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Ship-borne lidar measurements showing the progression of the tropical reservoir of volcanic aerosol after the June 1991 Pinatubo eruption.

Juan-Carlos Antuña-Marrero[1], Graham W. Mann[2,3], Philippe Keckhut[4], Sergey Avdyushin[5†], Bruno Nardi[6] and Larry W. Thomason[7]

[1]Departamento de Física Teórica, Atómica y Óptica, Universidad de Valladolid, 47002, España
[2]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.
[3]National Centre for Atmospheric Science (NCAS-Climate), University of Leeds, Leeds, UK
[4]Laboratoire Atmosphères, Milieux, Observations Spatiales, Université de Versailles Saint-Quentin, Versailles, 78280, France
[5]Fedorov Institute of Applied Geophysics, Moscow, Russia
[6]Nardi Scientific, LLC, Denver, CO, USA.
[7]NASA Langley Research Center, Hampton, Virginia, USA
[†]Deceased

Correspondence to: Juan-Carlos Antuña-Marrero (antuna@goa.uva.es)

Abstract:

A key limitation of volcanic forcing datasets for the Pinatubo period, is the large uncertainty that remains with respect to the extent of the optical depth of the Pinatubo aerosol cloud in the first year after the eruption, the saturation of the SAGE-II instrument restricting it to only be able to measure the upper part of the aerosol cloud in the tropics. Here we report the recovery of stratospheric aerosol measurements from two ship-borne lidars, both of which measured the tropical reservoir of volcanic aerosol produced by the June 1991 Mount Pinatubo eruption. The lidars were on-board two Soviet vessels, each ship crossing the Atlantic, their measurement datasets providing unique observational transects of the Pinatubo cloud across the tropics from Europe to the Caribbean (~40ºN to 8ºN) from July to September 1991 (the Prof Zubov ship) and from Europe to south of the Equator (8ºS to ~40ºN) between January and February 1992 (the Prof Vize ship). Our philosophy with the data recovery is to follow the same algorithms and parameters appearing in the two peer-reviewed articles that presented these datasets in the same issue of GRL in 1993, and here we provide all 48 lidar soundings made from the Prof. Zubov, and 11 of the 20 conducted from the Prof. Vize, ensuring we have reproduced the aerosols backscatter and extinction values in the Figures of those two papers. These original approaches used thermodynamic properties from the CIRA-86 standard atmosphere to derive the molecular backscattering, vertically and temporally constant values applied for the aerosol backscatter to extinction ratio and the correction factor of the aerosols backscattering wavelength dependence. We demonstrate this initial validation of the recovered stratospheric aerosol extinction profiles, providing full details of each dataset in this paper's Supplement S1. We anticipate the data providing potential new observational case studies for modelling analyses, including a 1-week series of consecutive soundings (in September 1991) at the same location showing the progression of the entrainment of part of the Pinatubo plume into the upper troposphere and the formation of an associated cirrus cloud.. The Zubov lidar dataset illustrates how the

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tropically confined Pinatubo aerosol cloud transformed from a highly heterogeneous vertical structure in August 1991, maximum aerosol extinction values around 19 km for the lower layer and 23-24 for the upper layer, to a more homogeneous and deeper reservoir of volcanic aerosol in September 1991. We encourage modelling groups to consider new analyses of the Pinatubo cloud, comparing to the recovered datasets, with the potential to increase our understanding of the evolution of the Pinatubo aerosol cloud and its effects. Data described in this work , the original text files of the aerosols backscatter ratio, the calculated aerosols backscatter and aerosols extinction profiles are available at https://doi.pangaea.de/10.1594/PANGAEA.912770 (Antuña-Marrero et al., 2020).

