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Dust and smoke transport from Africa to South America: Lidar profiling over Cape Verde and the Amazon rainforest

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[1] Quasi-simultaneous vertically resolved multiwavelength aerosol Raman lidar observations were conducted in the near field (Praia, Cape Verde, 15°N, 23.5°W) and in the far field (Manaus, Amazon basin, Brazil, 2.5°S, 60°W) of the long-range transport regime between West Africa and South America. Based on a unique data set (case study) of spectrally resolved backscatter and extinction coefficients, and of the depolarization ratio a detailed characterization of aerosol properties, vertical stratification, mixing, and aging behavior during the long-distance travel in February 2008 (dry season in western Africa, wet season in the Amazon basin) is presented. While highly stratified aerosol layers of dust and smoke up to 5.5 km height were found close to Africa, the aerosol over Manaus was almost well-mixed, reached up to 3.5 km, and mainly consisted of aged biomass burning smoke. **Citation:** 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.

1. Introduction

[2] Atmospheric models in combination with spaceborne passive remote sensing provide an almost global but two-dimensional view of the long-range advection of aerosols between the continents [*Ramanathan et al.*, 2007], including the important transport from Africa to North and South America by which large amounts of mineral dust and biomass burning smoke cross the tropical North Atlantic [*Prospero et al.*, 1981; *Kaufman et al.*, 2005]. However, there is still a lack of detailed knowledge of the vertical stratification of smoke and dust, the height levels at which these particles typically travel across the ocean, of the mixing and aging behavior, and the corresponding changes in the optical, microphysical and chemical aerosol properties during the long-distance transport. Without such knowledge, the quantification of the influence of aerosol particles on solar radiative transfer (direct effect) and cloud processes (indirect effect) with atmospheric models seems to be impossible.

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[3] There is a clear need for vertically resolved observations with advanced multiwavelength lidars. Modern aerosol lidars are able to measure profiles of volume extinction coefficient at two wavelengths and thus of the Ångström exponent, which contains information about particle size. The spectral slope of the measured extinction-to-backscatter ratio (lidar ratio) yield information on aerosol type and light-absorption characteristics. Measures of particle depolarization enable us to characterize the mixing state, especially to estimate the relative amount of dust in an aerosol plume.

[4] Here, we present a unique case study by applying two of such advanced lidars. One was deployed at Praia, Cape Verde (15°N, 23.5°W), 500 km west of the African Atlantic coast, relatively close to the areas of biomass burning in West Africa. A second lidar was deployed at the Silvicultura site (2.5°S, 60°W) of the National Institute for Research in Amazonia (INPA), 45 km north of Manaus, Brazil, about 6000–7500 km downstream of the African sources of mineral dust and fire smoke. The study addresses the long-range transport during northern hemispheric winter (November to April, dry season in central Africa, wet season in the Amazon rainforest) and provides insight into the changes in aerosol profile characteristics, dust-to-smoke ratio, and aging (growth) of the smoke particles during transport. It is often argued that mainly dust is advected towards America [*Formenti et al.*, 2001]. This letter shows that the opposite (mainly smoke advection) can occur, too. Our observations corroborate the findings of *Kaufman et al.* [2005].

2. Experiment

[5] The lidar observations were conducted in the framework of the Saharan Mineral Dust Experiment (SAMUM) and the European Integrated Project on Aerosol Cloud Climate and Air Quality Interactions (EUCAARI). The employed aerosol Raman lidars [*Althausen et al.*, 2008; *Tesche et al.*, 2009a] permit us to determine vertical profiles of volume extinction coefficients of particles at 355 and 532 nm, backscatter coefficients at 355, 532, and 1064 nm, lidar ratios at 355 and 532 nm, and depolarization ratios at 355 nm (Brazil) and 710 nm (Cape Verde). The computation of backscatter and extinction coefficients as well as microphysical properties is described by *Ansmann and Müller* [2005]. Regarding the determination of the depolarization ratio we followed *Freudenthaler et al.* [2009]. The measured signal profiles are smoothed with window lengths of 660 m (Praia), 750 m (Manaus, <2.1 km), and 1500 m (Manaus, >2.1 km) to reduce the influence of signal noise. The presence of cirrus clouds was used at both sites to

