GACP Progress Report September 2001

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TITLE: Satellite study of the smoke indirect radiative forcing.

Summary

When we started this project the indirect effect was the largest unknown in estimating the total anthropogenic forcing that causes climate change. Except for the ship track experiments, some conflicting in situ studies and the pioneering satellite observational work of Kaufman and Nakajima (1993) and Kaufman and Fraser (1997) there was little observational evidence that the indirect effect actually existed over areas large enough to contribute to global climate change. Since then, our work and others establish without question that the indirect effect is real and sufficiently widespread to be an effective agent of climate change.

In our study we investigate smoke indirect radiative forcing on three fronts. (1) Observations from remote sensing. (2) Modeling the processes. (3) Understanding the limitations of our remote sensing tools. In addition, we have begun an exciting new study of indirect effect on a much more localized scale at the Southern Great Plains CART site. This new study, led by Graham Feingold, supports our results from the South American observational and theoretical investigations.

(1) The observations show us both the persistence and variability of the indirect radiative forcing by South American smoke during the biomass burning season. We identify the indirect effect using different sensors with varying spatial scales from 50 m to 1 km. The indirect effect persists from year to year, although we note the interannual variability in magnitude and geographical distribution. (2) The modeling results demonstrate the interplay between aerosol optical depth and aerosol physical characteristics with the resulting cloud response. We see that aerosol properties alone can determine the magnitude and saturation of the indirect effect. We now have a better understanding of the variability we see in the observations. (3) We investigate the limitations of satellite sensors to quantify smoke radiative forcing in the remote regions of the Southern Hemisphere. We find that satellite sensors that measure aerosol optical thickness can only determine the forcing to within 16-60%. Strategies that use the satellite data to derive flux directly or use the data in conjunction with ground-based remote sensing and aerosol transport models can reduce these uncertainties.

Final Progress Report

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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 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. Lastly we use the results of global aerosol transport models to estimate the geographical extent of the smoke in the Southern Hemisphere and then evaluate how much of the smoke we will be able to determine from satellite remote sensing, given the limitations of current sensors.

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) Multiple years AVHRR data analyzed. Interannual variation noted.
(4) Precipitable water vapor ruled out as controlling factor in indirect effect.
(5) 1995 MAS data analyzed. Indirect effect identified using 50 m resolution data.
(6) Numerical cloud model performed simulations over a broad range of parameter space.
(7) Development of methodology to link satellite data analysis and numerical modeling.
(8) Expansion of Twomey's approach to include aerosol parameters besides concentration.

(9) Detailed numerical study to identify the processes controlling indirect effect completed.
(10) Manuscript accepted by J. Geophys. Res. extending Twomey's approach with combination of satellite observations and modeling results.
(11) Global transport model results compared and adjusted to AERONET data near sources of smoke aerosol.
(12) Adjusted global transport model results used to evaluate effectiveness of remote sensing to determine smoke radiative forcing in the Southern Hemisphere.
(13) Manuscript accepted by JAS-GACP special issue demonstrating limitations of satellite remote sensing to determine smoke radiative forcing in the Southern Hemisphere.
(14) Preliminary analysis of Southern Great Plains CART site data suggest a relationship between increasing aerosol extinction at cloud base and decreasing cloud droplet radius.

1st YEAR RESULTS which focus on aerosol indirect effect detection and preliminary model studies are detailed in the 1st year progress report, available on the GACP web site.

2nd YEAR RESULTS: which focus on using the numerical cloud model to investigate processes controlling indirect effect are detailed in the 2nd year progress report, available on the GACP web site.

3rd YEAR RESULTS:

Two papers accepted for publication. The first summarizes the observational and theoretical work (Feingold et al., 2001). The second explores the limitations of remote sensing to quantify smoke forcing in the Southern Hemisphere (Remer et al., 2001). Summaries of these results are detailed below under 'Final Results'. In addition, a new study was begun that analyzes data collected at the Southern Great Plains CART site. A summary of this preliminary work also appears below.

