

SIMULATION OF THE PINATUBO AEROSOL CLOUD IN GENERAL CIRCULATION MODEL

Byron A. Boville¹, James R. Holton², and Philip W. Mote²

Abstract. A high resolution stratospheric version of the NCAR Community Climate Model (CCM2) with an annual cycle was used to simulate the global transport and dispersion of the Pinatubo aerosol cloud. A passive tracer was injected into the model stratosphere over the Philippine Islands on model day June 15, and the transport was simulated for 180 days using an accurate semi-Lagrangian advection scheme.

The simulated volcanic aerosol cloud initially drifted westward and expanded in longitude and latitude. The bulk of the aerosol cloud dispersed zonally to form a continuous belt in longitude, and remained confined to the tropics (30°N – 25°S) centered near the 20 mb level for the entire 180 day model run, although a small amount was transported episodically into the upper troposphere in association with convective disturbances. Aerosol transported to the troposphere was dispersed within a few weeks into the Northern Hemisphere extratropics. In the Southern Hemisphere the aerosol was mixed into the region equatorward of the core of the polar night jet during the first 50 days, but penetration into Southern Polar latitudes was delayed until the final warming in November.

These results, which are generally consistent with observed behavior of the El Chichon aerosol, will be compared with observations of the Pinatubo cloud in the course of the next several months.

Introduction

The volcano Pinatubo in the Philippine Islands (120.19°E, 15.09°N) underwent a number of eruptions during June 1991. These culminated in a massive eruption on June 15, which injected a large cloud of volcanic debris into the stratosphere. Early indications [EOS, 1991] suggest that the total mass of SO₂ injected by this eruption was about 20 megatons, which is at least double the stratospheric mass injected by El Chichon in April 1982, and is probably the largest volcanic SO₂ injection of the century. The center of mass of the stratospheric injection appears to be near the 25 km level, although secondary maxima occur at lower levels, perhaps associated with earlier less powerful eruptions.

Evidence from the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus 7 satellite suggests that the gaseous SO₂ injected into the stratosphere by the eruption was converted to stratospheric aerosol by gas to particle conversion processes within a month or two (Bluth, G., S. Doiron, A. Krueger, L. Walter, and C. Schnetzler, manuscript submitted to *GRL*, 1991). Such conversion processes are known to primarily produce submicron aerosol particles with negligible

settling velocities (see, for example, Warneck [1988]). Thus, it can be assumed that total sulfur (SO₂ gas plus sulfate aerosol) is a conservative tracer.

Volcanic aerosols in the tropical stratosphere may absorb sufficient solar radiation to significantly perturb the temperature field [Labitze et al., 1983]. Calculations by Pitari [1987] for the El Chichon volcanic aerosol indicated, however, that volcanic aerosol perturbations to the diabatic circulation were less than 10%. Thus, aerosol 'self lofting' should be sufficiently small to neglect in a first study of the global aerosol transport, even for the massive stratospheric aerosol cloud produced by Pinatubo. In this study the total sulfur cloud is treated as a passive tracer whose mixing ratio is affected only by the processes of advection by large-scale motions and dispersion by unresolved turbulent eddies.

The Numerical Model and Initial Conditions

The dynamical model used in this study is a new version of the NCAR spectral general circulation model (CCM2) which has 35 levels with vertical grid increments of about 2 km. In the simulation reported here the model is run at a horizontal spectral truncation of T42, which is equivalent to a horizontal grid spacing of about 300 km. The model incorporates a number of improvements in tropospheric physics and also includes an entirely new semi-Lagrangian algorithm for 3-dimensional advection of trace constituents [Rasch and Williamson, 1991]. This algorithm is designed to force conservation of the tracer mass at each time step, and can advect tracers that have very strong horizontal or vertical gradients without introducing negative values or new maxima. Thus, it is particularly suitable for studying transport of a tracer injected at a single point.

The model is run in an annual cycle mode. The zonal mean climatology (Figure 1) for the Northern Hemisphere is in good agreement with observations in all seasons. In the Southern Hemisphere, however, the stratospheric polar night jet is nearly double its observed strength, and the polar temperatures are much too cold. Thus, caution must be used in comparing model results with observations in the Southern winter.

