Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

Mineral nutrients in Saharan dust and their potential impact on Amazon rainforest ecology

Joana A. Rizzolo[1], Cybelli G.G. Barbosa[1], Guilherme C. Borillo[1], Ana F.L. Godoi[1], Rodrigo A.F. Souza[2], Rita V. Andreoli[2], Antonio O. Manzi[3], Marta O. Sá[3], Eliane G. Alves[3], Christopher Pöhlker[4], Isabella H. Angelis[4], Florian Ditas[4], Jorge Saturno[4], Daniel Moran-Zuloaga[4], Luciana V. Rizzo[5], Nilton E. Rosário[5], Theotonio Pauliquevis[5], Carlos I. Yamamoto[6], Meinrat O. Andreae[4], Philip E. Taylor[7*], and Ricardo H.M. Godoi[1**]

Corresponding Authors: School of Life and Environmental Sciences, Deakin University, Australia. e-mail address: philip.taylor@deakin.edu.au (P.E.Taylor); Environmental Engineering Department, Federal University of Parana, Brazil. e-mail address: rhmgodoi@ufpr.br (R.H.M. Godoi**).

[1] Environmental Engineering Department, Federal University of Parana, Curitiba, PR, Brazil.

[2] State University of Amazonas - UEA, Meteorology Department, Manaus, AM, Brazil.

[3] Instituto Nacional de Pesquisas da Amazônia, Programa de Grande Escala Biosfera Atmosfera na Amazônia, Manaus, Brasil.

[4] Max Planck Institute for Chemistry, Biogeochemistry Department, Mainz, Germany.

[5] Universidade Federal de São Paulo, Instituto de Ciências Ambientais, Químicas e Farmacêuticas, Diadema, Brasil.

[6] Chemical Engineering Department, Federal University of Parana, Curitiba, PR, Brazil.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

[7] Deakin University, CCMB and CMMR, School of Life and Environmental Sciences, Geelong, Vic, Australia.

Abstract

The intercontinental transport of aerosols from the Sahara is likely to play a significant role in nutrient cycles in the Amazon rainforest, since it carries many types of minerals to these otherwise low-fertility lands. Iron is one of the micronutrients essential for plant growth, and the Amazon rainforest is iron-limited. The main aim of this study was to assess the input and potential impact of iron bioavailability from Saharan dust, namely, the soluble fraction Fe(II)/Fe(III). Seven other soluble elements that are also essential for plants were measured. Dust particles entrained in the air were collected and analyzed, but not dust deposited in rainfall as atmospheric washout. The sampling campaign was carried out at the ATTO site (Amazon Tall Tower Observatory), from March to April 2015, and samplers were placed both above and below the canopy. Mineral dust aerosol at ATTO showed peak concentrations for Fe(III) (47.6 ng m^{-3}), Fe(II) (16.2 ng m^{-3}), Na (470 ng m^{-3}), Ca (194 ng m^{-3}), K (64.7 ng m^{-3}), and Mg (88.8 ng m^{-3}) during the presence of dust transported from the Sahara, as determined by remote ground-based and satellite sensing data and backward trajectories. Atmospheric transport of weathered Saharan dust, followed by surface deposition, results in substantial iron bioavailability across the rainforest canopy. The seasonal deposition of dust rich in soluble iron and other minerals is likely to affect both bacteria and fungi within the topsoil and on canopy surfaces, and especially benefit highly bioabsorbent epiphytes, such as lichens. In this scenario, Saharan dust can provide essential macronutrients and micronutrients to plant roots, and also directly to plant leaves. The influence on the ecology of the forest

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

canopy and topsoil would likely be different from that of nutrients from the weathered Amazon bedrock, which provides the main source of soluble mineral nutrients.

Key words: Amazon forest, Sahara dust, mineral nutrients, bioavailable, soluble iron, outbreak event, dust transport

1 Introduction

The Sahara is the largest source of desert dust to the atmosphere (Ginoux et al., 2012). Studies are beginning to reveal the extent of the Saharan dust influence on nutrient dynamics and biogeochemical cycling in both oceanic and terrestrial ecosystems in North Africa and far beyond, due to frequent long-range transport across the Atlantic Ocean, the Mediterranean Sea and the Red Sea, and on to the Americas, Europe and the Middle East (Goudie and Middleton, 2001; Hoornaert et al., 2003, Yu et al., 2015; Salvador et al., 2016).

Saharan dust affects climate and atmospheric chemistry at both regional and global scales. Large scale and mesoscale atmospheric circulation have a key role to play in the emission and transport of mineral aerosols. Research is ongoing into the effects of year to year and decade to decade variability of loadings and transport of dust in the atmosphere (Washington and Todd, 2005).

The Amazon Basin, which contains the world's largest rainforest (Garstang et al., 1988; Aragão, 2012; Doughty et al., 2015) receives annually about 28 million tons of African dust each year (Yu et al., 2015). There have been suggestions that Saharan dust transport across the Atlantic may act as a valuable fertilizer of the Amazon rainforest, providing fundamental nutrients (Swap et al., 1992; Koren et al., 2006; Ben-Ami et al., 2010; Abouchami et al., 2013). However, little is known about the bioavailability of these nutrients and their potential affect on rainforest ecology. It is, therefore, important

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

to understand the source types, source strengths, and the physical and chemical properties of mineral dust aerosol particles over the Amazon Basin (Guyon et al., 2004).

Plants require many nutrients for healthy development (Marschner, 2012). Iron (Fe) is an essential micronutrient for plant growth (Morrissey and Guerinot, 2009) and it is a key element in several important functions and physiological processes. It participates in chlorophyll function and is required for enzymes critical for photosynthesis, such as catalase, peroxidase, nitrogenase, and nitrate reductase (Hochmuth, 2011). Plant bio-functions, such as photosynthesis, respiration and hormonal balance, also require Fe, along with other elements (Pérez-Sanz et al., 1995).

Under natural soil conditions, Fe(III) occurs bound to minerals, such as hematite, that are not soluble in water (Isaac, 1997; Zhu, 1997), and Fe dissolution is dependent on the water's ligand capacity as well as on than the type or quantity of dust deposited on the surface (Mendez, 2010).

Two distinct pathways of Fe uptake have been identified in plant roots. Pathway I, present mainly in dicot plants, reduces Fe(III) to Fe(II) by acidification of the rhizosphere. After this reduction, Fe(II) is transported into cells. In pathway II, compounds with high affinity for iron are secreted into the rhizosphere, where they react with Fe(III) and form a chelate complex. This complex is moved into cells by specific transporters (Hell and Stephan, 2003; Morrissey and Guerinot, 2009). In the forest, microorganisms, such as fungi and bacteria, play a role in nutrient cycling, and often employ multiple distinct iron-uptake systems simultaneously (Philpott, 2006).

Furthermore, Fe-rich dust particles can be transported over long distances and have considerable time and surface area to take up acids (Shi et al., 2011). An increased proportion of soluble iron has recently been reported in high altitude Saharan dust compared with ground-based samples (Ravelo-Perez et al., 2016). Thus, particle size, solu-

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

bility, and bioaccessibility of iron oxides in dust will determine the ultimate influence of these materials on environmental and biological processes (Reynolds, 2014).

Besides iron uptake, other elements are also essential for plants. Magnesium and Cu are required for photosynthesis and protein synthesis. Calcium is essential for cell wall and membrane stabilization, osmoregulation, and as a secondary messenger allowing plants to regulate developmental processes in response to environmental stimuli (Gruzak, 2001). Zinc is directly involved in the catalytic function of many enzymes, and with regulatory and structural functions (Broadley et al., 2007). Potassium regulates osmotic pressures, stomata movement, cell elongation, cytoplasm pH stabilization, enzymatic activation, protein synthesis, photosynthesis, and transport of sugars in the phloem (Kerbauy, 2012).

Atmospheric mineral dust contributes thousands of tons of minerals to tropical rain forests (Okin et al., 2004; Bristow et al., 2010) and likely contributes to plant nutrition, especially compensating for the poor soils with low inherent fertility (Worobiec et al., 2007). Amazon lowland rainforest soils are shallow and have almost no soluble minerals; added to this, heavy rains readily leach soluble nutrients from the ground that are added from litter decomposition and weathered rocks (Koren et al., 2006).

Saharan desert aerosol can compensate for P leaching from the poor soils of the Amazon (Gross et al., 2015). Intercontinental transport of dust is likely to be of great importance to the forest, as it might help to maintain or possibly influence an ecosystem that has roles in global climate regulation, in addition to maintaining regular rainfall and storing vast amounts of carbon (Karanasiou et al., 2012). A number of studies have stated that Saharan dust contributes as a fertilizer to the forest (Swap et al., 1992; Koren, 2006; Bristow et al., 2010; Martin, 2010; Abouchami et. al, 2013; Yu et al., 2015). Oth-

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

er than for P, the amount of this dust that is available to plants as soluble micronutrients and macronutrients is unknown, as is the potential influence on forest ecology.

Considering that iron is absorbed by plants only as soluble Fe(II)/Fe(III), it is essential to quantify the intake of this mineral from long-range transported African dust, and evaluate its potential utilization and effect on the Amazon rainforest as an essential micronutrient. This research aims to assess the bioavailability of iron, and other elements in the particulate matter in the Amazon atmosphere transported within African dust. This is then used to assess the likely effect on rainforest ecology.

2 Methods

2.1 Dust sampling

Sampling was performed on a 80 m walk-up tower at the Amazon Tall Tower Observatory (ATTO) site (Andreae et al., 2015), from 19 March to 25 April 2015, which is within the typical period that dust transport to the Amazon Basin has been observed (Swap et al., 1992; Prospero et al., 2014; Yu et al., 2015). Aerosols were sampled above the canopy at 60 m height and below the canopy at 5 m height, without size cut-off, and transported in a laminar flow through a 2.5 cm diameter stainless steel tube into an air-conditioned container. The sample humidity at 60 m height was kept below 40% using a silica dryer. The sample humidity at 5 m height was kept dry with a silica gel diffusion dryer installed on the inlet line. Atmospheric particles were collected on Nuclepore® polycarbonate filters at a flow rate of 10 l min^{-1}.

The aerosol sampling was performed using the inlet below the canopy at 5 m height for the first 11 days, and the inlet at 60 m height for the other 26 days. The samples were collected over 24 or 48 h periods, consecutively, in order to accumulate sufficient mass to be detected by ion chromatography-UV-VIS. After sampling, the filters

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

were immediately stored in flasks containing nitric acid solution (HNO_3 Suprapur) pH 2.0-2.5, in order to interrupt the transition process between the two iron oxidative states (Fe(II) and Fe(III)) and to stabilize the iron concentrations, according to the methodology adapted from Siefert (1998), Bruno et al. (2000), and US-EPA Method 3052 (EPA, 1996).

