# RADIATIVE FORCING OF THE PINATUBO AEROSOL AS A FUNCTION OF LATITUDE AND TIME

by

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**Abstract.** We present calculations of the radiative forcing of the Mt. Pinatubo aerosols as a function of latitude and time after the eruption and compare the results with GOES satellite data. The results from the model indicate that the net effect of the aerosol was to cool the earth-atmosphere system with the most significant radiative effect in the tropics (corresponding to the location of the tropical stratospheric reservoir) and at latitudes greater than 60°. The high-latitude maximum is a combined effect of the high-latitude peak in optical depth (Trepte et al 1994) and the large solar zenith angles. The comparison of the predicted and measured net flux shows relatively good agreement, with the model consistently under predicting the cooling effect of the aerosol.

## 1. Introduction

The massive eruption of Mt. Pinatubo in the Philippines (15N, 120E) occurred on June 15, 1991 releasing 14 - 20 million metric tons of $SO_2$ into the atmosphere (Bluth et al. 1992). The eruption significantly altered the state of the stratosphere for several years and has provided scientists with an unparalleled opportunity to observe the workings of the stratosphere. Hansen et al (1993; 1995 ), Lacis et al. (1992; 1995), and Dutton and Cox (1995) have estimated the radiative effects from the stratospheric aerosol produced by Mt. Pinatubo, while Minnis et al. (1993) analyzed the ERBE data to show the effect of the aerosol. Hansen et al. (1995) concluded that the reduction in the solar flux at the surface by the aerosol was enough to reduce the surface temperature of the earth by 0.5 °C emphasizing the significance of volcanic eruptions on the earth's climate. The relatively good prediction of the cooling effect of the Pinatubo aerosol has been cited as one of the successes of the global climate modeling community.(IPCC, 1995).

This paper presents predictions of the radiative forcing of the Pinatubo aerosol as a function of latitude and time after eruption and compares the predictions with observations made by the GOES satellite. The input data for the model are zonally-averaged satellite data for the optical depth (Long and Stowe 1994), effective radius estimates from Russell et al. (1996), climatalogical mean values of cloudiness, and estimates of the stratospheric

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temperature and ozone effects of the aerosol. An earlier version of the radiative transfer model was used to estimate the aerosol heating from the Pinatubo aerosol cloud (Kinne et al. 1992, Russell et al., 1993) as well as radiative forcing over Mauna Loa Observatory (Russell et al, 1993).

## 2. Characteristics of the Pinatubo Cloud

The Pinatubo eruptions put a cloud of gases and particles at 20-25 km height directly above Mt. Pinatubo in mid-June 1991. The cloud circled the earth at three week intervals, spreading out latitudinally to about 15° S and 10° N in two months time. A significant amount of the plume moved upward to about 26 km and also southward of the equator due to the time of year when the eruption occurred and the radiative heating due to the sulfuric acid particles that were formed (Kinne et al. 1992, Young et al. 1994, Young et al. 1995). By September and October of 1991, the cloud was fairly well diffused in the tropics with a relatively sharp boundary at 20 degrees north and south (Grant et al. 1995, Lambert et al. 1993,). After October 1991, this tropical reservoir of aerosol slowly decayed in height and in amount (Mergenthaler, et al. 1993; Russell et al. 1996; Lambert et al. 1995, Grainger et al. 1995) while pieces of the cloud were transported from the tropical reservoir to higher latitudes (McCormick and Veiga, 1992; Hitchman, et al. 1994).

The three most important variables for estimating the radiative effects are the aerosol optical depths, the vertical distribution and the size of the particles (Lacis et al. 1992).

### a. Optical Depths

Long and Stowe (1994) analyzed AVHRR data and estimated the zonally averaged optical depth resulting from the Pinatubo cloud for the first two years after the eruption. The Long and Stowe AVHRR estimates of optical depths resulting from the Pinatubo eruption are shown in Figure 1a (Russell et al. 1996). The data show clearly the increase in

the tropics due to the eruption and the decay with time. Also shown is a significant increase in optical depth at higher latitudes (both in the northern and southern hemispheres) relative to the subtropics (20-30 N and S).

