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Editorial
Introduction to the AMMA Special Issue on 'Advances in understanding atmospheric processes over West Africa through the AMMA field campaign'

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1. Introduction

African Monsoon Multidisciplinary Analysis (AMMA) is an international project to improve our knowledge and understanding of the West African monsoon (WAM), as well as the environmental and socio-economic impacts of its variability (Redelsperger *et al.*, 2006). A specificity of AMMA is its multi-scale and multi-component approach to understanding and forecasting the WAM variability and its response to the current climate change. A key motivation of AMMA is that basic processes involved in the WAM system are insufficiently documented and understood. In order to achieve this goal, AMMA relies on the largest and most expensive field programme ever attempted in Africa as detailed in the first paper of this Special Issue by Lebel *et al.* (2010). The heavily instrumented Special Observation Periods (SOPs) occurred in 2006. Subsequent years have been dedicated to processing and scientific exploitation of this unique dataset documenting all components of the WAM system (atmosphere, surface, ocean, chemistry and aerosols) from the regional to the local scales. This focus on process studies constitutes an important step paving the way towards analyses of the couplings between the different WAM components, integrating all new knowledge on processes to understand the whole WAM system. Ultimately an improved modelling of the WAM variability will be achieved by using better parametrizations that include our new knowledge of processes.

Three years after the SOP, this Special Issue (SI) gathers a selection of 29 papers on the first results from the AMMA observing period for atmospheric processes. It aims at demonstrating the enormous progress we have made in the documentation and understanding of the atmospheric processes involved in the WAM system including some studies addressing the coupling of the atmosphere with the surface and the ocean. Nevertheless it is not possible to cover the wealth of studies performed in such a huge multidisciplinary project in one single SI. Hence, we refer the interested reader to the half dozen AMMA SIs that have already been published or are to be published, focussing on atmospheric chemistry ('AMMA tropospheric chemistry and aerosols' in *Atmospheric Chemistry and Physics*), hydrology ('Surface processes and water cycle in West Africa, studied from the AMMA-observing system' in the *Journal of Hydrology*), agriculture and adaptation ('Climate variability and rural adaptation in the Sahel' in *Cahiers Agricultures*), forecasting ('West African weather prediction and predictability' in *Weather and Forecasting*), climate ('West African climate' *in Climate Dynamics)* and the NASA AMMA campaign ('TCSP NAMMA' in the *Journal of Atmospheric Sciences*).

To guide the readers of this SI, this short introduction paper first presents a conceptual WAM model and highlights its key features (section 2). It then summarizes some major results of this issue (section 3).

2. Basic WAM conceptual model and its key features

Figure 1 provides a schematic three-dimensional view of the WAM system, highlighting some of its key features. First it is important to recall that the WAM is a coupled atmosphere–ocean–land system characterized by summer rainfall over the continent and winter drought. Indeed the thermal contrast between the hot African continent in summer and the cooler surrounding oceans (Atlantic and Mediterranean Sea) and their evolution are the primary driving mechanisms for WAM seasonal migration over the continent. In particular in spring, the cooling in the Gulf of Guinea by the establishment of

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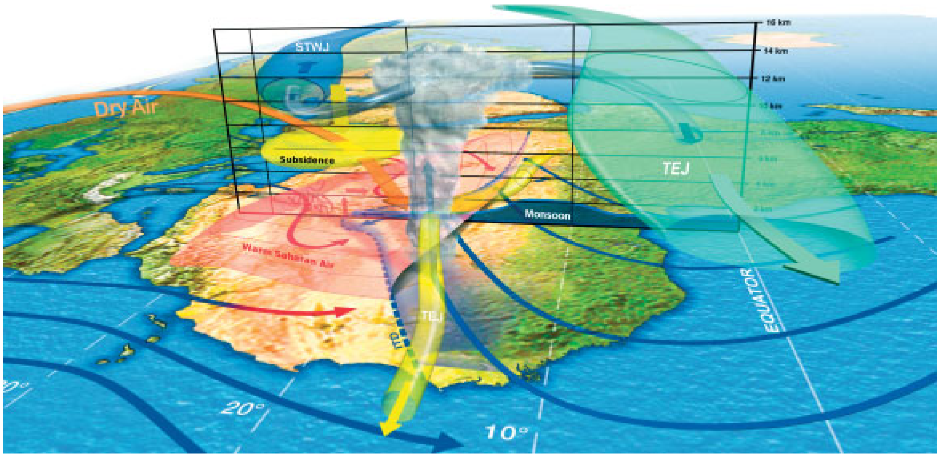

Figure 1. Three-dimensional schematic view of the West African monsoon (see text for details). Adapted from Lafore (2007). Illustration: François Poulain.

the cold tongue reinforces this contrast, preparing the monsoon onset at the end of June (Sultan and Janicot, 2003).

