Further evidence for significant smoke transport from Africa to Amazonia

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[1] Polarization-Raman-lidar observations of vertical aerosol profiles were performed 60 km north of Manaus, Brazil, in the Amazon rain forest during Amazonia's wet season from January to May 2008. Very clean background conditions with a mean AOD (532 nm) of 0.03 ± 0.02 were frequently found. However, in about one third of all lidar measurements advection of smoke and dust aerosol from Africa were observed. The contribution of African smoke and Saharan dust particles to the total backscatter and extinction coefficient was determined by means of the measured particle depolarization ratio. A decreasing contribution of smoke particles to the total particle extinction coefficient from values around 60%–80% in January and February 2008, to values of 0%–50% in May 2008 was observed. Smoke–related extinction coefficients and optical depths up to 80 Mm^{-1} and 0.15 at 532 nm, respectively, were recorded. **Citation:** Baars, H., A. Ansmann, D. Althausen, R. Engelmann, P. Artaxo, T. Pauliquevis, and R. Souza (2011), Further evidence for significant smoke transport from Africa to Amazonia, *Geophys. Res. Lett.*, *38*, L20802, doi:10.1029/2011GL049200.

1. Introduction

[2] The Amazon Basin is the largest area of tropical rain forest in the world. While during the dry season a high fire activity on the South American continent heavily influences the aerosol conditions in Amazonia, the region is assumed to be very clean in terms of aerosol concentration and almost free of anthropogenic influence during the wet season [*Martin et al.*, 2010a]. *Pöschl et al.* [2010] even state that aerosol conditions in Amazonia's wet season "approach to those of the pristine pre-industrial era". However, it was shown [*Talbot et al.*, 1990; *Swap et al.*, 1992; *Formenti et al.*, 2001] that events of Saharan dust advection do occasionally take place and can significantly change the atmospheric aerosol conditions over the Amazon rain forest during the wet season. Recent studies suggest that even biomass burning aerosol (BBA) is advected from Africa toward the Amazon Basin during the wet season [*Ansmann et al.*, 2009; *Ben-Ami et al.*, 2010]. These studies corroborate satellite observations presented by *Kaufman et al.* [2005]. An improved knowledge of the characteristics of particles arriving in Amazonia from Africa is a prerequisite for a reliable simulation of aerosol effects on the radiation budget and on cloud and precipitation formation over the tropical Atlantic and Amazonia.

[3] Here, we provide an extended lidar study that confirms a strong smoke contribution to the aerosol plumes that are transported from central and western Africa to South America during Amazonia's wet season. The separation of smoke and dust contributions to the measured particle backscatter coefficient profiles is based on the observed particle depolarization ratios.

2. Experiment

[4] For the first time, long-term measurements of the vertical aerosol structure in Amazonia were conducted in 2008 in the framework of EUCAARI (European Integrated Project on Aerosol, Cloud, Climate, Air Quality Interactions [*Kulmala et al.*, 2011]) and AMAZE-08 (Amazonian Aerosol Characterization Experiment 2008 [*Martin et al.*, 2010b]). Vertical profiles of the particle backscatter coefficient at 355, 532, and 1064 nm, of the extinction coefficient at 355 and 532 nm, and of the depolarization ratio at 355 nm were measured with the automated, multiwavelength polarization-Raman lidar Polly^{XT} [*Althausen et al.*, 2009; *Ansmann et al.*, 2009]. Due to the frequent and almost persistent occurrence of low-level clouds, rain, and fog during the wet season, possible data analysis intervals were short and rare. As a consequence, only the retrieval of the backscatter coefficients and the depolarization ratio was possible for most of the measurement cases. From the backscatter coefficient we computed the extinction coefficient by assuming an extinction-to-backscatter ratio (lidar ratio) of 60 ± 20 sr, indicated by the few measurements of the lidar ratio with the Raman technique that were possible during the wet season. A lidar ratio of 60 ± 20 sr covers the typical range of aged dust and smoke plumes [*Tesche et al.*, 2009; *Ansmann et al.*, 2009].