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1. Introduction

Observations by satellite and in situ measurements showed that major volcanic eruptions enhance the stratospheric aerosol layer for several years (Stratospheric Processes and their Role in Climate -SPARC, 2006). Such enhancement causes radiative, thermal, dynamical and chemical perturbations in different regions of the earth's atmosphere, resulting in a perturbation of the earth's climate (e.g. Robock, 2000; Timmreck, 2012). Current research on those perturbations demand detailed information about the 3D spatial and temporal distributions of stratospheric aerosols both under background conditions and after the volcanic eruptions. The June 1991 Mt. Pinatubo eruption is the most used for such research activities because it has been the largest and best documented eruption for the XX century up to the present. Still there are notable gaps in the information collected because the lack of enough measurements but also because several of the measurements conducted and reported in the literature have not been shared by the scientist and institutions that conducted them.

This work is a contribution to the Data Rescue Activity of the Stratospheric Sulfur and its Role in Climate (SSiRC) recently included in this SPARC initiative. This data rescue activity is aimed to "…foster new collaborations between scientists to recover, re-digitize and re-calibrate other historic stratospheric aerosol data sets, and invite scientists to contribute to this activity and to provide advice and expertise on how best to recover other incomplete long term observations of stratospheric composition," (SSiRC, 2020). In its current initial stage particular attention to gather datasets to characterize the progression of the aerosol cloud during the initial months after the 1991 Pinatubo eruption, the main motivation for the work we present here.

Among the envisaged applications of the two Mt Pinatubo's stratospheric aerosols lidar datasets we are presenting is the contribution to future improvements of the Global Space-based Stratospheric Aerosol Climatology, (GloSSAC). GloSSAC is the most complete source of information about the global spatial and temporal distribution of the stratospheric aerosols optical properties from 1979 to the present (Thomasson et al., 2018). From 1979 to mid-2005 the climatology relies mainly on the observations from the Stratospheric Aerosol and Gas Experiment (SAGE) series of satellite instruments. Only two lidar datasets in the tropics were used for filling the gap in SAGE II aerosols extinction profiles in this region in GloSSAC (Thomasson et al., 2018), produced by the dense stratospheric aerosols layer (McCormick and Veiga, 1992).

In section 2 the datasets are briefly described, providing the detailed description, format and inventory of the datasets contained on Supplement S1. Following section 3 describe the processing conducted to try to reproduce the values of the aerosol's extinction profiles at 532 nm for both ship borne lidars Zubov and Vize respectively. Section 4 show and discuss the results comparing them with the available information reported in Avdyushin et al, (1991) and Nardi et al., (1991). The section includes

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the discussion of several features of the stratospheric aerosols from Mt. Pinatubo eruption during the period the measurements were taken to illustrate the importance of the rescued datasets. Follows section 5 showing an application of the reconstructed dataset in the validation of Mt Pinatubo modeling simulations. The article conclude with the summary and outlook.

2. Aerosols Scattering Ratio Datasets

2.1 Lidar datasets:

Here we report the two sets of scattering ratio profiles measured by two Soviet ship borne lidars a few months after the Mt Pinatubo June 1991 eruption across the north Atlantic Ocean. Professor Zubov ship carried a lidar from July to September 1991, and Professor Vize, in January and February 1992 (Avdyushin et al., 1993; Nardi et al., 1993). The measurements campaign was part of a joint effort between the Roscomhydromet of the former Soviet Union and the Service d'Aeronomie du CNRS of France. It included another ship borne lidar on the French military ship Henry Poincare, based in Brest, and two ground based lidars. The lidars were located at the Observatory of Haute-Provence (OHP: 44 °N, 6 °E) and at the Centre d'Essai des Landes at Biscarosse (CEL: 44 °N, 1°W). A broad description appears in Nardi et al., (1993) and Avdyushin et al., (1993).

Because of the particular spatio temporal distribution of the lidar measurements from Zubov they contribute in characterizing the variability of the Mt Pinatubo stratospheric aerosols (SA) vertical extinction profiles at certain points and regions of the North Atlantic Ocean between July and September 1991. Spatially the variability covers both latitudinal and longitudinal and temporally the daily variability of two Atlantic locations where lidar measurements were conducted for several consecutive and nonconsecutive days.

