CLSM simulations for ALMIP2:
Design and preliminary analysis

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1. Introduction

Land-atmosphere coupling has been shown to exert a significant influence on the West-African Monsoon (e.g. Nicholson, 2000 ; Philippon et al., 2005 ; Taylor et al., 2011). In the framework of the AMMA project (African Monsoon Multidisciplinary Analysis ; Redelsperger et al., 2006 ; Lebel et al., 2009), the goal of ALMIP (AMMA Land Surface Model Intercomparison Project) is to help improving land surface models (LSMs) in this region.

To this end, several state-of-the-art LSMs are compared in off-line mode (without atmospheric feedback), using the best quality and highest resolution data available (in space and time) to better understand the key land surface processes. The strategy is to compare the models' results between themselves and to available observations, to relate discrepancies to processes that are either missing or not adequately modeled.

In the first phase of the project (hereafter referred to as ALMIP1 ; Boone et al., 2009), the domain of interest was the large-scale AMMA domain, extending from -20 to 30 °E, and -5 to 20 °N. The models were run over a 0.5° grid-mesh, using 3-hourly meteorological forcing over 2002-2007 with the same spatial resolution. It revealed difficult to compare model results to observations at the chosen scale, because the spatial resolution of the models was not easily amenable to comparison with *in situ* data, and because pertinent large-scale observational data sets were limited (remotely-sensed brightness temperature, de Rosnay et al., 2009; remotely-sensed continental water storage changes from GRACE, Grippa et al., 2010).

To address these limitations, the second phase (ALMIP2 ; Boone et al., 2012) focuses on three heavily instrumented supersites from the AMMA-CATCH observing system (Lebel et al., 2009), in Mali, Niger, and Benin. Two main experiments will be performed over the 2005-2008 period. In the first one, the models will be run at the mesoscale for each of the three super sites, with 1/2-hourly forcing data at the 0.05° resolution (approximately 5 km). A second set of experiments will be performed at the local scale for several selected sites within each of the mesoscale squares.

We report below the main features of the simulations performed at laboratory Sisyphe with the model CLSM, for the first experiment only. We will not provide local-scale runs with this model.

2. Model description

2.1. Overview

CLSM stands for Catchment Land Surface Model (Koster et al., 2000 ; Ducharne et al., 2000). As a land surface model (LSM), it is designed to simulate the diurnal cycle of land surface water and energy fluxes as a function of near-surface meteorology (precipitation, short-wave and long-wave incident radiation, surface pressure, air temperature and humidity at 2 m, wind speed at 10 m), and it and can either be coupled to a GCM or used off-line as in the present study. The CLSM belongs to a new generation of LSMs which rely on the concepts of the hydrological model TOPMODEL (Beven and Kirkby, 1979) to account for lateral water fluxes along topography, their influence on the small scale variability of soil moisture, runoff and evapotranspiration, thus on larger scale water budget.

The simulated domain is discretized into elementary units, all including a shallow water table, described following TOPMODEL. The elementary units are designed to be watersheds but they can be grid-cells, as in ALMIP1. We use the distribution of the topographic index (section 3.2) in each unit as a template to laterally distribute the water table depth around its mean value, which varies in time as a result of the catchment water budget. The water table distribution controls base flow to the streams and water exchanges with the root zone (recharge and capillary rise), thus runoff and evapotranspiration, which are described using classic soil–vegetation–atmosphere transfer (SVAT) formulations, mostly taken from the Mosaic LSM (Koster and Suarez, 1992).

Some modifications were introduced to the original version of Koster et al. (2000), as described in Ducharne (2011):

- The most important one relates to the partitioning of each elementary unit into three fractions with a different soil moisture status, so that the saturated and stressed fractions vary *monotonically* with respect to the catchment deficit and root zone excess (two of the three soil moisture prognostic variables in CLSM). The behavior of the new partitioning scheme is illustrated in Appendix 1. The diagnostic of the surface soil moisture (swsrf) is also modified, also to ensure monotonic variations with respect to the three soil moisture prognostic variables.
- Another change is that the parameter r_{sca}, involved in the resistance to bare soil evapotranspiration, is multiplied by two, but it must be in the noise of the vegetation roughness parameters (section 3.3).
- In each elementary unit, a mosaic of vegetation types is allowed, based on the eight vegetation classes of the Mosaic LSM. The different tiles share the soil moisture variables, but different intercepted water amounts are maintained. Note that this feature, which was used in ALMIP1, is useless in ALMIP2 since only the dominant vegetation type is provided (section 3.3).
- Finally, the aerodynamic resistance is computed with respect to a reference height of 2m, at which the 10-m wind speed is brought by classical logarithmic transformation (`turb.f`).

2.2. *Differences with ALMIP1*

We use in ALMIP2 the exact same version of CLSM as in ALMIP1. Thus, the only differences between the ALMIP1 and ALMIP2 runs come from:

- the integration time step : it was 20 minutes in ALMIP1 with an interpolation of the hourly meteorological forcing to 20 minutes ; it has been increased to 30 minutes in ALMIP2 to follow the half-hourly meteorological forcing
- the spatial resolution : the model was run over a regular grid-mesh of 0.5° in ALMIP1, which is refined to a 0.05° grid-mesh in ALMIP2 (*ca.* 5 km)
- the forcing files :
  - ALMIP2 provides input files regarding near-surface meteorology (with two interpolation procedures for precipitation fields : a Thiessen or nearest-neighbour method, and a Lagrangian krigging, Vischel et al. 2009), vegetation properties (from ECOCLIMAP2, Kaptué et al., 2010) and soil properties (either from ECOCLIMAP2 or from a site-specific analysis the Mali mesosite)
  - We kept in ALMIP1 the Mosaic values for canopy and zero-plane displacement height. We chose here to more closely follow the information conveyed by ECO-II, which define smaller forest canopies than in Mosaic, and with a potentially different seasonality. These two parameters are thus deduced from the ECO-II roughness length and LAI (section 3.3)
  - topographic information is required to define a distribution of the topographic index (Beven and Kirkby, 1979). We used the Hydro1k data base in ALMIP1, with 1-km pixels, which are not amenable to give a good topographic index distribution in grid-cells of 25km^2. Thus, we moved to HydroSHED, with a resolution of 3-arc-sec (*ca*. 90 m).

3. Pre-processing of input data

3.1. *Three mesosites*

The main features of the three mesosites are summarized in Table 1. Regarding meteorological input, reference height is 10 m wind speed, air temperature and humidity. No convective fraction is provided for rainfall, assuming that a convective event is “smaller” than a grid-cell.

Meso-square	Reference paper	Domain	Rain Forcing (dt) & Soil Data	Time Period
Niger	Cappelaere et al. 2009	1.55°E to 3.15°E 12.85°N to 14.15°N (ncol=32; nrows=26)	*T, L (30 min)* *ECO-II*	2005-2008
Benin	Séguis et al. 2011	1.45°E to 2.85°E 8.95°N to 10.20°N (ncol=28; nrows=25)	*T, L (30 min)* *ECO-II*	2005-2008
Mali	Mougin et al. 2009	-1.90°E to -1.20°E 15.0°N to 15.7°N (ncol=14; nrows=14)	*T, L (30 min)* *ECO-II or GET*	2006-2008 (T) 2008 (L)

Table 1: The CONTROL mesoscale experiment summary. For rain forcing, T and L represent Thiessen, and Lagrangian-krigged, respectively. The default soil and vegetation parameters are from ECOCLMAP-II for the Niger, Bénin-Ouémé and Mali. Note that for the Mali site, 2 different soil databases are provided. The domain coordinates correspond to the domain limits (with a horizontal spatial resolution, d, and the number of grid points indicated). The total number of year-long simulations to be reported from the above total is 8 for the Niger, 8 for Bénin-Ouémé and 12 for Mali (from Boone et al., 2012).

3.2. Topography

We computed the topographic indices based on the hydrologically-conditioned elevation provided at the 3-arc-sec resolution in the HydroSHEDS data base, yielding to 3600 pixels in each 0.05° cell. This elevation layer is based on a combination of the original SRTM-3 and DTED-1 elevation models of SRTM, where “no-data” voids have been filled using interpolation algorithms, followed by an iterative hydrological conditioning and correction process, to achieve the best drainage directions as possible. See http://hydrosheds.cr.usgs.gov/ for technical details. Endorheic basins (inland sinks) are "seeded" with a no-data cell at their lowest point in order to terminate the flow, but no such cell was found in the processed areas.

During his master's thesis in 2011, Zakaria Ouissa downloaded the above elevation data, over rectangles larger than the meso-sites to ensure a correct representation of the upstream contributing areas. This could not be achieved, though, along the Niger stream, where the upstream contributing areas are thus underestimated. Slope, drainage direction and flow accumulation were calculated in ArcGIS10 using the D8 single-flow direction method. Appendix 2 illustrates these different steps.

The calculation of the topographic index (TI) was performed by Claire Magand outside from ArcGIS, using R. In each DEM pixel, the TI x is calculated by $x=\ln(a)/S$. The specific area per unit contour length is given by $a=(n+1)C$, where n is the number of upstream pixel, as given by the flow_accumultation layer in ArcGIS, and C is the pixel length, given in Table 2. The local slope S is the one computed by ArcGIS, except when the value is zero : instead of replacing it by a minimum slope Smin, we use a random value taken in [Smin/10; 2*Smin]. Smin is defined with respect to the precision of the DEM in z (1m in HydroSHEDS): $Smin=1/(2C(1+\sqrt{2}))$.

The resulting values are plotted in Appendix 2 and summarized in Table 2.

		Benin	Niger	Mali
C [m]		92	90.9	91.5
TI [ln(m)]	min	5.75	4.60	4.82
	max	27.04	25.11	24.28
	mean	10.35	9.58	10.43
	std dev	2.12	1.90	2.13

Table 2: Main statistics of the topographic index (TI) distribution in the three mesosites. The second row gives the pixel size C used in the topographic index calculation.