[5] The statistical and systematic error for the determination of the particle backscatter coefficient after applying cloud-screening and temporal averaging is less than 10 %. The uncertainty of the particle depolarization ratio determination is in the same range. Large uncertainties in the laser-beam receiver-field-of-view correction in the near-range restrict the retrieval of the vertical aerosol profiles to heights above about 400 m (Raman lidar method) or 750 m agl (Klett method). As part of the quality assurance program, a careful calibration of the lidar following the calibration procedure outlined by *Mattis et al.* [2009] was performed after the EUCAARI campaign to account for polarization effects in the lidar receiver.

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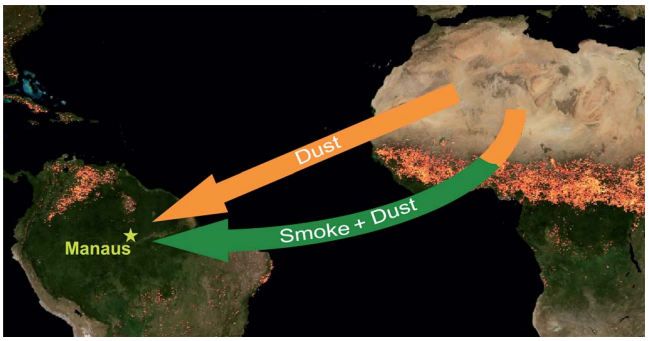

Figure 1. Schematic illustration of aerosol transport from Africa toward the Amazon Basin during Amazonia's wet season. The star indicates the lidar location. The underlying fire map shows the monthly composite of MODIS fire counts (red, orange, and yellow spots) for February 2008 (source: NASA's Earth Observatory Web site http://neo.sci.gsfc.nasa.gov).

[6] The almost continuous lidar measurements were performed at 2° 35.9′ S and 60° 2.3′ W at 83 m height above sea level. Pristine tropical rain forest surrounds the field site 60 km north of Manaus in the central, northern part of the Amazon Basin. The observation period lasted from 22 January to 10 November 2008 and thus covered most of the wet and dry season in Amazonia. During the 10-month observational period, lidar measurements could be performed on 211 days resulting in more than 2500 hours of tropospheric aerosol and cloud profile observations.

3. Smoke and Dust Quantification

[7] The particle backscatter coefficient of desert dust $\beta^{\mathrm{par}}_{\mathrm{dust}}(z)$ is obtained from the measured particle backscatter coefficient $\beta^{\mathrm{par}}_{\mathrm{meas}}(z)$ and the measured particle depolarization ratio $\delta^{\mathrm{par}}_{\mathrm{meas}}(z)$ at 355 nm by applying the following equation [*Tesche et al.*, 2009]:

$$\frac{\beta^{\mathrm{par}}_{\mathrm{dust}}(z)}{\beta^{\mathrm{par}}_{\mathrm{meas}}(z)} = \frac{\left(\delta^{\mathrm{par}}_{\mathrm{meas}}(z) - \delta^{\mathrm{par}}_{\mathrm{smoke}}\right)\left(1 + \delta^{\mathrm{par}}_{\mathrm{dust}}\right)}{\left(\delta^{\mathrm{par}}_{\mathrm{dust}} - \delta^{\mathrm{par}}_{\mathrm{smoke}}\right)\left(1 + \delta^{par}_{\mathrm{meas}}(z)\right)} \quad (1)$$

The dust fraction $\beta^{\mathrm{par}}_{\mathrm{dust}}(z)/\beta^{\mathrm{par}}_{\mathrm{meas}}(z)$ describes the contribution of dust to the total particle backscatter coefficient. $\delta^{\mathrm{par}}_{\mathrm{dust}}$ and $\delta^{\mathrm{par}}_{\mathrm{smoke}}$ are the particle depolarization ratio values for pure dust and aged smoke, respectively. *Groß et al.* [2011] measured the particle depolarization ratio at 355 nm of long-range transported Saharan dust at Cape Verde during the Saharan Mineral Dust Experiment SAMUM-2. A mean value of $\delta^{\mathrm{par}}_{\mathrm{dust}} = 0.25 \pm 0.03$ was obtained. Maximum particle depolarization ratios observed in Amazonia were $\delta^{\mathrm{par}}_{\mathrm{meas}} =$ 0.24–0.27 and thus also in the range of values found for pure dust at Cape Verde. We therefore assume that the particle depolarization ratio of dust does not significantly change during long-range transport.

