GCM Aerosols and Sub-Grid Cloud Heterogeneity

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Introduction

In the terrestrial climate system, clouds and aerosols exhibit a great deal of spatial and temporal variability. This makes it difficult both to characterize fully their radiative properties from observations and to model accurately their radiative forcing in climate simulations with general circulation models (GCMs). In addition, aerosols are highly variable in size and composition which further complicates accurate modeling of their climate impact. Likewise, clouds exhibit a complex variability over different time and spatial scales which raises questions on the accuracy of cloud specification in climate GCMs. Furthermore, aerosols impact cloud microphysics and produce an indirect radiative forcing which might exceed their direct radiative forcing.

The study of this indirect cloud/aerosol forcing is an active topic of interest in current GCMs. We describe here the basic treatment and specification of clouds and aerosols that are used in the Goddard Institute for Space Studies (GISS) climate GCM, and we note that a new prognostic cloud scheme has been implemented to include the indirect aerosol forcing effect.

GCM Radiation

A brief overview of the GISS GCM radiation model was given previously in Lacis et al. (1998). Gaseous absorbers of solar radiation are H_2O, CO_2, O_3, O_2, and NO_2, utilizing 15 spectrally non-contiguous, vertically correlated k-distribution intervals. Thermal radiation utilizes the correlated k-distribution approach whereby k-distributions from non-contiguous spectral regions are merged and weighted by Planck spectral radiation (Lacis and Oinas 1991). The model utilizes a new configuration of 33 k-intervals tabulated as functions of pressure, temperature, and absorber amount that accurately reproduces stratospheric cooling by CO_2, and overlapping absorption by H_2O, including as well, the absorption by O_3, CH_4, N_2O, CFC-11, and CFC-12.

For cloudy-sky conditions, the thermal radiances are calculated formally without scattering, but include a parameterized correction for multiple scattering effects for the outgoing radiation based on cloud emissivity. A 3-point numerical quadrature (for μ = 1.0, 0.5, and 0.1) is used to compute fluxes from the directional radiances.

Multiple scattering of solar radiation utilizes the doubling/adding method (Lacis and Hansen 1974) with single Gauss point adaptation to reproduce sun angle, μ_o, dependence for reflected solar radiation by clouds and aerosols with the same degree of precision as the full doubling-adding for conservative

scattering. This is achieved by means of a brute-force look-up table in τ,g,μ_o, which returns an "effective" asymmetry parameter value g' to be used in the single Gauss point doubling algorithm to reproduce the correct albedo for any cloud optical depth τ. Cloud and aerosol radiative parameters (extinction cross-section, single-scattering albedo, and asymmetry parameter) are calculated using Mie theory with compensation for nonspherical effects for dust and ice clouds (Lacis and Mishchenko 1995).

Cloud Radiative Treatment

For numerical tractability, clouds are taken to be plane-parallel. Cloud cover is fractional in time, and clouds may be single or multi-layered. The cloud water content, optical depth, and particle size distribution are set by the prognostic cloud water parameterization (Del Genio et al. 1996).

$$\tau_o = \pi a^2(1-b)(1-2b)\, Q_x\, H\, N\ ,$$

$$LWC = 4/3\, \pi a^3(1-b)(1-2b)\, \rho\, H\, N$$

where a = the cloud particle effective radius
b = the effective variance of the size distribution
Q_x = the extinction efficiency factor at $\lambda = 0.55\ \mu m$
ρ = the mass density
H = the column height
N = the cloud particle number density per unit volume.

This defines the (Mie) optical depth τ_o, asymmetry parameter, $g_o(a)$, and single-scattering albedo, $\omega_o(a)$.

The cloud heterogeneity parameterization (Cairns et al. 1999) is derived from rigorous Monte Carlo modeling simulations for inhomogeneous density distributions and readily meets the criteria for GCM simplicity in that the plane-parallel homogeneous cloud parameters τ_o,g_o,ω_o are simply related by the relative variance V, where $V = \exp(\delta^2) - 1$, with δ the log standard deviation of the droplet density distribution.

$$\tau = \tau_o /(1 + V)$$

$$\omega = \omega_o /[\ 1 + V(1-\omega_o)\ ]$$

$$g = g_o\ [\ 1 + V(1-\omega_o)\ ]/[\ 1 + V(1-\omega_o g_o)\ ]$$

The probability distribution function (PDF) of liquid water path can be estimated from Gamma distribution parameters obtained from the D1 reprocessed version of International Satellite Cloud Climatology Program (ISCCP) data. Monthly-mean maps of observed cloud variability are shown in Figure 1. Persistently greater cloud variability occurs along the equator. Substantial seasonal changes are seen over continental areas and along coastal ocean areas. In those regions with small variability

