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Tropospheric aerosols over West Africa: highlights from the AMMA international program

B. Marticorena,^{1*} J. Haywood,^{2,3} H. Coe,⁴ P. Formenti,¹ C. Liousse,⁵ M. Mallet⁵ and J. Pelon⁶

¹LISA, IPSL, UMR CNRS, UPEC, UPD, France

²Met Office, Exeter, UK

³College of Engineering, Mathematics, and Physical Science, University of Exeter, UK

⁴Centre For Atmospheric Science, S. E. A. E. S., University of Manchester, UK

⁵LA, UMR CNRS, UPS, Toulouse, France

⁶LATMOS, IPSL, UMR CNRS, UPMC, UVSQ, Paris, France

*Correspondence to:

B. Marticorena, LISA, IPSL, UMR
CNRS, UPEC, UPD, France.

E-mail: marticorena@lisa.u-pec.fr

Abstract

West Africa is the world's largest source of mineral dust and biomass burning aerosols. The AMMA (African Monsoon Multidisciplinary Analysis) project developed an integrated strategy combining field measurements, remote sensing and modelling studies to better quantify aerosol emissions, to extensively document their physico-chemical properties and to describe their horizontal and vertical distributions and seasonal variability. Using this information in climate and numerical weather prediction models will lead to better climate projections and better simulations of dust storms, visibility, and air quality and the impacts upon human health. Copyright © 2011 Royal Meteorological Society

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1. Introduction

The AMMA (African Monsoon Multidisciplinary Analysis) program (Polcher *et al.*, 2011) made an integrated observational and modelling study, using ground-based and airborne and satellite measurements, to characterise the aerosol loads over continental West Africa. The programme has enabled us to describe aerosol processes from emission through atmospheric transport, to deposition or advection outside the African domain and physico-chemical properties that control their impacts, and in particular their direct radiative effect.

2. Aerosol sources: typical spatial and seasonal patterns

Specific inventories of carbonaceous aerosols have been developed for the 2000–2007 period over the African continent (Liousse *et al.*, 2010). Aerosol emissions from biomass burning are estimated based on satellite observations of burned areas and type of combustion (Liousse *et al.*, 2010). In the northern hemisphere, they are maximum in December and mainly located in Central Africa, with a few hot spots in Western Africa and a year-to-year variability as high as 50%. Regional inventories of anthropogenic emissions due to fossil fuel and biofuel (gasoline, diesel, wood, crop residues, etc.) consumption, includes regional specificities, such as traffic from two-wheel vehicles (Assamoi and Liousse, 2010).

These inventories highlight the local contribution of large African cities (e.g. Lagos, Cotonou), in agreement with observations (Reeves *et al.*, 2010). Regional and global simulations using these new inventories better agree with observations (Liousse *et al.*, 2010; Tummou *et al.*, 2010). The anthropogenic emissions (fuel/biofuel/traffic/industry) of carbonaceous aerosols are comparable to those from open biomass burning, with emission scenarios suggesting a likely future increase.

Mineral dust was ubiquitously found in the troposphere over West Africa all along the year. However, a typical seasonal dust cycle is observed with maximum surface concentrations in winter due to Saharan dust transport, although extremely high daily concentrations ($>4000 \mu\text{g m}^{-3}$) are recorded during both dry and wet seasons (Marticorena *et al.*, 2010). In the rainy season, these pulses of high dust concentrations are due to local emissions by Mesoscale Convective Systems (MCSs) (Marticorena *et al.*, 2010). These MCSs also bring precipitation to the Sahel and wet deposition acts extremely efficiently remove dust from atmosphere (Flamant *et al.*, 2008). The Sahel is therefore a region of Saharan dust deposition during the dry season (Rajot *et al.*, 2008), but also an intense source of local dust emission at the beginning of the wet season. Several severe dust events (Flamant *et al.*, 2007; Slingo *et al.* 2008) provide well-documented case studies for testing and improving mesoscale dust models (Menut *et al.*, 2008; Tulet *et al.*, 2008).

