ATMOSPHERIC SCIENCE LETTERS
Atmos. Sci. Let. **12**: 13–18 (2011)
Published online 16 August 2010 in Wiley Online Library
(wileyonlinelibrary.com) **DOI:** 10.1002/asl.289

RMetS
Royal Meteorological Society

Atmospheric composition of West Africa: highlights from the AMMA international program

Céline H. Mari,[1]* Claire E. Reeves,[2] Katherine S. Law,[3] Gérard Ancellet,[3] Maria Dolores Andrés-Hernández,[4] Brice Barret,[1] Joëlle Bechara,[15] Agnès Borbon,[15] Idir Bouarar,[3] Francesco Cairo,[5] Roisin Commane,[11] Claire Delon,[1] Matthew J. Evans,[12] Federico Fierli,[5] Cédric Floquet,[11] Corinne Galy-Lacaux,[1] Dwayne E. Heard,[11] Carine D. Homan,[6] Trevor Ingham,[11] Niels Larsen,[13] Alastair C. Lewis,[7] Catherine Liousse,[1] Jennifer G. Murphy,[8] Emiliano Orlandi,[5] David E. Oram,[2] Marielle Saunois,[1,9] Dominique Serça,[1] David J. Stewart,[14] Daniel Stone,[11,12] Valérie Thouret,[1] Peter van Velthoven[10] and Jason E. Williams[10]

[1]*Laboratoire Aerologie, University of Toulouse, CNRS, Toulouse, France*
[2]*School of the Environmental Sciences, University of East Anglia, Norwich, UK*
[3]*UPMC, Université de Paris 06, Université Versailles St-Quentin, CNRS/INSU, LATMOS-IPSL, Paris, France*
[4]*Institute of Environmental Physics, University of Bremen, Bremen, Germany*
[5]*ISAC, Institute for Atmospheric Sciences and Climate, National Research Council, Italy*
[6]*Department of Physics, University of Wuppertal, Germany*
[7]*National Centre for Atmospheric Science, University of York, Heslington, York, UK*
[8]*Department of Chemistry, University of Toronto, Ontario, Canada*
[9]*National Center for Atmospheric Research, Boulder, Colorado, USA*
[10]*Royal Netherlands Meteorological Institute, De Bilt, The Netherlands*
[11]*School of Chemistry, University of Leeds, Leeds, UK*
[12]*School of the Environment, University of Leeds, Leeds, UK*
[13]*Danish Meteorological Institute, Danish Climate Center, Copenhagen, Denmark*
[14]*Department of Chemistry, University of Reading, Reading, UK*
[15]*Laboratoire Interuniversitaire des Systèmes Atmosphèriques, Universités de Paris 12 et Paris 7, CNRS, Créteil, France*

**Correspondence to:*
Céline H. Mari, Laboratoire Aerologie, Universite de Toulouse, CNRS, 31400 Toulouse, France.
E-mail:
celine.mari@aero.obs-mip.fr

Received: 11 February 2010
Revised: 22 June 2010
Accepted: 16 July 2010

Abstract

The atmospheric composition of West Africa reflects the interaction of various dynamical and chemical systems (i.e. biogenic, urban, convective and long-range transport) with signatures from local to continental scales. Recent measurements performed during the African Monsoon Multidisciplinary Analyses (AMMA) observational periods in 2005 and 2006 provide new data which has allowed new insight into the processes within these systems that control the distribution of ozone and its precursors. Using these new data and recently published results, we provide an overview of these systems with a particular emphasis on ozone distributions over West Africa during the wet season. Copyright © 2010 Royal Meteorological Society

Keywords: West Africa; AMMA; atmospheric chemistry; convection; long-range transport; biogenic emission; biomass burning; urban pollution; ozone

1. Background

The West African subregion is an important provider of ozone and aerosols, which are radiatively active components in the climate system. Prior to the African Monsoon Multidisciplinary Analyses (AMMA) program, our knowledge about the distribution of O_3 and its precursors over West Africa was limited. Measurements performed during the AMMA observational periods in 2005 and 2006 revealed a variety of new dynamical and chemical mechanisms that control the distribution of ozone and its precursors in this subregion. Details of the field campaigns are available in Lebel *et al*. (2010).

During the dry season (boreal winter), West Africa is marked by strong emissions of pollutants from biomass burning. During the wet season (typically from May to September), the region is influenced by mesoscale convective systems (MCSs), which impact the composition of the atmosphere through several processes (i.e. rapid vertical transport of gases and aerosols to the upper troposphere (UT), heterogeneous processing, emissions of NOx by lightning and alteration of the land surface wetness affecting the liberation of NOx from soils). Combustion of fuelwood for domestic energy is a continual source of air pollution primarily in urban areas. Vegetated regions emit large amounts of biogenic organic compounds which influence the production of ozone. During the AMMA program, an experimental strategy was set up to quantify these processes and to understand their impact at the global scale.