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FINAL RESULTS:

AVHRR Analysis: We have identified the indirect effect in South America 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. Figure 1 shows graphically (on the left side panels) the relationships between cloud droplet effective radius and smoke optical thickness, both derived from AVHRR 1 km data. Each plotted point represents mean values for a 1 degree box. The panels on the right side depict the relationship between cloud optical thickness and the smoke. Cloud droplets become smaller and clouds become brighter as the smoke increases for most geographical and precipitable water categories in both years. The original hypothesis of precipitable water vapor acting as the controlling factor is not supported by these subsequent data.

Below is a Table giving a short summary of the results. IE = -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. Positive 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	-0.16	3.5-4.5	0.34	0.31
11-20S	0.33	0.34	>4.5	0.24	0.36

The differences in the indirect effect between 1987 and 1995 are a consequence of changes in the regional distributions in smoke and cloud, as illustrated by Figure 2.

Greater detail is given in Feingold et al. (2001) accepted by JGR.

MODIS Airborne Simulator Analysis: To see if we could detect the indirect effect with a different instrument using a different spatial scale, we apply a similar analysis to images from the MODIS Airborne Simulator (MAS) that has a 50 m resolution. We group the data into 1 km boxes instead of the AVHRR analysis boxes of 1 degree latitude/longitude.

Figure 3 illustrates a sample of the results. The top panel shows the relationship between visible reflectance (0.66 μm) and the smoke optical thickness. The visible reflectance is proportional to cloud and aerosol optical thickness. As expected, the green line has positive slope demonstrating the linear relationship between aerosol optical thickness and visible reflectance of the non-cloudy pixels. The slope of the blue line is also positive demonstrating that cloud optical thickness is increasing with the smoke. This is the indirect effect of clouds becoming brighter with increased smoke amounts. The brown line is especially interesting because it represents the total smoke forcing, including both the direct and indirect effects and any contribution by mixed pixels that could not be separated into cloudy or non-cloudy categories. In this particular example, we see that the indirect effect dominates the total radiative forcing of the smoke and that light absorption by black carbon does not severely dampen the cloud brightening.

The bottom panel shows the relationship between middle infrared (mid-IR) reflectance (2.13 μm) and the smoke optical thickness. The mid-IR reflectance is inversely proportional to cloud droplet size, and is transparent to smoke in cloud-free pixels. As expected, the green points have no relationship to the smoke optical thickness. The mid-IR penetrates to the surface, and the surface reflectance is not correlated to the smoke. The blue line has positive slope indicating that cloud droplets are becoming smaller as smoke increases. Again, this is demonstration of the indirect effect.

The corroboration between the AVHRR and MAS data, one at 1 km averaged to 1 degree squares and the other at 50 m, averaged to 1 km boxes, is strong evidence of the importance of indirect radiative forcing in South America during the biomass burning season.

Modeling Study: We use a numerical cloud model and conduct a series of numerical experiments to explore the factors which determine the magnitude of the response of clouds to smoke aerosol. Figure 4 illustrates the results of the modeling study. The figure shows plots of IE, defined as -dlnre/dlntau in (N_a, r_g) space where N_a is the aerosol number concentration and r_g is the median radius of the aerosol number size distribution. w is the vertical velocity; ε is a measure of the amount of soluble material in the particles; and β is a measure of how close to adiabatic the clouds are. These plots show how changes in aerosol parameters affect the droplet-size response of the clouds.

We find that the droplet-size response to an increase in smoke optical depth decreases with increasing aerosol optical depth, increasing median size of particles, and increasing hygroscopicity. For very thick smoke when competition for water vapor is great, there is a saturation in response and under certain conditions, the model even indicates an increase in drop size with increasing optical depth (Figures 4c and 4d). Two maxima in response may exist; the first (expected) peak exists at small number concentrations and small sizes (i.e, cleaner conditions), and the second at high number concentrations and large sizes. It is suggested that this second peak results from the suppression of supersaturation by abundant large particles and the prevention of activation of smaller particles. Therefore, although to first order smoke optical depth is a good proxy for aerosol indirect forcing, under some conditions the size distribution and hygroscopicity can be important factors.

Our modeling study is a solid first step towards understanding the complex processes that govern aerosol-cloud interaction. Further work will, of course, be required. Greater detail is given in Feingold et al. (2001) accepted by JGR.

