FORM A: GACP ACCOMPLISHMENT REPORT

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TITLE: Satellite study of the smoke indirect radiative forcing.

ABSTRACT: The magnitude of the aerosol indirect radiative forcing of climate, in which aerosols can affect the earth's climate by modifying cloud microphysics and altering cloud albedo and cloud fraction, is the largest unknown in estimating the total anthropogenic forcing that causes climate change. Due to its complex geographic and seasonal variability, aerosol forcing was suggested as a possible fingerprint to the response of the climate system to human impact. Not much observational evidence of the indirect aerosol effect exists and existing observations present a confusing picture of partial answers and contradictions. Previous studies using AVHRR satellite data in the biomass burning regime of Brazil were successful in identifying the indirect effect on a regional scale and suggesting the intervention of an additional controlling factor - water vapor. Satellite data provide a large statistical sampling of the aerosol effect on clouds, an advantage in sorting between the many factors affecting the properties of individual clouds. We propose a study that would continue in the same spirit as these previous AVHRR studies, using three data sets with different spatial resolutions. The range of spatial resolutions spans the 50 m of the ER-2 MODIS Airborne Simulator to the 1 and 4 km of AVHRR and later EOS-MODIS which will be launched in the summer of 1998. We plan to use several proven retrieval methods to study the aerosol effect on clouds. The analysis will be applied independently to data from several years and locations. The study will concentrate on smoke aerosol because it is this aerosol type that presents the most established link between optical thickness measured by satellite and the cloud condensation nuclei (CCN) that influence cloud microphysics. The recently performed SCAR-B (Smoke Cloud And Radiation-Brazil) experiment provides a wide body of knowledge on the smoke properties that will be used in this study. The proposed study will attempt not just to document the indirect effect when it occurs but also to understand the factors that control and modify the aerosol effect on cloud droplet size, cloud albedo and possibly also cloud coverage. To this end, we plan to use model simulations of the interactions of aerosol and clouds in the presence of varying atmospheric conditions (e.g. water vapor concentration and temperature profile).

The expected results will include comprehensive analysis of the effect of smoke on clouds in South America and other regions. The impact of water vapor, other atmospheric parameters, cloud size and type on the indirect aerosol forcing of climate will be derived empirically from the satellite data and understood using simulations by models. The intended results will also include an algorithm that can be applied to any AVHRR data set and run independently in order to generate a comprehensive data base of cloud macro and microphysical properties, aerosol optical thickness and precipitable water vapor open to the wider community of climate researchers.

GOALS: (1) To determine the anthropogenic component of the global aerosol radiative forcing, both direct and indirect. (2) To refine remote sensing techniques in order to better meet goal (1).

OBJECTIVES: To use airborne and satellite imagery over tropical biomass burning regions in order to identify possible smoke indirect radiative forcing. To combine satellite imagery analysis and cloud modeling to identify the physical processes controlling the effect. To estimate the ability of remote sensing to quantify the global indirect radiative forcing produced by tropical biomass burning smoke.

APPROACH: We use AVHRR 1 km data to determine cloud and aerosol properties over South America during the biomass burning season, and combine these data with water vapor data acquired from the Goddard Data Assimilation Office (DAO). This provides our primary multi-year data base in which to look for relationships between cloud properties, smoke optical thickness and precipitable water vapor. The SCAR-B MODIS Airborne Simulator (MAS) data from 1995 allows us to test our AVHRR results with finer resolution data, and to help quantify the role of mixed cloud-clear pixels in both the analysis and in the physical process. In addition we are looking for an understanding of the physical relationships between variables with a numerical cloud model, and use global transport models with ISCCP cloud climatology to estimate the ability of remote sensing to quantify the global indirect radiative forcing produced by tropical biomass burning smoke.

TASKS COMPLETED: (1) DAO precipitable water vapor data validated with AERONET sunphotometer data. (2) Software developed to ingest and process DAO water vapor data with AVHRR data. (3) Two years of AVHRR data analyzed. (4) Numerical cloud model initiated and tested. (5) Numerical cloud model performed simulations over a broad range of parameter space. (6) Four days of MAS data analyzed for aerosol optical thickness and precipitable water vapor. (7) Scale analysis of remote sensing of indirect effect using MAS data started. (8) Preliminary results obtained for estimates of remote sensing effectiveness in observing the indirect effect using two transport models and ISCCP cloud climatology.

