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Latitudinal distribution of stratospheric aerosols during the EASOE winter 1991/92

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Abstract. Lidar measurements of stratospheric aerosols were made at several Arctic and mid-latitude stations as part of the European Arctic Stratospheric Ozone Experiment (EASOE) in 1991/92. Volcanic aerosols were observed throughout the winter at all stations. High latitude stations observed an aerosol-free stratosphere during most of the winter at altitudes above 450 K potential temperature (above 16 km). An even latitudinal distribution of volcanic aerosols was observed below this level. This is interpreted as indicative of latitudinal transport into the polar region throughout the winter.

Introduction

After the eruption of Mt. Pinatubo (Philippines, 15°N, 120°E) in mid-June 1991, stratospheric aerosols spread surprisingly rapidly to high northern latitudes. Satellite observations show patches of volcanic aerosol at 50°N in July 1991 (McCormick and Veiga, 1992). At the stations included in this study, Pinatubo-related aerosols were detected as early as July 1st at l'Observatoire de Haute Provence (OHP), the beginning of August at Andøya (Fricke et al., this issue), and August 11th at Ny-Ålesund, Spitsbergen (Neuber et al., 1992b), in all cases at altitudes below 18 km. Hence, when the Arctic stratospheric vortex formed in fall 1991, volcanic aerosols of the Mt. Pinatubo eruption had already reached high northern latitudes. When the EASOE-campaign commenced in late November 1991, volcanic aerosols were immediately detected at all stations. At that time, half a year after the eruption, most of the physico-chemical transformation of the original gaseous SO_2 to droplets of H_2SO_4 / H_2O had been completed (e.g. Bluth et al., 1992). Nevertheless other processes like coagulation and sedimentation might still have had an effect on the aerosol layer and must be taken into account when interpreting lidar data in detail. However here we are concerned with gross features of the transport in the stratosphere and will treat the aerosols as tracers of atmospheric transport.

Data are presented from six lidar stations ranging from southern Europe to deep inside the Arctic circle (Table 1). Although the lidar instruments vary in detail, they all use the second harmonic output of Nd:YAG lasers at a wavelength of 532 nm, linearly polarized. In this study the total backscatter ratio, R, at this wavelength (532 nm) will be used. This ratio is given as

$$R(z) = (\beta_a(z) + \beta_m(z)) / \beta_m(z)$$

with β_a and β_m the aerosol and molecular backscattering coefficients and z the altitude. R becomes unity for an atmosphere without aerosols. The profile of the molecular backscatter coefficient is determined from meteorological soundings from a nearby weather station except for Andøya, where the nitrogen Raman signal is used. The procedures for the calculation of R vary from station to station e.g. with respect to the correction of the aerosol extinction. However, this introduces only minor differences in the data, which can be neglected, as here we are interested in the qualitative behaviour of the aerosol layer only.

The polar vortex consists of a low pressure system, with atmospheric layering inside the vortex reduced in altitude compared to outside. As the different lidar stations had different and changing positions with respect to the vortex, a common altitude scale for all stations is necessary to compare aerosol signals from corresponding altitudes. Such a scale is

TABLE 1. Groundbased lidar stations during EASOE

Station	Location	Data available	Ref.*
l' Observatoire de Haute Provence, France	44°N, 6°E	1. Dec. 1991 - 28. March 1992	
Aberystwyth Wales, UK	52°N, 4°W	11. Nov. 1991 - 30. March 1992	1
Sodankylä, Finnland	67°N, 26°E	2. Dec. 1991 - 12. March 1992	2
Andøya, northern Norway	69°N, 16°E	16. Nov. 1991 - 23. March 1992	3
Thule, Greenland	76°N, 69°W	3. Dec. 1991 - 22. March 1992	4
Ny-Ålesund, Spitsbergen	79°N, 12°E	1. Dec. 1991 - 27. March 1992	5

* (1) Vaughan et al., this issue. (2) Stein et al., this issue. (3) Fricke et al., this issue. (4) Di Girolamo et al., this issue. (5) Neuber et al., 1992a.

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potential temperature, which we calculated for each lidar profile from meteorological soundings obtained nearby in space and time. The use of potential temperature as a height scale eliminates adiabatic vertical motions. In addition we choose Ertels potential vorticity to describe a geographical position with respect to the polar vortex. Values of potential vorticity were made available via the data center at the Norwegian Institute for Air Research (NILU) for each day of the EASOE campaign and for levels of potential temperature at 350 K, 360 K, 380 K, 400 K, 425 K, 475 K, 550 K and 700 K (e.g. Braathen et al., 1992). Intermediate values were determined by linear interpolation.

