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The 16 April 2010 major volcanic ash plume over central Europe: EARLINET lidar and AERONET photometer observations at Leipzig and Munich, Germany

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Received 29 April 2010; revised 1 June 2010; accepted 14 June 2010; published 15 July 2010.

[1] The optically thickest volcanic ash plume ever measured over Germany was monitored with multiwavelength Raman lidars and Sun photometer at Leipzig and Munich. When this ash layer, originating from the Eyjafjoll eruptions in southern Iceland, crossed Leipzig between 2.5 and 6 km height on 16 April 2010, the total 500 nm aerosol optical depth reached 1.0, and the ash–related optical depth was about 0.7. Volume light–extinction coefficients (40–75–minute mean values) measured over Leipzig and Munich at 355 and 532 nm reached values of 400–600 Mm^{-1} and ash mass concentrations were on the order of 1000 ± 350 $\mu g/m^3$ in the center of the main ash layer. Extinction–to–backscatter ratios ranged from 55 ± 5 sr (Munich) to 60 ± 5 sr (Leipzig) in the main ash layer, and the particle linear depolarization ratio was close to 0.35 at both wavelengths. Rather low photometer–derived Ångström exponents (500–1640 nm wavelength range) indicated the presence of a significant amount of large ash particles with diameters >20 μm. **Citation:** Ansmann, A., et al. (2010), The 16 April 2010 major volcanic ash plume over central Europe: EARLINET lidar and AERONET photometer observations at Leipzig and Munich, Germany, *Geophys. Res. Lett.*, *37*, L13810, doi:10.1029/2010GL043809.

1. Introduction

[2] The optically strongest volcanic ash plumes ever measured over central Europe reached the continent on 16 April 2010 and caused an almost complete disruption of the air traffic over western, central, and northern Europe for several days, for the first time since the second world war. Due to favorable meteorological conditions the free tropospheric ash clouds originating from strong eruptions of the Eyjafjoll volcano in southern Iceland on 14 April 2010 were advected to Europe within less than two days. This major event can be regarded as a natural experiment to investigate the impact of fresh and aged volcanic ash on weather and climate, especially on radiative transfer in the atmosphere and cloud processes as, e.g., the role of volcanic ash on cloud ice formation. Atmospheric transport models can be validated by means of this unique free tropospheric tracer.

[3] High ash–related aerosol optical depths on the order of 1.0 (500 nm) were measured over central Europe with the European Aerosol Research Lidar Network (EARLINET) lidar at Hamburg and the Aerosol Robotic Network (AERONET) photometers at Heligoland in the North Sea and at Hamburg in the morning hours of 16 April 2010. The ash front crossed the EARLINET stations at Cabauw, the Netherlands, and Leipzig in the afternoon, and Munich in the evening and the following night. Here we report the Raman lidar observations and Sun photometer measurements at Leipzig (51.4°N, 12.4°E, 125 m height above sea level, asl) on 16 April 2010 and measurements with two Raman/polarization lidars at Munich (Maisach, 48.2°N, 11.3°E, 520 m height asl) in the following night. First quantitative data on the optical properties (light–extinction coefficient, optical depth, extinction–to–backscatter or lidar ratio, depolarization ratio) of the major ash plume and estimates of the maximum mass load are provided and document this unique event. After a brief description of the instrumentation in section 2, the results are discussed in section 3. A short summary is given in section 4.

2. Instrumentation

[4] The employed aerosol Raman lidars [*Mattis et al.*, 2004; *Freudenthaler et al.*, 2009] permit us to determine vertical profiles of volume extinction coefficient of particles at 355 and 532 nm, backscatter coefficient at 355, 532, and 1064 nm, lidar ratio at 355 and 532 nm, and depolarization ratio at 355 and 532 nm. The uncertainties in the optical properties of the ash plume reported here are on the order of 5%–10% (particle backscatter coefficient), 5%–15% (particle extinction coefficient), and <5% (depolarization ratio). The Leipzig AERONET Sun photometer measures the particle optical depth from 340–1640 nm, and performs sky radiance observations at 380, 500, 870, and 1020 nm. The uncertainty in the retrieved optical depths is on the order of 0.0005–0.003.