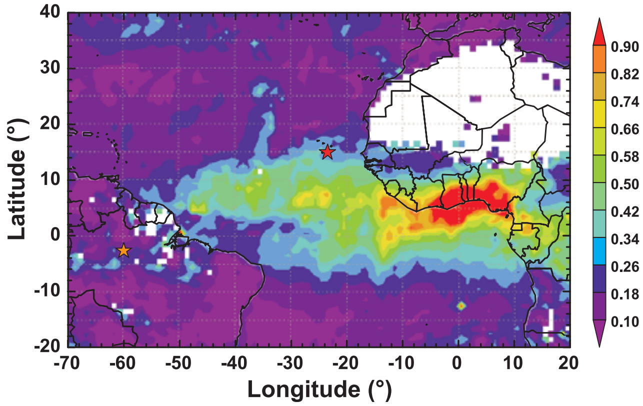

Figure 1. Mean particle optical depth (550 nm, 2–10 February 2008) observed with MODIS (http://disc.sci.gsfc.nasa.gov/giovanni/). Stars indicate the lidar sites, west of Africa at 15°N, and in the Amazon basin at 2.5°S.

intercalibrate the backscatter coefficient profiles by assuming equal cirrus backscattering at all lidar wavelengths.

3. Observations

[6] During the SAMUM campaign from 15 January to 14 February 2008, complex layering of Saharan dust and biomass burning smoke was observed at Praia, Cape Verde. As Figure 1 indicates, extensive aerosol plumes crossed the tropical Atlantic towards South America in February 2008. According to Moderate Resolution Imaging Spectroradiometer (MODIS) measurements the particle optical depth ranges from 0.25 to 0.45 over the Cape Verde area to >0.9 over the tropical Atlantic south of West Africa. The African plumes reach the South American coast (40°W) where the aerosol optical depth is still high with values of 0.2–0.35. The influence of African aerosol over the Amazon basin (60°W) is reflected by optical depths from 0.1 to 0.3. As shown in Figure 2, the aerosol plume consists of many layers over Praia up to 5.5 km height on 3 February 2008. Over Manaus, the aerosol plume is less inhomogeneous and less stratified.

[7] The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) backward trajectories in Figure 3 provide further context. The 500 m backward trajectory arriving at Praia shows that Saharan dust is advected to Cape Verde from the northeast on 3 February. This desert air mass travels towards South America (see Manaus, 500 m backward trajectory) and reaches the Amazonian lidar site on 10 February (9–10 days after the emission in the Sahara). The smoke over Praia is mainly above 2 km height and stems from western African sources, travel time is 3–4 days. The smoke/dust mixture that crosses the tropical Atlantic towards South America reaches Manaus 8–12 days

