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1. SPATIAL AND TEMPORAL EVOLUTION OF THE OPTICAL THICKNESS OF THE PINATUBO AEROSOL CLOUD IN THE NORTHERN HEMISPHERE FROM A NETWORK OF SHIP-BORNE AND STATIONARY LIDARS

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Abstract. The vertical profiles of the extinction coefficient and the total optical thickness of the Pinatubo aerosol layer obtained from a network of 5 Rayleigh-Mie lidars are presented here. Three ship-borne lidars (PROFESSOR ZUBOV[†], PROFESSOR VIZE[†], HENRI POINCARÉ*) and two fixed lidar stations (OHP* and CEL*) are operated respectively by the Roscomhydromet[†], of Russia and of the Service d'Aeronomie du CNRS* of France. The measurements presented are in the altitude range 15-35 km. They were obtained between July 1991 - April 1992 and cover 8°S-60°N latitude and 80°W-6°E longitude. This represents extensive coverage of the western sector of the northern hemisphere, which is partly coincident with UARS satellite coverage. Optical depths of up to 0.2 were observed and maximum extinction coefficient values of 0.03 km⁻¹ were obtained at 24 km and 18°N latitude.

Introduction

Since the eruptions of Mount Pinatubo between 12-16 June 1991, it has been an important concern to characterize the aerosol cloud that resulted from this eruption, since the presence of aerosols has a large effect on remote sounding measurements and on the chemistry and radiative budget of the lower stratosphere. We present here the optical thickness and extinction measurements, taken over a ten month period in equatorial and northern midlatitudes with a network of Russian and French lidars. These data give a good indication of the vertical, horizontal and temporal morphology of the Pinatubo cloud and could be used to validate or correct UARS data.

Instrumentation

The lidar network consists of five Rayleigh-Mie lidars operating in the wavelength range, 532-589 nm. Two Russian lidars stations operated by the Roscomhydromet are on-board the ships PROFESSOR ZUBOV and PROFESSOR VIZE. Three French lidar stations operated by CNRS are located at the Observatory of Haute-Provence (OHP: 44°N, 6°E), at the Centre d'Essai des Landes at Biscarosse (CEL: 44°N, 1°W) and on-board the military ship HENRI POINCARÉ based at Brest (herein referred to as LIMA).

The three French lidar stations have been described in previous publications [Chanin and Hauchecorne, 1991; Hauchecorne et al., 1991, 1992], so their description here will be limited to the tabulated summary in Table 1. However, it should be pointed out here that a significant difference exists in the receiver configurations of the OHP and CEL lidar stations. OHP uses two independent receiving telescopes for the two channels corresponding to the low and high altitude ranges of

the measurements, whereas CEL uses one telescope in conjunction with a beam splitter which is sensitive to polarization angle of the Rayleigh backscattered component of photons. The OHP lidar configuration is therefore more ideally suited for the measurements presented in this paper.

The Roscomhydromet ship-borne lidar station on-board PROFESSOR ZUBOV operates on a 539.5 nm wavelength, using a doubled yttrium aluminum laser, which emits 0.2 J/pulse at 25 Hz. The pulse counting system has a 1 μs resolution corresponding to an altitude resolution of 150 meters. The transmitting telescope produces a beam of width 5x10⁻⁴ rad. The diameter of the parabolic mirror of the receiving telescope is 110 cm, with a focal length of 300 cm. To minimize the background photons, an interference filter is placed in front of the detector with a bandpass width of 0.5 nm FWHH (full width at half height).

The Roscomhydromet ship-borne lidar station on-board PROFESSOR VIZE uses a dye laser with an R6W active element and operates at 589 nm. It emits 0.4 J/pulse at 5 Hz. The pulse counting system has an effective 2 μs resolution (300 meter altitude resolution). The transmitting and receiving telescopes have the same characteristics as those of the ZUBOV lidar, and the interference filter has a bandpass width of 0.8 nm FWHH. These characteristics are summarized in Table 1.