3. Observations

[5] The strong eruption of the Eyjafjoll volcano on 14 April 2010 was followed by several weaker eruptions during the next days. From 16–24 April 2010 pronounced volcanic ash layers were observed throughout the free troposphere up to about 10 km height with the lidars at Leipzig and Munich. During this time period persistent meteorological conditions with a high–pressure system over and west of the British Isles and a low–pressure system over Scandinavia caused an almost steady flow of volcanic ash from Iceland to central Europe. The highest ash–related (coarse mode) particle optical depths of 0.8–1.2 at 500 nm

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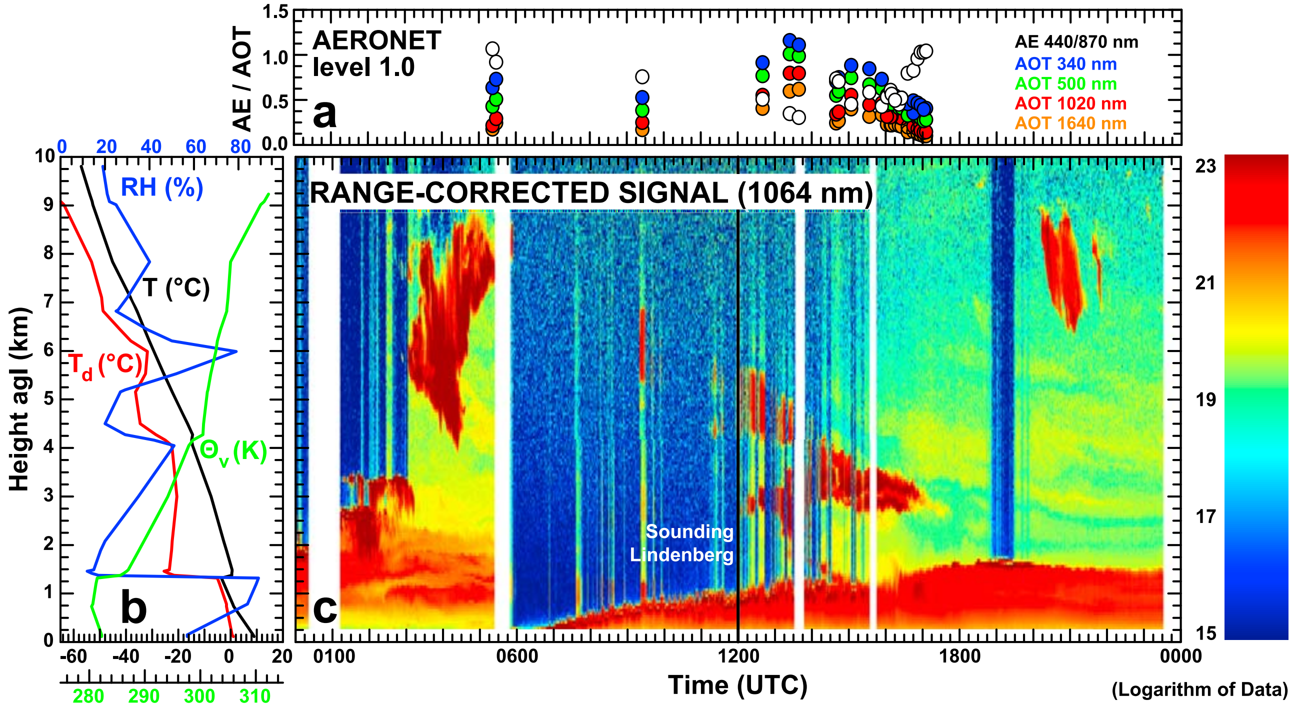

