The ALMIP Experience: Implications for land-atmosphere coupled systems

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1. Introduction

The monsoon flow is driven by land-sea thermal contrast. The atmosphere-land surface interactions are modulated by the magnitude of the associated north-south gradient of heat and moisture in the lower atmosphere. The links between land surface processes and the WAM have been demonstrated in numerous numerical studies using global climate models (GCMs) and regional scale atmospheric climate models (RCMs) over the last several decades. They have examined the influence of the land surface on the WAM in terms of surface albedo , the vegetation spatial distribution , and the soil moisture (see Boone et al., 2009a, for a complete review). It should be emphasized that interpretation of the results from any one of such studies, must be tempered by the fact that there are substantial discrepancies in African land-atmosphere coupling strength among current state-of-the-art GCMs (Koster et al., 2002).

The deficiencies, with respect to modeling the African monsoon, arise from both the paucity of observations at sufficient space-time resolutions, and because of the complex interactions of the relevant processes between the biosphere, atmosphere and hydrosphere over this region. The African Multidisciplinary Monsoon Analysis (AMMA) has organized comprehensive activities in data collection and modeling to further increase our understanding of the relevant processes, in order to improve prediction of the WAM (Redelsperger et al., 2006). Ruti et al. (2010) gives a comprehensive overview of several atmospheric multi-model initiatives within AMMA). The modeling of the land surface component of the WAM is being addressed by the AMMA Land-surface Model Intercomparison Project (ALMIP: Boone et al., 2009a: http://www.cnrm.meteo.fr/amma-moana/amma_surf/almip), which is described herein.

2. ALMIP Land Surface Modeling Initiative

In recent years, there have been a number of land surface model (LSM) intercomparison projects on an international level. In particular, the Project for the Intercomparison of Land-surface Parameterization Schemes (PILPS) has increased the understanding of LSMs, and it has lead to many model improvements. In Phase-2 of PILPS (Henderson-Sellers et al., 1995), LSMs were used in so-called ‘offline’ mode (i.e. the LSM is uncoupled from an atmospheric model and is therefore driven using prescribed atmospheric forcing either from observations, satellite products, atmospheric model data or some combination of the three aforementioned sources), and the resulting simulations were compared to observational data. The first attempt by PILPS to address LSM behavior at a regional scale was undertaken in PILPS-2c (Wood et al., 1998). The Global Soil Wetness Project Phase 2 (GSWP-2: Dirmeyer et al., 2006) was an offline global-scale LSM intercomparison study which produced the equivalent of a land-surface re-analysis consisting in 10-year global data sets of soil moisture, surface fluxes, and related hydrological quantities. The main idea behind ALMIP is to take advantage of the significant international effort of the intensive field campaign, and the various modeling efforts in order to better understand the role of land surface processes in the WAM.

The main objectives of ALMIP are; i) to inter-compare results from an ensemble of state-of-the-art models, and study model sensitivity to different parameterizations and forcing inputs, ii) to determine which processes are missing, or not adequately modeled, by the current generation of LSMs over this region, iii) to examine how the various LSM respond to changing the spatial scale, iv) to develop a multi-model climatology of 'realistic' high resolution surface and energy budget diagnostics at the surface (which can then be used for coupled land-atmosphere model evaluation, case studies, etc...), v) to valuate how relatively simple LSMs simulate the vegetation response to the atmospheric forcing on seasonal and inter-annual time scales. ALMIP is an ongoing project, and will be presented in this paper. We present a brief overview of intercomparison results, along with some examples of evaluation efforts, which are under way. Finally applications and perspectives for continuing work are discussed.

2.1. Forcing and Soil and vegetation Data

The ECOCLIMAP database provides land surface parameters (albedo, vegetation cover fraction, surface roughness, leaf area index, soil texture, etc...) over the entire globe at a maximum spatial resolution of 1 km. It is intended for use by LSMs which are coupled to GCM, numerical weather prediction (NWP), mesoscale meteorological research or hydrological models.

The atmospheric forcing is based on the European Centre for Medium-range Weather Forecasts (ECMWF) NWP model forecasts for the years 2002-07. The forcing variables consist in the air temperature, specific humidity and wind components at 10m, the surface pressure, the total and convective rain rates, and the downwelling longwave and shortwave radiative fluxes. ECMWF data was selected because the forecast data was available at approximately 50 km spatial resolution over West Africa, and this model simulated relatively well the regional scale circulation over West Africa compared to several other NWP models. The forcing based purely on ECMWF forecast data comprised the data for Experiment 1.

