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Mesoscale water cycle within the West African Monsoon

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Abstract

We review the main studies on mesoscale water cycle from the African Monsoon Multidisciplinary Analysis (AMMA) project. The estimations of precipitation and evapotranspiration, which are the coupling terms between the atmosphere and the surface water cycles, are addressed. Advances in the evaluation of the various components of atmospheric and surface water budgets are reported, and the yearly surface budgets for the Benin and Niger AMMA mesoscale sites are given as examples. The major outcomes and limitations of atmosphere-surface model coupling exercises are also reported. The paper concludes with suggestions on the research directions on which the community should make future efforts. Copyright © 2011 Royal Meteorological Society

Keywords: mesoscale; water cycle; water budget; atmosphere; land surface

1. Introduction

An integrated understanding (across disciplines and scales) of the water cycle and an improved representation in numerical models is crucial for West African monsoon studies. It implies a better knowledge of the various processes, driving mechanisms and feedback loops. This is particularly true at the mesoscale, where strong couplings occur between the atmosphere and the land surface and subsurface. This scale is defined here for domains ranging from 10^3 to 10^5 km^2 and a few minutes to interannual time periods.

The evaluation of the water budget at various time scales is a comprehensive way to assess our knowledge of the water cycle. A conceptual representation of this approach is shown in Figure 1, where an atmospheric box (an air column) exchanges water and energy with an underlying surface box (a watershed). Each box is affected by its own processes and associated scales, and interacts with the larger scale (e.g. humidity advection, easterly waves, interactions with larger rivers or regional aquifers). Mesoscale surface–atmosphere couplings are conditioned by the scales of precipitation. The location and occurrence of convective cells control soil moisture patterns. The surface feedback from these wet patches is driven by the diurnal cycle of solar radiation (Taylor *et al.*, 2011), and the landscape properties/heterogeneities control water redistribution in the other compartments of the cycle (runoff, ground water recharge).

The water balance equations for each box (Figure 1) highlight the couplings between the land and atmospheric water cycles through precipitation (P) and evapotranspiration (E). The water storage variation in the surface box (dS/dt), or the runoff (R), represents the temporal dynamics of surface and ground water resources; hence, this approach is also interesting for impact studies.

Previous experiments such as GCIP (Roads *et al.*, 2003) or LBA (Silva Dias *et al.*, 2002), have focused on the coupled surface–atmosphere water cycle at the regional scale. For the African continent, COPT81 (Sommeria and Testud, 1984) and HAPEX-Sahel (Goutorbe *et al.*, 1994) provided the initial knowledge on the mesoscale-coupled water cycles. A few studies have focused on the water budget within the West African squall lines (Chong and Hauser, 1989; Caniaux *et al.*, 1994).

Following HAPEX-Sahel and previous field campaigns, the major mechanisms driving the Sahelian water cycle at the local scale have been identified, but few attempts were made to upscale the results at the mesoscale (Séguis *et al.*, 2011). The competing effects of climate and land cover changes have been shown, as for example increasing the runoff observed in the last decades in southwest Niger induced by land use changes, despite rainfall reduction (Favreau *et al.*, 2009). While a robust understanding existed for surface rainfall over Sahel, very few studies reported on the other coupling term (E) at this scale. Further south,

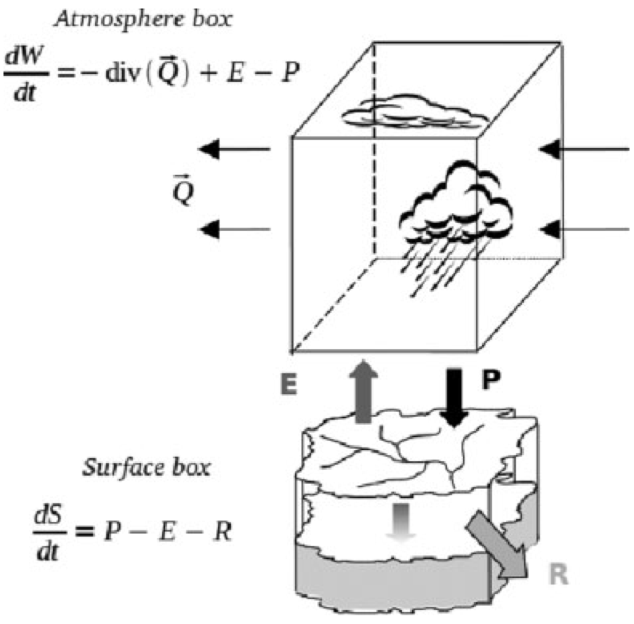

Figure 1. Surface and atmospheric water cycles, and water balance equations, with W: atmospheric water content, Q: vertically integrated humidity flux, P: surface rainfall, E surface evapotranspiration, R: runoff, S: surface and ground water content.

the Sudanian area had been poorly investigated prior to the AMMA.