Figure 1. (a–c) Evolution of the major ash plume over Leipzig on 16 April 2010 (in red, 2–7 km height, 0900–1700 UTC) in terms of 1064–nm range–corrected lidar signal (arbitrary units). White areas indicate measurement interruptions. The 1200 UTC Lindenberg radiosonde profiles of temperature T, virtual potential temperature Θ_v, dew point T_d, and relative humidity RH are shown in Figure 1b. The sonde (indicated by a black vertical line) was launched 180 km northeast of Leipzig. Horizontal wind speeds (not shown) were 10–15 m/s (2–5 km height) and 15–20 m/s (5–10 km height), wind direction was northwest at all heights above the boundary layer. Aerosol optical depths (AOT) from AERONET Sun photometer at wavelength from 380–1640 nm and the corresponding 440–870 nm Ångström exponent (AE) are shown in Figure 1a.

were measured at the AERONET stations Heligoland (German Bight, North Sea, 0600–0630 UTC) and Hamburg (0630–0700 UTC). The Leipzig AERONET photometer registered peak aerosol optical depths around 1.0 and ash–related values up to 0.7 at 500 nm from 1320–1340 UTC on 16 April 2010. The ash front reached Munich at 1800 UTC, but clouds prohibited quantitative lidar observations until the early morning of 17 April.

[6] Figure 1 provides an overview of the Leipzig lidar observations performed on 16 April 2010. First traces of ash (yellow colors above 3 km height) arrived at Leipzig shortly after midnight. A cirrus deck was embedded in the ash between 4 and 9 km height before 0600 UTC (0800 local time). A thick, aged European haze layer caused strong backscattering (orange to red colors) below 3 km height at that time. Strong cumulus development in the convectively active boundary layer after sunrise disturbed the ash plume monitoring until the early afternoon as indicated by the blue areas above the red boundary layer in Figure 1 (0600–1200 UTC). Nevertheless, shortly after 0900 UTC the lidar observations reveal an ash plume (in red) from 5–7 km height which descends to 4–5 km at 1300 UTC. Another dense plume is detected between 2.0 and 4.0 km from 1200–1700 UTC. A similar layering was observed with the Hamburg EARLINET Raman lidar about 5–6 hours earlier. According to the Lindenberg radiosonde wind measurements the horizontal extent of the main ash front was about 250 km (time period from 1200–1700 UTC times 12.5 m/s).

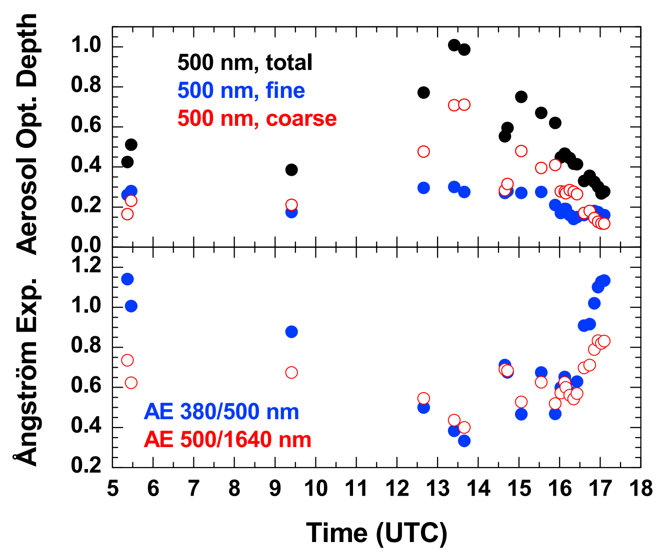

Figure 2. AERONET Sun photometer observations (Leipzig, 16 April 2010, http://aeronet.gsfc.nasa.gov/) of (top) 500 nm aerosol optical depth (level 1.0 data) and (bottom) Ångström exponents (AE) computed from the optical depths measured at 380, 500, and 1640 nm. The fine–mode–related (for particles with diameters <1 μm) and coarse–mode–related aerosol optical depth (diameters >1 μm) are shown in addition (Figure 2, top).