[8] The EUCAARI lidar observations in Amazonia during the dry season showed that fresh and aged fire smoke plumes do almost not depolarize backscattered light ($\delta^{\mathrm{par}}_{\mathrm{smoke}} < 0.03$). This finding is in agreement with the SAMUM-2 smoke observations at Cape Verde in January and February 2008 and observations of aged Siberian and Canadian forest fire smoke over Germany [*Müller et al.*, 2005]. Thus, based on these observations, we use $\delta^{\mathrm{par}}_{\mathrm{dust}} = 0.25 \pm 0.03$ and $\delta^{\mathrm{par}}_{\mathrm{smoke}} = 0.03 \pm 0.02$ for the dust-smoke separation.

[9] Despite the fact that the dust-smoke separation is performed at 355 nm, we present results in terms of the extinction coefficient at 532 nm because this is the parameter and wavelength range most commonly used to describe aerosol optical effects. As shown by *Ansmann et al.* [2009], the spectral dependence of the extinction coefficient of dust and aged smoke is weak in the 355-to-532 nm wavelength range so that the extinction coefficients at 355 nm are also representative for 532 nm.

4. Results

[10] Figure 1 illustrates schematically the aerosol long-range transport from Africa toward the Amazon Basin which occurs occasionally between January and May each year (Amazonia's wet season). Desert dust is either directly advected from the Sahara, or after crossing the fire areas in central and western Africa from northeast to southwest as a mixture of dust and smoke. The transport time of the aerosol from Africa to Amazonia is approximately 10 days according to HYSPLIT (R. Draxler and G. Rolph, Hybrid Single-Particle Lagrangian Integrated Trajectory Model access via NOAA ARL READY Web site, http://ready.arl.noaa.gov/HYSPLIT.php) backward trajectories. Because of the persistent northeasterly trade winds, fires in South America (north and south of the field site) and pollution from the two-million-inhabitants city Manaus (60 km south) had practically no influence on the lidar measurements in central Amazonia in the first half year of 2008 as the HYSPLIT backward trajectory analysis showed. Investigations of the dispersion of the Manaus plume reported by *Kuhn et al.* [2010] corroborate this finding.

[11] Vertical aerosol profiles could be obtained for 53 lidar observations days during the wet season 2008. The aerosol optical depth (AOD) at 532 nm for these 53 observations is shown in Figure 2. The AOD was obtained by integrating the vertical profile of the particle extinction coefficient. For the height range up to 750 m agl at which extinction coefficients were not available, a well-mixed atmosphere with a height-independent extinction coefficient (equal to the extinction at the lowest reliable lidar profile height) was assumed. This assumption leads to errors of 10–20% in the determination of the AOD as comparison with AERONET sun photometer measurements during the dry season showed.

[12] As can be seen in Figure 2, very clean conditions with an AOD well below 0.05 were frequently found. A mean AOD of 0.03 ± 0.02 was observed for such conditions. The minimum AOD of 0.011 ± 0.004 was measured on 18 April, which is the lowest value we ever measured with our lidars over a continental site during the last 20 years. The analysis of the vertical profiles of the particle backscatter coefficient for all cases with AOD < 0.05 revealed that the aerosol was trapped in the lowermost 2 km and thus was most likely of regional origin. On average, the 532 nm particle extinction coefficients were less than 20 Mm^{-1} in the lowermost part of the troposphere.