Table 1: Technical features of the two ship borne lidars. Ya: Yttrium-aluminum. From table 1 Avdyushin et al., (1991)

Lidar Technical Features	Professor Zubov	Professor Vize
Laser type	Doubled-Ya	Dye:R6W
Wavelength (nm)	539.5	589
Energy/pulse (J)	0.2	0.4
Frequency (s^{-1})	25	5
Power (W)	5	2
Emitted Beam Width (rad)	5 x 10^{-4}	5 x 10^{-4}
Receiver telescope diameter (cm)	110	110
Filter FWHH (nm)	0.5	0.8
Vertical resolution (m)	150	300

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2.2 Data source

Prof Philippe Keckhut contributed the lidar scattering ratios (SR) profiles dataset derived from the lidar measurements conducted by Zubov and Vize vessels for the PhD dissertation research of the lead author in 1999. The goal of that research was to validate the Mt Pinatubo SA extinction profiles measured by the Stratospheric Aerosols and Gas Experiment II (SAGE II) with ground based lidar observations (Antuña et al., 2002; 2003). However, we found very low information to comply with the proposed goal due to the combination of two facts. Firstly, the SAGE II profiles were truncated above the main core of the SA layer in the tropics during almost half a year after the June 1991 Mt Pinatubo eruption. It was the result of the elevated atmospheric opacity produced by the SA (McCormick and Veiga, 1992). Secondly the few coincident vessel's lidar and SAGE II extinction profiles measurements, because of the coincidence criteria selected (Antuña et al, 2002). The dataset was not used and remained stored in the lead author archives since then.

2. 3 Dataset description

In brief, the datasets consist of 48 data files from the Professor Zubov vessel containing daily profiles of the lidar SR(z) profiles and 11 lidar SR(z) profiles from Professor Vize vessel. It should be taken into account that in the case of the Vize lidar we have only 11 of the 20 measurements reported to be conducted (Avdyushin et al., 1993; Nardi et al., 1993).

3. Data processing

To comply with the goal to reproduce the aerosols extinction vertical profiles ($\alpha_{ext}(z)$) reported in Avdyushin et al., (1993) and Nardi et al., (1993) from the available SR(z), we used the same algorithms and parameters they mention. They used the Rayleigh backscattering cross section coefficient of $5.7x10^{-32}$ m^2 sr^{-1} at 532 nm. In the case of Zubov no wavelength dependence was accounted for considering negligible the differences between the 532 nm and 539 nm. A correction factor of the Rayleigh backscattering cross section coefficient at 532 nm ($589^{-4}/532^{-4} = 0.666$) considering the 589 nm of VIZE data, was used (Avdyushin et al., 1991)

Then Rayleigh backscatter at the surface was calculated and for each lidar measurement the Rayleigh backscatter profiles ($\beta mol(z)$) were derived using the vertical profiles of pressure (P(z)), and temperature (T(z)) from the CIRA-86 atmospheric model (Flemming et al., 1988). The procedure consisted in determining the geopotential height (Zg(z)) and T(z) at the mandatory P(Z) levels from 1000 to 0.1 hPa from the CIRA-86 atmosphere taking into account the month the measurement

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was conducted and latitude of the ship for each individual measurement. Then the Zg(z) were converted to geometric altitude (z). Following the P(z) were logarithmically interpolated in the vertical to the altitude of the lidar SR levels. Similar step was conducted for T(z) but using lineal interpolation. Then the $\beta_{mol}(z)$ is derived using the standard procedure (Bucholtz, 1995). Following the aerosols backscattering profiles ($\beta_{aer}(z)$) were derived using equation 1 (Russell et al., 1979). To avoid cero or negative values in $\beta_{aer}(z)$, produced by SR(z) equal or lower than 1 respectively, we replaced those SR(z) values by 1.01 following, the value proposed by Russell et al., (1979) for the SR(z) minimum aerosol level. At the levels where this change took place the magnitude of $\beta_{aer}(z)$ is two orders lower than the magnitude of $\beta_{mol}(z)$ at the same level. Equation 1 was used to derive $\beta_{aer}(z)$:

$$\beta_{aer}(z) = [SR(z) - 1] \times \beta_{mol}(z) \quad (1)$$

The next step consisted in calculating the $\alpha_{aer}(z)$ from the $\beta_{aerl}(z)$ using equation 2, using a constant value in time and altitude of 0.04 sr^{-1} for the aerosols backscattering to extinction ratio (Advyushin et al., 1991).