Limitations of satellite remote sensing: Satellite remote sensing detects aerosol with the least amount of relative error when aerosol loading is high. Satellites are less effective when aerosol loading is low. We use the monthly mean results of two global aerosol transport models to simulate the spatial distribution of smoke aerosol in the Southern Hemisphere during the tropical biomass burning season. Figure 5 illustrates this concept. The top panel shows the simulated distribution of smoke aerosol. The bottom panel shows the signal to noise ratio calculated using the uncertainty of MODIS aerosol retrievals as the “noise”. Signal-to-noise ratio is high near the smoke source regions, but the ratio is near one in the remote areas of the Southern Hemisphere.

The uncertainty of quantifying the smoke aerosol forcing in the Southern Hemisphere depends on the uncertainty introduced by errors in estimating the background aerosol, errors resulting from uncertainties in surface properties and errors resulting from uncertainties in assumptions of aerosol properties. These three errors combine to give overall uncertainties of 1.2 to 2.2 Wm-2 (16-60%) in determining the Southern Hemisphere smoke aerosol forcing. Strategies that use the satellite data to derive flux directly or use the data in conjunction with ground-based remote sensing and aerosol transport models can reduce these uncertainties.

Greater detail is given in Remer et al. (2001) accepted by JAS – GACP special issue.

<u>Southern Great Plains Study</u>: This is new work led by Graham Feingold. Intrigued by the possibility of isolating the aerosols at cloud base that actually enter a cloud and affect the cloud microphysical properties, we have turned to a data set collected at the Southern Great Plains CART site. There we use Raman lidar to characterize the aerosol loading at cloud base beneath clouds in terms of total aerosol extinction. We use cloud radar and microwave radiometer data to derive cloud droplet radius. Figure 6 shows a schematic of the concept and a plot of preliminary results. The preliminary results (bottom panel) show the relationship between these two variables. Cloud droplet radius decreases as total aerosol extinction increases, as expected from the theory behind the indirect effect.

These are preliminary data, but they do show a direct response of the cloud to the aerosols that actually enter that particular cloud. This is a more straightforward observation of the indirect effect than the statistical analyses of the satellite remote sensing observations. Because these observations are more straightforward, they should be more applicable to modeling studies. We anticipate learning even more about the processes behind the indirect effect from combining the Southern Great Plains data with another modeling study.