Note finally that the calculated baseflow, as in TOPMODEL, depends on mean TI, which is dependent on DEM resolution. In ALMIP1, we used a 1-km DEM, and the correction of Wolock and McCabe (2000) to get values corresponding to a 100-m DEM, as in Ducharne et al. (2000), such as to use the corresponding values of hydraulic conductivity to calculate baseflow. In ALMIP2, we use a 90m-DEM, and to keep the same hydraulic conductivity values, we brought the resulting mean TI in each grid-cells to those from a 100-m DEM, using the correction proposed by Ducharne (2009):

$$x_{100}=x_{90}+\ln(100/90)\simeq x_{90}+0{,}1$$

3.3. Vegetation

The input vegetation parameters are from the ECOCLIMAP-II-Africa database (hereafter ECO-II; Kaptué et al., 2010). The vegetation cover is classified into 12 basic land classes, also called *patches*, which are converted into one of the 8 vegetation classes of CLSM (Table 3). The varying vegetation parameters (LAI, roughness length, etc.) are provided for each decade of 2005-2007, with one average value per grid-cell. The ECO-II database should be extended to include 2008, by the end of June 2012.

ECOCLIMAP-II		Mosaic-CLSM	
1	bare ground	8	Desert soil
2	rocks		
3	permanent snow	-	
4	deciduous forest	2	Broadleaf deciduous trees
5	conifer forest	3	Needleleaf trees
6	evergreen broadleaf trees	1	Evergreen broadleaf trees
7	C3 crops	4	Grassland
8	C4 crops		
9	irrigated crops		
10	grassland (C3)		
11	tropical grassland (C4)		
12	garden and parks		

Table 3: Correspondence between the ECO-II 12 patches and Mosaic 8 classes (Koster and Suarez, 1996).

Dominant vegetation in each 0.05° cell

Contrarily to ALMIP1, patch-specific parameters are not provided, what leads to consider the dominant vegetation class in each grid-cell. This strategy is supported by Table 4, which shows that the two vegetation classifications (fractional *vs* dominant) give consistent results on average over the ALMIP2 meso-sites. A comparison is also given with the mean fractional coverage deduced in the meso-sites from the ALMIP1 vegetation data (ECOCLIMAP, Masson et al., 2003). The main change is found in the Benin meso-site, where ALMIP2 describes a much larger forest fraction, in agreement with remote sensing data. Note also that the dominant vegetation strategy gives consistent results every year (Table 5).

The fractional vegetation strategy could be examined as well, especially in the Benin, where the forest is often a clear forest. This would require that patch-specific seasonal cycles are provided. Then, the average of the different patch-values in a grid-cell would need to be made equal to the ECO-II average value for the decade.

	ALMIP2 - 2005						ALMIP1		
	Fractional vegetation %			Dominant vegetation %			Fractional vegetation %		
	Forest	Grass	Bare Soil	Forest	Grass	Bare Soil	Forest	Grass	Bare Soil
Benin	51	40	9	69	31	0	16	73	11
Niger	6	43	51	0	57	43	4	51	44
Mali	6	29	65	0	37	65	0	33	66

Table 4: Comparaison of the mean vegetation cover in the three meso-sites, using ALMIP2 data (ECO-II) for 2005 (either keeping the fractional cover or reducing it to the dominant vegetation class in each grid-cell) and ALMIP1 data. For simplicity, the classes of vegetation are reduced to three main types (Forest, Grassland and Bare soil).

Year	Benin			Niger			Mali		
	Forest	Grass	Bare Soil	Forest	Grass	Bare Soil	Forest	Grass	Bare Soil
2005	69	31	0	0	57	43	0	35	65
2006	69	31	0	0	57	43	0	35	65
2007	69	31	0	0	57	43	0	35	65

Table 5: Dominant vegetation fraction in each mesosite between 2005 and 2007 (from ECO-II).

Greeness fraction

This parameter is required by CLSM but not provided in ECO-II, and it is deduced from relationships to between LAI and greeness fraction in ALMIP1: linear regressions are characterized between greeness fraction (green) and LAI in each meso-site based on the spatial mean of ALMIP1 values in the meso-sites

Mali: green = 0.0432 +0.3137 * LAI $R^2 = 0.995$

Niger: green = 0.0735 + 0.3008 * LAI $R^2 = 0.9933$

Benin: green = 0.2068 + 0.2092 * LAI $R^2 = 0.97$

Displacement height and canopy height

These parameters, dd and z2 respectively, are required by CLSM but not provided in ECO-II, nor in the ECOCLIMAP data set used in ALMIP1, for which we thus kept dd and z2 from Mosaic.

A first set of ALMIP2 runs is thus performed as in ALMIP1, using Mosaic's values of z2 and dd. However, the ECO-II values of z0 can be larger in some grid-cells than z2-dd, what leads to incorrect results (it brings negative values of u2fac, thus r_{sca}, what would lead to reduce r_{bs} instead of increasing it). Therefore, we change a bit the boundary layer calculations and impose that log((z2-dd)/z0) > 1, as it is the case using Mosaics values. Note that this problem may have occurred in ALMIP1, and led to higher bare soil evaporation than expected, as it does not create any numeric problem.

Another strategy would be to more closely follow the information conveyed by ECO-II, the LAI of which seems to define smaller forest canopies than in Mosaic, and with a potentially different seasonality. This led us to deduce z2 and dd from relationships to roughness length (z0) in Mosaic, with several difficulties:

- Note that dd and z2 must remain consistent together and with z0 to prevent numerical issues (NaN) in the boundary layer parameters (routine pmonth of CLSM), where we define

  u2fac = alog((z2-dd)/z0), which must be greater than 0

- In each grid-cell, we first deduced canopy height (z2) from roughness length, the relationship being established from Mosaic values :

  z2 = 0.4860 + z0max * 13.9093 $R^2=0.97$

  The simpler relationship was eventually preferred as it gives values that seem sensible in the AMMA context (shorter trees, taller grass)

  z2 = 10 * z0max

  Note that Jérome Demarty uses a different relation : z0 = 0.13 z2 ⇔ z2 = 7.7 z0

- For zero-plane displacement height (dd), we first tried to use the monthly values for each class embedded in the Mosaic LSM (Koster and Suarez, 1996)

  Mosaic class 2 : dd = 10.871 + 5.428 * z0 $R^2=0.99$

  Mosaic class 4 : dd = 0.2066 + 0.0255 * LAI $R^2=0.98$
  WARNING: This gives too small dd, inconsistent with z2 and z0.The reason is probably that Mosaic's grasslands are small grasslands (dd<0.32m)

To make sure that z2-dd>z0, we chose a simpler strategy, inspired by the relationship found in Guyot (1999, p85) : dd= 0.7 * z2. We use time-varying z0, with a smaller slope (0.5*z2) to bring ln((z2-dd)/z0) to higher values (ln(5)= 1.609) in better agreement with Mosaic.

For both vegetation classes 2 and 4, we thus use

dd = 5 * z0

- To preserve consistency, we also used Mosaic's values for desert soil for dd and z2 when required by the dominant vegetation. This leads to change z0 and we can have smaller z0 in the vegetated cells than in the bare soil cells.

- This strategy also requires to change process to transmit z2, what has not been coded yet, so that the above diagnosed z2, dd and z0 have not been used.

LAI and roughness length

These parameters are taken from ECO-II without any change. The only exception is that the ratio of (z2-dd)/z0 which is forced to remain greater that, what can be seen as a change in z0.

Note that the ECO-II LAI values are consistently lower than the ones used in ALMIP1 (Figure 1 in Appendix 3).

Emissivity

This parameter is not used in CLSM which assumes that the emissivity is equal to one.

Statistics of the vegetation properties used in CLSM runs

Table 11 in Appendix 3 shows the yearly variability in the vegetation parameters and a lot of similarity between the Mali and Niger sites. Putting a minimum to the roughness length in the bare soil cells does not change much the statistics.

3.4. Soils

The standard soil data in ALMIP2 is given in the ECOCLIMAP-II-Africa database, and includes sand and clay fractions, based on the FAO database at 10 km spatial resolution. Soil depths (root zone, Drz, and total, Dtot) are also provided, and deduced from the vegetation cover. CLSM also require a surface layer depth, which is taken as 2cm, as in ALMIP1.

An alternative soil data set has also been proposed by the GET for the Mali meso-site, based on remote-sensing and in-situ observations. It is labeled by GET in Tables 2 and 6.

Soil parameters depending on soil texture

We start by defining the grid-cell soil texture, based on sand and clay fractions in the USDA triangle. We then deduce the required parameters :

- porosity, hydraulic conductivity and matric potential at saturation, parameter b to relate saturated and unsaturated parameters, following the values of Cosby et al., 1984, which are reported in Gascoin (2009), p 125.

- temporary wilting point (calculated for pF=4) and residual water content (calculated for pF=6)

Soil depth

The first runs will be done in each meso-site using ECO-II values. Note that in ALMIP1, a special constraint was imposed so that Dtot ≥ 1m et Drz≤ Dtot*0.75, what led to overestimate the total soil depth Dtot in 2.5% of the grid cells.

The sensitivity to this constraint will be analysed in ALMIP2 since a significant fraction of the Mali and Niger meso-sites have a total soil depth lower Dtot≤ 1m in ECO-II. Runs without this constraint will also be performed, especially when using the additional soil data set for the Mali, where the northern area has “no soil” (Table 6). As it is not possible to describe a soil with a zero depth, we impose a minimum total depth, set to 20 cm.

4. Formatting of output data

We use a very similar output formatting as in ALMIP1, with one netcdf file per year for each mesosite run (netcdf header in Appendix 4). We add latitude and longitude, and a “time_representation” to the description of time varying variables. The adaptation of the non traditional soil moisture prognostic variables of CLSM (catchment deficit, root zone and surface excess) to water contents in three soils layers is explained in Gascoin (2009), p129.

5. Performed simulations

5.1. Description of the simulations

All the CLSM simulations (Table 6) start from their own initial conditions, which are defined by spin-up, from reference initial conditions in each mesosite. These reference conditions are defined for the beginning of years 2005 to 2008 from the spatial average of the ALMIP1-Exp3 in the mesosites.