[13] In the following, we assume that an AOD > 0.05 indicates long-range transport of particles. This hypothesis is corroborated by the fact that situations with AOD > 0.05 typically lasted for several days and were usually charac-

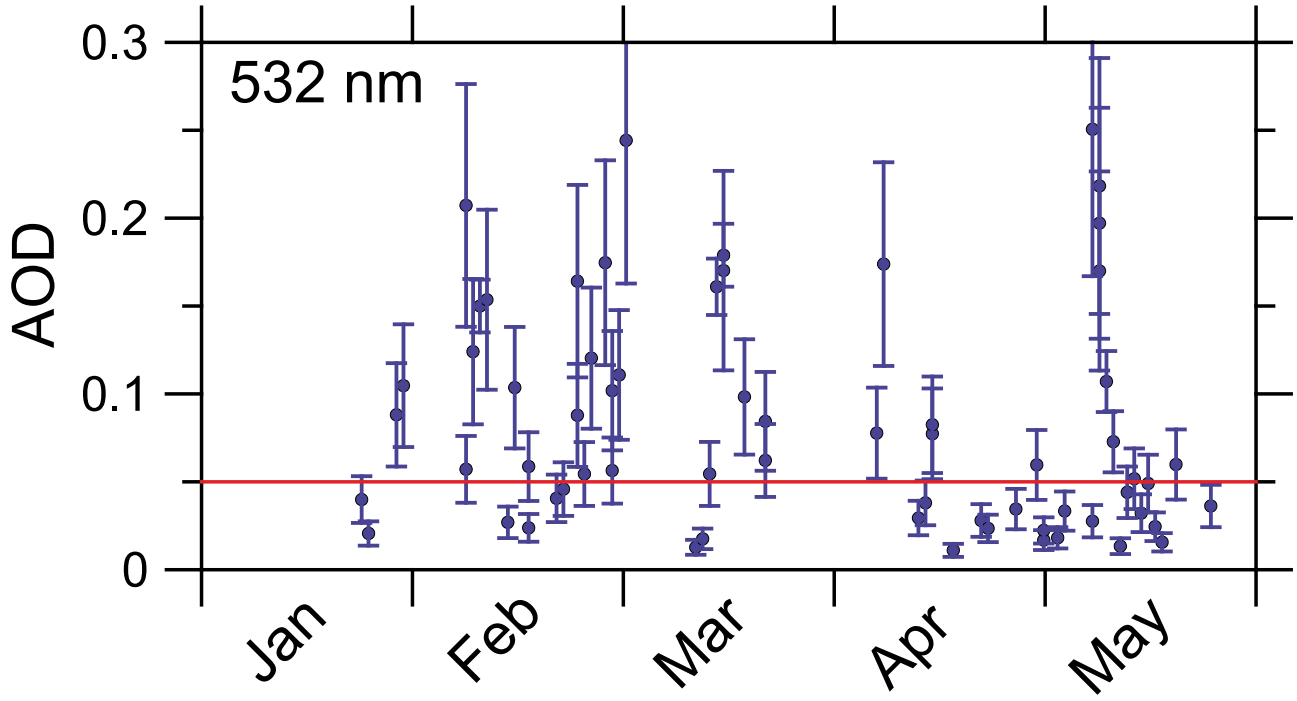

Figure 2. Temporal evolution of the AOD at 532 nm during the wet season 2008. Error bars indicate the uncertainty due to the applied lidar ratio. AOD values below the red line indicate background aerosol conditions.

terized by an enhanced particle depolarization ratio, which is indicative for Saharan dust. An AOD > 0.05 together with an enhanced particle depolarization ratio were observed for 17 lidar measurements in the wet season 2008 (32% of the 53 lidar sessions). *Ansmann et al.* [2009] discussed the advection of smoke and dust from Africa toward the lidar site in detail based on the observation taken on 10 February 2008. Here, we provide a more general view of the aerosol long–range transport. The study is based on the statistical results of all the 17 events observed.

[14] In Figure 3, 9 of the 17 cases covering the period from end of January to mid May 2008 are shown in terms of particle extinction coefficient at 532 nm and the calculated dust fraction. Uncertainties in the respective profiles are computed by applying the law of Gaussian error propagation. Four major episodes of African aerosol advection were observed. The first period lasted from 8–15 February 2008, a second pronounced period occurred from 25 February–1 March 2008, consistent with the dust and smoke transport over the Atlantic ocean discussed by *Ben-Ami et al.* [2010], and the third one was recorded from 8–11 May 2008. Another period with strongly enhanced AOD occurred mid March. Rarely, advection of African aerosol for one day only was observed.