2. Tropical biogenically dominated environments

In the lower troposphere over West Africa during the wet season, the ozone distribution shows a significant

south–north gradient with lower values over forested regions and higher values north of 12°N (Adon *et al.*, 2010; Reeves *et al.*, 2010) (Figure 1). From dense rain forest in the coastal belt to the sub-Sahelian savanna in the north, there are 72 million hectares of forest in West Africa. Dry deposition loss of ozone to vegetation is the main driver of the ozone minimum over the forested areas, but factors relating to the biogenic emissions also affect the observed ozone latitudinal profile (Saunois *et al.*, 2009).

Vegetated regions, south of 10°N, emit large amounts of biogenic volatile organic compounds (VOCs) (Ferreira *et al.*, 2010; Murphy *et al.*, 2010) (Figure 1). Emissions from vegetation are dependent both on environmental conditions and plant type; high emission rates of isoprene were observed for West African native plants, while a non-native plant originating from South America was found to be more important for monoterpenes (Saxton *et al.*, 2007). Aircraft measurements of OH and HO_2 radicals (Commane *et al.*, 2010) indicate that the maximum concentrations of both species occur over the forested region. HO_2 is controlled by relatively simple photochemical processes (Stone *et al.*, 2010). In contrast, the high reactivity of the short-lived biogenic VOCs leads to model underestimates of OH, similar to that found in other low NOx regions of the world impacted by biogenic VOCs (Saunois *et al.*, 2009). Conversely, longer-lived and secondary organics can be oxidized north of the forested area where they are transported and/or produced and contribute to the ozone maximum there (Saunois *et al.*, 2009) (Figure 1).

Enhanced concentrations of NOx and O_3 observed in the boundary layer over semiarid Sahelian regions following the passage of precipitating MCSs (Stewart *et al.*, 2008) were interpreted as being due to the release of NOx from soils. A mesoscale model study in which NOx emissions from soils were defined by an algorithm driven by various environmental parameters (e.g. soil moisture and pH) supported these conclusions (Delon *et al.*, 2008). As part of the IDAF network, long-term measurements over diverse African ecosystems confirmed that, in the wet season, concentrations of nitrogen components were highest over the dry savannas (Adon *et al.*, 2010) and that the nitrogen cycle of the whole Sahelian region is impacted by these strong NOx emissions together with the ammonia source from animals (Galy-Lacaux *et al.*, 2009). Saunois *et al.* (2009) showed that the soil NOx emissions combined with northward advection of biogenic VOCs play a key role in producing enhanced ozone concentrations over the dry savanna regions, with production rates of up to about 7 ppbv/day.

This large-scale impact of biogenic emissions was also verified by Williams *et al.* (2009) who found that biogenic VOCs released from Africa are estimated to contribute 2–4% of the global burden of VOC and that 2–45% of tropospheric O_3 over equatorial Africa may come from African soil NOx emissions. Further, these emissions also contribute to enhanced ozone production over the tropical Atlantic downwind of West Africa (Williams *et al.*, 2009).

3. Urban environments and air quality

Air pollution, particularly in urban centres, is an emerging issue for human health in many West African countries. Increasing levels of toxic pollutants are a result of industrial emissions and vehicle exhausts as