The transport from the tropical reservoir to the high southern latitudes in late 1992 has been discussed by McCormick and Veiga, (1992), Trepte, et al. (1993) Hitchman et al. (1994), and Grant et al. 1995, and is believed to be due to planetary waves. The optical depths may also have been influenced by the eruption of Mt. Hudson in mid August 1991 (see Pitts and Thomason, 1993).

Figure 1 shows that the optical depths in the high northern latitudes stay relatively small until the winter and spring of 1992 when there is a large increase. Again, the optical depth is larger at high latitudes than in subtropics. As discussed by Trepte (1994) and Kent et al. (1995), this is evidently due to the sloping down of the potential temperature surfaces at higher latitudes (i.e. a thicker layer of Pinatubo aerosol leading to larger optical thicknesses).

A similar latitude - time plot for optical depth is shown in Figure 1b for the SAGE II data. Russell et al. (1996) discuss the differences between the AVHRR and the SAGE II data and recommend that the SAGE II data be used for everywhere except the tropical reservoir prior to 1/92. For the tropical reservoir during 7-12/91, they recommend reducing the AVHRR values by a factor of 0.84 (following an analysis similar to Long and Stowe 1994). For this paper we used the optical depth data as recommended by Russell et al. (1996).

## b. Vertical Distribution

Figure 2 shows a sequence of zonally averaged vertical distributions of aerosol volume from September-October 1991 to April-May 1993 showing the decay of the tropical reservoir (Grainger, personal communication). These volumes are derived from

UARS extinction measurements at 12.11 μm (assuming the particles are % 75 sulfuric acid, see Grainger et al. 1995).

Initially after the eruption the plume was a relatively well defined cloud in the vertical with a maximum concentration at about 22 km (Kinne, et al. 1992). During September and October of 1991 the center of the plume rose from 22 km to 26 km and then fell slowly over the next several years. The data in Figure 2 also show the sloping downward of the cloud as it spreads to higher latitudes.

The UARS measurements do not show the large optical depth values at high latitudes that are in the AVHRR and SAGE II data (compare Figure 1 and Figure 2). The most likely reason for this may be that the large optical depths at the high latitudes seen in the AVHRR and SAGE II could be due to aerosols that are below the UARS height cut off of 16 km. (Grant et al. 1995; Mergenthaler, personal communication.)

For this study we used the aerosol vertical distributions for the tropical reservoir from the UARS data and scaled them to yield the optical depths in agreement with the optical depth data. At higher latitudes, we used estimations from the SAGE II data (Trepte et al. 1994). Before the UARS satellite we used estimates from several lidar measurements (for example, DeFoor et al..1992).

## c. Size of the particles

Initially, the newly formed Pinatubo particles grew rapidly by condensation and coagulation in the first few months reaching effective radii of about 0.3 - 0.5 μm (Russell et al. 1996). Analysis of the sunphotometer and SAGE II data by (Russell et al..1996) indicates that the aerosol effective radius continued to grow to a global average value of about 0.7 μm in about one year. This is well below the effective radius where the infrared effects on the global radiation balance will dominate and cause heating of the earth-atmosphere system (Lacis, et al. 1992).

Grainger, et al. (1995) have estimated the size of the Pinatubo aerosols by using a correlation of the volume of the aerosol to the surface area. Their results show somewhat

smaller effective radii than Russell et al. (1996) during September and October of 1991 and even smaller values thereafter. Our calculations show that the effective radius difference between Russell et al. (1996) and Grainger et al. (1995) has relatively little effect on the radiative transfer calculations. We used the effective radius values from Russell et al. (1996).

## 3. Radiative Transfer model

The radiative transfer calculations are based on a two-stream method that is described in Kinne et al. (1992). The calculations were performed for ten different latitudes in two-month timesteps. The atmospheric conditions were based on AFGL-standard atmospheres (Anderson et al., 1986). The cloud data, total and high-, mid- and low level cloud cover fractions, were taken from the 3DNEPH climatological data (Koenig et al., 1987). Tropospheric background aerosol data were based on AVHRR satellite data (Stowe, personal communication).

