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The West African climate system: a review of the AMMA model inter-comparison initiatives

P. M. Ruti,[1]* J. E. Williams,[2] F. Hourdin,[3] F. Guichard,[4] A. Boone,[4] P. Van Velthoven,[2] F. Favot,[4] I. Musat,[3] M. Rummukainen,[5] M. Domínguez,[6] M. Á. Gaertner,[6] J. P. Lafore,[4] T. Losada,[7] M. B. Rodriguez de Fonseca,[7] J. Polcher,[3] F. Giorgi,[8] Y. Xue,[9] I. Bouarar,[10] K. Law,[10] B. Josse,[4] B. Barret,[11] X. Yang,[12] C. Mari[11] and A. K. Traore[13]

[1] *ENEA-UTMEA, Climate and Impact modeling Lab, Roma, Italy*
[2] *KNMI, Chemistry and Climate Division, AE De Bilt, the Netherlands*
[3] *L.M.D., Jussieu, CNRS/UPMC, Paris, France*
[4] *CNRM-GAME, Meteo France, Toulouse, France*
[5] *SMHI and Lund University, Lund, Sweden*
[6] *Instituto de Ciencias Ambientales, Universidad de Castilla la Mancha, Toledo, Spain*
[7] *Departamento de Geofisica y Meteorologia, Facultad de Ciencias Fisicas, Universidad Complutense, Madrid, Spain*
[8] *ICTP, Trieste, Italy*
[9] *Department of Geography, UCLA, Los Angeles, CA, USA*
[10] *LATMOS-IPSL, UPMC Univ. Paris 06, UVSQ, CNRS/INSU, Paris, France*
[11] *Laboratoire d Aerologie, UMR5560 CNRS/UPS, Universite de Toulouse, Toulouse, France*
[12] *Department of Chemistry, Centre for Atmospheric Science, University of Cambridge, UK*
[13] *LPAOSF, UCAD, Dakar, Senegal*

**Correspondence to:
P. M. Ruti, ENEA, Climate Section, SP91, Via Anguillarese 301, 00060 Roma, Italy.
E-mail: paolo.ruti@enea.it*

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Abstract

We review the African Monsoon Multidisciplinary Analysis (AMMA) model inter-comparison activities for West Africa. The Model Inter-comparison Project is an evaluation exercise of how global and regional atmospheric models represent seasonal and intra-seasonal variations of the climate and rainfall over the Sahel. The Land surface Model Inter-comparison Project in turn focuses on modelling critical land surface processes over West Africa and on their link with the atmosphere. The CHEmistry Model Inter-comparison Project (CHEMIP) is a comparison of the tropospheric composition as simulated by a number of Chemical Transport Models (CTM) and Chemistry-Climate Models. We highlight the main model limitations and provide recommendations for future development. Copyright © 2011 Royal Meteorological Society

Keywords: **regional and global model uncertainties; systematic errors; African monsoon**

1. Background

Global coupled climate models are not yet mature enough to simulate the West-African climate accurately (IPCC 2007, AR4). For example, a number of models do not locate the rainfall maxima over West Africa correctly during the monsoon season (Cook and Vizy, 2006). It is difficult to determine the most relevant error sources in terms of processes and parameterizations considering only individual coupled simulations (Cook and Vizy, 2006; Biasutti *et al.*, 2008). Better guidance can be gained by systematic approaches with targeted inter-comparison experiments. The recent African Monsoon Multidisciplinary Analysis (AMMA) project (Redelsperger *et al.*, 2006) provided the framework to develop such an approach. The main goal of AMMA was to achieve a better understanding of the processes underlying the West-African Monsoon (WAM).

A specific part of the project was dedicated to the following:

1. Evaluating the modelling tools involved in AMMA and identifying their weaknesses
2. Making the model results available for use in operational planning and in wider scientific activities

Prior to AMMA, the deficiencies with respect to model development and assessment for the African monsoon stemmed from the paucity of observations at sufficient spatial and temporal resolutions and from the complexity of the interactions across the biosphere, atmosphere and hydrosphere over this region, which occur at a range of temporal and spatial scales. In AMMA, a high priority was given to the influence of the spatial and temporal variability of surface processes on the atmospheric circulation patterns and the regional-scale water and energy cycles. This led to the evaluation of new model components such as atmospheric chemistry and aerosols. This is particularly relevant as the chemical composition of the atmosphere over Africa is significantly influenced by emissions of trace gases and aerosols from natural and anthropogenic surface and tropospheric sources.