If we prepare the initial conditions of a run starting in 2005 in the Mali mesosite, we take the Mali reference conditions for the beginning of 2005. Then, we follow the recommendation of ALMIP2 Whitepaper (Boone et al., 2012) and spin-up over 2005 (using the correct 2005 meteorological forcing, T or L according to the run specification) until adequate convergence is obtained.

Mesosite	Simulation label	Met. forcing	Period	ECO-II veget.	Soil data	Dtot ≥ 1m	OK
Niger	Niger_exp1L_d1m	L	2005-2007	Dom	ECO-II	yes	x
	Niger_exp1T	T	2005-2007	Dom	ECO-II	no	x
	Niger_exp1L	L	2005-2007	Dom	ECO-II	no	x
Benin	Benin_exp1T	T	2005-2007	Dom	ECO-II	yes=no	x
	Benin_exp1L	L	2005-2007	Dom	ECO-II	yes=no	x
Mali	Mali_exp1T_d1m	T	2006-2007	Dom	ECO-II	yes	x
	Mali_exp1T	T	2006-2007	Dom	ECO-II	no	x
	Mali_exp1L	L	2008	Dom	ECO-II	no	
	Mali_exp1T_get	T	2006-2007	Dom	GET	no	x
	Mali_exp1L_get	L	2008	Dom	GET	no	

Table 6: Main features of the simulations performed with CLSM for ALMIP2. The mandatory runs appear in blue. 2008 not done yet as ECO-II is missing. Sensitivity simulations regarding vegetation roughness are also planned. In the Benin mesosite, complementary simulations might be performed regarding the deep water table (increased soil depth or inclusion of an additional linear reservoir). Finally, exploratory simulations with a coarser resolution may also be attempted.

The first criterion is that total soil moisture at all pixels within the mesosite changes by less than 1% or 0.1% of the precipitation (whichever is larger) between Jan. 1 and Dec. 31 of the spin-up year. The convergence of surface temperature is also be examined, and the results are summarized in Table 7.

Note also that for runs with smaller soil depths than in ALMIP1, the reference initial value of the catchment deficit should be increased. As a first guess, we use proportionality between the total soil depths and the initial values of catchment deficit.

Year	Mean P	Mean SMi	Mean SMf	SM not OK	Mean Tsi	Mean Tsf	Ts not OK
Mali_exp1T_d1m (2006)							
1	377	306.6208	96.11682	196	288.1374	289.1029	0
2	377	96.11682	95.74844	4	289.1029	289.11078	0
3	377	95.74844	95.745705	0	289.11078	289.11102	0
Niger_exp1T_d1m (2005)							
1	543	363.62894	131.25876	832	292.7021	291.45206	0
2	543	131.25876	131.71178	58	291.45206	291.44598	0
3	543	131.71178	131.67792	0	291.44598	291.44635	0
Benin_exp1T (2005)							
1	1068	620.3354	484.37238	700	293.69028	292.51566	
2	1068	484.37238	480.59232	231	292.51566	292.54514	0
3	1068	480.59232	480.3888	1	292.54514	292.54633	0
4	1068	480.3888	480.39407	1	292.54633	292.54428	0
5	1068	480.39407	480.4082	0	292.54425	292.54337	0

*Table 7: Convergence of soil moisture (SM) and surface temperature (Ts) during the repeated years of the spin-up procedure. The 5^{th} and 8^{th} columns give the number of grid-cells when convergence is not realized for SM and Ts respectively, given the chosen criteria: see text for SM ; for Ts, it is a variation in Ts smaller than 0.05*Tsi (ca 14.5 K, thus too loose to be useful).*

5.2. Sanity checks

We checked that the water and energy budgets are closed in all simulations.

We also analyzed 10 variables : precipitation rates (ptot), total runoff (runtot, which is almost entirely surface runoff in the Mali and Niger), evapotranspiration (evap), sensible heat flux (shfx), surface temperature (Tsurf), and CLSM specific variables (see section 2.1 and Appendix 1), namely the catchment deficit (catdef), root zone excess (rzex), root zone flow (rzflw), Asat and Atr (ar1 and ar2).

The produced diagnostics include interannual means (Tables 8-10), 3-yr time series (2-yr in the Mali meso-site), mean annual cycles of the meso-site spatial averages (Figures 1 and 2), and maps of interannual averages over the year, as in Figure 4. The comparison to the ALMIP1 spatial averages over the the mesosites in 2005-2007 was also performed.

The ALMIP2 results show rather reasonable values, but they notably differ from ALMIP1, probably because of differences in precipitation input (obvious from Tables 8-10), other meteorological forcing fields, and land surface properties (see the differences in LAI in Appendix 3, Figure 5).

Benin		**ALMIP1**	**exp1T**	**exp1L**
ptot	(mm/d)	2,78	4,55	4,32
runtot	(mm/d)	0,62	1,39	0,93
evap	(mm/d)	2,18	1,57	1,89
catdef	(mm)	316,5	325,63	271,58
shfx	(W/m2)	47,41	80,16	72,74
rzex	(mm)	-22,41	-13,8	-11,07
rzflow	(mm/d)	0,23	0,06	0,16
ar1	(-)	0,03	0,01	0,02
tc	(C)	301,14	26,72	26,45
ar2	(-)	0,56	0,65	0,73

Table 8: Comparison of ALMIP1 and ALMIP2 results on average over the Benin meso-site: interannual means over 2005-2007 for the main simulated variables.

Niger		ALMIP1	exp1T	exp1L	exp1L_d1m
ptot	(mm/d)	1,57	2,22	2,12	2,12
runtot	(mm/d)	0,18	0,61	0,41	0,37
evap	(mm/d)	1,40	0,88	1,01	1,06
catdef	(mm)	372,14	259,67	254,06	318,66
shfx	(W/m2)	48,24	45,07	42,60	41,86
rzex	(mm)	-2,19	-2,71	-2,85	-3,57
rzflow	(mm/d)	0,05	0,00	0,00	0,00
ar1	(-)	0,02	0,03	0,04	0,02
tc	(C)	304,41	30,97	30,78	30,69
ar2	(-)	0,38	0,27	0,29	0,35

Tableau 9: Comparison of ALMIP1 and ALMIP2 results on average over the Niger meso-site: interannual means over 2005-2007 for the main simulated variables.

Mali		ALMIP1	exp1T	exp1T_d1m	exp1T_get
ptot	(mm/d)	1,28	1,53	1,53	1,53
runtot	(mm/d)	0,18	0,40	0,37	0,42
evap	(mm/d)	1,13	0,62	0,65	0,59
catdef	(mm)	326,68	200,16	311,49	370,06
shfx	(W/m2)	35,13	43,31	42,69	43,57
rzex	(mm)	-0,44	-0,35	-1,11	-1,81
rzflow	(mm/d)	-0,01	0,00	0,00	0,00
ar1	(-)	0,05	0,04	0,02	0,03
tc	(C)	303,64	30,62	30,55	30,67
ar2	(-)	0,37	0,20	0,30	0,33

Tableau 10: Comparison of ALMIP1 and ALMIP2 results on average over the Niger meso-site: interannual means over 2006-2007 for the main simulated variables.

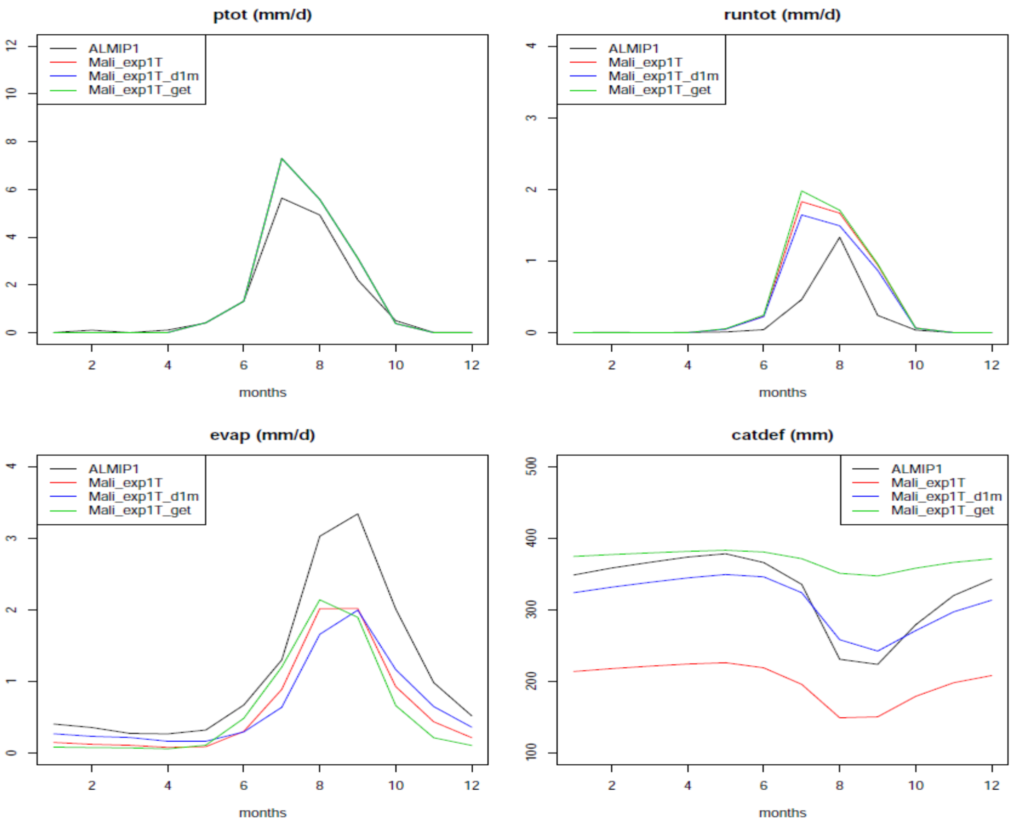

Figure 1: Spatial averages over the Mali meso-site: mean annual cycles of precipitation rates, total runoff, total evapotranspiration and catchment deficit over 2006-2007, for the three ALMIP2 simulations (Table 6) and the Exp3 ALMIP2 simulation.

