Radiative Forcing by Smoke Aerosols Determined from Satellite and Surface Measurements

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Introduction

As a potential offsetting agent to the greenhouse effect, aerosols are receiving increasing attention in the atmospheric science community. Notwithstanding, our knowledge of the impact of aerosols on radiation and climate is rather poor and falls well behind that of the greenhouse effect (IPCC 1995). Direct radiative forcing (DRF) of aerosols is an important climatic parameter measuring the influence of aerosols on earth's climate. Observational studies of aerosol DRF usually suffer from a shortage of in situ measurements of aerosol optical properties. This study introduces a new approach to determine atmospheric DRF due to smoke aerosols from fires in a boreal forest region under any sky conditions using satellite and surface measurements.

Methodology

The method involves the use of a satellite algorithm that retrieves solar radiation in the visible region from 400 nm to 700 nm (Li and Moreau 1996). This radiation is often referred to as photosynthetically active radiation (PAR), because it is the radiation in this spectral region that governs the photosynthesis of vegetation growth. The unique advantage of using this algorithm is that the retrieval is affected by very few atmospheric parameters, most notably the absorbing aerosols. Without the presence of absorbing aerosols, clouds have negligible absorption in the PAR wavelengths and so do conservative aerosols, water vapor, and other atmospheric constituents. Weak absorption due to ozone and oxygen is accounted for by the algorithm. Therefore, the difference between observed and estimated surface PAR is affected mainly by the atmospheric absorption of absorbing aerosols. In remote areas of the boreal forests in Northern Canada, the loading of background aerosols is so low that its fluctuation in the summer season is caused primarily by forest fires (Markham et al. 1997). Therefore, we can further attribute the difference to smoke DRF in the atmosphere.

The algorithm of Li and Moreau (1996) was derived from comprehensive radiative transfer modeling. It has been validated using National Ocean and Atmospheric Administration/advanced very high resolution radiometer (NOAA/AVHRR) and surface PAR measurements (Li et al. 1997a). The algorithm has the following input parameters: top of the atmosphere (TOA) visible albedo, atmospheric ozone content, solar zenith angle, and absorptive aerosol optical thickness. Aerosol optical thickness is set to zero when computing the aerosol DRF.

Data

All data employed in this study were acquired during the Boreal Ecosystem - Atmosphere Study (BOREAS) (Sellers et al. 1995). The experiment took place in the boreal forest regions of Saskatchewan and Manitoba, Canada, between 1994 and 1996. Intensive field campaigns were conducted in 1994 during which a variety of observations were made including PAR absorbed at the surface (APAR) at observational towers located in the middle of uniform forest stands. The measurements represent spatial averages over areas of several square kilometers. These ground-based observations were matched to satellite data. TOA visible albedo was derived from the Geostationary Operational Environmental Satellite (GOES) every half hour. This permitted an extensive validation of the algorithm, and calculation of daily and monthly mean DRF. The spatial resolution of the data is approximately 0.83 x 1.78 km^2 in the area of the BOREAS study region (Gu and Smith 1997). Calibration of the GOES data was based on Minnis et al. (1995). It was validated against data from the Scanner for Radiation Budget (ScaRaB) (Trishchenko and Li 1997). Using some ground control points obtained from high-resolution image chips, the GOES pixels were registered around the surface observation sites. Data collected in the summer of 1994 are analyzed here which is a fire active season in this region (Li et al. 1997b). By means of visual image inspection and satellite-based automatic detection, sky conditions were classified into clear, smoky, and cloudy days.

Analysis

To substantiate the argument that the difference between observed and estimated APAR approximates atmospheric DRF due to absorbing aerosols, a series of comparisons between observed and estimated APAR are presented. Figure 1 are comparisons for some benchmark cases of clear, smoky, and cloudy days. The agreement is very good for the clear-sky smoky-free day (June 8), good for the cloudy days (May 30 and June 24), and bad for the smoky day (July 30). The relatively large fluctuations in the comparisons of cloudy days originate from the mismatch in time and space of the scenes observed from space and at the surface. Such differences are smoothed out by averaging. The good agreements under clear and cloudy conditions also have bearings on the recent debate of atmospheric absorption. The comparison results do not support any significant absorption anomaly in the visible solar spectrum.