Moreover, the long-range transport of tropospheric pollutants can have important effects. For example, transport of ozone out of southern Africa during the dry season induces a strong influence on the marine boundary layer over the tropical Atlantic (Williams *et al*., 2009) and the tropical upper troposphere (Real *et al*., 2010). In addition to enhancing the radiative forcing in the Tropics through enhanced absorption on incoming solar radiation, such pollutants affect the local air quality (and thus crop yields), precipitation patterns and the atmospheric lifetime of greenhouse gases such as methane (Mari *et al*., 2011, and references therein for further discussion).

The strategy of model evaluation within AMMA was to develop focused exercises on particularly important components of the systems, which can provide insights into specific relevant processes. This is addressed through an integrated approach by performing three main inter-comparison exercises:

1. *Land surface modelling (LSM)*: the AMMA Land Surface Model Intercomparison (ALMIP) was conceived as a step towards a better understanding and description of surface processes over West Africa (Boone *et al*., 2009a). The first ALMIP phase included simulations with the land surface running in off-line or uncoupled (without atmospheric feedbacks) mode. The idea was to develop a forcing database with the best quality and highest spatial and temporal resolution data available and use this database to force state-of-the-art LSMs in order to better understand key processes at different scales. (http://www.cnrm.meteo.fr/amma-moana/amma_surf/almip/index.html.)
2. *Regional and global climate models*: the AMMA-MIP (AMMA Model Intercomparison Project) exercise aimed to test the performance of global climate models (GCMs) and regional climate models (RCMs) over the WAM region in terms of different monsoon features (e.g., jumps and breaks in monsoon rainfall, their relation with the mean meridional circulation, penetration of the monsoon flow, strength of the Saharan heat low and surface fluxes), using AMIP sea surface temperature data. Because they are of prime importance for impact studies, the inter-comparison is focused on hydrological parameters and convection at seasonal and intra-seasonal time scales. Key years that were selected for the study are 2000 (dry year in the Sahel), 2003 (relatively wet year) and the AMMA field campaign year of 2006.

The AMMA-MIP (Hourdin *et al*., 2010) favoured the collaboration with other international initiatives, such as the ENSEMBLES-EU project and its GCM and RCM simulations (van der Linden and Mitchell, 2009), and the West African Monsoon Modeling and Evaluation project (WAMME, GEWEX/CEOP initiative, Xue *et al*., 2010).

3. *Modelling the atmospheric composition (aerosols and trace gases)*: the CHEMIP (CHEmistry Model Intercomparison Project) evaluated the capability of existing models to represent the distribution of aerosols and trace gases over West Africa, and their interaction with the dynamics of the WAM. The recently derived L3JRCv2 emission dataset was adopted with both anthropogenic and biomass burning components (Liousse *et al*., 2010). Simulations were performed for both the selected evaluation year (2000) and the AMMA measurement year of 2006, using four different large-scale global chemistry transport models (CTMs): TM4, p-TOMCAT, MOCAGE and LMDz_INCA (see Williams *et al*., 2010a for further details). The models were either forced or nudged with meteorological analyses. Using a pre-defined 2D cross section (averaged between 3°W and 6°E), monthly and seasonal averages of selected trace gas species and passive tracers introduced to investigate convective transport were compared. The models exhibited diverse behaviour over West Africa in terms of convective uplift, advective mixing and the composition of the tropical troposphere (Williams *et al*., 2010a).

In Sections 2 and 3, we briefly highlight the main deficiencies that have been identified across the various models and in Section 4 we outline the issues associated with future improvement of LSMs, climate models and large-scale CTMs in the Tropics.