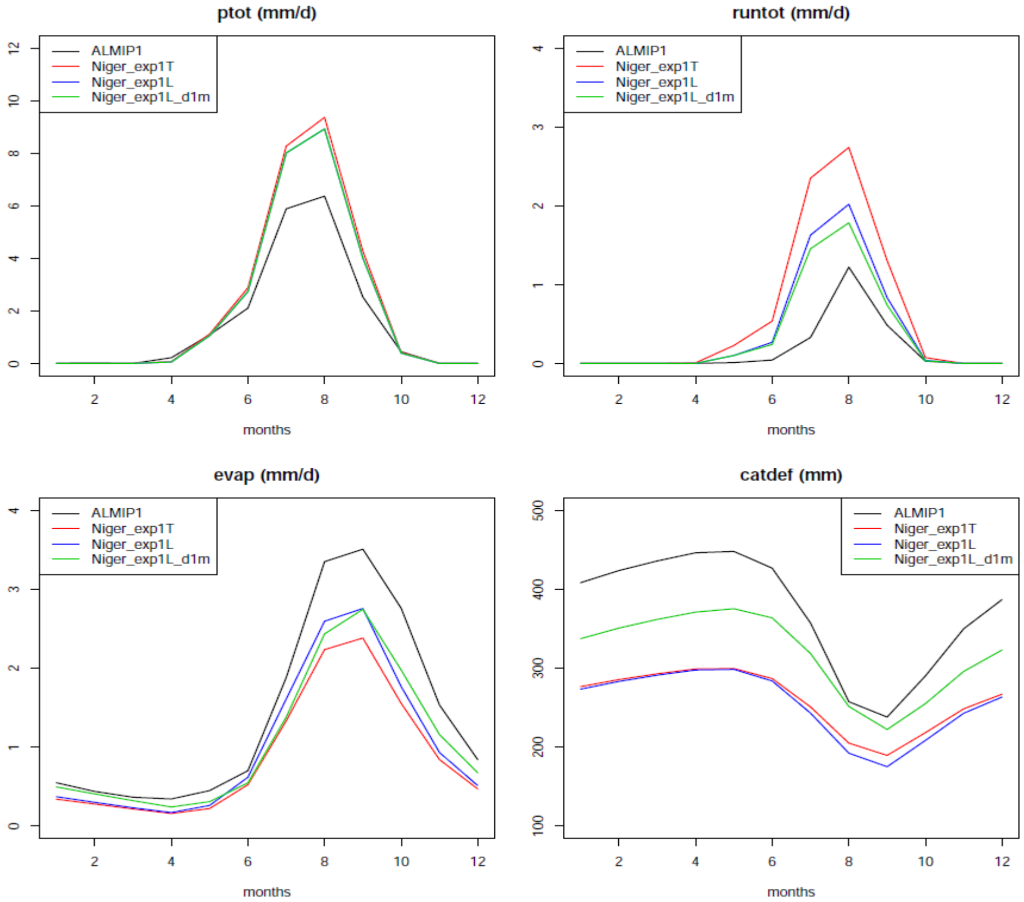

Figure 2: Spatial averages over the Niger meso-site: mean annual cycles of precipitation rates, total runoff, total evapotranspiration and catchment deficit over 2006-2007, for the three ALMIP2 simulations (Table 6) and the Exp3 ALMIP2 simulation.

Sensitivity to soil depth

In Niger and Mali, the ECO-II total soil depth can drop below 1m, whereas the ALMIP1 simulations were performed by forcing total soil depth to be larger than 1 m (section). We first compare the results of simulations with and without this constraint, in the Niger and Mali meso-site (using the Lagrangian and Thiessen rain forcing respectively). Figures 1 and 2 show similar sensitivities in both meso-sites. When total soil depth is larger (simulations “d1m”), total runoff is smaller and evapotranspiration is higher. The main reason is that a deeper soil allows the water table to have a deeper mean equilibrium depth (as indicated by the larger catchment deficit all the year long), so that the saturated fraction gets smaller. Surface runoff, which is by far the largest contribution to total runoff, is then decreased.

An additional simulation is analyzed in the Mali (Mali_exp1T_get), where the GET provided an alternative soil data set, with total soil depth and texture deduced from the detailed analysis of LANDSAT images at the 30-m resolution, using supervised classification. Together with topography (Figure 3), this defines three main zones, structured by latitude, and all subjected to endorheism for different reasons:

- the Northern part exhibits shallow soils, with surface runoff concentrated in ponds (topographic endorheism);
- the central part is characterized by deep sandy soils (dunes), with almost no runoff (functional/local-scale endorheism, or even arheism)
- the Southern part is characterized by the presence of low lands, flooded yearly for 3-4 months. According to Montpellier's meeting in November 2011, these zones are endorheic, *i.e.* are not connected the Niger's main stream. Always according to the meeting, forests are present in this zone, but ECO-II does not describe any.

In addition to this general structure, some areas are not covered by real soils but by outcropping rocks, where the GET data set considers that soil depth is zero. As this is not possible in CLSM, as probably in most LSMs, we rather imposed a minimum total depth, set to 20 cm, which is the minimum non-zero soil depth in the GET data base.

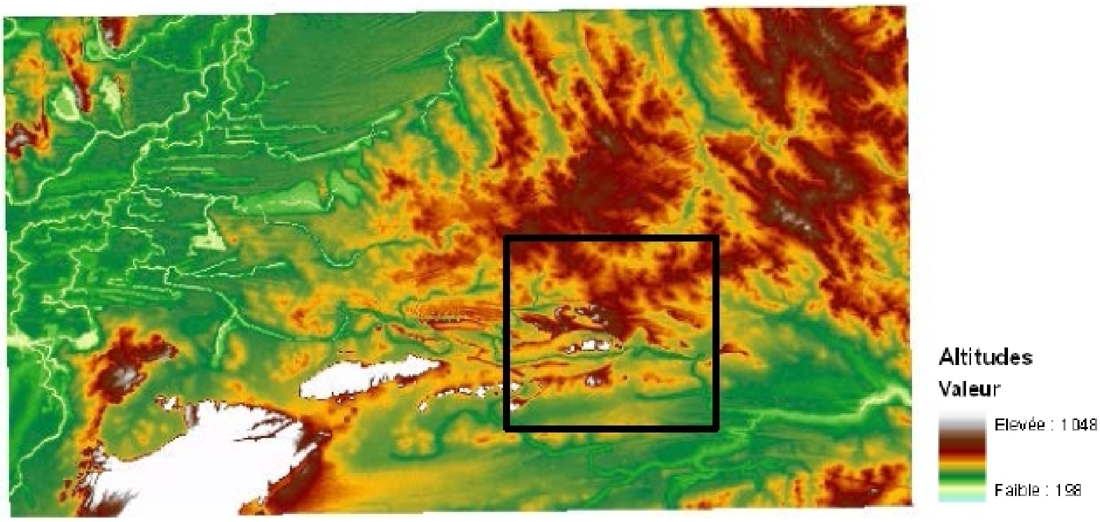

Figure 3: Topography of the Mali meso-site, inside the black square.

Comparing simulations "Mali_exp1T_get" and "Mali_exp1T" spatially does not reveal marked differences in runoff patterns (Figure 4). The main differences are that :

- **the minimum annual runoff is found in the central part of the meso-site using the GET soil information, whereas is it in the northern part using ECO-II;**
- **the maximum runoff, logically found in the South for meteorological reasons, is slightly higher in "Mali_exp1T_get".**

The resemblance, however, is larger than the dissemblance.

The mean annual cycles (Figure 1) are also very much alike. The mean runoff is slightly larger in simulation Mali_exp1T_get, despite a deeper mean water table. This counter-intuitive result is probably related to the fact that the changes in soil depth are far from being uniform between the two simulations (which also differ by their soil texture). The increase of water table depth and catchment deficit are probably mostly found in the central part, where mean annual runoff does decrease but remains very small in both simulations.

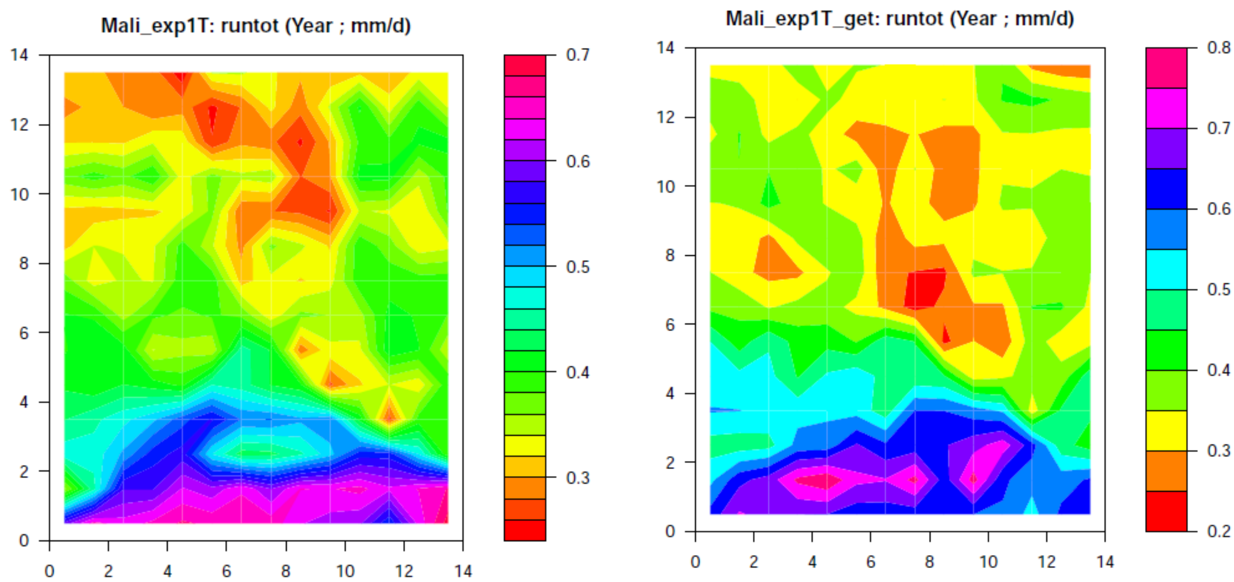

Figure 4: Comparison of the patterns of mean annual runoff between simulations Mali_exp1T and Mali_exp1T_get.