2.2 Particle physical properties

Aerosol particle physical properties were determined at ATTO during the entire campaign at 60 m height. Mass concentration and particle size distribution were measured by an Optical Particle Sizer (OPS, TSI model 3330; size range: 0.3–10 μm), sampling every 5 min (Andreae et al., 2015). Equivalent black carbon concentrations (BC_e) were obtained by a MAAP (Multi Angle Absorption Photometer), and the spectral dependency of particle absorption coefficients was determined using a 7-wavelength Aethalometer (Model AE33), both with 1 min resolution. Particle scattering coefficients were obtained at three wavelengths using an Integrating Nephelometer (Ecotech, model Aurora 3000). Details of the instrumentation setup are given by Andreae et al. (2015).

2.3 Determination of mineral aerosol

Soluble species were determined by ion chromatography (Dionex, ICS-5000) using conductivity detection for cations and UV-VIS for soluble transition metals. For cation separation, a capillary column CS12A was used, and for transition metals, a CS5A column (calibrated to quantify traces of Fe(II) and Fe(III)). Each analysis occurred in triplicate and all measurements were performed from a standard curve injected under the same conditions as the samples, using Chromeleon® software for processing the generated chromatograms.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

172

173 **2.4 Modeling, remote sensing and meteorological data**

174 Air mass backward trajectories were calculated using the Hybrid Single Particle
175 Lagrangian Integrated Trajectory (HYSPLIT) Model from the NOAA Air Resource
176 Laboratory, USA, (National Oceanic and Atmospheric Administration), indicating the
177 airflow toward the ATTO site (Draxler and Rolph, 2015). Thus, dust source areas were
178 inferred by tracking individual dust plumes back to their place of origin (Schepanski et
179 al., 2012) as well as determining transport paths. Trajectories were calculated at three
180 different heights within the atmospheric boundary layer (50, 500, and 1000 m) up to
181 240 h previous. Every 24 h from 19 March to 25 April 2015, a trajectory was calculated
182 with a finishing point at the center of the ATTO site (S 2° 08.752' W 59° 00.335'), at 19
183 h UTC.

184 To analyze Saharan dust outbreak events and transport toward ATTO during the
185 campaign, ground-based and satellite remote sensing products and *in situ* measurements
186 of aerosol particle optical properties were integrated with the atmospheric large-scale
187 wind field. The wind field product was taken from the Modern-ERa Retrospective
188 Analysis (MERRA), a reanalysis data based on the Goddard Earth Observing System
189 Data Assimilation System Version 5 (GEOS-5, Rienecker et al., 2011). Ground-based
190 and satellite remote-sensing aerosol optical properties, namely Aerosol Optical Depth
191 (AOD), were obtained, respectively, from aerosol products of the AErosol RObotic
192 NETwork (AERONET, Holben et al., 1998) and of the Moderate-Resolution Imaging
193 Spectroradiometer (MODIS) aboard the Terra satellite (Remer et al., 2005). Particle
194 optical properties were continuously monitored *in situ* at the ATTO site in 2015 at a
195 height of 55 m. Particle scattering coefficients were measured at three wavelengths us-
196 ing an integrating nephelometer (Ecotech Aurora 3000). Absorption coefficients were

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

measured at 637 nm using a Multi-Angle Aerosol Photometer (MAAP). Particle single scattering albedo was calculated based on measured absorption and scattering retrieved by interpolation at 637 nm. All measurements were taken under dry conditions (RH<50%).

Micrometeorological data were obtained by sensors installed on the micrometeorological tower at the ATTO site, at 80 m (Andreae et al., 2015). Daily values were calculated for vertical wind speed median (W), accumulated precipitation (PRP), and average air temperature (Tair).

Table 1 shows the sampling frequencies, micrometeorological measurements, sensors (manufacturers), and sensor heights. For the treatment of high frequency data (10Hz), computational routines were used. First, the sonic raw data was reduced to 1-min medians. Subsequently, daily values were calculated.

Table 1. List of instruments installed on the walk-up tower (adapted from Andreae et al., 2015).

Sampling frequency	Measurement	Instrument used	Height/Depth (m)	Unit
0.1 s	u, v,w (wind components	3D ultrasonic anemometer (Windmaster, Gill Instruments Ltd.)	81.65; 46.0; 36.0	m/s
60 s	Rainfall	Rain gauge (TB4, Hydrological Services Pty. Ltd.)	81.0	mm
	Air temperature probe	Thermohygrometer (HMP45C, Vaisala, CS215, Rotronic Measurement Solutions)	81.65; 40.0; 36.0	^{o}C

2.5 Spore samples

A Sporewatch spore sampler (Burkard Scientific Pty Ltd, UK) was operated at 80 m height for 24 h on 16 separate days between 28 March and 23 April. Particles

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

larger than 2 µm diameter were impacted onto an adhesive-coated tape attached to a drum within the sampler. This tape was removed, mounted onto a microscope slide and examined with an Olympus BX60 light microscope with brightfield optics. Line scans were performed to identify fungi, and counts were averaged over 24 h and expressed per cubic meter of air sampled. All aerosol concentrations are given with respect to air volumes at ambient temperature and pressure.

3 Results and discussion

The sampling campaign was performed during a typical period for the occurrence of dust transport events in the Amazon forest. Sampling covered a total of 38 days (19 March– 25 April 2015) and 26 samples of particulate matter were collected.

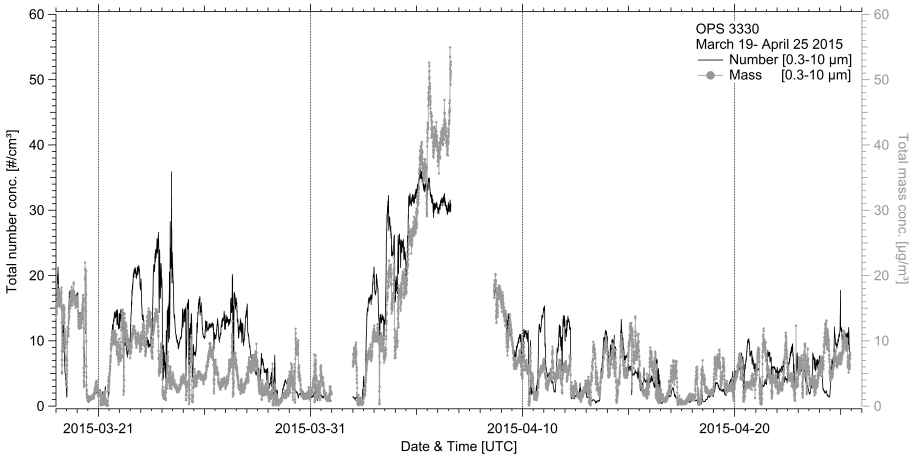
3.1 Characterization of particle physical properties

The mass concentration of particles over the Amazon Basin in the wet season is typically around 10 µg m^{-3} in locations that are influenced by biomass burning emissions. In the central Amazon, where the influence of biomass burning is less, the mass concentration is even lower. However, elevated concentrations may occur due to African dust events that reach the Amazon forest (Martin et al., 2010). The highest hourly aerosol concentration recorded during our entire campaign was around 55 µg m^{-3} at the ATTO site (5 April), with a daily average of 23 µg m^{-3} (Figure 1), and often concentrations were well below 10 µg m^{-3}. Previous studies conducted by Worobiec et al. (2007) at a nearby forest site in Balbina, Amazonia, had also detected an abundance of dust particles during the same season (23 - 29 March 1998). Artaxo et al. (2013) observed, only trace levels of P, K, and Zn during the wet season in the central Amazon region. These were thought to have a biogenic source.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

242



243

244 Figure 1. Number concentration (solid lines) and mass concentration (dashed lines) time
245 series from the OPS instrument (size range: 0.3-10 µm).

246

247 For comparison, during Saharan dust events in the Cape Verde archipelago, par-
248 ticulate matter concentration often exceeds 100 µg m^{-3}; a relatively high concentration
249 when compared to the average aerosol background level of 10-50 µg m^{-3} (Gross et al.,
250 2015). Obviously, the enhancement in concentrations induced by the plume is highest
251 near the source, so a larger mass of dust is deposited over the Sahara and the adjacent
252 Atlantic than over the Amazon rainforest. Notably, the concentrations at ATTO were
253 still very high in view of the large distance from Africa.

254 The highest concentrations of black carbon equivalent (BC_e) measured online
255 during this intensive campaign were 0.45 µg m^{-3} (3 April) and 0.37 µg m^{-3} (5 April).
256 This coincided with the highest mass concentrations of particulate matter. The BC_e con-
257 centrations were retrieved from light absorption measurements. The particle types that
258 mostly contribute to light absorption are: combustion generated BC, mineral dust, and
259 biogenic particles (Moosmüller et al., 2009; Guyon et al., 2004). Therefore, part of the

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

observed BC could be mineral dust. We further characterized the relative contributions to BC_e by considering the Absorption Angstrom Exponents (AAE), which reflect the spectral variability of absorption. Bulk BC particles are expected to have an AAE ≤1 due to increased absorption efficiency at shorter wavelengths (<400 nm). The observed variability of AAE is further discussed in section 3.3. During the 2008 wet season in the central Amazon, at a site near Manaus, BC_e concentrations fluctuated between 0.10 and 0.15 µg m^{-3} (Martin et al., 2010). Episodic input of Saharan dust and biomass smoke transported over long distances from Africa explains the presence of BC_e detected at ATTO (Andreae et al., 2015).

3.2 Determination of Mineral Aerosol

The dominant elements in the soluble fraction of the dust samples were Fe(III), Zn, Na, K, and Mg (Table 2). The blank fields in the Table correspond to values below the detection limits, which were calculated according to Method 300.1 USEPA (1997). The expanded uncertainty (ng m^{-3}) was calculated for 95% confidence level, according to BIPM/GUM (2008).

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

277 Table 2. Mineral aerosol characterization of 26 samples collected during the Saharan

278 dust event that arrived in the Amazon forest during 2015.