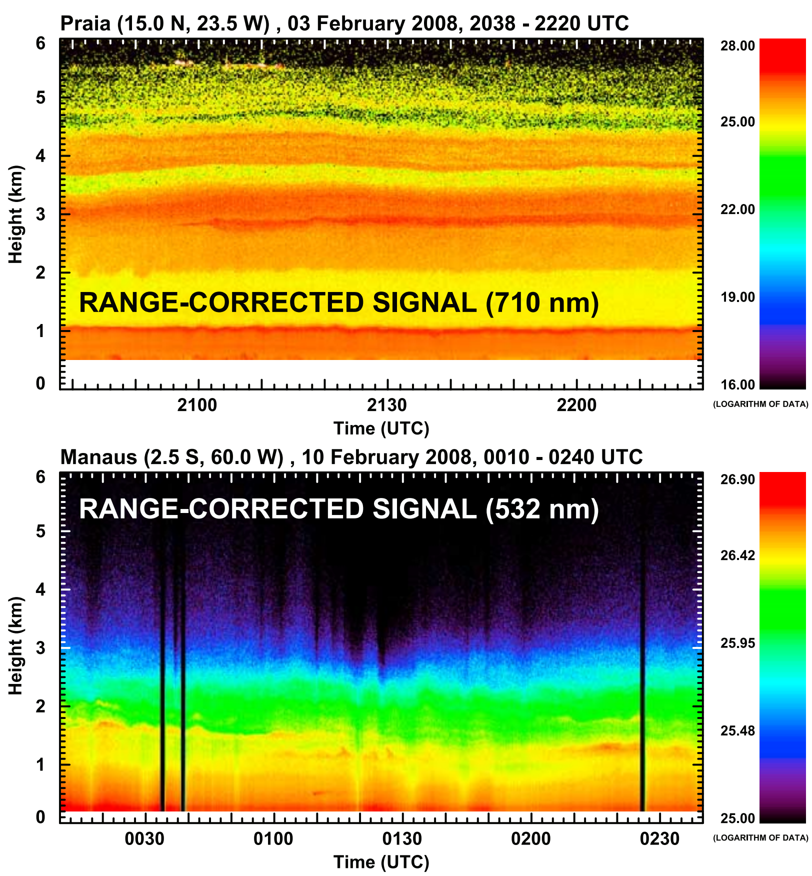

Figure 2. Range-corrected lidar signals (arbitrary units), shown with vertical and temporal resolution of 15 m and 10 s (Praia) and 15 m and 30 s (Manaus), respectively. (top) Complex vertical layering of dust and smoke up to 5.5 km height was observed over Praia, Cape Verde, on 3 February 2008. (bottom) Vertically less inhomogeneous and less stratified aerosol distribution was found at Manaus, in the Amazon rainforest on 10 February 2008.

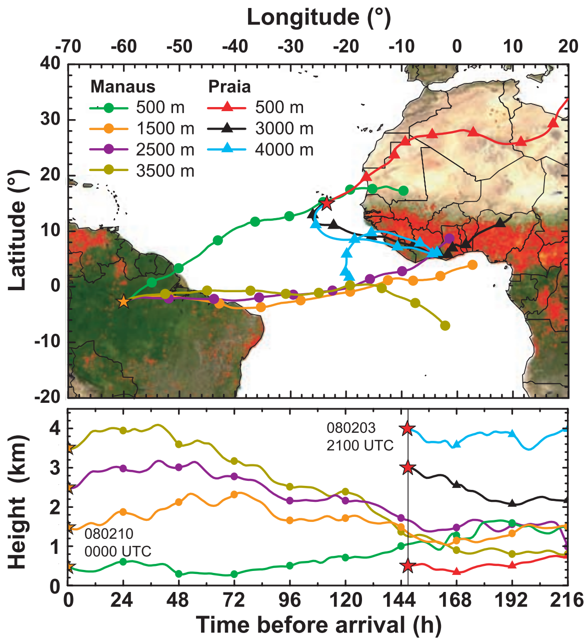

Figure 3. The 9-day HYSPLIT backward trajectories (http://www.arl.noaa.gov/ready/hysplit4.html) ending at Praia, Cape Verde, on 3 February 2008, 2200 UTC, and at Manaus, Brazil, on 10 February 2008, 0000 UTC. The underlying fire map derived from MODIS observations (http://rapidfire.sci.gsfc.nasa.gov) shows all fires (red spots) detected during the 21–30 January period.

after release according to the 1.5 km and 2.5 km backward trajectories shown in Figure 3.

[8] Figure 4 shows the optical properties observed over Praia and Manaus. Only profile segments not corrupted by transmitter-receiver overlap effects, and detector or alignment problems are considered. The profiles of backscatter coefficient and particle depolarization ratio indicate the Saharan air layer below 1.1 km height over Praia. Volume depolarization ratios, which reach a peak of 0.3, drop down to very low values in the 400 m thick maritime boundary layer. The pronounced smoke/dust layer from 1.8 to 5.5 km height is well identified by the depolarization ratio, too. Particle depolarization values of 0.15–0.30 indicate a smoke contribution from about 10% (0.30) to 60% (0.15) to total particle backscattering at 710 nm [*Tesche et al.*, 2009b], assuming a pure dust depolarization ratio of 0.33 [*Freudenthaler et al.*, 2009] and a smoke-related depolarization ratio of 0.05 [*Müller et al.*, 2005].

[9] In Figure 4b, the particle extinction coefficients at 532 nm range from 50 to 100 Mm^{-1} in the central part of the pollution plume over Praia. The respective particle optical depth of the lofted layer is 0.3. We obtain a value of 0.40–0.45 for the total 532 nm particle optical depth by including the maritime boundary layer and the dust layer below 1200 m. Smoke contributed about 30%–40% and dust 50%–60% to the total particle optical depth. The contribution of maritime particles (below 400 m after Figures 4a and 4e) was assumed to be about 10% (0.04–0.05 maritime optical depth).

[10] The lidar ratios in Figure 4c also indicate a mixture of dust (50–60 sr) [*Tesche et al.*, 2009a] and highly light-absorbing biomass burning smoke (80–100 sr). Note that the lidar ratios are roughly 70–80 sr at both wavelengths. This behavior is characteristic of the presence of fresh smoke. The computed backscatter and extinction-related Ångström exponents in Figure 4d range from 0.5 to 1.0, and also indicate a mixture of dust (0–0.4) [*Tesche et al.*, 2009a] and smoke (0.8–1.8).