FUTURE PLANS: Expand AVHRR analysis for multi-year comparisons. Begin to include mixed pixels in the AVHRR analysis, while simultaneously using the MAS data to look at sensitivity to different spatial scales and how mixed cloudy/clear pixels affect the results. Continue with the cloud modeling studies to further identify the different physical processes and parameters affecting the indirect effect. Continue with theoretical studies using global transport models and ISCCP data to better estimate the effectiveness of remote sensing to observe the indirect effect.

RESULTS:

<u>AVHRR Analysis</u>: We have identified the indirect effect in Brazil in a second year of data (1995). There are differences between the two years. In 1995, the indirect effect tends to saturate at lower optical thickness than in 1987. There are indications that the indirect effect is stronger in the northern regions. Yet when categorized according to precipitable water vapor, it is the drier pixels that exhibit the strongest indirect effect. However, the differences between latitudinal zones and precipitable water vapor categories are small. Below is a Table giving a short summary of the results. dlnre/dlntau is the log derivative representing the change in effective cloud droplet radius with change in aerosol optical

thickness, our measure of the indirect effect. Negative values indicate that cloud droplets become smaller as smoke amounts increase.

	1987	1995		1987	1995
Lat	dlnre/dlntau		PWV(cm)	dlnre/dlntau	
0-5N	-0.36	-0.41	<2.5	-0.47	-0.73
0-5S	-0.30	-0.35	2.5-3.5	-0.38	-0.56
5-10S	-0.22	0.157	3.5-4.5	-0.34	-0.31
11-20S	-0.33	-0.34	>4.5	-0.24	-0.36

<u>Cloud Modeling Analysis</u>: (1) We have found a linear relationship between cloud liquid water path (LWP) and precipitable water vapor (PWV) that might indicate that the stronger aerosol indirect response observed in the 1987 data at higher PWV is associated with clouds with higher LWP. However this link between PWV and LWP weakens as clouds become progressively subadiabatic. (2) The response of cloud effective radius to a change in smoke optical depth (dln re/dln tau) depends on the size parameters of the smoke aerosol, aerosol solubility, and the cloud updraft velocity. For clouds of similar liquid water content, a *stronger response* of effective radius to smoke optical depth occurs under the following conditions: (a) *decreasing* aerosol concentration (b) *decreasing* aerosol median size (c) *increasing* cloud updraft velocity (d) *increasing* soluble mass fraction of the aerosol. (3) We have performed simulations over a broad range of smoke aerosol parameter space and obtained regressions for the relationship between cloud optical depth and aerosol optical depth. Further analysis of these regressions yields a theoretical framework for describing the relative response of cloud effective radius for a relative change in smoke optical depth. (4) Assuming that the smoke optical depth is primarily due to the number concentration of aerosol, we arrive at the result that dln re/dln tau is a constant, and independent of cloud LWP.

<u>Effectiveness of Remote Sensing</u>: Direct aerosol forcing is proportional to the aerosol optical thickness, while the indirect forcing is proportional to the increase in number of soluble particles. There may also be a saturation effect. Most of the indirect effect may occur in pristine environments far from the aerosol sources. We see in Brazil, especially in 1995, that most of the signal in indirect effect occurs for the lowest values of optical thickness. A satellite such as MODIS cannot retrieve aerosol amounts at very low optical thickness. Using global transport models and the ISCCP cloud climatology we find that approximately 75% of the global direct forcing occurs at values of optical thickness within the measurement range of MODIS, while only 50% of the indirect forcing does so.

FORM B: GACP SIGNIFICANT HIGHLIGHTS

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SIGNIFICANT HIGHLIGHTS:

(1) AVHRR analysis using 1995 data confirms initial findings from 1987 data that cloud droplet size decreases with increasing smoke, and subsequently cloud reflectance increases. The indirect effect defined as the relative response of cloud effective radius (r_e) for a relative change in smoke optical depth (τ_s) and indicated by the quantity

$$IE = \frac{d \ln r_e}{d \ln \tau_s}$$

is listed below for each season in South America, and from a numerical cloud model run for a broad range of smoke aerosol parameter space.