3. Chemical and physical properties and processing

Physico-chemical properties of mineral dust, and in particular those controlling their radiative effect, have been extensively investigated. For the first time, size-resolved mineral dust emission fluxes have been measured *in situ*, confirming the change in the emitted dust size-distribution with dynamical conditions (Sow *et al.*, 2009). Significantly different size distributions are recorded between locally produced and advected dust (Rajot *et al.*, 2008). While the non-sphericity of mineral dust particles has been clearly stated, their aspect ratio (1.7) was found almost constant on the whole size-spectrum (Chou *et al.*, 2008). Regional signatures in iron oxides have been distinguished according to dust origin (Formenti *et al.*, 2008). Despite their low contribution to the dust mass (2.4–4.5%, i.e. 46% and 59% of total iron), iron oxides strongly influence dust absorption characteristics (McConnell *et al.*, 2010) and may thus impact the sign of the dust direct radiative effect.

Evidence of internal mixing of mineral dust with biomass burning particles were given during the dry season (Hand *et al.*, 2010). Dust chemical properties are also modified during the wet season by their incorporation into cloud droplets, becoming internally mixed with sulphate, chloride and nitrate (Crumeyrolle *et al.*, 2009; Matsuki *et al.*, 2010). Mineral dust radiative and CCN properties may thus be significantly impacted by interactions with biomass burning aerosols in the dry season and with soluble organic and inorganic components brought by the monsoon flow in the wet season.

During the dry season, biomass burning is the overwhelming source of submicron organic aerosol, with size evolving by coagulation from 0.08 μm close to the sources, to 0.1–0.2 μm for aged biomass burning aerosol (Johnson *et al.*, 2008; Capes *et al.*, 2009). A constant ratio between organic mass and carbon monoxide has been observed in biomass burning plumes, close to and far downwind fire sources, while the oxygen to carbon ratio increases. This implies a loss of carbon within the plume, as highlighted in some, though not all, field and chamber studies (Grieshop *et al.*, 2009). During the wet season, secondary organic material formed from oxidation of biogenic precursors dominates the submicron organic mass (Capes *et al.*, 2009). The observed organic mass is grossly underestimated by the production yields derived from simulation chamber studies (Capes *et al.*, 2009). This highlights very large gaps in our understanding of the evolution of organic aerosol in West Africa.

4. Aerosol spatial distribution over West Africa

The spatial redistribution of aerosols in the atmosphere is linked to large-scale dynamical patterns. Field

observations from AMMA show that various small scale and mesoscale processes are also involved in the generation of mineral dust, aerosol mixing in the boundary layer, and vertical transport to upper atmospheric layers.

During the dry season, two main anticyclonic regions are located close to the Azores and Saint Helena islands, with low pressure over central Africa linked to large-scale heating. The InterTropical Convergence Zone (ITCZ) is located slightly north of the Equator and a reduced monsoon inflow prevails south of the Sahel. The so-called ‘Harmattan Front’ separates the dusty air to the north from the biomass burning laden air to the south although significant mixing occurs at the boundary (Haywood *et al.*, 2008). The stronger heating to the South causes the relatively unstable, moist, warm and biomass burning laden air to be undercut by drier cooler dust-laden air. This leads to a two-layer structure: the lower (elevated) layer being dominated by dust (biomass burning aerosol). Ground-based and airborne (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations, CALIPSO) lidar systems offered the unique capability to monitor aerosol vertical distribution, and demonstrates the persistency of this two-layer structure at the regional and multi-annual scale (Léon *et al.*, 2009; Cavalieri *et al.*, 2010).

In the summer, the energy budget of the system is modified. A strong heat low develops over Sahara, reinforcing the pressure gradient with the Gulf of Guinea. The ITCZ moves north, and the monsoon inflow reaches the North Sahel (Lafore *et al.*, 2011). Meanwhile, the anticyclone in the southern hemisphere extends over land and into central Africa. These dynamical patterns and the development of boundary layer height over northern Africa by solar heating (Milton *et al.*, 2008) favour dust transport over the Atlantic and the Caribbean Sea by the trade winds in the Saharan Air Layer (SAL). The vertical structure of this dust-laden SAL has been documented from the central Sahara (Cuesta *et al.*, 2009) to the Atlantic coast, where the maximum summer aerosol optical depth (AOD) is associated with a maximum in the SAL elevation (up to 6 km) (Léon *et al.*, 2009).

The systematic formation of nocturnal gusts, evidenced locally by several lidar observations (Haywood *et al.*, 2008) and from satellite (MODIS Deep Blue; SEVIRI/MSG) is one of the possible processes leading to increased dust content in the lower Saharan boundary layer. During summer, ‘density currents’ linked to convective clouds are responsible for additional dust emissions in the Sahara (Marsham *et al.*, 2008). It has also been shown that the dynamics of the Intertropical frontal disturbance cause significant dust vertical transport from the boundary layer aloft, both in the winter season for the biomass particles (Pelon *et al.*, 2008) and for dust in the summer season (Boukaram *et al.*, 2008).