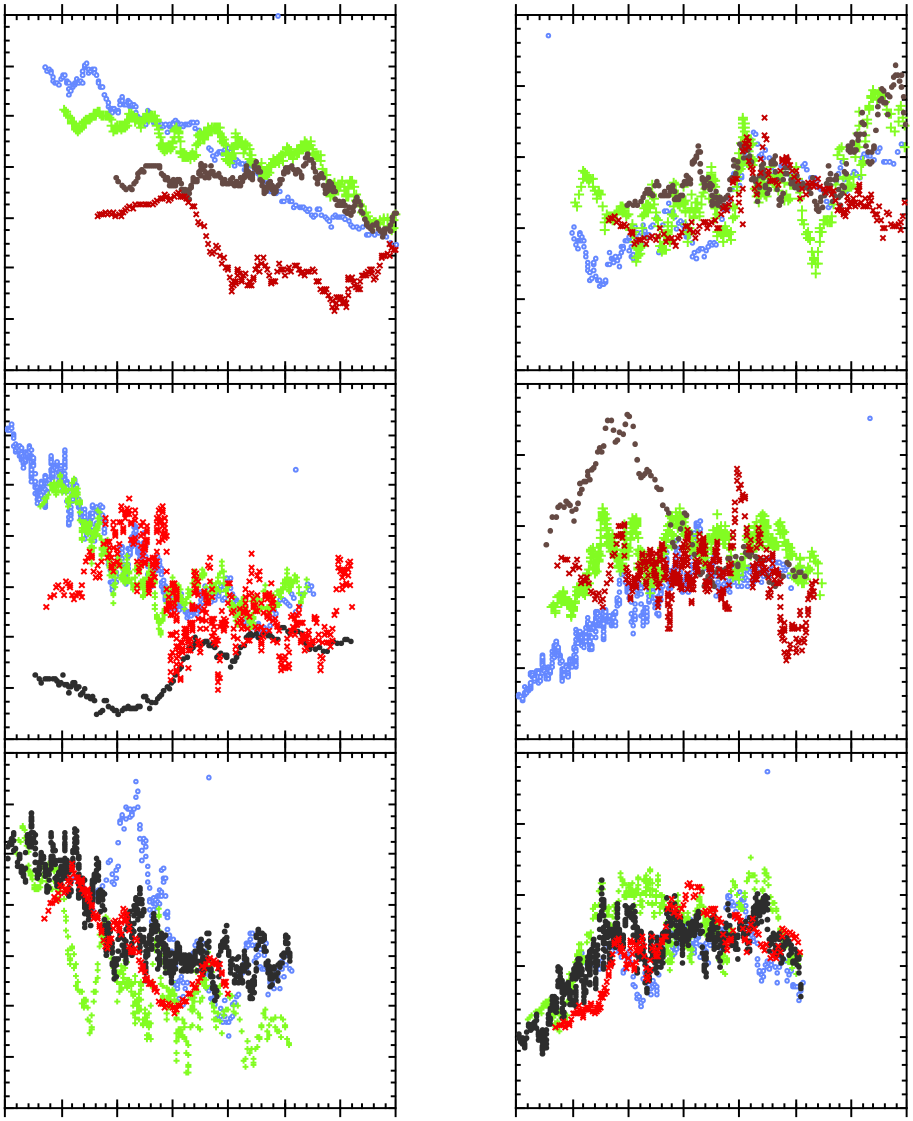

Figure 1 shows cloud droplet radius (left) and cloud reflectance (right) as a function of smoke optical thickness. The top two panels are 1987 data divided by latitude categories. The middle two panels are 1995 data divided by latitude categories and the bottom panels are 1995 data divided into precipitable 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.