We modified the standard atmospheric profiles to include the observed changes in stratospheric temperatures and ozone amounts. The temperature changes for different stratospheric altitudes were based on microwave satellite data (Christy, personal communication). The changes in lower stratospheric ozone concentrations reflect the ozone column changes of the TOMS satellite data (Newmann, personal communication).

## 4. Results

Using the radiative transfer model, we estimated the impact of the Pinatubo aerosol on the atmospheric radiation for the ten equal area latitude zones as a function of time after the eruption. The results for the effect on the radiant energy at the top of the atmosphere (TOA) are shown in Figure 3 for the ten equal area latitude bands.

The longwave ($\lambda > 4\mu$m) effect of the Pinatubo aerosol is primarily a warming effect (i.e. a greenhouse effect) while the shortwave ($\lambda < 4\mu$m) effect is always a cooling effect (since the sulfuric acid particles absorb very little solar radiation). The net effect is simply the sum of the two. As shown in Figure 3, the primary net effect of the aerosol on the earth-atmosphere system is cooling. However, the differences between the effect in the tropics and high latitudes are significant. The net cooling effect in the tropics decays monotonically from the maximum two months after the eruption. The high latitude zones show a large seasonal variation due to the relatively high optical depth (discussed above) and the long solar day in the polar summer.

We compared the model results to observations of the radiative flux observed by the GOES satellite instruments. The years 1985-1990 were used as a base case and the difference from the base case was used as an estimate of the Pinatubo effect.

Figure 4 shows a direct comparison of the net flux effect from the GOES data and the model. The subtropic region (23°-36°) is not shown as there is little effect in either the model or the GOES data. The high latitude GOES data was not available. The general agreement for the TOA net flux is relatively good, in that both the model and the data show a net cooling effect that falls off in about two years. However, the model consistently shows values that are less than the GOES data. The difference is believed to be related to the amount of cloudiness and temperature changes during the period after the Pinatubo eruption (an El Nino occurrence). In other words, if the period after the Pinatubo eruption had different cloudiness that the preceding five year average then the results of the model and the satellite data will be affected.

Comparison of the shortwave flux and longwave fluxes individually (not shown) show a larger difference between the predictions and the observations than the net flux does. However, the differences are strongly correlated and seem to indicate that the cloudiness during 1991-1993 may be different than the climatalogical average.

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Hansen et al. (1993, 1995) have calculated the Pinatubo aerosol forcing for use in the GISS climate model. They used optical depths calculated from the SAGE II data (whereas we used the modified AVHRR data for the tropical core prior to 1/92 and SAGE II data for all other times and locations - see Sect 2b, above) and predicted a maximum global TOA net flux change of -3.5 watts/m2 at 6 months after the eruption. Our maximum calculated global TOA net flux is -2.3 watts/m2 at 4 months after the eruption. (The ERBE data indicate a maximum of about -3.0 watts/m2 at 2 months after the eruption for the region of 40S to 40N.) Hansen et al. (1995) calculated a time averaged global TOA forcing from July 1991 through December 1992 of -3.6 (watts/m2)/year, whereas the ERBE data (restricted to 40S to 40N) indicate that the time averaged global TOA net flux forcing was - 2.1 (watts/m2)/year. Our calculations yield an time averaged global TOA net flux change of -1.8 (watts/m2)/year.

## 5. Conclusions

We have calculated the effect of the Pinatubo aerosol on the atmospheric radiant flux. The results show that the net effect of the aerosol was a negative radiative forcing of the earth-atmosphere system at all latitudes. (The brief and small positive forcings at 23-36 N and S in Figure 3 are considered to be within the noise of the input data and are small compared to the negative forcing obtained elsewhere.) The tropical regions show a monotonically decreasing net effect from a maximum at about 2 months after the eruption. The high latitude regions show much more variability due to the polar summer and winter period. The comparision between calculations and observed GOES data is good however, the model consistently underestimates the net cooling.

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