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### **detailed response to reviewer #2**

Paper HYDROL7104 entitled "Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali", by P. de Rosnay, C. Gruhier, F. Timouk, F. Baup, E. Mougin, P. Hiernaux, L. Kergoat, V. Le Dantec.

The authors thank very much this reviewer for his very helpful comments and discussion on this paper. Here is addressed the minor comment of the second revision.

*" The authors have significantly improved the manuscript and well responded to the comments by the reviewers. The only remark I have is how the wording related to correlation from line 367 and onwards.  $R^2$  is the explained variance of a regression and is as a rule expressed in percentage while  $R$  is the (multiple) correlation of the regression. The latter is as a rule not expressed in percentage. It is unclear in the text what "correlation value" means -  $R^2$  or  $R$ ? I advise publication after this minor revision."*

Yes we agree. The term correlation is used everywhere in the text.  $R$  indicates the correlation (while  $R^2$  would be indicated as the determination coefficient). In this study, the figures given are all correlation  $R$  (not  $R^2$ ). This inconsistency has been removed everywhere in the text, in Table 4 and in Figures 6 and 7, where the term  $R$  is now used. Accordingly, percentage are not used anymore.

# Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali

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## Abstract

This paper presents the ground soil moisture measurements performed over the so-called Gourma meso-scale site in Mali, Sahel, in the context of the African Monsoon Multidisciplinary Analysis (AMMA) project. The Gourma meso-scale soil moisture network is part of a complete land surface processes observing and modelling strategy and is associated to vegetation and meteorological field measurements as well as soil moisture remote sensing. It is spanning 2° in latitude between 15°N and 17°N. In 2007, it includes 10 soil moisture stations, of which 3 stations also have meteorological and flux measurements. A relevant spatial sampling strategy is proposed to characterise soil moisture at different scales including local, kilometer, super-site and meso-scales. In addition to the local stations network, transect measurements were performed on different coarse textured (sand to sandy-loam) sites, using portable impedance probes. They indicate mean value and standard deviation (STD) of the

surface soil moisture (SSM) at the kilometer scale. This paper presents the data set and illustrates soil moisture spatial and temporal features over the Sahelian Gourma meso-scale site for 2005-2006. Up-scaling relation of SSM is investigated from (i) local to kilometer scale and (ii) from local to the super site scale. It is shown to be stable in space and time (2005-2006) for different coarse textured sites. For the Agoufou local site, the up-scaling relation captures SSM dynamics at the kilometer scale with a 0.9% accuracy in volumetric soil moisture. At the multi-site scale, an unique up-scaling relation is shown to be able to represent kilometer SSM for the coarse textured soils of the meso-scale site with an accuracy of 2.2% (volumetric). Spatial stability of the ground soil moisture stations network is also addressed by the Mean Relative Difference (MRD) approach for the Agoufou super site where 5 soil moisture stations are available (about 25km  $\times$  25km). This allows the identification of the most representative ground soil moisture station which is shown to be an accurate indicator with low variance and bias of the soil moisture dynamics at the scale of the super site. Intensive local measurements, together with a robust up-scaling relation make the Gourma soil moisture network suitable for a large range of applications including remote sensing and land surface modelling at different spatial scales.

*Key words:* Soil Moisture, ground measurements, up-scaling, Sahel, AMMA

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## 1 Introduction

West Africa, and more specifically the Sahel, is pointed out by Koster et al. (2004) to be one of the regions of the world with the strongest feedback mechanism between soil moisture and precipitation. This hot spot ”indicates where the routine monitor-

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5 ing of soil moisture, with both ground-based and space-based systems, will yield the  
6 greatest return in boreal summer seasonal forecasting.” One of the key objectives of  
7 AMMA (African Monsoon Multidisciplinary Analysis) project, is to improve our un-  
8 derstanding and our modelling capabilities of the effect of land surface processes on  
9 monsoon intensity, variability and predictability (Redelsperger et al. 2006). AMMA  
10 is supported by a very strong observational program. Three meso-scale sites are  
11 instrumented in Mali, Niger and Bénin, providing information along the North-  
12 South gradient between Sahelian and Soudanian regions (Redelsperger et al. 2006).  
13 The instrumental deployment in the Gourma region (the sahelian site of Mali) fo-  
14 cuses on quantification of water, CO<sub>2</sub> and energy fluxes between the surface and  
15 the atmosphere (**Mougin et al., this issue**). Among the surface processes under  
16 consideration, emphasis is put on evapotranspiration which is the most important  
17 process coupling the physical, biological and hydrological processes at the conti-  
18 nental scale. Soil moisture is a crucial variable that affects many processes includ-  
19 ing land-surface-atmosphere interactions (Taylor et al. 2007; Taylor and Ellis 2006;  
20 Monteny et al. 1997; Nicholson et al. 1997), land surface fluxes (Timouk et al. this  
21 issue; Lloyd et al. 1997), vegetation phenology (Seghieri et al. this issue), and soil  
22 respiration (Le Dantec et al. 2006). The diversity of processes and the correspond-  
23 ing large range of spatial and temporal scales involved in the monsoon dynamics  
24 require accurate estimate of soil moisture dynamics at local scale, meso-scale and  
25 regional scale. Ground measurements provide vertical soil moisture profiles with a  
26 high accuracy but they are limited to the local scale. In contrast, remote sensing ap-  
27 proaches provide spatially integrated measurements of surface soil moisture (SSM)  
28 but they are limited to the very first top centimetres of the soil (Kerr 2007). Soil  
29 moisture estimation from microwave remote sensing was investigated during the Hy-  
30 drological and Atmospheric Pilot Experiment in the Sahel (HAPEX-SAHEL), using  
31 both passive microwave radiometry from airborne measurements (Schmugge 1998;  
32 Chanzy et al. 1997; Calvet et al. 1996) and active microwave remote sensing with

33 ERS satellite data (Magagi and Kerr 1997). These studies were based on local soil  
34 moisture ground measurements acquired for a few month during the 1992 sum-  
35 mer campaign. Extensive field measurement campaigns have been conducted in  
36 other regions of the Earth to characterise the soil moisture variability, as for exam-  
37 ple in the U.S. Midwest, South Central Georgia and Southern Great Plains (SGP)  
38 (De Lannoy et al. 2007; Bosch et al. 2006; Famiglietti et al. 1999), and in Australia  
39 (Rüdiger et al. 2007). Using airborne based remote sensing information, Kim and  
40 Barros (2002) examined the statistical structure of soil moisture (40 x 250 km)  
41 obtained during the SGP 1997 hydrology experiment. In Sahel, where field instru-  
42 mentation and extensive field campaigns are more difficult, extensive soil moisture  
43 measurements were not available until now. In the framework of AMMA the Gourma  
44 meso-scale site has been instrumented for soil moisture measurements. It is described  
45 in this paper.

46 For the purpose of satellite validation it is of crucial importance to address up-scaling  
47 issues of ground soil moisture measurements. Baup et al. (2007) used ground soil  
48 moisture measurements over the Agoufou local site, in Mali, for the purpose of EN-  
49 VISAT/ASAR soil moisture inversion. To this end they used surface soil moisture  
50 measurements from one local station, up-scaled to the 1km remotely sensed pixel for  
51 2005. In the present paper, surface soil moisture up-scaling of ground measurements  
52 is investigated at the single site scale and extended to (i) the multi-site spatial scale,  
53 within the Gourma meso-scale windows, and (ii) the inter-annual temporal scale.

54 A complementary approach, suitable for larger scale applications, consists of de-  
55 riving spatially representative soil moisture estimates from ground observation net-  
56 works. The method, first proposed by Vachaud et al. (1985), is based on the Mean  
57 Relative Difference (MRD) and deviation between stations of the same network. It  
58 was applied by Cosh et al.(2004) to the Soil Moisture EXperiment (SMEX) 2002  
59 (Jackson et al. 2003) for the validation of the Advanced Microwave Scanning Ra-  
60 diometer on Earth Observing System (AMSR-E) soil moisture. De Lannoy et al.

61 (2007) used the MRD approach combined with cumulative distribution function  
62 matching to estimate the spatial mean soil moisture. Based on the MRD, Gruhier  
63 et al. (2008) used the Gourma meso-scale soil moisture measurements to validate  
64 the soil moisture products obtained for 2005 from AMSR-E.

65 Ground soil moisture measurements are also highly relevant to validate Land Sur-  
66 face Models (LSMs). As for satellite validation, up-scaling is crucial to characterise  
67 soil moisture at the scale of the LSM. In turn, land surface models allow for the ex-  
68 tension of local scale measurements to larger spatial scales. This is being addressed  
69 over West Africa through the AMMA Land Surface Model Intercomparison Project  
70 (ALMIP, Boone et al. 2008).

71 The main purpose of this paper is to describe the Gourma meso-scale soil moisture  
72 network and to presents soil moisture measurements for 2005-2006. Based on local  
73 and transect measurements and using the Mean Relative Difference method, this  
74 paper also presents some features of the soil moisture characteristics and investi-  
75 gates the potential of the Gourma soil moisture measurements to address surface  
76 soil moisture up-scaling. Next section describes the Gourma meso-scale soil mois-  
77 ture network. Section 3 presents the soil moisture dynamics for different stations  
78 along the 15°N to 17°N climatic gradient for 2005 and 2006. Section 4 focuses on  
79 surface soil moisture up-scaling. Representativity of ground soil moisture station is  
80 addressed in section 5 for the Agoufou super site, where the Mean Relative Differ-  
81 ence approach is applied to the Gourma soil moisture network. Section 6 concludes.



## 82 2 Experimental design and ground soil moisture measurements

### 83 2.1 The Mali site

84 The AMMA project aims at providing a better understanding of the African mon-  
85 soon processes. AMMA relies on an extensive field campaign experiment for which  
86 three meso-scale sites are instrumented in Bénin, Niger and Mali (Redelsperger et al. 2006).  
87 Instrumental deployment over the Mali site includes three monitoring scales de-  
88 scribed hereafter (Mougin et. al, this issue).

89 • The Gourma meso-scale site (30,000km<sup>2</sup>, 14.5°N-17.5°N; 1°W-2°W) is shown in  
90 Figure 1. The location of the soil moisture stations (10 stations) is indicated on  
91 the map by white stars. Each soil moisture station also includes a rain-gauge for  
92 rainfall measurements and three stations (in Bamba, Eguérit, Agoufou) include  
93 complete weather station and flux measurements. More detail on rainfall measure-  
94 ments over Gourma are provided in Frappart et al. (this issue), while Lebel and  
95 Ali (this issue) investigate the rainfall regime fluctuations in Sahel. The Gourma  
96 meso-scale site is characterised by a Sahelian to saharo-sahelian climate (isohyets  
97 500-100 mm). Soil is coarse textured (sand, loamy sand, sandy loam) for 65% of  
98 the area, where vegetation is composed of a layer of natural annual herbs with  
99 scattered trees and shrubs (Hiernaux et al. this issue). 28% of the meso-scale site  
100 is characterised by flat and shallow soils and rock outcrops (loamy colluvium,  
101 schist, sandstone outcrops and hard pan). Vegetation on these rocky-loam areas  
102 consists of scattered shrubs. The remaining 7% of the area are clay plains, tem-  
103 porarily flooded woodlands and flooded depressions. Data on herbs and woody  
104 vegetation are collected on 43 local sites among which some are also used for vali-  
105 dation of remote sensing products (LAI, Net Primary Productivity, soil moisture)  
106 derived from SPOT-VGT, MODIS, AMSR-E, ENVISAT/ASAR, ERS (Gruhler

107 et al. 2008; Zribi et al. this issue; Baup et al. 2008; Jarlan et al. 2008).

108 • The Agoufou super site (2,250km<sup>2</sup>, 15.3°N-15.58°N; 1.38°W-1.65°W) is shown  
109 in Figure 1 (right). At this scale, ground measurements focus on land surface  
110 fluxes measurements as well as on spatial heterogeneities of fluxes and vegetation  
111 characteristics.

112 • The Agoufou local intensive site (1km<sup>2</sup>, 15.3°N; 1.3°W) is indicated on Figure  
113 1. Annual mean precipitation is 370mm (1920-2003). The site has measurements  
114 of vegetation, soil moisture, meteorology and land surface fluxes (energy, water,  
115 CO<sub>2</sub>). The data collected on this site are used to parameterise, test and validate  
116 LSMs. The Agoufou local site is also a main validation site for remote sensing  
117 products.

## 118 *2.2 Ground soil moisture measurements*

119 The colours in Figure 1, obtained from a Landsat image, indicate the surface types  
120 on which the stations are deployed, with green for gently undulating coarse tex-  
121 tured dune systems, dark green for clay soil types and brown-pink for flat rocky-  
122 loam plains. Table 1 provides detailed information concerning soil moisture stations  
123 (number, name, soil type, location, sensors types and depth, date of installation).  
124 The same installation protocol is used for all the soil moisture stations, where Time  
125 Domain Reflectometry sensors are used (Campbell CS616), except for the Kelma  
126 station. For the later, Delta-T Theta Probe sensors are used since they are equipped  
127 with short rods which is more suitable for clay soils (a mention of the manufacturers  
128 is for information only and implies no endorsement on the part of the authors). The  
129 Gourma soil moisture stations all include a first measurement at 5cm depth, except  
130 in Eguérit (rocky) where the first measurement is at 10cm depth. Soil moisture pro-  
131 files are measured down to 50cm depth for Eguérit, and down to 4m for Agoufou

132 at the bottom of a hillslope. In order to capture the fast soil moisture dynamics,  
133 the vertical resolution of automatic soil moisture measurements in the soil is very  
134 fine at the surface, and measurements are acquired at 15 minutes time intervals.  
135 For remote sensing and land surface modelling purpose, both soil moisture and soil  
136 temperature profiles are monitored. For each station and each sensor depth, cal-  
137 ibration was performed, based on local soil density and gravimetric soil moisture  
138 measurements. Gravimetric measurements were performed at different stages of the  
139 rainy season to ensure calibration robustness in various soil moisture conditions.  
140 Soil moisture values provided in this paper are expressed in terms of volumetric  
141 units.

142 Soil texture measurements were performed for the first meter of soil, in the Agoufou  
143 local intensive site at the top and bottom of a hillslope (Table 2). Soil texture of the  
144 top 10cm of soil is slightly different between the top and bottom of the hillslope,  
145 with silt and clay content higher at the bottom than at the top of the hillslope.  
146 However the soil is very coarse textured, with more than 74% and 94% of sand  
147 particles at surface for the bottom and top of the hillslope respectively.

148 The Gourma soil moisture network documents soil moisture dynamics along the  
149 North-South climatic gradient, as well as at the dune scale, with three stations lo-  
150 cated on the Agoufou local site at different levels of a typical hillslope (top, middle  
151 and bottom). Eight stations are located on coarse textured soils (sandy to sandy-  
152 loam) which represents 65% of the meso-scale site area. One station, in Kelma (site  
153 21) is implemented on a clay soil, covered by acacia forest, representing 7% of the  
154 meso-scale area, and one station is located in Eguérit, on a rocky surface that rep-  
155 resents 28% of the area.

156 In addition to the local stations network, transect measurements have been man-  
157 ually performed every year since 2004 during the rainy season. They consist in  
158 monitoring surface soil moisture (0-5cm) by the means of a portable impedance  
159 probe (Theta probe) every 10m along a 1km straight transect. The location of each

160 point measurement along the transect is chosen to be different (separated by a  
161 few centimetres) from one transect date to another. This ensures avoiding soil dis-  
162 turbances that would affect the soil moisture measurements. This method allows  
163 estimating, for each transect measurement, both the mean value and standard de-  
164 viation of the surface soil moisture along the 1km transect. For practical reasons it  
165 is not possible to perform transect measurements on rocky surfaces (too hard to use  
166 the probe), nor in flooded plains (under water). Thus transect measurements have  
167 been performed on coarse textured soils, which represent the dominant soil texture  
168 type at meso-scale. Intensive transect measurements campaigns were performed on  
169 the Agoufou local site where soil moisture is the most intensively documented. For  
170 this site the 1km transect is the same as that used for vegetation measurements  
171 (Hiernaux et al. this issue). It is located on the Agoufou site with the starting and  
172 closest point located about 100m from the Agoufou bottom of the hillslope sta-  
173 tion (P1) and about 300m from the top of hillslope (P3) and middle of hillslope  
174 (P2) stations. In 2005 and 2006, transect measurements were also extended to the  
175 other coarse textured sites of Bangui Mallam, Ekia and Bamba. For these 3 sites,  
176 the 1km transects start exactly from the soil moisture stations. The 1km transects  
177 aim to provide information on mean surface soil moisture at the kilometer scale.  
178 These measurements are not combined with topography measurements. In 2006 an  
179 additional transect was defined on the Agoufou local intensive site for the purpose  
180 of hydrological applications and vegetation monitoring in relation to soil moisture  
181 along a topographic profile. SSM measurements performed along the hydrological  
182 transect are combined with elevation measurements. In contrast to the 1km tran-  
183 sects, this hydrological transect is not straight. It is 1255m long and cuts across 7  
184 catchments located partly within the Agoufou intensive site. It starts from the top  
185 of hillslope (P3) station, passes on the bottom of hillslope station (P1) and it is at a  
186 distance of about 100m from the middle of hillslope station (P2). Table 3 indicates  
187 the number of transect measurements performed on each site for these two years.

188 Remote sites, more difficult to access, are less documented, as in Bamba where only  
189 1 transect measurement was performed.

190 [Table 1 about here.]

191 [Table 2 about here.]

192 [Table 3 about here.]

193 [Fig. 1 about here.]