Sampled period (Month/ day)	Fe(III) (ng m^{-3})	Fe(II) (ng m^{-3})	Cu (ng m^{-3})	NH_4 (ng m^{-3})	Zn (ng m^{-3})	Na (ng m^{-3})	Ca (ng m^{-3})	K (ng m^{-3})	Mg (ng m^{-3})
3-19	15±0.7	-	-	147±4	105±8	95±7	92±13	54±12	13±2
3-19	11±0.8	-	-	-	14±7	41±6	-	40±8	9.0±1.0
3-20	5.6±0.1	-	-	163±1.7	6.5±3.7	-	-	-	-
3-21	5.8±0.1	-	-	-	3.5±1.8	84±6	40±3	26±3	13±1
3-23	7.1±0.1	-	-	56±2	6.4±3	73±3	-	40±4	10.1±0.5
3-24	4.8±0.1	-	-	33±1	4.2±1.9	25±2	-	29±2	3.0±0.3
3-25	1.8±0.1	-	-	-	2.0±0.9	44±3	-	32±2	6.0±0.6
3-27	2.0±0.1	-	-	-	3.4±1.6	12±1	-	22±2	1.7±0.2
3-28	1.9±0.2	-	0.89±0.87	9.7±1.8	5.0±2.2	18±2	5.9±2.5	25±3	2.6±0.3
3-30	4.1±0.1	-	-	5.2±1.3	5.8±3.8	10±3	-	-	1.2±0.5
3-31	4.1±0.1	-	2.7±0.8	-	4.7±1.9	17±2	-	8.0±5.4	1.7±1.1
4-02	8.5±0.1	-	2.5±1.5	-	8.3±3.7	135±3	12±6	32±4	16±1
4-03	33±0.1	-	-	-	4.6±1.8	441±4	126±4	65±2	67±1
4-05	48±0.1	16±3	-	-	8.4±3.6	470±4	194±4	64±4	89±1
4-06	33±0.1	12±2	0.85±0.75	-	4.3±1.9	220±22	128±8	44±4	49±3
4-08	14±0.2	3.3±3.1	-	16±1	8.9±3.7	148±3	29±4	26±4	244±2
4-09	19±1	1.6±1.6	-	6.6±0.8	5.3±1.9	57±2	29±2	15±2	8.6±0.3
4-11	5.5±0.1	-	-	68±1	9.7±3.7	84±3	-	18±4	8.8±0.5
4-12	5.7±0.2	-	6.4±0.8	-	5.7±1.9	38±2	5.0±1.9	9.6±2.2	5.5±0.2
4-14	6.7±0.2	-	-	20.4±1.19	10.2±3.68	24±3	-	9.4±4.3	3.2±0.5
4-15	12±0.1	-	88±1	98.5±5.45	-	15±2	-	7.4±2.05	10±1
4-17	7.4±0.2	-	9±1	-	10.2±3.9	24±3	-	8.2±4.5	3.7±0.5
4-18	1.1±0.1	-	2.6±0.8	-	4.8±1.7	19±2	3.5±1.7	9.7±2.2	2.7±0.2
4-20	1.2±0.2	-	-	370±1	9.5±3.5	29±3	8.6±3.5	20±4	5±0.6
4-21	2.9±0.2	-	13±0.7	55±1	2.1±1.7	14±2	-	-	4.30±0.2
4-23	2.4±0.1	-	1.0±0.8	-	2.2±1.9	28±2	-	5.4±2.2	3.1±0.3

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

279 During the wet season in the central Amazon Basin, Artaxo et al. (2002), Martin
280 et al. (2010), and Arana and Artaxo (2014), found similar values of K, Fe, Cu and Zn to
281 those found in our campaign. K, Cu, and Zn are generally considered to be tracer ele-
282 ments of biogenic emissions from the rainforest, although they also have other sources.
283 Potassium in submicron aerosols also has a major source from vegetation fires and is
284 frequently used as a tracer for biomass burning aerosols (Andreae et al., 1983; Martin et
285 al., 2010). Zhang et al. (2015) studied aerosols from a Chinese tropical rainforest, and
286 reported that the high abundance of K in fine particles was likely a result of long-range
287 transport from biomass burning.

288 Iron, Ti and Al are mainly soil dust related elements (Artaxo et al., 1990; Artaxo
289 et al., 1994), and are typically present at the highest concentrations during the early wet-
290 to-dry season transition (February to May), as has been shown in previous studies
291 (Pauliquevis et al., 2012; Andreae et al., 2015). This is mainly driven by large-scale
292 atmospheric circulation patterns that favor the transport of dust plumes in a trans-
293 Atlantic airflow from the Sahara and Sahel regions toward the Amazon basin (Artaxo et
294 al., 1990; Formenti et al., 2001; Graham et al., 2003; Martin et al., 2010; Baars et al.,
295 2011; Ben-Ami et al., 2012).

296 During the wet season, the biogenic aerosol over Amazonia is overprinted peri-
297 odically by episodes of intense transatlantic transport, which bring Atlantic marine aer-
298 osols in addition to dust and biomass burning emissions (Bristow et al., 2010; Andreae
299 et al., 2015). For example, Zhu et al. (1997) studied North African dust entrained in the
300 trade winds over Barbados (Caribbean) in September, and measured Na concentrations
301 of 2.4 to 6.5 μg m^{-3}. Barbados is in a region that receives large amounts of Na enriched
302 marine aerosols due its localization. While these concentrations are higher than those
303 recorded in the present study at ATTO (220 to 470 ng m^{-3}), the co-occurrence of elevat-

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

ed concentrations of Na and the mineral dust elements, Al, Fe, and Ca, is evidence for the marine origin of Na in the central Amazon (Talbot et al., 1990).

Artaxo et al. (1990) studied aerosols from the Amazon Basin and noted that the concentration of total Fe in the fine mode (<2.5 μm) of soil dust were more than 10 times larger in the wet season than in the dry season (101 ng m^{-3} during daytime, 60 ng m^{-3} during the night and 6.5 ng m^{-3} in the dry season). Pauliquevis et al. (2012) observed increases in the concentration of total Fe with values reaching 60 ng m^{-3} in the fine mode mostly during February to April in the Amazon Basin, with a semester average of 36 ng m^{-3}. They attributed this to episodes of Saharan dust transport.

In contrast to the high bulk dust concentrations at Barbados, the Fe(II) concentrations recorded at ATTO during our sampling campaign (1.6 to 16 μg m^{-3}) were significantly higher than the Fe(II) concentrations of 0.63 to 8.2 ng m^{-3} measured in mineral dust particles collected from the marine atmospheric boundary layer at Barbados (Zhu et al., 1997). They showed that only a small fraction of the total iron in aerosol particles was present as Fe(II).

For soluble Fe(III), we found concentrations in the range of 1.10 to 47.6 ng m^{-3} (Figure 2), with the highest concentrations occurring three days in a row (33.7, 47.6 and 32.7 ng m^{-3}). This soluble Fe(III) is carried in dust particles that are mainly deposited onto canopy surfaces by dry sedimentation. Our soluble Fe(III) concentrations were significantly higher than those reported by Andreae et al. (2015) from earlier measurements at the same site. They had measured only 1.8 ng m^{-3} of soluble Fe(III) in 120 ng m^{-3} of total Fe and concluded that the aerosol transport of Fe is not likely to have a significant effect on the ecosystem at ATTO.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

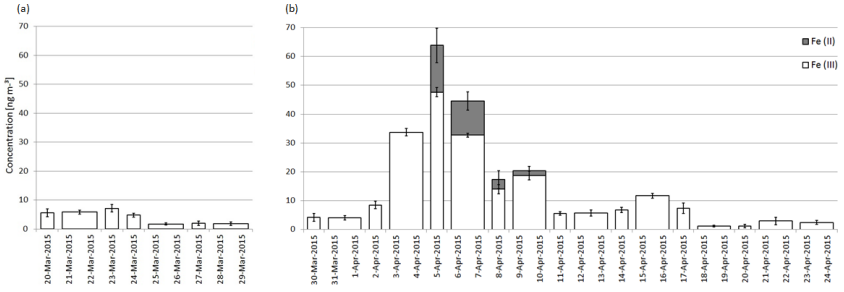


Figure 2. Soluble Fe(III) and Fe(II) concentrations in total particulate matter collected during the wet season, (a) sampled at 5 m height (20 March to 29 March 2015) and (b) at 60 m height (30 March to 24 April 2015). The width of bars corresponds to the sampling period: 24 or 48 h.

Desert dust plumes contain iron mainly in the Fe(III) oxidation state, whereas in industrial effluents Fe is mostly in the Fe(II) oxidation state (Reynolds et al., 2014). These same authors collected dust from the Sydney area (Australia) and strongly suggested that the addition of Fe(II)-bearing minerals was associated with industrial, urban, and transportation sources entrained in dust plumes that originally lacked these minerals.

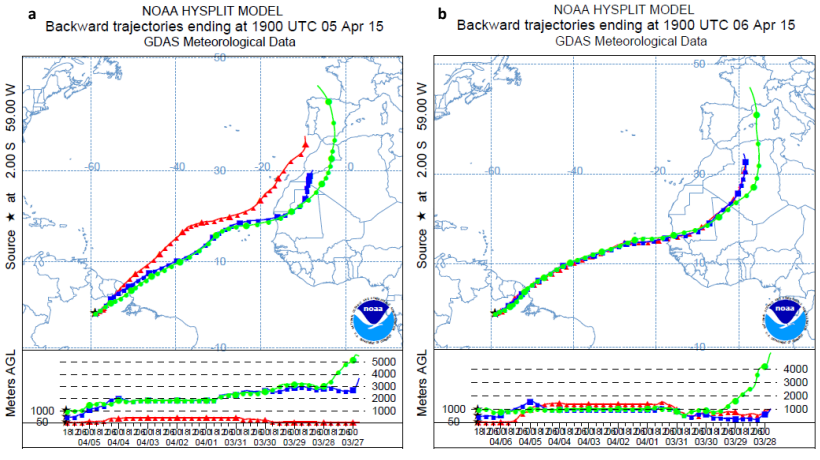
Bristow et al. (2010) analyzed aerosol samples collected from the Bodélé Depression, Chad, and suggested that the amounts of Fe in some samples likely indicate the presence of ferromagnesian minerals and also reflect the presence of Fe oxides such as goethite and hematite, or Fe sulfate salts that have been detected in Saharan dust.