2. Current limitations of land-surface and climate models

In the ALMIP inter-comparison (Boone *et al*., 2009a), a dozen different groups from the international community performed multi-year off-line simulations (2002–2007) over West Africa using multiple forcing input datasets. In terms of evaluation, the LSMs were able to produce spatial and temporal soil moisture patterns consistent with remotely sensed brightness temperatures (de Rosnay *et al*., 2009). Using aggregated fluxes from local-scale observational sites from the Mali Supersite (Timouk *et al*., 2009), grid-scale ALMIP surface sensible heat flux estimates were found to have the same basic response (amplitude and phase) as the observations during the wet season. Finally, ALMIP-simulated continental water storage changes were shown to compare well with estimates from GRACE (http://www.csr.utexas.edu/grace/asdp.html), especially in terms of the representation of the inter-annual variability. The results were used to evaluate both RCMs and GCMs within two inter-comparison efforts; the AMMA-MIP and WAMME (Boone *et al*., 2009b; Xue *et al*., 2010).

The AMMA-MIP exercise emphasized the difficulty of current climate models to correctly simulate the WAM (Hourdin *et al*., 2010). Although climate models are able to capture the main seasonal migration of rainfall over the Sahel along with the significant intra-seasonal variability associated with the mean zonal

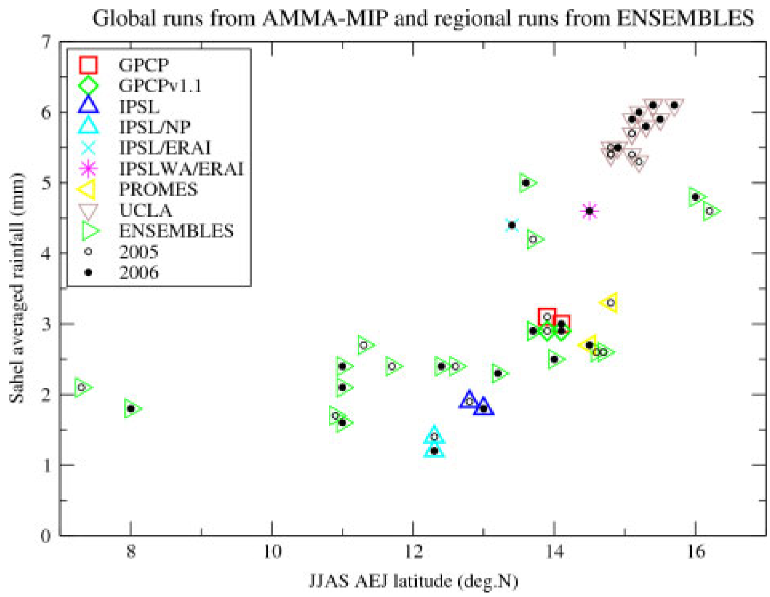

Figure 1. Latitude of African Easterly Jet (AEJ) *versus* mean rainfall over a Sahelian box (10 °W–10 °E, 13°–18°N) for all of the AMMA-MIP simulations and of the ENSEMBLES-RCMs outputs, for the Global Precipitation Climatology Project (GPCP), for JJAS season and 2005 (open circles) and 2006 (filled circles) years. The AEJ latitude for GPCP corresponds to the ERA-40 re-analyses.

wind, there is still an excessive spatial spread in the cumulative rainfall over the Sahel. A part of this dispersion is attributable to a latitudinal shift in the monsoon system compared with that in observations. The AMMA-MIP first results confirmed that the choice of the convection scheme significantly affects the model behaviour over the region and that surface fluxes show large biases.

Figure 1 shows a synthetic view of the AMMA-MIP results concerning the cumulative rainfall over the Sahel, along with the corresponding results from the ENSEMBLES-RCMs. A positive correlation between the AEJ core latitude and Sahelian mean rainfall is visible in the multi-model multi-run AMMA-MIP and ENSEMBLES-RCMs database, which suggests that a large part of the model biases derives from latitudinal shifts in the whole monsoon system. Noteworthily, past dry and wet years have been characterized by the strength of AEJ (Newell and Kidson, 1984). Moreover, it is possible to argue that higher rainfall leads to a northward shift of the WAM by increasing the potential vorticity (PV) anomaly to the south of the AEJ (Schubert *et al.*, 1991; Thorncroft and Blackburn, 1999). Moreover, it has been demonstrated that appropriate model output statistics could reduce the rainfall error using dynamical fields such as the AEJ (Philippon *et al.*, 2010).

