A General Circulation Model (GCM) Parameterization of Pinatubo Aerosols

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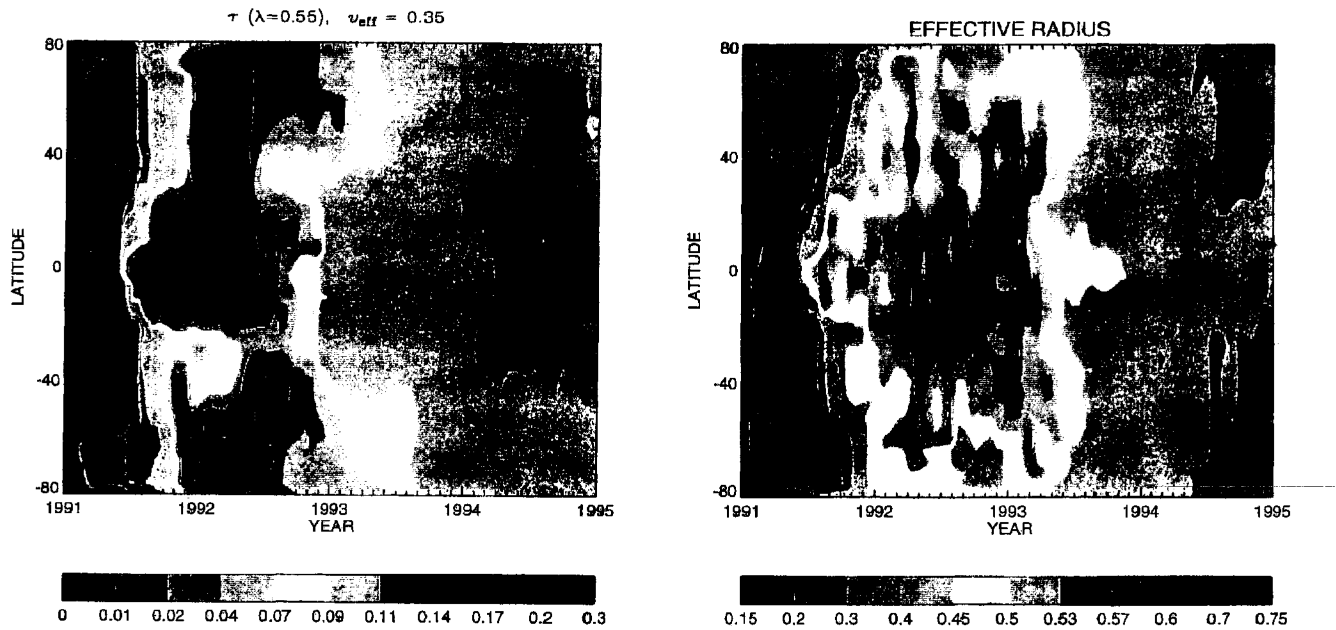
The June 1991 volcanic eruption of Mt. Pinatubo in the Philippines is by far the largest and the best documented global climate forcing experiment in recorded history. The time development and geographical dispersion of the Pinatubo aerosol has been closely monitored and sampled by a wide variety of satellite, airborne, and ground based instru-ments using visible, near-infrared (IR), and thermal wave-length measurements. The principal information regarding the optical depth, particle size, and vertical and geographic distribution of the aerosol is derived from the solar occulta-tion measurements at 385, 453, 525, and 1020 nm taken by the Stratospheric Aerosol and Gas Experiment (SAGE) II aboard the ERBS satellite (McCormick et al. 1995). Balloonborne measurements (Deshler et al. 1992) have identified the aerosol composition as concentrated sulfuric acid and have also characterized the particle size distribution. Limb-viewing measurements taken by ISAMS aboard UARS (Lambert et al. 1993) at thermal wavelengths provide key information about the variance (width) of the particle size distribution. The Pinatubo signature on the global energy balance was also recorded in the Earth Radiation Budget Experiment (ERBE) measurements of top of the atmosphere (TOA) solar and thermal fluxes (Minnis et al. 1993). Additional information obtained from a variety of lidar, sunphotometer, and *in situ* measurements is still being incorporated into the Pinatubo stratospheric aerosol data base to fill in remaining gaps and to cross-calibrate meas-urement results.

Given the above observational data, the spherical shape of the sulfuric acid droplets, and the real and imaginary refractive indices of sulfuric acid, Mie scattering can be used to calculate the aerosol radiative properties at all wave-lengths of the spectrum for a broad range of particle size distributions, thus making possible the accurate determination of the radiative forcing generated by the Pinatubo aerosols. Other observational constraints that help define the Pinatubo climate forcing experiment are provided by MSU measurements of stratospheric and tropospheric temperature (Spencer and Christy 1993) and by the global network of meteorological measurements of surface air temperature.

