AMMA forcing data for a better understanding of the West African monsoon surface–atmosphere–hydrology interactions

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Abstract West Africa has been subject to extreme climatic variability over the last half century which has lead to dramatic socio-economic consequences for the people and the relatively agrarian-dominated economies of this region. Seasonal to inter-annual prediction of the West African monsoon (WAM) has proven difficult due to both the paucity of observations at sufficient space–time resolutions, and because of the complex interactions of processes between the biosphere, atmosphere and hydrosphere. One of the main goals of the AMMA (African Monsoon Multidisciplinary Analysis) project is to improve the understanding and prediction of the WAM in order to ameliorate sustainable water management and related activities. Land–atmosphere coupling is theorized to be significant in this region, thus improvement of the modelling of the related processes is critical. To this end, a multi-scale land-surface model atmospheric and land-surface parameter forcing database is being constructed. One of the main uses of this database is to drive a host of land surface, vegetation and hydrological models over a range of spatial scales in order to gain better insights into the attendant processes.

Key words AMMA; hydrology; land surface models; forcing database; West Africa; monsoon

INTRODUCTION

West Africa has been subject to extreme climatic variability over the last half century, with relatively wet years during the 1950s and 1960s being followed by a much drier period during the 1970s–1990s. These radical fluctuations in the regional hydro-meteorological regime correspond to one of the strongest inter-decadal signals observed for the entire planet over the last century, and they have had dramatic socio-economic consequences for the people and the relatively agrarian-dominated economies of this region. Seasonal to inter-annual prediction of the West African monsoon (WAM), which is the main precipitation driving mechanism, has therefore become a research topic of importance. However, difficulties modelling the African monsoon arise from both the paucity of observations at sufficient space–time resolutions, and because of the complex interactions of the attendant processes, at various temporal and spatial scales, between the biosphere, atmosphere and hydrosphere over this region. Land–atmosphere coupling is theorized to be significant in this region of the globe (e.g. Koster *et al*., 2004). At the small scale, these interactions have an impact on convective cells within mesoscale storm systems, while at the regional scale they influence the position of the Intertropical Convergence Zone and the African

East Jet through a significant meridional surface flux gradient (Taylor *et al*., 1997), thus improvement of the modelling of the related processes is critical.

One of the main goals of the AMMA (African Monsoon Multidisciplinary Analysis) project is to improve the understanding and prediction of the WAM on both relatively short (sub-diurnal to several days) and long (seasonal) timescales in order to improve sustainable water management and related activities over western Africa. This is being addressed through a prolonged period of intensive and enhanced multi-year field observations, and through the development and use of various remote sensing-based products. To this end, a multi-scale land-surface model atmospheric and land surface parameter forcing database is being constructed using a variety of sources: numerical weather prediction (NWP) forecast data, remote sensing products and local scale observations.

One of the main applications of this database, which is currently under development, is to use the data to drive a host of land surface, vegetation and hydrological models over a range of spatial scales (local to regional) in order to gain better insights into the attendant processes. This is being done under the auspices of the AMMA Land surface Model Intercomparison Project (ALMIP), and through the development of an African Land Data Assimilation System (ALDAS). The offline simulated land surface state will have several potential uses. For example, the simulated state's surface fluxes will be compared to Global Climate Model (GCM) output as a part of the international West African Monsoon Modelling and Evaluation (WAMME: http://wamme.geog.ucla.edu) project. In addition, the offline simulated "realistic" soil moisture state will be used to investigate its impact on the initiation and subsequent life cycle of convection over West Africa through mesoscale atmospheric modelling studies.

DATABASE COMPOSITION

The land surface model forcing database is comprised of two components, one for the land surface parameters, and the other consisting of the atmospheric state variables, precipitation and downwelling radiative fluxes. The database considers three scales: regional, meso and local. The regional scale domain covers the rectangle defined as: –5 to 20°N, –20 to 30°E, at a 0.50 degree spatial resolution. The mesoscale domain is encompassed by the CATCH sub-regional window (which also contains the three mesoscale intensive study sites, see Fig. 1), and forcing is at a 0.10 degree resolution herein. Observational data from additional sites are being added as data is recovered from the EOP (Extended Observation Period: 2005–2007) and SOP (Special Observation Period: 2006) campaigns. This data also includes model evaluation metrics, such as soil moisture, surface fluxes, vegetation and hydrological measurements.