[15] The dust fraction was found to roughly increase with time from values <35% for the 8–15-February-period to values between 20% and 50% for the second episode (25 February–1 March) and the observations mid of March and April. In mid May, dust fractions up to 100% could be finally observed as a result of significantly decreasing fire activity at the beginning of the wet season in central Africa.

[16] The non-dust fraction for an AOD > 0.05 may be partly influenced by marine particles and local pollution events, but is mainly related to African smoke. Aged BBA particles show a clear signature in the spectral dependence of the particle backscatter and extinction coefficients, with the consequence of an increasing lidar ratio with increasing wavelength [*Ansmann et al.*, 2009]. The opposite (decreasing lidar ratio with increasing wavelength) is observed for local smoke and urban haze.

[17] The findings from the lidar observations are consistent with ground-based mass spectral characterization of sub-micron particles at the same location in February and March 2008 [*Chen et al.*, 2009]. The authors state that aerosol from outside the Amazon Basin occasionally influences the aerosol population. Marine aerosol and African smoke are suggested to be good candidates for that out-of-Basin aerosol. The advection of marine aerosol can not be ruled out. However, the analyzed optical properties do not indicate a significant influence of marine aerosol to the total optical properties. Particles of marine origin have lidar ratios well below 30 sr [*Groß et al.*, 2011]. Such low lidar ratios were never observed with the EUCAARI lidar in Amazonia in 2008.

[18] One general finding from the analyzed cases is that from January to March the Saharan dust and the African BBA were trapped in the lowermost 3–3.5 km at the lidar site. *Ben-Ami et al.* [2010] discussed the transport of two mixed smoke-dust plumes from Africa over the Atlantic Ocean from 17 February–1 March 2008 and showed that the aerosol plume extended up to 3.3 km along the Brazilian coastline on 24 February 2008. Consequently, the mixed aerosol plume did not significantly change its vertical extend during the 48-hour transport from the Brazilian coast over the continent toward the lidar site (compare 26 February in Figure 3).

[19] To quantify the contribution of dust and smoke particles to the aerosol conditions in Amazonia, the dust-related