Because of the scarcity of surface observations over most of western Africa, remotely sensed data is needed for creating large-scale LSM forcing. The radiative fluxes from OSI-SAF (Oceans and Ice Satellite Applications Facility: http://www.osi-saf.org) for 2004 and the LAND-SAF fluxes (Land Satellite Applications Facility) for 2005-07 are substituted for the corresponding NWP fluxes in Experiments 2 and 3. They have been evaluated over this region (and this work is ongoing as more observational data becomes available). Precipitation is the most critical forcing variable over this region. For ALMIP, two datasets were used. The EPSAT precipitation data (available during the core monsoon period, May-June, from 2004-06) was used for Exp.2. In Exp.3, the Tropical Rainfall Measurement Mission (TRMM) precipitation product 3B-42 was used.

The ECMWF model captures most of the main dynamical features of the WAM, but the simulated monsoon precipitation does not extend far enough to the north compared to the EPSAT rainfall (Fig. 1a). Clearly, the Exp.2 precipitation shows a northward displacement of the monsoon characterized by both increased precipitation to the north (roughly north of 8°N) and decreased values along the southern coast. In particular, the Exp.2 rainfall is approximately 9% higher over the Sahel region (indicated in Fig.1) where the Exp.1 2006 June-September average (JJAS) rainfall is 3.8 kg m-2 day-1 with the largest local relative increases over the northern part of this region. Downwelling shortwave radiation shows the same difference (Fig. 1b). The Exp.2 values are generally lower where precipitation and clouds have increased (the difference corresponds to about a 1% Sahel-average decrease for JJAS in Exp.2, although local decreases approach approximately 10%). This comparison emphasizes the importance of ancillary information to derive LSM forcings to reduce NWP model defaults or biases.

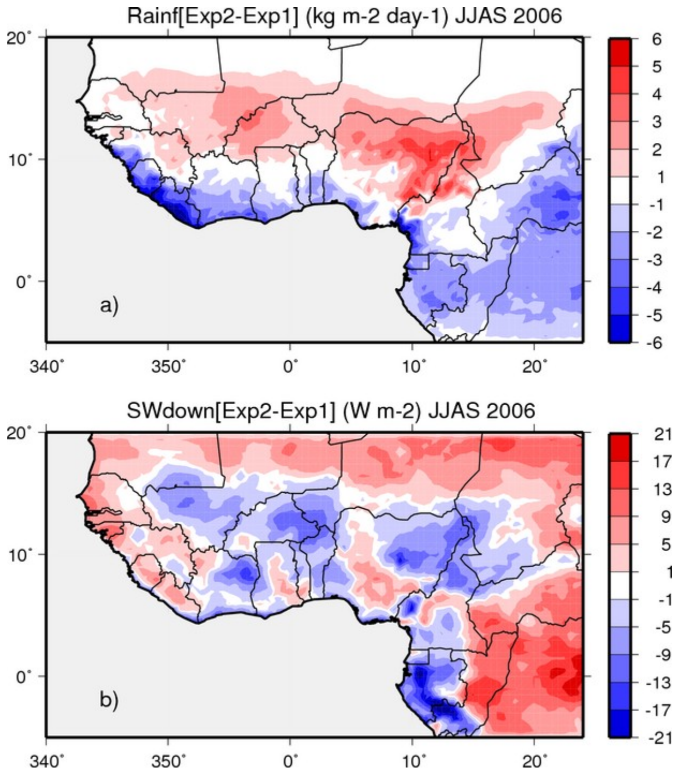

Figure 1(a) The JJAS average rainfall rate (Rainf) for 2006 from experiment 2 (EPSAT ECMWF forcing) less that from experiment 1 (pure ECMWF forcing) is shown. (b) The corresponding difference for the downwelling shortwave radiation (SWdown) is shown also, for which experiment 2 forcing consists in LSA SAF ECMWF data.

2.2. Simulated Surface Processes: Energy and Water Budgets over the Sahel

Eleven LSMs participated in ALMIP. Nine of the models used the provided ECOCLIMAP soil and monthly-varying vegetation parameter information, which implies that most of the inter-model differences should be related to LSM physics. A listing and more detailed description of the models and the experimental setup can be found in Boone et al. (2009a). In terms of climatology, the Sahel has a prolonged dry season (lasting approximately 5 months), followed by a steady increase in rainfall starting in about April with a peak during late July or August. Finally, there is a more rapid decrease until about the end of October. The analysis that follows covers this core monsoon period.