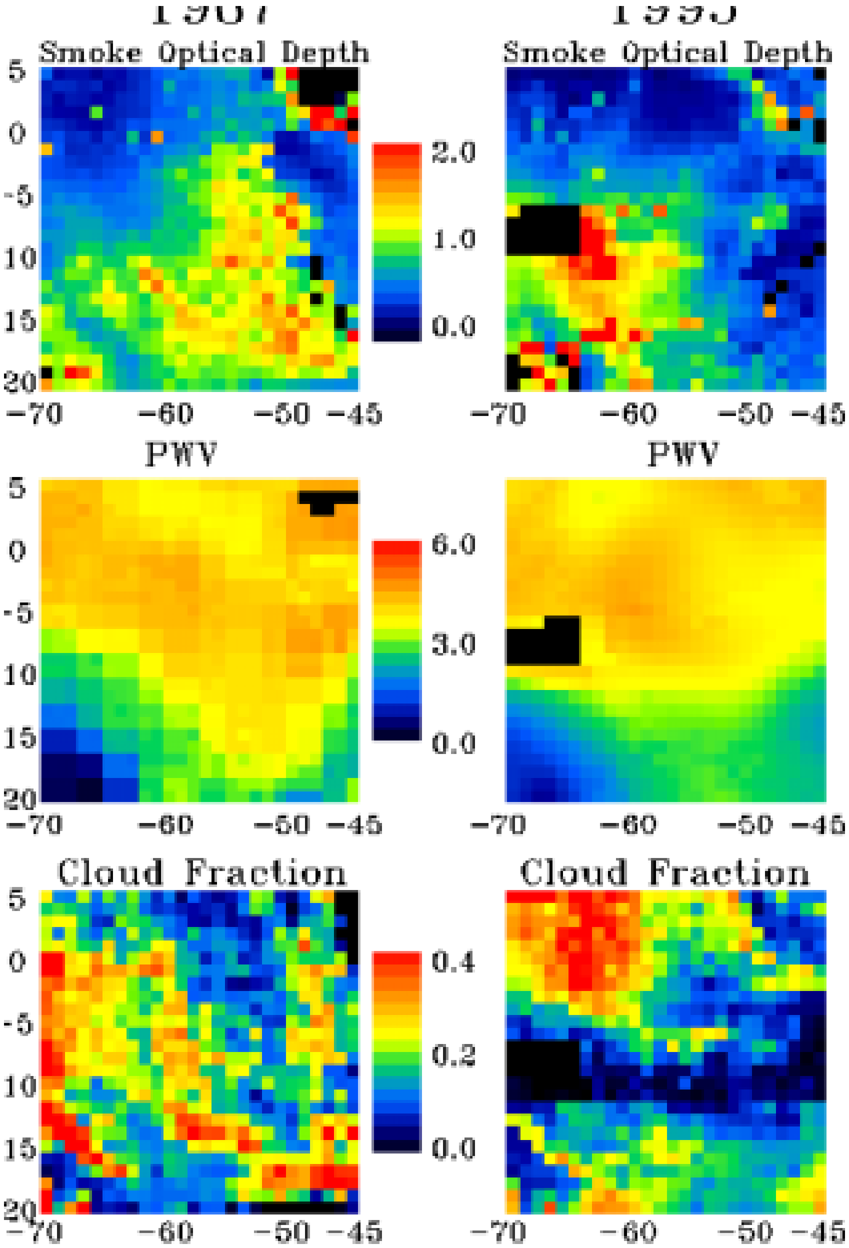

Figure 2 1987 analysis on the left and 1995 analysis on the right of smoke optical depth (top), precipitable water vapor (middle) and cloud fraction (bottom) for the August/September period of each year. We see the interannual variability of the smoke and cloud properties, leading to interannual variability in the strength and location of the indirect effect.

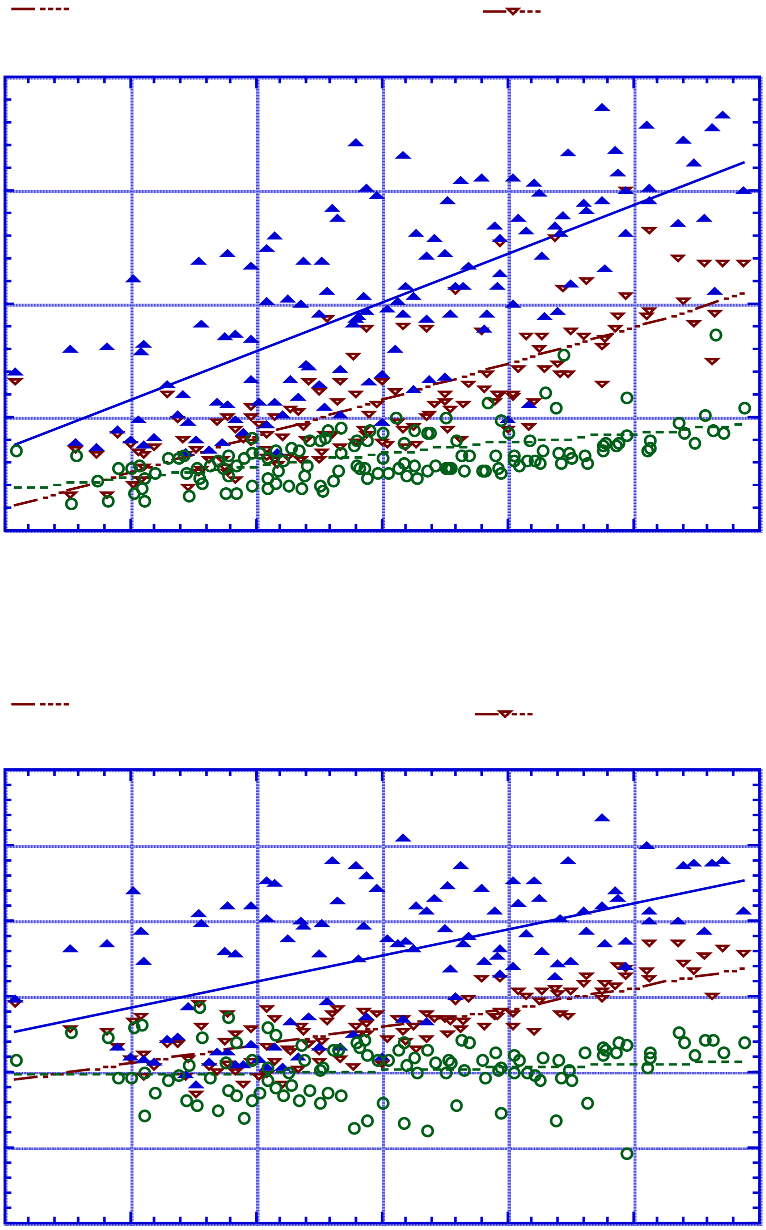

Figure 3. Analysis of 50 m MAS data. Measured reflectance at 0.66 µm (top) and 2.13 µm (bottom) as function of retrieved aerosol optical thickness. Brown points represent the mean reflectance of a 20 by 20 pixel box (1 km) including all pixels in the box (cloudy, non-cloudy or mixed). Blue points represent the reflectance of pure cloudy pixels in the box. Green points represent the reflectance of pure non-cloudy pixels in the box.