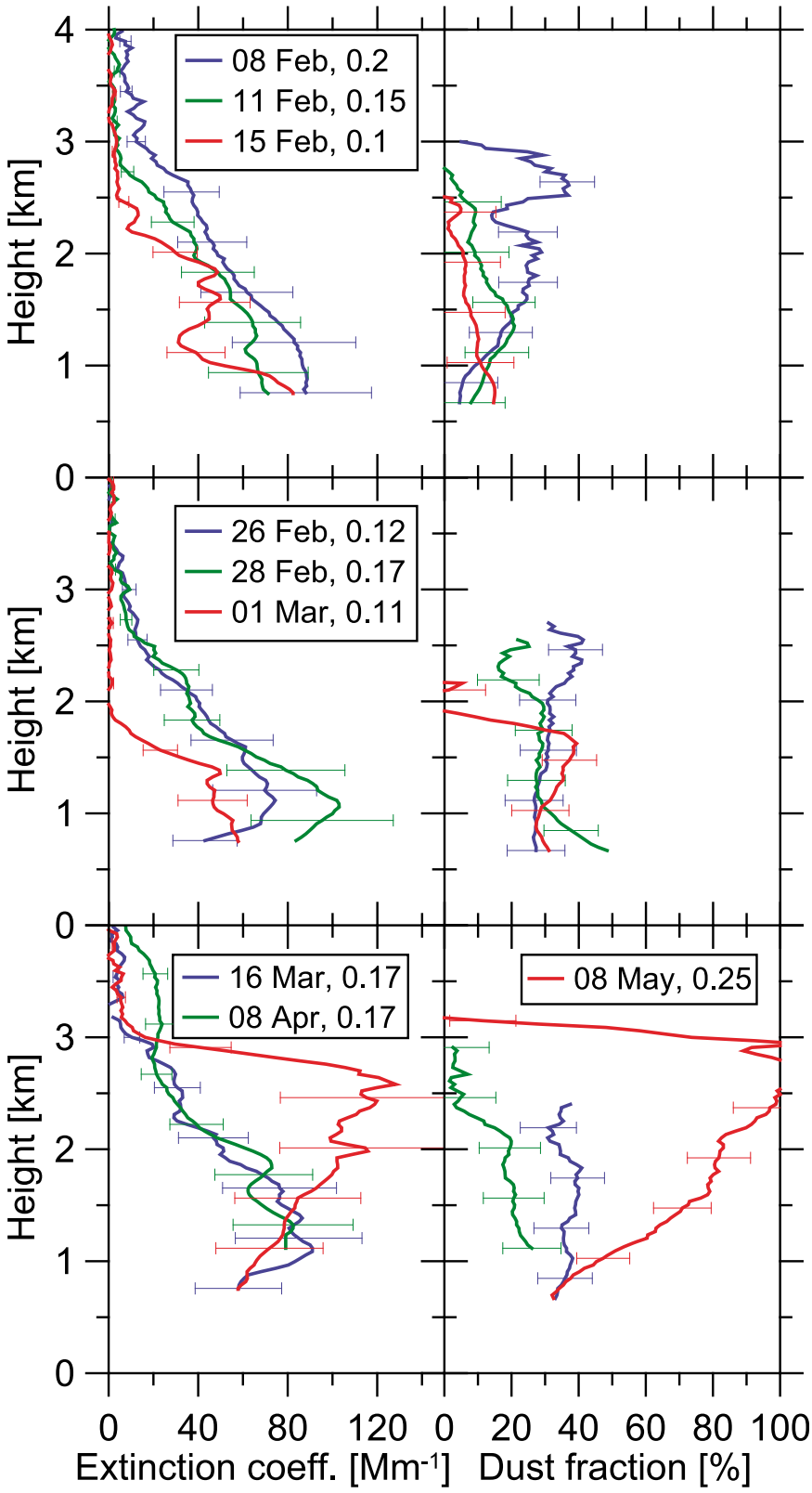

Figure 3. Vertical profiles of the particle extinction coefficient at 532 nm and the corresponding dust fraction (355 nm) for nine selected days. The legend indicates the date of the observation in 2008 and the measured AOD at 532 nm.