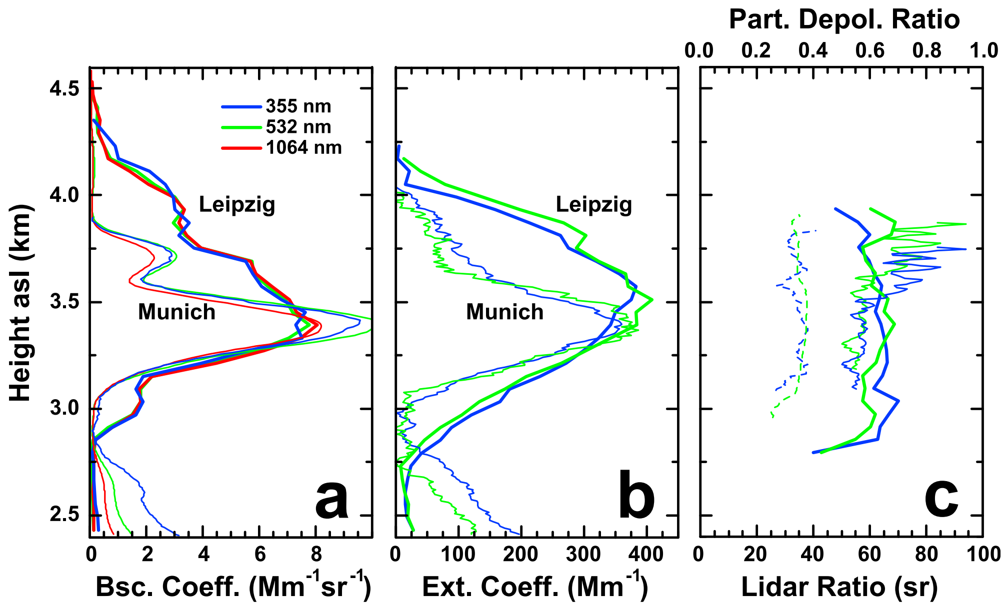

Figure 3. (a) Volume backscatter coefficient (180° scattering) at 355 (blue), 532 (green), and 1064 nm (red), (b) volume extinction coefficient, and (c) extinction–to–backscatter ratio (lidar ratio, Munich, thin lines, Leipzig, thick lines) and particle depolarization ratio (Munich, thin dashed lines) at 355 (blue) and 532 nm (green). Lidar signal profiles measured from 1415–1530 UTC on 16 April 2010 (Leipzig) and from 0140–0230 UTC on 17 April (Munich) are averaged (after cloud screening). Lidar signals are smoothed with 280–330 m (extinction, lidar ratio) and 60–75 m (backscatter, depolarization ratio) vertical window length before the computation of the optical properties. Calculation step width is 15 m (Munich) to 60 m (Leipzig).

After the passage of the ash clouds, traces of ash became visible above the boundary layer (top at 1500 m) throughout the entire troposphere. The relative humidity (Lindenberg sonde) was <50% in the lower ash plume (1.5–4.0 km height). Thus, the ash particles were dry.

[7] In Figures 1a and 2 the Leipzig AERONET photometer observations are shown. The 500 nm aerosol optical depth is 1.0 between 1300 and 1400 UTC. The fine–mode particle optical depth of 0.3 is comparable to the lidar–derived boundary–layer particle optical depth of about 0.35 at 532 nm (estimated from the 532 nm backscatter coefficient which is reliable down to low heights). The coarse–mode–related optical depth of 0.7 at 500 nm in Figure 2 can be interpreted as the ash–related optical depth. This is also in good agreement with the lidar observations. The 532 nm optical depth in the free troposphere decreased from values around 0.65 (1330 UTC) and 0.3–0.4 (1500–1600 UTC) to values around 0.05 after 1800 UTC.