### 194 **3 Soil Moisture Dynamics over the Gourma meso-scale site**

#### 195 *3.1 Temporal dynamics*

196 Inter-annual variability between 2005 and 2006 is shown in Figure 2 for the surface  
197 (5cm depth) soil moisture monitored for eight stations located along the north-south  
198 gradient and for different soil types. The horizontal axis indicates the Day of Year  
199 (DoY). Note that the vertical axis is identical for each station except Kelma (P9,  
200 bottom right). Kinia (P11) and Agoufou middle (P2) are not presented since the  
201 data set is not complete for the considered period. In the In Zaket station, the 2005  
202 data set is limited to DoY 198-228, which provides one month of data between the  
203 station installation in July and its theft in August. The 2006 data set is complete  
204 after the station was reinstalled. Data are missing for Eguérit in early 2006 for tech-  
205 nical reasons. So inter-annual variability in monsoon onset is not visible for these  
206 two last stations.

207 The top panel shows SSM of the most northern stations in Bamba and In Zaket.  
208 They both present similar features in their surface soil moisture dynamics which is  
209 relatively slow and low amplitude. The second panel shows the surface soil mois-

210 ture dynamics for Ekia and Bangui Mallam and the third panel presents surface  
211 soil moisture for two stations located in the Agoufou super site at the top and bot-  
212 tom of the hillslope. Surface soil moisture is characterised by higher values and a  
213 larger temporal variability on these sites than on the northern sites. The bottom  
214 panel shows the surface soil moisture evolution for the two non-sandy sites of the  
215 Gourma soil moisture network, located in Eguérit (rocky) and in Kelma (clay).  
216 They both show a lower temporal variability in surface soil moisture. The Kelma  
217 site is characterised by much higher soil moisture values, due to the clay soil texture  
218 in this area. In addition, this site is flooded during the rainy season as indicated  
219 by the maximum soil moisture values maintained at saturation for more than one  
220 month during the monsoon season. For the top three panels, which present surface  
221 soil moisture monitored on coarse textured sites, differences between the sites are  
222 mainly governed by the strong North-South climatic gradient and by the precipita-  
223 tion variability. In contrast, for the bottom panel, the distances between the sites  
224 is less (all sites are within the super site) and the precipitation variability between  
225 the sites is lower. Accordingly, differences in soil moisture dynamics are mainly gov-  
226 erned for these sites by differences in surface properties (soil texture and vegetation  
227 cover) and subsequent land surface processes (partitioning between evapotranspira-  
228 tion and runoff).

229 For coarse textured soils the infiltration rate is very high according to the large  
230 amount of sand particles (higher than 74%). Surface ponding occurs rarely on these  
231 soils and it is located in very specific and limited areas (a few square meters) for very  
232 short periods (a few hours after rain). None of the soil moisture stations installed  
233 on coarse textured soils are affected by ponding. Despite temporal dynamics and  
234 absolute values of soil moisture being different between stations depending on both  
235 surface properties and location along the climatic transect, all the stations capture  
236 the later monsoon onset in 2006 than in 2005 that was described by Janicot et al.  
237 (2008).

239 *3.2 Vertical dynamics*

240 Figure 3 (top) depicts the temporal evolution of soil moisture at different depths  
241 at the Bangui Mallam station during the 2006 summer. It clearly shows that soil  
242 moisture dynamics is very fast at the surface, with rapid soil moisture response to  
243 precipitation occurrence, and fast soil drying afterwards. Soil moisture dynamics is  
244 getting slower with increasing depth, and at 120cm, 180cm and 250cm depth, soil  
245 moisture shows variability mainly at the seasonal time scale.

246 A major rainfall event (61.5mm at this station) occurred in the early morning of the  
247 DoY 210. It was associated with a large convective system that gave precipitation  
248 from Kelma to Ekia (Figure 1), as can be seen on Figure 2 with the surface soil  
249 moisture increasing on DoY 210 in 2006 for the 6 stations concerned. This event  
250 is chosen here to illustrate the vertical soil moisture dynamics at the Bangui Mal-  
251 lam site which is representative of vertical dynamics of coarse textured sites of the  
252 Gourma region.

253 Figure 3 (middle) shows the vertical structure of soil moisture evolution of the Ban-  
254 gui Mallam station at four different dates around this precipitation event, between  
255 July 28 (DoY 209) and August 2 (DoY 214) 2006. Figure 3 (bottom) shows the wa-  
256 ter budget as estimated from ground observations of soil moisture and precipitation  
257 for this period for the Bangui Mallam site. In particular it indicates the accumulated  
258 precipitation since DoY 209, and the variation in total soil water content ( $W$ ) for  
259 the 0-1m soil layer and for the 1-2m soil layer ( $dW$  0-1m and  $dW$  1-2m respectively).  
260 Vertically integrated soil water content is computed for each time step by the means  
261 of a linear vertical interpolation and integration of volumetric soil moisture profiles.  
262 Accordingly it must be taken with caution due to uncertainties associated to the  
263 vertical profiles. This is particularly the case for the second meter of soil where the

264 vertical sampling of soil sensors is more sparse (Table 1). After a rainfall event, the  
265 presence of a wetting front, associated to a discontinuity in the soil moisture profile,  
266 is also expected to affect the accuracy of the vertical interpolation. Despite of these  
267 uncertainties, when considering its temporal evolution, the vertically integrated wa-  
268 ter content provides an estimate of the time evolution of the soil water budget.

269 Soil moisture profiles shown in Figure 3 (middle) indicate very dry conditions (vol-  
270 umetric soil moisture below 2% ) on DoY 209 at all soil depths at the Bangui  
271 Mallam station. The strong precipitation event that occurred on DoY 210 led to  
272 a fast response of soil moisture in the first half meter of soil, with an increase to  
273 12.5% (volumetric) at 10cm depth. However the wetting front didn't reach yet the  
274 80cm deep soil moisture sensor for which the volumetric soil moisture was steady  
275 bellow 2%. The vertical profile depicted for DoY 211 shows that 1.5 days after the  
276 rain occurred, the wetting front got deeper, down to 80cm, while the first 30cm of  
277 soil already started to dry out. A few days later (DoY 214) while 2 rainfall events  
278 occurred (21.5mm each) in the morning and evening of the DoY 212, the vertical  
279 profile of soil moisture shows that the wetting front reached 120cm depth. Figure 3  
280 (bottom) shows that the cumulated rainfall between DoY 209 and 214 is 104mm.

281 The total soil water increase ( $dW_{0-1m} + dW_{1-2m}$ ) for this period is 85.3mm. The  
282 lower value of total soil water increase compared to accumulated precipitation, is  
283 explained by several processes, including direct soil evaporation, water uptake for  
284 plant transpiration and surface runoff. It is interesting to note that, for each of  
285 the three rainfall events, the 0-1m soil water content decreased rapidly as soon  
286 as the rain stopped. It is due to direct soil evaporation and strong rates of plant  
287 transpiration. In addition, the downward propagation of the wetting front, when  
288 it reached the 1-2m soil layer, strongly contributed to the 0-1m layer drying after  
289 DoY 213 (2.75 day after the first rainfall event). At the same time,  $dW_{1-2m}$  started  
290 to strongly increase accordingly on DoY 213, due to deep soil infiltration from the  
291 first meter to the second meter of soil.



## 293 4 Surface soil moisture up-scaling

294 Results of transect measurements are presented in this section. The local to kilo-  
295 meter up-scaling relation is investigated at the single-site scale, considering annual  
296 and inter-annual temporal scales, as well as at the multi-site scale. As described  
297 in section 2 and Table 3, transect measurements were performed in 2005 and 2006  
298 during intensive field campaign measurements conducted during the monsoon sea-  
299 son.

300

### 301 4.1 Bangui Mallam site

302 Figure 4 illustrates the surface soil moisture variability along the Bangui Mallam  
303 1km transect, for which measurements were performed at different dates between 11  
304 and 16 August 2006. A strong precipitation event occurred on August 9 (DoY 221),  
305 2 days before the first transect measurement, followed by a long drying period. This  
306 figure illustrates the strong spatial variability along the transect. However, values of  
307 standard deviation (STD) indicated on the figure for the three dates, also show that  
308 surface soil moisture spatial variability decreases when soil is drying. The relation-  
309 ship between the soil moisture mean value and its spatial variability is investigated  
310 further in section 4.3 at the multi-site scale. Figure 4 also shows the very fast tem-  
311 poral dynamics associated with the soil drying after a precipitation event. In five  
312 days, volumetric surface soil moisture drops from 10.8% to 1.0%. This fast drying  
313 of the soil surface is due to fast infiltration rates of coarse textured soils and large  
314 evaporation rates.

315

316

[Fig. 4 about here.]

317 Based on transect measurements and local station measurements at Bangui Mal-  
318 lam acquired at the same time, a relationship is established between the averaged  
319 1km transect surface soil moisture ( $SSM_{tra1km}$ ) and the local station surface soil  
320 moisture ( $SSM_{stoloc}$ ) for the Bangui Mallam site in 2006:

$$321 \quad SSM_{tra1km} = -2.2365 + 1.5458 \times SSM_{stoloc} \quad (1)$$

322 where both  $SSM_{tra1km}$  and  $SSM_{stoloc}$  are in % (volumetric). The slope larger than  
323 1 (1.5458) indicates slightly stronger surface soil moisture changes on the transect  
324 compared to the local station. This is explained by the difference of sensing depth  
325 between the local station and transect measurements. The top few centimetres of the  
326 soil are characterised by very strong soil moisture (and soil temperature) gradients.  
327 The very surface soil moisture, which is more directly exposed to the atmosphere,  
328 depicts slightly larger variations than at 5cm depth, where the variations are al-  
329 ready slightly attenuated. Thus the time evolution of the surface soil moisture is  
330 sensitive to the depth of measurement. This issue has important implications for  
331 remote sensing applications which measure about the top 1cm, 2cm and 5cm soil  
332 moisture at X-band, C-band and L-band respectively, as indicated by Le Morvan  
333 et al. 2008 and Jackson et al., 1997. In our study the first sensor of the station is  
334 horizontally placed at 5cm depth, whereas the transect measurements measure the  
335 averaged value between 0 and 5cm deep. Shallower measurements lead to slightly  
336 larger soil moisture variations along the transects than at the station. This is ex-  
337 pressed by a slope larger than one between transect and station measurements. This  
338 relationship applied to the station surface soil moisture measurements, allows ex-  
339 trapolating to the kilometer scale, for which  $SSM_{sta1km}$  will be used. Table 4 (first  
340 line) shows the statistical results of the comparison between the kilometer surface

341 soil moisture obtained from extrapolated station measurements ( $SSM_{sta1km}$ ) and  
342 from the transect measurements ( $SSM_{tra1km}$ ). Comparison is based on several indi-  
343 cators including Root Mean Square Error ( $RMSE$ ), **correlation coefficient ( $R$ )**,  
344 Efficiency (Nash coefficient ,  $EFF$ ) and BIAS. Although only seven transects are  
345 considered to determine this relation for the Bangui Mallam site in 2006, the very  
346 good agreement between the station and the transect measurements ( $R = 0.89$ ,  
347  $RMSE = 1.6\%$ ,  $EFF = 0.8$ ,  $BIAS = 10^{-4}$ ), indicates that the up-scaling relation  
348 provided in equation 1 is highly suitable to extrapolate from local station measure-  
349 ments at the Bangui Mallam site, to the kilometer scale. Since the station operates  
350 automatically, this approach is suitable to derive the kilometer scale surface soil  
351 moisture continuously at a fine temporal resolution (15 minute time step). These  
352 statistics are obtained when the complete transect data are used. They include 100  
353 measurements for each transect (1 measurement every 10 m). The sensitivity of the  
354 correlation to the spatial sampling along the transect is relatively low (not shown).  
355 For this site the correlation values stay in the range of **0.87 when measurements**  
356 **are taken every 200m (only 5 measurements), to 0.92** when measurements  
357 are taken every 80m (13 measurements). The stability of the temporal correlation for  
358 different spatial sampling distances indicates that the surface soil moisture temporal  
359 variability is rather homogeneous along the transect. This explains the robustness  
360 of the kilometer scale up-scaling relation.

#### 361 4.2 *Up-scaling relation for the Agoufou site*

362 Measurements performed in 2005 and 2006 on the Agoufou site are used here to  
363 investigate the inter-annual stability of the up-scaling relationship between surface  
364 soil moisture at the local station scale and at the kilometer scale. As indicated in  
365 Table 3, 34 1km-transect observations were made for this period on the Agoufou  
366 site. The transects cover a wide range of soil moisture conditions. The Agoufou

367 site includes 3 soil moisture stations, of which the data from two stations (top and  
368 bottom) are available for the whole 2005-2006 period (Table 1). The up-scaling  
369 relationship between local and kilometer surface soil moisture is computed and  
370 indicated below for these two stations.

371 For the Agoufou top of hillslope station:

$$372 \quad SSM_{tra1km} = -0.68855 + 1.7561 \times SSM_{staloc} \quad (2)$$

373 For the Agoufou bottom of hillslope station:

$$374 \quad SSM_{tra1km} = -5.272 + 1.1812 \times SSM_{staloc} \quad (3)$$

375 Lower slope and intercept parameters are obtained for the bottom of hillslope sta-  
376 tion than for the top of hillslope one. As expected, this is due to generally higher  
377 values of soil moisture content at the bottom than at the top of hillslope. These two  
378 relations are applied to the data continuously monitored by the stations in order to  
379 estimate the kilometer scale surface soil moisture. Figure 5 shows the scatter-plot  
380 of the comparison of the kilometer scale surface soil moisture between station and  
381 transect. Statistical results are indicated in Table 4 for Agoufou 2005-2006. Bottom  
382 of hillslope up-scaled soil moisture shows a slightly non-linear behaviour related to  
383 a pronounced saturation effect for high values of soil moisture.

384

385 [Fig. 5 about here.]

386 [Table 4 about here.]

387 For this two-year period, best results are obtained with the top of hillslope station,  
388 for which the up-scaling relation matches the transect measurements with an ac-  
389 curacy better than 1% (volumetric), and a **correlation coefficient of  $R = 0.97$** .  
390 Values of efficiency are also very high for both stations with 0.94 and 0.73 for the top

391 and bottom station respectively. These statistical results indicate that the up-scaling  
392 relation between local surface soil moisture and averaged surface soil moisture along  
393 the 1km transect is very stable at the inter-annual scale.

394 Further analysis is conducted to compare surface soil moisture up-scaling perfor-  
395 mances from the three stations of the Agoufou site, which was only possible for  
396 2006. Statistical results are shown in Table 4. The top of hillslope station (P3) is  
397 shown to be the most suitable to up-scale surface soil moisture to the kilometer  
398 scale.

### 399 *4.3 Multi-site up-scaling relation*

400 The spatial stability of the 1km up-scaling relation is addressed here at the multi-  
401 site scale. The 1km transects acquired on the Agoufou site and on the other coarse  
402 textured sites are considered for this study. Since much more measurements were  
403 acquired on Agoufou, only the year 2006 is considered for this site, while 2005 and  
404 2006 are considered for the other sites. According to the inter-annual robustness of  
405 the surface soil moisture up-scaling relation on Agoufou, eliminating 2005 data for  
406 Agoufou does not introduce any bias in the selected data set. It also equilibrates the  
407 number of transect measurements between Agoufou and the other sites. Accordingly,  
408 21 transect measurements are available, of which 9 for Agoufou and 12 for the other  
409 sites (Table 3). For each transect, the temporally collocated surface soil moisture of  
410 the station of the considered site is compared to the transect value. Based on the  
411 21 transects defined above, the multi-site 1km up-scaling relation is determined to  
412 be:

$$413 \quad SSM_{tra1km} = -0.52332 + 1.2995 \times SSM_{stoloc} \quad (4)$$

414 Figure 6 (left panel) shows the correspondence between the kilometer scale volumet-  
415 ric surface soil moisture measured from transect measurements and the volumetric

416 the soil moisture extrapolated from corresponding local stations. Statistical results  
417 are presented in Table 4. Although the dispersion ( $RMSE = 2.2\%$ ) is larger than  
418 that obtained at the single-site scale for the Agoufou and Bangui Mallam sites  
419 (0.9% and 1.6% respectively), high **correlation value** ( $R = 0.82$ ) and high effi-  
420 ciency ( $EFF = 0.66$ ) clearly show good skill of this up-scaling relation to describe  
421 the 1km volumetric surface soil moisture on the different coarse textured sites of  
422 the Gourma region. The robustness of the up-scaling relation at the multi-site scale  
423 indicates that surface soil moisture scaling characteristics are similar on the differ-  
424 ent coarse textured sites considered at meso-scale.

425 As mentioned above for the Bangui Mallam site (Figure 4), higher values of sur-  
426 face soil moisture are associated to higher values of absolute surface soil moisture  
427 variability. This relation between surface soil moisture and its spatial variability  
428 is investigated at the multi-site scale in Figure 6 (right panel). With a correlation  
429 of  $R = 0.82$ , it is shown to be representative at the meso-scale, where all coarse  
430 textured sites are considered.

431 [Fig. 6 about here.]

432 The multi-site results presented above indicate that (i) the up-scaling relation given  
433 in equation 4 describes the 1km scale volumetric surface soil moisture from any  
434 station of the meso-scale site with an averaged accuracy of 2.2%, and that (ii)  
435 characteristics of surface soil moisture variability are similar for the different sites  
436 of the meso-scale window, with a  $R = 0.82$  correlation obtained between surface soil  
437 moisture and its spatial variability at 1km.

438 This underlines the high degree of representativity of the soil moisture stations  
439 for the kilometer scale. The result also suggests highly robust scaling relation of  
440 surface soil moisture. It justifies the approach to use a unique multi-site relation for  
441 extrapolating kilometer scale soil moisture for each coarse textured site equipped  
442 with a soil moisture station. The stability of these relationships across period longer

443 than 2 years needs to be confirmed for future up-scaling applications. But for the  
444 considered years 2005 and 2006 this data set is shown to be suitable to validate  
445 of satellite products with ground station measurements (Gruhler et al. 2008; Zribi  
446 et al. this issue; Baup et al. 2008).