Variations in surface conditions are shown to influence the position and intensity of the AEJ (Cook, 1999). At least in idealized GCM experiments, the jet features are determined by the intensity and position of the strong temperature gradient near the latitude of the jet. Figure 2 shows some results of surface sensible and latent heat fluxes and downward shortwave (SW) fluxes. We consider all available simulations, and compare them with several re-analysis and observational data. Note that ERA-Interim and ERA-40 surface downwelling SW radiation are short-term forecast products whose reliability depends on the model behaviour within the Tropics. The RCMs, constrained by boundary conditions from the ERA-Interim re-analysis, show a generally better behaviour than GCMs that show a large inter-model spread and a tendency to overestimate the SW flux. A noteworthy finding is that both the AMMA-MIP and ENSEMBLES-RCM simulations show a positive SW bias over the heat low (Figure 2(a) and (b)), whose complex behaviour has been characterized for the first time during the AMMA project (Lafore *et al.*, 2011). Regarding the latent heat flux, the ALMIP data are used as a re-analysis product (mean and inter-model spread) and are compared with the model results (Figure 2(c) and (d)). GCMs show a tendency to overestimate the fluxes over the coastal region (south of the Sahelian band), while both RCMs and GCMs have a similar behaviour over the Sahelian band and northwards. Therefore, large-scale circulation systematic errors can partially explain the GCM behaviour. Recent papers suggest that the surface schemes and their interactions with the atmosphere also play a relevant role (Steiner *et al.*, 2009; Wu *et al.*, 2009; Alo and Wang, 2010; Xue e*t al.*, 2010) in improving the simulation of the WAM. The relationship between the surface fields and the dynamical behaviour of WAM has been widely diagnosed by the AMMA intercomparison initiatives (AMMA-MIP, Hourdin *et al.*, 2010; ALMIP, Boone *et al.*, 2009b; WAMME, Xue e*t al.*, 2010).

3. Current limitations of chemistry models

The inter-comparison of large-scale 3D chemistry and transport models (CTMs) for the African region has