[11] Figures 4f–4j show the optical properties derived from the Manaus lidar data. Compared to the Praia observation, all extinction and backscatter profiles indicate smooth aerosol changes with height. Lidar ratios and Ångström exponents in the well-mixed, aged plume are independent of height. The mixing zone between the polluted Amazon aerosol layer and the clean free troposphere extends from almost 2 km to 4 km height after the 8–12 day travel. Maximum extinction coefficients of 60 Mm^{-1} occur around 1.5 km. Integration of the extinction profile yields a particle optical depth of about 0.15 (assuming height-independent extinction in the lowermost 1 km). The extinction-related Ånsgtröm exponent varies around zero. Our findings are in good agreement with AERONET Sun photometer observation in the Amazon basin from 1999 to 2006 [*Schafer et al.*, 2008]. The day-mean 440 nm particle optical depth during the wet season is typically 0.1–0.15. Ångström exponents were found to be low during the wet season with values mainly in the range from 0.3 to 0.8 for the spectral range from 440 to 870 nm.

[12] The observed particle depolarization ratios, shown in Figure 4j, are low with values of 0.04–0.05, and indicate that dust was almost absent over Manaus on 10 February. The dust layer below 1.1 km over Praia did obviously not reach the Manaus lidar site. Dry and wet deposition in the ocean is most effective during the winter season. A striking feature of the dominance of aged biomass burning smoke is the spectral behavior of the lidar ratio. The 355 nm lidar ratio (40–50 sr) is considerably smaller than the 532 nm lidar ratio (60–70 sr), which corresponds to comparably large backscatter-related Ångström exponents and rather low (zero) extinction-related Ångström exponents. This is a unique and unambiguous characteristic of aged biomass burning smoke [*Müller et al.*, 2005].

4. Discussion

[13] *Kaufman et al.* [2005] quantified the dust and smoke transport from Africa to South America and the Caribbean based on MODIS observations from 2001 to 2003. The analysis revealed that a large fraction of biomass burning smoke is imbedded in dust in winter (45% smoke and 55% dust in December–March) due to savanna fires in the Sahel. The emitted, westward moving African aerosol caused a monthly mean (February 2001) optical depth of about 0.3 at 550 nm in the area from 0° to 30°N and 10° to 20°W (just east of Cape Verde). The particle optical depth slightly decreased during the westward transport over the Atlantic Ocean and showed a mean value (February 2001) of 0.22 in the latitudinal belts from 0° to 5°S (Manaus latitudes) near the South American coast (30°–40°W). Maritime particles contributed about 25%, dust 10%, and smoke 65% to this