The AMMA campaign offered unique opportunities for mesoscale water cycle studies, and the estimation of water budgets. Hydrometeorological ground networks provided high quality observations (rainfall, river discharge, soil moisture, ground water dynamics, turbulent surface fluxes) on the three contrasting sites of the AMMA-CATCH observing system (Mali, Niger, Benin; Lebel *et al.*, 2009). The high-frequency radio-sounding network centred over Benin, the GPS stations and various radars provided additional ground-based atmosphere explorations. The combinations of these observations with satellite products and the use of numerical simulations allowed retrieval of the various terms of the water (and heat) budgets.

This paper reviews the major advances in mesoscale water cycle research, reporting published AMMA work and a few unpublished preliminary results. Section 2 focuses on the estimations of rainfall and evapotranspiration terms, Section 3 on the analysis of the water budget terms for both the atmospheric and surface components, and Section 4 reports surface–atmosphere coupling experiments. The paper concludes with some recommendations for future research directions.

2. Estimations of rainfall and surface evaporation

First, we assess our current ability to provide mesoscale estimations of the two variables that modulate the coupling between the atmospheric and continental water budgets (Figure 1): the rainfall and the evapotranspiration.

Precipitation is the source term of the surface water balance. Over the AMMA region the precipitation mostly results from mesoscale convective systems (MCSs). It has been estimated (Moumouni *et al.*, 2008 for instance) that about two-thirds of the annual rainfall is provided by the convective part of these systems and is therefore characterised by a high spatial (down to kilometric) and temporal (down to a few minutes) variability. Vischel and Lebel (2007) have shown that if convective scale variability is ignored, hydrological models provide unrealistic runoff for mesoscale Sahelian basins. The sensitivity of the hydrological response to rainfall variability generally depends on the basin type and/or the time step considered. Accordingly, our ability to estimate precipitation, from observations or from models, has to be assessed as a function of scale.

Rainfall can be estimated down to the kilometric/minute scale with high-resolution rain gauge networks (such as the AMMA-CATCH meso-sites in Niamey or Oueme) and dynamic interpolation techniques (Vischel *et al.*, 2009), or also using meteorological radars (Gosset *et al.*, 2010). Outside of these research observing systems – and given the inadequacy of the operational networks – satellite products with a typical spatial resolution of 0.5° may be used. Recent evaluations of these products over West Africa show that they can provide satisfactory estimates at the decadal time scale (Jobard *et al.*, 2010 submitted), but they are less reliable for reproducing the correct rain distributions at the daily time scale (Roca *et al.*, 2009). One further challenge which remains is the downscaling of these products to the spatial/temporal resolution needed to force the mesoscale surface models (Paeth *et al.*, 2011).

Simulations from mesoscale atmospheric models constitute another source of rainfall estimation. However, these simulations are highly sensitive to a wide number of factors (initial and boundary conditions, resolution, physical parametrisations) and the quality of the resulting rain fields is highly variable among model/configurations (refer Section 4).

At the surface, evapotranspiration (E) is the largest sink term of the water budget. It can be estimated locally from observations (to the expense of complex experimental protocols) but models are still needed for upscaling. A major achievement of the AMMA is the sampling of latent and sensible heat fluxes up to 12 eddy correlation stations and from 2 scintillometers deployed in the AMMA-CATCH transect (Séguis *et al.*, 2011). These data are useful for model evaluation and improvement, especially for upscaling fluxes from the local to the mesoscale. The land surface model (LSM) ensemble simulations of the ALMIP regional-scale experiment provided the most comprehensive surface water budget estimates over the whole region (Boone *et al.*, 2009). On the Mali site, these authors showed that the sensible heat flux (H) from ALMIP simulations compared well with mesoscale aggregations of local measurements of H

(Timouk *et al.*, 2009). However, more detailed analyses at shorter time scales (sub-daily to intraseasonal) are needed, focusing on the latent heat flux as well, and extended to other sites. The scale discrepancies between the few local observed references (a few hundred metres) and the model results (0.5° for ALMIP) have to be handled. These are among the objectives of the second phase of ALMIP (refer Section 5).

