3C.3 ASSESSMENT OF WATER BUDGETS COMPUTED FROM NWP MODELS AND OBSERVATIONAL DATASETS DURING AMMA-EOP

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1. INTRODUCTION

Understanding the water cycle of the West African Monsoon (WAM) system is a major objective of AMMA (African Monsoon Multidisciplinary Analyses). The water cycle is the result of the interplay of various coupled atmospheric – ocean – land surface processes. The identification of the mechanisms involved and the scales at which they operate is a key factor for advancing on this issue. In the present study we compute continental water budgets for investigating the origin of the moisture that leads to precipitation (evapo-transpiration versus moisture convergence). Some insight is given into the intra-seasonal modulations and the inter-annual variability of the water budget terms over the AMMA-Enhanced Observing Period (EOP, 2005 to 2007).

Numerical Weather Prediction (NWP) models are often used for computing the atmospheric part of the water budget at global and regional scales (Higgins et al., 1996; Trenberth and Guillemot, 1998; Roads et al., 2002). In areas with dense radiosonde networks, observation-based water budgets can be computed also (e.g. Zangvil et al., 2001), with the advantage compared to NWP models that they do not rely on physical parameterizations. Over continental Africa, only NWP models allow for computing large-scale water budgets with reasonable horizontal resolution. In previous studies, Cadet and Nnoli, 1987, used winds from the ECMWF analysis and humidity fields from satellite-based retrievals, and Fontaine et al., 2003, used all terms of the budget equation (see section 2, below) from NCEP/NCAR reanalysis. However, several studies have pointed to significant deficiencies in NWP model analyses and reanalyses, especially regarding the hydrological cycle (Kanamitsu and Saha, 1996; Trenberth and Guillemot, 1998; Andersson et al., 2005; Drusch and Viterbo, 2007).

Therefore, in the present study, three different NWP model analyses and reanalyses available for the AMMA-EOP years are assessed over West Africa for the first time. Here, we compare the ECMWF-IFS operational analysis (http://www.ecmwf.int/research/ifsdocs/), the NCEP/NCAR reanalysis (referred to as NCEP-R1; Kalnay et al., 1996) and NCEP/DOE reanalysis (referred to as NCEP-R2; Kanamitsu et al., 2002). Comparing computations made from models which have different physical parameterizations and assimilation systems is a way commonly used to assess the uncertainty in the simulated quantities (Higgins et al., 1996). Here, we also use the unique observational data available over West-Africa from the AMMA project. First, we compute water budgets from the three NWP models and assess their consistency. Then we compute a hybrid budget, in which critical terms are taken from observational datasets and land surface modelling. We also present a preliminary investigation on the inter-annual variability in budget terms using the residual method (Kanamitsu et al., 2002).

2. DATA AND METHODOLOGY

The equation of conservation for water vapor is (Trenberth and Guillemot, 1998):

$$\frac{\partial PWV}{\partial t} + MFD = E - P \qquad (1)$$

where PWV is the precipitable water vapour, MFD is the horizontal moisture flux divergence integrated over the column (here, from P_{surf} to P_{top}=300hPa), E is the surface evapo-transpiration and P the total precipitation at the surface. It is verified that the vertical moisture flux through the top of the column is negligible.

All the terms in Eq. (1) can be obtained from NWP models. P and E are computed during the model integration and are thus forecasted (or simulated) terms. However these are C variables. PWV and MFD are computed from humidity (B variables) and horizontal wind (A variables). For these variables we prefer using analyses instead of forecasts because they are forced by and thus closer to observations during the assimilation cycle.

For the sake of consistency, all the NWP fields are used on the same horizontal grid and nearly the same vertical grid (i.e., pressure levels). The NCEP reanalyses were only available at a 2.5°x2.5° horizontal resolution, on which we thus regridded the ECMWF-IFS data from a former version at

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1.125°x1.125°. Monthly-mean budgets are computed in 2 boxes (see Fig. 1), West-Africa (WA, 10W-10E by 7.5N-20N, and Sahel (10W-10E by 12.5N-20N). For MFD and PWV we used 6-hourly instantaneous data (00, 06, 12, 18 UTC) and for E and P, forecasts integrated between +12 and +36h. MFD is computed as the net moisture flux through the lateral boundaries of the boxes, while E, P and ∂PWV/∂t are computed as spatial averages.

