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Lidar Observations of Mt. Pinatubo Aerosols: Effects on the Global Radiation Budget

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INTRODUCTION

Significant amounts of stratospheric aerosols can cause a cooling of the earth's surface due to the scattering of solar radiation back into space. Likewise a warming of the stratosphere where the particles reside will occur due to absorption of upwelling infrared radiation [1]. The eruption of the Pinatubo volcano in the Philippines (15.14°N, 120.35°E) on June 15, 1991, produced the largest impact on the stratosphere ever observed by modern airborne, spaceborne, and ground-based scientific instruments. The volcanic aerosols were ejected into the upper troposphere and the stratosphere to heights above 33 km. Due to their long residence time, the volcanic aerosols were transported around the globe in about three weeks [2]. The effects are spread in the meridional direction by the interactions of large scale planetary waves with the resivour regions about the equator. By September 27 small amounts were observed as far north as Norway.

Estimates, from the SAGE II experiment of NASA, place the aerosol mass injected by this eruption between 20 and 30 megatons, approximately twice the amount produced by El Chichon in 1982 [3]. NASA models also predict a surface temperature decrease, in 1992, of about three times the standard deviation of the annual global mean [1]. This temperature decrease is sufficient to reverse current global warming trends for the next couple of years. It is therefore important to study and understand aerosol distribution and variations in the stratosphere to see how they contribute to the thermodynamic exchange processes in the atmosphere.

INSTRUMENTATION AND DATA COLLECTION

The LAMP instrument was designed to operate as both a middle atmosphere sensor and a lower atmosphere meteorological sounder. To accomplish this task, the profiles of many atmospheric properties including nitrogen concentration, water vapor concentration, aerosols, density, and temperature must be monitored over a large altitude range simultaneously. The LAMP lidar is a rugged self-contained transportable instrument capable of operating in almost any environment, as was demonstrated by its operation aboard the German ice breaker RV Polarstern in Antarctica during December 1991.

The instrument uses a pulsed Nd:YAG laser transmitting near-infrared radiation of 1064 nm, 1.5 joules per pulse at a pulse repetition frequency of 20 Hz. The fundamental output frequency is doubled and tripled by nonlinear crystals to produce outputs at wavelengths of 532 nm and 355 nm with energies of 600 mJ and 250 mJ respectively. The system design is an advanced development from two earlier lidars, the GLINT and GLEAM systems developed by Philbrick at the Air Force Geophysics Laboratory (currently Phillips Laboratory) [4,5]. The five subsystems, transmitter, receiver, detector, data system, and control/safety system have all been integrated into a standard shipping container, which serves as a field laboratory. The lidar utilizes two independent receivers. The primary receiver is a 41 cm diameter Cassegrain telescope and the secondary receiver is an 20 cm Schmidt Cassegrain telescope. The 41 cm receiver collects the backscattered return from about 500 m to 80 km, while the 20 cm telescope covers the 8 - 35 km region for an independent check on system behavior. Measurements are made at the wavelengths of 355 and 532 nm for molecular scattering (Rayleigh and Raman) and particle scattering.

The Pennsylvania State University, The University of Bonn, and The University of Wuppertal were invited by the Alfred-Wegener-Institut of Germany for the voyage from Tromsø, Norway to Bremerhaven, Germany, to Puerto Madryn, Argentina, to Antarctica, to Punta Arenas, Chile. The voyage covered latitudes from 70°N to 65°S. The LAMP instrument first collected data on September 24, 1991, at the Andøya Rocket Range, Norway. The LADIMAS campaign began with a two-week period of testing and coordinated rocket measurements. The lidar was installed on the helicopter deck of the RV Polarstern at Tromsø, Norway on October 10, 1991. Several profiles of low altitude atmospheric data were collected in hazy and overcast conditions while the ship was in transit to Bremerhaven, Germany. Measurements were obtained on every clear night and several nights of poor weather conditions aboard the RV Polarstern as it sailed from Germany to Argentina, Antarctica and then to Chile.