The LSM surface overland runoff is slightly larger than the drainage. These two water budget terms have the largest relative variability, as well as the least agreement between the LSMs, as the intra model variance is comparable to the average. The drainage has the largest intra-LSM variance, but this is not surprising, as this variable is modulated by the surface runoff, the storage dynamics, vertical transfer, and finally, the evaporative uptake (in a sense, drainage is like a residual after the other aforementioned processes have acted). This highlights the continuing need to improve LSM hydrology, especially parameterizations of sub-grid surface runoff, vertical fluxes and drainage, and the vertical distribution of plant water uptake.

The soil water storage change average is comparable in magnitude to the total runoff. Of note, it has an extremely large temporal variance. This is directly related and similar in magnitude, to the temporal variance of the rainfall. The average soil water content simulated by the LSMs is quite different. This is usually the case among LSMs (e.g. Dirmeyer et al., 2006). Nonetheless, the relative intra-model agreement of the soil water storage change among the LSMs is quite good. The soil water dynamics are simulated in a fairly consistent manner in this region.

The remaining water budget variable is the evapotranspiration. This variable is the largest sink term (it corresponds to slightly over 60% of the rainfall for each of the 3 years). The relative variances are fairly low, and the LSMs generally agree. The sensible heat flux is slightly lower than the latent on average, but again the relative variances are fairly low. This implies that for a given rainfall over this region, the various LSMs simulate the surface-atmosphere transfer of heat and moisture fairly consistently (given the same atmospheric forcing and surface parameters). The net longwave and shortwave radiation fluxes have the lowest variances in the energy budget-especially the intra-model variance, as expected (since the downwelling components, surface albedo and emissivity were prescribed). So the model surface flux differences arise primarily from the partitioning of this energy.

2.3. Large Scale evaluation of surface variables

Numerous large scale evaluation efforts have been done and are ongoing. This section highlights a few of these activities.

2.3.1. Comparison with local scale observations

Comparing local flux data with model output over a grid square is a scale problem since there can be significant sub-grid heterogeneity on the grid-square scale. This problem is being addressed in ALMIP using spatially aggregated surface flux data. Observed sensible heat flux data from the Mali super-site square (an approximately 60x60 km^2, which is typical of the grid size of global-scale NWP models and relatively high resolution GCMs) was found to compare well with that simulated by LSMs once the data had been up-scaled to the LSM grid resolution. The LSM models captured the seasonal dynamic over a three year period (during the main AMMA field campaign). This technique will now be extended to the other super-sites.

2.3.2. Comparison with large scale satellite data

Knowledge of the land surface water storage is important for estimating vegetation growth, and may hold a key to increasing long range atmospheric predictability over West Africa. However, even though numerous local scale site measurements are now available within AMMA, measurements of the land water storage are not available at the regional scale. The Gravity Recovery And Climate Experiment (GRACE) satellite mission accurately measures gravity field variations, which are inverted to retrieve terrestrial water storage variations. Various products, based on different retrieval methods, are available. Simulated water stores from Exp.3 from 2005-2006 compared well with GRACE data: the temporal correlation is quite good over the Sahel (0.9), while differences in the amplitudes (the temporal variance for the mean of the ALMIP LSMs is 29 kg m^{-2}, while it is 45 kg m^{-2} for GRACE) can be due to a deficit in the precipitation forcing, or to an overestimation of the water storage anomalies derived from GRACE during the dry season. It is also possible that the ALMIP LSMs do not use sufficiently deep soil depths or that the removal of runoff from a pixel should be accounted for. A study is currently under way which shows that the satellite data reproduce the ALMIP Exp.3 LSM modeled, inter-annual variability over the Sahel during the study time period (2002-07). The next step is to use discharge to estimate the regional scale evaporation, and to examine the impact of including deep aquifers and river storage to the total storage estimates produced by LSMs over West Africa.

2.3.3. Regional scale NWP assimilation applications

Within the joint framework of the Soil Moisture and Ocean Salinity (SMOS) satellite mission and AMMA, we evaluated ALMIP soil moisture for 2006 for 8 LSMs from Exp.2. ALMIP-MEM (Microwave Emission Model) couples ALMIP soil moisture and temperature outputs to the Community Microwave Emission Model (CMEM) (de Rosnay et al., 2009). It permits a quantification of the relative impact of land surface modeling and radiative transfer modelling on the simulated brightness temperature background errors. We evaluated ALMIP-MEM brightness temperatures for 2006 against AMSR-E C-band data provided by the National Snow and Ice Data Center (NSIDC). This work has been a part of the effort to test different forward models for data assimilation in the ECMWF model.