The simulation is initialized at model day June 15 by inserting a tracer at 27 points in the grid domain in the region of Pinatubo. The tracer is specified to have a normalized 'mixing ratio' of 1.0 at the 24 mb level and 0.5 at the 17 mb and 35 mb levels in the grid column $n(i, j)$. Here i and j denote the latitude and longitude of the grid column closest to Pinatubo (this turns out to be only 91 km from Pinatubo). At each of these three levels the initial mixing ratio at the points $n(i \pm 1, j)$ and $n(i, j \pm 1)$ is taken to be 1/2 of that at the $n(i, j)$ point, and at the points $n(i \pm 1, j \pm 1)$ is taken to be 1/4 of that for the $n(i, j)$ point. This distribution simulates a stratospheric injection with center of mass near 25 km. The model accurately conserves total tracer mass for the entire 180 day integration.

¹ National Center for Atmospheric Research

² Atmospheric Sciences Department, University of Washington

Copyright 1991 by the American Geophysical Union.

Paper number 91GL02778
0094-8534/91/91GL-02778\$03.00

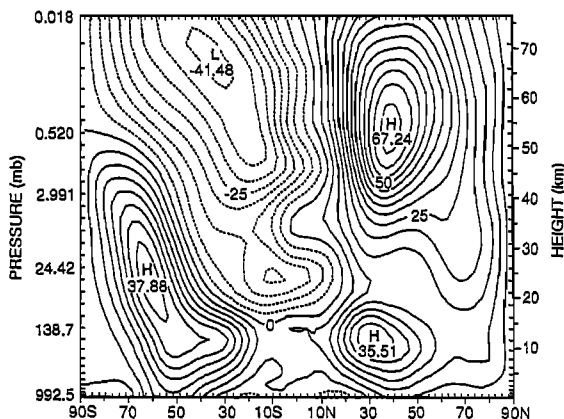
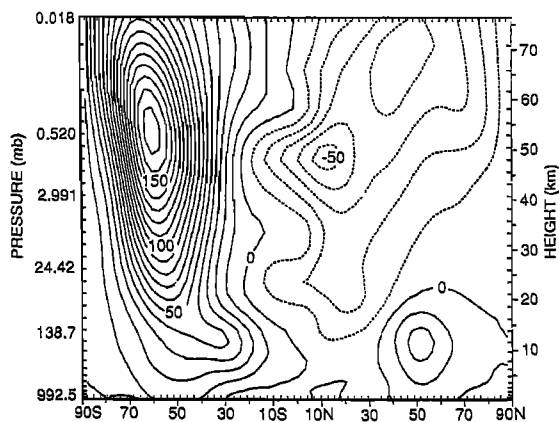


Fig. 1. Latitude-height distributions of mean zonal wind in the CCM2. Upper panel is averaged from July 15–August 14. Lower panel is Averaged from November 12 to December 11.

Simulation Results

For about the first ten days of the simulation the tracer cloud moves westward in the tropical easterlies and expands rapidly to a meridional width of about 30° and zonal extent of about 55° . Following June 25 the dispersion of the main tracer cloud

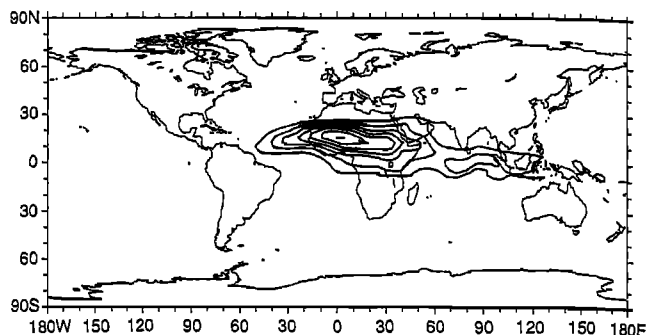


Fig. 2. Tracer mixing ratio distribution at the 24-mb level on day 30 (July 15). Contour interval is 70 ppb and the maximum contour is about 1 ppm.

at 24 mb is primarily zonal. By July 15 (Figure 2) the main tracer cloud has circled the globe about 1.5 times and has a zonal scale of about 120° , while the meridional scale remains about 30° . There is also a substantial 'tail' of tracer which has spread into the Southern Hemisphere where the westward drift is slower due to the weaker easterly winds. Zonal spreading of the main aerosol cloud continues so that by about July 30 there is a fairly continuous band of tracer circling the globe in the equatorial zone (not shown).