$$\alpha_{aer}(z) = \beta_{aer}(z) \left[\frac{\beta_{aer}}{\alpha_{aer}}\right]^{-1} \qquad (2)$$

4. Results

The tabulated lidar SR profiles and the calculated $\beta_{aer}(z)$ and $\alpha_{aer}(z)$ profiles at the wavelength of 532 nm from both lidars are available at https://doi.pangaea.de/10.1594/PANGAEA.912770 (Antuña-Marrero et al., 2020).

4.1 Validation of the reproduced dataset

No tabulated data is available for the $\alpha_{aer}(z)$ values used in the cited Avdyushin or Nardi's papers, the only published source of information about the measurements. In addition, the papers do not conduct detailed discussions or mentions of the extinction relevant features in the Zubov and Vize datasets. Here we make use of all the available information to conduct a semi-quantitative validation for the Zubov dataset. In the case of Vize only is possible to conduct a qualitative validation.

Figures 1a and 1b show the temporal/vertical cross section of the $\alpha_{aer}(z)$ measured by the lidars onboard the Professors Zubov and Vize ships. The black discontinuous line on top of the white background in figure 1a is the altitude of tropopause at the locations the lidar measurements were conducted. The tropopause altitudes were derived from the ERA-Interim reanalysis

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potential vorticity profiles, interpolating to the height levels of the lidar measurements and select the height of the 1.e-5 PV surface.

Figure 1a shows, the same pattern of the temporal/vertical cross section of the $\alpha_{aer}(z)$ for the entire Zubov trajectory that the one reported in figure 2 in Avdyushin et al., (1993). The magnitudes of the $\alpha_{aer}(z)$ are in the same order in both figures as it could be seen comparing the scales of the color bars in the right side of both them. A careful comparison between the areas painted in red (corresponding to the highest values of $\alpha_{aer}(z)$) in both figures show a larger area in Avdyushin et al, (1991) figure 2, an indication of slightly lower values in the values of $\alpha_{aer}(z)$ we reproduced. Moreover, the maximum $\alpha_{aer}(z)$ value in the reproduced dataset is 0.054 km^{-1} at 23.3 km of altitude on August 4th could be appreciated on figure 2a. Avdyushin et al, (1991) reported the maximum at 18 °N between 23 and 24 km of altitude with an $\alpha_{aer}(z)$ value of 0.08 km^{-1} the same day. All those facts demonstrate the agreement of the reproduced dataset with the original one.

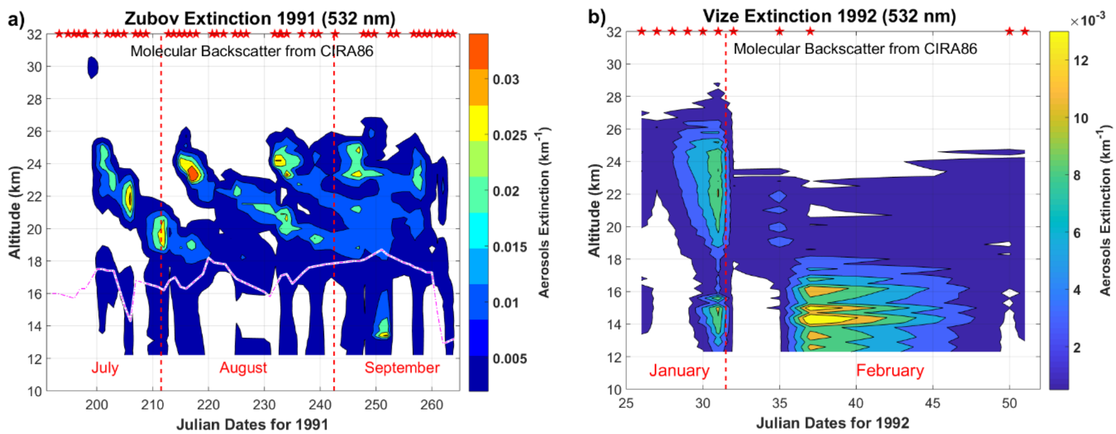

Figure 1: Temporal/vertical cross sections of the aerosols extinction at 532 nm measured by the lidar onboard the two ship borne lidars during their trajectories. a) Professor Zubov ship; b) Professor Vize ship.

