discrepancies among instruments on several dusty days degraded the short-term comparisons of AOD and SSI, and ΔF and β derivations. However, this dependence on dust days might be reduced in long-term analyses. Further long-term measurement with more careful calibration, field maintenance and analysis should help to quantify and reduce the observational uncertainties in climate aerosol forcing.