3. Water budgets

The experimental campaign of the AMMA (2005–2007) provided crucial observations for the coupled heat and water budgets at the surface and in the atmosphere.

In the atmosphere, this dataset is especially useful to document vertical structures which are known to be poorly handled by current model parametrisations in the tropical regions. Till date, the research efforts have focused on a few case studies only. The source and sink terms of the heat and moisture budgets for the 11 August 2006 squall line, computed with MANDOPAS (variational analysis method, Montmerle and Lemaître, 1998) and a unidimensional microphysical model, showed consistent results with previous studies (Chong and Hauser, 1989). They confirmed the role of the stratiform component of the squall line in the water budget, and pointed to distinct heat and moisture convective vertical transports, as already observed in other locations (Lin and Johnson, 1996). Ongoing studies have extended these analyses of atmospheric water budgets to multidaily to weekly time periods, with radio-sounding data corrected for systematic humidity biases (Nuret *et al.*, 2008; Bock *et al.*, 2011). Preliminary results show the monsoon flow and convective episodes govern the heating and moistening of the atmosphere in the lower atmosphere (below 2 km) with strong diurnal effects. However, Kohler *et al.* (2010) also pointed out the role of the surface fluxes on the daytime evolution of boundary layer heat and moisture budgets prior to as well as after the monsoon onset, from their site data in Burkina Faso. In the mid-levels (3–6 km), coupled cooling–drying and heating–moistening are observed at the scale of African easterly waves (3–5 days). Finally, the upper layers (6–15 km) are impacted by deep convection.

Complementary studies based on multiyear composites of high-frequency (1h) GPS observations show, for the first time, that the passage of MCSs is associated with coherent and very large fluctuations of precipitable water and moisture convergence in the Sahel (Bock *et al.*, 2009). Guichard *et al.* (2010) showed that such a behaviour can be simulated only by those mesoscale models which use high (a few km) horizontal resolution, and thus do not rely on a parametrisation of convection for the simulation of the MCS.

Meynadier *et al.* (2010) showed that, at spatial scales from 10^3 to 10^6 km^2 and at daily time scales, the closure of the integrated atmospheric water budget and the balance between the terms is still a crucial problem for many numerical weather prediction (NWP) systems. Both closure and balance are directly affected by systematic drifts in the model forecasts (temperature, humidity, precipitation and evapotranspiration). Errors in cloud cover, aerosols and soil moisture also have detrimental effects on radiation, heat and water budgets at the surface and at scales from the diurnal cycle to the seasonal cycle (Bock *et al.*, 2011). Hence, it is not surprising that mesoscale simulations are sensitive to the choice of the NWP analysis used for initial and boundary conditions.

At the surface, the rainfall partitioning and the relative magnitude of the budget components highly depend on the surface conditions and the geological substratum. In many Sahelian areas, runoff occurs mainly as a subgrid process (degraded drainage network, so-called endoreism) and R is negligible in Figure 1 (Séguis *et al.*, 2011). Around Niamey (Niger), the water cycle essentially consists of a vertical transfer, with competing evapotranspiration and groundwater recharge (Cappelaere *et al.*, 2009). The water table is a long-term sink since it receives the deep drainage and only weakly supplies E. Combined with the land use trends since 1950, there has been a rise of this water table (Favreau *et al.*, 2009). Further south, where drainage networks are structured, the AMMA investigations have shown that ground reservoirs play a major role in the water cycle: river discharge (R) is dominated by exfiltration from the top-soil reservoirs (2 m, slow, subsurface flow) with a lower contribution of rapid, surface runoff, and no contribution from deeper layers (10 m). Current studies are investigating the role of deep-rooted trees in water recycling from these deeper water tables.