In the figure 1a it should be also noted the presence of area of high values of the $\alpha_{aer}(z)$ at the tropical middle troposphere in September 1991 around the day 250. This signature is not seen on the temporal cross section from Zubov lidar on figure 2 in Avdyushin et al., (1991) because the vertical axes lower altitude is at 15 km. It appears more clearly in the temporal cross section of the SR(z) from Zubov lidar, the figure 4 in Nardi et al., (1993), having the vertical axes beginning at 12 km. This feature may be associated to the combination of what seems to be a downward transport of stratospheric aerosols with the presence of a thick cirrus cloud attached below. The profiles associated to this feature will be discussed later. The features

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described above demonstrate that the reproduced $\alpha_{aer}(z)$ dataset in the case of Zubov is in reasonable agreement with the reports in the only two papers available describing the measurements.

Figure 1b for Prof. Vize shows in general the same pattern than figure 3 in Avdyushin et al., (1993) although the $\alpha_{aer}(z)$ magnitudes in the reproduced dataset are lower. In some way the lack of 9 measurements (~ 45 %) of the 20 reported to be conducted (Avdyushin et al., 1993) contribute to those low $\alpha_{aer}(z)$ magnitudes in the Vize dataset. Also, in figure 1b the extension of the vertical axes down to the lower level the lidar information was available, 12 km, allows to see aerosols in the upper troposphere that is not the case in figure 3 in Avdyushin et al., (1993) figure 3.

4.2 Downward transport of stratospheric aerosols with a thick cirrus cloud below

The cited area of high values of $\alpha_{aer}(z)$ at the tropical middle troposphere in September 1991 around the day 250, shown in the figure 1a is associated to the $\alpha_{aer}(z)$ profile on figure 2 for August 8^{h} 1991, at 8ºN. The profile of $\alpha_{aer}(z)$ extents from 24 km in the lower stratosphere to 12 km, middle/upper tropical troposphere, across the tropopause located at 18.2 km. The most plausible explanation of the vertical extension of the layer is the occurrence of stratospheric aerosols downward transport into the upper and middle troposphere. The figures 2 also includes the values of the total AOD in the upper troposphere and the lower stratosphere (UTS-AOD) resulting from the contributions of the tropospheric AOD (UT-AOD) 0.087, from 12 km to the tropopause and the .stratospheric AOD (S-AOD) from the tropopause to 33 km. The UT-AOD value of 0.098 and the S-AOD 0.085 have contributions, in the same order of magnitudes, to the UTS-AOD value of 0.183, showing the notable magnitude of the stratospheric aerosols into the upper and middle troposphere.

The figure 2 also show that $\alpha_{aer}(z)$ decrease from 0.012 km^{-1} at the 18.2 km (tropopause) up to 0.02 km^{-1} at 17.3 km and then increases to ending in two sharp maximums at 14 and 13.4 km with $\alpha_{aer}(z)$ of 0.029 and 0.044 km^{-1} respectively. This double peak layer at the bottom of the Pinatubo stratospheric aerosols layer is a cirrus clouds, a phenomenon already reported for the Pinatubo. Similar lidar $\beta_{aerl}(z)$ profile structure is reported at Sodankyla (Finland) 66 °N, on figure 1 in Guasta et al., (1994) for February 3rd, 1992. This measurement conducted at Sodankyla was part of the European Arctic Stratospheric Ozone Experiment (EASOE) campaign during the December 1991 to March 1992 where cirrus clouds were reported in 50% of the 56 measurements conducted. Cirrus were reported to grow often within the stratospheric aerosols layer from Mt Pinatubo as in the case we are discussing (Guasta et al., 1994). This profile shows, probably, the earlier case of a cirrus observed in lidar measurements of the Mt Pinatubo stratospheric aerosols.

