GACP FINAL REPORT

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TITLE: An Investigation of the Indirect Effect of Aerosols on Climate: Coupled Chemistry-Climate Modeling and Satellite Validation

3rd YEAR RESEARCH RESULTS: We have converted the coupled chemistry-climate model that we developed for indirect effect studies from 9 to 18 vertical layers in order to better resolve the details of boundary layer cloud vertical structure that we had previously shown to have a significant impact on the indirect effect. We have also coupled our model to a Q-flux ocean model and are currently conducting multi-decadal equilibrium simulations with estimated aerosol loadings for 1950 and 1985 to determine the direct and indirect effects over a time scale constrained by observations, as opposed to the comparisons with fixed SSTs and poorly constrained pre-industrial aerosol loadings that are typically done to evaluate aerosol effects. We have participated in a study of scattering and absorption characteristics of droplets containing black carbon intrusions using ray tracing, Monte Carlo, and Lorenz-Mie calculations, showing that it is unlikely under normal conditions that black carbon aerosols can affect cloud radiative properties significantly except for geographic locations very close to major sources. We have analyzed cloud radar-retrieved ice crystal number concentrations for midlatitude continental and tropical island locations and isolated a population of clouds whose number concentrations appear to be constrained by convective vertical transport of aerosol from the boundary layer to detrainment levels, a second population whose number concentration is controlled by heterogeneous nucleation onto ambient upper troposphere aerosols, and a third population consistent with homogeneous nucleation independent of aerosols; this should serve as a basis for parameterizing for the first time the indirect effect of aerosols on cirrus clouds. Finally, we have identified several geographic locations downwind of major aerosol sources which exhibit significant synoptic time scale variability in the initial GACP aerosol climatology; these are target locations for an attempt to separate aerosol from meteorological influences on cloud properties by combining the GACP, ISCCP, and NCAR/NCEP reanalysis datasets.

SUMMARY OF RESULTS OVER GACP PROJECT PERIOD:

(1) We developed and conducted sensitivity tests with a coupled chemistry-climate model that incorporates the first and second indirect effects due to sulfate, organic carbon, and sea salt. We simulate combined indirect effects ranging from –1.6 to –4.6 W/m^2, with the results being quite sensitive to assumptions about pre-industrial aerosol sources and cloud parameterization elements that affect boundary layer cloud vertical structure and cloud scavenging of aerosol. Comparisons with available satellite indices of aerosol effects on cloud properties indicate that these data sets, which mix aerosol and meteorological influences, cannot by themselves constrain the indirect effect. We have also assisted in a study that demonstrates that black carbon effects

on cloud droplet visible radiative properties are not significant except in limited regions close to the black carbon source.

(2) We added black carbon direct forcing to the coupled model and evaluated its role in the current climate and under IPCC SRES (A2) scenarios for the next century, with different assumptions about the treatment of its solubility. For external mixing, positive and negative direct effects due to black and organic carbon almost cancel in the current climate, each being about half as large as the –0.65 W/m^2 sulfate direct forcing. In 2100, though, the black carbon positive direct effect plays a greater role - the seasonality of direct forcing in the current climate (most negative in Northern summer) reverses by 2100 to being least negative or even slightly positive in Northern summer. We have also documented trends in aerosol loadings over the period 1950-1990 as a basis for evaluating direct and indirect effects over a period more constrained by observations than the current vs. pre-industrial comparisons that are typically done.

(3) We have shown that the satellite-observed change in correlation between cloud optical thickness and droplet effective radius (from positive for thin clouds to negative for thick clouds) appears to be controlled in GCMs by the transition from non-precipitating to precipitating clouds. The onset of precipitation limits dynamically-induced changes in liquid water content and droplet size and allows the more subtle aerosol indirect effect to be detected for the thickest clouds. This implies that development of true global observational constraints on the indirect effect will require a systematic analysis of aerosol, cloud, and meteorological datasets that separates dynamical and aerosol impacts on cloud properties. A preliminary study of the NOAA aerosol climatology off the east coast of Asia shows that aerosol trends consistent with estimated trends in sulfate emissions over China can be detected in that data set, but that any associated trends in ISCCP cloud optical thickness are hidden by other larger sources of variability.

(4) We have analyzed cloud radar-retrieved ice crystal number concentrations for midlatitude continental and tropical island locations and isolated a population of clouds whose number concentrations appear to be constrained by convective vertical transport of aerosol from the boundary layer to detrainment levels, a second population whose number concentration is controlled by heterogeneous nucleation onto ambient upper troposphere aerosols, and a third population consistent with homogeneous nucleation independent of aerosols; this should serve as a basis for parameterizing for the first time the indirect effect of aerosols on cirrus clouds.

GACP-FUNDED PUBLICATIONS:

A. Papers in refereed journals and books

Koch, D., D. Jacob, I. Tegen, D. Rind and M. Chin, 1999: Tropospheric sulfur simulation and sulfate direct radiative forcing in the GISS GCM. *J. Geophys. Res.*, **104**, 23,799-23,822.

Koch, D., 2001: Transport and direct radiative forcing of carbonaceous and sulfate aerosols in the GISS GCM. *J. Geophys. Res.*, **106**, 20,311-20,332.

Liu, L., M.I. Mishchenko, S. Menon, A. Macke and A.A. Lacis, 2001: The effect of black carbon on scattering and absorption of solar radiation by cloud droplets. Submitted to *J. Quant. Spec. Rad. Trans.*

Lohmann, U., G. Tselioudis and C. Tyler, 2000: Why is the cloud albedo-particle size relationship different in optically thick and optically thin clouds? *Geophys. Res. Letters*, **27**, 1099-1102. (http://www.giss.nasa.gov/gpol/authors/gtselioudis.html)

Tegen, I., D. Koch, A.A. Lacis and M. Sato, 2000: Trends in tropospheric aerosol loads and corresponding impact on direct radiative forcing between 1950 and 1990: A model study. *J. Geophys. Res.*, **105**, 26,971-26,989.

Menon, S., A.D. Del Genio, D. Koch and G. Tselioudis, 2001: GCM simulations of the aerosol indirect effect: Sensitivity to cloud parameterization and aerosol burden. *J. Atmos. Sci.*, in press. (http://www.giss.nasa.gov/gpol/authors/smenon.html)

B. Printed technical reports, non-refereed papers and abstracts

Brenguier, J.-L., L. Schüller, H. Pawlowska, D. Roberts, J. Feichter, J. Snider, U. Lohmann, S. Menon and S. Ghan, 2000: Report on the First PACE (Parameterization of the Aerosol Indirect Climatic Effect) Meeting, European Comm. Rep. EVK2-CT-1999-00054.

Liu, J., 1999: Satellite observations of recent east Asian aerosol and cloud optical thickness trends. Masters Thesis (A. Del Genio, advisor), Columbia University Dept. of Earth and Environmental Science.

Menon, S., A. Del Genio, D. Koch and G. Tselioudis, 1999: An estimate of the aerosol indirect effect using a coupled chemistry-climate model and comparisons with satellite data. *EOS (AGU Trans.)*, **80**, F192-F193.

Menon, S., A.D. Del Genio, G. Tselioudis and D. Koch, 2001: An assessment of the aerosol indirect effect sensitivity to aerosols and cloud structure. Geophys. Res. Abs., 14th EGS Conf. On Clouds and Aerosols, 26-30 March 2001, Nice, France.