[8] The Ångström exponents computed for the short–wavelength range (AE 380/500 nm) and for the long–wavelength range (AE 500/1640 nm) from the AERONET data drop to values of 0.35–0.40, when the highest ash load was observed between 1300 and 1400 UTC. By considering a boundary layer optical depth of 0.35 at 532 nm, and assuming boundary–layer Ångström exponents of 1.0 for both, the 380–500 nm and the 500–1640 nm wavelength ranges, ash–related Ångström exponents (above the boundary layer, 0.65 aerosol optical depth in the free troposphere) of 0.0 to −0.1 (380–500 nm) and 0.2–0.3 (500–1640 nm) are required to reproduce the observed values of 0.30–0.45. These ash–related low Ångström exponents are rather similar to values for Saharan dust observed in southern Morocco [*Ansmann et al.*, 2009], and indicate the presence of a considerable amount of large to very large particles with diameters >20 μm in the ash layers.

[9] Figure 3 shows 75–minute (Leipzig) and 40–minute (Munich) mean profiles of the particle backscatter coefficient, extinction coefficient, lidar ratio, and particle depolarization ratio derived from the lidar measurements. The lidar signal profiles were carefully screened for clouds

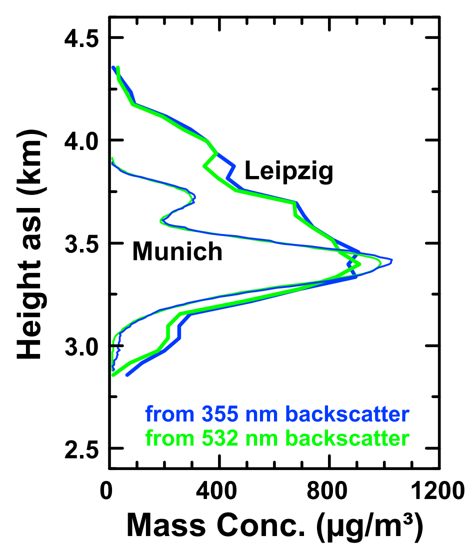

Figure 4. Mass concentrations estimated from the 355 and 532 nm backscatter profiles in Figure 3.

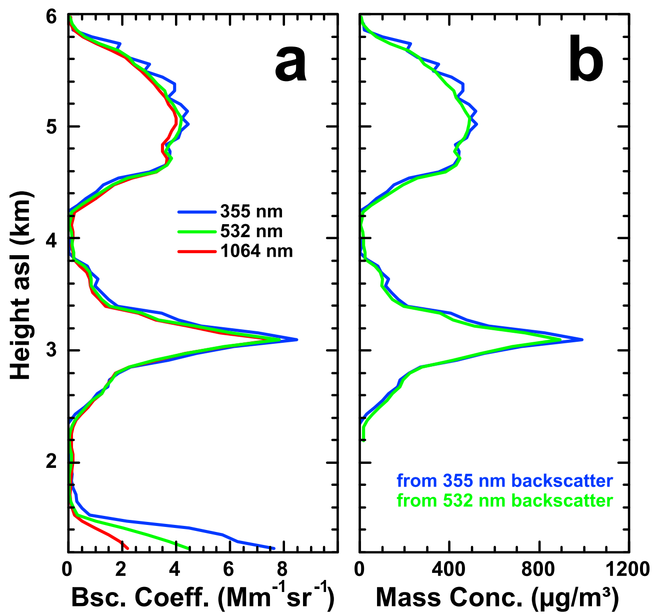

Figure 5. (a) 1200–1330 UTC mean particle backscatter coefficients at 355, 532, and 1064 nm, and (b) estimated ash mass concentrations (from 355 and 532 nm backscatter) for the lower (2.5–3.5 km) and upper (4–6 km) ash layer over Leipzig (see Figure 1).