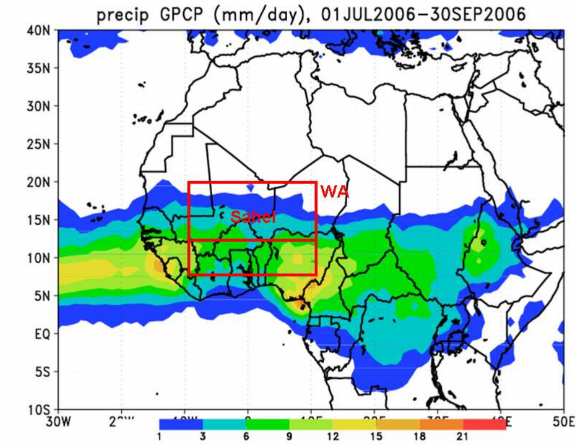

Fig. 1: Mean July-September 2006 rainfall from GPCP estimates. The water budgets are computed in the red boxes.

For the verification of NWP model fields, we used additional products and observations, namely: rainfall estimates from GPCP (Global Precipitation Climatology Project; Huffman et al., 1997), ETP estimates from ISBA land-surface model computed within the ALMIP project (Boone and de Rosnay, 2007), PWV estimates from the AMMA-GPS network (Bock et al., manuscript in preparation) and moisture fluxes computed from radiosonde data.

3. WATER BUDGET FROM NWP MODELS

Figure 2 shows the seasonal evolution in monthy-mean water budget terms (P, E, E-P, MFD, and ∂PWV/∂t) and the closure term (MFD+∂PWV/∂t-E+P) for the three AMMA-EOP years. This figure shows similarities and differences between the model budgets and years.

- Similarities: there is a large negative mis-closure in all three models with residuals reaching values nearly as large as the budget terms themselves. MFD is negative (moisture convergence) between April and October. It shows two peaks (also weakly revealed in P): in April and in August, corresponding to the rainy seasons in the Guinean and Sahelian regions, respectively.