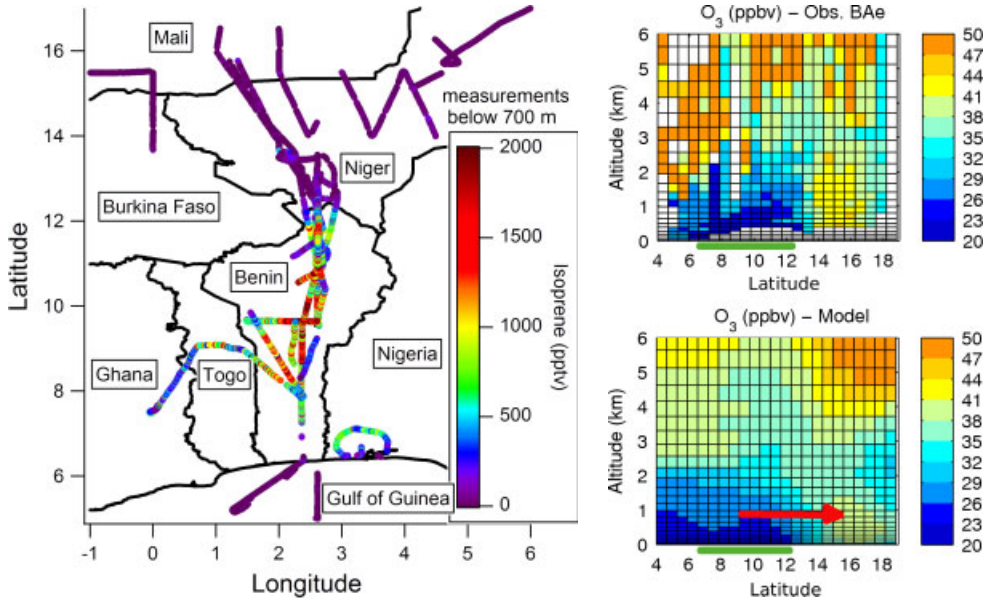

Figure 1. (Left) Observed isoprene-mixing ratio (in pptv) along the BAe-146 aircraft tracks below 700 m (refer Murphy *et al.*, 2010 for details on aircraft measurements). (Right) Latitude–altitude distribution of ozone simulated by a mesoscale model (bottom) and observed by the BAe-146 aircraft (top) in August 2006. The green bar marks the latitudinal extension of the vegetated area. The red arrow indicates the advection to northern latitudes by the nocturnal boundary layer jet (adapted from Saunois *et al.*, 2009).

well as the burning of coal, wood or other fuels to meet domestic energy requirements. Exceptionally high O_3 concentrations (up to 284 ppbv at 1 km altitude) observed during the dry season by the ozone sounding network in Cotonou, Benin, have been linked to an unusual combination of sources including biomass burning, urban pollution and the petrochemical industry (Minga *et al*., 2010). Hopkins *et al*. (2009) reported top–down emissions estimate for the Lagos megacity in Nigeria based on aircraft measurements. Annual emission fluxes for NOx were found to be comparable with previous bottom–up estimates for other developing megacities, whereas VOC and CO emissions per capita were among the highest ever reported. Interestingly, measured O_3 levels were not significantly elevated in this case, possibly due to titration in polluted conditions.

4. Convective environments

MOZAIC commercial aircraft data over the West African continent had previously shown that convection uplifts O_3-poor air into the UT and contributes to an observed O_3 minimum at 12–14 km (Sauvage *et al*., 2007; Saunois *et al*., 2008). This was further confirmed during the AMMA by ozonesondes (Cairo *et al*., 2010; Thouret *et al*., 2009) (Figure 2) and aircraft observations (Ancellet *et al*., 2009).

Using aircraft measurements, Bechara *et al*. (2009) observed up to three times higher concentrations of VOCs in the UT during convective conditions compared to non-convective conditions and model studies suggest that the UT is frequently perturbed by MCSs up to an altitude of about 14 km (Law *et al*., 2010). In addition, the MCS can produce NOx from lightning, but NOx production per standard stroke over West Africa was found to be 40% lesser than the thunderstorms over northern Australia and southern Germany (Höller *et al*., 2009). Despite this, NO concentrations were found to be enhanced in the UT (Figure 3).

Moreover, Andrés-Hernández *et al*. (2009), on occasions, found peroxy radical concentrations in the outflow of convective clouds to be coupled with NO indicating that either NOx and a radical precursor (e.g. formaldehyde, acetone or peroxides) have been simultaneously lifted from lower altitudes or that fresh NO emissions have occurred within uplifted air laden with a radical precursor. Significant O_3 production rates of around 1 ppb/h were calculated for these MCS outflows. At the cloud scale, MCSs have contrasting signatures with high O_3 production observed for MCSs which had existed for more than 1.5 days as this allows more peroxide formation, and for those MCS which originated south of 10°N where more CO is available for transport to the UT (Ancellet *et al*., 2009).

The NOx in the UT induces a quasi-persistent large-scale O_3 latitudinal gradient with an O_3 minimum in the intertropical convergence zone and lightning NOx-related O_3 maxima in the southern and the northern Hadley cells (Sauvage *et al*., 2007; Saunois *et al*., 2008). However, based on a multi-model study, Barret *et al*. (2010) demonstrated that global model simulations of lightning NOx (magnitude, altitude and geographical position) (Figure 3) are very sensitive to the convection scheme employed, in particular the detrainment flux levels and intensity. Interestingly, none of the models simulate a NOx maximum over Central Africa as might be expected given the maximum in lightning imaging sensor (LIS) flash frequencies over this region. Simulated O_3 enhancements induced by the lightning NOx source are the highest over the northern tropical Atlantic and West Africa.