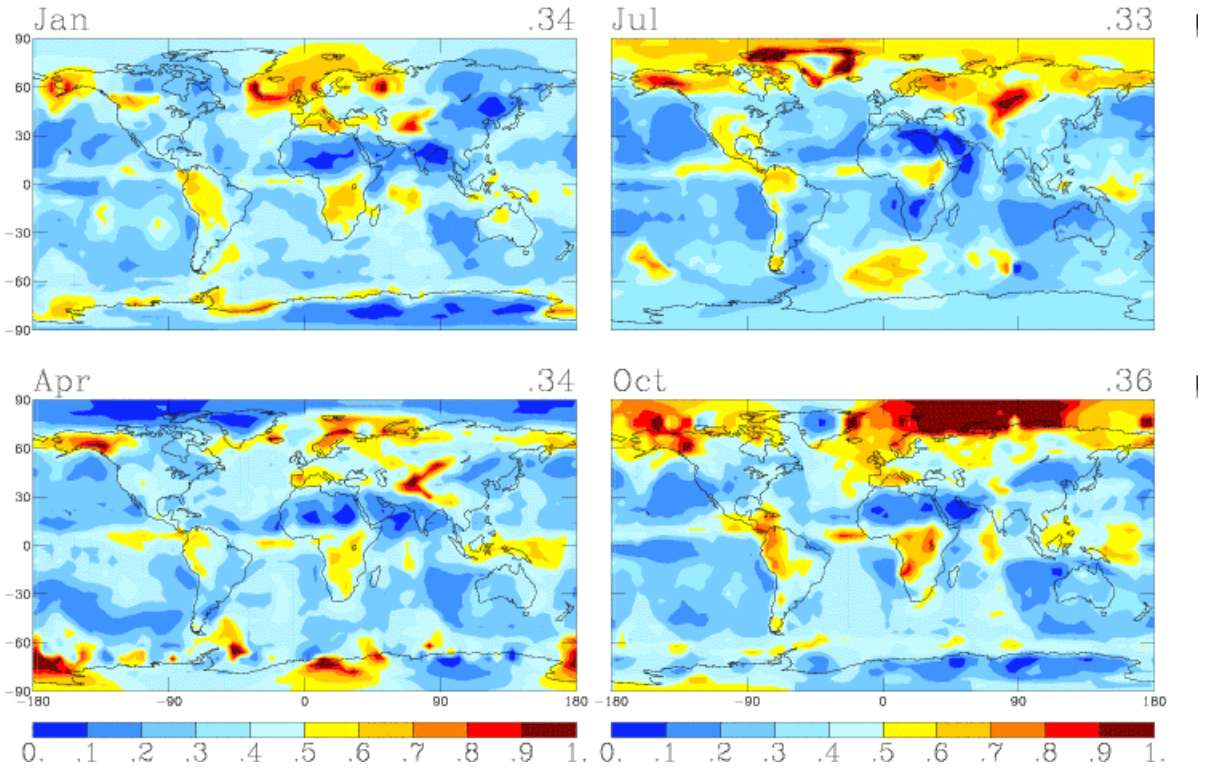

Figure 1. Seasonal variability of ISCCP derived cloud heterogeneity parameter.

(V ≈ 0), the homogeneous plane parallel approximation should be valid. In regions where V ≈ 1, the effective cloud optical depth and cloud liquid water content can differ by as much as a factor 2 compared to homogeneous plane parallel cloud results.

Aerosol Climatology

We have installed a comprehensive 50-year straw-man aerosol climatology in the GISS GCM as a part of an ongoing effort to model global climate change over decadal time scales. The climatology is based on the results of tracer and transport model studies, including chemistry/transport model analyses of historical carbon and sulfur emission rates and their geographical distributions (Liousse et al. 1996; Tegen et al. 1997; Koch et al. 1999). It is comprised of nine individual aerosol species shown in Figure 2, in the form of monthly-mean distributions of aerosol optical depth. Of these, anthropogenic sulfate and industrial carbon (black, organic) are the only species with adequately documented historical trends. They account for the steady growth in aerosol optical depth since 1950.