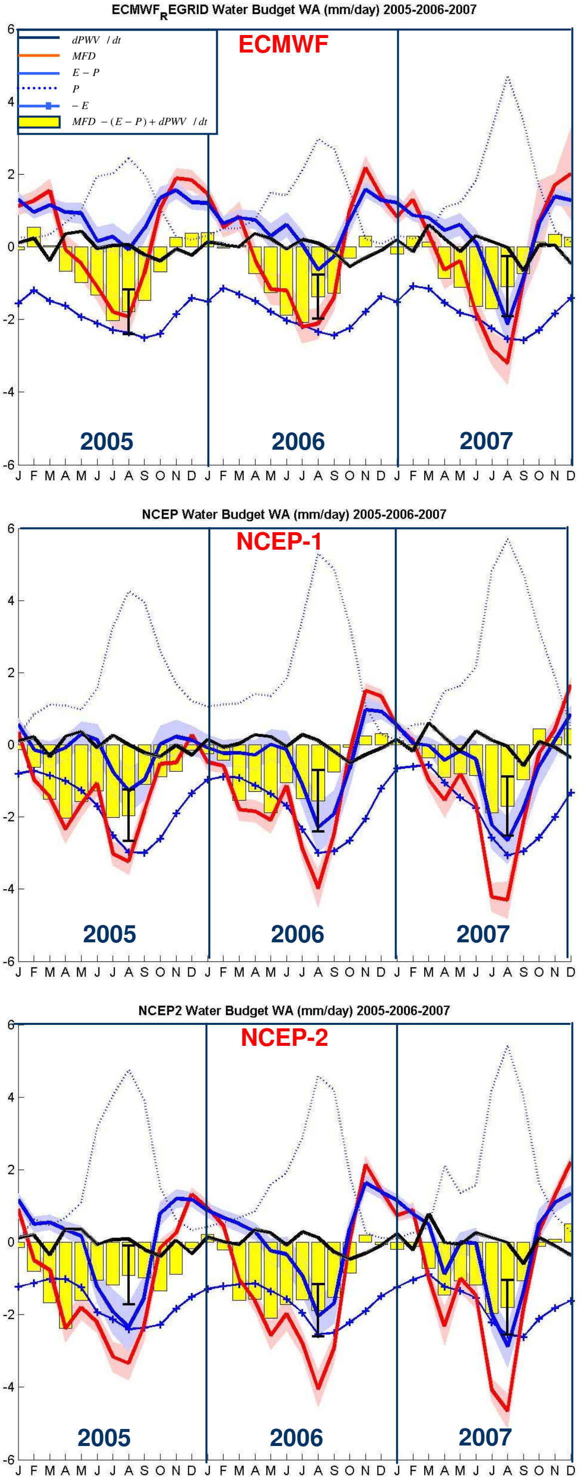

Fig. 2. Time series of monthy-mean water budget terms and closure for 2005-07, computed over the WA box (see Fig. 1), from the three NWP models. The shading on P and E and the error bar on the residual indicate ± one standard deviation of the monthly-mean values computed over all grid-points (i.e. spatial variability).

P and MFD are in phase, indicating that moisture convergence and precipitation are closely linked.

Evaporation is the largest in September-October (i.e. at the end of the rainy season).

- Differences: the seasonal modulation of E is much weaker in ECWMF, and P is much smaller (about 50%) compared to the NCEP reanalyses. The late spring-early summer unrealistic values of E in ECMWF are probably due to the assimilation scheme (Drusch and Viterbo, 2007). In summer, the weaker precipitation in ECMWF might be related to the fact that the precipitation belt is located too South (a well known problem with this model, Andersson et al., 2005; see also Fig. 3). The stronger trend between 2005 and 2007 toward larger values in P seen in the ECMWF model is not explained (it may be due to changes in the IFS model). The moisture convergence in the NCEP reanalyses is much stronger (nearly twice) than in ECMWF, especially in 2005 and 2006.

For all three models, the large negative mis-closure during the summer months might come from: either too strong E, too weak P, and/or MFD too negative (i.e. too strong moisture convergence) or more complex combinations of biases. Inspection of moisture fluxes through the boundaries of the WA box reveals that the largest differences occur at the southern boundary and lie in the lowest levels (between P_{surf} and 850hPa). Most of the discrepancy (up to 40%) in the moisture fluxes stems actually from differences in the wind fields (and hence mass fluxes) in this layer (not shown). Differences in the humidity field contribute also, but to a lesser extent (PWV-content differences between the models are at the level of 10%).

4. ASSESSMENT OF BUDGET TERMS AT INTRA-SEASONAL TIMESCALES

A large uncertainty in the water budget computed from NWP models comes actually from the E and P forecasts. Figure 3 shows time-latitude diagrams to highlight this point over the domain of interest for 2006. Evaporation in all three models is unrealistic over the Sahel, but especially in ECMWF-IFS, with too large values during the dry season (between November and March) compared to ISBA estimates. The summer precipitation zone is clearly located too South in the ECMWF model. The seasonal evolution in both E and P is overall better represented in NCEP2, though the rain-rate is overestimated between 6°N and 15°N in August-September 2006, compared to GPCP. The seasonal evolution of P in NCEP1 appears significantly different (and unrealistic). A correct prediction of rainfall is actually a difficult task for such models in the tropics, and over Africa in particular, because the convective systems that are responsible for most of the monsoonal rainfall are not well resolved. Hence, precipitation is mainly a result from model parameterizations. Differences in E from the three models most likely result from differences in the assimilation schemes of surface variables and on their convection scheme. Hence, understanding the differences in both E and P between these models requires further investigation in the way these variables are influenced by the forecast model physics and assimilation systems.

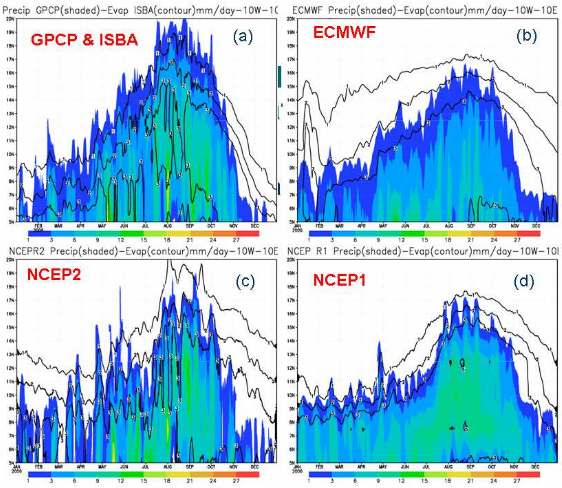

Fig. 3.Time-Latitude diagrams of P (shaded) and E (contour) averaged over 10°E-10°W, for year 2006, from: GPCP & ISBA (a), ECMWF analysis (b), NCEP2 (c) and NCEP1 (d). The variables are smoothed with a 5-day running average. Unit is mm/day.