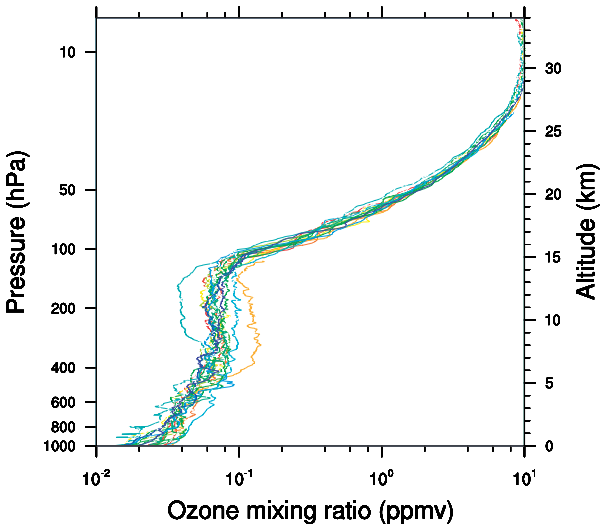

Figure 2. Vertical ozone-mixing ratio profiles from 17 ozone soundings in Niamey (Niger) between 27 July and 25 August 2006 (courtesy N. Larsen, adapted from Cairo *et al*., 2009).

5. Long-range transport

Surprisingly, the AMMA revealed a persistent influence of fires from the Southern Hemisphere in the mid and lower troposphere of West Africa during the wet season. Import of biomass burning emissions from Central Africa (Liousse *et al*., 2010) over the southern part of the region was originally proposed by Sauvage *et al*. (2005) based on MOZAIC data. These incidences of biomass burning import were found to be driven by the Southern Hemisphere African easterly jet activity (Mari *et al*., 2008) (Figure 4). Signatures of such transport were observed by ozone soundings made in Cotonou, Benin and co-located aircraft measurements with O_3 concentrations up to 120 ppbv in the lower troposphere (Thouret *et al*., 2009) (Figure 4). Significant O_3 production rates (7 ppbv/day) have been estimated in middle tropospheric biomass burning plumes transported downwind over the Atlantic Ocean (Real *et al*., 2010). Global model

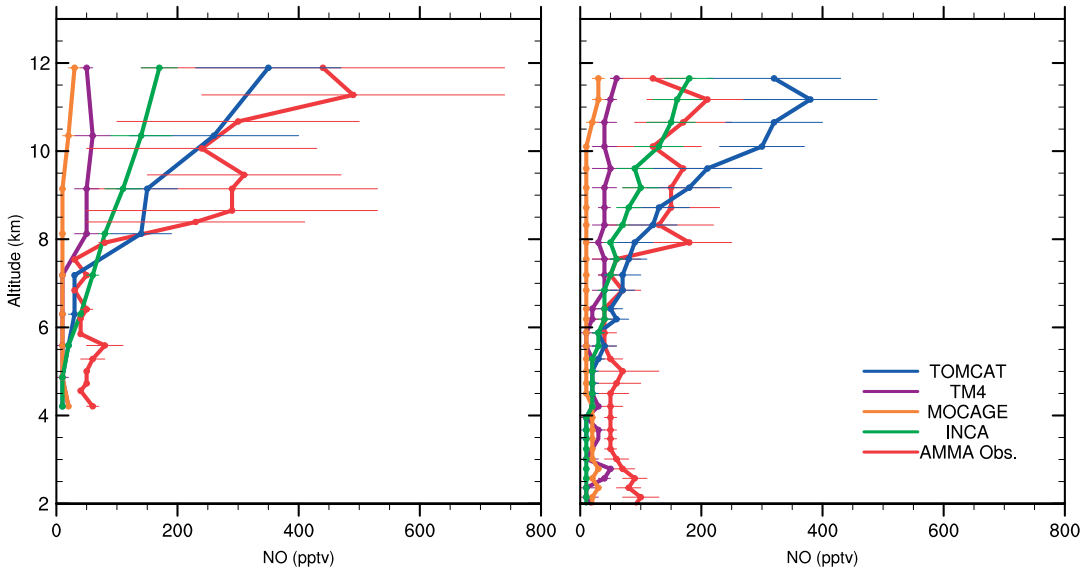

Figure 3. Vertical profiles of NO-mixing ratios observed during the AMMA Special Observational Period in August 2006 by the DLR Falcon 20 (red) and simulated by four chemistry transport models: MOCAGE, LMDz-INCA, TM4 and TOMCAT for (Left) observations that have been impacted by MCSs in the previous 3–4 days and (right) observations with no recent MCSs impact (courtesy I. Bouarar; adapted from Barret *et al.*, 2010).