The latitude–time dependence of the zonally averaged tracer mixing ratio at 24 mb is shown in Figure 3. (Note that the contour intervals are logarithmic). The figure clearly shows that for the first 120 days (until mid October) the zonal mean tracer mass is confined almost entirely equatorward of 30°N at this altitude. This is consistent with the absence of large scale eddies in the easterly regime of the summer hemisphere extratropical stratosphere. In the Southern Hemisphere, on the other hand, wave disturbances in the winter westerlies disperse tracer amounting to a few percent of the maximum tropical mixing ratio poleward to the latitude of the polar night jet core at about 60°S by day 50 (August 4). However, the strong potential vorticity gradient associated with the southern polar night jet acts as a strong barrier to transport (see, e. g., McIntyre,[1987]), so that very little tracer is transported into

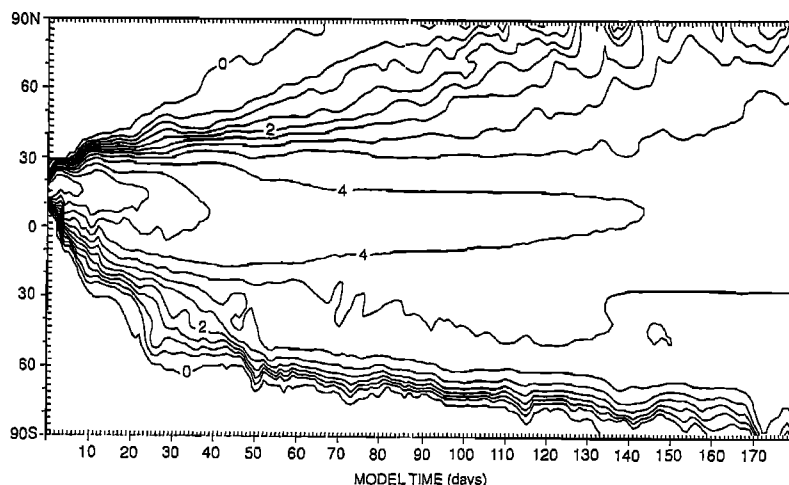


Fig. 3. Latitude-time plot of the zonal average of the tracer mixing ratio at the 24-mb level. Contour intervals are logarithmic; two contours correspond to an order of magnitude change. The 2.5 contour corresponds to about 1 ppb.

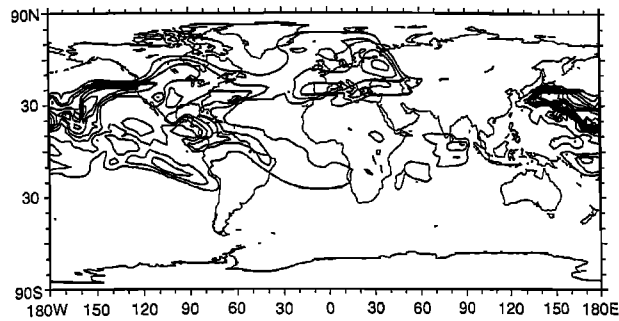


Fig. 4. Tracer mixing ratio distribution at the 140-mb level on day 30 (July 15). Contour interval is 2.8 ppb and the maximum contour is about 55 ppb.

the southern polar region until after the final warming in late November. This barrier effect may be somewhat exaggerated in the present model owing to the unrealistically strong polar night jet.

Although the initial tracer was all injected above the 50-mb level, small amounts of tracer quickly appeared in the equatorial upper troposphere, owing to stratosphere-troposphere exchange associated with parameterized convection in the Indian monsoon region and along the ITCZ. The 'blobs' of tracer injected into the troposphere at low latitudes are quickly sheared out by transient weather disturbances and transported into the extratropics in the form of elongated filaments. This is illustrated by the mixing ratio distribution at the 140-mb level on July 15 shown in Figure 4, which should be compared with the map for the 24-mb level in Figure 2. (The maximum mixing ratio at 24 mb is 17 times the maximum at 140 mb.)

The latitude-time distribution of the zonally averaged tracer mixing ratio in the troposphere (defined as the integral from the surface to the 200-mb level), is shown in Figure 5. There is a maximum in the tropospheric column abundance which appears near 30°N early in the integration, and gradually shifts poleward to about 45°N by day 120 (October 13). A weaker maximum occurs near 15°S between day 30 (July 15) and day 70 (August 24). These subtropical maxima may be due to exchange processes associated with transient cyclonic distur-

bances. The rapid meridional dispersion at lower levels is consistent with reports of enhanced aerosol backscatter observed by lidars in Southern France in the lower stratosphere about a month following the eruption of Pinatubo (Chanin, personal communication).