5. Aerosol optical properties and radiative impact

The single scattering albedo (SSA), i.e. the ratio of scattering to total light extinction (absorption plus scattering) is a critical parameter to determine the sign of the aerosol forcing. SSA and local direct radiative forcing were estimated at several locations of West Africa with different aerosol conditions.

Independent estimates consistently show that mineral dust is mainly scattering radiation in the visible range. The SSA of the submicron dust has been estimated to be $\sim 0.99 \pm 0.01$ (at $0.55 \mu\text{m}$) (Osborne *et al.*, 2008), and ~ 0.90 with the addition of the coarse mode (McConnell *et al.*, 2008). The dust SSA is lower in the summer than in the winter, possibly due to sources with different mineralogies. This range of SSA is consistent with previous estimations from the literature derived from ground-based, aircraft or satellite measurements in this region. The optical properties of biomass burning aerosol exhibit a much higher variability, likely due to different ages, sources, and combustion characteristics. From airborne observations, SSA of biomass burning aerosol over West Africa is 0.81 on average (Johnson *et al.*, 2008), i.e. comparable to estimates in Brazilian fires but significantly more absorbing than South African or boreal fires. Regions affected both by mineral dust and biomass burning particles display a large variability in the SSA ($0.81\text{--}0.98$ at $0.52 \mu\text{m}$, i.e. Mallet *et al.*, 2008) depending on the relative contributions of each aerosol, the lower (higher) value representing higher contributions from biomass burning (mineral dust).

During the dry season 2006 in Niamey, the mineral dust surface layer and the upper biomass burning aerosol layer contributed almost equally to a daytime solar direct radiative effect at the surface, ΔF_{SURF} , estimated at -56 W m^{-2} (Haywood *et al.*, 2008; Milton *et al.*, 2008). At the same period, in Djougou, the daily average ΔF_{SURF} was estimated to be -45 W m^{-2} (Mallet *et al.*, 2008). The daily forcing efficiency at the surface ($\Delta F_{\text{SURF}}/\text{AOD}$) has been estimated as $-31 \text{ W m}^{-2} \text{ AOD}^{-1}$ for heavy dust events and $-62 \text{ W m}^{-2} \text{ AOD}^{-1}$ for mixtures of biomass burning and dust aerosol (Derimian *et al.*, 2008). F_{SURF} is strongly influenced by the total AOD, while the radiative effect at the top of the atmosphere, F_{TOA} , is mainly controlled by the relative proportions of dust and biomass burning aerosols and the surface reflectance (Raut and Chazette, 2008). But the dusty layer possibly enhances the absorption of the upper biomass burning layer. These results underline the large direct radiative effect of mineral dust and biomass burning layers and highlight the importance of aerosol layering on this forcing. Finally, the solar atmospheric forcing (i.e. the amount of energy absorbed by the atmospheric layer), ΔF_{ATM} , is higher for biomass burning aerosols than for mineral dust. But a significant terrestrial ΔF_{ATM} is caused by absorption

and re-emission of terrestrial radiation by mineral dust (Mallet *et al.*, 2009).

6. Conclusion and perspectives

The AMMA project has provided valuable insights into the emissions, deposition and mixing processes of mineral dust, biomass burning, and biogenic aerosol over West Africa and a broad picture of their distribution, properties and radiative effects. This information is currently being ingested in climate and numerical weather prediction models to better describe their spatial and temporal variability and to assess their impacts. These results highlight the need to account for the absorption properties and vertical distribution of the different aerosols to properly estimate their radiative forcing. The intensity of this forcing implies a strong interaction with the local and regional dynamics. As an example, mineral dust was found to significantly impact on the vertical structure of the atmosphere (Tulet *et al.*, 2008) and on the simulation of convective activity in meteorological forecast models (Chaboureaud *et al.*, 2006). The AMMA program has initiated work at ECMWF and Hadley Centre to include aerosols in their forecasting models (Milton *et al.*, 2008). This will lead to better climate projections and better simulations of dust storms and visibility. Serious issues on air quality and human health have also been raised such as the impact of air pollution in African cities and the possible links between mineral dust and meningitis epidemics in the Sahel.

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