Figure 3 confirms two of the hypotheses for the large negative residuals seen in Fig. 2 during the monsoon season. Over the WA box, E is too strong south of 12.5°N and too small north of 15°N (this is especially true for ECMWF and NCEP1) and P is too small north of 15°N in all three models.

Figure 4 shows the comparison for MFD and uses E-P from ISBA and GPCP as a proxy for validating the MFD from the models (MFD and E-P should be in balance when the PWV tendency is small, which is nearly the case, see Fig. 1). The E-P diagram shows clearly that P dominates E most of the time, except after the monsoon retreat in the southern area.

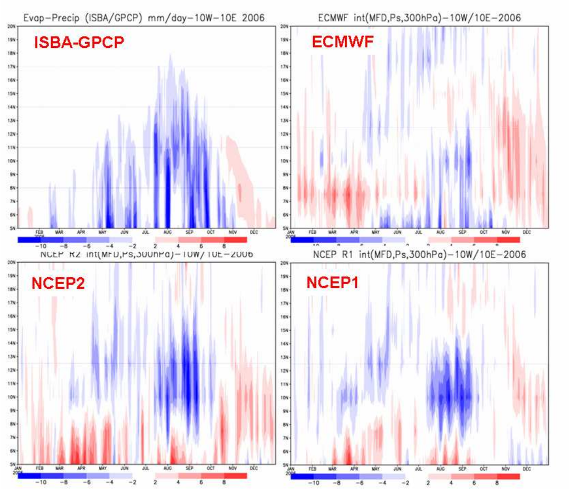

Fig. 4: Similar to Fig. 3 but showing MFD computed from the three NWP models and E-P computed from ISBA and GPCP.

Hence negative MFD should be observed when E-P < 0 (apart when moisture storage is significant). Instead, we see that all three models represent positive MFD over the Guinean area (around 7.5°N in ECMWF, between January and July, and around 5°N in the NCEP reanalyses). MFD is also stronger in the NCEP reanalyses between 7.5°N and 15°N during the monsoon season, consistently with our reference E-P. In ECMWF, instead, there is indication of moisture divergence between 12.5°N and 16°N in July-September 2006, which is clearly not realistic. This feature might be linked with the too southerly rainbelt and associated subsidence to the north of the deep-convective zone. Interestingly, however, all three models represent quite well the positive E-P period after the monsoon retreat and the net moisture convergence (negative MFD, consistent with positive PWV tendency) before the monsoon onset (between 10°N and 20°N in April-July).

Table 1 gives the differences (bias and standard deviation) of PWV from the three models to the independent GPS observations in 2006. Overall it is seen that the bias is largely varying from one site to another and is in the range -1.1 to 1.4 kg m^{-2} for the ECMWF analysis and -4.4 to +3.6 kg m^{-2} for the NCEP reanalyses. The standard deviations are varying also, in the range 1.7 – 4.8 kg m^{-2}, with slightly larger values for the NCEP reanalyses. The RMS error in PWV of the NWP models is thus at the level of 6.5 kg m^{-2} or ~18% of the average PWV. These results are consistent with those obtained from previous studies (e.g. Bock et al., 2007). Inspecting PWV time series reveals that the three models contain actually significant differences in the time variability. The quite large discrepancy between the GPS observations and the NWP models might be partly due to representativeness differences with the coarse grid used here (2.5°). However, biases in the radiosonde data assimilated over that region have been evidenced and have been shown to affect significantly the quality of NWP model analyses (Bock et al., manuscript in preparation). For this reason, prior to computing moisture fluxes from these radiosonde data for verifying the NWP models, we adjusted radiosonde humidity data to be consistent with the GPS PWV at collocated sites.