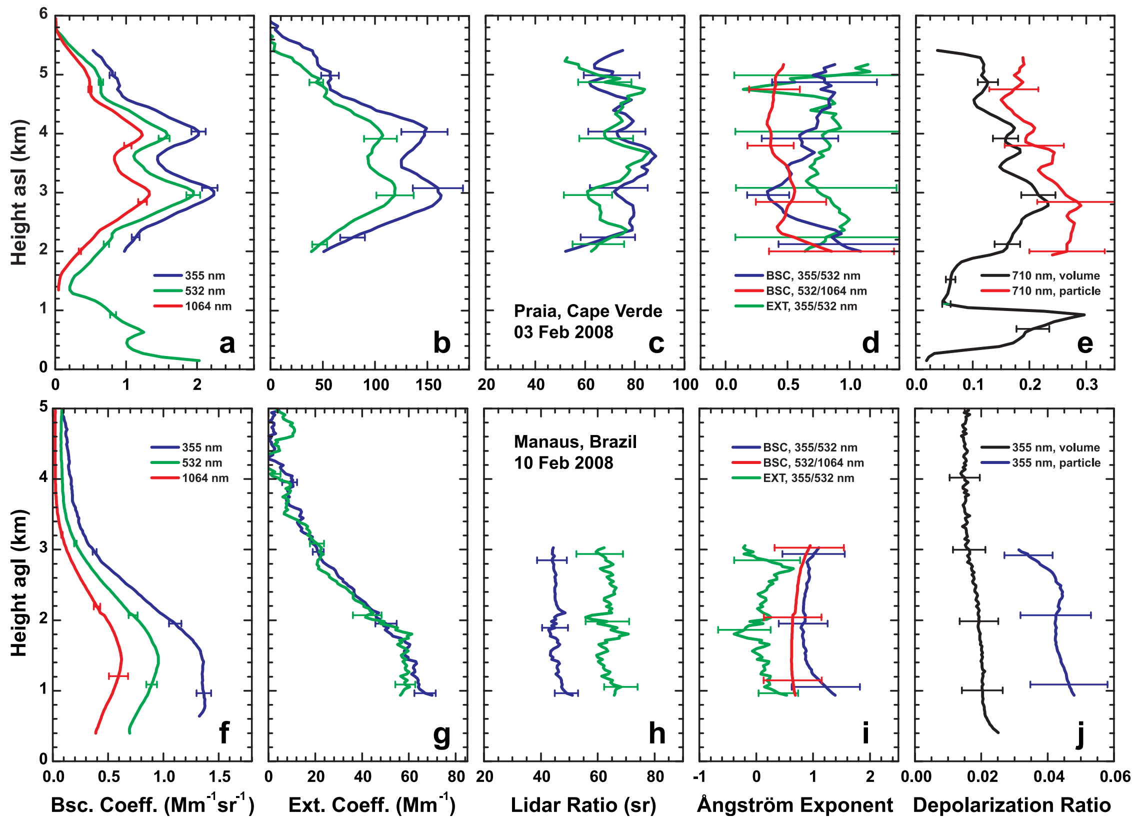

Figure 4. (a) and (f) The 2-hour mean volume backscatter coefficients (at three wavelengths), (b) and (g) extinction coefficients (at two wavelengths), (c) and (h) the corresponding extinction-to-backscatter ratios, (d) and (i) the corresponding backscatter-related and extinction-related Ångström exponents, and (e) and (j) depolarization ratios measured (top) at Praia on 3 February, 2038–2220 UTC and (bottom) at Manaus on 10 February, 0030–0230 UTC. Mean profiles for the periods shown in Figure 2 are presented. Error bars (standard deviation) include systematic uncertainties and signal noise. Both lidar stations are about 100 m above sea level (asl).

optical depth value of 0.22. The MODIS findings are in good agreement with our observations at Praia and Manaus.

[14] *Schafer et al.* [2008] mention that the low-average Ångström exponent (0.54 on average) found from the AERONET data for the wet season at sites around Manaus is consistent with the presence of large (dust-like) aerosol particles. Our Manaus lidar observations however document that even smoke can produce a rather flat spectral slope of the optical depth, which is caused by the growth of the smoke particles during the 8–12-day travel.

[15] *Müller et al.* [2007] investigated the growth of biomass burning particles as a function of travel time (5–25 days). The study was based on multiwavelength lidar observations of Canadian and Siberian forest fires. It turned out that the surface-area-weighted radius (effective radius) increases from values of 0.15–0.25 μm (2–4 days after the emission) to values of 0.3–0.4 μm after 10–20 days of travel time. A similar behavior is found here. The inversion of the lidar-derived optical data sets presented in Figure 4 yield smoke-related effective radii around 0.25 ± 0.10 μm in the lofted pollution plume over Praia. The smoke-related optical properties are obtained after subtracting the dust optical effects from the measured backscatter and extinction coefficients by applying the method of *Tesche et al.* [2009b]. For the Manaus optical data the inversions indicate effective radii from 0.35 to 0.45 μm for the aged biomass burning particles in accordance with the low extinction-related Ångström exponents. After an initial phase (two days) of condensational growth, coagulation dominates. The large effective radii over the Amazon basin partly result from water up-take by the particles over the rainforest.

5. Conclusions

[16] The long-range transport of dust and smoke from western Africa to the Amazon basin was studied based on lidar observations. A major finding was that a several kilometer thick African biomass burning smoke layer was observed over the central Amazon basin during the 2008 wet season. The case study was found to be in full agreement with MODIS observations from 2001 to 2003 [*Kaufman et al.*, 2005]. Since smoke and dust have different light absorbing and scattering properties and differently influence cloud formation, a careful consideration of the relative contribution of smoke and dust to the aerosol load and changes in the mixture during long-range transport in models is necessary to obtain a realistic view of the aerosol impact on climate in this region of the world. Long-range airborne and spaceborne lidar observations may provide the required information. Finally, it is often emphasized that the Amazon rainforest is a pristine site during the wet season. Our study shows that this is obviously not always the case.

Smoke and dust is immediately mixed down to the ground after entrainment into the local boundary layer.

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