Abouchami et al. (2013), studying the geochemical characteristics of the Bodélé Depression dust source and the relation with transatlantic dust transport to the Amazon Basin, found lower Na, K, Fe, and Ca concentrations in Amazon Basin soil samples than in the Bodélé samples, suggesting that this difference is a reflection of remobiliza-

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

347 tion and loss of these elements by chemical weathering under the hot, wet climate con-
348 ditions in the Amazon Basin.
349
350 **3.3 Modeling, Remote Sensing and Meteorological Data**
351 The largest deposition of iron occurs downwind of the main deserts of the world
352 - North Africa and the Middle East (Mahowald et al., 2009). Figure 3 (a and b) shows
353 the backwards trajectories coming not from North Africa nor the Middle East, but in-
354 stead from the Saharan desert (Formenti et al., 2001; Washington and Todd, 2005; Bris-
355 tow et al., 2010; Creamean et al., 2013). Koren et al. (2006) estimated that between No-
356 vember and March, the Bodélé Depression is responsible for most of the dust that is
357 deposited annually on the Amazon.
358 Using backward trajectories data (HYSPLIT model), it is possible to observe a
359 connection between the Sahara and the Amazon. Between 3 and 6 April, the highest
360 concentrations of Fe(III), Fe(II), Na, Ca, K and Mg in mineral dust samples were ob-
361 served. According to Figure 3, the air masses arriving in the Amazon during that period
362 came from the Saharan region.
363



364

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

Figure 3. Backward trajectories of air parcels at 50, 500, and 1000 m above the Amazon for 240 h during the sampling periods in which the greatest concentrations of dust from the Sahara arrived at ATTO.

High mass concentrations around 3-8 April 2015 coincided with the arrival of African dust in the Amazon Basin, according to OPS instruments and backward trajectories, respectively, Figure 1 and 3. Periodically in the wet season, long-range transport of sea spray, Saharan dust, and/or smoke from African biomass burning can deposit across the Amazon Basin (Martin et al., 2010; Baars et al., 2011; Andreae et al., 2015).

As identified by the AERONET ground based sunphotometers located in Dakar and in Ilorin, during the campaign period three major Saharan dust outbreaks occurred and eventually combined with smoke (Figure 4.a). The first outbreak peaked on 22 March and had a stronger effect on AOD over Ilorin compared to Dakar. This feature was corroborated by the MODIS mean AOD field from 20 to 25 March (Figure 5.a). During this first event, the atmospheric circulation was not able to promote a significant transport of the dust and smoke plume towards South America. The influence of African particle advection on aerosol optical properties observed at ATTO was weak, but still detectable. An increase in absorption and scattering coefficients was observed in comparison to the clean periods (25 March to 2 April and 16-24 April), however, no significant increase of AAE was observed during this event (Figure 4.b). A less active dust outbreak from 25 to 30 March followed the first event, as shown by ground-based and satellite data (Figure 4.a and 5.b).

A second dust outbreak event started at the beginning of April, according to the AERONET retrievals, and its effects on the African sites extended until 9 April. The satellite mean AOD field during this period (Figure 5.c) revealed a consistent pattern of

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

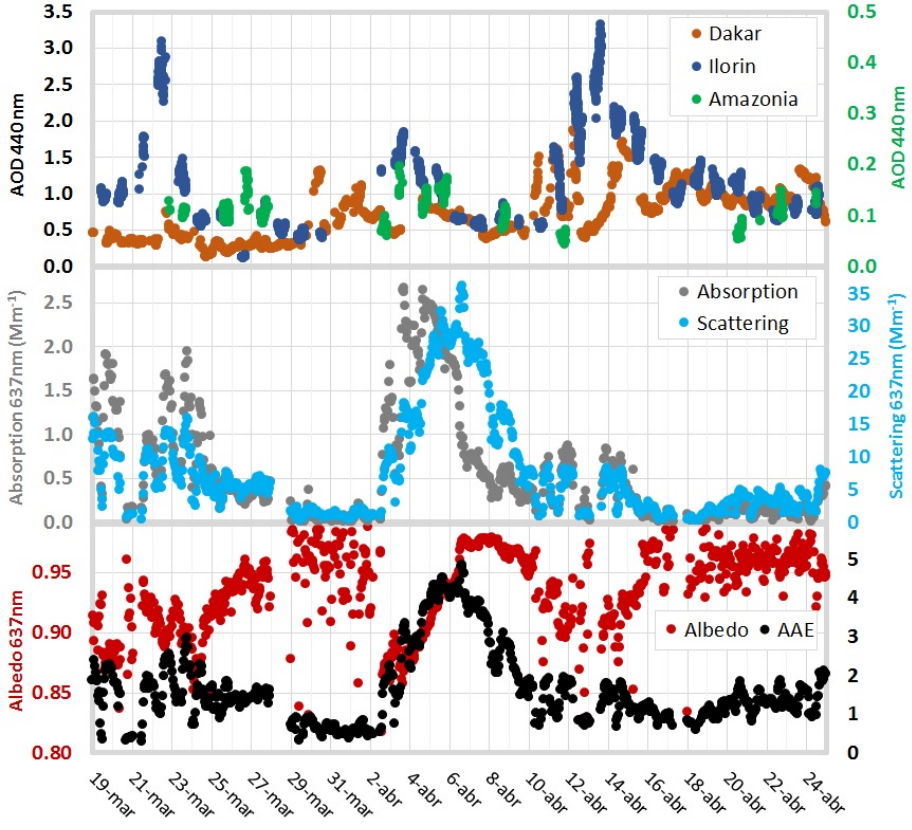
dust transport towards the northeast portion of the Amazon basin, with the wind flow in the direction of ATTO coming from regions effectively influenced by the Saharan dust plume. It is possible that smoke from biomass burning in the African sub-Sahel region joined with dust aerosols transported to the Amazon, since the Ilorin region is affected by biomass burning emissions in this season (Haywood et al., 2008). Fe(III) and Fe(II) concentrations in particulate matter increased between 3 and 9 April (Figure 2), and this correlated with an increase in particle absorption coefficients and a decrease in single scattering albedo (Figure 4.b and 4.c). The AAE during this event reached values higher than 5, and after 10 April returned to background levels. The increase in AAE is a strong indication that dust and/or biomass smoke particles contributed to the observed increases in absorption coefficients. The correlation between the concentration of crustal elements in particulate matter and aerosol absorption coefficients during African advection events has also been reported for another forest site in the Amazon (Rizzo et al., 2013). The observed changes in particle optical properties can be explained by the presence of Saharan dust particulate matter and biomass burning from the Sahel region. Beside the appropriate transport direction, during the second event the wind circulation speed was stronger than during the first event. This enhanced the Saharan dust advection toward ATTO and resulted in more substantial effects on particle chemical composition and optical properties at the site.

The third event that began around 10 April and lasted until 17 April, according to the African AERONET sites (Figure 4.a), and was the largest dust outbreak event that occurred during the campaign. This was corroborated by the significant increase registered in the AERONET AOD and by the large values and spread of AOD retrieved by MODIS (Figure 5.d). However, this massive dust transport toward the Atlantic basin did not translate into significant changes in the properties of particles sampled at the

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

415 ATTO site. As happened in the first dust outbreak event, atmospheric wind circulation
416 prevented the transport of the dust plume in the direction of the ATTO site. At this time,
417 a strong zonal wind (eastward) from the African west coast carried the dust plume core
418 toward the extreme north portion of South America, away from ATTO. Meanwhile, the
419 site received an influx of air mass predominantly from an area southward of the plume.
420



421

422 Figure 4. a) Instantaneous Aerosol Optical Depth (AOD) at 440 nm measured at three
423 AERONET sites: Dakar and Ilorin in Africa, and Embrapa/Manaus in Amazon. b) Par-
424 ticle absorption and scattering coefficients at 637 nm observed in situ at the ATTO site.
425 c) Particle single scattering albedo at 637 nm, and Absorption Angstrom Exponent
426 (AAE), retrieved from in situ observations of aerosol optical properties at ATTO.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

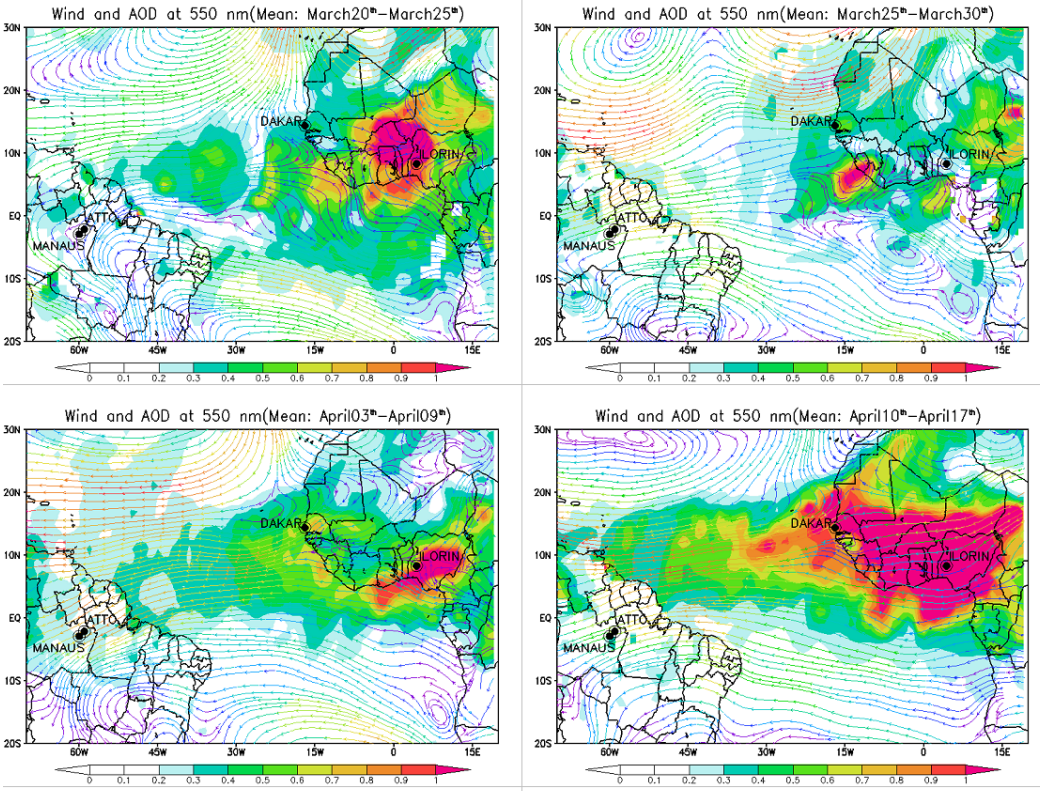


Figure 5. Mean distribution of aerosol optical depth at 550 nm (AOD) and wind at 850 hPa for four distinct periods within the campaign at ATTO site, during the dominance of: a) the first Saharan dust outbreak; b) a less active dust outbreak period; c) the second Saharan dust outbreak; d) the third Saharan dust outbreak.