6. Still to be done

The ALMIP2 project team is collectively in charge of comparing the different LSMs and hydrological models, between themselves and to the validation data, including analyzes of the sensitivity to the precipitation forcing (Thiessen *vs.* Lagrangian) and the soil data base (ECO-II *vs.* GET).

The above CLSM-specific studies could be usefully complemented by a map of the difference between the ECO-II and GET total soil depths, and by the analysis of the sensivity to the vegetation roughness parameters.

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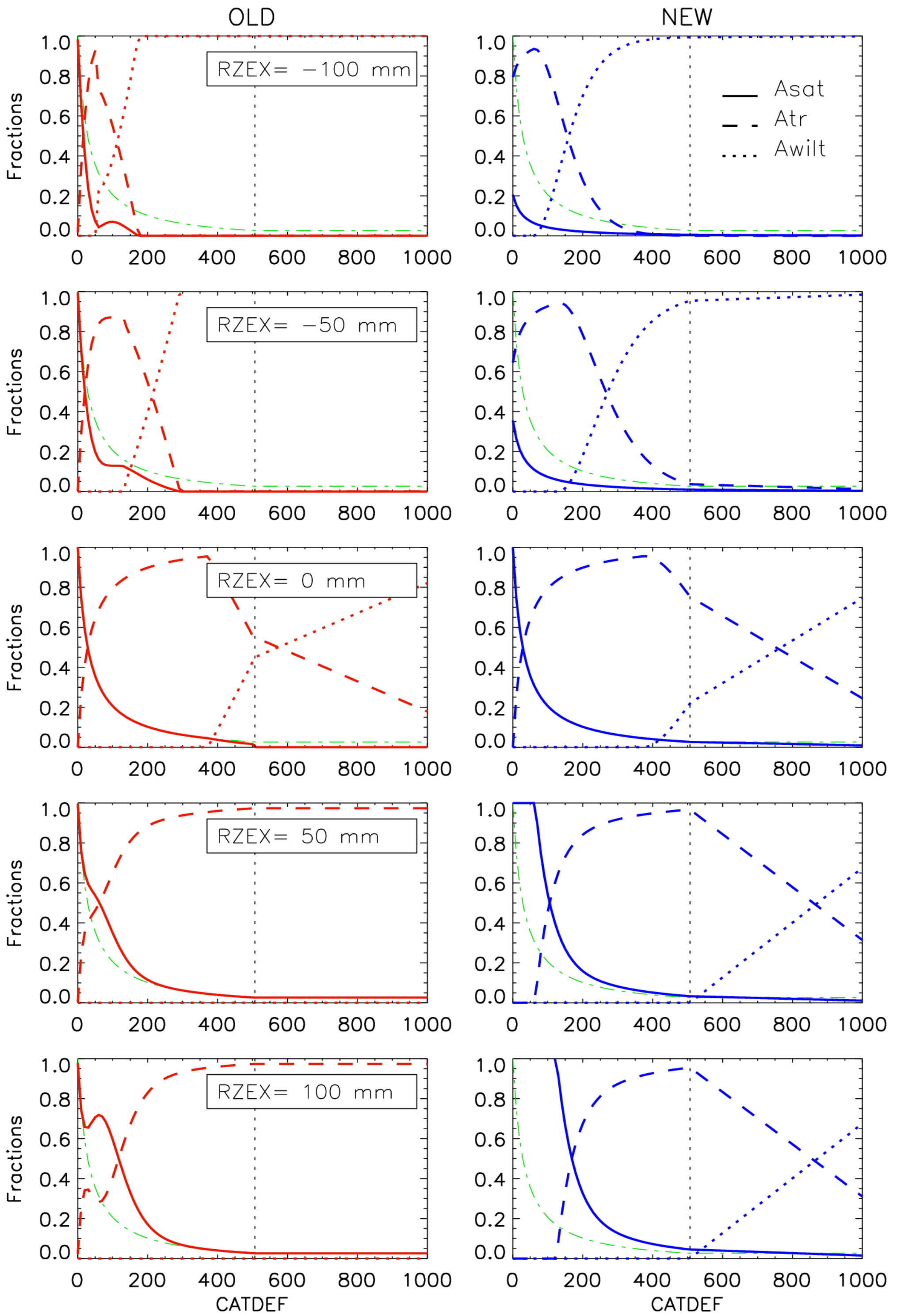
Appendix 1. Comparison of the original and modified partitioning schemes in CLSM



The partitioning of each elementary unit into three fractions with a different soil moisture status has been modified to ensure that the saturated and transpiring fractions (respectively Asat and Atr) vary *monotonically* with respect to the catchment deficit (CATDEF) and root zone excess (RZEX). The above figure shows the evolution of the fractions as a function of catchment deficit for five values of root zone excess, for the original parametrization from Koster et al. (2000) in red, and for modified parametrization in blue. The green curves show the saturated fraction at equilibrium (if RZEX=0). The calculations are performed for an elementary unit of the Seine watershed, assuming a wetness at wilting point of 0.5, and a depth to bedrock of 3m (noted zdep3 below, as in the source code).

In the above figure, the vertical dotted line shows the threshold catchment deficit cdcr1, which is defined as the maximum catchment deficit that allows the water table (WT) to follow the shape deduced from TOPMODEL. When the catchment deficit is above that value, the baseflow is turned to zero, and the processes which depend on the water table depth (partitioning, and rzflw, the vertical flow between the root zone and the water table) are linearly brought to the limit values for an extremely dry catchment, set when catdef=cdcr2. Then, rzflw=0, and Awilt=1 in the new partitioning scheme in absence of positive root zone excess.

In ALMIP2, cdcr1 and cdcr2 are defined as in Koster et al. (2000):

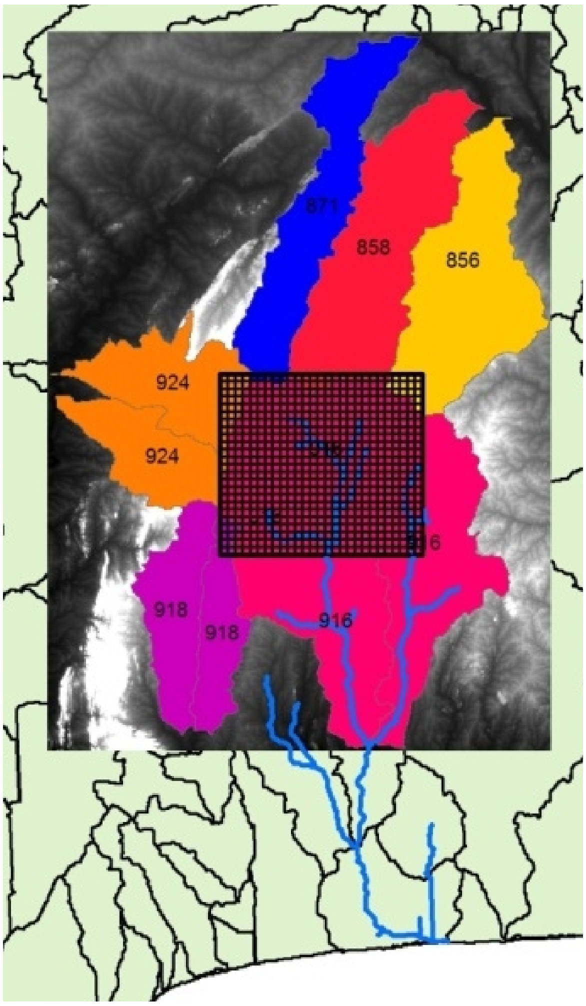
```
zmet=zdep3(n)/1000.
puiss=(bee(n)-1)/bee(n)
term1=-1+((psis(n)-zmet)/psis(n))**puiss
term2=psis(n)*bee(n)/(bee(n)-1)
cdcr1(n)=1000.*poros(n)*(zmet-(-term2*term1))
cdcr2(n)=(1.-residual(n))*poros(n)*zdep3(n)
```

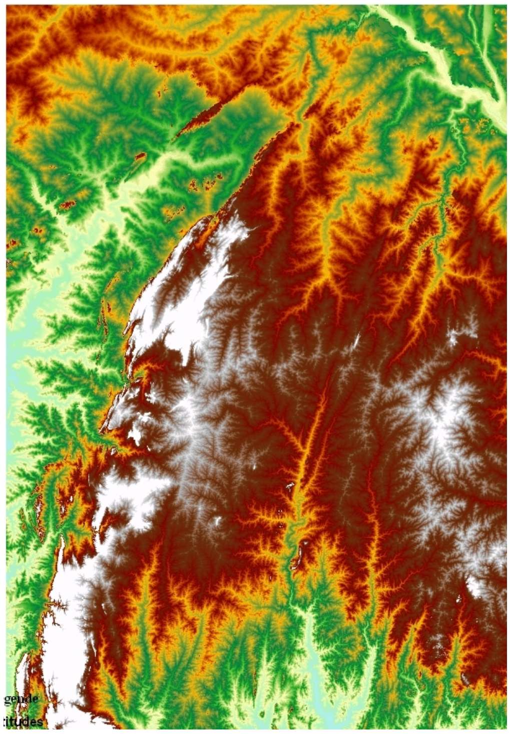
No rigorous benchmarking was performed to document the differences between the original and modified partitioning parametrization. Some comparisons were done over the Seine and Loire watershed and their rapid analysis did not reveal any noticeable difference.