Soil and vegetation parameters

The land surface parameters (based on ECOCLIMAP from CNRM: Masson *et al*., 2000) are at a decadal temporal resolution, and are available at up to a 1-km spatial resolution. ECOCLIMAP consists of data and software: land surface data is

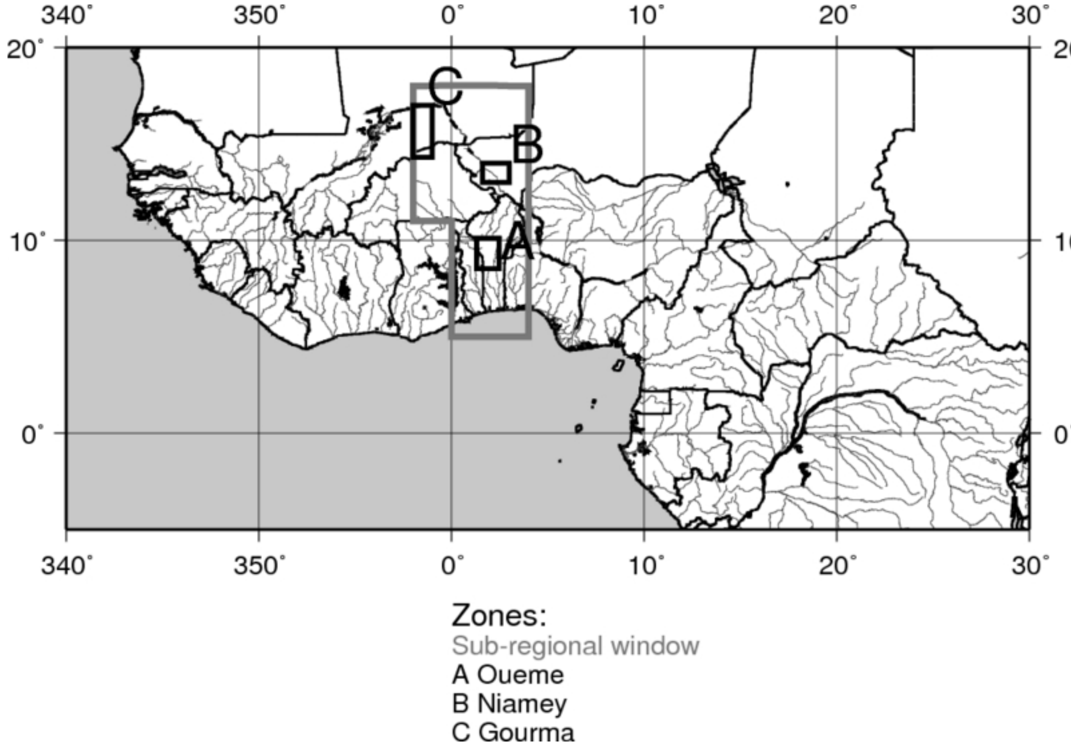

Fig. 1 The domain of the regional scale database. The sub-regional mesoscale database domain is indicated in grey, along with the location of the three intensive study zones, shown as thick rectangles. The name for each site is identified by a letter.

automatically scaled to the selected spatial scale using aggregation "rules" described in Masson *et al*. (2000) which are based, in large part, on the work of Noilhan & Lacarèrre (1996). The land surface parameters are therefore currently available at the regional (0.5 deg.) and mesoscale (0.10) spatial resolutions. Note that ECOCLIMAP is a climatology developed for NWP and GCM models, and currently there is one representative average annual cycle (i.e. the vegetation properties do not vary from one year to the next). The use of MODIS LAI data (monthly at a 0.01 degree resolution) from AMMA-SAT to modify ECOCLIMAP parameters is under investigation (which would be used to provide an additional set of vegetation parameters with inter-annual variability).

Atmospheric forcing

Local-scale forcings and observations are being incorporated as they become available after post-processing (removal of bad data, filling of data gaps, corrections, etc.). Local scale data from the Gourma site for 2004 has been incorporated into the database (in collaboration with E. Mougin and L. Kergoat CNRS/CESBIO). Additional data will be incorporated from the SOP and EOP as they are processed and submitted to the AMMA database (AMMA-DB: http://amma-international.org/database). A summary of the various inputs and their relationship with each database (classified by scale) is shown in Fig. 2. The scales are: (a) regional (–20°W to 30°E, 5°S to 20°N, as in Fig. 1,