The Saharan Heat-Low (SHL) is a major feature of the WAM (Thorncroft and Blackburn, 1999; Thorncroft *et al.*, 2003; Parker *et al.*, 2005; Lavaysse *et al.*, 2009) corresponding to a deep dry-convective Atmospheric Boundary Layer (ABL) (red dome in Figure 1). The SHL pressure minimum located on its southern flank drives the convergence of two opposing low-level flows along the InterTropical Discontinuity (ITD: dashed blue line): the northerly dry and hot flow (or harmattan) and the south-westerly moist and cooler monsoon flow. The resulting strong baroclinicity across this discontinuity is responsible for the midlevel African Easterly Jet (AEJ: yellow tube). Moreover, the low-level negative potential vorticity (PV) anomaly in the SHL region (weak vertical stability) together with the positive PV anomaly generated by convection in the ITCZ (InterTropical Convergence Zone) to the south of the ITD ($\sim$5°) is responsible for the PV sign-reversal that supports the barotropic/baroclinic growth of African easterly waves (AEWs: Thorncroft and Blackburn, 1999).

AEWs are the major synoptic weather systems in the WAM. They are westward-travelling waves originating east of 20°E, and develop through both barotropic and baroclinic energy conversions as they move along the AEJ located around 600 hPa. Their wavelength varies between 2000 and 4000 km, and they have a westward phase speed of about 8 m s^{-1} (leading to spectral periodicities between 3 and 5 days). Observations and modelling studies indicate that AEWs significantly interact with moist convection (Duvel, 1990; Diedhiou *et al.*, 1999). Kiladis *et al.* (2006) recently highlighted the composite structure of AEWs and how the phase relationship with convection varies with longitude. Over the continent, convection tends to be in the northerlies ahead of the trough. Near the west coast it shifts into the trough and just downstream of the continent into the southerlies. A complete understanding of the reasons for these phase shifts, how AEWs interact with convection and, in particular, how AEWs and mesoscale convective systems (MCSs) interact are still lacking.

Convection is organized in the ITCZ to the south of the ITD (Figure 1). When active, the associated upper-level anticyclonic and divergent flow feeds the tropical easterly jet (TEJ) and subtropical jet (STJ) on their southern and northern flank, respectively, as shown by cloud resolving model (CRM) simulations and idealized models (Diongue *et al.*, 2002; Peyrillé *et al.*, 2007). Fast-moving MCSs (Mathon *et al.*, 2002) account for most of the rain over the Sahel. The understanding, forecasting and representation of the MCSs in Global Circulation Models (GCMs) is one of the challenges for the WAM. Although the theory of such systems is now well established for this region (Rotunno *et al.*, 1988; Lafore and Moncrieff, 1989; Moncrieff and So, 1989), their interplay with the above-mentioned large-scale features (AEJ, AEWs, vortices, dry air, troughs. . .) and with the surface remains unclear. Of particular importance is their triggering, as the convective inhibition is large over the Sahel.

Recent work suggests strong interactions between the Tropics and extratropics. Knippertz (2007) reviewed tropical–extratropical interactions (TEI) related to upper-level troughs at low latitudes, including theoretical, modelling and observational studies. Such mechanisms are most prominent in winter and spring or at the monsoon onset. For the summer, Roca *et al.* (2005) identified 'dry intrusion' events in the mid-troposphere (relative humidity less than 5%) over the Sahel originating in the upper levels (200–250 hPa) on the anticyclonic side of the polar jet stream around 50°N (see orange sinking arrow in Figure 1). Such events may modulate the convective activity and organization. Recently, Vizy and Cook (2009) emphasized a mechanism by which Mediterranean cold air surges can influence North African and east Sahelian weather systems. Finally Chauvin *et al.* (2010) showed that such cold air surges are related to an intraseasonal mode of variability of the SHL excited by large-scale midlatitude intraseasonal fluctuations of the atmosphere.