The above analysis confirms that the differences between observed and estimated APAR can be considered as an approximate estimate of the DRF due to absorbing aerosols. The method thus bypasses the frequently-encountered difficulties in obtaining aerosol optical properties. Instantaneous aerosol DRF was computed every half hour from satellite and surface measurements. Daily and monthly mean DRF were then derived from instantaneous

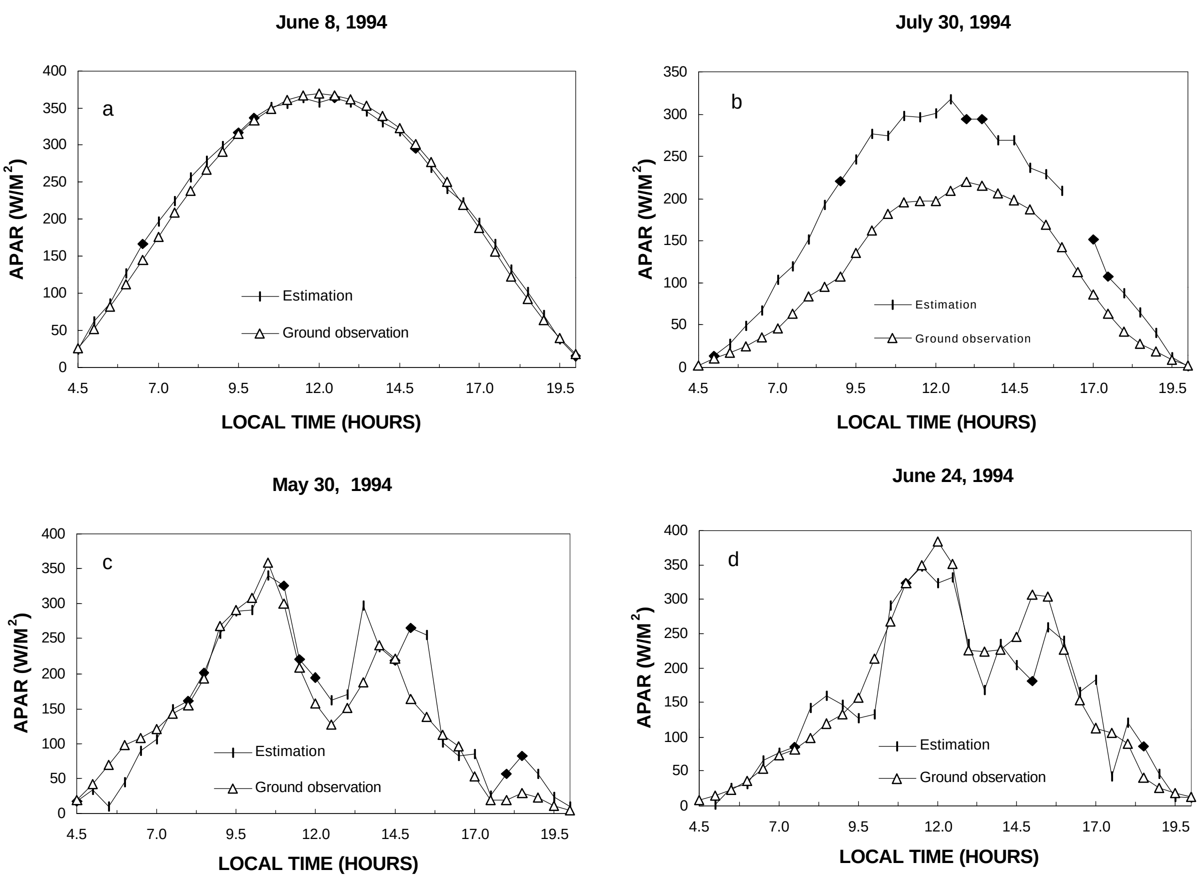

Figure 1. Comparisons of surface visible solar radiation observed at the ground and estimated from satellite (GOES) on a clear, smoke-free day (June 8), smoky day (July 30), and two cloudy days (May 30 and June 24).

values. Figure 2 plots the variation of daytime mean DRF, in comparison with daytime mean aerosol optical thickness from May 24 to September 9, 1994. Note that aerosol measurements were interrupted by the presence of clouds. Mean aerosol optical thickness was computed only for days having more than ten measurements. A strong day-to-day variation in DRF is seen, ranging from near zero to larger than 60 Wm^{-2}. The few negative values of DRF result from the artifacts caused mainly by mismatching satellite and surface observations. Each peak value of aerosol optical thickness corresponds to a local maximum of DRF.

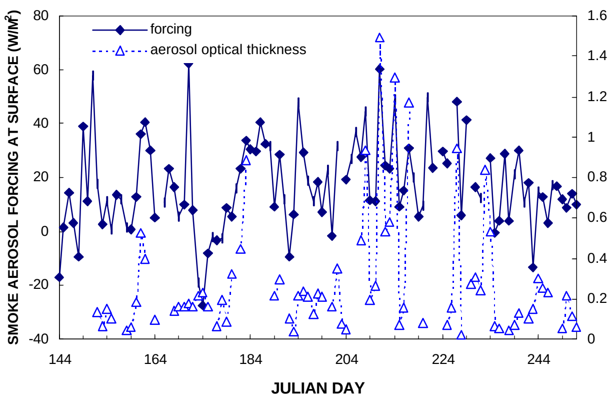

Figure 2. Day-to-day variation of the daytime mean direct radiative forcing by smoke aerosol with reference to daily mean aerosol optical thickness, averaged for days having at least ten measurements. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/li(1)-98.pdf*).