Results

There were only few records of Polar Stratospheric Clouds (PSCs) in winter 1991/92. Those were on single days only and mostly above the 475 K isentropic surface (about 19 km). These events are clearly discernible and are excluded from the analysis presented here.

When measurements were started for the EASOE campaign in November 1991, volcanic aerosols were already a persistent feature of the lower stratosphere. The time series of the backscatter ratio R is shown in Figure 1. There is a clear distinction between the mid-latitude stations (Figures 1e and 1f), where a broad aerosol layer with backscatter ratios above 3 is observed, and the high latitude stations (Figures 1a - 1d), where only peak ratios are found above a value of 3 until late in the winter. At the mid-latitude stations the upper part of the aerosol layer exhibits large day-to-day variations, especially above the 500 K surface. The lower isoline of R = 1.6 shows a slow and steady drift from the 400 K to the 350 K surface.

At the high-latitude stations R was larger at the beginning of December than later in the month, or in the first half of January. In this period, the polar vortex was very stable, and there appears to be little poleward transport above the 450 K surface. There was a strong minor warming in January, disturbing but not destroying the vortex (Naujokat et al., 1992). R exceeded 2.8 on the 500 K surface over Sodankylä soon after (Figure 1d), and increased on the 450 K surface over Thule (Figure 1a) towards the end of January. During February and the first half of March the vortex remained disturbed, as seen by the variable R values above Andøya and Sodankylä, stations near the edge of the vortex. Further inside