#### 447 4.4 *Hydrological transect over the Agoufou site*

448 In addition to the 1km transect performed on different sites, an hydrological transect  
449 was defined. This transect cuts across 7 catchments located within and next to  
450 the Agoufou local site. It is 1255m long and not straight in order to follow the  
451 landscape features. Measurements of surface soil moisture (every 10m) along this  
452 transect was repeated 10 times in 2006 as indicated in Table 3. The elevation was  
453 assessed by means of a Global Positioning System, so that surface soil moisture  
454 variations are monitored in relation with topography information. Figure 7 shows  
455 surface soil moisture monitored along this transect at 4 different dates, just after  
456 rain on 19 August 2006 am and pm, and a few days before, on August 13 and 15  
457 where no rainfall occurrence led to drying conditions. Topography (elevation in m)  
458 is indicated on the bottom panel.

459 [Fig. 7 about here.]

460 Hydrological transect measurements aim at studying hydrological processes at dif-  
461 ferent levels of the hillslope. Although they are limited to surface soil moisture, they  
462 provide complementary information compared to the three local stations of Agoufou  
463 which provide a complete vertical profile. Figure 7 qualitatively shows the influence  
464 of topography on the surface soil moisture value. In particular, persistent higher  
465 soil moisture values are observed near 500m, 875m, 1200m which all correspond to  
466 low elevation areas. At 1200m there is a relative elevation minimum. It is not very  
467 pronounced in the direction of the transect but more important in the orthogonal

468 direction. This explains the maximum soil moisture at this location. The correlation  
469 values,  $\mathbf{R}$ , between the SSM and the elevation are provided in the figure. They show  
470 that the surface soil moisture profile along the transect is negatively correlated to  
471 the elevation. This indicates that relatively wet conditions are encountered in low  
472 elevation areas, while soil is getting dryer when elevation increases. These significant  
473 negative correlation values also indicate limited precipitation heterogeneities along  
474 the transect. The negative correlation is stronger for wet conditions than for dry  
475 conditions. This shows that for wet conditions the soil water distribution along the  
476 transect is largely related to the soil topography. For dryer soils the negative corre-  
477 lation is less strong which indicates that other processes, such as evapotranspiration  
478 or slight variations in soil texture, also influence the spatial distribution of surface  
479 soil moisture. However negative correlation values persist for a large range of soil  
480 moisture conditions from very wet (19 August am, a few hours after precipitation)  
481 to very dry conditions (15 August, after 10 days without rain).

482 Figure 8 displays the amplitude of the Discrete Fourier Transform (DFT) of the sur-  
483 face soil moisture and the soil elevation along the hydrological transect. The DFT  
484 represents the partitioning of the sample variance into spatial frequency components  
485 (Greminger et al., 1985). In Figure 8 DFTs are obtained with a Hamming window.  
486 They are represented on a logarithmic scale and expressed in terms of spatial pe-  
487 riod. The soil moisture DFTs are provided for 3 of the 4 cases considered in Figure  
488 7, which allow the consideration of different soil moisture conditions. For the clarity  
489 of the figure the spectrum for the intermediate case of August 19pm is not shown.  
490 Process scales occur at spectral peaks, whereas spectral gaps represent spatial scales  
491 with minimum spectral variance. The dominant spectral peaks shown for the soil  
492 elevation are dominated by long wavelengths (spatial period larger than 100m). The  
493 dominant periods are the transect length, 250m (extending from 180m to 300m) and  
494 100m. The variability of soil moisture at long wavelength is in relatively good agree-  
495 ment with that of soil elevation. For wet conditions, significant peaks are shown for



496 periods of 100m and 200m in agreement with the soil elevation variability. For dryer  
 497 soil conditions (Aug. 15), these two peaks are still characterising the soil moisture  
 498 variability but their amplitude and spatial extension are reduced.

499 [Fig. 8 about here.]

500 Much less agreement between topography and soil moisture is shown for short spatial  
 501 periods (below 80m). This indicates that surface soil moisture variations at smaller  
 502 spatial scales are less related to the topography than larger scale variations. It is  
 503 also clear from Figure 8 that smaller scale surface soil moisture variations are of  
 504 lower amplitude than variations at larger scale.

## 505 5 Temporal stability of the Gourma soil moisture network

506 In this section the representativity of the ground soil moisture station is investigated  
 507 further by the means of Mean Relative Difference method. Built on the Vachaud  
 508 et al. (1985) approach,  $MRD_i$  is computed for each station  $i$ , as:

$$509 \quad MRD_i = \frac{1}{t} \sum_{j=1}^t \frac{SSM_{i,j} - \overline{SSM_j}}{\overline{SSM_j}} \quad (5)$$

510 where  $j$  is the time step,  $t$  is the number of time steps,  $SSM_{i,j}$  is the surface soil  
 511 moisture of station  $i$  at the time step  $j$ ,  $\overline{SSM_j}$  is the surface soil moisture aver-  
 512 aged over the different stations at the time step  $j$ . The value of  $MRD_i$  quantifies  
 513 the agreement of SSM between station  $i$  and the stations average. Its temporal  
 514 standard deviation  $STD_i$ , computed from  $(SSM_{i,j} - \overline{SSM_j})/(\overline{SSM_j})$  time series,  
 515 quantifies the agreement of surface soil moisture between the local station  $i$  and the  
 516 stations average in term of temporal variability.

517 This method is applied for the whole year 2006, to the Agoufou super site (Figure 1,  
 518 right): the three stations of Agoufou are considered together with those of Bangui

519 Mallam and Eguérit. These 5 stations encompass an area of about 25km × 25km,  
520 with soil surface types representative of 90% of the Gourma meso-scale site. Soil  
521 moisture data from each station are weighted according to the soil type distribution  
522 over the super site.

523

524 [Fig. 9 about here.]

525 Results of the MRD analysis on the Gourma super site are plotted in Figure 9 on a  
526 circle plot where the angle deviation from 45° gives the MRD value of each station  
527 and the radius indicates its standard deviation (STD). This figure clearly shows  
528 that the Agoufou middle of hillslope station, for which the MRD value is close to  
529 zero, captures almost perfectly the mean annual value of the super site averaged  
530 surface soil moisture. Lower values of MRD for the stations located at the top of the  
531 hillslope in Agoufou and in Bangui Mallam indicate that these sites are generally  
532 dryer than the super site average. In contrast Eguérit and Agoufou Bottom have  
533 higher values of their surface soil moisture MRD which indicate that they are wet-  
534 ter than the super site average. These results are in agreement with the qualitative  
535 features shown in Figure 2.

536 Beside its absolute value, surface soil moisture temporal variability is of highest im-  
537 portance. Standard deviation of MRD indicates for each station its representativity  
538 at the super site scale in terms of soil moisture temporal variability. The Agoufou  
539 top of hillslope station is shown to have the lowest STD (0.21), which shows that  
540 is in best agreement with SSM variability at the super site scale. The Bangui Mal-  
541 lam STD is 0.28, showing this site provides a good estimate of SSM variability as  
542 well. STD values of the three other stations are much higher with more than 0.4  
543 for Agoufou middle of hillslope, more than 0.6 for Agoufou bottom of hillslope and  
544 almost 0.7 for Eguérit. This indicates that, although surface soil moisture is low-  
545 biased for two of these stations, its temporal variability does not match with that

546 observed at the super site scale.

547 The Agoufou top of hillslope station, with lowest STD and reasonable MRD, is the  
548 most representative station of the surface soil moisture at the Agoufou super site  
549 scale. This is in agreement with the up-scaling analysis conducted in the previous  
550 section at the kilometer scale where the same station is shown to be representative  
551 of the kilometer scale SSM through a linear regression.

## 552 **6 Conclusion**

553 This paper presents the Gourma (Mali) meso-scale soil moisture network which has  
554 been implemented in the framework of the AMMA project. This soil moisture net-  
555 work is a component of the AMMA's multidisciplinary and multi-scale observing  
556 system (Redelsperger et al. 2006). Initially implemented in the context of the En-  
557 hanced Observing Period (EOP, 2005-2007), it has been extended to the Long term  
558 Observing Period (LOP, 2005-2009) of AMMA.

559 The Gourma soil moisture network aims at documenting soil moisture dynamics  
560 in the sahelian region of Mali, for a large range of temporal and spatial scales at  
561 which land surface processes and surface-atmosphere interaction occur. To this end  
562 a set of 10 soil moisture stations is spanning  $2^\circ$  between  $15^\circ\text{N}$  and  $17^\circ\text{N}$ . Different  
563 types of soil surfaces are instrumented according to their spatial distribution over  
564 the meso-scale site. Observing results from the 2005-2006 period are presented in  
565 this paper.

566 Soil moisture measurements on coarse textured sites, which represent 65% of the  
567 meso-scale area, clearly show that the temporal surface soil moisture dynamics is  
568 highly influenced by the climatic condition and the rainfall variability along the  
569 North-South transect (section 3). Northern stations of Bamba and In Zaket are  
570 characterised by lower soil moisture values and lower time variability, while stations  
571 located within the super site depict higher soil moisture values and variability. Soil

572 moisture dynamics is also strongly influenced by surface properties (soil and veg-  
573 etation types, topography). Flat rocky-loam surfaces, which represent 28% of the  
574 meso-scale site are shown to be characterised by a relatively slow temporal vari-  
575 ability. Clay area, covered by acacia forest is distinguished by its high values of soil  
576 moisture, due to the soil texture and to the soil flooding during the monsoon season.  
577 Beside these differences in soil moisture dynamics along the N-S gradient and for  
578 different surface types, all the soil moisture stations of the Gourma network show  
579 a 2005-2006 inter-annual variability which is characterised by a later monsoon in  
580 2006. This is in agreement with atmospheric observations described in Janicot et al.  
581 (2008).

582 A case study is investigated, based on Bangui Mallam measurements, to address the  
583 vertical structure of soil moisture dynamics on coarse textured soils (Figure 3). Soil  
584 water budgets are computed for soil boxes between 0-1m and 1-2m, and compared  
585 to precipitation input for a 6-day period between July 28 and August 2 2006 (DoY  
586 209-214). Fast soil water infiltration is depicted for the first meter of soil. After the  
587 61.5mm precipitation event that occurred on DoY 210, the wetting front is shown to  
588 reach 80cm depth 1.5 days after the rain. The 1-2m soil water content significantly  
589 increased about 2.75 day after a strong precipitation event occurred, whereas the  
590 0-1m soil moisture budget already decreased. While the first meter of soil is charac-  
591 terised by very fast response of soil moisture to the atmospheric forcing, deeper soil  
592 is shown to respond at the seasonal time scale to atmospheric forcing and resulting  
593 land surface processes (infiltration and water uptake).

594 An up-scaling analysis of surface soil moisture is conducted in this paper, based  
595 on kilometer scale transect measurements performed in 2005 and 2006 on different  
596 coarse textured sites of the meso-scale area (section 4). An up-scaling relationship is  
597 determined and shown to be highly suitable to extrapolate kilometer scale surface  
598 soil moisture on the Bangui Mallam site for 2006 (equation 1). The accuracy is  
599 shown to be 1.6%, with a **0.89 correlation** with transect measurements. The high

600 number of transect measurements performed at the Agoufou local site in 2005 and  
601 2006 allows showing the inter-annual stability of the up-scaling relation for this site.  
602 Accordingly, equation 2 extrapolates surface soil moisture at the scale of 1km from  
603 the Agoufou top of hillslope station, with an accuracy better than 1% in volumetric  
604 soil moisture. Based on the 2006 data set, the Agoufou top of hillslope station is  
605 shown to be the most representative station to derive the kilometer scale surface  
606 soil moisture at the Agoufou site.

607 This paper shows that the relationship between surface soil moisture and its 1km  
608 spatial variability is very stable among the different sites of the Gourma meso-scale  
609 for the two studied years. Due to this consistency among the sites, the use of an  
610 unique multi-site up-scaling relation is shown to be accurate within 2.2% (volumet-  
611 ric) to retrieve 1km scale surface soil moisture from station measurements.

612 This paper introduces measurements performed along an hydrological transect where  
613 elevation measurements were also performed. Discrete Fourier Transform of surface  
614 soil moisture and soil elevation show that significant variations of surface soil mois-  
615 ture are dominated by spatial periods of 250m and 100m. Same dominant periods  
616 are shown for the soil elevation, which indicates that the soil moisture spatial vari-  
617 ability is related to the soil topography along the transect. Soil moisture variations  
618 at scales smaller than 80m are of lower amplitude and less related to topography.  
619 More investigations are however required to address the relative role of land surface  
620 cover, soil texture class and precipitation variability on the small scale soil moisture  
621 variability.

622 Surface soil moisture scaling is investigated further in section 5, where the Mean  
623 Relative Difference approach is applied to the Gourma super site. The Agoufou  
624 top of hillslope station is shown to be the most representative of the surface soil  
625 moisture variability (lowest standard deviation of the MRD) at the super site scale.  
626 Consistency of the results at different scales, from local to kilometer and from local  
627 to super sites scale, and with different approaches (transects and MRD), indicates

628 that up-scaling features of surface soil moisture are consistent at the three con-  
629 sidered spatial scales (local, 1km, super site). Based on these preliminary results,  
630 additional measurements are required to address the relation between local, transect  
631 and super site measurements. Measurements along a 50km transect were performed  
632 in 2006 and 2007 (not shown here) and will be addressed in further studies.

633

634 The robustness of the surface soil moisture up-scaling relation for different coarse  
635 textured sites indicates that the Gourma meso scale soil moisture network is highly  
636 suitable for remote sensing and land surface modelling applications for which soil  
637 moisture is also required at larger scale than the station measurement. With the  
638 Bénin and Niger soil moisture networks, the Gourma soil moisture network has  
639 been selected to be a validation site for the future SMOS (Soil Moisture and Ocean  
640 Salinity Mission) (Kerr et al. 2001). Coordinated measurements of soil moisture,  
641 meteorological and flux measurements as well as vegetation measurements over  
642 the meso-scale site, makes the Gourma meso-scale soil moisture network of high  
643 interest in many research areas related to land surface processes and land-surface-  
644 atmosphere interaction studies.

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Gourma meso-scale site

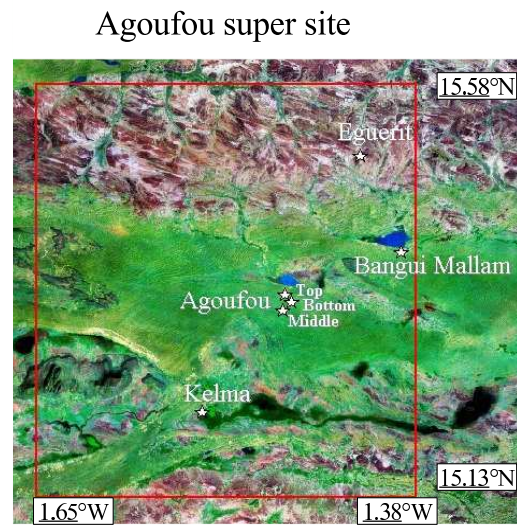


Fig. 1. Location of the 10 automatic soil moisture stations (white stars), for the Gourma meso-scale site (left) and for the super-site (right).