For each LSM, a simple correction has been applied to the simulated brightness temperatures based on the annual mean bias. LSMs need to reproduce features such as the observed wet patch centered at DoY 210 and 15.5°N, which can induce mesoscale circulations. All of the LSMs capture this wet patch, but either overestimate or underestimate the amplitude. The Taylor diagram in Fig. 2 emphasizes the general good agreement between the forward approach and the AMSR-E. Exceptions are the ECMWF LSMs using the old hydrology (TESSEL and CTESSEL) which over-estimated the variance. The newer (now operational) scheme has excellent agreement (HTESSEL) , although the correlation has decreased. For a more in depth analysis of these results, see de Rosnay et al., (2009).

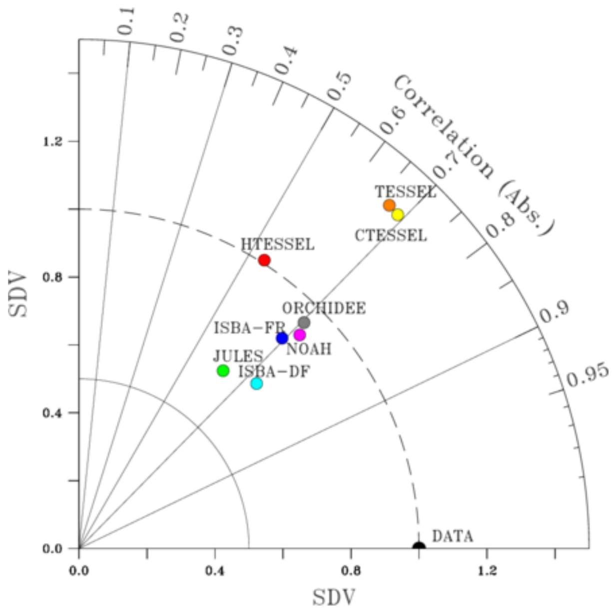

Figure 2: Taylor diagram of the statistical evaluation of the simulated ALMIP brightness temperature values. Data for this figure were taken from de Rosnay et al. (2009).

3. Summary

There is a need to better understand land-atmosphere and hydrological processes over western Africa due to their potential feedbacks with the WAM circulation. This is being addressed through a multiscale modeling approach using an ensemble of LSMs which rely on dedicated, satellite-based forcing, and land surface parameter products, and data from the AMMA observational field campaigns. The idea is to have the best estimate of surface processes for initializing and evaluating the surface component of atmospheric models, and to determine which LSM processes agree the least (in order to eventually improve the corresponding physics). The far reaching goal of this effort is to obtain better understanding and prediction of the WAM.

Offline, multi-LSM simulations using a mix of NWP and satellite-based forcing data comprise the equivalent of a multi-model reanalysis product. This currently represents the best estimate of the land surface processes over large scale regions, and ALMIP has produced such an analysis for West Africa from 2002-07. The use of using satellite-based forcings to correct systematic biases in NWP meteorological forcing significantly improves LSM simulated evapotranspiration, especially over the Sahel and areas slightly southward (which is theorized to be the zone with considerable coupling with the atmosphere. This implies that special care should be used when using NWP, or re-analysis data, to force LSMs over West Africa for hydrological or land surface studies.

It is difficult to evaluate the realism of the simulated turbulent fluxes at regional scales, but using an aggregation technique (using remotely sensed data), it was shown that LSMs are able to reasonably capture both the amplitude and the phase of the observed changes. At the regional scale, the simulated surface brightness temperature compared well with data from satellite (which is a first step for assimilating such data into LSMs for operational NWP). Finally, ALMIP outputs are also being used within AMMA to estimate the surface contribution for atmospheric water budget studies, and to estimate the production functions (evapotranspiration) for hydrological models.

In terms of atmospheric model applications, ALMIP offline results have been used for improved initialization. For example, ALMIP results are currently being used for numerous mesoscale case studies within AMMA (convective initiation and study of feedbacks between dust emissions and the atmosphere), and to examine the influence of initial soil moisture on NWP at ECMWF (Agusti-Panareda et al., 2010). ALMIP results have also been recently used for evaluating the land surface component of GCM and RCM models (e.g. Boone et al., 2010).

4. Perspectives

ALMIP is an ongoing project, and so further regional scale simulations, experiments, and model evaluation will also be done as improved input data is made available. Continuing work will focus on semi-arid land surface process parameterizations (Boone et al., 2009b). Indeed, they are quite diverse among LSMs and generally lack consideration of some fundamental processes specific to this region (reduced infiltration over dry crusty soils, drought resistant plant species, lateral transfer of surface runoff from bare soil to vegetated surface areas, etc.). In addition, input rainfall will be based on dense observational networks, which should improve the realism of the land surface and hydrological simulations.