Measurements

Analysis

The extinction coefficient α, is calculated with expression:

$$\alpha(z) = \beta_{\text{aer}}(z) \left(\frac{\beta_{\text{aer}}}{\alpha} \right)^{-1} \quad (1)$$

where the aerosol backscatter to extinction ratio in the brackets is a measurable quantity. The value used throughout the calculations was a constant value of 0.04 sr⁻¹, which corresponds to the 532 nm wavelength at 20 km after a major volcanic eruption. In fact the aerosol backscatter to extinction ratio can vary with aerosol content [Jäger and Hofmann, 1991] and is also expected to be variable with altitude, especially after a large volcanic eruption [Deshler et al., 1992; Thomason and Osborn, 1992]. The value chosen is roughly twice as large as expected under normal, aerosol-free conditions. The ratio was assumed to be constant in time because the post-eruption conditions were essentially present for the bulk of this data-set, certainly for the interesting part of it. It was assumed

TABLE 1. Summary of lidar characteristics.

	CEL	LIMA	OHP	VIZE	ZUBOV
laser type	doubled Nd-Yag	doubled Nd-Yag	doubled Nd-Yag	dye; R6W	doubled yttrium-aluminum
wavelength (nm)	532	532	532	589	539.5
energy/pulse (J)	0.2/0.4*	0.45	0.4/0.3‡	0.4	0.2
frequency (sec ⁻¹)	30	60	30/50‡	5	25
power (W)	6/12*	27	12/15‡	2	5
emitted beam width (rad)	1x10 ⁻⁴	<1x10 ⁻⁴	1x10 ⁻⁴	5x10 ⁻⁴	5x10 ⁻⁴
receiver tele.diam. (cm)	120	(8x) 50	80	110	110
filter FWHH (nm)	1	1	1	0.8	0.5
vertical resolution (m)	300	300	300	300	150

* since 1/92;

‡ since 30/11/91

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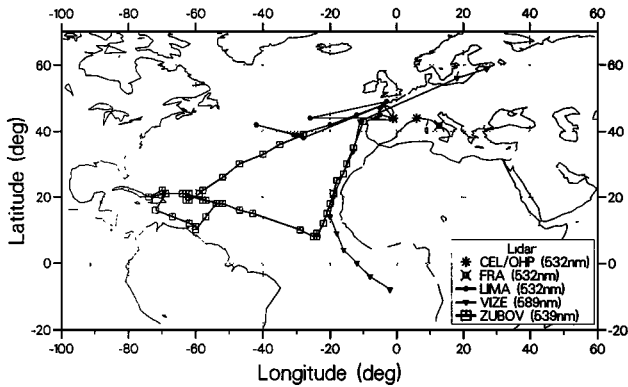


Fig. 1. Path of the 3 ships, PROFESSOR ZUBOV, PROFESSOR VIZE and HENRI POINCARÉ (LIMA) are shown on a Mercator projection along with the locations of the fixed stations, CEL, OHP and FRA.

constant with altitude because applicable measurements of this constant are highly limited. β_{aer} is the scattering coefficient of the Mie scattering from aerosols, obtained from,

$$\beta_{aer}(z) = (SR(z) - 1) \cdot \beta_{Ray}(z) \quad (2)$$

where $SR(z)$ is the scattering ratio obtained from the lidar measurements [Nardi et al., this issue] and β_{Ray} is the Rayleigh backscattering coefficient at 532 nm, $5.7 \times 10^{-32} \text{ m}^2 \text{ sr}^{-1}$. The wavelength dependence of the Rayleigh scattering cross section is accounted for in the VIZE data (589 nm) with a correction factor of $(589/532)^4 = 0.666$. The optical thickness given at 15 km altitude is calculated as,

$$\tau_{15km} = \int_{z=15}^{\infty} \alpha(z) dz \quad (3)$$

Data-set

The paths of the three ships, ZUBOV, VIZE and LIMA, during the period of measurements are summarized in Figure 1. The locations of the fixed stations, CEL and OHP are shown as asterisks.