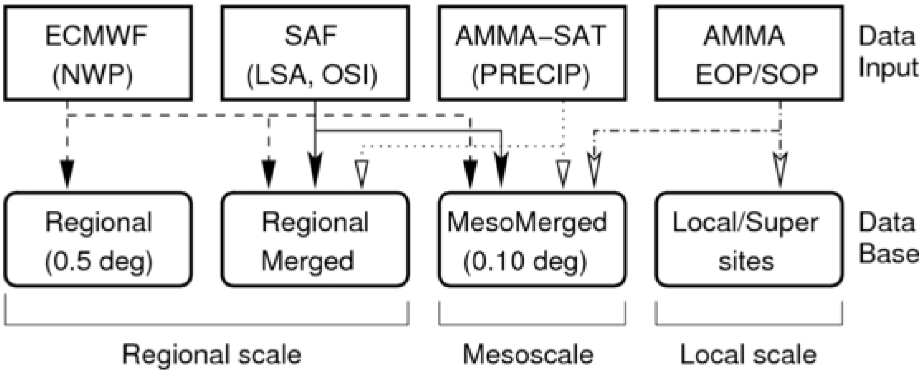

Fig. 2 Schematic showing the various sources for each of the scale-dependent components of the database. The rectangles in the upper part of the figure represent the various sources (see text for the definition of the acronyms), while the rounded rectangles in the lower part of the figure represent the four databases at three different spatial scales.

at 0.5 degrees and 3 hour resolutions); (b) mesoscale (CATCH window as shown in Fig .1, at 0.10 and 1 hour resolutions); and (c) local. SWdown, LWdown, PSurf, Tair, Qair, Wind, and Rainf represent the downwelling shortwave radiation, downwelling atmospheric longwave radiation, surface pressure, air temperature at 10 m above the surface, specific humidity at 10 m, wind speed at 10 m and rainfall (convective and large-scale components), respectively. The entire database has been written in NetCDF format using the standard map projections and grid definitions defined by the AMMA-SAT and AMMA-DataBase groups (Ramage & Cloche, 2003).

The regional scale atmospheric control forcing database currently consists in European Centre for Medium range Weather Forecasts (ECMWF) output forecast (FC) data. The so-called "merged" forcing database results from the merging of the aforementioned forecast data with satellite-based products from AMMA-PRECIP, GeoLand, and Satellite Application Facility (SAF) projects (see Fig. 2). Note that ECWMF deterministic forecast data is used as opposed to an ECMWF re-analysis product because currently such products are only available up to 2003. In addition, the forecast product is available at approximately two-times the spatial resolution of the reanalysis products over this region.

Land surface models (especially those used in meteorological applications) require forcing data with a time sampling adequate for resolving the diurnal cycle. In order to obtain a time series for forcing variables at each grid point, the 36-hour forecast beginning at 12:00 UTC (interpolated from the native ECMWF-FC model grid to one using a cylindrical equidistant/platte carré projection) each day was first obtained. Fields were extracted at the maximum available time step (three hours). Next, the first 12 hours of each 36-hour forecast period were removed in order to optimize the balance between mitigating the known precipitation spin-down problem in the ECMWF-FC model (Beljaars, 2004, pers. commun.; i.e. too much precipitation early in the forecast period as the model seeks an equilibrium state) and keeping the forecast period reasonably short (in order to minimize forecast errors). This process is repeated every 24 hours in order to obtain a continuous time series (using a three hour time step) over a several-year period.

Satellite-based forcing products

The ECMWF-FC product forms the basis for a control forcing database. This is referred to as the "control" because some model studies or applications use NWP data directly (ECMWF or National Center for Environmental Prediction (NCEP) data for the most part). It also represents the forcing that a coupled land-surface atmospheric model produces. However, many land surface or hydrological studies go a step further and merge NWP data with an ancillary product (based on satellite data or data from an observational network). The main advantages of incorporating satellite data are the improved spatial (and possibly temporal) coverage, and the fact that it can be used to improve or correct errors in NWP model fields (such as the positioning of regions of convection).

The most critical atmospheric variable is the precipitation (as NWP model errors in the location and intensity can be quite significant, especially in a convectively-dominant rainfall regime as found over the AMMA region). The next most critical variable is the incoming net radiation (as it provides the energy which drives the surface exchanges with the atmosphere). In this study, we take advantage of the availability of several new satellite-based products that are produced over West Africa. The precipitation probability product from AMMA-SAT called EPSAT-SG (Estimation des Pluies par SATellite – Seconde Génération; Chopin *et al.*, 2004) for 2004–5 has been interpolated from its native 3 km grid with a temporal resolution of 15 minutes, to a 0.10 degree grid and a time step of 30 minutes, in accordance with the conventions defined by AMMA-SAT (Ramage & Cloché 2003).