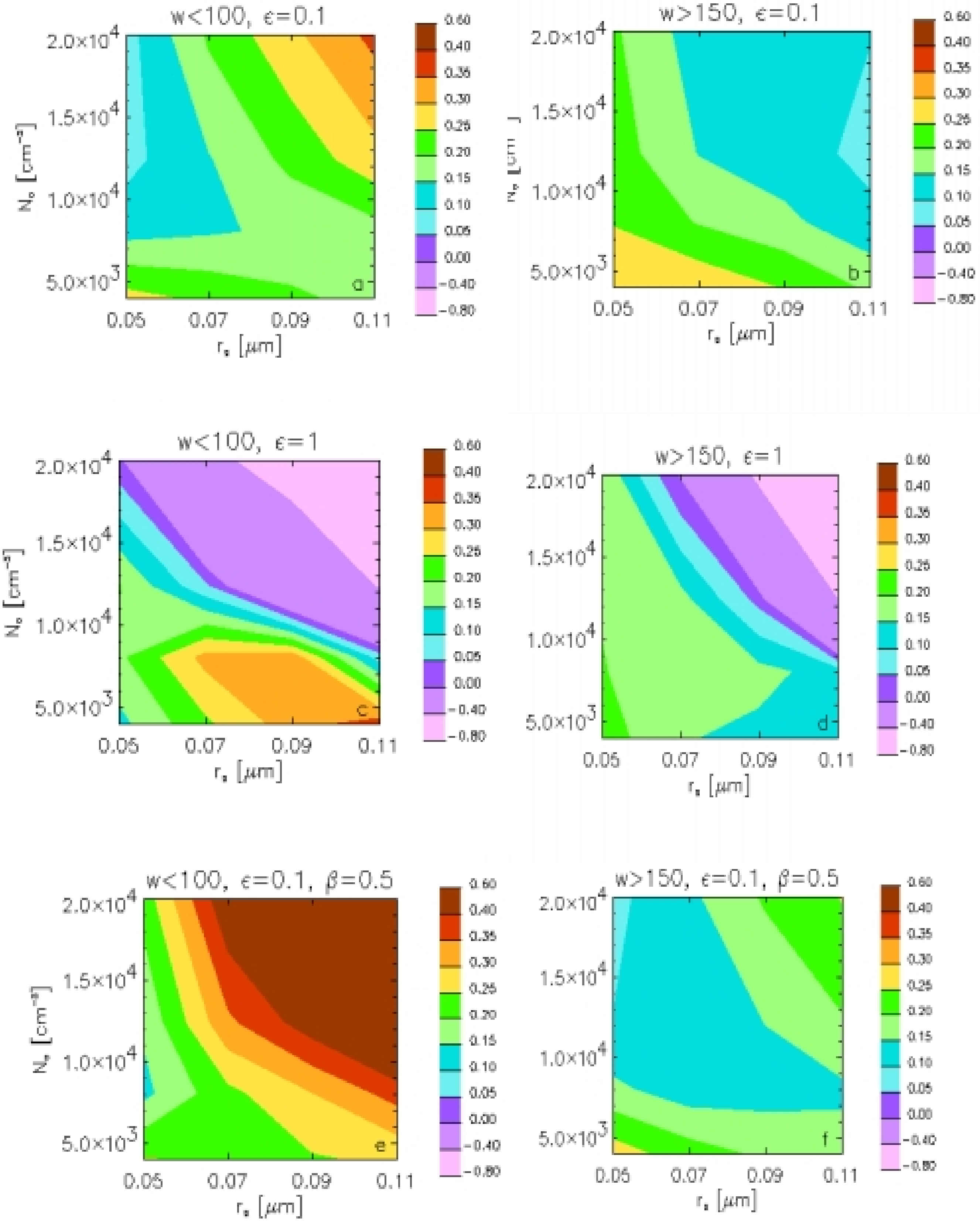

Figure 4. Explanation see text.