This voyage provided an excellent opportunity to collect profiles of the Pinatubo cloud as it spread latitudinally. The only other methods capable of measuring this cloud globally are satellite based instruments, such as the SAGE II experiment. However, satellite instruments cannot penetrate into the troposphere because of the large optical depth in limb sounding, and do not offer the spatial or temporal resolution available to lidar.

OBSERVATIONS

The aerosols from the Pinatubo eruption plume were first detected by the Penn State LAMP lidar in Andenes, Norway (69° 17' N, 16° 01' E) on September 27, 1991 [6]. The backscattered return from the laser pulses represents the total scattering, both molecular and aerosol. The backscatter ratio, R, is defined by,

$$R(\lambda,z) = [\beta_a(\lambda,z) + \beta_m(\lambda,z)]/\beta_m(\lambda,z), \tag{1}$$

where β_a and β_m are the volume backscatter cross sections for aerosols and molecules, respectively.

The largest optical thickness and largest backscatter ratio were observed near the equator, as expected. The most optically thick portions of the Pinatubo aerosols covered latitudes from 24°S to 30°N, and altitudes from 20 to 30 km. The aerosol cloud also settles to lower altitudes as it spreads north and south following the stratification contours established by the tropopause. The highest altitudes of enhanced aerosol scatter, above 30 km, are observed near the equator. As the cloud spreads southward it rises to about 33 km at 14°S and then the upper detectable altitude settles to 26 km at 62°S. The cloud's peak altitude steadily descends to 25 km as it spreads northward.

Figure 1 shows a plot of a two-color lidar return from the ground to 40 km on the night of November 22, 1991 during the LADIMAS campaign. These profiles represent a 30 minute average with a 150 m height resolution. The U.S Standard Atmosphere has been corrected for transmission loss using LOWTRAN 7. The profiles are then tied to this modified standard atmosphere above the Pinatubo aerosols where molecular scattering dominates. Since the molecular backscattering cross section is proportional to $1/\lambda^4$, the cross section for 355 nm is about 5 times the 532 nm backscattering cross section ($532^4/355^4 = 5.04$). The model return for 355 nm has been shifted by this same amount from the model return for 532 nm. The Pinatubo dust layer can be clearly seen on both wavelengths in the lower stratosphere between 20 and 30 km. However, between 7 and 12 km, a cirrus cloud dominates the 532 nm return, but has a much smaller signature in the 355 nm backscattered signal. This is because the molecular backscatter for the 355 nm signal is much stronger than that of the 532 nm signal, and thus the particle backscatter does not dominate the molecular backscatter at the 355 nm wavelength. We can then assume that the cirrus cloud consists of very large particles, maybe ice crystals, because the scattering intensity for both wavelengths has about the same magnitude. The particle backscatter ratio is now defined to add some understanding to the wavelength dependance of particle scattering.

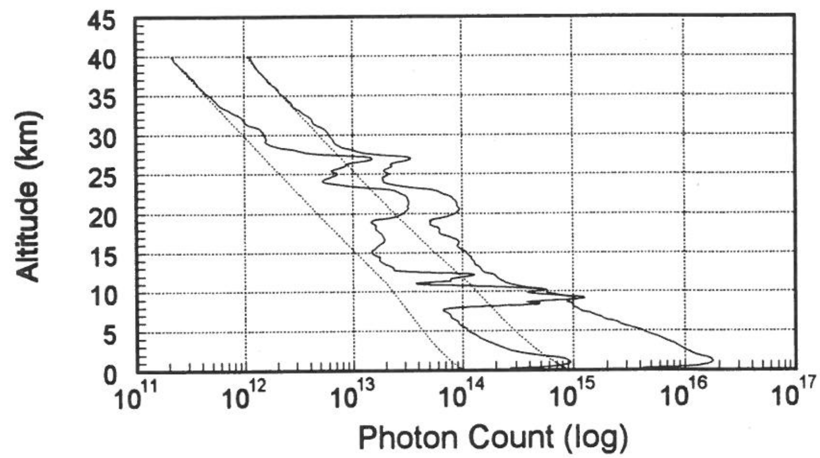

Figure 1. Lidar profiles for 355 and 532 nm wavelengths collected on November 22, 1991.