There is evidence that the monsoon (in terms of precipitation) simulated by the ECMWF model generally does not extend far enough to the north. This is illustrated in Fig. 3, where the July 2004 monthly average rainfall (expressed in mm day^{-1}) is compared to the EPSAT values on the 0.5 degree grid. Shown from the top panel down, is the precipitation from EPSAT (panel a), the precipitation from ECMWF (panel b) and the relative difference (c). Clearly, the EPSAT product shows a northward displacement of the monsoon, characterized by both increased precipitation to the north and decreased values along the southern coast.

The downwelling radiation products (shortwave and longwave) from the OSI-SAF (OceanS and Ice Satellite Application Facility) project are used for the monsoon season in 2004 (covering the same period as covered by EPSAT-SG, approximately June–September). The Land-SAF radiation products are used from July, 2005, onward. A comparison between the downwelling shortwave radiation from the OSI-SAF and the ECMWF model reveals that spatial patterns are similar, with minimum values along the southern coastline and maximum values over the Sahara, with a rather sharp N–S gradient. However, the OSI-SAF values are generally lower in the northern part of the domain between about –5°W and 10°W, which is associated with a further northward extension of the monsoon cloudiness. This emphasizes the importance of the use of ancillary (here satellite-based) information to derive forcings (in order to remove NWP model defaults or biases). Also, it is very important to maintain consistency between the radiation and precipitation products for land surface modelling. As all of the aforementioned (radiation and precipitation) satellite products are based on MSG, a certain degree of consistency is indeed expected.

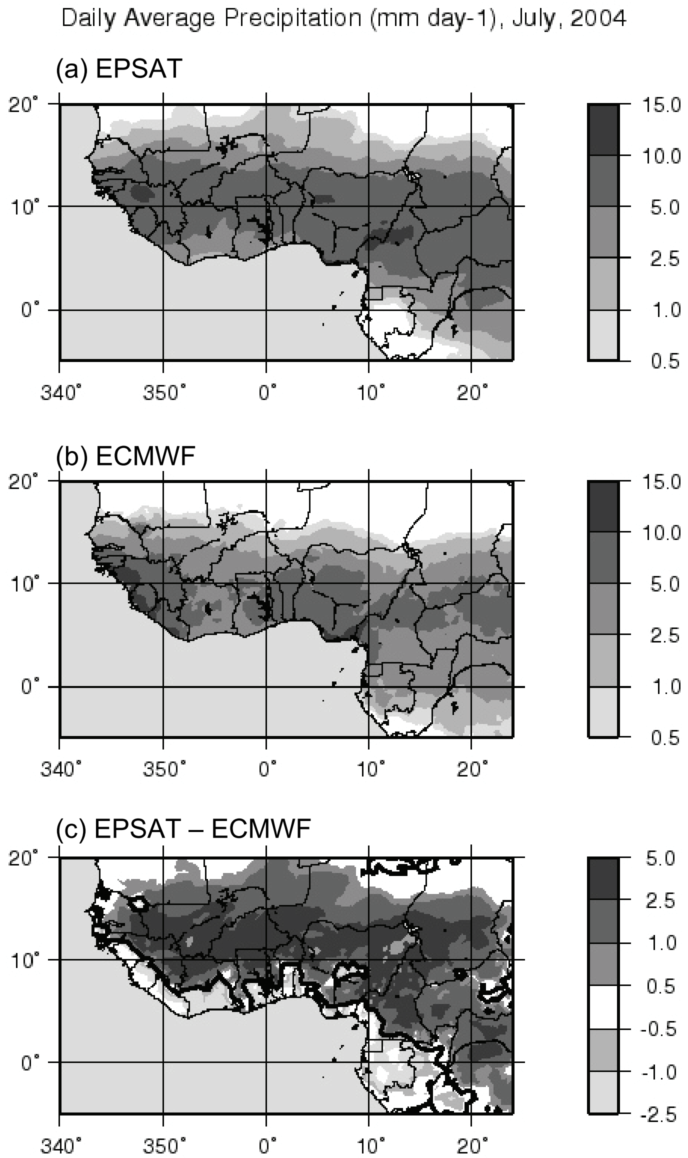

Fig. 3 Comparison between the EPSAT (a) and ECMWF (b) precipitation amounts for July 2004. The absolute difference in rainfall between EPSAT and ECMWF is shown in (c), where the thick black line marks the division between positive and negative differences.