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An interesting feature is that in the 48 $\alpha_{aer}(z)$ profiles from the lidar on Professor Zubov vessel between July and September 1991 only in one profile a cirrus cloud was detected, only 2 % of the profiles. However, in 4 of the 11 available $\alpha_{aer}(z)$ profiles from the lidar on Professor Vize vessel between January and February 1992, 4 profiles showed the presence of cirrus clouds, around 40% of the observations. These percentage is similar to the reported by a lidar located at Sodankyla, Finland (66 °N), during the EASOE campaign between December 1991 and March 1992 (Guasta et al., 1994).

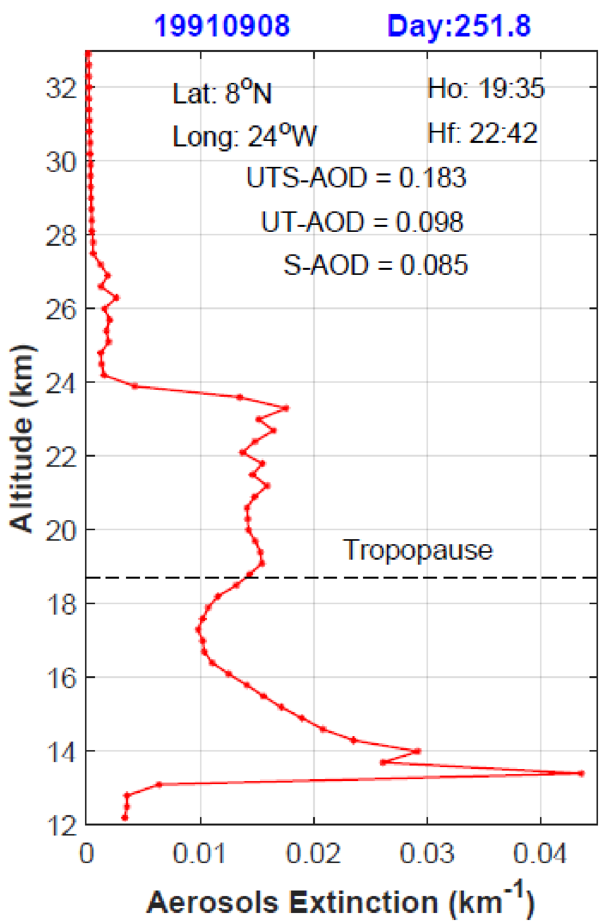

Figure 2: Profile of the $\alpha_{aer}(z)$ for September 8th at 8 °N, showing the presence of cirrus clouds between 13 and 14 km. It is evident the transport of stratospheric aerosols from the stratosphere into troposphere across the tropopause.

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4.3 Absolute maximum $\alpha_{aer}(z)$ value:

Figures 3a and b shows the $\alpha_{aer}(z)$ profiles on August 3rd and 4th 1991, the figure 3b belonging to the day the absolute maximum value of $\alpha_{aer}(z)$ was registered and the figure 3a to the day before. Both profiles were taken at the same latitude and only 1° apart in longitude, allowing to characterize the longitudinal evolution of the Mt. Pinatubo stratospheric aerosols evolution and variability. A double layer is present both days. The UT-AOD is almost the same for both days but S-AOD in one order of magnitude from 0.080 on August 3rd, 1991 to 0.119 the next day.