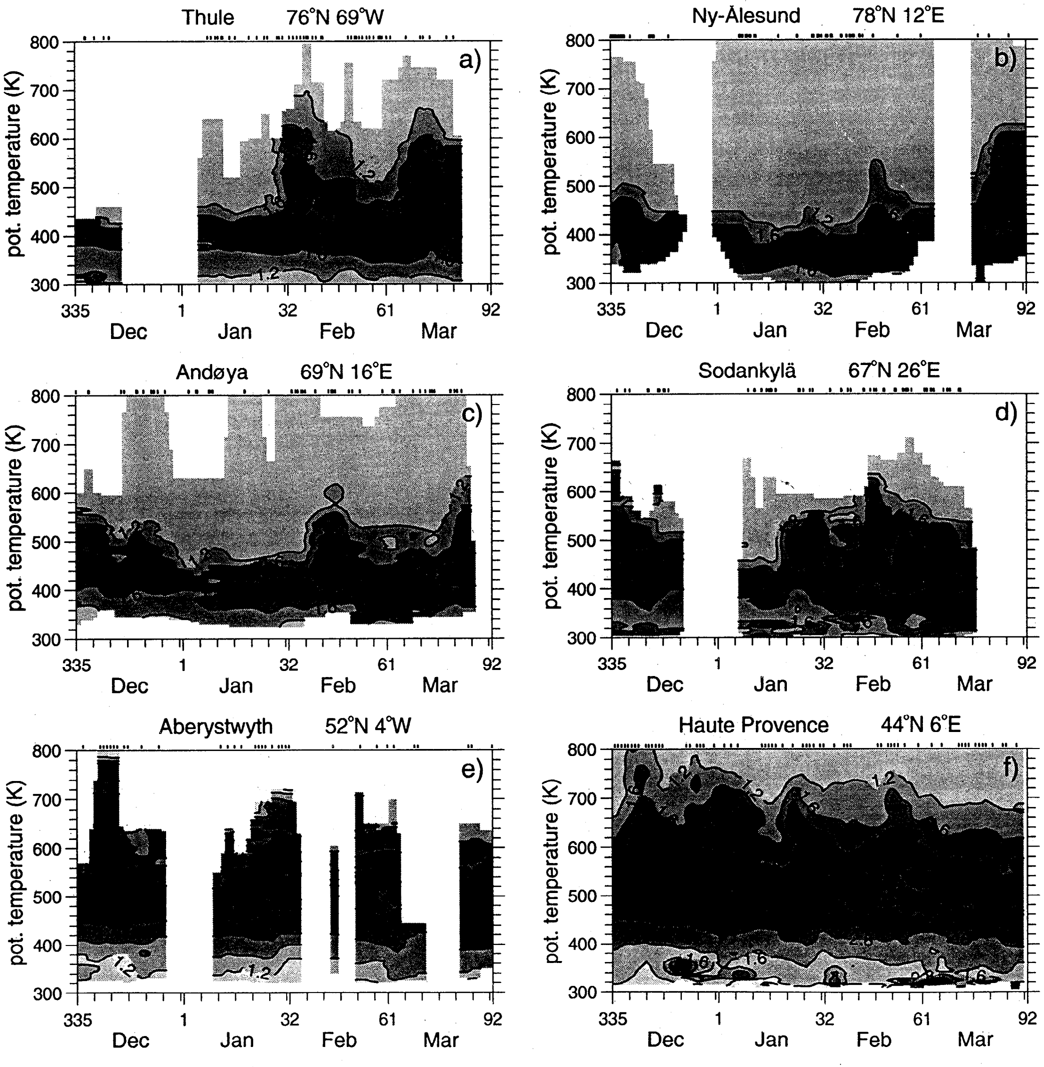

Fig. 1. Temporal development of the backscatter ratios at six lidar stations. Bars above the plots indicate times of measurements. Isolines are set to values of 1.2, 1.8, 2.6, and 5.4 in order to reveal greater details for the lower values.

the vortex, at Thule, R decreased again during February, while at Ny-Ålesund the effects of the warming are barely visible. The vortex broke up finally in the second half of March, and R increased very strongly above the 440 K surface over Thule, Ny-Ålesund, and Andøya.

Discussion

Relationship between backscatter ratio and the polar vortex. The Arctic polar vortex moved considerably during winter/spring 1991/92. Accordingly the position of the lidar stations changed with respect to the vortex boundary or the vortex centre. Maps of the fields of potential vorticity (PV) on isentropic surfaces were distributed by NILU (Braathen et al., 1992). They show that Haute Provence and Aberystwyth were outside of the vortex throughout the winter. For the stations north of the polar circle a negative correlation is found between the aerosol signal and potential vorticity. For a more detailed description however, two altitude regions should be distinguished and are treated separately below.

The altitude region above 450 K. On the 550 K isentropic surface the PV field already showed strong structure by early November, caused by the vortex. The gradient of PV was particularly steep between PV values of 78 and 102 units (1 PV unit = 10^{-6} K m^2 /kg/s). On the 475 K isentropic surface the PV field remained relatively flat until late November. Gradients then strengthened in the range of PV values from 30 to 42 units, with central values reaching up to 54 units by mid-December. The steep PV gradient indicates the vortex edge, which isolates the inner vortex air. Accordingly the aerosol content inside the vortex was low. Backscatter ratios of 1.2, which were observed in December at Andøya and Ny-Ålesund disappeared when potential vorticity values increased and the gradient steepened in December (see Figure 1). Later on these stations did not observe any volcanic aerosols above 460 K until February, indicating the good isolating effect of the polar vortex boundary. Similar results were obtained by Rosen et al. (1992), who observed that aerosols could not penetrate into the polar vortex above 20 km altitude (equivalent to 475 K potential temperature). In order to show the effect of the polar vortex, Figure 2 gives a scatter plot of the distribution of backscatter ratio R with potential vorticity Q on the 475 K and on the 425 K isentropic surfaces. At 475 K (Figure 2a) the data points appear separated into two areas. For potential vorticity values up to 30 PV units the mid-latitude stations at Haute Provence and Aberystwyth contribute the greater part of the points, with R values mostly between 3 and 6. At the higher potential vorticities, $Q>40$, all the points come from the other stations, and values of R are scattered between 1 and 2. In the range $30<Q<40$ values of R are scattered between 1 and 4; this is the range of Q where the gradient of Q is steepest and the vortex edge is located, statistically (e.g. Knudsen et al. (1992)). On the 550 K isentropic surface the scatter plot (not shown) subdivides even more distinctly.