As a final note, it is much more difficult to guarantee consistency between the satellite-based flux forcings (radiation, precipitation) and the NWP model atmospheric state variables (air temperature, specific humidity, wind, etc.). But in fact, this has been determined to be less critical on the regional scale. The reason for this is that the ECMWF forcings are provided at a three hour time step. The radiation and precipitation fluxes are averages (or cumulated values) over this time period, so that they have a “memory” of weather events occurring over the three hour time step. It is therefore critical that they be modified (using satellite or observational data) in a consistent manner. In contrast, the atmospheric state variables are instantaneous values and therefore have little to no memory, especially in a convective regime with relatively short characteristic timescales compared to the three-hour sampling (time step for output). The development of methods to force atmospheric state variables to be more consistent with changes in the atmospheric flux variables (radiation, precipitation) was explored, but it was found that general relationships were difficult to ascertain. It should be noted that, however, over the CATCH region, the increased observations of low level atmospheric state variables should contribute to a more coherent set of forcings (work on the mesoscale database is to begin in 2007).

Mesoscale forcing

A finer spatial (and generally temporal) scale forcing product is also being tested by disaggregating or interpolating the ECMWF data using the high resolution products (AMMA-PRECIP and SAF radiation fluxes at 0.10 degrees). The high resolution product will be developed over nearly the entire region, but initial tests and development will focus on the CATCH window since the database will be quite large and because a more detailed evaluation will be possible, starting in 2007, owing to various intensive observation campaigns. Continuous upgrading and enhancement of this database is envisioned as more observations become available and new techniques are developed by the various AMMA working groups.

DATABASE APPLICATIONS

The improvement of models and the understanding of land–atmosphere processes obviously depend upon having quality forcing and evaluation data. Many field experiments have been done over the years with the objective of improving the understanding of the link between the land-surface and the atmosphere. Some frequently cited studies are HAPEX-MOBILHY (André *et al.*, 1986), FIFE (Sellers *et al.*, 1988), BOREAS (Sellers *et al.*, 1997), and Cabauw, The Netherlands (Beljaars & Bosveld, 1997). These data sets have been of great value in terms of land surface model (LSM) development, evaluation and intercomparison studies. In particular, the Project for the Intercomparison of Land-surface Parameterization Schemes (PILPS: Henderson-Sellers *et al.*, 1993) has increased the understanding of LSMs, and it has lead to many improvements in the schemes themselves. In Phase-2 of PILPS (Henderson-Sellers *et al.*, 1995), LSMs have been used in so-called “offline mode” (driven using prescribed atmospheric forcing), and the resulting simulations have been compared to observed data.

The first attempt by PILPS to address LSM behaviour at a regional scale was undertaken in PILPS-2c (Wood *et al.*, 1998). LSM forcing data was constructed from a combination of atmospheric model and field data. The GSWP (Phase 1; Dirmeyer *et al.*, 1999) was an “offline” global-scale LSM intercomparison study which produced two-year global data sets of soil moisture, surface fluxes, and related hydrological quantities. This project relied heavily on remotely sensed data from the ISLSCP Initiative I (Meeson *et al.*, 1995; Sellers *et al.*, 1995), along with atmospheric model data. The Rhone-AGGregation LSM intercomparison project (Rhone-AGG; Boone *et* *al.*, 2004) differed from the aforementioned studies primarily because the impact of changing the spatial scale of the LSM simulations was investigated, which was made possible by higher spatial resolution forcing data (based mostly on observational data).

AMMA LAND SURFACE MODEL INTERCOMPARISON PROJECT

The AMMA Land surface Model Intercomparison Project (ALMIP; deRosnay *et al.*, 2006) is part of the AMMA-EU (European Union) and API (Action Programmée Interorganisme: AMMA French programme). It is being conducted at CNRM (Centre National de Recherches Météorologiques: National Center for Meteorological Research) and CESBIO (Centre Etudes Spatiales de la BIOsphère: Center for the Study of the Biosphere from Space) in Toulouse, France. The strategy proposed in AMMA to develop a better understanding of the fully coupled system is to break the various components into more manageable portions, which will then provide insight into the various important processes. The first step is to begin with the land surface in offline or uncoupled (without atmospheric feedbacks) mode. The idea is to force state-of-the-art land surface models with the best quality and highest (space and time) resolution data available in order to better understand the key processes and their corresponding scales (as was done in the aforementioned intercomparison studies). ALMIP is relying heavily on remotely sensed products for key regional and mesoscale atmospheric forcing. The regional and mesoscale model domains are shown in Fig. 1.