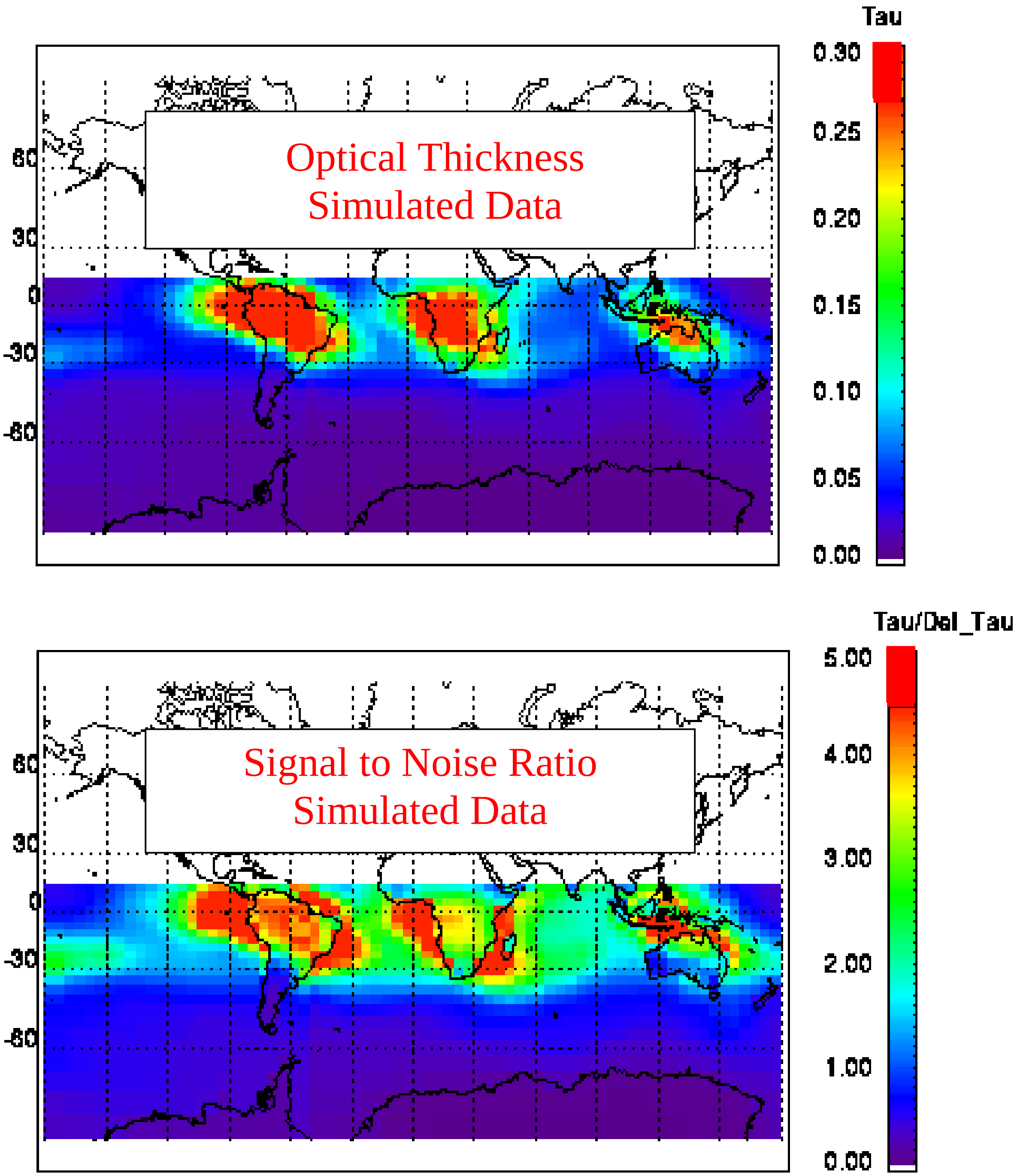

Figure 5. Southern Hemisphere distribution of simulated August monthly mean smoke optical thickness (top) and retrieval signal-to-noise ratio ($\tau/\Delta\tau$). Over much of the Southern Hemisphere signal-to-noise ratio approaches 1.0 and satellites cannot detect change in aerosol loading. Data is derived from the model of (Tegen et al., 1997).