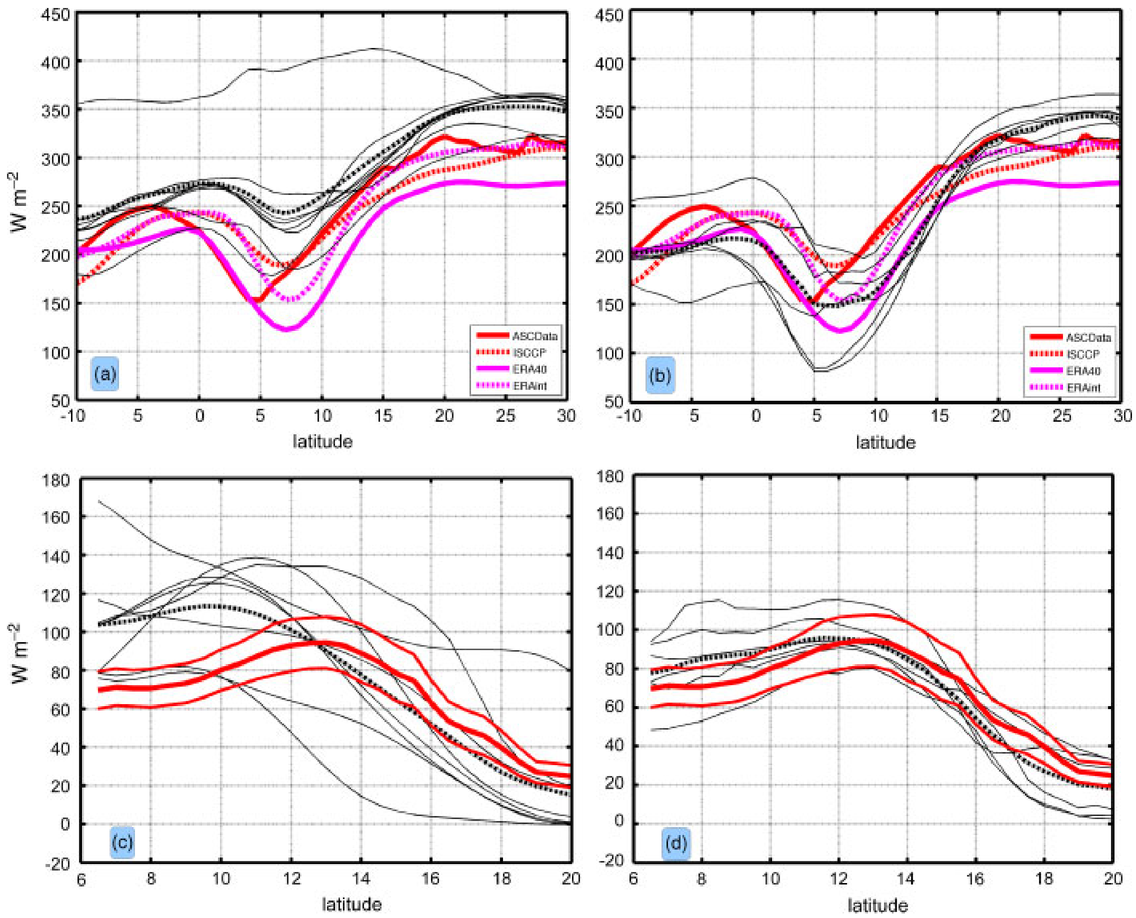

Figure 2. . Meridional profile (average 10°W–10°E). (a) Downward SW radiation for AMMA-MIP simulations (thin lines; dashed-dot line Ensemble Mean), observational data (NASA-ASCD, ISCCP) and re-analysis (ERA40, ERA-interim) – July–August 2003 average. (b) As for (a) but for ENSEMBLES-RCM simulations.(c) Latent heat flux for AMMA-MIP simulations (thin lines, dashed-dot line ensemble mean) and ALMIP re-analysis, mean and confidence interval – red lines (July–August 2003 average). (d) As for (c) but for ENSEMBLES-RCM simulations (Units, W m^{-2}).

shown that although there are diverse behaviours concerning both convective and advective transport in the tropical troposphere (Williams *et al*., 2010a), common discrepancies for the tropical region are also present (see Figure 3 for the variability between the different chemical schemes employed with respect to the OH radical). For equatorial Africa (EA) during the WAM, the result is very weak transport of CO to the north of the Equator in the middle troposphere, partially as a result of the meteorological fields used to drive such models placing the AEJ-S in the Southern Hemisphere (Williams *et al*., 2010b), and very strong transport of CO in the upper troposphere (Barret *et al*., 2010). This feature occurs for a number of different biomass burning emission inventories, in spite of a recent effort to improve the accuracy of such emission estimates (Liousse *et al*., 2010). Considering that the frequency of wildfires is likely to increase in a drying climate (Flanningan *et al*., 2009), the influence of burning events on the tropical troposphere will become more important in future decades, especially from perturbations in the frequency and strength of the El Niño Southern Oscillation. Another limitation regarding emission sources is that, e.g., the effect of variability in rainfall on emissions from soil and vegetation, which has been shown to be important for Central Africa (Delon *et al*., 2008; Williams *et al*., 2009), is difficult to capture even when using sophisticated approaches which include detailed information on land and vegetation type (Ferreira *et al*., 2010). Increased biogenic activity in a warmer, wetter climate for tropical regions has the potential to increase the importance of this emission source in Africa in future decades (Hauglustaine *et al*., 2005). Thus, either more robust biogenic emission algorithms or improved data regarding changes in e.g., land use are required.