Appendix 2. Topography analysis in ArcGIS10

BENIN : DEM in the rectangle larger than the mesosite

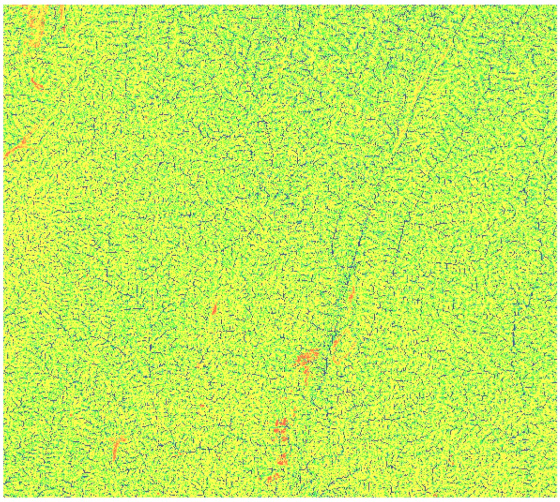
Left panel : the mesosite appears as the grid-mesh, and the rectangle is defined from the Hydro1K basins which overlay the mesosite (in color). Right panel : the DEM in the rectangle (green is low, brown is high).

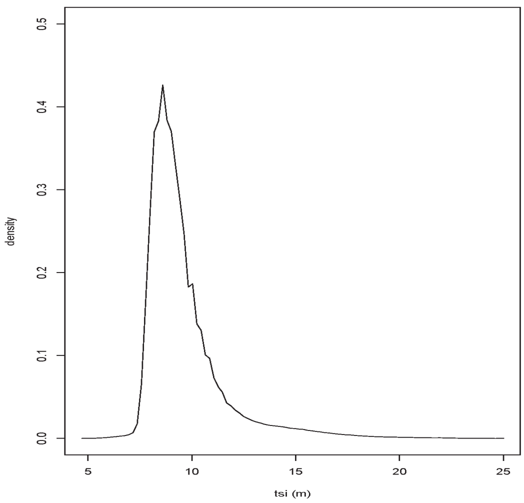




BENIN : Topographic index in the mesosite

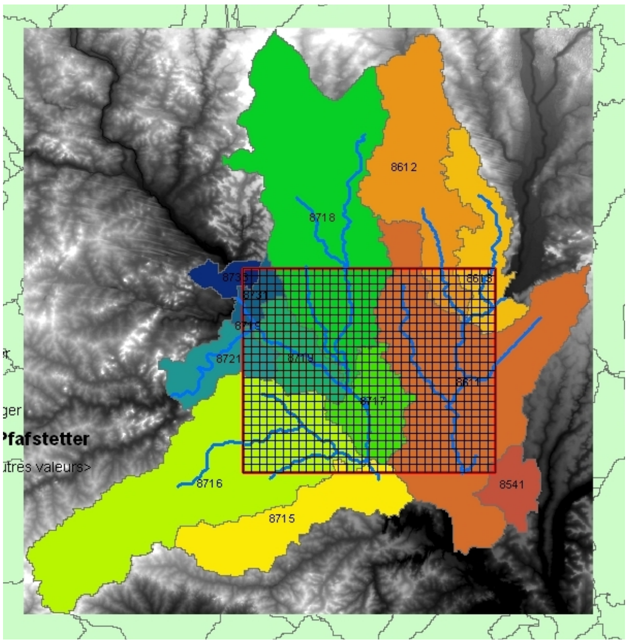
Left panel : Low values in red to high values in dark blue. Right panel : TI pdf

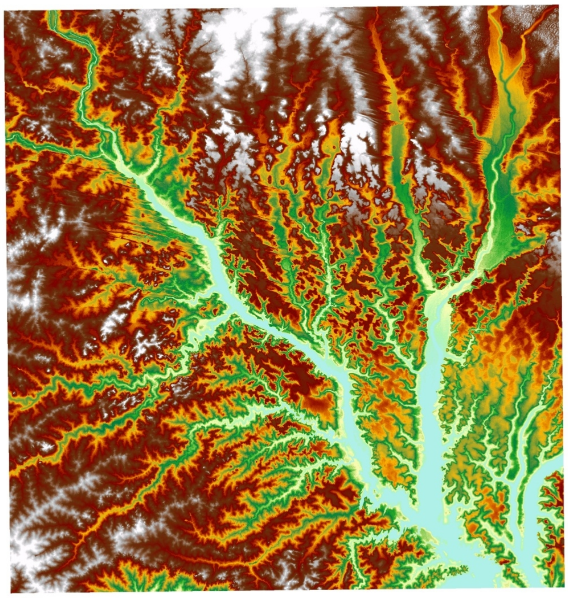




NIGER : DEM in the rectangle larger than the mesosite

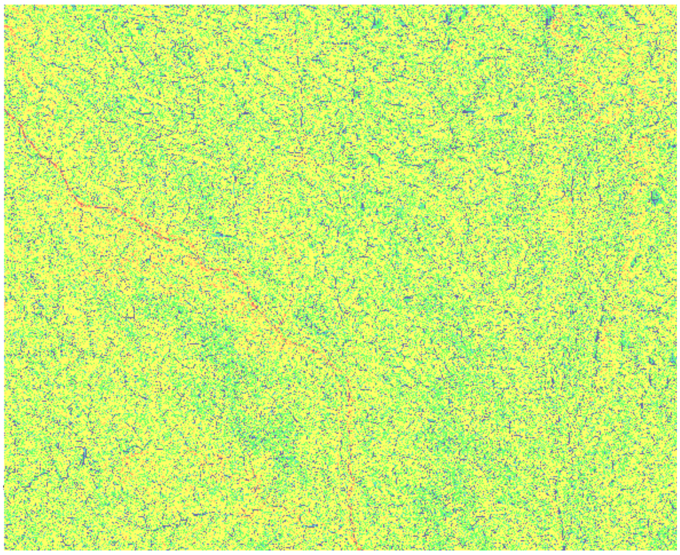
Left panel : the mesosite appears as the grid-mesh, and the rectangle is defined from the Hydro1K basins which overlay the mesosite (in color). Right panel : the DEM in the rectangle.

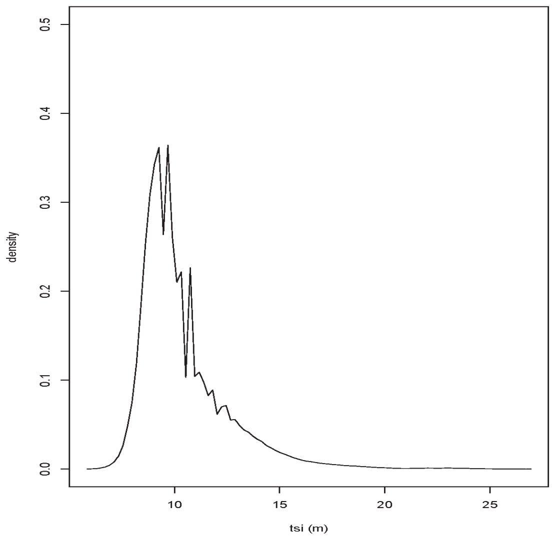




NIGER : Topographic index in the mesosite

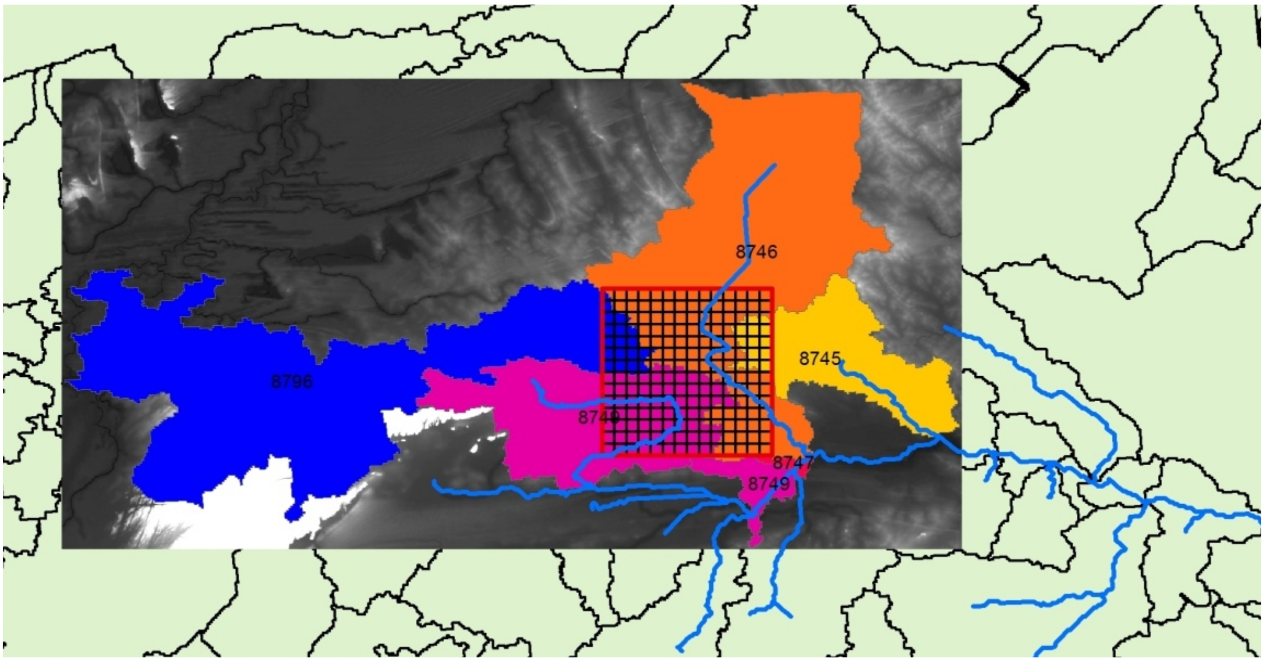
Left panel : Low values in red to high values in dark blue. Right panel : TI pdf