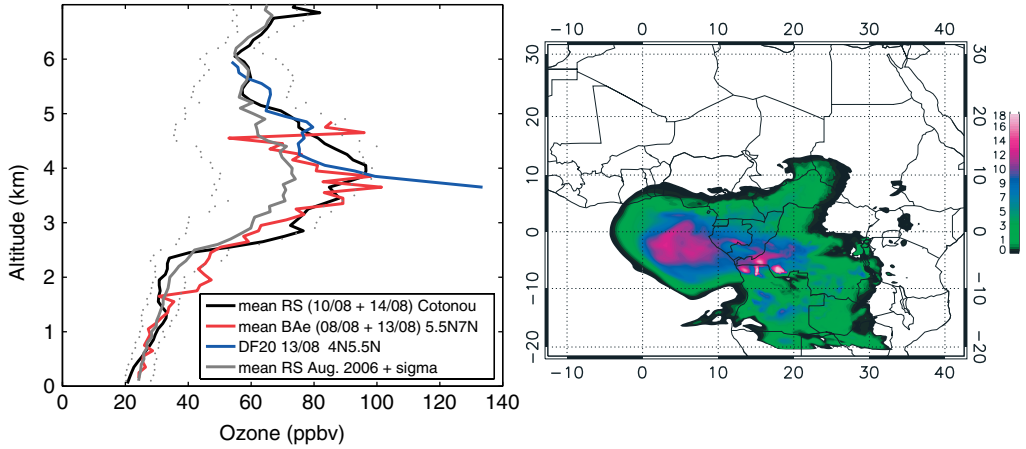

Figure 4. (Left) Vertical profiles of ozone up to 7 km from the ozone-sounding dataset: August monthly mean and standard deviation (grey), average of the two soundings on 10 and 14/08 (black); from BAe-146 in the region between 5.5 °N and 7°N on the 08 and 13/08 (red); and from D-F20 in the region 4–5.5 °N on the 13/08 (blue) (adapted from Thouret *et al.*, 2009). (Right) Simulated tracer concentration at 650 hPa on August 15 1200 UTC, originating from the Southern Hemispheric biomass burning emissions during an active phase of the southern African easterly jet (courtesy East Orlandi, adapted from Real *et al.*, 2010).

simulations of the transport of biomass burning emissions show that often transport from Central Africa occurs in the lower troposphere rather than the mid-troposphere when using the ECMWF meteorological analysis (Williams *et al.*, 2010).

Central African biomass burning emissions can also be injected periodically into the UT via deep convection over Central Africa and easterly transported in the lower Tropical tropopause layer (TTL) by the Tropical easterly jet (TEJ) (Mari *et al.*, 2008). Slow, but significant, ozone production (1–2 ppbv/day) has been estimated during downwind transport of these air masses around 200 hPa (Real *et al.*, 2010).

Much of the air in the TTL has been advected from the east in the TEJ rather than having been convectively lifted over West Africa. Barret *et al.* (2008) showed a clear influence of CO-rich air uplifted from Asia (Figure 5). Uplift of clean air over the Indian Ocean as well as transport of air from the lower stratosphere around the Tibetan High also affect trace gas concentrations in the TTL (Law *et al.*, 2010). Interestingly, the TTL also has enhanced levels of non-volatile particles, although the reasons are yet unknown (Borrmann *et al.*, 2009).

6. Challenges for the future

Measurements performed during the AMMA observational periods in 2005 and 2006 gave a first view of