The ZUBOV lidar made measurements during 48 nights within the 73 day period between 11-July-1991 and 21-September-1991. During the measurement sequence, the ship

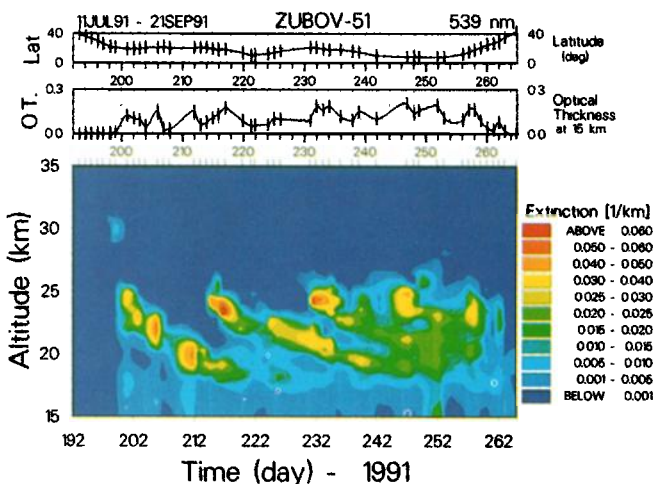


Fig. 2. The ZUBOV extinction coefficient, measured at 539 nm is shown as a function of time and altitude. Markers are placed on the abscissa above and below the map to indicate where data is available. The line plots above show the total optical depth at 15 km and the latitude position of the ship, respectively.

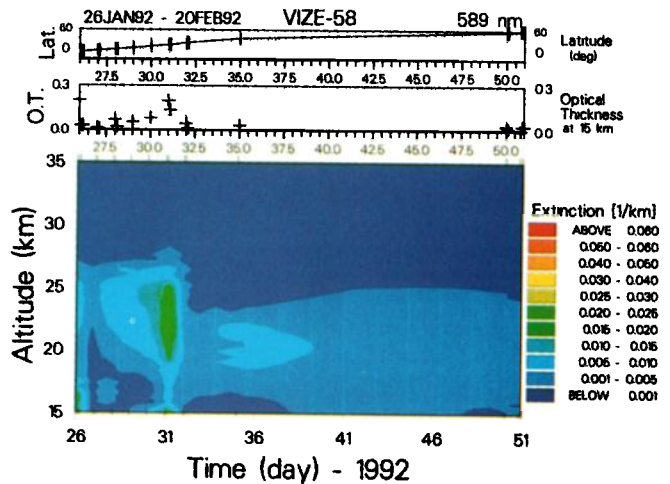


Fig. 3. The VIZE extinction coefficient, measured at 589 nm is shown as a function of latitude and altitude with the same format as in Figure 2.

followed a triangular route from 40° latitude in the Atlantic Ocean, toward Cuban waters and down to 10° latitude, toward the west coast of Africa and finally northward toward the northwestern coast of Spain. A large fraction of the data are confined to the 8°N-22°N latitude range. The extinction coefficient and optical thickness obtained on this path are plotted in Figure 2 along with the latitude position of the ship.

The VIZE lidar made measurements during 20 nights within the 26 day period between 26-January-1992 and 20-February-1992. During the measurement sequence, the ship followed a northward route from the south-Atlantic, toward the northwestern coast of Spain and back to St. Petersburg. Data were obtained between latitudes 8°S-34°N and 56°N-60°N, separated by a 15 day gap. The extinction coefficient and optical thickness are plotted in Figure 3.

The LIMA lidar made measurements during 26 nights within the 198 day period between 3-June-1991 and 17-December-1991. During the measurement sequence, the ship made a round trip from the northwest of France to the mid-Atlantic, in the latitude region 38°N-49°N. The extinction coefficient and optical thickness are plotted in Figure 4.