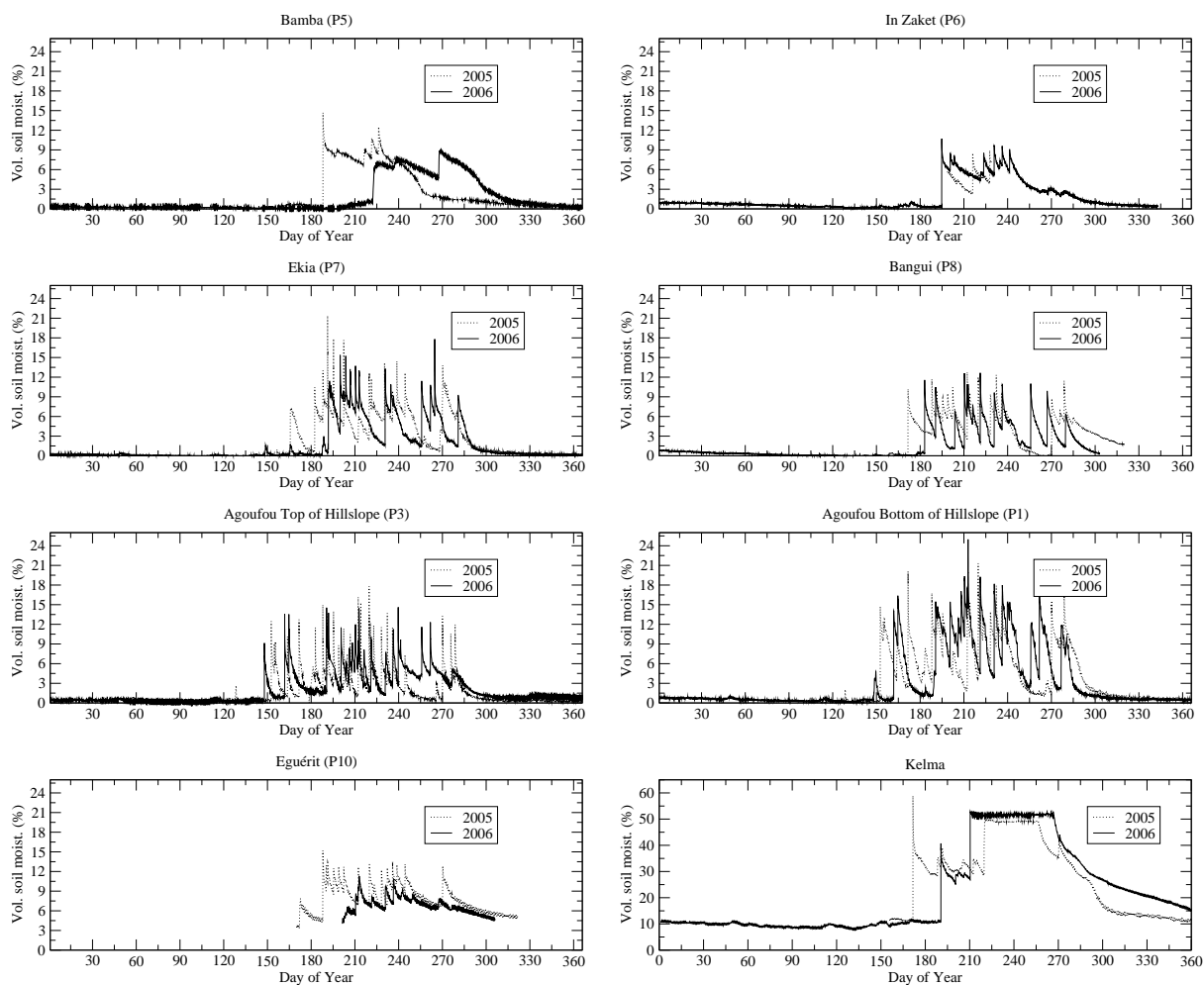


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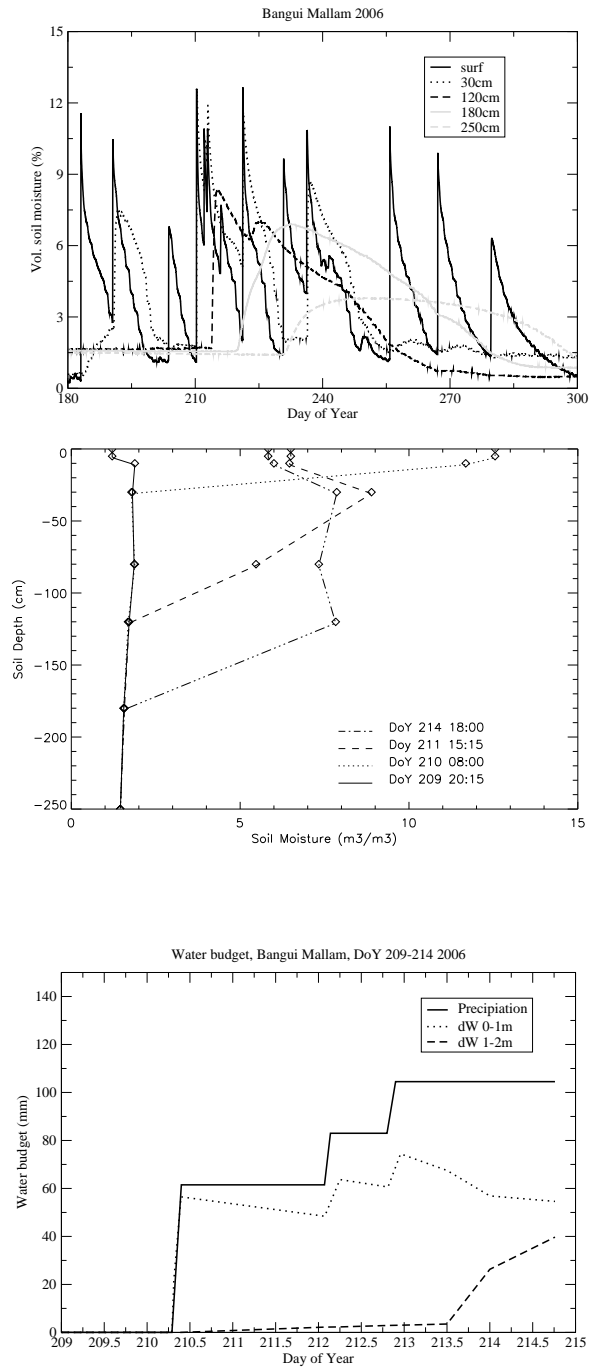


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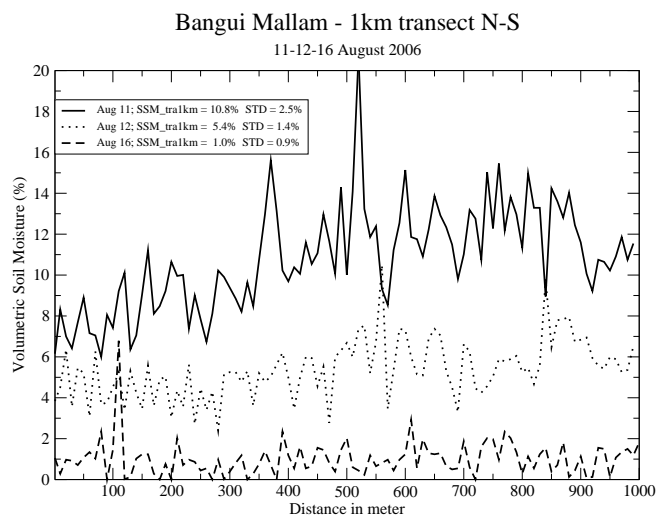


Fig. 4. Transect measurements of surface soil moisture at three different dates in August 2006. For each date, the mean value of surface soil moisture (SM) and its standard deviation (STD) are indicated.

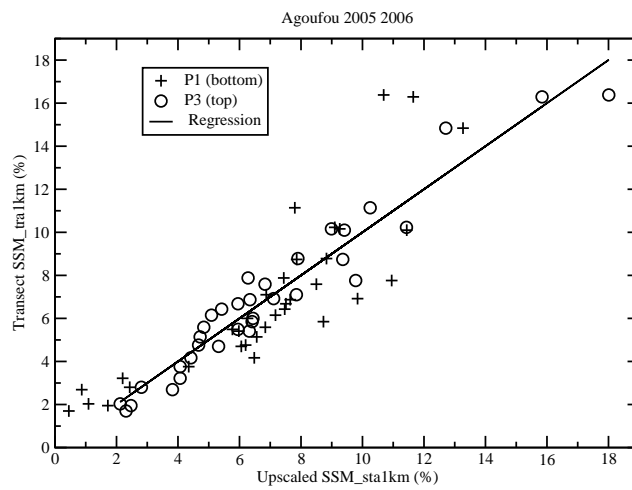


Fig. 5. Surface soil moisture estimated at the 1km scale from transect measurements (vertical axis) and from the local Agoufou top of hillslope station measurements to which was applied the equation 2 up-scaling relation (horizontal axis).

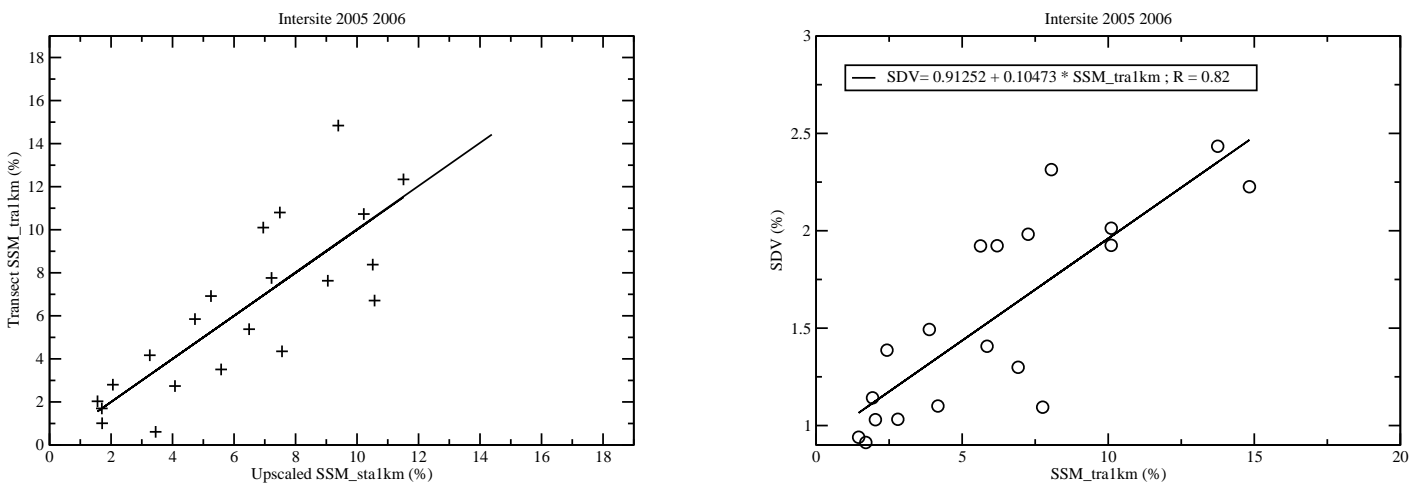


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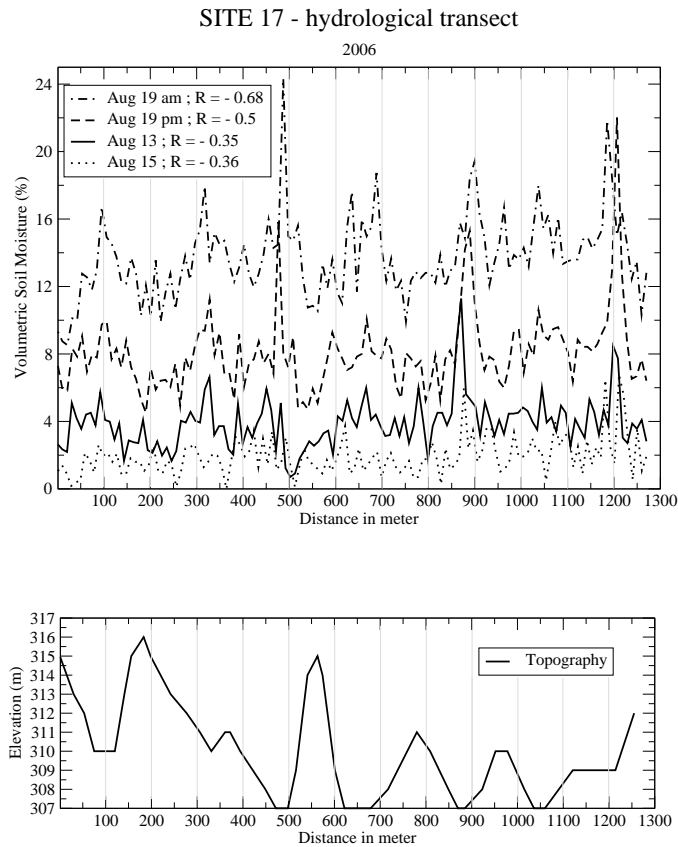


Fig. 7. Surface soil moisture (top panel) and topography (bottom panel) along the hydrological transect. Four transects are shown here for different soil moisture conditions. Very wet conditions are shown on 19 August since a heavy rainfall event occurred a few hour before, on the 18<sup>th</sup> August in the evening. 13 and 15 August are respectively 4 and 6 days after the rainfall event of the 9 August.

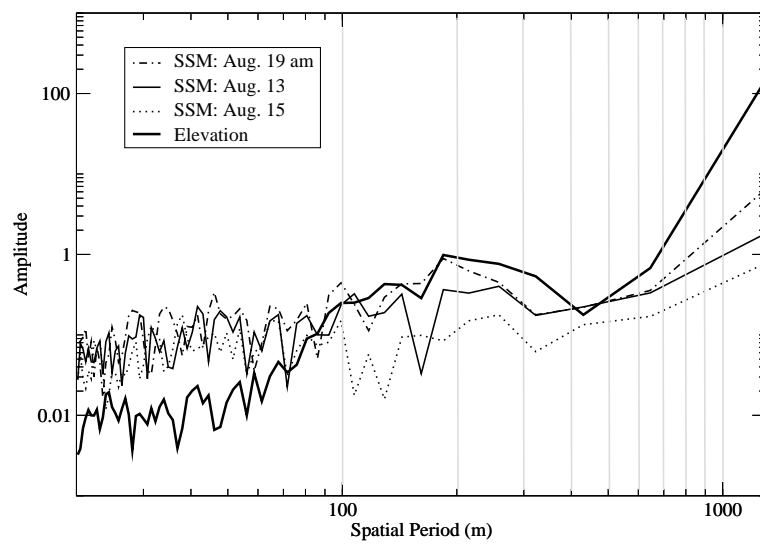


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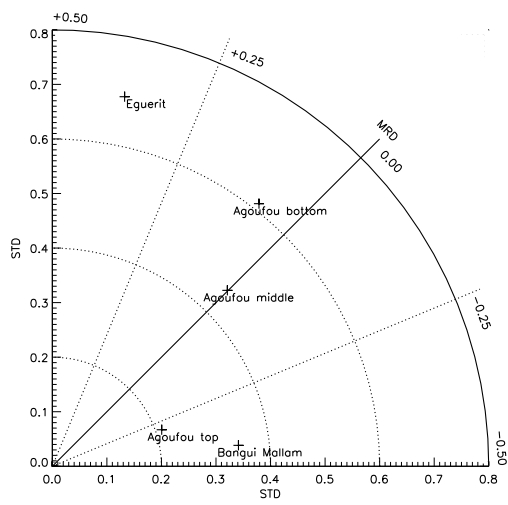


Fig. 9. Mean Relative Difference (MRD) and its time Standard Deviation (STD) (see text, section 5) for the volumetric surface soil moisture of each of the five stations considered at the Agoufou super site scale compared to the site average.

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870		number of observations is indicated by $N$ in the last column.	49



Number	Site		Location		Sensors types and depth (cm)		date
	Name	Soil Text.	Lat.	Lon.	Soil Moisture	Temperature	
17 - P1	Agoufou bottom	Sandy-Loam	15.341°N	1.479°W	7CS616	4 PT108	04-2005
					5, 30, 60, 120, 150, 250, 400	5, 30, 60, 120	
17 - P2	middle	Coarse	15.345°N	1.479°W	6 CS616	2 PT108	04-2006
					5, 30, 60, 120, 180, 250	5, 30	
17 - P3	top	Sand	15.345°N	1.479°W	5 CS616	2 PT108	04-2004
					5, 10, 40, 120, 220	5, 40	
BB - P5	Bamba	Coarse	17.099°N	1.402°W	6 CS616	5 PT108	04-2004
					5, 40, 80, 120, 180, 250	5, 10, 40, 80, 120	
4 - P6	In Zaket	Coarse	16.572°N	1.789°W	7 CS616	4 PT108	07-2005
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	
12 - P7	Ekia	Coarse	15.965°N	1.253°W	7 CS616	4 PT108	06-2005
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	
EM - P8	Bangui Mallam	Coarse	15.398°N	1.345°W	7 CS616	4 PT108	04-2005
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	
20 - P9	Kelma	Fine	15.218°N	1.566°W	4 Theta-probes	4 PT108	06-2005
					5, 20, 80, 100	5, 20, 80, 100	
40 - P10	Eguérit	Rock	15.503°N	1.392°W	2CS616	4 PT108	04-2005
					10, 50	10, 50	
25 - P11	Kinia	Coarse	15.051°N	1.546°W	7CS616	4 PT108	03-2007
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	

Table 1

Soil Moisture stations installed at the Gourma meso-scale site. Name and location of each stations are indicated, as well as the depth of measurements and date of installation. Qualitative indication of surface soil texture is indicated for each station, except for Eguérit which has rocky soil. US Department of Agriculture (USDA) soil texture is given for Agoufou top and bottom of hillslope, where texture measurements were performed (Table 2).

Bottom of hillslope					
Depth (cm)	Clay	Fine Silt	Coarse Silt	Fine Sand	Coarse Sand
5	96	89	69	352	394
10	53	31	28	338	550
20	68	31	18	348	535
30	78	32	15	355	520
40	87	31	19	392	471
50	82	27	15	377	499
60	90	26	26	438	420
70	86	26	11	445	432
80	90	22	12	505	371
90	86	18	15	524	357
100	78	13	19	544	346

Top of Hillslope					
Depth (cm)	Clay	Fine Silt	Coarse Silt	Fine Sand	Coarse Sand
5	34	11	13	385	557
10	34	14	13	421	518
20	37	18	6	418	521
30	44	11	4	431	510
40	47	8	1	507	437
50	42	9	3	469	477
60	40	6	8	448	498
70	42	2	5	462	489
80	36	4	4	465	491
90	33	3	2	453	509
100	29	11	8	533	419

Table 2

Vertical profile of soil texture on the Agoufou local site. Fractions are indicated in per thousand. Particle sizes are defined according to the USDA classification scheme, with clay (<0.002mm), fine silt (0.002-0.02mm), coarse silt (0.02-0.05mm), fine sand (0.05-0.2mm), coarse sand (0.2-2mm) (Gee and Bauder 1986).

Site	2005	2006	Direction
Agoufou	25	9	West
Bangui Mallam	1	7	South
Bamba	1	0	North
Ekia	1	2	South
Agoufou-hydro	0	10	Topographical
Total	28	28	

Table 3

Number of transect measurements performed in 2005 and 2006 on Agoufou and some of the others coarse textured sites.