Figure 6 shows that during days without rainfall, the vertical wind speed, W, was highest above the canopy level (81.65 m), due to the canopy heating the air above it. Without sunlight forcing, W values did not show significant difference at or below the canopy (46 m and 36 m height, respectively). Levels below the canopy were, on average, between a maximum of -0.0012 m/s and minimum of -0.03 m/s, and always negative, although very close to zero.

At the highest level of W, being positive (ascending air), we also observed the largest values for Fe(III) and MC.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

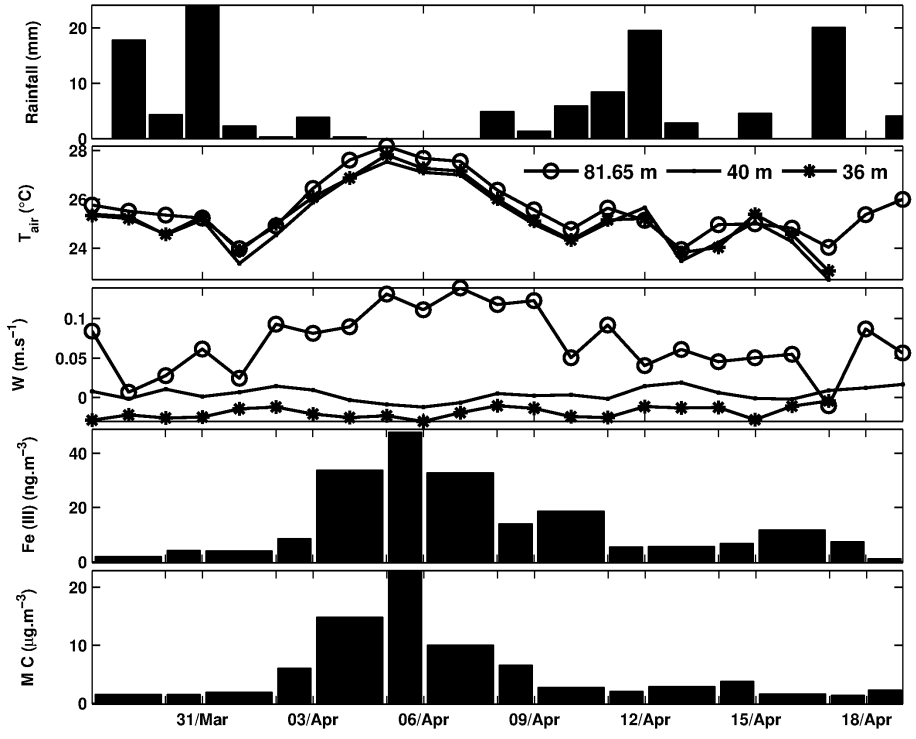


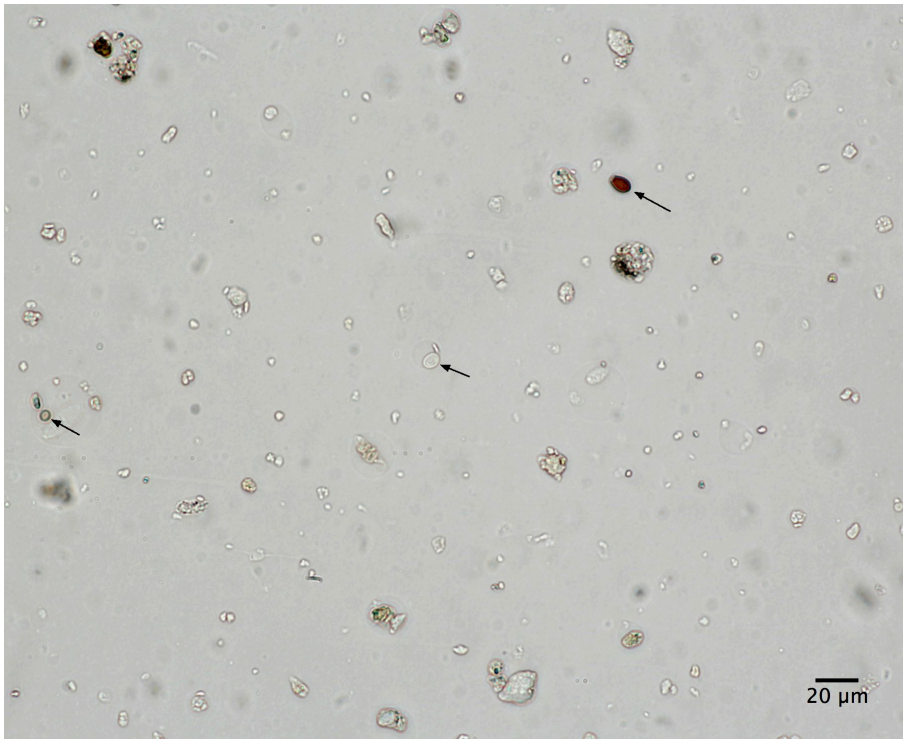
Figure 6. Daily comparison of micrometeorological variables (T_{air}, PRP and W) with measurements of Fe(III) and MC below the canopy.

3.4 Spore sample

Sporewatch sample analysis showed that very few coarse particles (> 2 µm diameter) occurred in the atmosphere until 2 April. On 3 April at 13 LT, coarse particles (2 to 10 µm) peaked in number and were black, hyaline or variously colored and of irregular shape. The amorphous particles were interspersed with a large diversity of small fungal particles. Fungi that were identified included basidiospores, ascospores, *Cladosporium, Ganoderma*, and uni- and bi-cellular hyaline conidia (Figure 7). All fungi detected had a diameter less than 12 µm, similar to adjacent coarse dust particles. The total fungal count was 1,587 spores per cubic meter of air, averaged over 24 h (2-3

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

452 April). High concentrations of fungi and other coarse particles persisted, peaking again
453 at approximately 16:30 LT on 5 April. From the afternoon of 6 April on, very few par-
454 ticles and only the occasional spore were observed.



455

456 Figure 7. Brightfield microscopy of particles collected in an air sampler at 80 m on 2
457 April 2015. The arrows point to three fungi: the one on the right is a basidiospore, at
458 center is a yeast-like conidia, and at left is a small fungal spore of unknown type.

459

460 As previously discussed, coarse particles observed between 2 and 6 April are
461 likely to be associated with the dust cloud arriving from Africa. The large diversity of
462 small fungal spores and conidia entrained in the dust collected at 80 m height are also
463 likely to be sourced to Africa. Smoke plumes are known to entrain fungi over long dis-
464 tances (Mims and Mims, 2004). Dust from Lake Chad is rich in bacteria and fungi (Fa-
465 vet et al., 2013). These fungi would have also contributed to the elements detected in air

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

samplers. Bacteria are likely to accompany the dust particles, attached to their surface (Yamaguchi et al., 2012; Prospero et al., 2005), but it is unknown whether any of these organisms are still viable upon sedimentation across the central Amazon forest.

Up to half of all micronutrients in the canopy are stored in epiphytes (Cardelus 2010). Fungi housed within lichens take advantage of the large surface area provided by their algal co-host, and are one of the most bio-absorbent organisms evolved for uptake of minerals and other nutrients from atmospheric gases and particulates, and from both dry deposition and rainfall. Another type of fungi common within the canopy are yeasts, such as Saccharomycetes (Elbert et al., 2007; Womack et al., 2016).

During dry weather, as well as during fog and light rain events, dust deposits onto the canopy and impacts directly onto leaves of vascular plants (e.g., trees and vines), as well as epiphytic vascular and non-vascular plants, such as bryophytes (e.g., lichens, mosses and liverworts). Dust also settles onto ferns, and fungi within the canopy. Air samples from 40 m height showed fungi are common in the canopy. The smallest and most metabolically active fungi detected in the canopy included lichens and yeasts (Womack et al., 2015).

Up to 25,000 tons of phosphorus has been calculated as being deposited each year on the Amazon. Meanwhile, a similar amount of phosphorus has been estimated to be leached from rainforest soils (Yu et al., 2015). While much of the emphasis has been on soil chemistry and root absorption, water-soluble minerals, as such as P and K, can also be absorbed by leaves. Minerals, such as Fe, can be absorbed through plant leaves as well (Fernandez and Brown, 2013). Thus, canopy deposition of Saharan dust is likely to provide soluble iron to plants via their leaves, in addition to having an influence on epiphytes and surface microorganisms.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

3.5 Iron availability

The iron measurement results presented here show a predominance of Fe(III) in the samples, while Fe(II), the form which plants can directly absorb, was measurable only in four samples. The interest in determining the concentration of Fe(II) in aerosols, besides being the ionic form absorbed by plants, is related to its much higher solubility than Fe(III) (Zhu 1997). However, the efficiency in absorbing iron varies among species and genotypes, although within plants the main form is Fe(III) (Kerbauy, 2012).

Therefore, plants develop specific strategies for Fe uptake (Hell and Stephan, 2003; Morrissey and Guerinot, 2009) and, added to this, abiotic factors such as pH, redox state, and temperature can influence mineral nutrient speciation and solubility, as can biotic factors. Plant roots also can modify the rhizosphere to affect nutrient availability; when challenged with a specific nutrient deficiency, plants can induce high-affinity transporters and other mechanisms in their roots, to assist in meeting their mineral nutrient requirements (Grusak, 2001).

The pH of the environmental is important for solubility and therefore the availability of iron to microorganisms. More iron is present in solution in acid soils, but Fe is less soluble in neutral or alkaline situations (Isaac, 1997). The majority of Amazon Basin soils are acidic (Schmink and Wood, 1978) and, similar to Fe, Zn is also better absorbed in soils with low pH (Broadley et al., 2007). In contrast, in alkaline soils, the availability of Zn, Fe and Cu is very low (Marschner, 2012). However, the efficacy of African dust as a fertilizer depends on many factors, such as particulate matter concentration, composition, solubility, and bioavailability of element minerals. In addition, fungi, the most common type of microorganism in the forest (Fracetto et al., 2013), can readily absorb iron, in soluble and insoluble chemical states. Therefore, it is possible

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

that a small amount of atmospheric iron could affect the microbiota in the canopy, rather than have a significant effect on soil and root uptake for plants.

