Aerosol Direct Radiative Forcing: A Five Year Climatology at the ARM SGP CART Site

Q. Fu, G. Lesins, and J. Higgins
Dalhousie University
Halifax, Nova Scotia, Canada

J. J. Michalsky
State University of New York
Albany, New York

Introduction

Aerosols are a suspension of small solid and liquid particles in the atmosphere. These particles can reflect and absorb solar radiation, which is the aerosol direct effect. Aerosols can also modulate the radiative energy budget through their impact on cloud particle size, cloud liquid/ice water content, and cloud lifetime, which is the aerosol indirect effect. The objective of this study is to analyze the aerosol direct radiative forcing at the top of the atmosphere using the data set collected at the Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains (SGP) central facility from 1994 to 1998. The focus here is to evaluate the uncertainty in the estimated aerosol radiative forcing.

The aerosol radiative forcing is defined as the difference between the outgoing solar flux without aerosols and the flux with aerosols under clear-sky conditions. The radiative flux in the atmosphere with aerosols can be derived from either satellite observations or model simulation using observed input data while the flux without aerosol can be derived from the model. In this study, we have analyzed the aerosol radiative forcing using a radiation model with input data collected at the ARM SGP central facility. Herein, we only consider cloud-free periods no shorter than 30 minutes (Fu et al. 1998a) so that we have in total 3604 30-minute averaged cases.

The radiation model used is the delta-four-stream radiative transfer algorithm for plane-parallel atmospheres (Liou et al. 1988; Fu and Liou 1993). The nongray gaseous absorption due to H_2O, CO_2, O_3, O_2, N_2O, and CH_4 has been parameterized using the correlated k-distribution (Fu and Liou 1992; Fu et al. 1998b). The model-input data include the temperature and water vapor profiles from radiosondes every three hours. The water vapor profiles have been scaled by the precipitable water vapor content derived from Microwave Radiometers. The ozone profiles are based on the U.S. standard atmosphere but scaled by the Dobson observation. For the surface albedo, we have considered the spectral dependence following Briegleb et al. (1986) for the grass/shrub surface, which is scaled by the measured broadband surface albedo. The aerosol optical depths at 0.413, 0.5, 0.609, 0.664, and 0.86-micron meter are derived from Multifilter Rotating Shadowband Radiometer (MFRSR) measurements (Harrison et al. 1994). The mean aerosol optical depth at a wavelength of 0.5-micron meter is 0.123 based on five years data, while the mean Angstrom exponent is 1.1. We have also found that the aerosol optical depth in the summer is larger than that in the winter.

Before we evaluate the aerosol radiative forcing at the top of the atmosphere, we first want to validate our radiation model with observed input data using the Baseline Surface Radiation Network (BSRN) surface solar radiation observations, which provide downward solar diffuse, normal direct, and total irradiances. The comparison of downward surface direct fluxes between the model and observations reveals that the mean difference is 3.6 W/m^2 out of the mean observed flux of 434.2 W/m^2. It should be noted here that the most reliable measurement of solar radiation is the direct beam measured by the cavity radiometer; its typical uncertainty is about 0.3% and the BSRN pyrheliometer is well calibrated using the cavity radiometer (Michalsky et al. 1997). This comparison suggests that reliable measurements of atmospheric profiles and aerosol optical depth are being used for radiation simulation and also demonstrates an accurate parameterization in our model for Rayleigh scattering and atmospheric gaseous absorption.

For downward surface solar diffuse fluxes, the mean difference between the model and measurements is about 20 W/m^2 out of the mean observed value of 76 W/m^2. Since we do not have aerosol composition and size distribution measurements, we have used the aerosol single-scattering albedo and asymmetry factor based on d'Almeida et al.'s (1991) rural aerosol type, which is considered to be the most likely present at the measurement site. The diffuse difference found here agrees with studies by Charlock and Alberta (1996), Kato et al. (1997), and Fu et al. (1998a).

There are several different hypotheses to explain the discrepancy between the model and measurements. The discrepancy can be largely due to the radiation measurement errors. The pyranometer measuring the diffuse fluxes is calibrated to cavity radiometers with the direct beam incident at 45 degrees. This is a high-level signal calibration compared to the typical clear-sky diffuse irradiance. In addition, there may be some problems associated with the cosine response of the instrumentation and its net thermal infrared (IR) energy loss. The bottom line is that there is no absolute calibration for diffuse instruments. However, it has been suggested that the diffuse measurement errors should not be significantly larger than 5 W/m^2 after considering the nighttime offset (E. Dutton, personal communication). Another possibility is the presence of more soot aerosols, which have strong absorption in the visible. However, in order to bring the model results within 5 W/m^2 of the observations, we need soot aerosol concentrations as high as those typical for urban areas. One idea suggested by Arking (1999) is that the H_2O continuum, which we neglect in the solar spectrum, may be responsible for the differences. If this is the case, the differences in the downward total surface fluxes between the model and measurements should be correlated to the precipitable water vapor. But our five-year data have shown zero correlation, which largely rules out the water vapor continuum hypothesis. Kato et al. (1997) have proposed an unknown absorbing gas "x" responsible for the discrepancy. The hypothesis we suggest is that background aerosols with small sizes may be responsible for the differences. These aerosols may have an optical depth of about 0.015 ~ 0.03 with a refractive index similar to carbonaceous or dust aerosols. However, if the aerosol particle is small enough, its absorption dominates and we would still have the Angstrom exponent of about one. The assumption of big dust aerosols can also bring the model results into agreement with measurements (T. P. Charlock, personal communication).