In order to address the known limited ability of LSMs to simulate the surface processes over western Africa, ALMIP has several objectives: (a) intercompare results from an ensemble of state-of-the-art models; (b) determine which processes are missing or not adequately modelled by the current generation of LSMs for this region; (c) examine how the various LSMs respond to changing the spatial scale (three scales will be analysed: the local, meso and regional scales); (d) develop a multi-model climatology of "realistic" high resolution (multiscale) soil moisture, surface fluxes, and water and energy budget diagnostics at the surface, that can then be used by other projects within AMMA; (e) examine the impact of satellite-based forcings on the simulations, and (f) evaluate how relatively simple LSMs simulate the vegetation response (in terms of leaf area index or biomass) to the atmospheric forcing, on seasonal and inter-annual timescales.

Twelve land surface modelling groups are currently participating in ALMIP, and the models range in application from operational hydrology and NWP, to research mesoscale meteorological models and global climate models (GCMs). The evapotranspiration fluxes averaged over the core monsoon season (June–September, 2004) for two such schemes (ISBA from Météo-France and TESSEL from ECMWF) are shown in Fig. 4. In (a), the control forcing (fully NWP based regional scale) was used to drive the models. Despite the fact that the models use the same forcing, spatial differences can be observed; generally, ISBA simulates a larger evaporative flux below 10 degrees north (while more fine scale differences also exist). Part of the goal of ALMIP is to better understand the reasons for such differences in terms of physics, model parameters, etc. In panels (c)–(d), the impact of using the merged (NWP plus satellite) forcings is shown. There is an overall northward shift in the spatial distribution of the evaporative flux, but again, there are significant differences in terms of the finer spatial

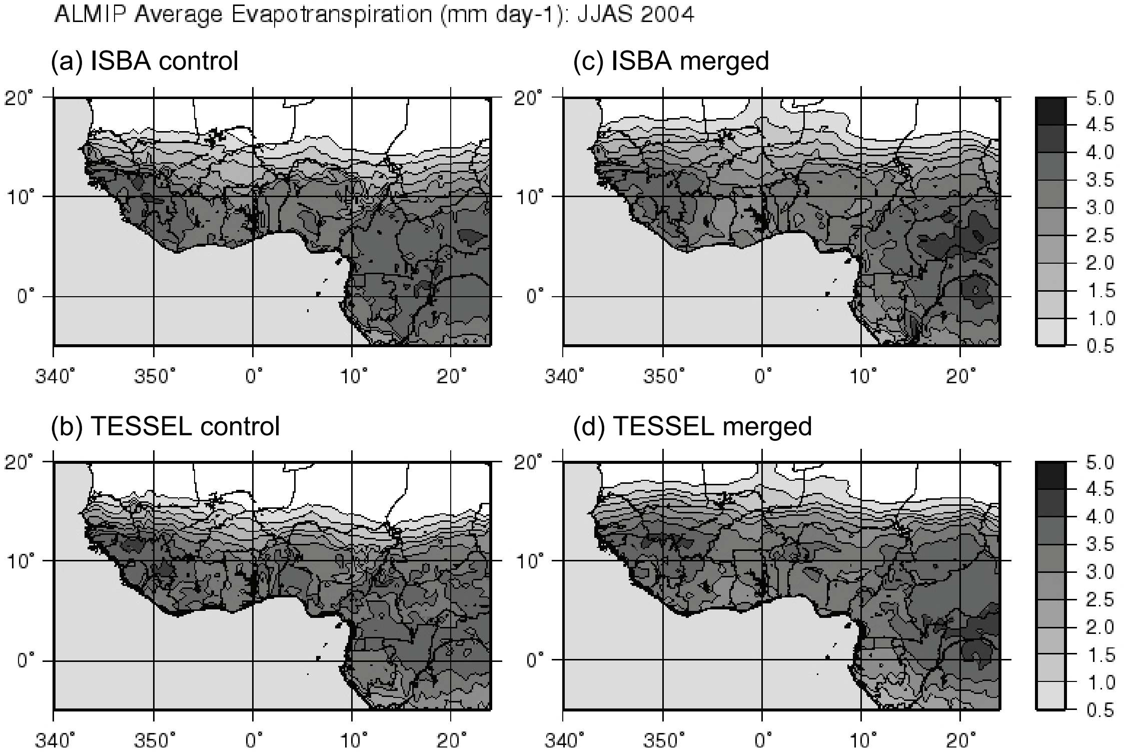

Fig. 4 Evapotranspiration averaged over the monsoon months (June–September: JJAS) from two land surface models: ISBA from CNRM-Météo France and TESSEL from ECMWF. The values using the control forcing are shown on the left side: (a) and (b), while on the right, (c) and (d), the merged forcing was used to drive the land surface models.