The monthly and daytime mean values of smoke DRF are shown in Figure 3. In July, it amounts to 26 Wm^{-2}. These values are halved for May and June. To put these estimates of smoke DRF in perspective, the total radiative forcing (TRF) at the surface was calculated. TRF represents the reduction of APAR by both clouds and aerosols. Following the concept of cloud radiative forcing, TRF is defined as the difference in the net radiative fluxes (down - up components) between all sky conditions and clear sky conditions. TRF can be determined as follows. First, surface observed APAR is plotted against the cosine of the solar zenith angle (SZA). Second, clear sky measurements with low aerosol loading (< 0.1) were identified according to surface and satellite observations. From these, a linear regression of APAR as a function of cos(SZA) is derived. Instantaneous TRF was determined as the difference between observed APAR given by the data points and the estimates of clear

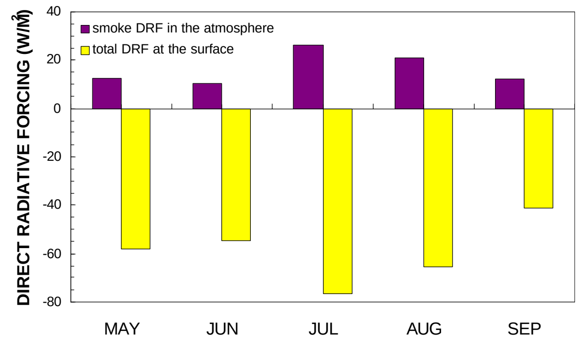

Figure 3. The monthly and daytime mean values of atmospheric direct radiative forcing by smoke aerosols, in comparison with the total radiative forcing at the surface due to both smoke and clouds. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/li(1)-98.pdf*).

sky values determined by the regression line for the corresponding SZA. Daytime mean TRF was computed as the average of instantaneous TRF values. It follows from Figure 3 that the atmospheric forcing by smoke contributes substantially to the reduction of solar radiation at the surface, especially in July and August when the former accounts for about one third of the latter.

Conclusions

Over the remote boreal forest region in western Canada, fire activities dominate the variation of aerosol loading during the summer season. A new method is introduced to determine the DRF of smoke aerosols. It does not require measurements of aerosol optical properties but observations of TOA reflection and surface transmission. Instantaneous, daily and monthly mean DRF due to smoke aerosols are computed. The monthly and daytime mean DRF caused by smoke reaches a maximum value of 26.0 Wm^{-2} in July 1994. In comparison, total radiative forcing due to both clouds and smoke amounts to -76.7 Wm^{-2} at the surface.

References

Gu, J., and E. Smith, 1997: High resolution estimates of total solar and PAR surface fluxes over large scale BOREAS study area from GOES measurements. *J. Geophys. Res*., in press.

Intergovernmental Panel on Climate Change (IPCC), 1995: *Climate change 1995: The science of climate change*, edited by J. T. Houghton et al., pp. 572. Cambridge University Press, Cambridge, United Kingdom.

Li, Z., L. Moreau, and J. Cihlar, 1997a: Estimation of the photosynthetically active radiation absorbed at the surface over the BOREAS region. *J. Geophy. Res.*, **102**, 29,717-29,727.

Li, Z., J. Cihlar, L. Moreau, F. Huang, and B. Lee, 1997b: Monitoring fire activities in the boreal ecosystem. *J. Geophys. Res.*, **102**, 29,611-29,624.

Li, Z., and L. Moreau, 1996: A new approach for remote sensing of canopy absorbed photosynthetically active radiation, I: Total surface absorption. *Rem. Sens. Environ.*, **55**, 175-191.

Markham, B. L., J. S. Schafer, B. N. Holben, and R. N. Halthore, 1997: Atmospheric aerosols and water vapor characteristics over north central Canada during BOREAS. *J. Geophys. Res.*, **102,** 29,737-29,745.

Minnis, P., W. L. Smith, D. P. Garber, J. K. Ayers, and D. R. Doelling, 1995: Cloud properties derived from GOES-7 for spring 1994 ARM intensive observation period using version 1.0.0 of ARM satellite data analysis program. *NASA Reference Publication*, 1366, 58 pp.

Sellers, P., F. Hall, H. Margolis, B. Kelly, D. Baldocchi, G. den Hartog, J. Cihlar, M. G. Ryan, B. Goodison, P. Crill, K. J. Ranson, D. Lettenmaier, and D. E. Wickland, 1995: The boreal ecosystem-atmosphere study (BOREAS): An overview and early results from the 1994 field year. *Bull. Amer. Meteorol. Soc.*, **76**, 1549-1577.

Trishchenko, A., and Z. Li, 1997: Use of ScaRaB measurements for validating a GOES-based TOA radiation product. *J. Appl. Meteor*., in press.