The two stationary ground-based lidar stations have been running in an operational mode: OHP since 1978 and CEL since 1986. We have isolated the data since July 1991, two

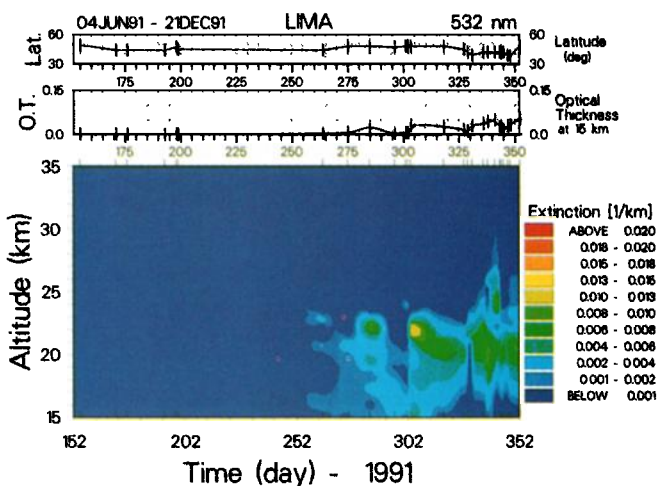


Fig. 4. The LIMA extinction coefficient, measured at 532 nm is shown as a function of time and altitude with the same format as in Figure 2.

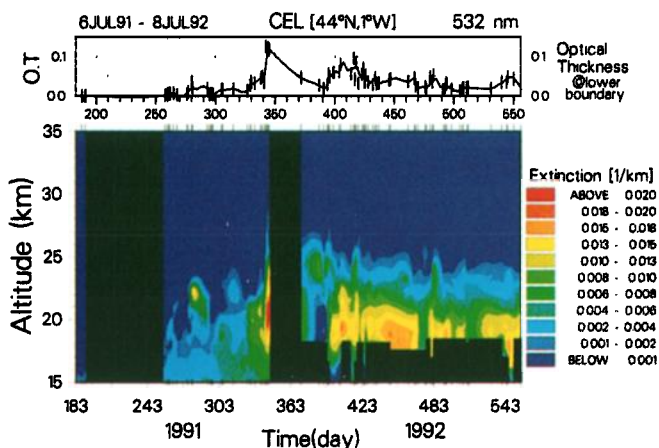


Fig. 5. The CEL extinction coefficient, measured at 532 nm is shown as a function of time and altitude. Black masks suppress regions where no data are available over extended periods or altitude ranges. Note that the optical depth plot above indicates the optical depth at the lowest available altitude, not necessarily 15 km.

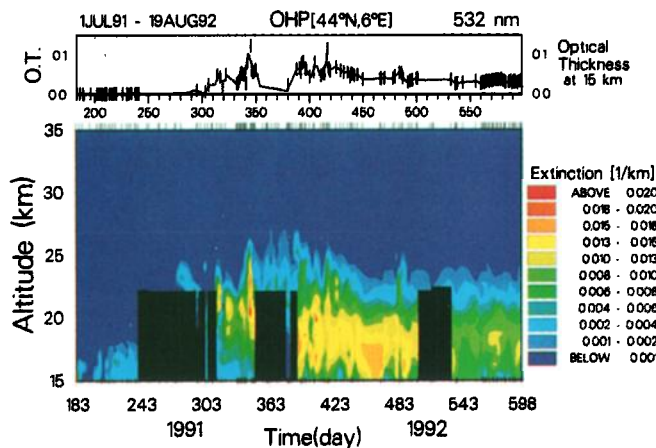


Fig. 6. The OHP extinction coefficient, measured at 532 nm is shown as a function of time and altitude with the same format as in Figure 5.

weeks after the Pinatubo eruptions of 12-16 June, which also correspond to the times where ship-borne data are available. Extensive data available for June show no signs of aerosols and are not reported here. The lidar station at CEL obtained measurements during 81 nights within the 369 day period between 6-July-1991 and 8-July-1992. The extinction coefficient and optical thickness are plotted in Figure 5. The lidar station at OHP obtained measurements during 149 nights within the 416 day period between 1-July-1991 and 19-August-1992. The extinction coefficient and optical thickness are plotted in Figure 6.