IE(1987) = -0.36 IE(1995)= -0.42 IE(model) = -0.15 to -0.24

Using IE to define the indirect effect is new (not in Kaufman and Fraser 1997) and arises from the cloud modeling part of our research. Theory predicts that if changes in τ_s are primarily due to changes in N, the aerosol number concentration, then IE is a constant, and independent of cloud liquid water path (LWP). In practice, because IE is a normalized, unitless parameter, it avoids uncertainty in the remote sensing method due to emission correction for the 3.7µm channel and in phase function and single scattering uncertainties in the retrieval of τ_s. The Kaufman and Fraser (1997) results were based on a different parameter, $dr_e/d\tau_s$, that depended on LWP and remote sensing assumptions and may not have given a true indication of the effect of smoke on the cloud parameters.

Figure 1 shows cloud droplet radius (left) and cloud reflectance (right) as a function of smoke optical thickness. The top two panels are 1987 data divided by latitude categories. The middle two panels are 1995 data divided by latitude categories and the bottom panels are 1995 data divided into precipitable water vapor categories. Although specific subcategories provide exceptions, in general we see a decrease in droplet size and an increase in cloud reflectance as smoke optical thickness increases. In both years the indirect effect reaches a saturation point. In 1995, the saturation occurs at lower optical thickness than 1987.

(2) Using the Tegen et al. (1997) aerosol transport model with the ISCCP cloud climatology, we determine the spatial distribution of global direct and indirect aerosol forcing. The results indicate that 70% of the direct forcing occurs in grid squares

with aerosol optical thickness greater than 0.10. For the indirect forcing, 50% of the forcing occurs in pristine regions with small aerosol optical thickness.

Figure 2 shows cumulative histograms of direct and indirect aerosol forcing. FORM C: FUTURE PLANS

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We will continue in much the same manner, combining observational and theoretical studies using AVHRR with 1 km resolution, the MODIS Airborne Simulator (MAS) with 50 m resolution, MODIS data with 250 – 1000 m resolution (if it becomes available) and a numerical cloud model. We will also continue to use results of global transport models and the ISCCP cloud climatology to look at the global picture of aerosol indirect forcing and to better determine the limitations of remote sensing in quantifying the forcing.

FORM D: GACP BIBLIOGRAPHY

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BIBLIOGRAPHY:

Papers, reports, and presentations refer to those published during GACP by the principal investigator, co-investigators, and other researchers supported by your agency for aerosol research. Include those in progress or planned.

a. List of publications (including books, book chapters, and refereed papers), using AMS bibliographic citation form.

Kaufman, Y.J., P. V. Hobbs, V. W. J. H. Kirchoff, P. Artaxo, L. A. Remer, B. N. Holben, M. D. King, D. E. Ward, E. M. Prins, K. M. Longo, L. F. Mattos, C. A. Nobre, A. M. Thompson, J. F. Gleason and S. A. Christopher, 1998: The Smoke Cloud and Radiation Experiment in Brazil (SCAR-B)., *J. Geophys. Res.*, *103*, 31,783-31,808.

Chu, D.A., Y. J. Kaufman, L. A. Remer and B. N. Holben, 1998: Remote sensing of smoke from MODIS airborne simulator during the SCAR-B experiment., *J. Geophys. Res.*, *103*.

Remer, L.A., Y. J. Kaufman, B. N. Holben, A. M. Thompson and D. McNamara, 1998: A model of tropical biomass burning smoke aerosol size distribution., *J. Geophys. Res.*, *103*, 31,879-31,892.

Yamasoe, M.A., Y. J. Kaufman, O. Dubovik, L. A. Remer, B. N. Holben and P. Artaxo, 1998: Retrieval of the real part of the refractive index of aerosols from sun/sky radiometers during SCAR-B., *J. Geophys. Res.*, *103*, 31,893-31,902.

Hegg, D.A. and Y. J. Kaufman, 1998: Measurements of the relationship between submicron aerosol number and volume concentration, *J. Geophys. Res.*, *103*, 5671-5678.

Remer, L.A. and Y. J. Kaufman, 1998: Dynamical aerosol model: Urban/industrial aerosol., *J. Geophys. Res.*, *103*, 13,859-13,871.