	BIAS (kg/m2)			STD (kg/m2)		
	ECMWF	NCEP R1	NCEP R2	ECMWF	NCEP R1	NCEP R2
DAKAR	-0,62	-3.28	-2,44	1.92	3,67	3,85
DJOUGOU	0,35	-1,54	0,52	2,25	3,12	3,55
GAO	1,44	-4,02	-2,71	2,42	4,77	4,18
NIAMEY	-1,1	1,09	3,57	1,72	2,42	3,22
OUAGADOUGOU	-0,29	-0,73	0,69	2,11	2,67	2,67
TAMANRASSET	-0,5	-0,48	1,55	1,74	3,05	3,19
TOMBOUCTOU	-0,65	-4,43	-3,46	3,07	4,47	4,32

Table 1: comparison of PWV from the three NWP models to PWV from GPS at seven sites during period June-September 2006 (bias on left part and standard deviation of daily mean values on right part).

Figure 5 shows an example of zonal and meridional moisture fluxes computed from GPS-adjusted radiosonde profiles at Niamey, Niger, and ECMWF analysis for August 2006. The zonal flux is evidently quite well represented (at least on the selected pressure levels), whereas the meridional flux from the model seems overestimated both at 700 hPa (northerly component) and below (southerly component). This result is consistent with the larger moisture convergence observed north of Niamey (13.5°N) and divergence in the vicinity of Niamey in Fig. 4.

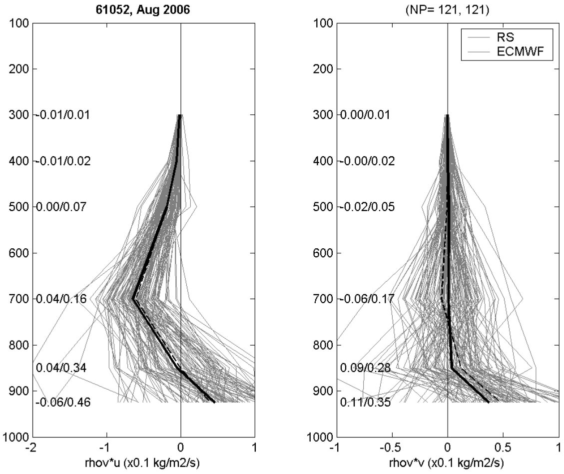

Fig. 5: moisture flux profiles computed from radiosondes and ECMWF analysis in August 2006 in Niamey: (left) zonal flux and (right) meridional flux. The thin gray lines represent all the soundings and the thick black lines the monthly means (soundings as solid line and ECMWF as dashed line).

5. COMBINATION OF NWP MODELS AND OBSERVATIONS

According to the results shown in section 3 and 4, E and P estimates from the NWP models suffer from the largest uncertainties. Though MFD estimates may not be perfect either, we nevertheless attempt here to compute more accurate budgets using these MFD estimates combined with E and P estimates from ISBA and GPCP. To our knowledge, this is the first time water budgets are computed over West Africa in this way.

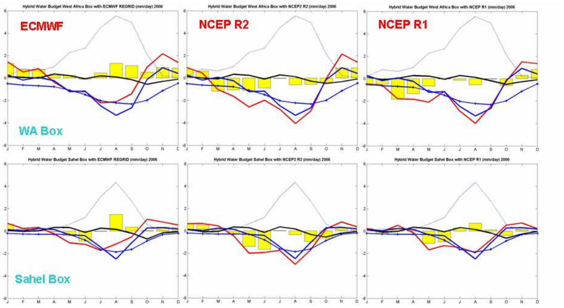

Fig. 6: Similar to Fig. 2 but for 2006 only and with E estimates from ISBA land surface model, P from GPCP, and MFD and ∂PWV/∂t from NWP models. The upper row shows the budgets terms and closure for the WA box (as in Fig. 2) and the lower row is for the Sahel box (see Fig. 1).

Figure 6 shows the budgets terms and closure for the WA and Sahel box for 2006 computed from this hybrid dataset. It is seen that the balance between (E-P) and MFD is significantly improved over the previous budget. Over the WA box, the absolute values of the residuals have been reduced by nearly a factor of 2, being now smaller than 1.5 mm/day with ECMWF and NCEP2 models. The largest residuals with the ECMWF model are linked to the erroneous MFD values discussed above (positive values around 7.5°N in the dry season and around 13.5°N during the wet season). For the NCEP reanalyses, MFD is slightly too negative all the time, leading to generally negative residuals. The balance in Sahel box is consistent with these characteristics but enhances more specifically a mis-closure from the ECMWF MFD in August and from the NCEP reanalyses in May-June. Note that part of the mis-closure observed here might also be due to uncertainties in the GPCP and ISBA products.