Météo-France is developing a new high resolution version of ECOCLIMAP over West Africa which includes vegetation inter-annual variability. This should further improve surface flux estimates. In addition, LSMs, which are designed to simulate the life-cycle of the vegetation, are increasingly used in atmospheric models. They theoretically enable a more realistic feedback between the vegetation and the atmosphere. Such models will be inter-compared and evaluated over this region.

Despite the advantages presented herein, multi-model offline forced simulations have obvious drawbacks: notably land-atmosphere feedbacks are neglected, so it is sometimes difficult to extrapolate findings to fully coupled configurations. In addition, land surface data assimilation could also further improve estimates of surface fluxes and near surface variables. Several GLASS activities will be addressing such issues in the near future (as discussed in this issue).

5. References

Agusti-Panareda, A., G. Balsamo, and A. Beljaars, 2010: Impact of improved soil moisture on the ECMWF precipitation forecast in West Africa. *Geophys. Res. Letters*, (submitted).

Boone, A., P. de Rosnay, G. Basalmo, A. Beljaars, F. Chopin, B. Decharme, C. Delire, A. Ducharne, S. Gascoin, M. Grippa, F. Guichard, Y. Gusev, P. Harris, L. Jarlan, L. Kergoat, E. Mougin, O. Nasonova, A. Norgaard, T. Orgeval, C. Ottlé, I. Poccard-Leclercq, J. Polcher, I. Sandholt, S. Saux-Picart, C. Taylor, and Y. Xue, 2009a: The AMMA Land Surface Model Intercomparison Project. *Bull. Amer. Meteor. Soc.,* **90**(12), 1865-1880.

Boone, A., A. C. V. Getirana, J. Demarty, B. Cappelaere, S. Galle, M. Grippa, T. Lebel, E. Mougin, C. Peugeot and T. Vischel, 2009b: The African Monsoon Multidisciplinary Analyses (AMMA) Land surface Model Intercomparison Project Phase 2 (ALMIP2). *GEWEX News*, Novemeber, **19**(4), 9-10.

Boone, A., Y. Xue, I. Poccard-Leclerq, J. Feng, F. de Sales, and P. deRosnay, 2010: Evaluation of the WAMME model surface fluxes using results from the AMMA land-surface model intercomparison project. *Clim. Dynamics*, (in press), DOI 10.1007/s00382-009-0653-1.

de Rosnay P., M. Drusch, A. Boone, G. Balsamo, B. Decharme, P. Harris, Y. Kerr, T. Pellarin, J. Polcher and J.P. Wigneron, 2008: Microwave Land Surface modelling evaluation against AMSR-E data over West Africa. The AMMA Land Surface Model Intercomparison Experiment coupled to the Community Microwave Emission Model (ALMIP-MEM). *J. Geophys. Res*., **114**, D05108, doi:10.1029/2008JD010724.

Dirmeyer, P. A., X. Gao, M. Zhao, Z. Guo, T. Oki, and N. Hanasaki , 2006: GSWP-2: Multi-model Analysis and Implications for Our Perception of the Land Surface. *Bull. Amer. Meteor. Soc*., **87,** 1381-1397.

Henderson-Sellers, A., A. J. Pitman, P. K. Love, P. Irannejad, and T. Chen, 1995: The project for intercomparison of land-surface parametrization schemes (PILPS): Phase 2 and 3. *Bull. Amer. Meteo. Soc*., **76**, 489-503.

Koster, R. D., P. A. Dirmeyer, A. N. Hahmann, R. Ijpelaar, L. Tyahla, P. Cox, and M. J. Suarez, 2002: Comparing the degree of land-atmosphere interaction in four atmospheric general circulation models. *J. Hydrometeor.*, **3**, 363-375.

Redelsperger, J.-L., C. D. Thorncroft, A. Diedhiou, T. Lebel, D. J. Parker, and J. Polcher, 2006: African Monsoon Multidisciplinary Analysis: An International Research Project and Field Campaign. *Bull. Amer. Meteor. Soc*., **87**, 1739-1746.

Ruti, P. M., J. E. Williams, F. Hourdin, F. Guichard, A. Boone, P. Van Velthoven, F. Favot, I. Musat, M. Rumukkainen, M. Domínguez, M. A. Gaertner, J.-P. Lafore, T. Losada, M. B. Rodriguez de Fonseca, J. Polcher, F. Giorgi,Y. Xue, I. Bouarar, K. Law, B. Josse, B. Barret, X. Yang, C. Mari, and A. K. Traore, 2010: Modeling the West African climate system: systematic errors and future steps. *Atmos. Sci. Let*., (submitted).

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