Iron availability in the canopy of forests has commonly been found to be limited for growth of epiphytes, bacteria, and fungi (Crichton, 2009). Addition of iron can have a variety of effects on plants and fungi, e.g., yeasts grown in iron-limiting culture show a change in metabolism from fermentation to respiration upon the addition of iron (Philpott et al., 2012). The ongoing deposition of micronutrients, such as iron, onto the Amazon biota is likely to increase both epiphytic growth and fungal and bacterial decomposition within the canopy. Previous observations described an increased tree fall rate attributed to an abundance of epiphytes (Swap et al., 1992). Increase in iron bioavailability is also known to increase the wood to root ratio, increase the rate of plant growth, and increase nutrient cycling within a forest (Benzing, 1998; Crichton, 2009; Cardelius, 2010). The full extent of the influence of Saharan dust is yet to be determined, although the majority of mineral nutrients available in the soil originate from the gradual weathering of bedrock in the Amazon basin (Abouchami et al., 2013).

4 Conclusion

The current deposition of Saharan dust onto the Amazon is providing an iron-rich source of essential macronutrients and micronutrients. The atmospheric deposition of this nutrient-rich dust on the canopy is likely have an influence on rainforest ecology. Previously unconsidered changes are likely occurring in growth patterns and decomposition rates within the canopy, which affect carbon storage, release, and cycling in the Amazon.

Overall, this study examined the bioavailability of soluble macro and micronutrients to plants of the Amazon Basin, and reported peaks in soluble Fe(III), Fe(II), Na,

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Ca, K, and Mg during a major dust transport event from the Saharan desert, according to meteorological (backward trajectories and wind field), remote sensing (aerosol optical depth), and *in situ* data analysis. In this way, the elemental contents of samples were correlated with the arrival of African aerosols.

Our study also reported on the amount of soluble iron in two oxidation states, Fe(II) and Fe(III), to understand how much of this element is bioavailable to the rainforest in the wet season.

Because these nutrients are added to the Amazon by atmospheric deposition they will likely: 1) directly affect fungi within the canopy, as well as fungal-associated epiphytes, such as lichens. 2) have an influence on bacteria, and 3) provide nutrients directly to leaves and roots of other plants.

Author contribution

All authors contributed to the work presented in this paper. R.H.M. Godoi, C.G.G. Barbosa, J.A. Rizzolo, A.F.F. Godoi, C. Pöhlker and A.O. Manzi developed the concept, designed the study and the experiments and J. Rizzolo and I.H. Angelis carried them out. C.I. Yamamoto, G. Borillo and A.O. Manzi provided reagents and gave analytical-technical support. C. Pöhlker, J. Saturno, D. Moran-Zuloagal and M.O. Sá collected and analyzed data. R.H.M. Godoi, C.G.G. Barbosa, J.A. Rizzolo, P.E. Taylor, L.V. Rizzo, N.E. Rosário, L.V. Rizzo, R.A.F. Souza, R.V. Andreoli, J. Saturno, D. Moran-Zuloaga and T. Pauliquevis analyzed data. C. Pöhlker, M.O. Andreae, F. Ditas, L.V. Rizzo, E.G. Alves, T. Pauliquevis and P.E. Taylor gave conceptual advice. J.A. Rizzolo prepared the manuscript and, with contributions from C.G.G. Barbosa, A.F.L. Godoi, E.G. Alves, C. Pöhlker, C.I. Yamamoto, J. Saturno, D. Moran-Zuloaga, L.V. Rizzo, N.E. Rosário, T. Pauliquevis, M.O. Andreae, P.E. Taylor and R.H.M. Godoi, discussed the results and implications at all stages.

Atmos. Chem. Phys. Discuss., doi:10.5194/acp-2016-557, 2016
Manuscript under review for journal Atmos. Chem. Phys.
Published: 7 July 2016

Atmospheric Chemistry and Physics Discussions

Acknowledgments

We acknowledge the support of the Fundação de Amparo à Pesquisa do Estado do Amazonas (FAPEAM) and the Financiadora de Estudos e Projetos (FINEP). We acknowledge logistical support from the Central Office of the Large Scale Biosphere Atmosphere Experiment in Amazonia (LBA), the Instituto Nacional de Pesquisas da Amazônia (INPA) and the Universidade do Estado do Amazonas (UEA). We also thank the Max Planck Society and INPA for continuous support. We acknowledge the support by the German Federal Ministry of Education and Research (BMBFcontract 01LB1001A) and the Brazilian Ministério da Ciência, Tecnologia e Inovação (MCTI/FINEP contract 01.11.01248.00) as well as the UEA, FAPEAM, LBA/ INPA and SDS/CEUC/RDS-Uatumã. We would like to especially thank all the people involved in the logistical support of the ATTO project, in particular Reiner Ditz and Hermes Braga Xavier. We acknowledge the micrometeorological group of the INPA/LBA for their collaboration concerning the meteorological parameters, with special thanks to Marta Sa and Antonio Huxley. The authors would like to thank Dr. Jose Henrique Pereira from Lawrence Berkeley National Laboratory for the enthusiastic and helpful suggestions.

References

Abouchami, W., Näthe, K., Kumar, A., Galer, S. G., Jochum, K. P., Williams, E., Horbe, A. M. C., Rosa, J. W. C., Balsam, W., Adams, D., Mezgeri, K., and Andreae, M. O.: Geochemical and isotopic characterization of the Bodélé Depression dust source

and implications for transatlantic dust transport to the Amazon Basin. Earth and Planetary Science Letters, 380, 112-123, doi:10.1016/j.epsl.2013.08.028, 2013.

Andreae, M. O., Soot carbon and excess fine potassium: Long-range transport of combustion-derived aerosols: Science, 220, 1148-1151, 1983.

Andreae, M. O., Acevedo, O. C., Araújo, A., Artaxo, P., Barbosa, C. G. G., Barbosa, H. M. J., Brito, J., Carbone, S., Chi, X., Cintra, B. B. L., Silva, N. F., Dias, N. L., Dias-Júnior, C. Q., Ditas, F., Ditz, R., Godoi, A. F. L., Godoi, R. H. M., Heimann, M., Hoffmann, T., Kesselmeier, J., Könemann, T., Krüger, M. L., Lavric, J. V., Manzi, A. O., Lopes, A. P., Martins, D. L., Mikhailov, E. F., Moran-Zuloaga, D., Nelson, B. W., Nölscher, A. C., Nogueira, D. S., Piedade, M. T. F., Pöhlker, C., Pöschl, U., Quesada, C. A., Rizzo, L. V., Ro, C.-U. Ruckteschler, N., Sá, L. D. A., Oliveira Sá, M. C. B., Sales, R. M. N., Santos, J., Saturno, J., Schöngart, M., Sörgel, Souza, C. M., Souza, R. A. F., Su, H., Targhetta, N., Tóta, J., Trebs, I., Trumbore, S., Eijck, A van, Walter, D., Wang, Z., Weber, B., Williams, J., Winderlich, J., Wittmann, F., Wolff, S., and Yáñez-Serrano, A. M.: The Amazon Tall Tower Observatory (ATTO): overview of pilot measurements on ecosystem ecology, meteorology, trace gases, and aerosols. Atmos. Chem. Phys., 15, 10723-10776, doi:10.5194/acp-15-10723-2015, 2015.

Aragão, L. E. O. C.: The rainforest's water pump. Nature, 489, 7415, 217-218, doi:10.1038/nature11485, 2012.

618 Arana, A., and Artaxo, P.: Composição elementar do aerossol atmosférico na região
619 central da Bacia Amazônica. Química Nova, 37(2), 268-276, 2014.
620
621 Artaxo, P., and Maenhaut, W.: Trace element concentrations and size distributions of
622 biogenic aerosols from the Amazon Basin during the wet season, Nucl. Instrum.
623 Methods Phys. Res., 49, 366-371, doi:10.1016/0168-583X(90)90277-2, 1990.
624
625 Artaxo, P., Gerab, F., Yamasoe, M. A., and Martins, J. V.: Fine mode aerosol composi-
626 tion at three long-term atmospheric monitoring sites in the Amazon Basin: J. Ge-
627 ophys. Res., 99, 22,857-22,868, doi:10.1029/94JD01023, 1994.
628
629 Artaxo, P., Martins, J. V., Yamasoe, M. A., Procópio, A. S., Pauliquevis, T. M., Andre-
630 ae, M. O., Guyon, P., Gatti, L. V., and Leal, A. M. C.: Physical and chemical proper-
631 ties of aerosols in the wet and dry seasons in Rondônia, Amazonia. Journal of Geo-
632 physical Research, 107(D20), 8081, doi:10.1029/2001JD000666, 2002.
633
634 Artaxo P., Rizzo, L. V., Brito, J. F., Barbosa, H. M. J., Arana A., Sena E. T., Cirino G.
635 G., Bastos W., Martins S. T., and Andreae M. O.: Atmospheric aerosol in Amazonia
636 and land use change: from natural biogenic to biomass burning conditions. Faraday
637 Discuss., 165, 203-235, doi:10.1039/C3FD00052D, 2013.
638
639 Baars, H., Ansmann, A., Althausen, D., Engelmann, R., Artaxo, P., Pauliquevis T., and
640 Souza R.: Further evidence for significant smoke transport from Africa to Amazonia.
641 Geophys. Res. Lett., 38, 1-6, doi:10.1029/2011GL049200, 2011.
642

643 Ben-Ami, Y., Koren I., Rudich Y., Artaxo P., Martin S T., and Andreae M. O.:
644 Transport of North African dust from the Bodélé depression to the Amazon Basin: a
645 case study. Atmos. Chem. Phys., 10, 7533-7544, doi:10.5194/acp-10-7533-2010,
646 2010.
647
648 Benzing, D. H.: Vulnerabilities of tropical forests to climate change: the significance of
649 resident epiphytes. Clim. Chang. 39, 519-540, doi:10.1023/A:1005312307709, 1998.
650
651 BIPM. Evaluation of measurement data – Guide to the expression of uncertainty in
652 measurement JCGM 100:2008 (GUM 1995 with minor corrections), Paris: BIPM
653 Joint Committee for Guides in Metrology, 2008.
654 Bristow, C. S., Hudson-Edwards, K. A., and Chappell, A.: Fertilizing the Amazon and
655 equatorial Atlantic with West African dust. Geophys. Res. Lett., 37, L14807,
656 doi:10.1029/2010GL043486, 2010.
657
658 Broadley, M. R, White, P. J, Hammond, J. P, Zelko, I., and Lux, A.: Zinc in plants. New
659 Phytol., 173, 677-702, doi:10.1111/j.1469-8137.2007.01996.x, 2007.
660
661 Bruno, P., Caselli, M., Gennaro, G., Ielpo, P., and Traini, A.: Analysis of heavy metals
662 in atmospheric particulate by ion chromatography. J. Chromatogr A., 888, 145-150,
663 doi:10.1016/S0021-9673(00)00503-3, 2000.
664
665 Cardelus, C. L.: Litter decomposition within the canopy and forest floor of three tree
666 species in a tropical lowland rain forest, Costa Rica. Biotropica, 42, 300-308,
667 doi:10.1111/j.1744-7429.2009.00590.x, 2010.