3. Major results of this issue

3.1. Planetary boundary layer and monsoon layer

Previous studies emphasised the significance of the low levels of the atmosphere for the WAM system, from the large scale (e.g. Eltahir and Gong, 1996; Cook, 1997), to the diurnal and mesoscale (Peyrillé and Lafore, 2007; Taylor *et al.*, 2003; Parker *et al.*, 2005). The following studies from this SI address the properties and driving mechanisms of these low-level features of the WAM. They are largely relying on analyses of observations documenting the fine scales, such as provided by aircraft, but also profilers, sodar and lidar, mostly instruments which were deployed over West Africa for the first time.

Canut *et al.* (this SI) and Saïd *et al.* (this SI) analyse aircraft daytime turbulence data in the lower troposphere in southern Niger. These observations allow the monitoring of the seasonal evolution of the ABL before and after the monsoon onset, as well as the role of the ABL on the interactions between the moist southwesterly monsoon flow and the dry northeasterly flow in the Saharan Air Layer (SAL) aloft. Canut *et al.* (this SI) have evidenced stronger entrainment at the top of the ABL during the early monsoon than during its active phase, and a large variability of the ratio of entrainment buoyancy flux over surface flux. Saïd *et al.* (this SI) found that the moisture flux distribution in the ABL was governed by top-down processes during the driest period and a mixture of top-down and bottom-up processes during the monsoon period.

Abdou *et al.* (this SI) use observations from Sonic Detection And Ranging (SODAR) also installed in southern Niger, to provide a very fine-scale dataset which documents the climatological significance of the low-level jet over the Sahel in spring and summer, when the ITD is located northwards. It allows characterizing the diurnal cycle of the wind shear in the lowest hundreds of metres of the atmosphere, which is found to be strongest during the middle of the night and associated with a nocturnal jet peaking typically between 200 and 400 m above ground level.

The AEJ (Figure 1) displays a relatively low elevation (700–600 hPa) within a region of large ABL growth. Such direct 'vertical' connections between the AEJ and the ABL had never been established. Wind profiler data from AMMA do reveal a strong influence of ABL turbulence on the AEJ (Kalapureddy *et al.*, this SI). In particular, the speed of the AEJ displays a significant diurnal cycle, which is linked to daytime surface heating and ABL growth, and is out of phase with the diurnal cycle of the SHL.

At larger spatial scale, the low levels can be affected by ITD displacements (Figure 1). The dynamics of such low-level features have received much attention in some places (e.g. the US Great Plains dryline: Schaefer, 1974). This is not the case for the ITD. Fine-scale microwave and wind profiler data together with satellite images allow for the first time the documentation of the remarkable diurnal dynamics of the ITD over West Africa in spring in the Soudanian region, and the evaluation of the mesoscale simulation of this major feature of the WAM (Pospichal *et al.*, this SI). The ITD is found to propagate northwards during the night by 1°–2° with a speed approaching 10 m s^{-1}.

3.2. Heat-low and monsoon surges

Messager *et al.* (this SI) have used airborne *in situ* and lidar observations acquired from two research aircrafts over the Sahara during the monsoon onset period to analyse the structure, dynamics and thermodynamics of the SAL. They show that the daytime SAL exhibits a remarkable split structure, with a well-mixed convective layer located beneath a residual layer whose dynamics appear to be nearly laminar. They also provide evidence that the broad features of the SHL thermodynamics and winds are successfully captured by the ECMWF operational analyses despite discrepancies.

Grams *et al.* (this SI) discuss the sea breeze-like inflow of cool and stably stratified air from the Atlantic via Mauritania into the southwestern part of the SHL. This so-called 'Atlantic Inflow' is stationary during the day and penetrates inland during the night with important impacts on the regional heat and moisture budgets. The strength and maximum extension of the inflow is controlled by larger-scale, higher-altitude fluctuations in temperature and humidity advection.