In all of these figures the altitude dependent extinction coefficient is shown as a function of time, with the total optical thickness (down to 15 km) plotted overhead. The abscissa is given in the day of the year; in the jump from 1991 to 1992 the day numbers continue to increase from 366 upwards. It is important to note that markers are placed on the abscissa above and below the map to indicate nights where data are available. Black masks are placed over the larger areas where no data are available to avoid misinterpretation of structure artificially introduced by the interpolation. Note that the color scale used with the CEL, OHP and LIMA plots is different from that used with the Russian data because much lower extinction values were obtained at midlatitudes.

Comparison

Individual profiles are compared where a reasonable degree of coincidence occurs, that is where existing measurements are within less than 1000 km and 24 hours of each other. In this data-set, coincidence occurred only for the stationary sites, CEL and OHP, as well as with a lidar facility stationed at Frascati, Italy (FRA: 41.8°N, 12.7°E) [Gobbi et al., 1992]. The ship-borne measurements given here covered specific regions in the Atlantic Ocean and therefore coincided neither with the stationary sites nor with each other.

Figure 7 shows a comparison of several individual extinction coefficient profiles between the various stationary sites. Extinction coefficients for Frascati were calculated using the scattering ratio profiles given in Gobbi et al. [1992] and were compared with OHP measurements (Figure 7a). The vertical structure and the magnitude of the extinction coefficient are very similar, with a slight difference in peak altitude of the layer. In the 3 part sequence of Figure 7(b-d), extinction coefficients from the OHP and CEL lidar stations are compared for 3 nights within an 8 day period. On any given night a difference in the fine vertical structure of the extinction coefficient is observed between stations, however the total optical thicknesses above 15.1 km are comparable. The first plot (b) shows an aerosol feature centered at 20 km, while the last plot (d) shows a significantly stronger double peaked feature with extinction coefficients reaching 0.02 km⁻¹ at 21 and 23 kms. Both plots show a high level of similarity

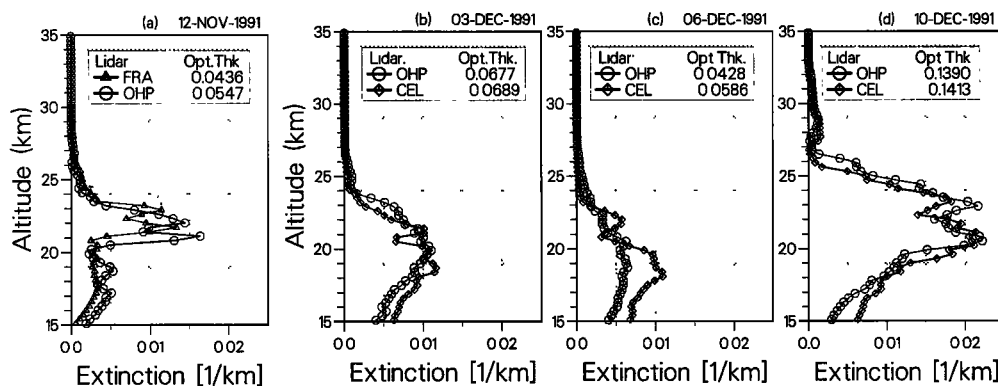


Fig. 7. The extinction coefficient profile at 532 nm are compared (a) between the lidars of Frascati (41.8°N, 12.7°E) and OHP (44°N, 6°E). Similar comparisons are shown for 3 profiles within an 8 day period (b), (c), (d) between the lidar

stations at OHP and CEL (44°N, 1°W). The distance between lidar stations in all cases shown is approximately 600 km. The total optical thicknesses above 15.1 km are indicated in the legend boxes.

between the aerosols over two stations (<2% difference in optical depth). However in the plot (c), both the vertical structure and the optical depth show a greater disparity (25% difference in optical depth). It is probable that the boundary of a strong aerosol cloud is passing overhead in (c), causing the difference over the 2 stations in this transition stage.