Site	Year	$RMSE(\%)$	$R$	EFF	BIAS	$N$
Bangui Mallam	2006	1.6	<b>0.89</b>	0.8	$10^{-4}$	7
Agoufou	2005-2006					
Top (P3)		0.9	<b>0.97</b>	0.94	$10^{-4}$	34
Bottom (P1)		1.9	<b>0.86</b>	0.73	$10^{-4}$	34
Agoufou	2006					
Top (P3)		0.97	<b>0.97</b>	0.94	$10^{-4}$	9
Bottom (P1)		1.7	<b>0.91</b>	0.83	$10^{-5}$	9
Middle (P2)		1.4	<b>0.94</b>	0.88	$10^{-4}$	9
Multi-site	2005-2006	2.2	<b>0.82</b>	0.66	$10^{-4}$	21

Table 4

Statistical results of the comparison between the kilometer scale surface soil moisture obtained by up-scaling of local station measurements,  $SSM_{sta1km}$ , and transect measurements,  $SSM_{tra1km}$  (see text). For each row a data set is selected corresponding to different sites and different years. The number of observations is indicated by  $N$  in the last column.

# Multi-scale soil moisture measurements at the Gourma meso-scale site in Mali

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## Abstract

This paper presents the ground soil moisture measurements performed over the so-called Gourma meso-scale site in Mali, Sahel, in the context of the African Monsoon Multidisciplinary Analysis (AMMA) project. The Gourma meso-scale soil moisture network is part of a complete land surface processes observing and modelling strategy and is associated to vegetation and meteorological field measurements as well as soil moisture remote sensing. It is spanning 2° in latitude between 15°N and 17°N. In 2007, it includes 10 soil moisture stations, of which 3 stations also have meteorological and flux measurements. A relevant spatial sampling strategy is proposed to characterise soil moisture at different scales including local, kilometer, super-site and meso-scales. In addition to the local stations network, transect measurements were performed on different coarse textured (sand to sandy-loam) sites, using portable impedance probes. They indicate mean value and standard deviation (STD) of the

surface soil moisture (SSM) at the kilometer scale. This paper presents the data set and illustrates soil moisture spatial and temporal features over the Sahelian Gourma meso-scale site for 2005-2006. Up-scaling relation of SSM is investigated from (i) local to kilometer scale and (ii) from local to the super site scale. It is shown to be stable in space and time (2005-2006) for different coarse textured sites. For the Agoufou local site, the up-scaling relation captures SSM dynamics at the kilometer scale with a 0.9% accuracy in volumetric soil moisture. At the multi-site scale, an unique up-scaling relation is shown to be able to represent kilometer SSM for the coarse textured soils of the meso-scale site with an accuracy of 2.2% (volumetric). Spatial stability of the ground soil moisture stations network is also addressed by the Mean Relative Difference (MRD) approach for the Agoufou super site where 5 soil moisture stations are available (about 25km  $\times$  25km). This allows the identification of the most representative ground soil moisture station which is shown to be an accurate indicator with low variance and bias of the soil moisture dynamics at the scale of the super site. Intensive local measurements, together with a robust up-scaling relation make the Gourma soil moisture network suitable for a large range of applications including remote sensing and land surface modelling at different spatial scales.

*Key words:* Soil Moisture, ground measurements, up-scaling, Sahel, AMMA

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## 1 Introduction

West Africa, and more specifically the Sahel, is pointed out by Koster et al. (2004) to be one of the regions of the world with the strongest feedback mechanism between soil moisture and precipitation. This hot spot ”indicates where the routine monitor-

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5 ing of soil moisture, with both ground-based and space-based systems, will yield the  
6 greatest return in boreal summer seasonal forecasting.” One of the key objectives of  
7 AMMA (African Monsoon Multidisciplinary Analysis) project, is to improve our un-  
8 derstanding and our modelling capabilities of the effect of land surface processes on  
9 monsoon intensity, variability and predictability (Redelsperger et al. 2006). AMMA  
10 is supported by a very strong observational program. Three meso-scale sites are in-  
11 strumented in Mali, Niger and Bénin, providing information along the North-South  
12 gradient between Sahelian and Soudanian regions (Redelsperger et al. 2006). The  
13 instrumental deployment in the Gourma region (the sahelian site of Mali) focuses  
14 on quantification of water, CO<sub>2</sub> and energy fluxes between the surface and the  
15 atmosphere (Mougin et al., this issue). Among the surface processes under con-  
16 sideration, emphasis is put on evapotranspiration which is the most important  
17 process coupling the physical, biological and hydrological processes at the conti-  
18 nental scale. Soil moisture is a crucial variable that affects many processes includ-  
19 ing land-surface-atmosphere interactions (Taylor et al. 2007; Taylor and Ellis 2006;  
20 Monteny et al. 1997; Nicholson et al. 1997), land surface fluxes (Timouk et al. this  
21 issue; Lloyd et al. 1997), vegetation phenology (Seghieri et al. this issue), and soil  
22 respiration (Le Dantec et al. 2006). The diversity of processes and the correspond-  
23 ing large range of spatial and temporal scales involved in the monsoon dynamics  
24 require accurate estimate of soil moisture dynamics at local scale, meso-scale and  
25 regional scale. Ground measurements provide vertical soil moisture profiles with a  
26 high accuracy but they are limited to the local scale. In contrast, remote sensing ap-  
27 proaches provide spatially integrated measurements of surface soil moisture (SSM)  
28 but they are limited to the very first top centimetres of the soil (Kerr 2007). Soil  
29 moisture estimation from microwave remote sensing was investigated during the Hy-  
30 drological and Atmospheric Pilot Experiment in the Sahel (HAPEX-SAHEL), using  
31 both passive microwave radiometry from airborne measurements (Schmugge 1998;  
32 Chanzy et al. 1997; Calvet et al. 1996) and active microwave remote sensing with

33 ERS satellite data (Magagi and Kerr 1997). These studies were based on local soil  
34 moisture ground measurements acquired for a few month during the 1992 sum-  
35 mer campaign. Extensive field measurement campaigns have been conducted in  
36 other regions of the Earth to characterise the soil moisture variability, as for exam-  
37 ple in the U.S. Midwest, South Central Georgia and Southern Great Plains (SGP)  
38 (De Lannoy et al. 2007; Bosch et al. 2006; Famiglietti et al. 1999), and in Australia  
39 (Rüdiger et al. 2007). Using airborne based remote sensing information, Kim and  
40 Barros (2002) examined the statistical structure of soil moisture (40 x 250 km)  
41 obtained during the SGP 1997 hydrology experiment. In Sahel, where field instru-  
42 mentation and extensive field campaigns are more difficult, extensive soil moisture  
43 measurements were not available until now. In the framework of AMMA the Gourma  
44 meso-scale site has been instrumented for soil moisture measurements. It is described  
45 in this paper.

46 For the purpose of satellite validation it is of crucial importance to address up-scaling  
47 issues of ground soil moisture measurements. Baup et al. (2007) used ground soil  
48 moisture measurements over the Agoufou local site, in Mali, for the purpose of EN-  
49 VISAT/ASAR soil moisture inversion. To this end they used surface soil moisture  
50 measurements from one local station, up-scaled to the 1km remotely sensed pixel for  
51 2005. In the present paper, surface soil moisture up-scaling of ground measurements  
52 is investigated at the single site scale and extended to (i) the multi-site spatial scale,  
53 within the Gourma meso-scale windows, and (ii) the inter-annual temporal scale.

54 A complementary approach, suitable for larger scale applications, consists of de-  
55 riving spatially representative soil moisture estimates from ground observation net-  
56 works. The method, first proposed by Vachaud et al. (1985), is based on the Mean  
57 Relative Difference (MRD) and deviation between stations of the same network. It  
58 was applied by Cosh et al.(2004) to the Soil Moisture EXperiment (SMEX) 2002  
59 (Jackson et al. 2003) for the validation of the Advanced Microwave Scanning Ra-  
60 diometer on Earth Observing System (AMSR-E) soil moisture. De Lannoy et al.



61 (2007) used the MRD approach combined with cumulative distribution function  
62 matching to estimate the spatial mean soil moisture. Based on the MRD, Gruhier  
63 et al. (2008) used the Gourma meso-scale soil moisture measurements to validate  
64 the soil moisture products obtained for 2005 from AMSR-E.

65 Ground soil moisture measurements are also highly relevant to validate Land Sur-  
66 face Models (LSMs). As for satellite validation, up-scaling is crucial to characterise  
67 soil moisture at the scale of the LSM. In turn, land surface models allow for the ex-  
68 tension of local scale measurements to larger spatial scales. This is being addressed  
69 over West Africa through the AMMA Land Surface Model Intercomparison Project  
70 (ALMIP, Boone et al. 2008).

71 The main purpose of this paper is to describe the Gourma meso-scale soil moisture  
72 network and to presents soil moisture measurements for 2005-2006. Based on local  
73 and transect measurements and using the Mean Relative Difference method, this  
74 paper also presents some features of the soil moisture characteristics and investi-  
75 gates the potential of the Gourma soil moisture measurements to address surface  
76 soil moisture up-scaling. Next section describes the Gourma meso-scale soil mois-  
77 ture network. Section 3 presents the soil moisture dynamics for different stations  
78 along the 15°N to 17°N climatic gradient for 2005 and 2006. Section 4 focuses on  
79 surface soil moisture up-scaling. Representativity of ground soil moisture station is  
80 addressed in section 5 for the Agoufou super site, where the Mean Relative Differ-  
81 ence approach is applied to the Gourma soil moisture network. Section 6 concludes.

## 82 2 Experimental design and ground soil moisture measurements

### 83 2.1 The Mali site

84 The AMMA project aims at providing a better understanding of the African mon-  
85 soon processes. AMMA relies on an extensive field campaign experiment for which  
86 three meso-scale sites are instrumented in Bénin, Niger and Mali (Redelsperger et al. 2006).  
87 Instrumental deployment over the Mali site includes three monitoring scales de-  
88 scribed hereafter (Mougin et. al, this issue).

89 • The Gourma meso-scale site (30,000km<sup>2</sup>, 14.5°N-17.5°N; 1°W-2°W) is shown in  
90 Figure 1. The location of the soil moisture stations (10 stations) is indicated on  
91 the map by white stars. Each soil moisture station also includes a rain-gauge for  
92 rainfall measurements and three stations (in Bamba, Eguérit, Agoufou) include  
93 complete weather station and flux measurements. More detail on rainfall measure-  
94 ments over Gourma are provided in Frappart et al. (this issue), while Lebel and  
95 Ali (this issue) investigate the rainfall regime fluctuations in Sahel. The Gourma  
96 meso-scale site is characterised by a Sahelian to saharo-sahelian climate (isohyets  
97 500-100 mm). Soil is coarse textured (sand, loamy sand, sandy loam) for 65% of  
98 the area, where vegetation is composed of a layer of natural annual herbs with  
99 scattered trees and shrubs (Hiernaux et al. this issue). 28% of the meso-scale site  
100 is characterised by flat and shallow soils and rock outcrops (loamy colluvium,  
101 schist, sandstone outcrops and hard pan). Vegetation on these rocky-loam areas  
102 consists of scattered shrubs. The remaining 7% of the area are clay plains, tem-  
103 porarily flooded woodlands and flooded depressions. Data on herbs and woody  
104 vegetation are collected on 43 local sites among which some are also used for vali-  
105 dation of remote sensing products (LAI, Net Primary Productivity, soil moisture)  
106 derived from SPOT-VGT, MODIS, AMSR-E, ENVISAT/ASAR, ERS (Gruhler

107 et al. 2008; Zribi et al. this issue; Baup et al. 2008; Jarlan et al. 2008).

108 • The Agoufou super site (2,250km<sup>2</sup>, 15.3°N-15.58°N; 1.38°W-1.65°W) is shown  
109 in Figure 1 (right). At this scale, ground measurements focus on land surface  
110 fluxes measurements as well as on spatial heterogeneities of fluxes and vegetation  
111 characteristics.

112 • The Agoufou local intensive site (1km<sup>2</sup>, 15.3°N; 1.3°W) is indicated on Figure  
113 1. Annual mean precipitation is 370mm (1920-2003). The site has measurements  
114 of vegetation, soil moisture, meteorology and land surface fluxes (energy, water,  
115 CO<sub>2</sub>). The data collected on this site are used to parameterise, test and validate  
116 LSMs. The Agoufou local site is also a main validation site for remote sensing  
117 products.

## 118 2.2 *Ground soil moisture measurements*

119 The colours in Figure 1, obtained from a Landsat image, indicate the surface types  
120 on which the stations are deployed, with green for gently undulating coarse tex-  
121 tured dune systems, dark green for clay soil types and brown-pink for flat rocky-  
122 loam plains. Table 1 provides detailed information concerning soil moisture stations  
123 (number, name, soil type, location, sensors types and depth, date of installation).  
124 The same installation protocol is used for all the soil moisture stations, where Time  
125 Domain Reflectometry sensors are used (Campbell CS616), except for the Kelma  
126 station. For the later, Delta-T Theta Probe sensors are used since they are equipped  
127 with short rods which is more suitable for clay soils (a mention of the manufacturers  
128 is for information only and implies no endorsement on the part of the authors). The  
129 Gourma soil moisture stations all include a first measurement at 5cm depth, except  
130 in Eguérit (rocky) where the first measurement is at 10cm depth. Soil moisture pro-  
131 files are measured down to 50cm depth for Eguérit, and down to 4m for Agoufou

132 at the bottom of a hillslope. In order to capture the fast soil moisture dynamics,  
133 the vertical resolution of automatic soil moisture measurements in the soil is very  
134 fine at the surface, and measurements are acquired at 15 minutes time intervals.  
135 For remote sensing and land surface modelling purpose, both soil moisture and soil  
136 temperature profiles are monitored. For each station and each sensor depth, cal-  
137 ibration was performed, based on local soil density and gravimetric soil moisture  
138 measurements. Gravimetric measurements were performed at different stages of the  
139 rainy season to ensure calibration robustness in various soil moisture conditions.  
140 Soil moisture values provided in this paper are expressed in terms of volumetric  
141 units.

142 Soil texture measurements were performed for the first meter of soil, in the Agoufou  
143 local intensive site at the top and bottom of a hillslope (Table 2). Soil texture of the  
144 top 10cm of soil is slightly different between the top and bottom of the hillslope,  
145 with silt and clay content higher at the bottom than at the top of the hillslope.  
146 However the soil is very coarse textured, with more than 74% and 94% of sand  
147 particles at surface for the bottom and top of the hillslope respectively.

148 The Gourma soil moisture network documents soil moisture dynamics along the  
149 North-South climatic gradient, as well as at the dune scale, with three stations lo-  
150 cated on the Agoufou local site at different levels of a typical hillslope (top, middle  
151 and bottom). Eight stations are located on coarse textured soils (sandy to sandy-  
152 loam) which represents 65% of the meso-scale site area. One station, in Kelma (site  
153 21) is implemented on a clay soil, covered by acacia forest, representing 7% of the  
154 meso-scale area, and one station is located in Eguérit, on a rocky surface that rep-  
155 resents 28% of the area.

156 In addition to the local stations network, transect measurements have been man-  
157 ually performed every year since 2004 during the rainy season. They consist in  
158 monitoring surface soil moisture (0-5cm) by the means of a portable impedance  
159 probe (Theta probe) every 10m along a 1km straight transect. The location of each

160 point measurement along the transect is chosen to be different (separated by a  
161 few centimetres) from one transect date to another. This ensures avoiding soil dis-  
162 turbances that would affect the soil moisture measurements. This method allows  
163 estimating, for each transect measurement, both the mean value and standard de-  
164 viation of the surface soil moisture along the 1km transect. For practical reasons it  
165 is not possible to perform transect measurements on rocky surfaces (too hard to use  
166 the probe), nor in flooded plains (under water). Thus transect measurements have  
167 been performed on coarse textured soils, which represent the dominant soil texture  
168 type at meso-scale. Intensive transect measurements campaigns were performed on  
169 the Agoufou local site where soil moisture is the most intensively documented. For  
170 this site the 1km transect is the same as that used for vegetation measurements  
171 (Hiernaux et al. this issue). It is located on the Agoufou site with the starting and  
172 closest point located about 100m from the Agoufou bottom of the hillslope sta-  
173 tion (P1) and about 300m from the top of hillslope (P3) and middle of hillslope  
174 (P2) stations. In 2005 and 2006, transect measurements were also extended to the  
175 other coarse textured sites of Bangui Mallam, Ekia and Bamba. For these 3 sites,  
176 the 1km transects start exactly from the soil moisture stations. The 1km transects  
177 aim to provide information on mean surface soil moisture at the kilometer scale.  
178 These measurements are not combined with topography measurements. In 2006 an  
179 additional transect was defined on the Agoufou local intensive site for the purpose  
180 of hydrological applications and vegetation monitoring in relation to soil moisture  
181 along a topographic profile. SSM measurements performed along the hydrological  
182 transect are combined with elevation measurements. In contrast to the 1km tran-  
183 sects, this hydrological transect is not straight. It is 1255m long and cuts across 7  
184 catchments located partly within the Agoufou intensive site. It starts from the top  
185 of hillslope (P3) station, passes on the bottom of hillslope station (P1) and it is at a  
186 distance of about 100m from the middle of hillslope station (P2). Table 3 indicates  
187 the number of transect measurements performed on each site for these two years.

188 Remote sites, more difficult to access, are less documented, as in Bamba where only  
189 1 transect measurement was performed.

190 [Table 1 about here.]

191 [Table 2 about here.]

192 [Table 3 about here.]

193 [Fig. 1 about here.]

### 194 **3 Soil Moisture Dynamics over the Gourma meso-scale site**

#### 195 *3.1 Temporal dynamics*

196 Inter-annual variability between 2005 and 2006 is shown in Figure 2 for the surface  
197 (5cm depth) soil moisture monitored for eight stations located along the north-south  
198 gradient and for different soil types. The horizontal axis indicates the Day of Year  
199 (DoY). Note that the vertical axis is identical for each station except Kelma (P9,  
200 bottom right). Kinia (P11) and Agoufou middle (P2) are not presented since the  
201 data set is not complete for the considered period. In the In Zaket station, the 2005  
202 data set is limited to DoY 198-228, which provides one month of data between the  
203 station installation in July and its theft in August. The 2006 data set is complete  
204 after the station was reinstalled. Data are missing for Eguérit in early 2006 for tech-  
205 nical reasons. So inter-annual variability in monsoon onset is not visible for these  
206 two last stations.