The production of nitrogen oxides by lightning ($LiNO_x$) also remains a large source of uncertainty concerning upper tropospheric O_3 in the Tropics. Although the largest impact of the WAM $LiNO_x$ source is simulated over the tropical Atlantic ocean across a range of global CTMs, the different parameterizations for the description of $LiNO_x$ and convection are responsible for large differences concerning the amount of $LiNO_x$ produced during the WAM (a factor of 3–4) and the latitude of maximum impact (5–15°N) (Barret *et al*., 2010). The lack of measurements of NO_x profiles in the Tropics often means that those measured at mid-latitudes are

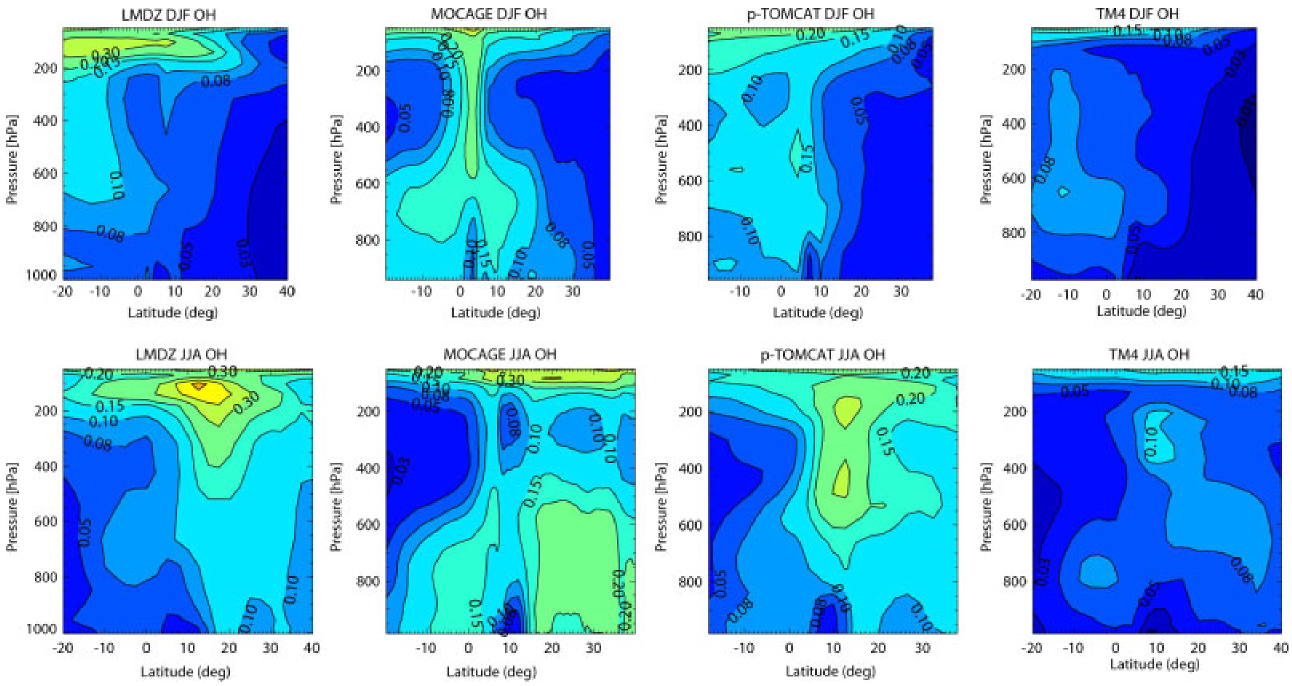

Figure 3. Seasonal DJF and JJA comparisons of OH radical concentrations (pptv) between the four CTMs involved in the AMMA inter-comparison exercise of chemistry models. The distribution and magnitude of this very shortlived trace species governs the cleansing capacity of the African troposphere and atmospheric lifetime of trace gases such as methane.

often adopted globally. Moreover, the distribution of inter-cloud and cloud-to-ground flashes, which most large-scale parameterizations adopt (Price and Rind, 1993), has recently been re-assessed altering the ratio from 9 : 1 towards unity, which has the potential to redistribute $LiNO_x$ through the troposphere (Ott *et al*., 2010).