The height dependence of the tracer transport can also be deduced from the latitude-height cross sections of tracer mixing ratio for August 14, October 13, and December 11 shown in Figure 6. Above 50 mb the bulk of tracer remains in the equatorial region, and the maximum mixing ratio decreases by less than a factor of 4 from August 14 to December 11, which is qualitatively consistent with the long residence times for volcanic aerosols in the stratosphere reported by Hofmann [1990]. Below the 100-mb level there is already substantial transport into high Northern latitudes at August 14, and the mixing ratio in the northern extratropics near the 140-mb level increases by 50% between August 14 and October 13. Figure 6 also clearly shows the confinement of the tracer equatorward of the polar night jet at 60°S.

Discussion

The global transport and dispersion of the passive tracer in this model is qualitatively in accord with reports of the evolution of the Pinatubo aerosol cloud during the first month following the eruption, which indicate that the main aerosol mass near 25 km remained in the equatorial region, while filaments of aerosol at lower altitudes penetrated into the extratropics. In the model all of the aerosol was injected above 50 mb. There is evidence, however, that a number of minor eruptions of Pinatubo just prior to the June 15 eruption may have injected aerosol clouds near the 100-mb level. Thus, while in the simulation the aerosol at the 140-mb level was all transported downward, in reality there were direct sources that could account for the observed upper tropospheric and lower stratospheric aerosol layers.

Results from this experiment may also be compared to the observed evolution of the aerosol cloud produced by El Chichon (McCormick et al. [1984]). El Chichon is at a latitude close to that of Pinatubo, and the main eruption of El Chichon occurred in April of 1982 when the summer stratospheric east-

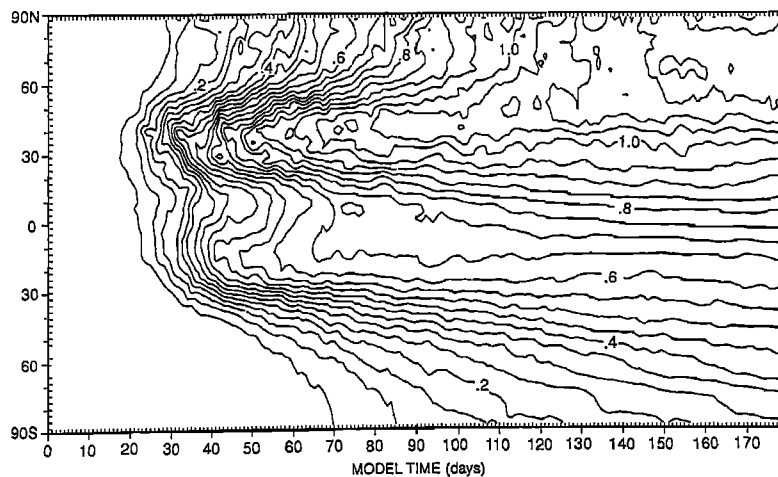


Fig. 5. Latitude-time section of the zonal average of the total tracer mass in the column between the surface and 200 mbs. (Contour value of 1 unit equals 35 gm m^{-2} .)