Based on preliminary estimates of the Pinatubo aerosol loading, Hansen et al. (1992) made general circulation model (GCM) predictions of the impact on global climate due to the Pinatubo aerosol. The predicted decrease in the global surface air temperature by 0.5°C by the end of 1992 with recovery to normal by 1995 has proven to be remark-ably accurate, though not all for the right reasons. Since the presentation of these preliminary model calculations, signif-icant improvements have been made to the radiative forcing input and to the Goddard Institute for Space Studies GCM. Model improvements include a more physically based cloud prediction scheme and an improved parameterization for the radiative transfer modeling of aerosols.

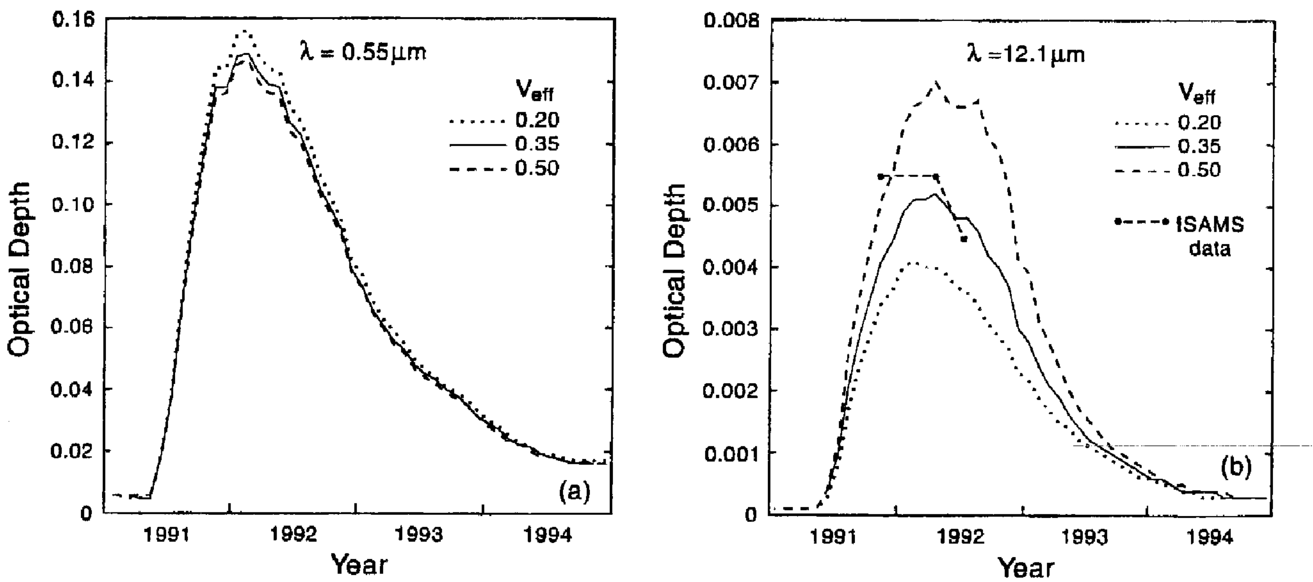
The radiative input to the GCM is obtained by least-squares fitting of a mono-modal size distribution to the zonally averaged SAGE II column extinction data at 385, 453, 525, and 1020 nm. The spectral range of the SAGE data is too limited to constrain the size distribution variance. However, extinction at 12.1 µm from ISAMS limb-viewing observa-tions can be used to infer a size distribution variance of order $v_{eff} = 0.35$. Since nearly all of the stratospheric heating is produced by the absorption of upwelling thermal radiation, the size distribution variance is closely related to the amount of stratospheric heating and also to the amount of greenhouse warming that counteracts the surface cooling effect due to reflected solar radiation.

The time-latitude evolution of the Pinatubo aerosol cloud is shown in Figure 1. The zonal mean column optical depth at λ=0.55 µm derived from SAGE II measurements is displayed in Figure 1a, and the time-latitude evolution of the effective particle size is shown in Figure 1b. The Pinatubo aerosol was found to increase steadily in size following the eruption, reaching a maximum effective radius of over 0.7 µm near the end of 1993. It is interesting to note that the particle size maximum does not coincide with peak optical depth, occurring instead nearly a year later. The constraints that are placed on the aerosol size distribution by the ISAMS 12.1-µm measurements are illustrated in Figure 2.



(a) (b)

Figure 1. Zonally averaged latitude-time dependence of Pinatubo aerosol optical depth (a) at reference wavelength λ=0.55 µm, and (b) effective particle radius derived from SAGE II data for effective size distribution variance v_{eff} = 0.35.