In this study, we find that the various hypotheses that have been put forward to explain the discrepancy between the model and measurements would result in very different aerosol radiative forcing at the top of the atmosphere. By using d'Almeida et al.'s (1991) rural aerosol single-scattering albedo and asymmetry factor, the five years averaged aerosol radiative forcing at the top of the atmosphere is

-6.5 W/m^2. Therefore, the aerosol has a cooling effect on the earth-atmosphere system. This is the case by assuming that the diffuse discrepancy is largely caused by the radiation flux measurement errors. By adjusting the aerosol single-scattering albedo to bring the model results into agreement with measurements to within 5 W/m^2, we obtain an aerosol radiative forcing at the top of the atmosphere of 1.8 W/m^2. Therefore, the aerosol has a warming effect on the earth-atmosphere. This is the case that the absorbing aerosol is assumed to be responsible for the difference, which can be soot aerosol, small background absorbing aerosol, or big dust aerosol. By assuming an unknown absorbing gas "x" to be responsible for the diffuse difference, we have the aerosol forcing of about -4.5 W/m^2.

The conclusions of this study are as follows:

- The discrepancy between the model and measurements in downward surface solar diffuse fluxes is still a mystery.
- Different hypotheses to explain the discrepancy result in large differences in aerosol direct radiative forcing.
- The uncertainty in aerosol direct radiative forcing has highlighted the need for closure experiments, which require accurate radiation measurements and an observing strategy for the aerosol composition and size distribution profiles.

Acknowledgments

The research work contained herein has been supported by U.S. Department of Energy, Grant DE-FG02-97ER62363.

References

Arking, A., 1999: Bringing climate models into agreement with observations of atmospheric absorption. *J. Climate*, **12**, 1589-1600.

Briegleb, B. P., P. Minnis, V. Ramanathan, and E. Harrison, 1986: Comparison of regional clear-sky albedos inferred from satellite observations and model computations. *J. Clim. Appl. Meteor*., **25**, 214-226.

Charlock, T. P., and T. L. Alberta, 1996: The CERES/ARM/GEWEX experiment (CAGEX) for the retrieval of radiative fluxes with satellite data. *Bull. Amer. Meteor. Soc*., **77**, 2673-2683.

d'Almeida, G., P. Koepke, and E. P. Shettle, 1991: Atmospheric aerosols-global climatology and radiative characteristics. A Deepak.

Fu, Q., and K. N. Liou, 1992: On the correlated k-distribution method for radiative transfer in nonhomogeneous atmosphere. *J. Atmos. Sci*., **49**, 2139-2156.

Fu, Q., and K. N. Liou, 1993: Parameterization of the radiative properties of cirrus clouds. *J. Atmos. Sci.*, **49**, 2139-2156.

Fu, Q., G. Lesins, J. Higgins, T. Charlock, P. Chylek, and J. Michalsky, 1998b: Broadband water vapor absorption of solar radiation tested using ARM data. *Geophys. Res. Let.*, **25**, 1169-1172.

Fu, Q., G. Lesins, W. B. Sun, and J. Higgins, 1998a: Downward surface diffuse solar irradiances in clear atmospheres: Comparison between model and observation. In *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, DOE/ER-0738. U.S. Department of Energy, Washington, D.C.

Harrison, L., J. Michalsky, and J. Berndt, 1994: Automated multifilter rotating shadow-band radiometer: An instrument for optical depth and radiation measurements. *Appl. Opt.*, **33**, 5118-5132.

Kato, S., et al., 1997: Uncertainties in modeled and measured clear-sky surface shortwave irradiances. *J. Geophys. Res.*, **102**, 25,881-25,898.

Liou, K. N., Q. Fu, and T. P. Ackerman, 1988: A simple formulation of the delta-four-stream approximation for radiative transfer parameterizations. *J. Atmos. Sci.*, **45**, 1940-1947.

Michalsky, J., et al., 1997: Optimal measurement of surface shortwave irradiance using current instrumentation: The ARM experience. 9th Conference on Atmospheric Radiation, Long Beach, California.