668

669 Creamean, J. M., Kaitlyn J., Suski, Rosenfeld, D., Cazorla, A., DeMott, P. J., Sullivan,
670 R. C., White, A. B., Ralph, F., M., Minnis, P., Comstock, J. M. Tomlinson, J. M.,
671 and Prather, K. A.: Dust and Biological Aerosols from the Sahara and Asia Influence
672 Precipitation in the Western U.S. Science, 339, 1572, doi:10.1126/science.1227279,
673 2013.

674

675 Crichton R. Inorganic biochemistry of iron metabolism: from molecular mechanisms to
676 clinical consequences 3rd Ed, Chichester: John Wiley and Sons, pp 461,
677 doi:10.1002/9780470010303, 2009.

678

679 Doughty, C. E., Metcalfe, D. B., Girardin, C. A. J., Amézquita, F. F., Cabrera, D. G.,
680 Huaraca Huasco, W., Silva-Espejo, J. E., Araujo-Murakami, A., Costa, M. C., Ro-
681 cha, W., Feldpausch, T. R., Mendoza, A. L. M., Costa, A. C. L., Meir, P., Phillips, O.
682 L., and Malhi, Y.: Drought impact on forest carbon dynamics and fluxes in Amazo-
683 nia. Nature. 519, 78-82, doi:10.1038/nature14213, 2015.

684

685 Draxler, R. R. and Rolph, G. D.: HYSPLIT (Hybrid Single-Particle Lagrangian Inte-
686 grated Trajectory) Model access via NOAA ARLREADY Website, available at:
687 http://www.arl.noaa.gov/ready/hysplit4.html (last access: 15 January 2016), NOAA
688 Air Resources Laboratory, Silver Spring, MD., 2015.

689

690 Elbert, W., Taylor, P. E., Andreae, M. O., and Pöschl, U.: Contribution of fungi to pri-
691 mary biogenic aerosols in the atmosphere: wet and dry discharged spores, carbohy-

692 drates, and inorganic ions. Atmos. Chem. Phys.7, 4569-88, doi:10.5194/acp-7-4569,
693 2007.
694
695 Favet, J., Lapanje, A., Giongo, A., Kennedy, S., Aung, Y. Cattaneo, A., Davis-
696 Richardson, A. G., Brown, C. T. Kort, R., Brumsack, H., Schnetger, B., Chappell,
697 A., Kroijenga, J., Beck, A., Schwibbert, K., Mohamed, A. H., Kirchner, T., Dorr de
698 Quadros, P., Triplett, E. W., Broughton, W. J., and Gorbushina, A. A.: Microbial
699 hitchhikers on intercontinental dust: catching a lift in Chad. The ISME Journal, 7,
700 850-867, doi:10.1038/ismej.2012.152, 2013.
701
702 Fernandez V. and Brown P.: From plant surface to plant metabolism: the uncertain fate
703 of foliar applied nutrients. Front. Plant Sci., 4, 289, doi:10.3389/fpls.2013.00289,
704 2013.
705
706 Fracetto, G. M., Azevedo, L. C. B., Fracetto, F. J. C., Andreote, F. D., Lambais, M. R.,
707 and Pfenning, L. H.: Impact of Amazon land use on the community of soil fungi.
708 Sci. Agric. 70, 2, 59-67, doi:10.1590/S0103-90162013000200001, 2013.
709
710 Formenti, P., M. O. Andreae, L. Lange, G. Roberts, J. Cafmeyer, I. Rajta, W. Maenhaut,
711 B. N. Holben, P. Artaxo, and J. Lelieveld.: Saharan dust in Brazil and Suriname dur-
712 ing the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)-
713 Cooperative LBA Regional Experiment (CLAIRE) in March 1998. J. Geophys. Res.,
714 106, 14919-14934, doi:10.1029/2000JD900827, 2001.
715

716 Garstang, M., Scala, J., Greco, S., Harris, R., Beck, S., Browell, E. Sacuse, G., Gregory,
717 G., Hill, G., Simpson, J., Tao, W., and Torre, A.: Trace gas exchange and convective
718 transports over the Amazonian rainforest. J. Geophys. Res., 93, 1528-1550,
719 doi:10.1029/JD093iD02p01528, 1988.
720
721 Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C., and Zhao, M.: Global-scale attribu-
722 tion of anthropogenic and natural dust sources and their emission rates based on
723 MODIS Deep Blue aerosol products: Rev. Geophys., 50, RG3005,
724 doi:10.1029/2012RG000388, 2012.
725
726 Goudie, A.S., and Middleton, N.J.: Saharan dust storms: nature and consequences.
727 Earth-Sci. Rev., 56, 179-204, doi:10.1016/S0012-8252(01)00067-8, 2001.
728
729 Graham, B., Guyon, P., Taylor, P. E., Artaxo, P., Maenhaut, W., Glovsky, M. M., Flag-
730 an, R. C., and Andreae, M. O.: Organic compounds present in the natural Amazonian
731 aerosol: Characterization by gas chromatography-mass spectrometry. J. Geophys.
732 Res., 108, 4766, doi:10.1029/2003JD003990, 2003.
733
734 Gross, A., Goren, T., Pio, C., Cardoso, J., Tirosh, O., Todd, M. C., Rosenfeld, D.,
735 Weiner, T., Custódio, D., and Angert, A.: Variability in Sources and Concentrations
736 of Saharan Dust Phosphorus over the Atlantic Ocean. Environ. Sci. Technol. Lett.,
737 2 (2), 31-37, doi:10.1021/ez500399z, 2015.
738
739 Gruzak, M. A.: Plant Macro- and Micronutrient Minerals. Encyclopedia of Life Scienc-
740 es. Nature Publishing Group, doi:10.1038/npg.els.0001306, 2001.

741

742 Guyon, P., Graham, B., Roberts,G. C., Mayol-Braceroa, O. L., Maenhaut, W., Artaxo,
743 P., and Andreae, M. O.: Sources of optically active aerosol particles over the Ama-
744 zon forest. Atmos. Environ., 38, 1039-1051, doi:10.1016/j.atmosenv.2003.10.051,
745 2004.

746

747 Haywood, J. M., Pelon, J., Formenti, P., Bharmal, N., Brooks, M., Capes, G., Chazette,
748 P., Chou, C., Christopher, S., Coe, H., and Cuesta, J. Overview of the dust and bio-
749 mass-burning experiment and African monsoon multidisciplinary analysis special
750 observing period-0. Journal of Geophysical Research: Atmospheres, 113(D23),
751 doi:10.1029/2008JD010077, 2008.

752

753 Hell, R., and Stephan U. W.: Iron uptake, trafficking and homeostasis in plants. Planta,
754 216, 541-551, doi:10.1007/s00425-002-0920-4, 2003.

755

756 Hochmuth, G.: Iron (Fe) nutrition in Plant U.S. Department of Agriculture, UF/IFAS
757 Extension Service, University of Florida, IFAS Document SL353, 2011.

758

759 Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E.,
760 Reagan, J. A., Kaufman, Y. J., Nakajima, F., Lavenu, F., Jankowiak, I., and
761 Smirnov, A.: AERONET - A federated instrument network and data archive for aer-
762 osol characterization, Rem. Sens. Environ., 66, 1-16, doi:10.1016/S0034-
763 4257(98)00031-5, 1998.

764

765 Hoornaert, S., Godoi, R. H. M., and Grieken, R. V.: Single particle characterization of

766 aerosol in the marine boundary layer and free troposphere over Tenerife, NE Atlan-
767 tic, during ACE-2. J. Atmos. Chem., 46, 271-293, doi:10.1023/A:1026383403878,
768 2003.
769
770 Isaac, S.: Iron is relatively insoluble and often unavailable in the natural environment:
771 How do fungi obtain sufficient supplies? Mycologist., 11, 41-42, 1997.
772
773 Karanasiou, A., Moreno, N., Moreno, T., Viana, M., Leeuw, F., and Querol, X.: Health
774 effects from Sahara dust episodes in Europe: Literature review and research gaps.
775 Environ. Int., 47, 107-114, doi:10.1016/j.envint.2012.06.012, 2012.
776
777 Kerbauy, G. B. Fisiologia Vegetal. 2A edição, Rio de Janeiro: Guanabara Koogan, pp
778 431 2012.
779
780 Koren, I., Kaufman, Y. J., Washington, R., Todd, M. C., Rudich, Y., Martins, J. V., and
781 Rosen-feld, D.: The Bodélé depression: a single spot in the Sahara that provides most
782 of the mineral dust to the Amazon forest. Environ. Res. Lett., 1, 1-5,
783 doi:10.1088/1748-9326/1/1/014005, 2006.
784
785 Mahowald, N. M., Engelstaedter, S., Luo, C., Sealy, A., Artaxo, P., Benitez-Nelson, C.,
786 Bonnet, S., Chen, Y., Chuang, P. Y., Cohen, D. D., Dulac, F., Herut, B., Johansen, A.
787 M., Kubilay, N., Losno, R., Maenhaut, W., Paytan, A., Prospero, J. M., Shank, L. M.,
788 and Siefert, R. L.: Atmospheric Iron Deposition: Global Distribution, Variability, and
789 Human Perturbations. Annu. Rev. Mar. Sci., 1, 245-78,
790 doi:10.1146/annurev.marine.010908.163727, 2009.

791

792 Marschner, H.: Mineral nutrition of higher plants. Academic Press, London, pp 672,
793 2012.

794

795 Martin, S. T., Andreae M. O., Artaxo P., Baumgardner D., Chen Q., Goldstein A. H.,
796 Guenther, A., Heald C. L., Mayol-Bracero, O. L., McMurry, P. H., Pauliquevis, T.,
797 Poschl, U., Prather, K. A., Roberts, G. C., Saleska, S. R., Silva Dias, M. A., Sprack-
798 len, D. V., Swietlicki, E., and Trebs I.: Sources and properties of Amazonian aerosol
799 particles. Rev. Geophys., 48, RG2002, doi:10.1029/2008RG000280, 2010.