It is also of benefit to compare optical depths obtained by ZUBOV at the lower latitudes with independent measurements made with different techniques. Optical depths were obtained by Valero et al. [1992] using airborne radiometer measurements of the solar radiative flux within the wavelength range 380-1064 nm. His values of optical depth at 500 nm of 0.15 - 0.3 in the latitude range 20°N-10°N respectively, are slightly higher than the ZUBOV optical depths at 532 nm of 0.05 - 0.2 in the same latitude range. However this difference can be attributed, at least in part, to the wavelength difference of the measurements; the optical depth is expected to decrease at higher wavelengths in this spectral region.

Discussion

The data show that there is a great deal of variability in the structure of the aerosol cloud. However, it can be generally stated that the extinction coefficients indicate presence of aerosols primarily in the altitude range of 17-25 km, though they have on occasion been measured as high as 32 km.

Comparison of the generally low latitude measurements of ZUBOV and VIZE with those at the midlatitude region of OHP, CEL, LIMA shows that at low latitudes there is a presence of a strong high altitude cloud at 24 km as well as a weaker low altitude cloud at 17 km, whereas at midlatitudes there is the persistent presence of only the lower altitude cloud near and below 20 km with weaker, higher altitude features that pass through sporadically.

At low latitudes (equatorward of 40°N, primarily between 8°N-22°N) the mean optical depth was 0.1 and reached values of almost 0.2 on a regular, nearly periodic basis. The maximum extinction coefficient was 0.08 km⁻¹ at 23-24 km measured by ZUBOV in July 1991 (day 217).

At midlatitudes (40°N-44°N), the first evidence of aerosols appeared in early July at altitudes of 15-17 km, in agreement with Gobbi et al. [1992], with measured extinction coefficients of 0.013 km⁻¹ at OHP (day 183) and 0.0024 km⁻¹ at CEL (day 188). The first clear evidence of elevated aerosol concentrations above 18 km appeared at CEL and LIMA on 21-September-1991 (day 264), with extinction values of 0.0025 km⁻¹. High extinction levels at this altitude were first detected at all three midlatitude sites during the second week of October (days 280-286), when extinction coefficients of up to 0.017 km⁻¹ were measured at CEL. On average, the optical depth at midlatitudes was near 0.05. However on one occasion (December 8-11; days 342-5), both CEL and OHP measured high optical depth values of up to 0.125 with peak extinction coefficients of 0.021 km⁻¹ at 23 km (CEL). On this same occasion, higher than normal extinction values (up to 0.001 km⁻¹) were measured at record high altitudes (near 30 km) by all three midlatitude sites.

The data at CEL in the 6 month period after January 1992 have been normalized to the mean OHP measurements of the same period because low extinction values at the CEL station resulted from a polarization effect introduced into the detected signal by the beam splitter. Though there is some evidence of periodic behavior in OHP, CEL and LIMA data, it is by far much less pronounced than for the lower latitude data of ZUBOV, which is further studied in the follow-up article [Nardi et al., this issue]. This means that aerosol features detected are probably aerosols that have broken off from the main low latitude cloud and that pass through the field-of-view of the midlatitude lidars one time on their way to higher latitudes.

Care should be used in interpreting the data because it is not always available at evenly spaced intervals. One can see that in

the measurements of CEL, OHP and LIMA, significantly long data gaps may exist. One consequence of this is that certain aerosol features may be missing in the data presentation.

The data presented here shows clearly, the advantage of having a network of ground-based and ship-borne lidar facilities to obtain the medium and long term behavior of the aerosol cloud on a global basis.

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