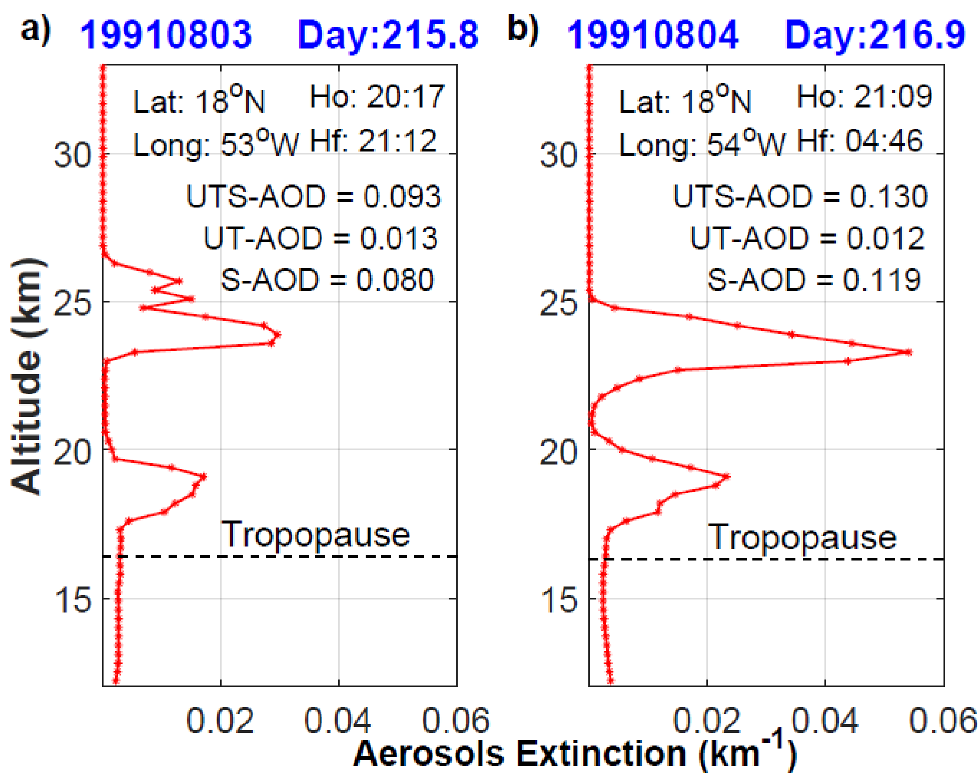

Figure 3: Profiles of the $\alpha_{aer}(z)$ for August 3rd and 4th at 18 °N.

On table 2 the geometrical and optical parameters of the higher and lower layers present in both the August 3rd and 4th $\alpha_{aer}(z)$ profiles. It could be appreciated the altitude descend of both the higher and lower layers from August 3rd to 4th, with both layers keeping their depths. The altitude of the $\alpha_{aer}(z)$ absolute maximum in the top layer decreased a little more than half a kilometer, but the maximum in the lower layer maintains its altitude. The magnitudes of the maximums $\alpha_{aer}(z)$ in each layer increase, in

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2.45 x 10^{-2} km^{-1} in the upper layer reaching the absolute maximum value of the entire record and in the lower layer in 0.62 x 10^{-2} km^{-1}. The individual layers AOD's increases in 0.028 in the higher layer and 0.023 in the lower. These is an example of the usefulness of the rescued dataset allowing to quantify those magnitudes during the early stages of the Mount Pinatubo.

Table 2. Geometrical and optical parameters of the higher and lower layers present in the August 3rd and 4th $\alpha_{aer}(z)$ profiles.

	HIGHER Layer		**LOWER Layer**	
DATE	**19910803**	**19910804**	**19910803**	**19910804**
Top [km]	26.6	25.1	20.6	20.9
Base [km]	23.0	21.5	16.4	16.7
ΔH [km]	3.6	3.6	4.2	4.2
AOD	0.049	0.077	0.031	0.054
Max. $\alpha_{aer}(z)$ [km^{-1}]	2.96 x 10^{-2}	5.41 x 10^{-2}	1.71 x 10^{-2}	2.33 x10^{-2}
Max. Height [km]	29.9	29.3	19.1	19.1

4.4 Evolution of the daily AOD, maximum $\alpha_{aer}(z)$ and its altitude along the Zubov trajectory

Figure 4 shows the temporal evolution, along the entire ship trajectory, of the daily maximum $\alpha_{aer}(z)$, its altitude and S-AOD. The three months are denoted as the latitudinal and longitudinal bands the lidar sampled during the Zubov trajectory. Daily maximum $\alpha_{aer}(z)$ values are mainly in the range between 0.0541 and 5.7 x 10^{-5} km^{-1}, with a mean and standard deviations values of 0.018 and 0.013 km^{-1}. The altitudes of the maximum $\alpha_{aer}(z)$ values range between 30.8 and 12.2 km, with mean of 21.8 km and standard deviation of 3.5 km. The S-AOD mean value is 0.053 with a standard deviation of a 0.037, showing its maximum value of 0.136 on September 3rd at 8 ºN and 25 ºE.