800

801 Mendez, J., Guieu, C., and Adkins, J.: Atmospheric input of manganese and iron to the
802 ocean: Seawater dissolution experiments with Saharan and North American dusts.
803 Mar. Chem., 120, 34-43, doi:10.1016/j.marchem.2008.08.006, 2010.

804

805 Mims, S. A., and Mims, F. M.: Fungal spores are transported long distances in smoke
806 from biomass fires. Atmos. Environ., 38, 5, 651-655,
807 doi:10.1016/j.atmosenv.2003.10.043, 2004.

808

809 Moosmüller, H., Chakrabarty, R. K., Ehlers, K. M., and Arnott, W. P.: Absorption Ång-
810 ström coefficient, brown carbon, and aerosols: basic concepts, bulk matter, and
811 spherical particles. Atmospheric Chemistry and Physics, 11(3), 1217-1225,
812 doi.org/10.5194/acp-11-1217-2011, 2011.

813

814 Morrissey, J. and Guerinot, M. L.: Iron uptake and transport in plants: The good, the
815 bad, and the ionome. Chem. Rev., 109, 10, 4553-4567, doi:10.1021/cr900112r, 2009.

816

817 Okin, G. S., Mahowald, N., Chadwick, O. A., and Artaxo, P.: Impact of desert dust on
818 the biogeochemistry of phosphorus in terrestrial ecosystems, Global Biogeochem.
819 Cycles, 18, GB2005, doi:10.1029/2003GB002145, 2004.

820

821 Pauliquevis, T., Lara, L. L., Antunes, M. L., and Artaxo, P.: Aerosol and precipitation
822 chemistry measurements in a remote site in Central Amazonia: the role of biogenic
823 contribution. Atmos. Chem. Phys., 12, 4987-5015, doi:10.5194/acp-12-4987, 2012.

824

825 Pérez-Sanz, A., and Lucena, J. J.: Synthetic iron oxides as sources of Fe in a hydropon-
826 ic culture of sunflower. In: ABADIA, J. Iron nutrition in soils and plants. Dordrecht:
827 Kluwer Academic, 241-246, doi:10.1007/978-94-011-0503-3_35, 1995.

828

829 Philpott, C.: Iron uptake in fungi: A system for every source. BBA-Mol Cell Res., 1763,
830 7, 636-645, Iron uptake in fungi: A system for every source, 2006.

831

832 Philpott, C. C., Leidgens, S., and Frey, A. G.: Metabolic remodeling in iron-deficient
833 fungi. Biochim Biophys Acta., 1823, 1509-1520, doi:10.1016/j.bbamcr.2012.01.012,
834 2012.

835

836 Prospero, J. M., Blades, E., Mathison, G., and Naidu, R.: Interhemispheric transport of
837 viable fungi and bacteria from Africa to the Caribbean with soil dust: Aerobiologia,
838 21, 1-19, doi:10.1007/s10453-004-5872-7, 2005.

839

840 Prospero, J. M., Collard, F. X., Molinie, J., and Jeannot, A.: Characterizing the annual
841 cycle of African dust transport to the Caribbean Basin and South America and its
842 impact on air quality and the environment. Global Biogeochem. Cycles, 29, 757-773,
843 doi:10.1002/2013GB004802, 2014.
844
845 Ravelo-Pérez, L. M., Rodríguez, S., Galindo, L., García, M. I., Alastuey, A., and López-
846 Solano, J.: Soluble iron dust export in the high altitude Saharan Air Layer. Atmos.
847 Env., 133:49-59, doi:10.1016/j.atmosenv.2016.03.030, 2016.
848
849 Remer, L. A., Kaufman, Y. J., Tandré, D., Mattoo, S., Chu, D. A., Martins, J. V., Li, R-
850 R., Ichoku, C., Levy, R. C., Kleidman, R. G., Eck, T. F., Vermonte, E., and Holben,
851 B. N.: The MODIS Aerosol Algorithm, Products, and Validation Journal of the At-
852 mospheric Sciences. Special Section Volume, 62, 947-973, doi:10.1175/JAS3385.1,
853 2005.
854
855 Reynolds, R. L., Cattle, S. R., Moskowitz, B. M., Goldstein, H. L., Yauk, K., Flagg, C.
856 B., Berquó, T. S., Kokaly, R. F., Morman, S., and Breit, G. N.: Iron oxide minerals in
857 dust of the Red Dawn event in eastern Australia, September 2009. Aeolian Res., 15,
858 1-13, doi:10.1016/j.aeolia.2014.02.003, 2014.
859
860 Rienecker, M. R., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosi-
861 lovich, M. G., Schubert, S. D., Takacs, L., Kim, G. K., Bloom, S., Chen, J., Collins,
862 D., Conaty, A., Silva, A. et al. MERRA: NASA's Modern-Era Retrospective Analy-
863 sis for Research and Applications. J. Climate, 24, 3624-3648, doi:10.1175/JCLI-D-
864 11-00015.1, 2011.

865

866 Rizzo, L. V., Artaxo, P., Müller, T., Wiedensohler, A., Paixão, M., Cirino, G. G., Arana,
867 A., Swietlicki, E., Roldin, P., Fors, E. O., Wiedemann, K. T., Leal, L. S. M., and
868 Kulmala, M.: Long term measurements of aerosol optical properties at a primary for-
869 est site in Amazonia. Atmos. Chem. Phys., 13(17), 2391-2413, doi:10.5194/acp-13-
870 2391, 2013.

871

872 Salvador, P., Almeida, S. M., Cardoso, J., Almeida-Silva, M., Nunes, T., Cerqueira, M.,
873 Alves, C., Reis, M. A., Chaves, P. C., Artíñano, B., and Pio, C.: Composition and
874 origin of PM10 in Cape Verde: characterization of long-range transport episodes.
875 Atmos. Environ., 127, 326-339, doi:10.1016/j.atmosenv.2015.12.057, 2016.

876

877 Schepanski, K., Tegen, I., and Macke, A.: Comparison of satellite based observations of
878 Saharan dust source areas. Remote Sens. Environ., 123, 90-97,
879 doi:10.1016/j.rse.2012.03.019, 2012.

880

881 Schmink, M. and Wood, C.: Frontier Expansion in Amazonia, University of Florida
882 press, Gainseville, Florida, 1978.

883

884 Shi, Z., Bonneville, S., Krom, M. D., Carslaw, K. S., Jickells, T. D., Baker, A. R., and
885 Benning, L. G.: Iron dissolution kinetics of mineral dust at low pH during simulated
886 atmospheric processing. Atmos. Chem. Phys., 11, 995-1007, doi:10.5194/acp-11-
887 995, 2011.

888

889 Siefert, R. L., Johansen A. M., and Hoffmann, M. R.: Measurements of trace metal (Fe,
890 Cu, Mn, Cr) oxidation states in fog and stratus clouds. J. Air & Waste Manage. As-
891 soc., 48, 128-143, doi:10.1080/10473289.1998.10463659, 1998.
892
893 Swap, R., Garstang, M., Greco, S. Talbot, R., and Kållberg, P.: Saharan dust in the Am-
894 azon Basin. Tellus, 44, 133-149, 1992.
895
896 Talbot, R. W., Andreae, M. O., Berresheim, H., Artaxo, P., Garstang, M., Harriss, R. C.,
897 Beecher, K. M., and Li, S. M.: Aerosol chemistry during the wet season in Central
898 Amazonia: The influence of long-range transport: J. Geophys. Res., 95, 16,955-
899 16,969, 1990.
900
901 Trail. F., Xu. H., Loranger. R., and Gadoury, D.: Physiological and environmental as-
902 pects of ascospore discharge in *Gibberella zeae* (anamorph *Fusarium gramine-*
903 *arum*). Mycologia, 94, 181–189, 2002.
904
905 U.S. Environmental protection Agency. Test Methods for Evaluating Soil Waste, Physi-
906 cal/Chemical Methods, Method 3052: Microwave assisted acid digestion of siliceous
907 and organically based matrices. EPA SW-846, 1996.
908
909 U.S. Environmental protection Agency. Determination of inorganic anions in drinking
910 water by ion chromatography, Method 300.1. EPA, 1997.
911

912 Washington, R. and Todd, M. C.: Atmospheric controls on mineral dust emission from
913 the Bodélé Depression, Chad: The role of the low level jet, Geophys. Res. Lett., 32,
914 L17701, doi:10.1029/2005GL023597, 2005.
915
916 Womack, A. M., Artaxo, P. E., Ishida, F. Y., Mueller, R. C., Saleska, S. R.,
917 Wiedemann, K. T., Bohannan, B. L. M., and Green, J. L.: Characterization of active
918 and total fungal communities in the atmosphere over the Amazon rainforest. Biogeo-
919 sciences, 12, 6337-6349, doi:10.5194/bg-12-6337, 2015.
920
921 Worobiec, A., Szalóki, I., Osán, J., Maenhaut, W., Stefaniak, E. A., and Grieken, R. V.
922 Characterization of Amazon Basin aerosols at the individual particle level by X-ray
923 microanalytical techniques.: Atmos. Environ., 41, 9217-9230,
924 doi:10.1016/j.atmosenv.2007.07.056 , 2007.
925
926 Yamaguchi, N., Ichijo, T., Sakotani, A., Baba, T., and Nasu, M.: Global dispersion of
927 bacterial cells on Asian dust. Sci Rep. 2, 525, doi:10.1038/srep00525, 2012.
928
929 Yu, H., Chin, M., Yuan, T., Bian, H., Remer, L. A., Prospero, J. M., Omar, A., Winker,
930 D., Yang, Y., Zhang, Y., Zhang, Z., and Zhao, C.: The fertilizing role of African dust
931 in the Amazon rainforest: A first multiyear assessment based on data from Cloud-
932 Aerosol Lidar and Infrared Pathfinder Satellite Observations. Geophys. Res. Lett.,
933 42, 1984-1991, doi:10.1002/2015GL063040, 2015.
934
935 Zhang, Z., Engling, G., Zhang, L., Kawamura, K., Yang, Y., Tao, J., Zhang, R., Chan,
936 C., and Li, Y.: Significant influence of fungi on coarse carbonaceous and potassium

937 aerosols in a tropical rainforest. Environ. Res. Lett., 10, 034015, doi:10.1088/1748-
938 9326/10/3/034015, 2015.
939
940 Zhu, X. R., Prospero, J. M., and Millero, F. J.: Diel variability of soluble Fe(II) and sol-
941 uble total Fe in North African dust in the trade winds at Barbados. J. Geophys. Res.,
942 102, 21297-21305, doi:10.1029/97JD01313 , 1997.
943
944