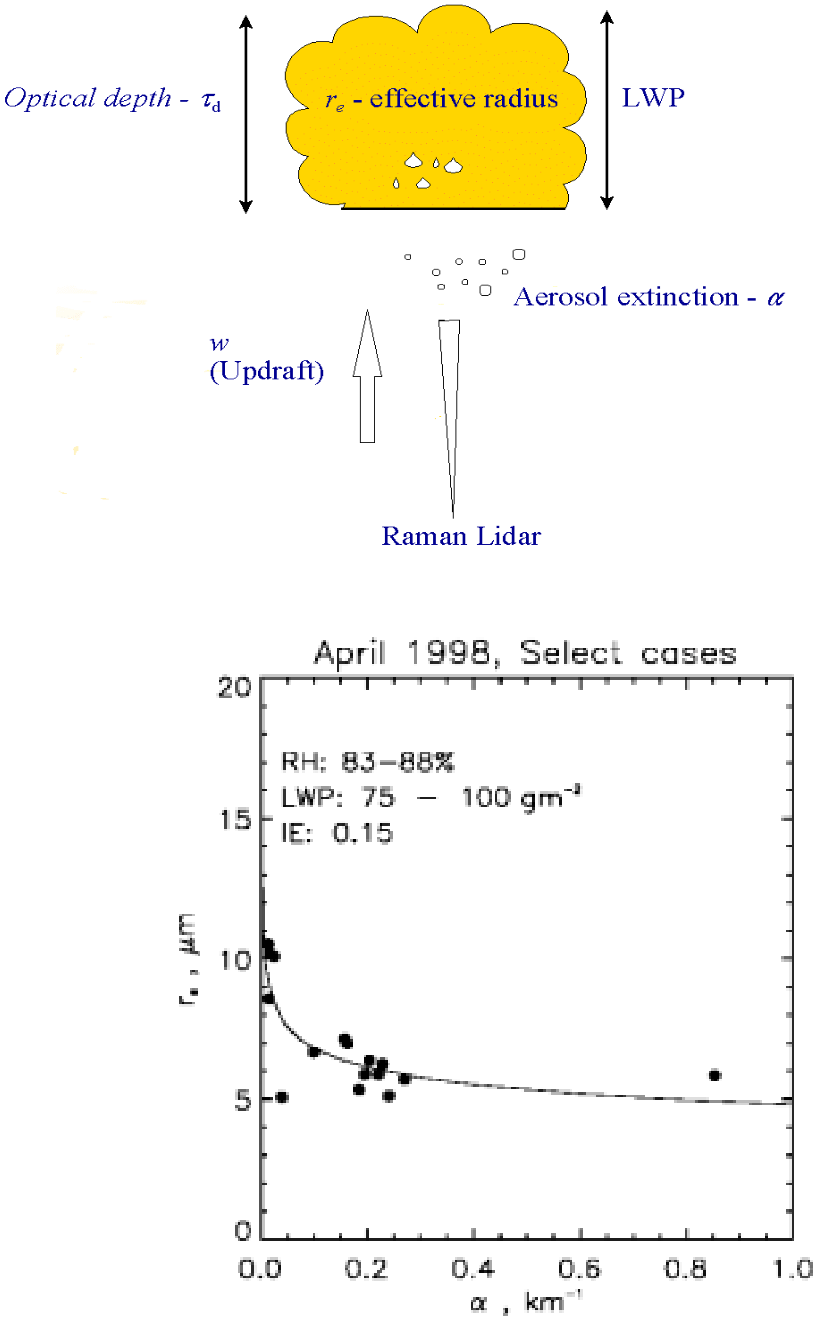

Figure 6. (top) Schematic of the Southern Great Plains CART site analysis. We use Raman lidar to characterize the aerosol loading at cloud base beneath clouds in terms of total aerosol extinction. We use cloud radar and microwave radiometer data to derive cloud droplet radius. In this way we isolate the specific aerosols entering the cloud that will affect cloud microphysics. (bottom) Cloud droplet radius as a function of the total aerosol extinction measured directly below cloud base. As aerosol extinction increases, cloud droplets decrease.

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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.

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