before the computation of the optical properties. Volume extinction coefficients reached values of 400 Mm^{-1} (computed from signals smoothed with about 300 m vertical window length) in the center of the plume at both sites. Lidar ratios were in the range from 50–60 sr (Munich, 532 nm) and 55–65 sr (Leipzig, 355 nm). The backscatter coefficients (multiplied with the lidar ratio of 55–60 sr) obtained with high vertical resolution thus indicate peak extinction coefficients close to 600 Mm^{-1}. The particle depolarization ratios of 35%–40% clearly indicate irregularly shaped ash particles. The depolarization values are higher than the ones for pure Saharan dust of 25%–35% [*Freudenthaler et al.*, 2009], and may be caused by the complex morphology of the large ash particles, partly glass particles with sharp edges. As in the case of Saharan dust, a wavelength dependence of the volume extinction coefficient is not found. This also supports the hypothesis that a considerable amount of rather large ash particles was still present in these ash plumes after a travel of 1–2 days, and dominated the observed optical properties. At Cabauw, Hamburg, Leipzig, and Munich similar backscatter and extinction coefficients were measured (D. Donovan, KMNI, de Bilt, the Netherlands, I. Serikov, MPI, Hamburg, personal communication) on 16 April until the morning of the next day (Munich). Short–term (few–minute average) peak values of the backscatter and extinction coefficients were as high as 15 Mm^{-1} sr^{-1} and 800 Mm^{-1}.

[10] Figure 4 presents mass concentrations estimated from the measured backscatter profiles in Figure 3. The mass–to–backscatter conversion factor is computed from the volume–to–extinction conversion factor of 0.75×10^{-6} m (for a unit volume) for desert dust size distributions according to the OPAC (Optical Properties of Aerosols and Clouds) [*Hess et al.*, 1998] data base (considering the removal of the largest dust particles after one day of transport), by assuming a mean mass density of 2600 kg/m^3 for the ash particle mixture consisting of volcanic glass, minerals, and lithic fragments (http://volcanoes.usgs.gov/ash/properties.html), and by further considering the measured extinction–to–backscatter ratios of 55 sr (Munich) and 60 sr (Leipzig). Backscatter coefficients are used in Figure 4 because they are obtained with the highest vertical resolution.

[11] The uncertainty in the estimation of the mass concentration is about 35%. The uncertainty is estimated from the uncertainty in the volume–to–extinction ratio estimate (20%), in the lidar ratio (10%), and in the mass density estimate (25%) caused by the unknown morphological properties, coating of the ash particles with sulfuric acid, and the actual composition of the particle aggregates.

[12] Figure 4 indicates that mass concentrations were most probably on the order of 1000 $\mu g/m^3$ in the densest ash layer over Leipzig and Munich. Short–term peak values were close to 1500 $\mu g/m^3$. Another measurement example is shown in Figure 5. At that time (1200–1330 UTC), two ash layers occurred. Again large mass concentrations were found in these ash layers.

4. Summary

[13] Volcanic–ash–related optical depths as high as 0.7–1.2 at 500 nm were observed over Germany on 16 April 2010. Volume light–extinction coefficients ranged from 400–600 Mm^{-1} (40–75–minute mean values) and mass concentrations were on the order of 1000 $\mu g/m^3$ in the center of the ash plume. Lidar ratios of 50–65 sr and particle depolarization ratios of 0.35–0.4 at 355 and 532 nm wavelength are clear indications for a complex morphology of the ash particles and allow us to unambiguously discriminate the ash from cirrus layers (cirrus lidar ratios are <35 sr). Rather low Ångström exponents furthermore indicated the presence of a significant amount of large particles with diameters >20 μm in the 16–April ash front. This short letter demonstrates the important role of lidar remote sensing. Valuable information on volcanic ash (not masked by boundary layer effects as in the case of Sun photometry) is provided. Only by means of lidar network observations a satisfactory validation of atmospheric transport models is possible in the case of lofted, free tropospheric aerosol layers.

[14] **Acknowledgments.** The financial support for EARLINET by the European Commission under grant RICA–025991 is gratefully acknowledged. The authors also acknowledge the ESA financial support under ESTEC contract 21487/08/NL/HE. We thank the AERONET team for providing us with an always well calibrated Sun photometer and high–quality AERONET data products.

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