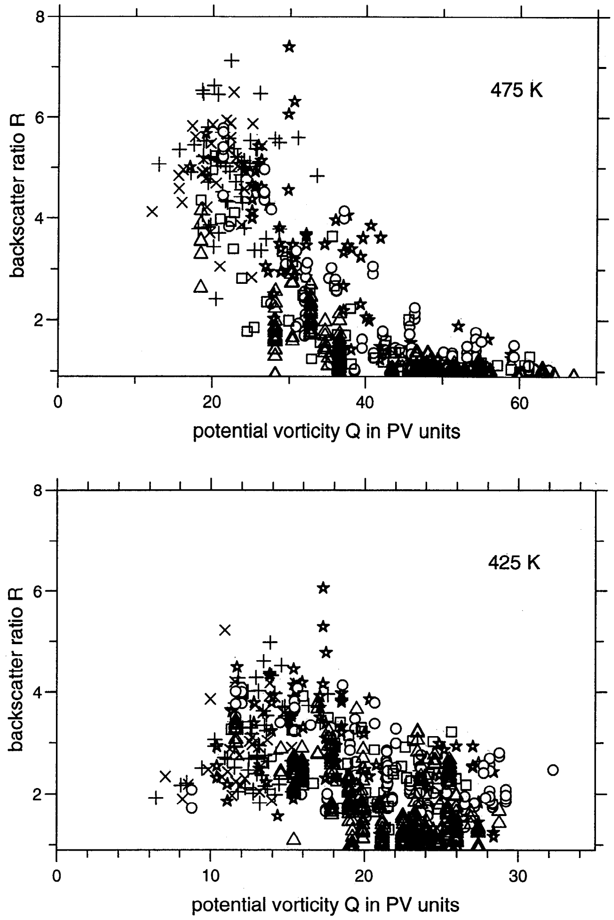

Fig. 2. Scatter plots of backscatter ratio R and pot. vorticity Q at the 475 K (a) and 425 K (b) isentropic surfaces. Data from l' Observatoire de Haut Provence (+), Aberystwyth (x), Andøya (o), Sodankylä (*), Thule (□) and Ny-Ålesund (Δ), all available measurements from 1. Dec. to 31. March.

The altitude region from the tropopause to 450 K. In this altitude range volcanic aerosols have been found throughout the whole winter at every station. Already the fast transport of the initial aerosol loads to the northern stations during summer 1991 (see above) indicates a different scheme of latitudinal transport at these altitudes as compared to the mid-stratosphere. Figures 1a) to 1d) suggest that the bottom of the polar vortex is at those altitudes, where the aerosol load diminishes with increasing altitude. At higher altitudes aerosols were excluded from the polar vortex at the vortex boundary. On the other hand, between the tropopause and about 450 K altitude only moderate changes in the aerosol load were observed. The backscatter ratios at the 400 K level are between 1.6 and 2 at all stations, indicating an even distribution of the aerosol content. This is also consistent with the distribution of ozone laminae found during EASOE (Reid et al., this issue). Figure 2b again gives a scatter plot of the distribution of R with Q, here at the 425 K isentropic level. This plot shows much less structure than Figure 2a. There is a widespread range of R and Q values with contributions from all stations to all values of Q. Plots for lower isentropic surfaces (not shown) give similar results. Hence, it seems that during winter 1991/92 below the 450 K isentropic surface an isolating vortex did not develop, allowing latitudinal transport throughout the winter, which led to the even distribution of the aerosol content. An early inclusion and subsequent isolation of aerosols at the altitudes below the 450 K level is improbable, as there are only very moderate increases of R observed associated with the warming events at the end of January or at the end of March.

Summary

Aerosols originating from the eruption of Mt. Pinatubo were persistent during the EASOE campaign throughout the whole winter. At the mid-latitude stations volcanic aerosols were found from the tropopause up to the 700 K isentropic surface (about 27 km altitude). In contrast, at stations on the polar side of the stratospheric jet stream, the backscatter ratios from levels above the 450 K isentropic surface (above 19 km altitude) remained low until the strong minor warming in January. Backscatter ratios comparable to those observed in mid-latitudes were not recorded until after the break-up of the vortex. On the other hand, below the 450 K isentropic surface all stations showed similar backscatter ratio values, independent from values of potential vorticity. The significant height dependent difference in the occurrence of the aerosols indicates efficient latitudinal transport processes from mid- to northern latitudes between the tropopause and 450 K, while they show the isolating properties of the polar vortex above. Measurements of the depolarization of lidar returns indicated only few events of polar stratospheric clouds in December and January above Andøya and Sodankylä. Otherwise the main aerosol layer did not show depolarization, suggesting that it was composed predominantly of spherical particles. Depolarization values ranging up to 4 % were found only below the main aerosol layer, which could be caused by solid volcanic debris.

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