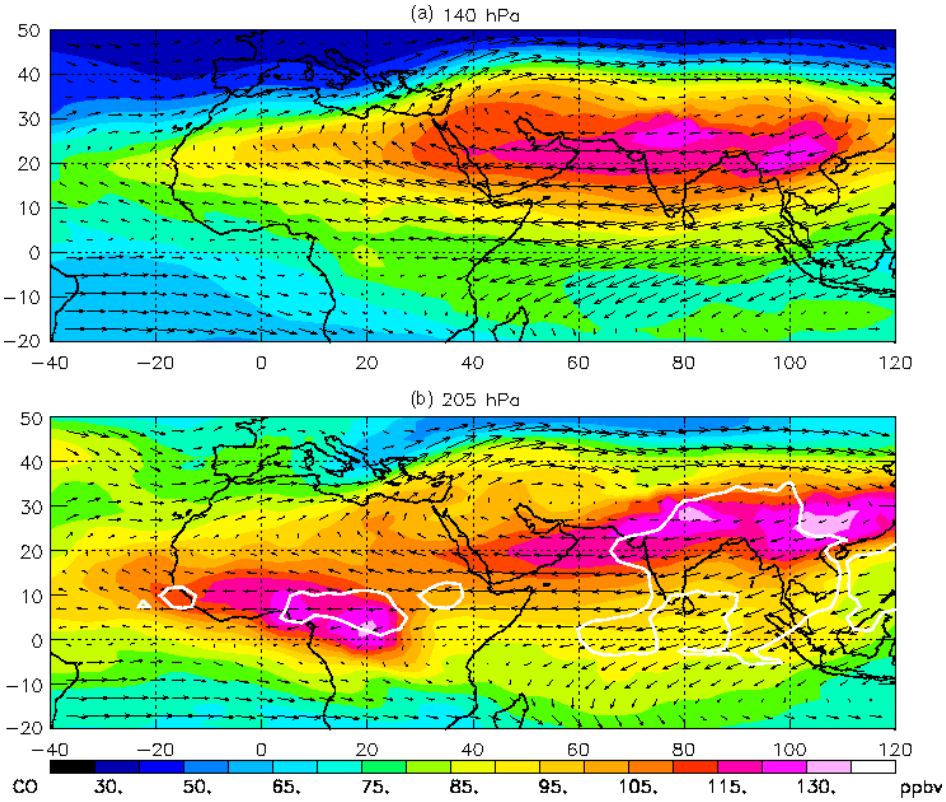

Figure 5. CO fields, in ppbv, assimilated in the MOCAGE global model, averaged over the period 5–31 July 2006 at 140 hPa (top) and 205 hPa (bottom). Horizontal winds from the ECMWF operational analyses are superimposed as black arrows. White contours at 205 hPa indicate deep convection (OLR contours at 220 W/m^2) (adapted from Barret *et al.*, 2008).

the atmospheric composition over West Africa. Several questions remain on the contributions of different components of the vegetation to natural emissions of chemical species and how they change with season and rainfall. How will deforestation and desertification, in a changing climate, modify the chemical emissions? Rapid urbanization and concentration of economic activities in Western Africa's urban centres is an emerging issue for the West African population. The impact of emissions from industry, motor vehicles and households on air quality is a major concern. *In situ* observations in several cities of West Africa (Dakar, Ouagadougou, Bamako and Lagos) have revealed concentrations of pollutants (black carbon aerosols and NO_2) comparable to those observed in Asian megacities (Liousse and Galy-Lacaux, 2010). Current emission inventories estimate only a small contribution of anthropogenic emissions from West Africa, but, based on first evaluations against *in situ* data, these may be underestimated. The question thus remains concerning the evolution of these emissions especially since Africa is the continent with the highest projected increase in the population in the next few decades.

Acknowlegdements

The support of the AMMA project is gratefully acknowledged (see http://onlinelibrary.wiley.com/doi/10.1002/asl.331/full for full acknowledgement).

References

Adon M, Galy-Lacaux C, Yoboue V, Delon C, Lacaux JP, Castera P, Gardrat E, Pienaar J, Al Ourabi H, Laouali D, Diop B, Sigha-Nkamdjou L, Akpo A, Tathy JP, Lavenu F, Mougin E. 2010. Long term measurements of sulfur dioxide, nitrogen dioxide, ammonia, nitric acid and ozone in Africa using passive samplers. *Atmospheric Chemistry and Physics Discussion* **10**: 4407–4461.

Ancellet G, Leclair de Bellevue J, Mari C, Nedelec P, Kukui A, Borbon A, Perros P. 2009. Effects of regional-scale and convective transports on tropospheric ozone chemistry revealed by aircraft observations during the wet season of the AMMA campaign. *Atmospheric Chemistry and Physics* **9**: 383–411.

Andrés-Hernández MD, Kartal D, Reichert L, Burrows JP, Meyer Arnek J, Lichtenstern M, Stock P, Schlager H. 2009. Peroxy radical observations over West Africa during AMMA 2006: photochemical activity in the outflow of convective systems. *Atmospheric Chemistry and Physics* **9**: 3681–3695.

Barret B, Ricaud P, Mari C, Attié J-L, Bousserez N, Josse B, Le Flochmoën E, Livesey NJ, Massart S, Peuch V-H, Piacentini A, Sauvage B, Thouret V, Cammas J-P. 2008. Transport pathways of CO in the African upper troposphere during the monsoon season: a study based upon the assimilation of spaceborne observations. *Atmospheric Chemistry and Physics* **8**: 3231–3246.

Barret B, Williams JE, Bouarar I, Yang X, Josse B, Law K, Le Flochmoën E, Liousse C, Peuch V-H, Carver G, Pyle J, Sauvage B, vanVelthoven P, Mari C, Cammas J-P. 2010. Impact of West African Monsoon convective transport and lightning NOx production upon the tropical upper tropospheric composition: a multi-model study. *Atmospheric Chemistry and Physics Discussion* **10**: 2245–2302.

Bechara J, Borbon A, Jambert C, Colomb A, Perros PE. 2009. Evidence of the impact of deep convection on reactive volatile organic compounds in the upper tropical troposphere during the AMMA experiment in West Africa. *Atmospheric Chemistry and Physics Discussion* **9**: 20309–20346.