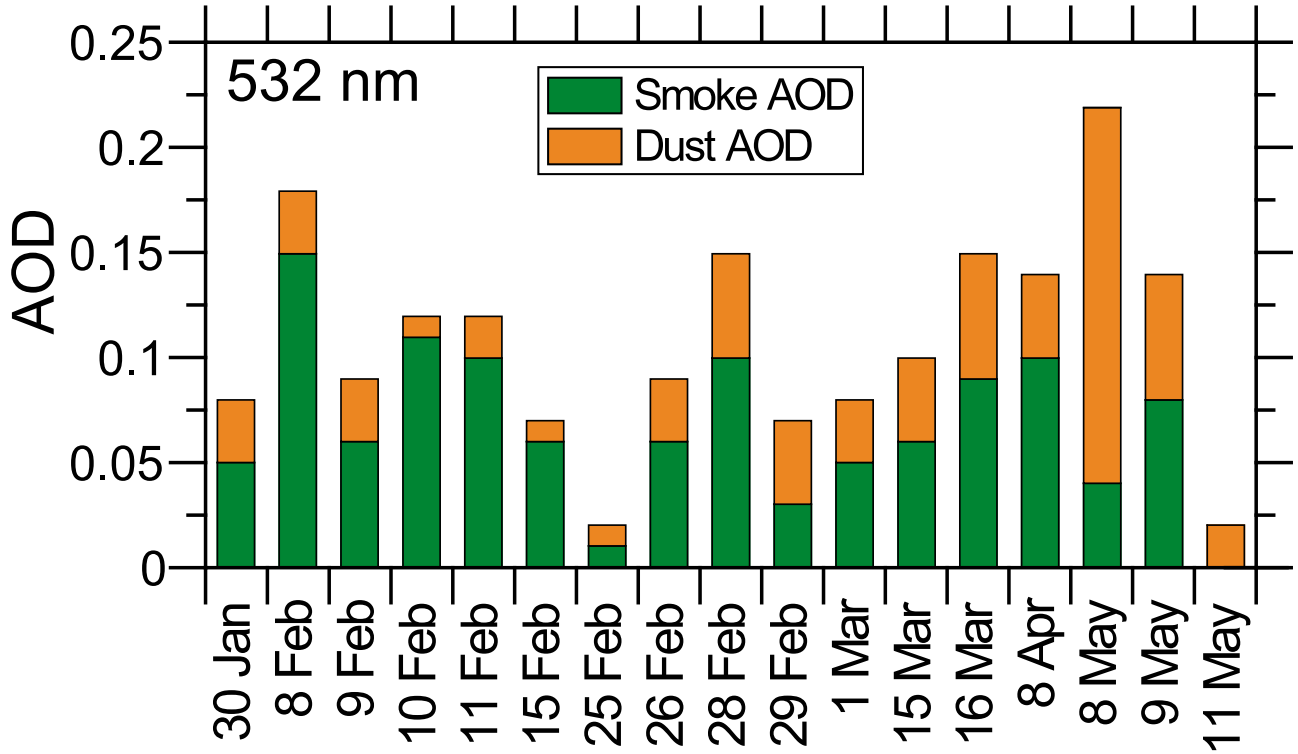

Figure 4. Smoke and dust AOD for the 17 observation cases in 2008 indicating the advection of African aerosol toward Amazonia. The measured total particle optical depth is obtained by adding 0.03 to the shown AOD (full green-orange bar).

and smoke-related AOD was computed from the vertical profiles of the dust fraction and the particle extinction coefficient. Figure 4 shows the results for the 17 cases of long-range transport. We subtracted an AOD of 0.03 from the smoke-related AOD to account for the local, natural impact (background AOD in Amazonia). From Figure 4 one can conclude that the 532 nm AOD was between 0.05 and 0.15 for African BBA particles during the 8–15-February-period. The BBA contribution to the AOD was up to 0.1 for the period end of February and between 0.06–0.09 for the mid of March period. A strong Saharan dust event was observed only on one day (8 May 2008) with a dust-related AOD value up to 0.18. The absolute smoke contribution to the AOD was highest in February 2008 with values up to 0.15.

5. Conclusion

[20] Episodes of long-range transported African aerosol (smoke and dust) can significantly disturb the Amazonian aerosol background conditions, expressed by an AOD of 0.03 ± 0.02 at 532 nm. For the first time, a vertically resolved documentation of African smoke transport was performed based on long-term lidar observations in the Amazon Basin in 2008. Dust and smoke contributions to the measured optical properties were separated by means of the measured particle depolarization ratio. In about one third (32%) of all lidar observations during Amazonia's wet season, African aerosol (predominantly smoke and dust) were detected. In about half of these cases, African smoke particles contributed to more than 50% to the total AOD. The smoke transport from Africa toward Amazonia occurs predominantly between January and April when the fire activity in Central Africa is highest. Saharan dust–laden air masses are enriched by the fire smoke particles when these air masses cross the fire areas in Africa from northeast to southwest.

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References

Althausen, D., R. Engelmann, H. Baars, B. Heese, A. Ansmann, D. Müller, and M. Komppula (2009), Portable Raman lidar PollyXT for automated profiling of aerosol backscatter, extinction, and depolarization, *J. Atmos. Oceanic Technol.*, *26*, 2366–2378, doi:10.1175/2009JTECHA1304.1.

Ansmann, A., H. Baars, M. Tesche, D. Müller, D. Althausen, R. Engelmann, T. Pauliquevis, and P. Artaxo (2009), Dust and smoke transport from Africa to South America: Lidar profiling over Cape Verde and the Amazon rainforest, *Geophys. Res. Lett.*, *36*, L11802, doi:10.1029/2009GL037923.