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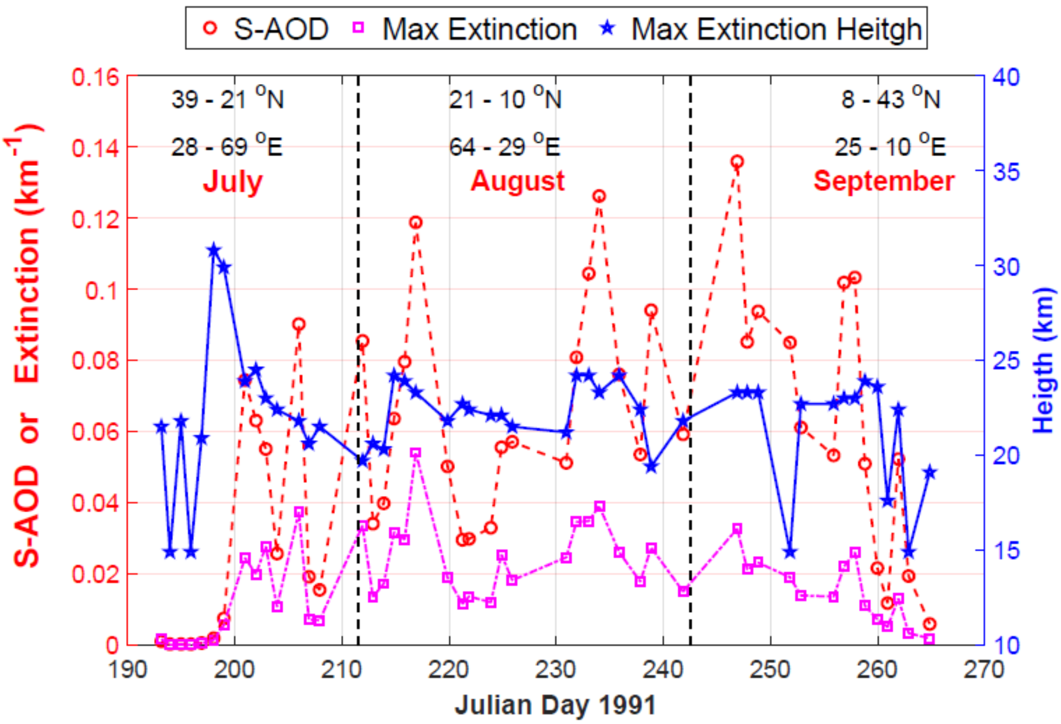

Figure 4: Temporal section of the AOD, maximum extinction and its altitude from the individual lidar profiles measured by Zubov along its trajectory.

5. Data availability

Data described in this work are available at https://doi.pangaea.de/10.1594/PANGAEA.912770 (Antuña-Marrero et al., 2020).

6. Summary and outlook

Here we present a reproduced version of the stratospheric aerosol extinction profiles derived from lidar measurements conducted by Professor Zubov and Vize vessels already referenced in the literature (Avdyushin et al., 1993; Nardi et al., 1993) but unavailable until the present. The data presented consist on two sets of vertical profiles of the SR(z), $\beta_{aer}(z)$ and $\alpha_{aer}(z)$ at 300 m vertical resolution, one for each vessel. In the case of Professor Zubov the set include 48 measurement days conducted between July and September 1991 and for Professor Vize 11 measurements days between January and February 1992.

We expect this dataset to contribute to some of the current and future research to simulate the early stages of the Mt Pinatubo eruption. It will also contribute to a future GloSSAC updates, helping to fill the SAGE II gaps produced by the dense stratospheric aerosols cloud during the first months after the eruption.

Competing Interest: The authors declare that they have no conflict of interest.

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