Borrmann S, Kunkel D, Weigel R, Minikin A, Deschler T, Wilson JC, Curtius J, Shur GN, Belyaev GV, Law KS, Cairo F. 2009. Aerosols in the tropical and sub-tropical UT/LS: in-situ measurements of submicron particle abudance and volatility. *Atmospheric Chemistry and Physics Discussion* **9**: 24587–24628.

Cairo F, Pommereau JP, Law KS, Schlager H, Garnier A, Fierli F, Ern M, Streibel M, Arabas S, Borrmann S, Berthelier JJ, Blom C, Christensen T, D'Amato F, Di Donfrancesco G, Deshler T, Diedhiou A, Durry G, Engelsen O, Goutail F, Harris NRP, Kerstel ERT, Khaykin S, Konopka P, Kylling A, Larsen N, Lebel T, Liu X, MacKenzie AR, Nielsen J, Oulanowski A, Parker DJ, Pelon J, Polcher J, Pyle JA, Ravegnani F, Rivière ED, Robinson AD, Röckmann T, Schiller C, Simões F, Stefanutti L, Stroh F, Some L, Siegmund P, Sitnikov N, Vernier JP, Volk CM, Voigt C, von Hobe M, Viciani S, Yushkov V. 2010. An introduction to the SCOUT-AMMA stratospheric aircraft, balloons and sondes campaign in West Africa, August 2006: rationale and roadmap. *Atmospheric Chemistry and Physics* **10**: 2237–2256.

Commane R, Floquet C, Ingham T, Stone D, Evans MJ, Heard DE. 2010. Observation of OH and HO_2 radicals over West Africa. *Atmospheric Chemistry and Physics Discussion* **10**: 7265–7322.

Delon C, Reeves CE, Stewart DJ, Serça D, Dupont R, Mari C, Chaboureau J-P, Tulet P. 2008. Biogenic nitrogen oxide emissions from soils – impact on NOx and ozone over West Africa during AMMA: modelling study. *Atmospheric Chemistry and Physics* **8**: 2351–2363.

Ferreira J, Reeves CE, Murphy JG, Garcia-Carreras L, Parker DJ, Oram DE. 2010. Isoprene emissions modelling for West Africa using MEGAN. *Atmospheric Chemistry and Physics Discussion* **10**: 6923–6953.

Galy-Lacaux C, Laouali D, Descroix L, Gobron N, Liousse C. 2009. Long term precipitation chemistry and wet deposition in a remote dry savanna site in Africa (Niger). *Atmospheric Chemistry and Physics* **9**: 1579–1595.

Höller H, Betz H-D, Schmidt K, Calheiros RV, May P, Houngninou E, Scialom G. 2009. Lightning characteristics observed by a VLF/LF lightning detection network (LINET) in Brazil, Australia, Africa and Germany. *Atmospheric Chemistry and Physics* **9**: 7795–7824.

Hopkins JR, Evans MJ, Lee JD, Lewis AC, Marsham JH, McQuaid JB, Parker DJ, Stewart DJ, Reeves CE, Purvis RM. 2009. Direct estimates of emissions from the megacity of Lagos. *Atmospheric Chemistry and Physics* **9**: 8471–8477.

Law KS, Cairo F, Fierli F, Palazzi E, Borrmann S, Schlager H, Streibel M, Viciani S, Ravegnani F, Volk M, Schiller C *et al*. 2010. Air mass origins influencing TTL chemical composition over West Africa during 2006 summer monsoon. *Atmospheric Chemistry and Physics Discussion* **10**: 15485–15536.

Lebel T, Parker DJ, Flamant C, Bourles B, Marticorena B, Mougin E, Peugeot C, Diedhiou A, Haywood JM, Ngamini JB, Polcher J, Redelsperger JL, Thorncroft CD. 2010. *Quarterly Journal of the Royal Meteorological Society* **136**: 8–33.

Liousse C, Galy-Lacaux C. 2010. Urban pollution in West Africa. *IGBP Newsletter* in press.

Liousse C, Guillaume B, Grégoire JM, Mallet M, Galy C, Poirson A, Solmon F, Pont V, Mariscal A, Dungal L, Rosset R, Yoboué V, Bedou X, Serça D, Konaré A, Granier C, Mieville A. 2010. African aerosols modeling during the EOP-AMMA campaign with updated biomass burning emission inventories. *Atmospheric Chemistry and Physics Discussion* **10**: 7347–7382.

Mari CH, Cailley G, Corre L, Saunois M, Attié JL, Thouret V, Stohl A. 2008. Tracing biomass burning plumes from the Southern Hemisphere during the AMMA 2006 wet season experiment. *Atmospheric Chemistry and Physics* **8**: 3951–3961.