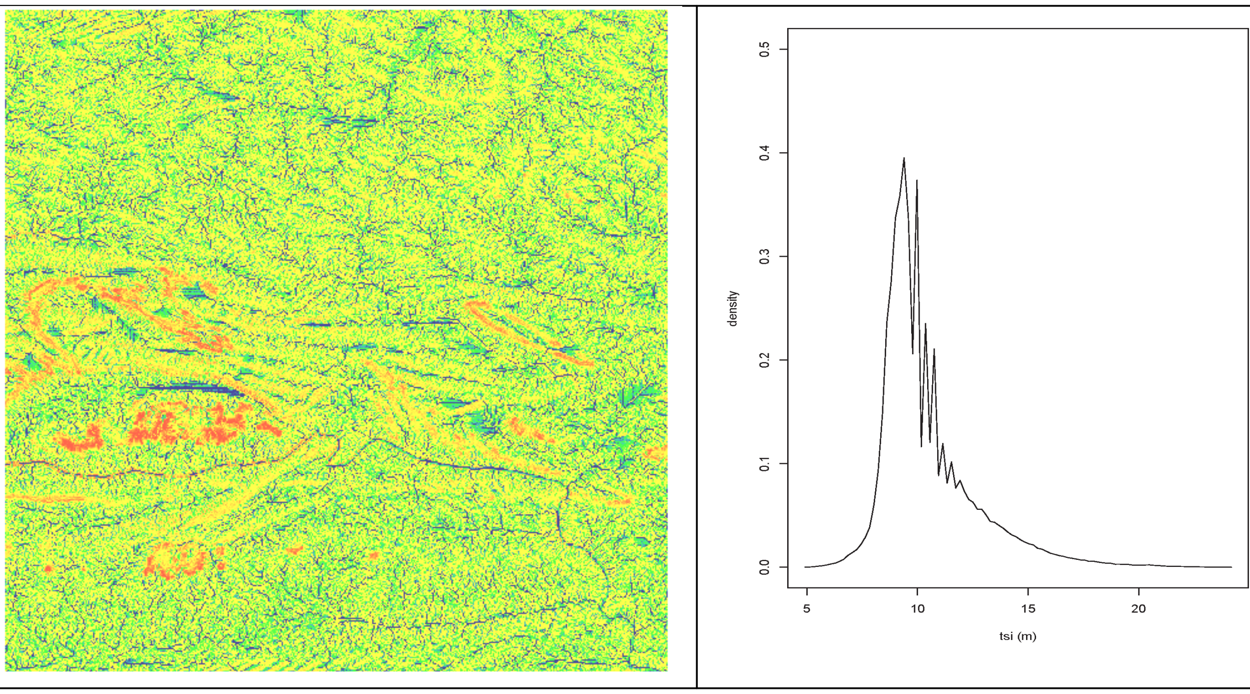
MALI : DEM in the rectangle larger than the mesosite

The mesosite appears as the grid-mesh, and the rectangle is defined from the Hydro1K basins which overlay the mesosite (in color).



MALI : Topographic index in the mesosite

Left panel : Low values in red to high values in dark blue. Right panel : TI pdf



Appendix 3. Statistics of vegetation properties

Year	Parameter	Benin			Niger			Mali		
		Min	Max	**Moy**	Min	Max	**Moy**	Min	Max	**Moy**
2005	Input LAI	0,084	2,257	**1,083**	0,000	0,978	**0,324**	0,000	0,978	**0,235**
	Input z0	0,027	0,431	**0,295**	0,003	0,064	**0,010**	0,004	0,105	**0,032**
	Modified z0	*0,027*	*0,417*	***0,295***	*0,003*	*0,064*	***0,011***	*0,004*	*0,051*	***0,011***
	Albedo	0,097	0,200	**0,162**	0,247	0,347	**0,309**	0,201	0,349	**0,308**
	Veg. Frac.	0,049	0,742	**0,444**	0,000	0,444	**0,165**	0,000	0,444	**0,120**
	Greeness Frac.	*0,224*	*0,679*	***0,433***	*0,001*	*0,368*	***0,091***	*0,001*	*0,254*	***0,041***
	dd	*0,1370*	*2,1570*	***1,4750***	*0,0001*	*0,3190*	***0,0290***	*0,0001*	*0,2540*	***0,0180***
	z2	*0,519*	*4,315*	***3,171***	*0,100*	*0,638*	***0,211***	*0,100*	*0,508*	***0,140***
2006	Input LAI	0,138	2,245	**1,129**	0,000	0,980	**0,318**	0,000	0,960	**0,230**
	Input z0	0,027	0,433	**0,293**	0,003	0,073	**0,009**	0,004	0,105	**0,031**
	Modified z0	*0,027*	*0,433*	***0,293***	*0,003*	*0,073*	***0,010***	*0,004*	*0,058*	***0,011***
	Albedo	0,097	0,198	**0,162**	0,246	0,347	**0,309**	0,201	0,349	**0,308**
	Veg. Frac.	0,079	0,740	**0,460**	0,000	0,445	**0,161**	0,000	0,438	**0,116**
	Greeness Frac.	*0,236*	*0,676*	***0,443***	*0,001*	*0,368*	***0,089***	*0,001*	*0,331*	***0,038***
	dd	*0,1370*	*2,1660*	***1,4660***	*0,0001*	*0,3660*	***0,0280***	*0,0001*	*0,2900*	**0,017**
	z2	*0,498*	*4,332*	***3,188***	*0,100*	*0,732*	***0,227***	*0,100*	*0,580*	**0,145**
2007	Input LAI	0,099	1,718	**0,951**	0,000	0,885	**0,295**	0,000	0,847	**0,210**
	Input z0	0,027	0,431	**0,294**	0,003	0,068	**0,009**	0,004	0,105	**0,032**
	Modified z0	*0,027*	*0,431*	***0,294***	*0,003*	*0,068*	***0,010***	*0,004*	*0,054*	***0,011***
	Albedo	0,097	0,198	**0,162**	0,244	0,347	**0,309**	0,212	0,349	**0,308**
	Veg. Frac.	0,058	0,643	**0,409**	0,000	0,404	**0,152**	0,000	0,394	**0,109**
	Greeness Frac.	*0,228*	*0,566*	***0,406***	*0,001*	*0,342*	***0,088***	*0,001*	*0,310*	***0,039***
	dd	*0,1370*	*2,1580*	***1,4690***	*0,0001*	*0,3420*	***0,0280***	*0,0001*	*0,2710*	***0,0170***
	z2	*0,526*	*4,314*	***3,171***	*0,100*	*0,683*	***0,217***	*0,100*	*0,543*	***0,141***

Tableau 11: Statistics of the vegetation parameters in the three mesosites from 2005 to 2007. The modified z0 results from the imposing that z0 in the bare soil fraction takes Mosaic value (0.0112). The values in italic are computed (see above for details).

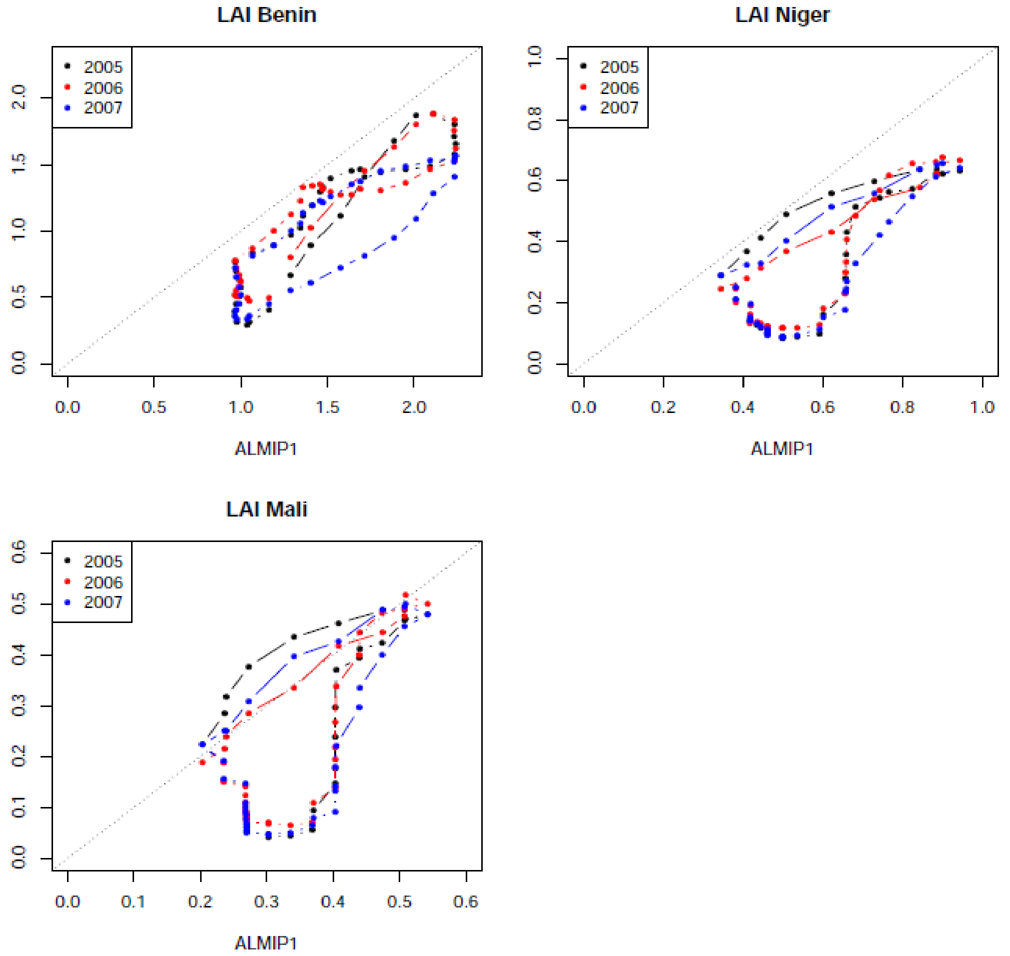


Figure 5: Comparison of LAI values from ECOCLIMAP (ALMIP1) and ECO-II (ALMIP2), on spatial average over the meso-sites (36 decades per year).