During summer 2006, the intensity of the SHL exhibited a strong decrease during the first couple of weeks of September. Simultaneously, widespread convective activity over the Sahel was detected. Lavaysse *et al.* (this SI) analyse the reasons for this decrease of SHL activity, the possible relationship with convection, and assess the representativeness of such an event on a climatological time-scale. Unfavourable conditions in the 3–10 days band-period are associated with moist and cool advection in the lower troposphere linked to the southerly sector of AEWs, which increases the convective activity over the Sahel. This humid and cold advection is more pronounced when the AEW interacts with a midlatitude depression. In the 10–30-day period, the impact of midlatitude circulation is evidenced. During the collapsing period of the 10–30-day pulsations of the SHL thickness, an upper-level trough is seen over northern West Africa. This situation generates a surge of cold air at 700 hPa from Libya into the Sahara, an increase of the 925 hPa anticyclonic circulation and a significant increase in convective activity over the Sahel.

Couvreux *et al.* (this SI) investigate the synoptic variability of the monsoon flow during the establishment of the WAM using observations and ECMWF analyses. They highlight variability at a 3–5-day time-scale, characterized by successive northward excursions of the monsoon flow. They propose a conceptual model of these so called monsoon surges where the SHL reinforcement is the driving mechanism to accelerate the low-level meridional wind. Budget analysis of mesoscale simulations suggest that turbulent mixing also plays a significant role by vertically redistributing moisture and in shaping the low-level flow. Such surge events are in some cases coupled with AEWs.

After the monsoon onset, monsoon surges still occur but are strongly coupled with enhanced convective activity. Cuesta *et al.* (this SI) provide intriguing examples of intense rainfall events over the Hoggar Massif where monsoon bursts have been identified as the major controlling factor. They are particularly valuable over these northern areas, where rainfall events are scarce. Strong links between bursts and other synoptic features such as the AEW, the SHL circulations and eventually convectively generated cold pools have been established; they actually connect the Hoggar rainfall to the WAM.

3.3. Convection

Barthe *et al.* (this SI) investigate the multi-scale processes associated with a sequence of convective events occurring over Niamey during the period 25–26 July 2006. This period corresponds to an intense monsoon surge and to the passage of a strong AEW. The large SOP dataset, in particular the UHF radar and the MIT Doppler radar in Niamey, are used in combination with realistic high-resolution (5 and 10 km) nested simulations to understand the convective organization and its interaction with the environment. It is suggested that MCSs generally act to reduce the monsoon flow and to generate southerlies at midlevels, which can enhance the rotation of the wind at the AEW trough passage. Also the low-level wind shear weakening and rotation to the north appear together as an important ingredient to explain the suppressed character of the convection after the trough passage.

Chong (this SI) provides a detail documentation of the 11 August 2006 fast-moving squall line as observed from the MIT Doppler radar in Niamey. Results of the wind synthesis reveal several features commonly observed in tropical squall lines, such as the deep convective cells in front of the system, fed by the monsoon air and extending up to 15 km altitude, and the well-marked stratiform rain region at the rear, associated with mesoscale vertical motions.

Risi *et al.* (this SI) investigate the evolution of stable water isotopic composition of the rain as observed during the passage of four squall lines over Niamey. Despite a large variability among the different events, some robust isotopic features appear. Owing to the development of a 2D transport model representing microphysics and isotopic fractionation, and forced by the wind field retrieved by Chong (this SI), they point to subsidence in the rear of the system as well as rain re-evaporation as key processes affecting the isotopic composition.

Two studies focus on analysing relationships between radar variables and rainfall rates for the storms observed over Niger and Benin, both on a statistical and on an individual storm basis. Gosset *et al.* (this SI) used polarimetric weather radars, rain-gauge network and disdrometers to analyse the convective systems and the rainfall in Benin. Three years of disdrometer data acquired during the Enhanced Observing Period (EOP) are used to compute theoretical relationships between X-band polarimetric variables and rainfall rates for the region of interest. Results from direct comparisons between X-band polarimetric radar estimates and rain-gauges are found to be consistent with the disdrometer-based analysis.

Russell *et al.* (this SI) used two years of MIT C-band radar observations and rainfall measurements in Niamey to establish power-law relationships between calibrated radar reflectivity (Z_e) and rainfall rates (R) for the convective and stratiform regions of individual squall lines. They show that comparisons of radar and gauge measurements of storm total rainfall show substantially better agreement for the stratiform regime than the convective regime. They also provide evidence that the prefactors in the Z_e-R power-law fits are systematically smaller than prefactors for published $Z-R$ fits on disdrometer data, but that this discrepancy does not impair the rainfall estimates using the radar data.