Minga A, Thouret V, Saunois M, Delon C, Serça D, Sauvage B, Mariscal A, Leriche M, Cros B. 2010. What caused extreme ozone concentrations over Cotonou in December 2005? *Atmospheric Chemistry and Physics* **10**: 895–907.

Murphy JM, Oram DE, Reeves CE. 2010. Measurements of volatile organic compounds over West Africa. *Atmospheric Chemistry and Physics Discussion* **10**: 3861–3892.

Real E, Orlandi E, Law KS, Fierli F, Josset D, Cairo F, Schlager H, Borrmann S, Kunkel D, Volk M, McQuaid JB, Stewart DJ, Lee J, Lewis A, Hopkins JR, Ravegnani F, Ulanovski A, Liousse C. 2010. Cross-hemispheric transport of central African biomass burning pollutants: implications for downwind ozone production. *Atmospheric Chemistry and Physics* **10**: 3027–3046.

Reeves CE, Formenti P, Afif C, Ancellet G, Attie J-L, Bechara J, Borbon A, Cairo F, Coe H, Crumeyrolle S, Fielri F, Flamant C, Gomes L, Hamburger T, Jambert C, Law KS, Mari C, Matsuki A, Methven J, Mills GP, Minikin A, Murphy JG, Nielsen JK, Oram DE, Parker DJ, Richter A, Schlager H. 2010. Chemical and aerosol characterisation of the troposphere over West Africa during the monsoon period as part of AMMA. *Atmospheric Chemistry and Physics Discussion* **10**: 7115–7183.

Saunois M, Mari C, Thouret V, Cammas JP, Peyrille P, Lafore JP, Sauvage B, Volz-Thomas A, Nedelec P, Pinty JP. 2008. An idealized two-dimensional approach to study the impact of the West African monsoon on the meridional gradient of tropospheric ozone. *Journal of Geophysical Research* **113**: D07306, DOI:10.1029/2007JD008707.

Saunois M, Reeves CE, Mari C, Murphy JG, Stewart DJ, Mills GP, Oram DE, Purvis RM. 2009. Ozone budget in the West African lower troposphere during the AMMA (African Monsoon Multidisciplinary Analysis) campaign. *Atmospheric Chemistry and Physics* **9**: 6979–7032.

Sauvage B, Thouret V, Cammas J-P, Gheusi F, Athier G, Nédélec P. 2005. Tropospheric ozone over Equatorial Africa: regional aspects from the MOZAIC data. *Atmospheric Chemistry and Physics* **5**: 311–335.

Sauvage B, Thouret V, Cammas JP, Brioude J, Nedelec P, Mari C. 2007. Meridional ozone gradients in the African upper troposphere. *Geophysical Research Letters* **34**: Art. No. L03817, DOI:10.1029/2006GL028542.

Saxton JE, Lewis AC, Kettlewell JH, Ozel MZ, Gogus F, Boni Y, Korogone US, Serça D. 2007. Isoprene and monoterpene emissions from secondary forest in northern Benin. *Atmospheric Chemistry and Physics* **7**: 4095–4106.

Stewart DJ, Taylor CM, Reeves CE, McQuaid JB. 2008. Biogenic nitrogen oxide emissions from soils: impact on NOx and ozone over west Africa during AMMA (African Monsoon Multidisciplinary Analysis): observational study. *Atmospheric Chemistry and Physics* **8**: 2285–2297.

Stone D, Evans MJ, Commane R, Ingham T, Floquet C, McQuaid JB, Brookes DM, Monks PS, Purvis R, Hamilton J, Hopkins J, Lee J, Lewis AC, Stewart D, Murphy J, Mills G, Oram D, Bandy BJ. 2010. HOx observations over West Africa during AMMA: impact of isoprene and NOx. *Atmospheric Chemistry and Physics Discussion* **10**: 17029–17072.

Thouret V, Saunois M, Minga A, Mariscal A, Sauvage B, Solete A, Agbangla D, Nédélec P, Mari C, Reeves CE, Schlager H. 2009. An overview of two years of ozone radiosoundings over Cotonou as part of AMMA. *Atmospheric Chemistry and Physics* **9**: 6157–6174.

Williams JE, Scheele MP, van Velthoven PFJ, Cammas J-P, Thouret V, Galy-Lacaux C, Volz-Thomas A. 2009. The influence of biogenic emissions from Africa on tropical tropospheric ozone during 2006: a global modeling study. *Atmospheric Chemistry and Physics* **9**: 5729–5749.

Williams JE, Scheele MP, van Velthoven PFJ, Thouret V, Saunois M, Reeves CE, Cammas J-P. 2010. The influence of biomass burning on tropospheric composition over the tropical Atlantic Ocean and equatorial Africa during the West African Monsoon. *Atmospheric Chemistry and Physics Discussion* **10**: 7507–7552.