Appendix 4. Header of output file

Some changes are performed compared to CLSM ALMIP1 outputs:

- we add longitude, latitude
- we change RadT to AvgSrfT
- we add “time_representation” to the description of most variables

Note that snowfall is set to zero, so that snow processes are not active, and we do not output snow variables.

```
netcdf CLSM_Benin_exp1L_2005 {

dimensions:

        x = 28 ;

        y = 25 ;

        time = UNLIMITED ; // (0 currently)

        elevel = 6 ;

        wlevel = 3 ;

variables:

        float latitude(y, x) ;

                latitude:long_name = "latitude" ;

                latitude:units = "degrees_north" ;

        float longitude(y, x) ;

                longitude:long_name = "longitude" ;

                longitude:units = "degrees_east" ;

        float SWnet(time, y, x) ;

                SWnet:long_name = "Net shortwave radiation" ;

                SWnet:units = "W/m^2" ;

                SWnet:missing_value = 1.e+20f ;

                SWnet:time_representation = "average over time step" ;

        float LWnet(time, y, x) ;

                LWnet:long_name = "Net longwave radiation" ;

                LWnet:units = "W/m^2" ;

                LWnet:missing_value = 1.e+20f ;

                LWnet:time_representation = "average over time step" ;

        float Qle(time, y, x) ;

                Qle:long_name = "Latent heat flux" ;

                Qle:units = "W/m^2" ;

                Qle:missing_value = 1.e+20f ;

                Qle:time_representation = "average over time step" ;

        float Qh(time, y, x) ;

                Qh:long_name = "Sensible heat flux" ;
```

```
		Qh:units = "W/m^2" ;
		Qh:missing_value = 1.e+20f ;
		Qh:time_representation = "average over time step" ;
	float Qg(time, y, x) ;
		Qg:long_name = "Soil heat flux" ;
		Qg:units = "W/m^2" ;
		Qg:missing_value = 1.e+20f ;
		Qg:time_representation = "average over time step" ;
	float DelSurfHeat(time, y, x) ;
		DelSurfHeat:long_name = "Change in surface heat storage" ;
		DelSurfHeat:units = "J/m^2" ;
		DelSurfHeat:missing_value = 1.e+20f ;
		DelSurfHeat:time_representation = "at end of time step compared to beginning of time
step" ;
	float LWup(time, y, x) ;
		LWup:long_name = "Upward longwave radiation" ;
		LWup:units = "W/m^2" ;
		LWup:missing_value = 1.e+20f ;
		LWup:time_representation = "average over time step" ;
	float DelIntercept(time, y, x) ;
		DelIntercept:long_name = "Change in interception storage" ;
		DelIntercept:units = "kg/m^2" ;
		DelIntercept:missing_value = 1.e+20f ;
		DelIntercept:time_representation = "at end of time step compared to beginning of time
step" ;
	float DelSoilMoist(time, y, x) ;
		DelSoilMoist:long_name = "Change in soil moisture" ;
		DelSoilMoist:units = "kg/m^2" ;
		DelSoilMoist:missing_value = 1.e+20f ;
		DelSoilMoist:time_representation = "at end of time step compared to beginning of time
step" ;
	float Evap(time, y, x) ;
		Evap:long_name = "Total evapotranspiration" ;
		Evap:units = "kg/m^2/s" ;
		Evap:missing_value = 1.e+20f ;
		Evap:time_representation = "average over time step" ;
	float Qs(time, y, x) ;
		Qs:long_name = "Surface runoff" ;
		Qs:units = "kg/m^2/s" ;
		Qs:missing_value = 1.e+20f ;
		Qs:time_representation = "average over time step" ;
	float Qsb(time, y, x) ;
		Qsb:long_name = "Subsurface runoff" ;
```

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        Qsb:units = "kg/m^2/s" ;
        Qsb:missing_value = 1.e+20f ;
        Qsb:time_representation = "average over time step" ;
float Rainf(time, y, x) ;
        Rainf:long_name = "Rainfall rate" ;
        Rainf:units = "kg/m^2/s" ;
        Rainf:missing_value = 1.e+20f ;
        Rainf:time_representation = "average over time step" ;
float Albedo(time, y, x) ;
        Albedo:long_name = "Average albedo" ;
        Albedo:units = "-" ;
        Albedo:missing_value = 1.e+20f ;
        Albedo:time_representation = "average over time step" ;
float AvgSrfT(time, y, x) ;
        AvgSrfT:long_name = "Average surface temperature" ;
        AvgSrfT:units = "K" ;
        AvgSrfT:missing_value = 1.e+20f ;
        AvgSrfT:time_representation = "instantaneous value at end of time step" ;
float CanopInt(time, y, x) ;
        CanopInt:long_name = "Total canopy water storage" ;
        CanopInt:units = "kg/m^2" ;
        CanopInt:missing_value = 1.e+20f ;
        CanopInt:time_representation = "instantaneous value at end of time step" ;
float Acond(time, y, x) ;
        Acond:long_name = "Aerodynamic conductance" ;
        Acond:units = "m/S" ;
        Acond:missing_value = 1.e+20f ;
        Acond:time_representation = "average over time step" ;
float ECanop(time, y, x) ;
        ECanop:long_name = "Interception evaporation" ;
        ECanop:units = "kg/m^2/s" ;
        ECanop:missing_value = 1.e+20f ;
        ECanop:time_representation = "average over time step" ;
float ESoil(time, y, x) ;
        ESoil:long_name = "Bare soil evaporation" ;
        ESoil:units = "kg/m^2/s" ;
        ESoil:missing_value = 1.e+20f ;
        ESoil:time_representation = "average over time step" ;
float RootMoist(time, y, x) ;
        RootMoist:long_name = "Root zone soil moisture" ;
        RootMoist:units = "kg/m^2" ;
```

```
        RootMoist:missing_value = 1.e+20f ;
        RootMoist:time_representation = "instantaneous value at end of time step" ;
float TVeg(time, y, x) ;
        TVeg:long_name = "Vegetation transpiration" ;
        TVeg:units = "kg/m^2/s" ;
        TVeg:missing_value = 1.e+20f ;
        TVeg:time_representation = "average over time step" ;
float SoilWet(time, y, x) ;
        SoilWet:long_name = "Total soil wetness" ;
        SoilWet:units = "-" ;
        SoilWet:missing_value = 1.e+20f ;
        SoilWet:time_representation = "instantaneous value at end of time step" ;
float WaterTableD(time, y, x) ;
        WaterTableD:long_name = "Water table depth" ;
        WaterTableD:units = "m" ;
        WaterTableD:missing_value = 1.e+20f ;
        WaterTableD:time_representation = "instantaneous value at end of time step" ;
float ar1(time, y, x) ;
        ar1:long_name = "Fractional area of saturated soil" ;
        ar1:units = "-" ;
        ar1:missing_value = 1.e+20f ;
        ar1:time_representation = "instantaneous value at end of time step" ;
float ar2(time, y, x) ;
        ar2:long_name = "Fractional area of unsaturated unstressed soil" ;
        ar2:units = "-" ;
        ar2:missing_value = 1.e+20f ;
        ar2:time_representation = "instantaneous value at end of time step" ;
float ar4(time, y, x) ;
        ar4:long_name = "Fractional area of stressed soil" ;
        ar4:units = "-" ;
        ar4:missing_value = 1.e+20f ;
        ar4:time_representation = "instantaneous value at end of time step" ;
float rzflw(time, y, x) ;
        rzflw:long_name = "Root zone flow" ;
        rzflw:units = "kg/m^2/s" ;
        rzflw:missing_value = 1.e+20f ;
        rzflw:time_representation = "average over time step" ;
float dew(time, y, x) ;
        dew:long_name = "Dew (negative evaporation)" ;
        dew:units = "kg/m^2/s" ;
        dew:missing_value = 1.e+20f ;
```

```
        dew:time_representation = "average over time step" ;
float rzeq(time, y, x) ;
        rzeq:long_name = "Root zone equilibrium" ;
        rzeq:units = "kg/m^2" ;
        rzeq:missing_value = 1.e+20f ;
        rzeq:time_representation = "instantaneous value at end of time step" ;
float rzex(time, y, x) ;
        rzex:long_name = "Root zone excess" ;
        rzex:units = "kg/m^2" ;
        rzex:missing_value = 1.e+20f ;
        rzex:time_representation = "instantaneous value at end of time step" ;
float srfex(time, y, x) ;
        srfex:long_name = "Surface excess" ;
        srfex:units = "kg/m^2" ;
        srfex:missing_value = 1.e+20f ;
        srfex:time_representation = "instantaneous value at end of time step" ;
float catdef(time, y, x) ;
        catdef:long_name = "Catchment deficit" ;
        catdef:units = "kg/m^2" ;
        catdef:missing_value = 1.e+20f ;
        catdef:time_representation = "instantaneous value at end of time step" ;
float w_wilt(y, x) ;
        w_wilt:long_name = "Wilting point volumetric water content" ;
        w_wilt:units = "m^3/m^3" ;
        w_wilt:missing_value = 1.e+20f ;
float w_sat(y, x) ;
        w_sat:long_name = "Volumetric water content at saturation" ;
        w_sat:units = "m^3/m^3" ;
        w_sat:missing_value = 1.e+20f ;
float elevelD(elevel, y, x) ;
        elevelD:long_name = "elevel depth (SoilTemp)" ;
        elevelD:units = "m" ;
        elevelD:missing_value = 1.e+20f ;
float SoilTemp(time, elevel, y, x) ;
        SoilTemp:long_name = "Average layer soil temperature" ;
        SoilTemp:units = "K" ;
        SoilTemp:missing_value = 1.e+20f ;
        SoilTemp:time_representation = "instantaneous value at end of time step" ;
float wlevelD(wlevel, y, x) ;
        wlevelD:long_name = "wlevel depth (SoilMoist)" ;
        wlevelD:units = "m" ;
```

```
                wlevelD:missing_value = 1.e+20f ;
        float SoilMoist(time, wlevel, y, x) ;
                SoilMoist:long_name = "Average layer soil moisture" ;
                SoilMoist:units = "kg/m^2" ;
                SoilMoist:missing_value = 1.e+20f ;
                SoilMoist:time_representation = "instantaneous value at end of time step" ;
}
```