3.4. Anvils

Radar studies during AMMA of the mesoscale anvils trailing West African squall lines in papers of this SI by Chong, Evaristo *et al.* and Russell *et al.* have shown front-to-rear extents as great as any squall lines anywhere in the world. Polarimetric radar observations (Evaristo *et al.*), vertically-pointing W-band radar observations (Penide *et al.*), *in situ* aircraft sampling (Bouniol *et al.*) and microphysical modelling studies (Penide *et al.*) are consistent in showing that rimed aggregates are the dominant hydrometeor type in the mesoscale anvils above the radar bright band. Co-ordinated measurements with surface electrical sensors, global extra-low frequency (ELF) sensors and C-band radar observations (Williams *et al.*, this SI) have shown that these mesoscale anvils are strongly electrified and produce the energetic spider lightning and ground flashes of positive polarity causal to sprites in the mesosphere over the African continent.

Finally Protat *et al.* (this SI) explore and compare the statistical properties of tropical ice clouds generated by the West African and Australian monsoons from ground-based radar–lidar observations. In particular, over Darwin the frequency of ice cloud occurrence is much larger, thicker and with a larger diurnal cycle than over Niamey. In contrast, ice clouds over Niamey are characterized by smaller particle sizes and fall speeds but in much larger concentrations, thereby carrying more ice water and producing more visible extinction.

3.5. Dynamics

Several papers address the dynamics of specific meteorological phenomena within the WAM system using field observations and modelling case-studies (Grams *et al.*, this SI; Schwendike *et al.*) as well as statistical investigations of gridded analysis and satellite data (Leroux *et al.*).

Schwendike *et al.* (this SI) investigate the transition of mesoscale convective systems embedded in an AEW over the West African continent into Hurricane Helene over the eastern tropical Atlantic, using budgets of potential temperature and relative humidity. They find significant differences between the structure of convection over land and water including an upward increase of relative vorticity due to eddy fluxes over the continent and a downward increase due to stretching over the ocean. Interestingly, the cyclogenesis was initiated when the mid-level vorticity associated with the AEW moved over a positive low-level vorticity anomaly originating in the Saharan heat-low.

Leroux *et al.* (this SI) use time filtering and regression analysis to investigate the relationship between the AEJ, AEWs and convection on synoptic to intraseasonal time-scales. They find that episodes of enhanced transient perturbation kinetic energy are characterized by a strengthened AEJ in the jet entrance region and enhanced convection over Darfur prior to the peak activity, followed by a northward displacement in the jet exit regions consistent with forcing by AEW-like transients. Increased transient activity is associated with enhanced convection at the regional scale on intraseasonal time-scales.

Hagos and Zhang (this SI) propose a methodology for identifying the distinct physical processes shaping atmospheric circulations within the WAM as seen from different reanalyses. The divergent circulation is partitioned into latent-heating and non-latent-heating driven components, and their relative role on the moisture transport is analysed. They emphasize in particular the significance of the shallow meridional circulation for the WAM and point to substantial drying induced by remote deep convection via advection over the Sahel.

3.6. Coupling with surfaces (ocean and continent)

De Coetlogon *et al.* (this SI) analyse statistically the intraseasonal variability of the ocean–atmosphere coupling in the Gulf of Guinea during boreal spring and summer, largely on the basis of satellite observation. In particular the role of the St Helena anticyclone in setting up the SST anomaly, and its negative feedback, are suggested resulting in a 2-week oscillation. The potential impact of this mode of variability on the WAM variability and on its onset in particular needs further investigation.

The AMMA campaign has enabled the provision of new scientific contributions pertaining to the strength and importance of land–atmosphere feedbacks in the Sahel region. Time series of surface and soil measurements combined with frequent radiosoundings collected during the SOP at specific locations confirmed the dominant role of near-surface conditions on the convective boundary layer state (Kohler *et al.*, this SI). For documented mesoscale convective systems, aircraft measurements and satellite imagery have revealed that soil moisture heterogeneities tend to favour the initiation of convection over dry soils, whereas more intense mature convection was noticed over pre-existing wet soils (Taylor *et al.*, this SI). Sensitivity studies performed with numerical models simulating the passage of mesoscale convective systems over dry or wet soil anomalies (Gantner and Kalthoff, this SI; Gaertner *et al.*, this SI) reached different conclusions, thereby indicating the complexity of soil moisture–precipitation feedbacks.

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