The growth of mega-cities is estimated to be ~2.7% year^{-1} (Gurjar and Lelieveld, 2005), thus large conurbations such as Lagos, Nigeria and Nairobi, Kenya will become more important for local air quality in the twenty-first century. For instance, emissions of CO and volatile organic compounds from increased use of motor vehicles, local (small-scale) power generation and waste incineration are already estimated to be high around, e.g., Lagos, Nigeria (Hopkins *et al*., 2009), meaning that any subsequent increases will result in poorer air quality by increasing particulate matter, organic aerosols and photo-chemical smog formation. Finally, to assess whether large-scale models have the ability to capture the changing atmosphere over Africa requires more frequent measurements to be made throughout the continent. The scarcity of long-term datasets for the region currently makes it difficult to assess whether the current generation of large-scale models is adequate for simulating the tropical troposphere.

4. Conclusions and outlook

There is an increasing focus in the research community on climate model evaluation and improvement. The WCRP program CMIP5 (Coupled Models Intercomparison Project, 2008–2013) will provide a strong operational framework towards this purpose. Regarding RCMs, the CORDEX program (Cordinated regional climate Downscaling Experiment, Giorgi *et al*., 2009), another WCRP initiative, will develop a framework to evaluate and improve the regional climate downscaling techniques. The AMMA model inter-comparison experience provides a relevant contribution in terms of diagnostics and metrics for model assessment and improvement.

Regarding the LSMs, the AMMA results showed that they tend to underestimate surface sensible heat flux and possibly baseflow runoff and overestimate evaporation from the vegetation canopy. During the monsoon season, evapotranspiration is generally the most significant component of the water budget, acting to recycle much of the rainfall, in particular, over the Sahel. However, qualitative estimates of recycling by the LSMs must be interpreted in view of the fact that the LSMs have a large inter-model scatter over the Sahel. Finally, there is considerable inter-model scatter in the simulation of the meridional gradient in evapotranspiration, which is a concern as this is very likely the most relevant surface influence on the regional atmospheric circulation. Towards the integration of new model components, hydrological schemes will be incorporated at the mesoscale. This scale is important because the spatio-temporal resolution of the observational network within the AMMA mesoscale study areas is quite high and will therefore aid in developing a more realistic representation of the surface parameters at the regional scale.

According to the AMMA-MIP inter-comparison, there is a good correlation between the cumulated rainfall over the Sahel and the latitude of the AEJ, suggesting that part of the biases come from deficiencies in capturing the latitudinal location of this monsoon structure. The surface fluxes, which strongly affect the WAM dynamics, are not realistically represented in most of the AMMA GCMs and RCMs (AMMA-MIP and WAMME results). The downward SW has evident biases over the heat low latitudes. Promising model improvements have been implemented and tested to address this problem. The use of a Planetary Boundary Layer (PBL) scheme that includes vertically integrated PBL turbulent kinetic energy (University Complutense of Madrid) has resulted in a significant improvement of the simulated latent and sensible heat fluxes, leading to a better simulation of the precipitation and dynamics associated with the WAM system. The inclusion of atmospheric aerosols could be another relevant contribution to reduce the SW biases and to improve the climate models skill over the region. Last but not least, we should better quantify the relationship between large-scale and regional/local contribution to the model errors over Western Africa.

One main focus for the next-generation large-scale atmospheric chemistry models should be the incorporation of improved coupling with other components of the climate system. For instance, many models are moving towards aerosol modules coupled to precipitation and dynamics and the inclusion of biogenic emission modules (Guenther *et al.*, 2006) dependent on temperature, solar irradiance and soil moisture. It is also clear that improvements are needed to anthropogenic emission inventories with recent data showing high and increasing levels of pollutants in African cities. Although there are still uncertainties associated with the modelling of the composition of the present atmosphere, efforts are ongoing to couple CTMs with either GCMs or forecast systems to allow future decadal scale. Another important point is that new knowledge is still needed on key chemical processes relevant for the atmosphere (e.g., OH oxidation, Lelieveld *et al.*, 2008). This necessitates the further development of parameterizations for the inclusion of new reaction pathways as observed in recent laboratory studies (Paulot *et al.*, 2009). Moreover, inclusion of the chemical conversion and scavenging of trace gas species in atmospheric aerosols is still ongoing, and the perturbations they introduce via enhanced scattering and absorption of solar radiation are other important effects that require a proper treatment.

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