207 The top panel shows SSM of the most northern stations in Bamba and In Zaket.  
208 They both present similar features in their surface soil moisture dynamics which is  
209 relatively slow and low amplitude. The second panel shows the surface soil mois-

210 ture dynamics for Ekia and Bangui Mallam and the third panel presents surface  
211 soil moisture for two stations located in the Agoufou super site at the top and bot-  
212 tom of the hillslope. Surface soil moisture is characterised by higher values and a  
213 larger temporal variability on these sites than on the northern sites. The bottom  
214 panel shows the surface soil moisture evolution for the two non-sandy sites of the  
215 Gourma soil moisture network, located in Eguérit (rocky) and in Kelma (clay).  
216 They both show a lower temporal variability in surface soil moisture. The Kelma  
217 site is characterised by much higher soil moisture values, due to the clay soil texture  
218 in this area. In addition, this site is flooded during the rainy season as indicated  
219 by the maximum soil moisture values maintained at saturation for more than one  
220 month during the monsoon season. For the top three panels, which present surface  
221 soil moisture monitored on coarse textured sites, differences between the sites are  
222 mainly governed by the strong North-South climatic gradient and by the precipita-  
223 tion variability. In contrast, for the bottom panel, the distances between the sites  
224 is less (all sites are within the super site) and the precipitation variability between  
225 the sites is lower. Accordingly, differences in soil moisture dynamics are mainly gov-  
226 erned for these sites by differences in surface properties (soil texture and vegetation  
227 cover) and subsequent land surface processes (partitioning between evapotranspira-  
228 tion and runoff).

229 For coarse textured soils the infiltration rate is very high according to the large  
230 amount of sand particles (higher than 74%). Surface ponding occurs rarely on these  
231 soils and it is located in very specific and limited areas (a few square meters) for very  
232 short periods (a few hours after rain). None of the soil moisture stations installed  
233 on coarse textured soils are affected by ponding. Despite temporal dynamics and  
234 absolute values of soil moisture being different between stations depending on both  
235 surface properties and location along the climatic transect, all the stations capture  
236 the later monsoon onset in 2006 than in 2005 that was described by Janicot et al.  
237 (2008).

239 *3.2 Vertical dynamics*

240 Figure 3 (top) depicts the temporal evolution of soil moisture at different depths  
241 at the Bangui Mallam station during the 2006 summer. It clearly shows that soil  
242 moisture dynamics is very fast at the surface, with rapid soil moisture response to  
243 precipitation occurrence, and fast soil drying afterwards. Soil moisture dynamics is  
244 getting slower with increasing depth, and at 120cm, 180cm and 250cm depth, soil  
245 moisture shows variability mainly at the seasonal time scale.

246 A major rainfall event (61.5mm at this station) occurred in the early morning of the  
247 DoY 210. It was associated with a large convective system that gave precipitation  
248 from Kelma to Ekia (Figure 1), as can be seen on Figure 2 with the surface soil  
249 moisture increasing on DoY 210 in 2006 for the 6 stations concerned. This event  
250 is chosen here to illustrate the vertical soil moisture dynamics at the Bangui Mal-  
251 lam site which is representative of vertical dynamics of coarse textured sites of the  
252 Gourma region.

253 Figure 3 (middle) shows the vertical structure of soil moisture evolution of the Ban-  
254 gui Mallam station at four different dates around this precipitation event, between  
255 July 28 (DoY 209) and August 2 (DoY 214) 2006. Figure 3 (bottom) shows the wa-  
256 ter budget as estimated from ground observations of soil moisture and precipitation  
257 for this period for the Bangui Mallam site. In particular it indicates the accumulated  
258 precipitation since DoY 209, and the variation in total soil water content ( $W$ ) for  
259 the 0-1m soil layer and for the 1-2m soil layer ( $dW$  0-1m and  $dW$  1-2m respectively).  
260 Vertically integrated soil water content is computed for each time step by the means  
261 of a linear vertical interpolation and integration of volumetric soil moisture profiles.  
262 Accordingly it must be taken with caution due to uncertainties associated to the  
263 vertical profiles. This is particularly the case for the second meter of soil where the



264 vertical sampling of soil sensors is more sparse (Table 1). After a rainfall event, the  
265 presence of a wetting front, associated to a discontinuity in the soil moisture profile,  
266 is also expected to affect the accuracy of the vertical interpolation. Despite of these  
267 uncertainties, when considering its temporal evolution, the vertically integrated wa-  
268 ter content provides an estimate of the time evolution of the soil water budget.

269 Soil moisture profiles shown in Figure 3 (middle) indicate very dry conditions (vol-  
270 umetric soil moisture below 2% ) on DoY 209 at all soil depths at the Bangui  
271 Mallam station. The strong precipitation event that occurred on DoY 210 led to  
272 a fast response of soil moisture in the first half meter of soil, with an increase to  
273 12.5% (volumetric) at 10cm depth. However the wetting front didn't reach yet the  
274 80cm deep soil moisture sensor for which the volumetric soil moisture was steady  
275 bellow 2%. The vertical profile depicted for DoY 211 shows that 1.5 days after the  
276 rain occurred, the wetting front got deeper, down to 80cm, while the first 30cm of  
277 soil already started to dry out. A few days later (DoY 214) while 2 rainfall events  
278 occurred (21.5mm each) in the morning and evening of the DoY 212, the vertical  
279 profile of soil moisture shows that the wetting front reached 120cm depth. Figure 3  
280 (bottom) shows that the cumulated rainfall between DoY 209 and 214 is 104mm.

281 The total soil water increase ( $dW_{0-1m} + dW_{1-2m}$ ) for this period is 85.3mm. The  
282 lower value of total soil water increase compared to accumulated precipitation, is  
283 explained by several processes, including direct soil evaporation, water uptake for  
284 plant transpiration and surface runoff. It is interesting to note that, for each of  
285 the three rainfall events, the 0-1m soil water content decreased rapidly as soon  
286 as the rain stopped. It is due to direct soil evaporation and strong rates of plant  
287 transpiration. In addition, the downward propagation of the wetting front, when  
288 it reached the 1-2m soil layer, strongly contributed to the 0-1m layer drying after  
289 DoY 213 (2.75 day after the first rainfall event). At the same time,  $dW_{1-2m}$  started  
290 to strongly increase accordingly on DoY 213, due to deep soil infiltration from the  
291 first meter to the second meter of soil.

## 293 4 Surface soil moisture up-scaling

294 Results of transect measurements are presented in this section. The local to kilo-  
295 meter up-scaling relation is investigated at the single-site scale, considering annual  
296 and inter-annual temporal scales, as well as at the multi-site scale. As described  
297 in section 2 and Table 3, transect measurements were performed in 2005 and 2006  
298 during intensive field campaign measurements conducted during the monsoon sea-  
299 son.

300

### 301 4.1 Bangui Mallam site

302 Figure 4 illustrates the surface soil moisture variability along the Bangui Mallam  
303 1km transect, for which measurements were performed at different dates between 11  
304 and 16 August 2006. A strong precipitation event occurred on August 9 (DoY 221),  
305 2 days before the first transect measurement, followed by a long drying period. This  
306 figure illustrates the strong spatial variability along the transect. However, values of  
307 standard deviation (STD) indicated on the figure for the three dates, also show that  
308 surface soil moisture spatial variability decreases when soil is drying. The relation-  
309 ship between the soil moisture mean value and its spatial variability is investigated  
310 further in section 4.3 at the multi-site scale. Figure 4 also shows the very fast tem-  
311 poral dynamics associated with the soil drying after a precipitation event. In five  
312 days, volumetric surface soil moisture drops from 10.8% to 1.0%. This fast drying  
313 of the soil surface is due to fast infiltration rates of coarse textured soils and large  
314 evaporation rates.

315

316

[Fig. 4 about here.]

317 Based on transect measurements and local station measurements at Bangui Mal-  
318 lam acquired at the same time, a relationship is established between the averaged  
319 1km transect surface soil moisture ( $SSM_{tra1km}$ ) and the local station surface soil  
320 moisture ( $SSM_{stoloc}$ ) for the Bangui Mallam site in 2006:

$$321 \quad SSM_{tra1km} = -2.2365 + 1.5458 \times SSM_{stoloc} \quad (1)$$

322 where both  $SSM_{tra1km}$  and  $SSM_{stoloc}$  are in % (volumetric). The slope larger than  
323 1 (1.5458) indicates slightly stronger surface soil moisture changes on the transect  
324 compared to the local station. This is explained by the difference of sensing depth  
325 between the local station and transect measurements. The top few centimetres of the  
326 soil are characterised by very strong soil moisture (and soil temperature) gradients.  
327 The very surface soil moisture, which is more directly exposed to the atmosphere,  
328 depicts slightly larger variations than at 5cm depth, where the variations are al-  
329 ready slightly attenuated. Thus the time evolution of the surface soil moisture is  
330 sensitive to the depth of measurement. This issue has important implications for  
331 remote sensing applications which measure about the top 1cm, 2cm and 5cm soil  
332 moisture at X-band, C-band and L-band respectively, as indicated by Le Morvan  
333 et al. 2008 and Jackson et al., 1997. In our study the first sensor of the station is  
334 horizontally placed at 5cm depth, whereas the transect measurements measure the  
335 averaged value between 0 and 5cm deep. Shallower measurements lead to slightly  
336 larger soil moisture variations along the transects than at the station. This is ex-  
337 pressed by a slope larger than one between transect and station measurements. This  
338 relationship applied to the station surface soil moisture measurements, allows ex-  
339 trapolating to the kilometer scale, for which  $SSM_{sta1km}$  will be used. Table 4 (first  
340 line) shows the statistical results of the comparison between the kilometer surface

341 soil moisture obtained from extrapolated station measurements ( $SSM_{sta1km}$ ) and  
342 from the transect measurements ( $SSM_{tra1km}$ ). Comparison is based on several in-  
343 dicators including Root Mean Square Error ( $RMSE$ ), correlation coefficient ( $R$ ),  
344 Efficiency (Nash coefficient ,  $EFF$ ) and BIAS. Although only seven transects are  
345 considered to determine this relation for the Bangui Mallam site in 2006, the very  
346 good agreement between the station and the transect measurements ( $R = 0.89$ ,  
347  $RMSE = 1.6\%$ ,  $EFF = 0.8$ ,  $BIAS = 10^{-4}$ ), indicates that the up-scaling relation  
348 provided in equation 1 is highly suitable to extrapolate from local station measure-  
349 ments at the Bangui Mallam site, to the kilometer scale. Since the station operates  
350 automatically, this approach is suitable to derive the kilometer scale surface soil  
351 moisture continuously at a fine temporal resolution (15 minute time step). These  
352 statistics are obtained when the complete transect data are used. They include 100  
353 measurements for each transect (1 measurement every 10 m). The sensitivity of the  
354 correlation to the spatial sampling along the transect is relatively low (not shown).  
355 For this site the correlation values stay in the range of 0.87 when measurements  
356 are taken every 200m (only 5 measurements), to 0.92 when measurements are taken  
357 every 80m (13 measurements). The stability of the temporal correlation for different  
358 spatial sampling distances indicates that the surface soil moisture temporal variabil-  
359 ity is rather homogeneous along the transect. This explains the robustness of the  
360 kilometer scale up-scaling relation.

#### 361 4.2 Up-scaling relation for the Agoufou site

362 Measurements performed in 2005 and 2006 on the Agoufou site are used here to  
363 investigate the inter-annual stability of the up-scaling relationship between surface  
364 soil moisture at the local station scale and at the kilometer scale. As indicated in  
365 Table 3, 34 1km-transect observations were made for this period on the Agoufou  
366 site. The transects cover a wide range of soil moisture conditions. The Agoufou

367 site includes 3 soil moisture stations, of which the data from two stations (top and  
368 bottom) are available for the whole 2005-2006 period (Table 1). The up-scaling  
369 relationship between local and kilometer surface soil moisture is computed and  
370 indicated below for these two stations.

371 For the Agoufou top of hillslope station:

$$372 \quad SSM_{tra1km} = -0.68855 + 1.7561 \times SSM_{staloc} \quad (2)$$

373 For the Agoufou bottom of hillslope station:

$$374 \quad SSM_{tra1km} = -5.272 + 1.1812 \times SSM_{staloc} \quad (3)$$

375 Lower slope and intercept parameters are obtained for the bottom of hillslope sta-  
376 tion than for the top of hillslope one. As expected, this is due to generally higher  
377 values of soil moisture content at the bottom than at the top of hillslope. These two  
378 relations are applied to the data continuously monitored by the stations in order to  
379 estimate the kilometer scale surface soil moisture. Figure 5 shows the scatter-plot  
380 of the comparison of the kilometer scale surface soil moisture between station and  
381 transect. Statistical results are indicated in Table 4 for Agoufou 2005-2006. Bottom  
382 of hillslope up-scaled soil moisture shows a slightly non-linear behaviour related to  
383 a pronounced saturation effect for high values of soil moisture.

384

385 [Fig. 5 about here.]

386 [Table 4 about here.]

387 For this two-year period, best results are obtained with the top of hillslope station,  
388 for which the up-scaling relation matches the transect measurements with an accu-  
389 racy better than 1% (volumetric), and a correlation coefficient of  $R = 0.97$ . Values  
390 of efficiency are also very high for both stations with 0.94 and 0.73 for the top and

391 bottom station respectively. These statistical results indicate that the up-scaling re-  
392 lation between local surface soil moisture and averaged surface soil moisture along  
393 the 1km transect is very stable at the inter-annual scale.

394 Further analysis is conducted to compare surface soil moisture up-scaling perfor-  
395 mances from the three stations of the Agoufou site, which was only possible for  
396 2006. Statistical results are shown in Table 4. The top of hillslope station (P3) is  
397 shown to be the most suitable to up-scale surface soil moisture to the kilometer  
398 scale.

### 399 4.3 Multi-site up-scaling relation

400 The spatial stability of the 1km up-scaling relation is addressed here at the multi-  
401 site scale. The 1km transects acquired on the Agoufou site and on the other coarse  
402 textured sites are considered for this study. Since much more measurements were  
403 acquired on Agoufou, only the year 2006 is considered for this site, while 2005 and  
404 2006 are considered for the other sites. According to the inter-annual robustness of  
405 the surface soil moisture up-scaling relation on Agoufou, eliminating 2005 data for  
406 Agoufou does not introduce any bias in the selected data set. It also equilibrates the  
407 number of transect measurements between Agoufou and the other sites. Accordingly,  
408 21 transect measurements are available, of which 9 for Agoufou and 12 for the other  
409 sites (Table 3). For each transect, the temporally collocated surface soil moisture of  
410 the station of the considered site is compared to the transect value. Based on the  
411 21 transects defined above, the multi-site 1km up-scaling relation is determined to  
412 be:

$$413 \quad SSM_{tra1km} = -0.52332 + 1.2995 \times SSM_{stoloc} \quad (4)$$

414 Figure 6 (left panel) shows the correspondence between the kilometer scale volumet-  
415 ric surface soil moisture measured from transect measurements and the volumetric

416 the soil moisture extrapolated from corresponding local stations. Statistical results  
417 are presented in Table 4. Although the dispersion ( $RMSE = 2.2\%$ ) is larger than  
418 that obtained at the single-site scale for the Agoufou and Bangui Mallam sites  
419 (0.9% and 1.6% respectively), high correlation value ( $R = 0.82$ ) and high efficiency  
420 ( $EFF = 0.66$ ) clearly show good skill of this up-scaling relation to describe the  
421 1km volumetric surface soil moisture on the different coarse textured sites of the  
422 Gourma region. The robustness of the up-scaling relation at the multi-site scale in-  
423 dicates that surface soil moisture scaling characteristics are similar on the different  
424 coarse textured sites considered at meso-scale.

425 As mentioned above for the Bangui Mallam site (Figure 4), higher values of sur-  
426 face soil moisture are associated to higher values of absolute surface soil moisture  
427 variability. This relation between surface soil moisture and its spatial variability  
428 is investigated at the multi-site scale in Figure 6 (right panel). With a correlation  
429 of  $R = 0.82$ , it is shown to be representative at the meso-scale, where all coarse  
430 textured sites are considered.

431 [Fig. 6 about here.]

432 The multi-site results presented above indicate that (i) the up-scaling relation given  
433 in equation 4 describes the 1km scale volumetric surface soil moisture from any  
434 station of the meso-scale site with an averaged accuracy of 2.2%, and that (ii)  
435 characteristics of surface soil moisture variability are similar for the different sites  
436 of the meso-scale window, with a  $R = 0.82$  correlation obtained between surface soil  
437 moisture and its spatial variability at 1km.

438 This underlines the high degree of representativity of the soil moisture stations  
439 for the kilometer scale. The result also suggests highly robust scaling relation of  
440 surface soil moisture. It justifies the approach to use a unique multi-site relation for  
441 extrapolating kilometer scale soil moisture for each coarse textured site equipped  
442 with a soil moisture station. The stability of these relationships across period longer

443 than 2 years needs to be confirmed for future up-scaling applications. But for the  
444 considered years 2005 and 2006 this data set is shown to be suitable to validate  
445 of satellite products with ground station measurements (Gruhier et al. 2008; Zribi  
446 et al. this issue; Baup et al. 2008).