The particle backscattering ratio (PBR) is defined as the ratio of the aerosol backscattering cross section at 532 nm to the aerosol backscattering cross section at 355 nm. The ratio of the aerosol backscattering cross sections for two wavelengths defines a relation that provides information on the particle size and distribution. Figure 2 shows the PBR for the lidar profiles in Figure 1. The PBR through the stratospheric aerosol layer between 19 and 32 km is almost constant at 0.5, while the PBR through the cirrus cloud between 9 and 10 km is clearly not constant. We can assume that the Pinatubo cloud consists of a uniform distribution of particles that remains constant through the region from 19 to 32 km. However, the cirrus cloud must contain a variety of particle shapes, sizes, and/or distributions.

$$\textit{Particle Backscattering Ratio} = \frac{\beta_{a532}}{\beta_{a355}} = \frac{(R_{531}-1)\beta_{m532}}{(R_{355}-1)\beta_{m355}} \qquad (2)$$

Because the PBR is constant through the Pinatubo aerosols we can assume that the particle size and distribution are also constant. This allows us to calculate the wavelength dependance of the aerosols using the two wavelength measurements (355 and 532 nm) obtained from the LAMP lidar. The 532 nm lidar profile was tied to the U.S. Standard Atmosphere density at 45 km. Figure 3 is a plot of the Pinatubo layer after the U.S. Standard density was subtracted from the lidar return in the region of the aerosols. The aerosol particle scattering can be expressed in terms of additional molecular scattering at that wavelength. From this information the actual atmospheric transmission at both wavelengths can be calculated. This wavelength dependence is applied to the input solar radiance curve to define the solar radiance that reaches the earth's surface.

The large data base collected aboard the RV Polarstern during the LADIMAS campaign provides measurements of aerosol extinction in the stratosphere between 70°N and 65°S. An estimate of the decrease in the global solar radiance will be calculated.

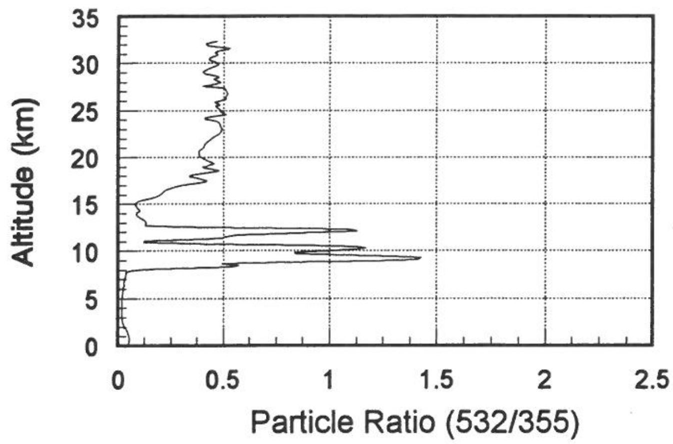

Figure 2. Particle backscattering ratio (PBR) through the Pinatubo aerosols.

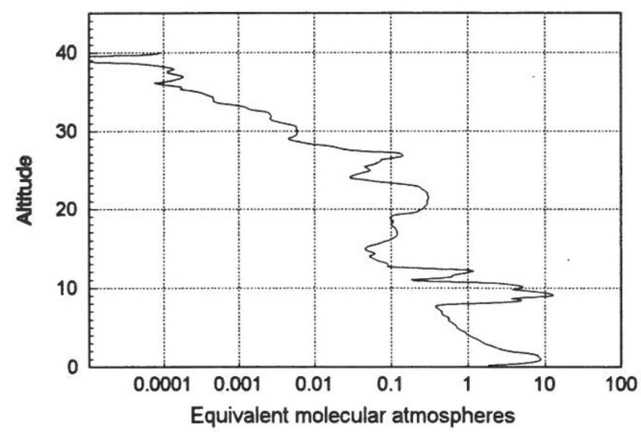

Figure 3. The Pinatubo aerosols scattering at 532 nm plotted in terms of additional equivalent atmospheres.

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