Mesoscale estimations cannot be derived directly from observations for all the water budget components (for e.g. surface evaporation is measured only locally), and models are needed to combine those data in a coherent framework. However, the resulting budgets may differ depending on the model used, as illustrated in Figure 2 (ongoing work) for year 2005 on the Oueme site (Benin). The TOPAMMA hydrological model (Le Lay *et al.*, 2008) underestimates E and overestimates the storage term (dS/dt), relatively to the ensemble ALMIP simulations, which in turn overestimate R (TOPAMMA's runoff matches the observed value). These differences can be attributed to an overly simple evapotranspiration scheme in TOPAMMA, and to the difficulty for LSMs to correctly simulate runoff at this resolution (0.5°). This example points to the role of the physical parametrisations in the estimations of the budget terms. The scales at which the evaluation is conducted is also important, as stated for example by Ruti *et al.* (2011), who found an opposite, underestimation of the ALMIP runoff at the regional scale. New model intercomparison exercises and specific evaluation of each of the budget components are

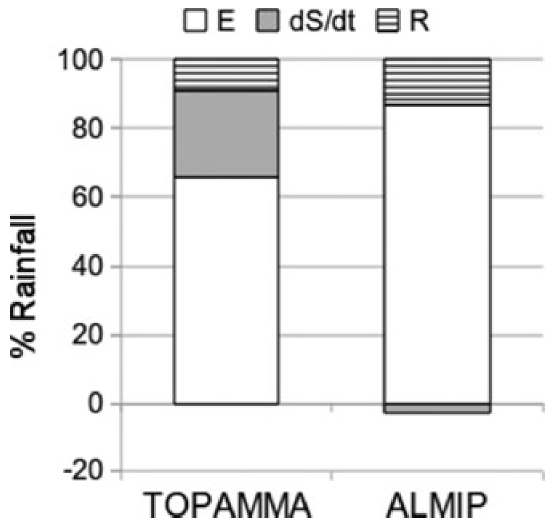

Figure 2. Comparison of TOPAMMA and ALMIP annual budgets over the Oueme basin, 2005.

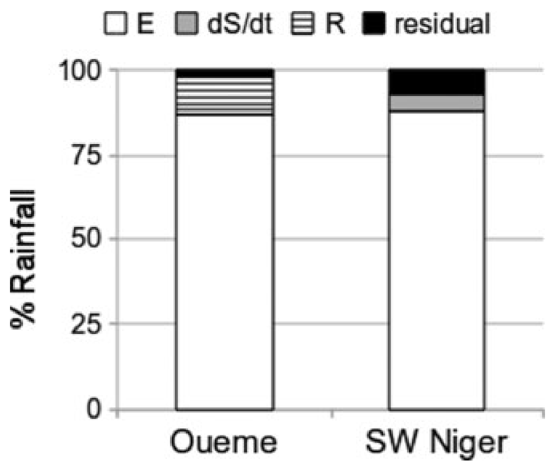

Figure 3. Surface water budget on the Oueme and SW Niger sites, year 2005, expressed in % of yearly rainfall.

needed to validate or improve the representation of the water cycle in the models.

Combining the best available estimation of each term, such as the estimations of *R* and *dS/dt* derived from the observations and *E* from LSMs simulations, coherent annual water budgets were constructed for the Oueme and southwest Niger sites, for the year 2005 (Figure 3 and Table I). The low closure errors (2% and 7% of the yearly rainfall, respectively, for Benin and Niger), as well as the acceptable uncertainty range, suggest a global consistency of these estimations. Approximately 90% of the rainfall returns to the atmosphere on both sites; the magnitude of the other terms strongly depends on the local hydrologic context. In future work, these figures (and associated uncertainties) will be refined, to allow a better comparison of the budget on these two contrasting sites (denser vegetation and larger rain amount on the Oueme site).

Table I. Surface water budget on the Oueme and southwest Niger site, in 2005. Estimated values and uncertainties in brackets (when available) expressed in % of yearly rainfall, and data source (italic).

	Oueme	Southwest Niger
E	87 (11)*	88 (–)
	ALMIP	*Saux-Picart et al., 2009*
dS/dt	0 (–)	5 (2)
	Observations	*Favreau et al., 2009*
R	11 (2)	0 (–)
	Observations	*Observations*

* Ensemble mean and intermodel standard deviation.

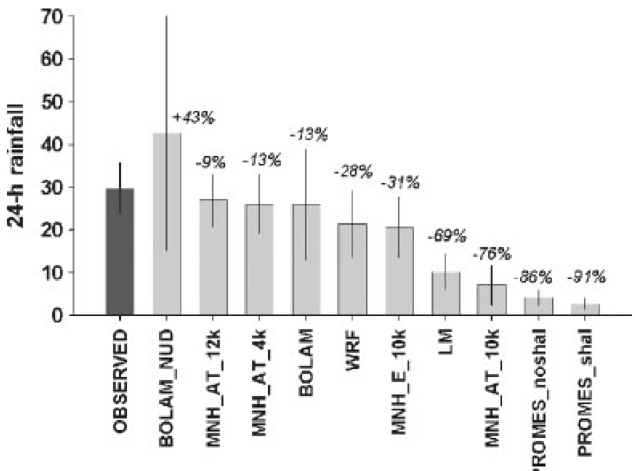

Figure 4. Areal mean of daily rainfall simulated by the models compared to the observations (dark grey), associated biases (figures) and measures of the spatial variability of the rain fields (standard deviation, error bars).