Strong seasonal variability in aerosol optical depth is evident in both the global mean value (Figure 3) and in the geographic distribution (Figure 4). The aerosol climatology serves both as an estimate of anthropogenic aerosol forcing on decadal temperatures and as input to the new prognostic cloud scheme to explore the indirect aerosol forcing contribution. Because of its present rudimentary nature, there is need for validation of both the compositional components (which affect the single-scattering albedo) and of the optical depth variations against available observational data.

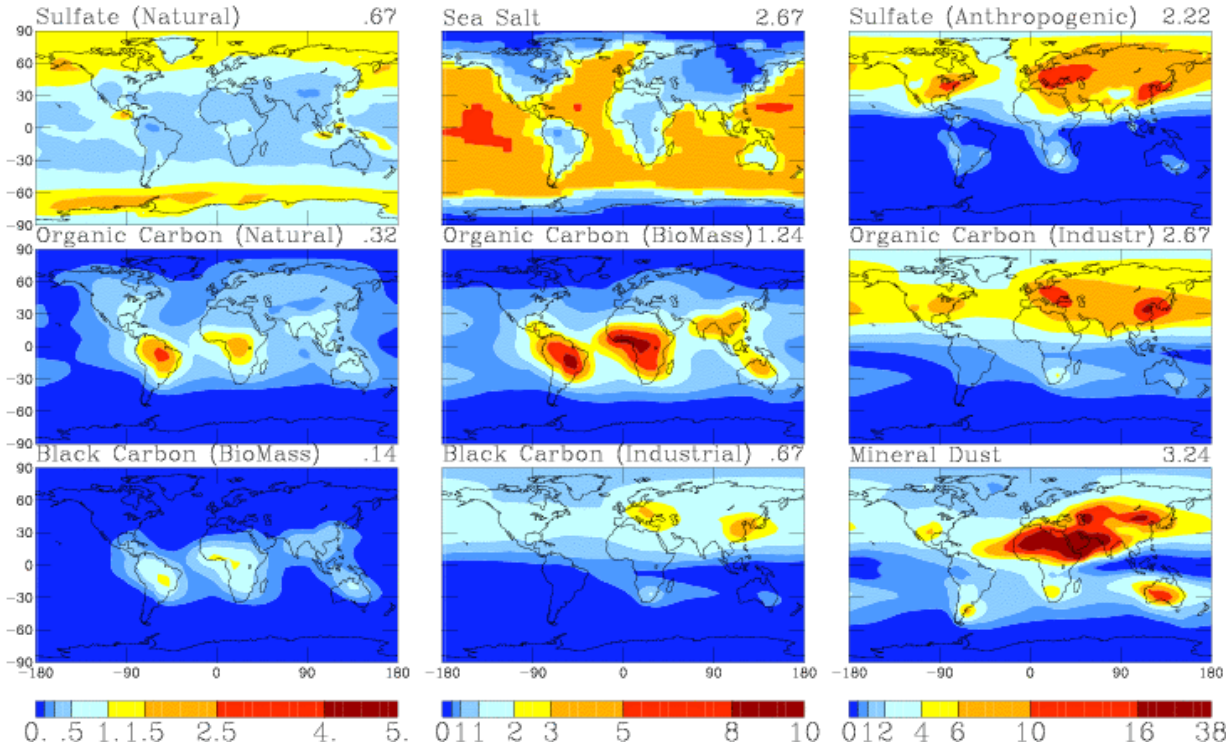

Figure 2. 1990 annual-mean optical depth (x 100) distribution of atmospheric aerosol species.