scale detail and the overall magnitudes of the fluxes. In addition, it should be mentioned here that the ECMWF is currently investigating the impact of using the ALMIP-based soil moisture on the forecasts by the operational NWP model (Beljaars & Balsamo, pers. commun.).

Towards ALDAS

The African Land Data Assimilation System (ALDAS) is currently under development. It builds upon the infrastructure developed within ALMIP, but in contrast it will operate in the quasi real-time mode. Currently, EPSAT precipitation and LAND-SAF downwelling radiative products have been re-gridded and reformatted by IPSL and Medias, France, for direct use by land surface and atmospheric models. These forcing data will again be merged with a combination of observational and NWP data to produce atmospheric forcing for a group of land surface schemes in order to derive a realistic land surface state for NWP model initialization. This is similar to the methodology used within the Land Data Assimilation System (LDAS; Rodell *et al.*, 2004). In addition, both observations and additional remotely-sensed data will be directly assimilated into the system (such as in the European LDAS, ELDAS; Meetschen *et al.*, 2004). Testing will begin near the end of 2007 and into 2008.

Coupled surface–atmosphere studies

The offline simulated soil moisture and surface fluxes over West Africa will be used for several land–atmosphere coupled actions: two AMMA-related examples are discussed here. At CNRM, the soil moisture simulated by the ISBA land surface model (Noilhan & Mahfouf, 1996) in August 2005, will be used to explore the impact of changing the soil moisture initial condition on short-term forecasts using the French mesoscale meteorological model MesoNH (Lafore *et al.*, 1998). The first objective is to use the offline simulated soil moisture (as an initial condition or as a relaxation term) in order to determine how much it influences both the initiation and subsequent development of convection, and its spatial and temporal distributions.

The simulated surface states and the LAND-SAF products themselves will be used within the international project West African Monsoon Model Evaluation (WAMME, Y. Xue, UCLA, B. Lau, NASA-GSFC, and K. Cook). The support of WAMME by GEWEX is based on the project's potential ability to break new ground in monsoon systems research with the objective to unravel the effect of aerosol–monsoon water cycle interaction in monsoon systems around the world. Since the West African monsoon variability is strongly affected by external forcings and their interactions, WAMME will necessarily encompass vegetation–ocean–atmosphere–aerosol interactions and is an interdisciplinary project. An ensemble of GCMs will simulate several years which overlap with the period covered by ALMIP. The simulated soil moisture states and surface fluxes will then be compared to the offline simulated values.

SUMMARY

One of the main goals of the AMMA is to obtain a better understanding of the intra-seasonal and inter-annual variability of the West African monsoon (WAM). A key process is the interaction between the land and the atmosphere, which is theorized to be significant over this region, especially in terms of the soil moisture memory (and its feedback with the atmosphere through surface fluxes). The first step towards improving understanding of the coupled land–atmosphere system is to begin with the land surface in offline or uncoupled mode. The idea is to force an ensemble of state-of-the-art land surface models with the best quality and highest (space and time) resolution data available in order to better understand the key processes and their corresponding scales. To meet this goal, atmospheric forcing data are needed to drive land surface models, but NWP models have some inherent difficulties in terms of simulating the WAM. It is therefore of utmost importance to use ancillary data with high spatial and temporal coverage, which is a need that can only be addressed using remotely-sensed data. The two key variables driving land surface processes are the precipitation and the solar radiative flux, both of which are derived using satellite based data during the monsoon season. The multi-scale land-surface database being constructed at CNRM in conjunction with other laboratories, notably CESBIO and ECMWF, is to be used for many projects, commencing from near the end of 2006, and then beyond.

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REFERENCES

André, J. C., Goutorbe, J. P. & Perrier, A. (1986) HAPEX\u2013MOBILHY: A hydrologic atmospheric experiment for the study of water budget and evaporation flux at the climatic scale. *Bull. Am. Met. Soc.* **67**, 138–144.