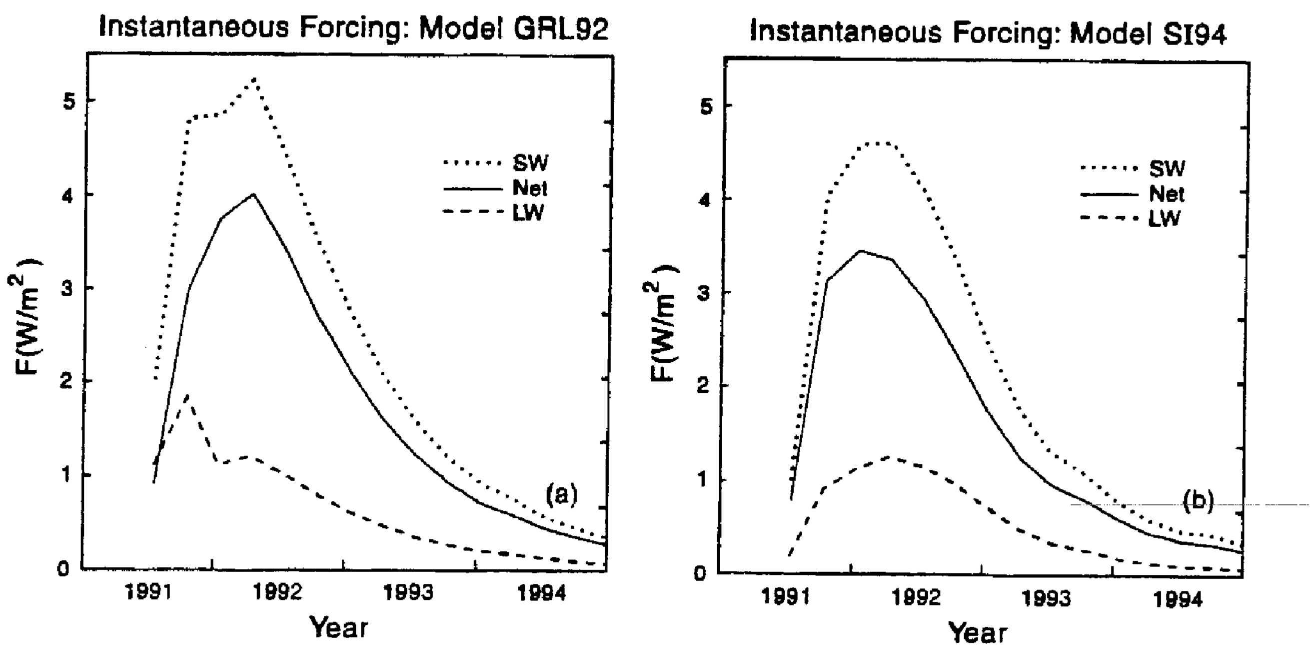
(a) (b)

Figure 2. Global mean optical depth at (a) 0.55 µm and (b) 2.1 µm for several values of effective variance based on multi-spectral extinction measured by SAGE II.

The radiative transfer model used in the calculations is based on the doubling/adding method (Lacis and Hansen 1974). Six spectral intervals are used to represent the wavelength dependence of the aerosol radiative properties in the solar spectrum. The single gauss point adaptation of the doubling/adding method has been parameterized to yield the same solar zenith angle dependence for conservative scattering as obtained by the full angle integrated doubling/adding results. The thermal spectrum is subdivided into 25 non-contiguous k-distribution intervals (Lacis and Oinas 1991). The flux calculations are done without scattering, using Mie-calculated absorption cross-sections and a 3-point numerical quadrature to integrate radiances over emission angle.

Using the radiative modeling parameterization outlined above, the radiative forcing by the Pinatubo aerosol is computed interactively at each gridbox as a function of optical depth, particle size, and variance based on the SAGE II measurements. The distribution of the aerosol with height is prescribed with 5-km vertical resolution, also based on SAGE II measurements. The globally integrated instanta-neous radiative forcing is shown in Figure 3 where the earlier forcing used in the Hansen et al. (1992) study is compared with current results. The broader size distribution used in the current treatment yields a somewhat greater greenhouse effect and a somewhat smaller solar forcing. With the present Pinatubo data base and GCM radiative treatment, the maximum net Pinatubo forcing is about 3.5 Wm^{-2} compared with 4.0 Wm^{-2} obtained previously.

While comparison of the GCM calculated radiation balance anomalies due to the Pinatubo aerosol shows qualitatively good agreement with ERBE measurements (Minnis et al. 1993), some TOA flux differences need further investigation. Some of these differences might be due to the significant changes in stratospheric ozone that were associated with the Pinatubo volcanic aerosol, but have not yet been included in model simulations. Stratospheric water vapor may also have been affected. The possibility of other feedback interactions with the Pinatubo aerosol that have an observable radiative effect clearly cannot be discounted. Thus the Pinatubo eruption with its growing data base of detailed observational constraints presents intriguing possibilities for further investigation and climate model validation.



(a) (b)

Figure 3. Seasonally averaged instantaneous radiative forcing assumed in the (a) Hansen et al. (1992) aeroso l model and (b) based on present analysis of SAGE II data.

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