4. Towards coupling of atmospheric and hydrological models

The 28–29 August 2005 case study focused on a mesoscale convective event observed over Niger and Benin. It provided a framework to assess the coupling capabilities and current limitations of state-of-the-art atmospheric and hydrological models (Guichard *et al.*, 2010). The exercise involved the TOPAMMA hydrological model and six atmospheric models. When initialised and forced at their boundaries in the same way, the mesoscale atmospheric models were able to forecast, as observed, a propagating mesoscale rainfall structure. However, incorrect travel speeds and/or paths in most simulations resulted in a system which did not cross the target area (Oueme basin, Benin), and led to biases in the associated rain fields (Figure 4). Those models using a fine horizontal resolution (∼10 km) succeeded in reproducing the observed mean areal rain depth, however, with a very different spatial structure (Guichard *et al.*, 2010). The BOLAM run with assimilated satellite brightness temperature (nudging) produced significantly overestimated rainfall, although it had good skill for the 11 August 2006 case study (Orlandi *et al.*, 2010). The use of these aggregated (daily) rain fields as input to the TOPAMMA hydrological model showed that the biases in rainfall totals induced biases in the hydrological response of the same magnitude. A transformation of the rain fields to make them match the statistics of the observed field (areal mean or spatial distribution) resulted in a strong reduction of the bias in the hydrological response (Peugeot *et al*., unpublished). Expecting a perfect timing and location of simulated MCSs, and a correct rainfall amount, is probably not realistic given the limitations of the current models (see a review in Ruti *et al*., 2011; Paeth *et al*., 2011). However, this work suggests that bias correction methods can be helpful for coupled surface–atmosphere simulations or impact studies. In future work, this type of analyses should extend to other mesoscale domains and involve more hydrological models.

5. Conclusion and perspectives

The results presented above are still the object of extensive research, and some more work is needed to consolidate them. However, they revealed a number of problems and limitations, from which it is possible to draw future research directions.

At short time scales (daily or lower) and high space resolution, ground-based observations (gauges and/or radar data) provide the more accurate estimations of rainfall fields. State-of-the-art satellite rainfall products are reliable only at aggregated time/space scales (as from 10 days and 0.5°). Disaggregation techniques have to be developed if one wants to use those products for hydrologic applications or small scale simulations.

The mesoscale model experiments were quite innovative, but the current model performances hinder any use of the raw simulated rain fields in coupled simulations or impact studies. The simulation of reliable atmospheric water budgets requires major improvements of physical parametrisations in mesoscale models. Higher horizontal resolution using explicit convection appears promising, but model performance also relies heavily on the quality of initial conditions (atmosphere and surface), and on the realism of the other controlling processes (surface, boundary layer, aerosol and cloud processes). The identification of those rain field properties to which the impact or surface models are sensitive (e.g. mean areal rainfall) should guide the definition of bias correction methods.

The intercomparison of surface budgets obtained from different approaches (observations-based, hydrological or LSMs) is a good way to identify the weaknesses of model parametrisations. The preliminary work done so far will be developed in the forthcoming ALMIP-II experiment, dedicated to mesoscale simulations by a large variety of surface models. It is an ideal framework to make progress in water cycle representation, such as runoff and drainage in LSMs and evaporation in hydrological models. The impact of the convective-scale variability of rainfall on the land surface response, and the role of ground reservoirs, such as uptake by deep-rooted trees, will also be explored in this framework.

Then, a medium-range objective would be an intercomparison of the water budgets as derived from a surface or an atmospheric perspective, in order to evaluate whether those independent estimates of, for example, evaporation or rainfall are consistent, and at which scales. These analyses associating both the atmospheric and surface boxes as illustrated in Figure 1 would reveal the remaining limitations in the representation of the water cycle at the mesoscale.

Lastly, the AMMA project has permitted various communities (atmosphere, hydrology, land surface) to start fruitful collaborations, and this is promising for future advances in the integrative view of the water cycle in the monsoon system.

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