Beljaars, A. C. M. & Bosveld, F. C. (1997) Cabauw data for the validation of land surface parameterization schemes. *J. Climate* **10**, 1172–1193.

Boone, A., Habets, F., Noilhan, J., Clark, D., Dirmeyer, P., Fox, S., Gusev, Y., Haddeland, I., Koster, R., Lohmann, D., Mahanama, S., Mitchell, K., Nasonova, O., Niu, G.-Y., Pitman, A., Polcher, J., Shmakin, A. B., Tanaka, K., van den Hurk, B., Vérant, S., Verseghy, D., Viterbo, P. & Yang, Z.-L. (2004) The Rhone-Aggregation Land Surface Scheme Intercomparison project: an overview. *J. Climate* **17**, 187–208.

Chopin, F., Berges, J. C., Desbois, M., Jobard, I. & Lebel, T. (2004) Multi-scale precipitation retrieval and validation in African monsoon systems. Presented at 2nd International TRMM Science Conference, 6–10 Sept., Nara, Japan.

deRosnay, P., Boone, A., Beljaars, A. & Polcher, J. (2006) AMMA land–surface modeling and intercomparison projects. *GEWEX News*, February **16**(1), 10–11.

Dirmeyer, P. A., Dolman, A. J. & Sato, N. (1999) The Global Soil Wetness Project: A pilot project for global land surface modeling and validation. *Bull. Am. Met. Soc.* **80**, 851–878.

Henderson-Sellers, A., Pitman, A. J., Love, P. K., Irannejad, P. & Chen, T. (1995) The project for inter-comparison of land-surface parameterization schemes (PILPS): Phase 2 and 3. *Bull. Am. Met. Soc.* **76**, 489–503.

Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E. & co-authors (2004) Regions of strong coupling between soil moisture and precipitation. *Science* **305**(5687), 1138–1140.

Lafore, J. P., Stein, J., Asencio, N., Bougeault, P., Ducrocq, V., Duron, J., Fischer, C., Hereil, P. Mascart, P., Pinty, J. P., Redelsperger, J. L., Richard, E. & Vila-Guerau de Arellano, J. (1998) The Meso-NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations. *Ann. Geophys.* **16**, 90–109.

Meeson, B. W. & co-authors (1995) *ISLSCP Initiative I-Global Data Sets for Land-Atmosphere Models, 1987–1988*, vols. 1–5. NASA CD-ROM.

Meetschen, D., van den Hurk, B., Ament, F. & Drusch, M. (2004) Optimized surface radiation fields derived from Meteosat imagery and a regional atmospheric model. *J. Hydromet*. **5**, 1091–1101.

Noilhan, J. & J.-F. Mahfouf (1996) The ISBA land surface parameterization scheme. *Global Planet. Change* **13**, 145–159.

Ramage, K. & Cloché, S. (2003) Base de Données AMMA-SAT – Document de Spécification Technique (AMMA-SAT Database – Technical Specifications Document). No. AMMA-SAT-bdd-ST-spe1-R05, Release 5, Nov. 18.

Rodell, M., Houser, P. R., Jambor, U., Gottschalk, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J. K., Walker, J. P., Lohmann, D. & Toll, D. (2004) The Global Land Data Assimilation System. *Bull. Am. Met. Soc.* **85**, 381–394.

Sellers, P. J. & co-authors (1995) *An Overview of the ISLSCP Initiative I Global Data Sets*, vols. 1–5, NASA CD-ROM.

Sellers, P. J. & co-authors (1997) BOREAS in 1997: Experiment overview, scientific results, and future directions. *J. Geophys. Res*. **102**, 28731–28769.

Taylor, C. M., Said, F. & Lebel, T. (1997) Interactions between the land surface and mesoscale rainfall variability during HAPEX-Sahel. *Mon. Weather Rev*. **125**, 2211–2227.

Wood, E. F., Lettenmaier, D., Liang, X., Lohmann, D., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C., Duan, Q., Ek, M., Gusev, Y., Habets, F., Irannejad, P., Koster, R., Nasanova, O., Noilhan, J., Schaake, J., Schlosser, A., Shao, Y., Shmakin, A., Verseghy, D., Wang, J., Warrach, K., Wetzel, P., Xue, Y., Yang, Z.-L. & Zeng, Q. (1998) The Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) Phase-2c Red-Arkansas River Basin experiment: 3. experiment description and summary intercomparisons. *Global Planet. Change* **19**, 115–139.