Ben-Ami, Y., I. Koren, Y. Rudich, P. Artaxo, S. T. Martin, and M. O. Andreae (2010), Transport of North African dust from the Bodélé depression to the Amazon Basin: A case study, *Atmos. Chem. Phys.*, *10*(16), 7533–7544, doi:10.5194/acp-10-7533-2010.

Chen, Q., et al. (2009), Mass spectral characterization of submicron biogenic organic particles in the Amazon Basin, *Geophys. Res. Lett.*, *36*, L20806, doi:10.1029/2009GL039880.

Formenti, P., et al. (2001), Saharan dust in Brazil and Suriname during the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)-Cooperative LBA Regional Experiment (CLAIRE) in March 1998, *J. Geophys. Res.*, *106*, 14,919–14,934, doi:10.1029/2000JD900827.

Groß, S., M. Tesche, V. Freudenthaler, C. Toledano, M. Wiegner, A. Ansmann, D. Althausen, and M. Seefelder (2011), Characterization of Saharan dust, marine aerosols and mixtures of biomass burning aerosols and dust by means of multi-wavelength depolarization and Raman measurements during SAMUM 2, *Tellus, Ser. B*, *63*(4), 706–724, doi:10.1111/j.1600-0889.2011.00556.x.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Tanré, P. Ginoux, and S. Fan (2005), Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean, *J. Geophys. Res.*, *110*, D10S12, doi:10.1029/2003JD004436.

Kulmala, M., et al. (2011), General overview: European Integrated project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI)—Integrating aerosol research from nano to global scales, *Atmos. Chem. Phys. Discuss.*, *11*(6), 17,941–18,160, doi:10.5194/acpd-11-17941-2011.

Kuhn, U., et al. (2010), Impact of Manaus City on the Amazon Green Ocean atmosphere: Ozone production, precursor sensitivity and aerosol load, *Atmos. Chem. Phys.*, *10*(19), 9251–9282, doi:10.5194/acp-10-9251-2010.

Martin, S. T., et al. (2010a), Sources and properties of Amazonian aerosol particles, *Rev. Geophys.*, *48*, RG2002, doi:10.1029/2008RG000280.

Martin, S. T., et al. (2010b), An overview of the Amazonian Aerosol Characterization Experiment 2008 (AMAZE-08), *Atmos. Chem. Phys.*, *10*, 11,415–11,438, doi:10.5194/acp-10-11415-2010.

Mattis, I., M. Tesche, M. Grein, V. Freudenthaler, and D. Müller (2009), Systematic error of lidar profiles caused by a polarization-dependent receiver transmission: Quantification and error correction scheme, *Appl. Opt.*, *48*(14), 2742–2751.

Müller, D., I. Mattis, U. Wandinger, A. Ansmann, D. Althausen, and A. Stohl (2005), Raman lidar observations of aged Siberian and Canadian forest fire smoke in the free troposphere over Germany in 2003: Microphysical particle characterization, *J. Geophys. Res.*, *110*, D17201, doi:10.1029/2004JD005756.

Pöschl, U., et al. (2010), Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon, *Science*, *329*, 1513–1516, doi:10.1126/science.1191056.

Swap, R., M. Garstang, S. Greco, R. Talbot, and P. Kållberg (1992), Saharan dust in the Amazon Basin, *Tellus, Ser. B*, *44*, 133–149, doi:10.1034/j.1600-0889.1992.t01-1-00005.x.

Talbot, R. W., M. O. Andreae, H. Berresheim, P. Artaxo, M. Garstang, R. C. Harriss, and K. M. Beecher (1990), Aerosol chemistry during the wet season in central Amazonia: The influence of long-range transport, *J. Geophys. Res.*, *95*, 16,955–16,969, doi:10.1029/JD095iD10p16955.

Tesche, M., A. Ansmann, D. Müller, D. Althausen, R. Engelmann, V. Freudenthaler, and S. Groß (2009), Vertically resolved separation of dust and smoke over Cape Verde using multiwavelength Raman and polarization lidars during Saharan Mineral Dust Experiment 2008, *J. Geophys. Res.*, *114*, D13202, doi:10.1029/2009JD011862.

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