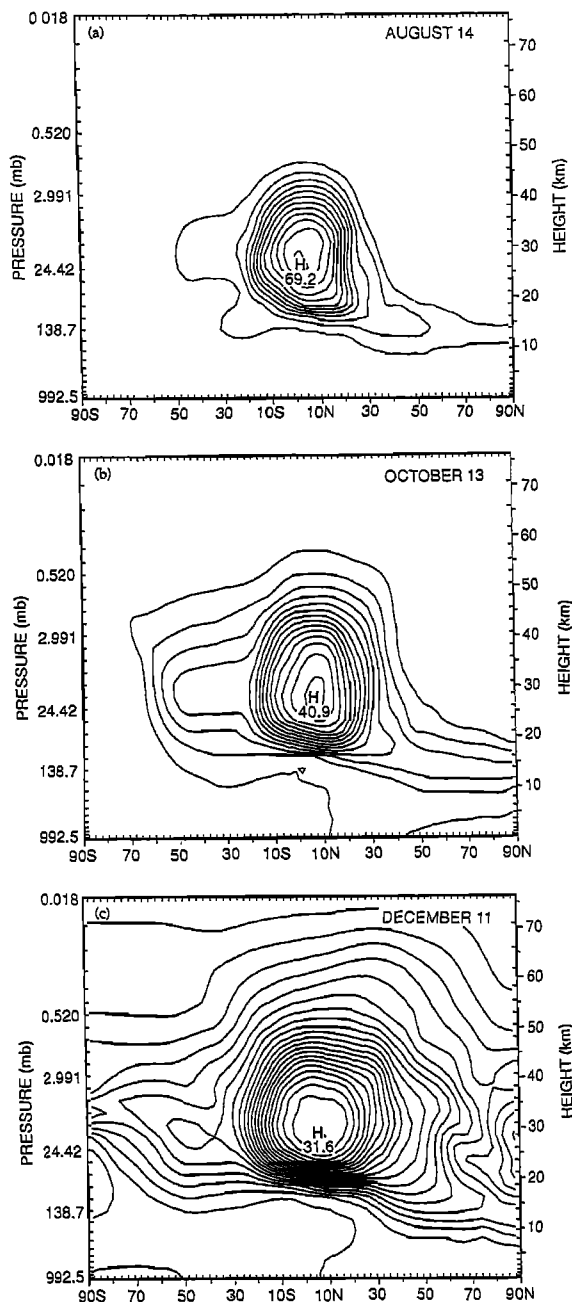


Fig. 6. Latitude-height cross sections of the zonally averaged tracer mixing ratio in ppb on (a) August 14 (contour interval 5.6 ppb); (b) October 13 (contour interval 2.8 ppb); and December 11 (contour interval 1.4 ppb). The maximum mixing ratio value is plotted in each panel.

erly regime was already established in the Northern hemisphere. The aerosol cloud of El Chichon was observed to quickly disperse into the latitude band between the equator and 30°N. The main mass of aerosol, which as in the case of

Pinatubo was centered near the 25 km level, did not penetrate poleward of 30°N until the stratospheric zonal wind switched to westerly in October. Aerosol at lower altitudes dispersed into the extratropics much quicker, as also occurred in this simulation.

In conclusion, the results of this simulation are generally consistent with observed behavior of the El Chichon aerosol and with early observations of the Pinatubo aerosol. Observations of the Pinatubo aerosol cloud over the next several months will provide a unique opportunity to test the stratospheric transport climatology of the GCM.

Acknowledgements. This material is based upon work supported in part by the Physical Meteorology Program of the National Science Foundation under Grant No. ATM-8813971 and the National Aeronautics and Space Administration, NASA Grants W-16,215 (NCAR) and NAGW-662 (UW).

References

- EOS, Pinatubo cloud measured, *EOS Trans. AGU*, 72, 305-306, 1991.
- Hofmann, D. J., Increase in the stratospheric background sulfuric acid aerosol mass in the past 10 years, *Science*, 248, 996-1000, 1990.
- Labitzke, K., B. Naujokat and M. P. McCormick, Temperature effects on the stratosphere of the April 4, 1982 eruption of El Chichon, Mexico, *Geophys. Res. Lett.*, 10, 24-26, 1983.
- McCormick, M. P., T. J. Swissler, W. H. Fuller, W. H. Hunt and M. T. Osborne, Airborne and ground-based lidar measurements of the El Chichon stratospheric aerosol from 90°N to 90° S, *Geof. Int.*, 23, 187-221, 1984.
- McIntyre, M. E., *Dynamics and tracer transport in the middle atmosphere: An overview of some recent developments*, G. Visconti and R. Garcia, Reidel, Dordrecht, 267-296, 1987.
- Pitari, G., M. Verdecchia and G. Visconti, A transformed Eulerian model to study possible effects of the El Chichon eruption on the stratospheric circulation, *J. Geophys. Res.*, 92, 10,961-10,975, 1987.
- Rasch, P. J. and D. L. Williamson, The sensitivity of a general circulation model climate to the moisture transport formulation, *J. Geophys. Res.*, 96, 13,123-13,137, 1991.
- Warneck, P., *Chemistry of the Natural Atmosphere*, Academic Press, 1988.

B. A. Boville, National Center for Atmospheric Research, POB 3000, Boulder, CO, 80307

J. R. Holton and P. W. Mote, Atmospheric Sciences, AK40, University of Washington, Seattle, WA 98195.

(Received September 25, 1991;
accepted October 17, 1991)