We attempt now to evaluate the interannual variability in the budget terms using seasonal averages (from which we expect some higher accuracy than from monthly averages). Following Zangvil et al., 2001, we estimate E as a residual from the water budget equation (hence using P from GPCP dataset, and PWV and MFD from the NWP models). In this case, we compute MFD as an spatial average and decompose it into two components: the horizontal advection (HA) and vertical advection (VA) integrated over the total column (P_{surf} - 300hPa). Table 2 shows the results for the July-August mean values. Precipitation is seen to increase over the three years (+40%), along with E (+80%), while MFD remains nearly constant. Verification against ISBA indicates that E might be overestimated by ~20% in 2006. PWV is also increasing (+10%), confirming that 2007 is wetter than 2005 and 2006 in July-August (i.e. both in terms of precipitation and moisture content, the latter being confirmed from GPS observations). Interestingly, and though MFD remains constant, there is a strong variation in VA, consistent with P. In 2007, VA is much stronger than in 2005 and 2006, indicating that the increased precipitation over the Sahel in 2007 is a result of both increased water vapor supply from the land surface and increased horizontal convergence associated with strong vertical advection of moisture.

6. DISCUSSION

According to these results, we can estimate that with the best datasets presently available, it is likely that water budgets cannot be evaluated to an accuracy better than 1.5 mm/day on monthly timescales and over areas on the order of $2\cdot10^6$ km^2. Such budget calculations are actually subject to numerous error sources which have been discussed extensively in the past (e.g., Trenberth 1991; Trenberth and Guillemot, 1995; Kanamitsu and Saha, 1996). Apart from the uncertainties in NWP model analysis and forecast fields mentioned above, these authors highlighted also the importance of spatial and temporal resolution of the atmospheric variables used for computing MFD and $\partial PWV/\partial t$. Among these error sources, those effecting most likely our calculations are (in an arbitrary order): (1) the time truncation error linked with the fact MFD and $\partial PWV/\partial t$ are computed from 6-hourly data and are not integrated continuously over time; (2) the analysis increment resulting from inconsistencies between the assimilated observations and the model first-guess; (3) the horizontal and vertical resolution of upper air model fields. We have quantified the latter one by comparing the 2.5°x2.5° moisture fluxes and MFD computed from wind and humidity fields on pressure levels with other versions of the ECMWF analysis (higher horizontal resolution and/or model levels). We found that when changing simultaneously the horizontal resolution from 0.25°x0.25° (close to the native reduced Gaussian grid) to 2.5°x2.5° and the vertical representation from model levels to pressure levels (38 and 7 levels below 300 hPa, respectively), the monthly mean spatial averaged MFD can change by up to 50% in July-September and by up to 80% in May-June (consistent with Trenberth 1991). At least for this reason we consider using model levels for future water budget computations. The other error sources will be addressed in the near future using corrected radiosonde profiles and high-resolution (1-hourly) GPS PWV estimates. As an ultimate assessment of accuracy, MFD and $\partial PWV/\partial t$ terms from the NWP models will be compared to observation-based water budget computations (such as used by Zangvil et al., 2001). A similar work and confrontation to observations is also planned for the AMMA reanalysis presently under realization at ECMWF with a more recent version of the IFS (including namely a new convection scheme and corrected radiosonde humidity data, A. Agusti-Panareda, personnal communication). With this improved NWP model

Year	E_residual	P	E-P	MFD	VA	HA	dPWV	PWV
2005 (Jul-Aug)	1,58	2,98	-1,40	-1,49	-0,34	-1,15	0,09	36,54
2006 (Jul-Aug)	2,14	3,29	-1,15	-1,39	-0,84	-0,55	0,23	36,92
2006 with E_ISBA	1,75							
2007 (Jul-Aug)	2,83	4,14	-1,31	-1,37	-1,50	0,13	0,06	40,57

Table 2 : Variation in the water budgets terms for the Sahel box for the AMMA-EOP years, with E computed as a residual from the budget equation, P from GPCP and the other terms from NWP models (MFD=VA+HA is computed from an spatial average).

estimates of MFD, the hybrid water budget calculation should yield more accurate estimates of budget terms and help understanding some fundamental aspects of the hydrological cycle of the West African Monsoon system. Therefore, improved E and P estimates might be necessary also, such as E estimates from ensembles of models (or at least a comparison of several models seems necessary) and P from a ground-based precipitation network, as available in some target areas over West Africa during AMMA.

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