Remer, L.A., Y. J. Kaufman and B. N. Holben, 1999: Interannual variation of ambient aerosol characteristics on the east coast of the United States, *J. Geophys. Res.*, *104*, 2223-2232.

Tanré, D., L. A. Remer, Y. J. Kaufman, S. Mattoo, P. V. Hobbs, J. M. Livingston, P. B. Russell and A. Smirnov, 1999: Retrieval of aerosol optical thickness and size distribution over ocean from the MODIS Airborne Simulator during TARFOX, *J. Geophys. Res.*, *104*, 2261-2278.

Longo, K.M., A. M. Thompson, V. W. J. H. Kirchoff, L. A. Remer, S. R. d. Freitas, M. A. F. SilvaDias, P. Artaxo, W. Hart, J. D. Spinhirne and M. A. Yamasoe, 1999: Correlation between smoke and tropospheric ozone concentrations in Cuiaba during Smoke, Clouds and Radiation-Brazil (SCAR-B)., *J. Geophys. Res.*, *104*, 12,113-12,129,

Kaufman, Y.J., D. Tanré, A. Karnieli and L. A. Remer, 1999: Re-evaluation of dust radiative forcing using remote measurements of dust aborption of sunlight., *J. Geophys. Res.*, *submitted*.

Remer, L.A., A.E. Wald and Y.J. Kaufman, Angular and seasonal variation of spectral surface reflectance ratios: Implications for the remote sensing of aerosol over land. In preparation.

Feingold, G., W. R. Cotton, S. M. Kreidenweis, and J. T. Davis, 1999: Impact of giant cloud condensation nuclei on drizzle formation in marine stratocumulus: Implications for cloud radiative properties. In Press J. Atmos. Sci.

Feingold, G., S. M. Kreidenweis, and Y. Zhang, 1998: Stratocumulus processing of gases and cloud condensation nuclei: Part I: trajectory ensemble model. J. Geophys. Res., 103, 19,527-19,542.

Zhang, Y., S. M. Kreidenweis, and G. Feingold, 1999: Stratocumulus processing of gases and cloud condensation nuclei: Part II: chemistry sensitivity analysis. In Press J. Geophys. Res.

Wulfmeyer, V., and G. Feingold, 1999: On the relationship between relative humidity and particle backscattering coefficient in the marine boundary layer determined with differential absorption lidar. Accepted J. Geophys. Res.

b. List of printed technical reports and non-refereed papers.

c. List of oral presentations or posters at professional society meetings and conferences.

Remer, L.A., Y.J. Kaufman, D. Tanré, D.A. Chu, 1999: Principles of remote sensing of aerosol from MODIS. At the ALPS99 meeting on the remote sensing of aerosol in Meribel France.

Remer, L.A., 1999: What will we learn from MODIS data about global aerosols? At the Climate and Radiation Branch seminar series on March 24, 1999, NASA/GSFC in Greenbelt MD.

Feingold, G., S. Yang, R. M. Hardesty, and W. R. Cotton, 1998: Feasibility of retrieving cloud condensation nucleus properties from Lidar, Doppler cloud radar, and Microwave Radiometer. AMS Cloud Physics Conference, Everett, WA, August 1998, 101--104.

Feingold, G., W. R. Cotton, and S. M. Kreidenweis, 1998: Impact of Giant Cloud Condensation Nuclei on Stratocumulus Microphysics, optical properties, and Boundary Layer Dynamics. AMS Cloud Physics Conference, Everett, WA, August 1998, 279--282.

Kreidenweis, S. M., G. Feingold, and Y Zhang, 1998: Cloud Processing of Aerosol and Gases in a Trajectory Ensemble Model. AMS Cloud Physics Conference, Everett, WA, August 1998, 191--192.

Feingold, G., S. M. Kreidenweis, and Y. Zhang, 1998: Cloud processing of particles and gases in stratocumulus: implications for aerosol direct and indirect effects. International Global Atmospheric Chemistry (IGAC) Conference, University of Washington, Seattle, August 19--25 1998.

Cotton, W. R., H. Jiang, and G. Feingold, 1999: Entrainment of free tropospheric aerosol into the Arctic boundary layer. Preliminary Simulations of the 18 May 1998 Case. FIRE/SHEBA Workshop, Jan. 1999.