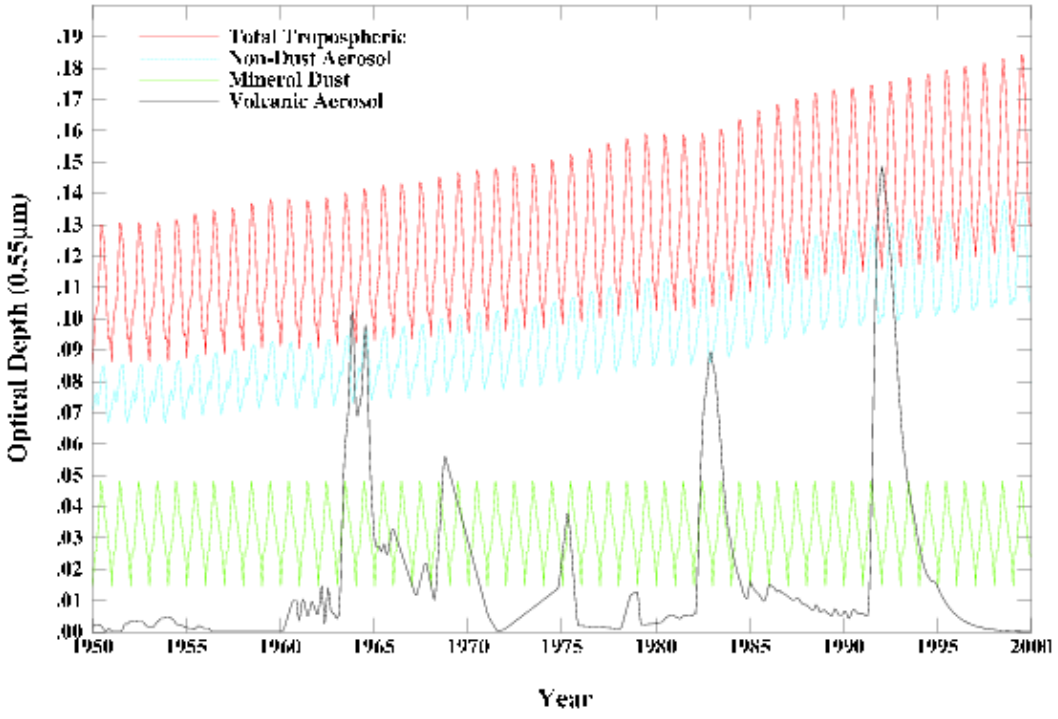

Figure 3. 50-year monthly-mean variation of global atmospheric aerosol optical depth.

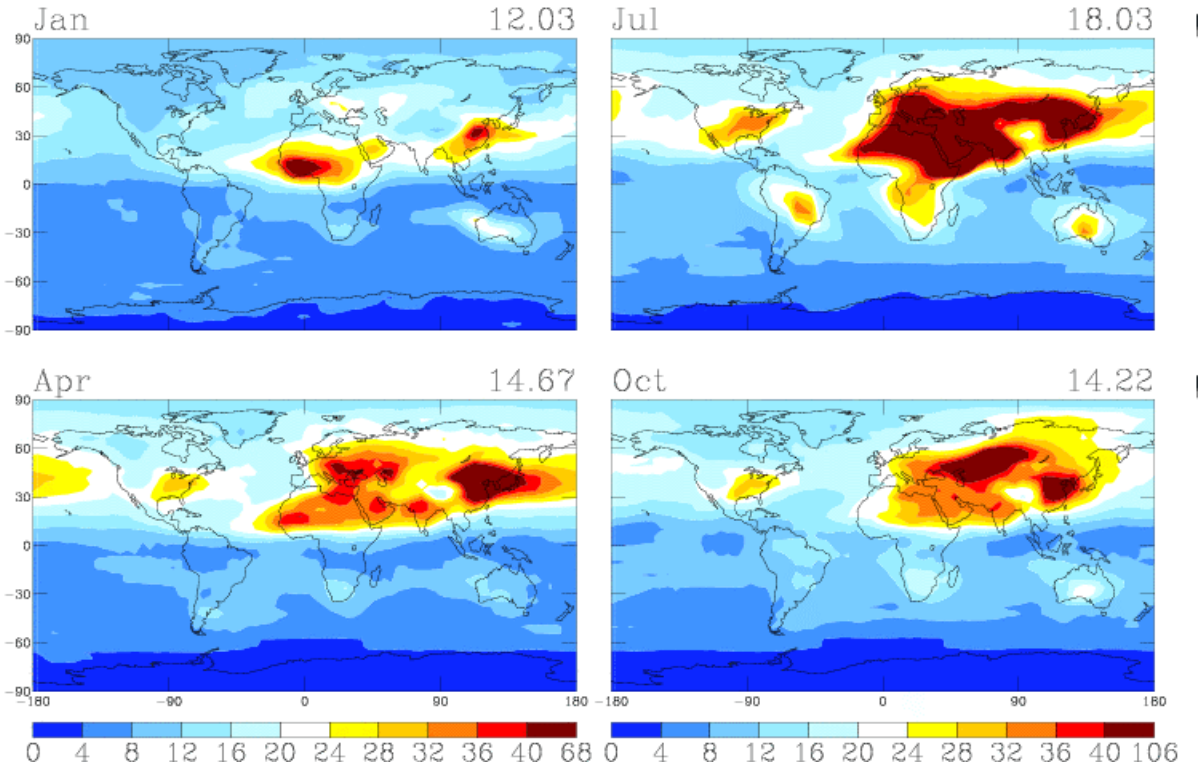

Figure 4. Seasonal variation of total tropospheric aerosol optical depth (x 100).

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