#### 447 4.4 *Hydrological transect over the Agoufou site*

448 In addition to the 1km transect performed on different sites, an hydrological transect  
449 was defined. This transect cuts across 7 catchments located within and next to  
450 the Agoufou local site. It is 1255m long and not straight in order to follow the  
451 landscape features. Measurements of surface soil moisture (every 10m) along this  
452 transect was repeated 10 times in 2006 as indicated in Table 3. The elevation was  
453 assessed by means of a Global Positioning System, so that surface soil moisture  
454 variations are monitored in relation with topography information. Figure 7 shows  
455 surface soil moisture monitored along this transect at 4 different dates, just after  
456 rain on 19 August 2006 am and pm, and a few days before, on August 13 and 15  
457 where no rainfall occurrence led to drying conditions. Topography (elevation in m)  
458 is indicated on the bottom panel.

459 [Fig. 7 about here.]

460 Hydrological transect measurements aim at studying hydrological processes at dif-  
461 ferent levels of the hillslope. Although they are limited to surface soil moisture, they  
462 provide complementary information compared to the three local stations of Agoufou  
463 which provide a complete vertical profile. Figure 7 qualitatively shows the influence  
464 of topography on the surface soil moisture value. In particular, persistent higher  
465 soil moisture values are observed near 500m, 875m, 1200m which all correspond to  
466 low elevation areas. At 1200m there is a relative elevation minimum. It is not very  
467 pronounced in the direction of the transect but more important in the orthogonal



468 direction. This explains the maximum soil moisture at this location. The correlation  
469 values,  $R$ , between the SSM and the elevation are provided in the figure. They show  
470 that the surface soil moisture profile along the transect is negatively correlated to  
471 the elevation. This indicates that relatively wet conditions are encountered in low  
472 elevation areas, while soil is getting dryer when elevation increases. These significant  
473 negative correlation values also indicate limited precipitation heterogeneities along  
474 the transect. The negative correlation is stronger for wet conditions than for dry  
475 conditions. This shows that for wet conditions the soil water distribution along the  
476 transect is largely related to the soil topography. For dryer soils the negative corre-  
477 lation is less strong which indicates that other processes, such as evapotranspiration  
478 or slight variations in soil texture, also influence the spatial distribution of surface  
479 soil moisture. However negative correlation values persist for a large range of soil  
480 moisture conditions from very wet (19 August am, a few hours after precipitation)  
481 to very dry conditions (15 August, after 10 days without rain).

482 Figure 8 displays the amplitude of the Discrete Fourier Transform (DFT) of the sur-  
483 face soil moisture and the soil elevation along the hydrological transect. The DFT  
484 represents the partitioning of the sample variance into spatial frequency components  
485 (Greminger et al., 1985). In Figure 8 DFTs are obtained with a Hamming window.  
486 They are represented on a logarithmic scale and expressed in terms of spatial pe-  
487 riod. The soil moisture DFTs are provided for 3 of the 4 cases considered in Figure  
488 7, which allow the consideration of different soil moisture conditions. For the clarity  
489 of the figure the spectrum for the intermediate case of August 19pm is not shown.  
490 Process scales occur at spectral peaks, whereas spectral gaps represent spatial scales  
491 with minimum spectral variance. The dominant spectral peaks shown for the soil  
492 elevation are dominated by long wavelengths (spatial period larger than 100m). The  
493 dominant periods are the transect length, 250m (extending from 180m to 300m) and  
494 100m. The variability of soil moisture at long wavelength is in relatively good agree-  
495 ment with that of soil elevation. For wet conditions, significant peaks are shown for

496 periods of 100m and 200m in agreement with the soil elevation variability. For dryer  
 497 soil conditions (Aug. 15), these two peaks are still characterising the soil moisture  
 498 variability but their amplitude and spatial extension are reduced.

499 [Fig. 8 about here.]

500 Much less agreement between topography and soil moisture is shown for short spatial  
 501 periods (below 80m). This indicates that surface soil moisture variations at smaller  
 502 spatial scales are less related to the topography than larger scale variations. It is  
 503 also clear from Figure 8 that smaller scale surface soil moisture variations are of  
 504 lower amplitude than variations at larger scale.

## 505 5 Temporal stability of the Gourma soil moisture network

506 In this section the representativity of the ground soil moisture station is investigated  
 507 further by the means of Mean Relative Difference method. Built on the Vachaud  
 508 et al. (1985) approach,  $MRD_i$  is computed for each station  $i$ , as:

$$509 \quad MRD_i = \frac{1}{t} \sum_{j=1}^t \frac{SSM_{i,j} - \overline{SSM}_j}{\overline{SSM}_j} \quad (5)$$

510 where  $j$  is the time step,  $t$  is the number of time steps,  $SSM_{i,j}$  is the surface soil  
 511 moisture of station  $i$  at the time step  $j$ ,  $\overline{SSM}_j$  is the surface soil moisture aver-  
 512 aged over the different stations at the time step  $j$ . The value of  $MRD_i$  quantifies  
 513 the agreement of SSM between station  $i$  and the stations average. Its temporal  
 514 standard deviation  $STD_i$ , computed from  $(SSM_{i,j} - \overline{SSM}_j)/(\overline{SSM}_j)$  time series,  
 515 quantifies the agreement of surface soil moisture between the local station  $i$  and the  
 516 stations average in term of temporal variability.

517 This method is applied for the whole year 2006, to the Agoufou super site (Figure 1,  
 518 right): the three stations of Agoufou are considered together with those of Bangui

519 Mallam and Eguérit. These 5 stations encompass an area of about 25km × 25km,  
520 with soil surface types representative of 90% of the Gourma meso-scale site. Soil  
521 moisture data from each station are weighted according to the soil type distribution  
522 over the super site.

523

524 [Fig. 9 about here.]

525 Results of the MRD analysis on the Gourma super site are plotted in Figure 9 on a  
526 circle plot where the angle deviation from 45° gives the MRD value of each station  
527 and the radius indicates its standard deviation (STD). This figure clearly shows  
528 that the Agoufou middle of hillslope station, for which the MRD value is close to  
529 zero, captures almost perfectly the mean annual value of the super site averaged  
530 surface soil moisture. Lower values of MRD for the stations located at the top of the  
531 hillslope in Agoufou and in Bangui Mallam indicate that these sites are generally  
532 dryer than the super site average. In contrast Eguérit and Agoufou Bottom have  
533 higher values of their surface soil moisture MRD which indicate that they are wet-  
534 ter than the super site average. These results are in agreement with the qualitative  
535 features shown in Figure 2.

536 Beside its absolute value, surface soil moisture temporal variability is of highest im-  
537 portance. Standard deviation of MRD indicates for each station its representativity  
538 at the super site scale in terms of soil moisture temporal variability. The Agoufou  
539 top of hillslope station is shown to have the lowest STD (0.21), which shows that  
540 is in best agreement with SSM variability at the super site scale. The Bangui Mal-  
541 lam STD is 0.28, showing this site provides a good estimate of SSM variability as  
542 well. STD values of the three other stations are much higher with more than 0.4  
543 for Agoufou middle of hillslope, more than 0.6 for Agoufou bottom of hillslope and  
544 almost 0.7 for Eguérit. This indicates that, although surface soil moisture is low-  
545 biased for two of these stations, its temporal variability does not match with that

546 observed at the super site scale.

547 The Agoufou top of hillslope station, with lowest STD and reasonable MRD, is the  
548 most representative station of the surface soil moisture at the Agoufou super site  
549 scale. This is in agreement with the up-scaling analysis conducted in the previous  
550 section at the kilometer scale where the same station is shown to be representative  
551 of the kilometer scale SSM through a linear regression.

## 552 **6 Conclusion**

553 This paper presents the Gourma (Mali) meso-scale soil moisture network which has  
554 been implemented in the framework of the AMMA project. This soil moisture net-  
555 work is a component of the AMMA's multidisciplinary and multi-scale observing  
556 system (Redelsperger et al. 2006). Initially implemented in the context of the En-  
557 hanced Observing Period (EOP, 2005-2007), it has been extended to the Long term  
558 Observing Period (LOP, 2005-2009) of AMMA.

559 The Gourma soil moisture network aims at documenting soil moisture dynamics  
560 in the sahelian region of Mali, for a large range of temporal and spatial scales at  
561 which land surface processes and surface-atmosphere interaction occur. To this end  
562 a set of 10 soil moisture stations is spanning  $2^\circ$  between  $15^\circ\text{N}$  and  $17^\circ\text{N}$ . Different  
563 types of soil surfaces are instrumented according to their spatial distribution over  
564 the meso-scale site. Observing results from the 2005-2006 period are presented in  
565 this paper.

566 Soil moisture measurements on coarse textured sites, which represent 65% of the  
567 meso-scale area, clearly show that the temporal surface soil moisture dynamics is  
568 highly influenced by the climatic condition and the rainfall variability along the  
569 North-South transect (section 3). Northern stations of Bamba and In Zaket are  
570 characterised by lower soil moisture values and lower time variability, while stations  
571 located within the super site depict higher soil moisture values and variability. Soil

572 moisture dynamics is also strongly influenced by surface properties (soil and veg-  
573 etation types, topography). Flat rocky-loam surfaces, which represent 28% of the  
574 meso-scale site are shown to be characterised by a relatively slow temporal vari-  
575 ability. Clay area, covered by acacia forest is distinguished by its high values of soil  
576 moisture, due to the soil texture and to the soil flooding during the monsoon season.  
577 Beside these differences in soil moisture dynamics along the N-S gradient and for  
578 different surface types, all the soil moisture stations of the Gourma network show  
579 a 2005-2006 inter-annual variability which is characterised by a later monsoon in  
580 2006. This is in agreement with atmospheric observations described in Janicot et al.  
581 (2008).

582 A case study is investigated, based on Bangui Mallam measurements, to address the  
583 vertical structure of soil moisture dynamics on coarse textured soils (Figure 3). Soil  
584 water budgets are computed for soil boxes between 0-1m and 1-2m, and compared  
585 to precipitation input for a 6-day period between July 28 and August 2 2006 (DoY  
586 209-214). Fast soil water infiltration is depicted for the first meter of soil. After the  
587 61.5mm precipitation event that occurred on DoY 210, the wetting front is shown to  
588 reach 80cm depth 1.5 days after the rain. The 1-2m soil water content significantly  
589 increased about 2.75 day after a strong precipitation event occurred, whereas the  
590 0-1m soil moisture budget already decreased. While the first meter of soil is charac-  
591 terised by very fast response of soil moisture to the atmospheric forcing, deeper soil  
592 is shown to respond at the seasonal time scale to atmospheric forcing and resulting  
593 land surface processes (infiltration and water uptake).

594 An up-scaling analysis of surface soil moisture is conducted in this paper, based  
595 on kilometer scale transect measurements performed in 2005 and 2006 on different  
596 coarse textured sites of the meso-scale area (section 4). An up-scaling relationship  
597 is determined and shown to be highly suitable to extrapolate kilometer scale sur-  
598 face soil moisture on the Bangui Mallam site for 2006 (equation 1). The accuracy  
599 is shown to be 1.6%, with a 0.89 correlation with transect measurements. The high

600 number of transect measurements performed at the Agoufou local site in 2005 and  
601 2006 allows showing the inter-annual stability of the up-scaling relation for this site.  
602 Accordingly, equation 2 extrapolates surface soil moisture at the scale of 1km from  
603 the Agoufou top of hillslope station, with an accuracy better than 1% in volumetric  
604 soil moisture. Based on the 2006 data set, the Agoufou top of hillslope station is  
605 shown to be the most representative station to derive the kilometer scale surface  
606 soil moisture at the Agoufou site.

607 This paper shows that the relationship between surface soil moisture and its 1km  
608 spatial variability is very stable among the different sites of the Gourma meso-scale  
609 for the two studied years. Due to this consistency among the sites, the use of an  
610 unique multi-site up-scaling relation is shown to be accurate within 2.2% (volumet-  
611 ric) to retrieve 1km scale surface soil moisture from station measurements.

612 This paper introduces measurements performed along an hydrological transect where  
613 elevation measurements were also performed. Discrete Fourier Transform of surface  
614 soil moisture and soil elevation show that significant variations of surface soil mois-  
615 ture are dominated by spatial periods of 250m and 100m. Same dominant periods  
616 are shown for the soil elevation, which indicates that the soil moisture spatial vari-  
617 ability is related to the soil topography along the transect. Soil moisture variations  
618 at scales smaller than 80m are of lower amplitude and less related to topography.  
619 More investigations are however required to address the relative role of land surface  
620 cover, soil texture class and precipitation variability on the small scale soil moisture  
621 variability.

622 Surface soil moisture scaling is investigated further in section 5, where the Mean  
623 Relative Difference approach is applied to the Gourma super site. The Agoufou  
624 top of hillslope station is shown to be the most representative of the surface soil  
625 moisture variability (lowest standard deviation of the MRD) at the super site scale.  
626 Consistency of the results at different scales, from local to kilometer and from local  
627 to super sites scale, and with different approaches (transects and MRD), indicates

628 that up-scaling features of surface soil moisture are consistent at the three con-  
629 sidered spatial scales (local, 1km, super site). Based on these preliminary results,  
630 additional measurements are required to address the relation between local, transect  
631 and super site measurements. Measurements along a 50km transect were performed  
632 in 2006 and 2007 (not shown here) and will be addressed in further studies.

633

634 The robustness of the surface soil moisture up-scaling relation for different coarse  
635 textured sites indicates that the Gourma meso scale soil moisture network is highly  
636 suitable for remote sensing and land surface modelling applications for which soil  
637 moisture is also required at larger scale than the station measurement. With the  
638 Bénin and Niger soil moisture networks, the Gourma soil moisture network has  
639 been selected to be a validation site for the future SMOS (Soil Moisture and Ocean  
640 Salinity Mission) (Kerr et al. 2001). Coordinated measurements of soil moisture,  
641 meteorological and flux measurements as well as vegetation measurements over  
642 the meso-scale site, makes the Gourma meso-scale soil moisture network of high  
643 interest in many research areas related to land surface processes and land-surface-  
644 atmosphere interaction studies.

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Gourma meso-scale site

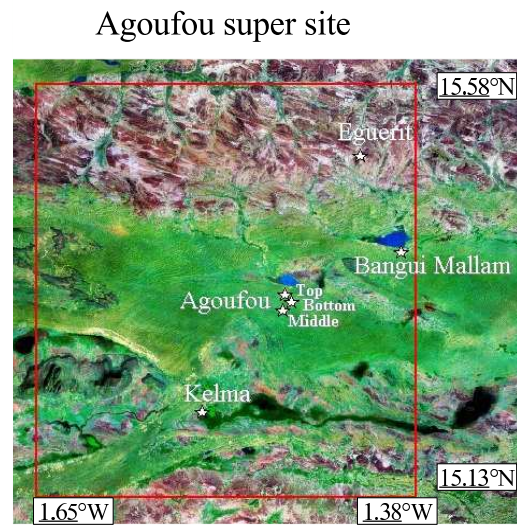


Fig. 1. Location of the 10 automatic soil moisture stations (white stars), for the Gourma meso-scale site (left) and for the super-site (right).



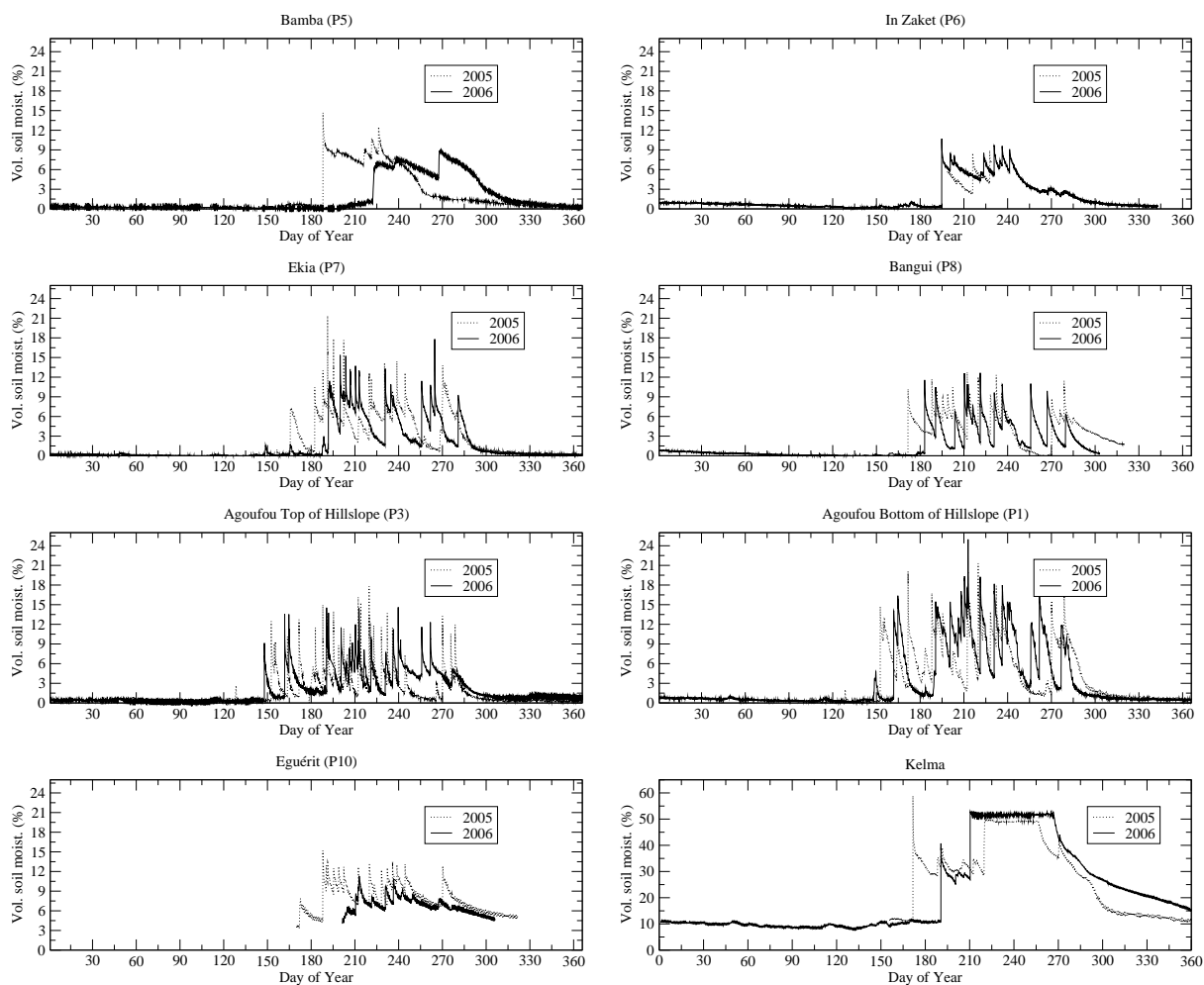


Fig. 2. Volumetric surface (5cm) soil moisture (in %), evolution for 2005 and 2006 for eight different sites located along the North-South gradient of the Gourma region of Mali.

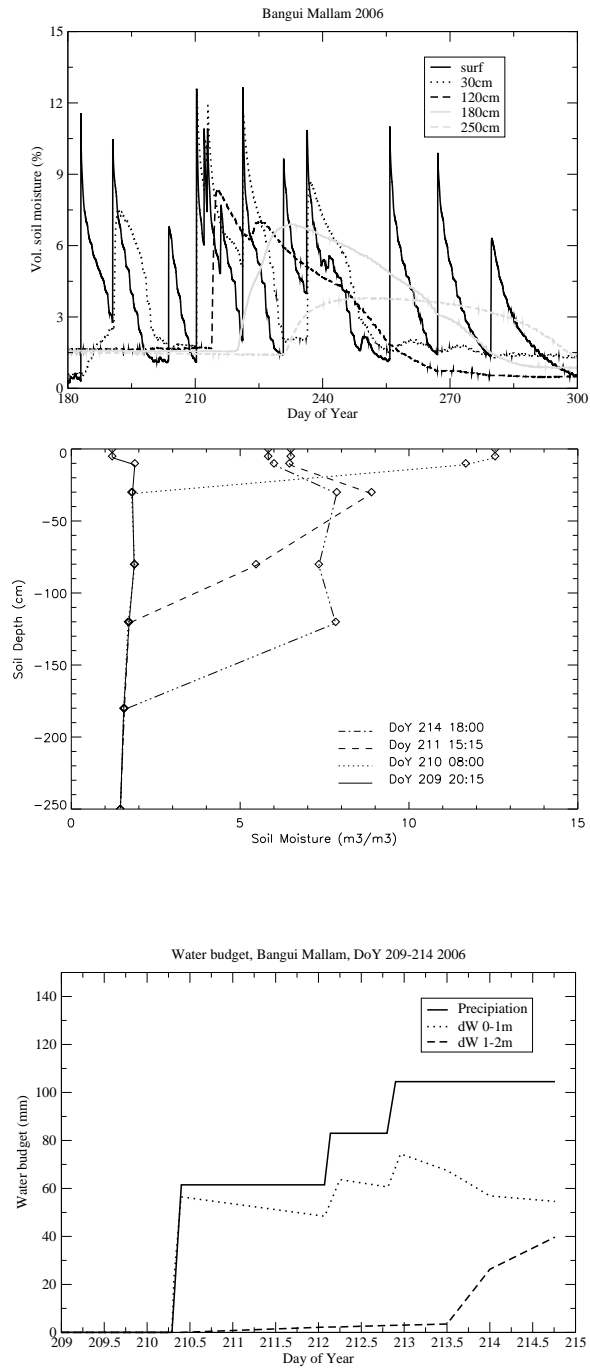


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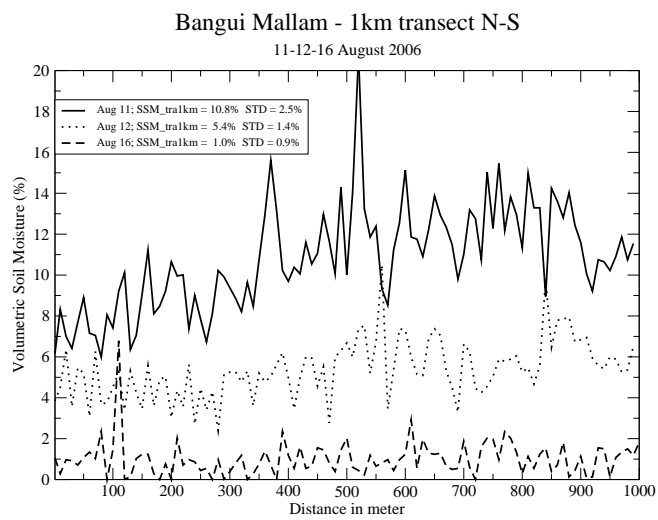


Fig. 4. Transect measurements of surface soil moisture at three different dates in August 2006. For each date, the mean value of surface soil moisture (SM) and its standard deviation (STD) are indicated.

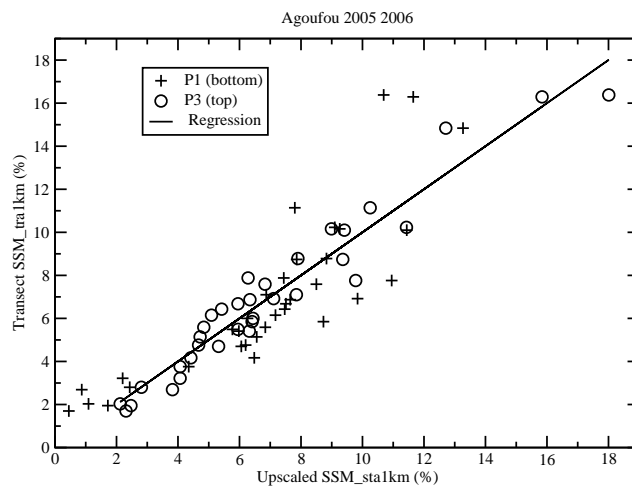


Fig. 5. Surface soil moisture estimated at the 1km scale from transect measurements (vertical axis) and from the local Agoufou top of hillslope station measurements to which was applied the equation 2 up-scaling relation (horizontal axis).

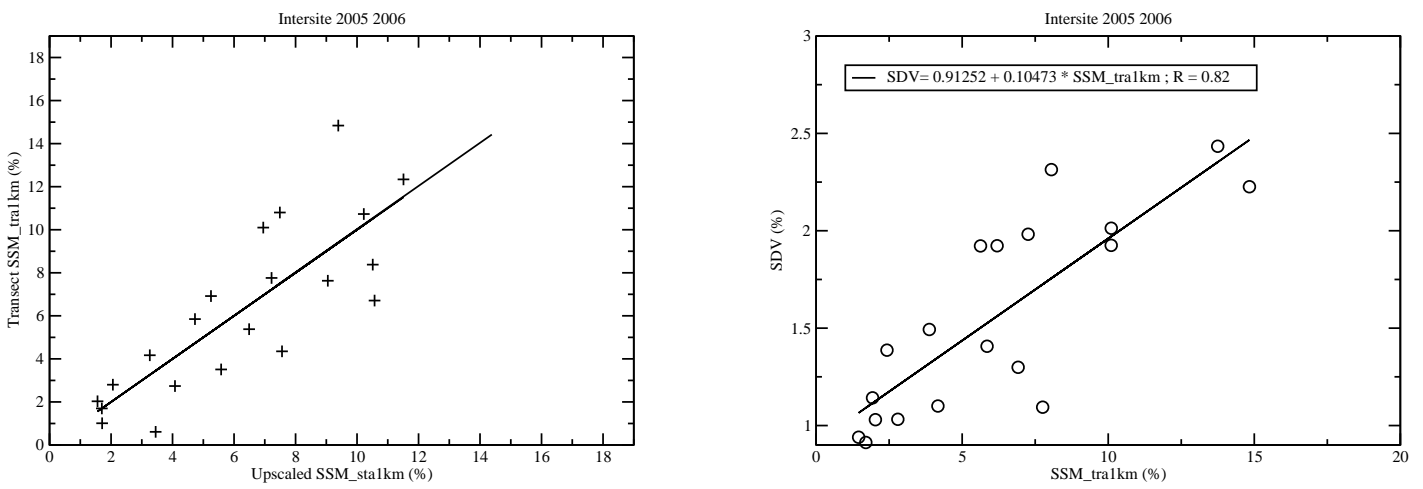


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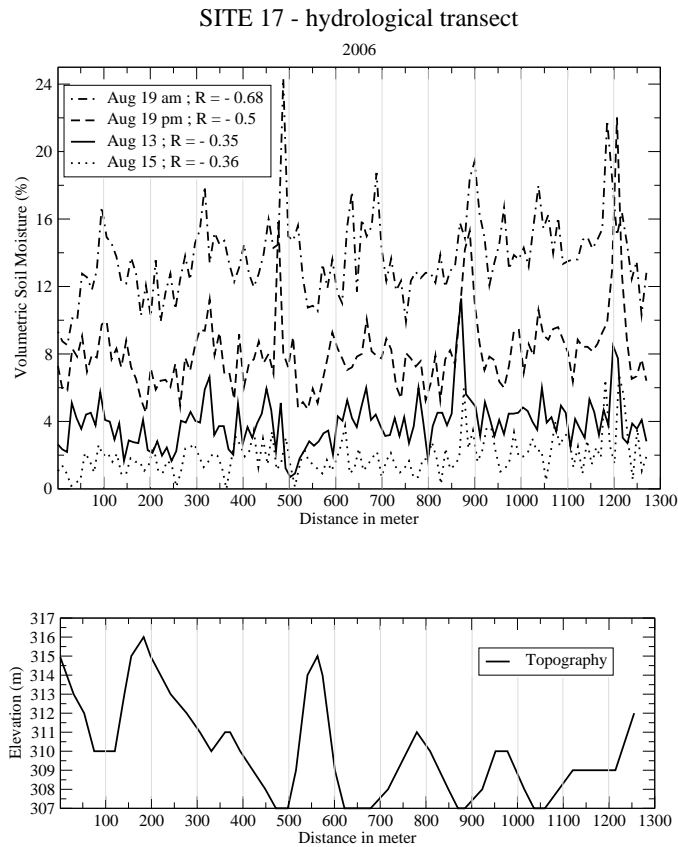


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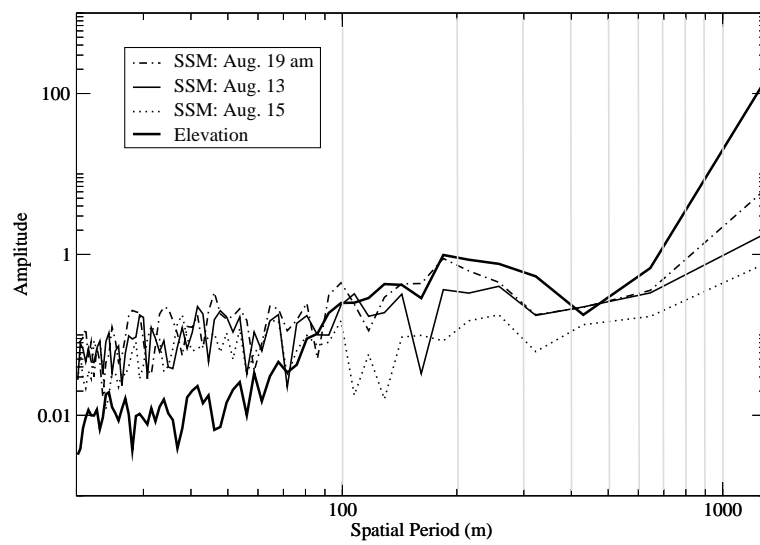


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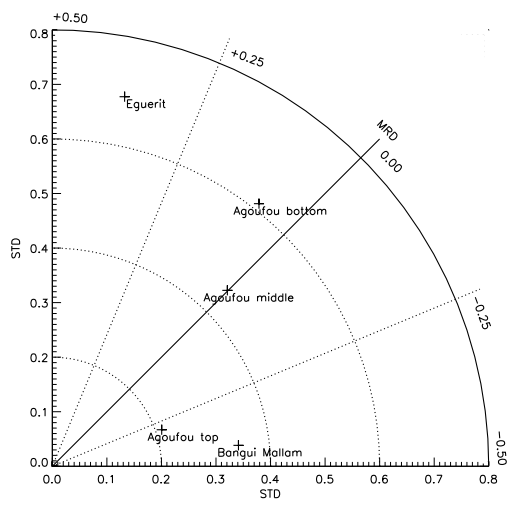


Fig. 9. Mean Relative Difference (MRD) and its time Standard Deviation (STD) (see text, section 5) for the volumetric surface soil moisture of each of the five stations considered at the Agoufou super site scale compared to the site average.



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868		corresponding to different sites and different years. The	
869		number of observations is indicated by $N$ in the last column.	49

Number	Site		Location		Sensors types and depth (cm)		date
	Name	Soil Text.	Lat.	Lon.	Soil Moisture	Temperature	
17 - P1	Agoufou bottom	Sandy-Loam	15.341°N	1.479°W	7CS616	4 PT108	04-2005
					5, 30, 60, 120, 150, 250, 400	5, 30, 60, 120	
17 - P2	middle	Coarse	15.345°N	1.479°W	6 CS616	2 PT108	04-2006
					5, 30, 60, 120, 180, 250	5, 30	
17 - P3	top	Sand	15.345°N	1.479°W	5 CS616	2 PT108	04-2004
					5, 10, 40, 120, 220	5, 40	
BB - P5	Bamba	Coarse	17.099°N	1.402°W	6 CS616	5 PT108	04-2004
					5, 40, 80, 120, 180, 250	5, 10, 40, 80, 120	
4 - P6	In Zaket	Coarse	16.572°N	1.789°W	7 CS616	4 PT108	07-2005
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	
12 - P7	Ekia	Coarse	15.965°N	1.253°W	7 CS616	4 PT108	06-2005
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	
EM - P8	Bangui Mallam	Coarse	15.398°N	1.345°W	7 CS616	4 PT108	04-2005
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	
20 - P9	Kelma	Fine	15.218°N	1.566°W	4 Theta-probes	4 PT108	06-2005
					5, 20, 80, 100	5, 20, 80, 100	
40 - P10	Eguérit	Rock	15.503°N	1.392°W	2CS616	4 PT108	04-2005
					10, 50	10, 50	
25 - P11	Kinia	Coarse	15.051°N	1.546°W	7CS616	4 PT108	03-2007
					5, 10, 30, 80, 120, 180, 250	5, 10, 30, 80	

Table 1

Soil Moisture stations installed at the Gourma meso-scale site. Name and location of each stations are indicated, as well as the depth of measurements and date of installation. Qualitative indication of surface soil texture is indicated for each station, except for Eguérit which has rocky soil. US Department of Agriculture (USDA) soil texture is given for Agoufou top and bottom of hillslope, where texture measurements were performed (Table 2).

Bottom of hillslope					
Depth (cm)	Clay	Fine Silt	Coarse Silt	Fine Sand	Coarse Sand
5	96	89	69	352	394
10	53	31	28	338	550
20	68	31	18	348	535
30	78	32	15	355	520
40	87	31	19	392	471
50	82	27	15	377	499
60	90	26	26	438	420
70	86	26	11	445	432
80	90	22	12	505	371
90	86	18	15	524	357
100	78	13	19	544	346

Top of Hillslope					
Depth (cm)	Clay	Fine Silt	Coarse Silt	Fine Sand	Coarse Sand
5	34	11	13	385	557
10	34	14	13	421	518
20	37	18	6	418	521
30	44	11	4	431	510
40	47	8	1	507	437
50	42	9	3	469	477
60	40	6	8	448	498
70	42	2	5	462	489
80	36	4	4	465	491
90	33	3	2	453	509
100	29	11	8	533	419

Table 2

Vertical profile of soil texture on the Agoufou local site. Fractions are indicated in per thousand. Particle sizes are defined according to the USDA classification scheme, with clay (<0.002mm), fine silt (0.002-0.02mm), coarse silt (0.02-0.05mm), fine sand (0.05-0.2mm), coarse sand (0.2-2mm) (Gee and Bauder 1986).

Site	2005	2006	Direction
Agoufou	25	9	West
Bangui Mallam	1	7	South
Bamba	1	0	North
Ekia	1	2	South
Agoufou-hydro	0	10	Topographical
Total	28	28	

Table 3

Number of transect measurements performed in 2005 and 2006 on Agoufou and some of the others coarse textured sites.

Site	Year	$RMSE(\%)$	$R$	EFF	BIAS	$N$
Bangui Mallam	2006	1.6	0.89	0.8	$10^{-4}$	7
Agoufou	2005-2006					
Top (P3)		0.9	0.97	0.94	$10^{-4}$	34
Bottom (P1)		1.9	0.86	0.73	$10^{-4}$	34
Agoufou	2006					
Top (P3)		0.97	0.97	0.94	$10^{-4}$	9
Bottom (P1)		1.7	0.91	0.83	$10^{-5}$	9
Middle (P2)		1.4	0.94	0.88	$10^{-4}$	9
Multi-site	2005-2006	2.2	0.82	0.66	$10^{-4}$	21

Table 4

Statistical results of the comparison between the kilometer scale surface soil moisture obtained by up-scaling of local station measurements,  $SSM_{sta1km}$ , and transect measurements,  $SSM_{tra1km}$  (see text). For each row a data set is selected corresponding to different sites and different years. The number of observations is indicated by  $N$  in the last column.