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5 **Title: AMMA-CATCH, a critical zone observatory in West Africa,**
 6 **monitoring a region in transition**

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47

48 **Core ideas:**

- 49 • AMMA-CATCH is a long-term critical zone observatory in West Africa
50 • Four sites sample the sharp eco-climatic gradient characteristic of this region
51 • Combined measurements of meteorology, water and vegetation dynamics began in
52 1990
53 • Intensification of rainfall and hydrological cycles is observed
54 • The strong overall re-greening may hide contrasted changes
55

56 **Keywords (5):** hydrology, meteorology, ecology, long-term monitoring, tropical climate

57

58

59 Abstract:

60 West Africa is a region in fast transition from climate, demography and land use
61 perspectives. In this context, the AMMA-CATCH long-term regional observatory was
62 developed to monitor the impacts of global change on the critical zone of West Africa, and
63 to better understand its current and future dynamics. The observatory is organized into three
64 thematic axes which drive the observation and instrumentation strategy: (1) analyze the
65 long-term evolution of eco-hydro-systems from a regional perspective; (2) better understand
66 critical zone processes and their variability; and (3) meet socio-economic and development
67 needs. To achieve these goals, the observatory has gathered data since 1990 from four
68 densely instrumented mesoscale sites ($\sim 10^4$ km² each), located at different latitudes (Benin,
69 Niger, Mali and Senegal) so as to sample the sharp eco-climatic gradient that is
70 characteristic of the region.

71 Simultaneous monitoring of the vegetation cover and of various components of the water
72 balance at these four sites has provided new insights into the seemingly paradoxical eco-
73 hydrological changes observed in the Sahel over the last decades: groundwater recharge
74 and/or runoff intensification despite rainfall deficit; subsequent re-greening with still
75 increasing runoff. Hydrological processes and the role of certain key landscape features are
76 highlighted, as well as the importance of an appropriate description of soil and sub-soil
77 characteristics. Applications of these scientific results for sustainable development issues
78 are proposed. Finally, detecting and attributing eco-hydrological changes and identifying
79 possible regime shifts in the hydrologic cycle are the next challenges that need to be faced.

80

81 **Abbreviations list**

- 82 ALMIP: AMMA Land surface Model Intercomparison Project
- 83 AMMA: African Monsoon Multisciplinary Analysis
- 84 AMMA-CATCH: AMMA-Couplage de l'Atmosphère Tropicale et du Cycle eco-
85 Hydrologique (Coupling the Tropical Atmosphere and the eco-Hydrological Cycle)
- 86 Cal/Val: Calibration/Validation
- 87 ERT: Electrical Resistivity Tomography
- 88 HAPEX-Sahel: Hydrologic Atmospheric Pilot EXperiment in the Sahel
- 89 IDF: Intensity Duration Frequency
- 90 IPCC: Intergovernmental Panel on Climate Change
- 91 ISMN: International Soil Moisture Network
- 92 MRS: Magnetic Resonance Sounding
- 93 OZCAR: Observatoires de la Zone Critique Application et Recherche (Critical Zone
94 Observatories Application and Research)
- 95 PI: Principal Investigator
- 96 SMOS: Soil Moisture and Ocean Salinity

97 **1. Introduction**

98 West Africa is a hot spot of global change in all its components, with drastic consequences
99 for the equilibrium of the critical zone. The critical zone extends between the rocks and the
100 lower atmosphere, it is “critical” for life that develops there. On the one hand, regional
101 warming has reached 1.5 °C (IPCC, 2014), almost the double of the global average. On the
102 other hand, West Africa is home to five percent of the world’s population, reaching 372
103 million inhabitants in 2017 (United Nations, 2017). Its five-fold increase since 1950, when
104 73 million people lived in the region, makes the West African population the fastest
105 growing worldwide. As a direct consequence, the increase rate of cultivated areas is also the
106 highest for the whole of Africa, from a 22% coverage of the landscape in 1975 to 42% in
107 2000 (Eva et al., 2006), with considerable associated deforestation and land degradation.
108 Prospect for the decades to come is a continuation – if not a reinforcement – of this sharp
109 transitional phase, with a population that may double by 2050 (United Nations, 2017) and a
110 further temperature increase of 1.5°C to 2°C, both figures corresponding to median
111 scenarios. This would mean a total increase of roughly 3°C and a 10-fold multiplication of
112 the population over the period 1950-2050. In such a context, the critical zone is more at
113 threat than anywhere else on the planet.

114 However there is considerable uncertainty regarding the exact trajectory of this transition,
115 since both climatic (e.g. Bony et al., 2013) and demographic (e.g. (Bello-Schünemann,
116 2017) scenarios may deviate from a linear extrapolation of current tendencies in presence of
117 tipping elements. In their seminal paper, Lenton et al. (2008) identified West Africa as a
118 region where ongoing perturbations could qualitatively alter the future fate of the system,
119 especially since the land-atmosphere coupling is extremely strong (Koster et al., 2004;
120 Wolters et al., 2010; Taylor et al., 2011; Maurer et al., 2015; Mande et al., 2015): land

121 degradation, as it affects soil moisture and vegetation, may feedback on rainfall occurrence
122 and intensity generating further land changes. Furthermore, the atmospheric circulation of
123 the inter-tropical band is at the heart of the redistribution of energy and atmospheric water at
124 the global scale; a change in its functioning will probably have an impact on the circulation
125 and climate of the extra-tropical zones (Hu and Fu, 2007; Seidel et al., 2008; Bony et al.,
126 2013; Voigt and Shaw, 2015).

127 The water cycle plays a major role in this coupling, and the Hapex-Sahel experiment
128 (Goutorbe et al., 1997) was conceived at the end of the 1980's precisely in order to provide
129 data for a better understanding of the mechanisms at work. The AMMA-CATCH observing
130 system (Lebel et al., 2009) was then set-up after the HAPEX-Sahel experiment, in order to
131 provide the long term observations needed to document rainfall pattern changes,
132 hydrological regime modifications and land use/land cover changes. This unique set of
133 observations has allowed to unravel some major characteristics of the transformations
134 accompanying the ongoing transition, such as rainfall intensification (Panthou et al., 2018),
135 the aquifer rising in a context of rainfall deficit (the so-called Sahelian paradox, Leduc et al.,
136 2001) or the modification of the partitioning between sensible heat fluxes and latent heat
137 fluxes (Guichard et al., 2009), not to mention many other results presented below in section
138 7 of this paper.

139 Over the years, AMMA-CATCH has grown from a rainfall observatory to a holistic
140 observing system, documenting most of the continental water cycle at high frequency,
141 thanks to the momentum gained from the setup of the AMMA program in 2002
142 (Redelsperger et al., 2006; Lebel et al., 2011). This paper starts by summarizing the
143 motivations for maintaining such a complex observing system (section 2) and by describing
144 the main eco-climatic characteristics of the sites instrumented in AMMA-CATCH (section

145 3). Sections 4, 5 and 6 detail the long term observation strategy, some specific campaigns
146 embedded in the AMMA-CATCH framework, and data management. Some new findings
147 obtained from the Observatory are presented in section 7 and the perspectives for the future
148 conclude this paper (section 8).

149

150 **2. Motivation and Science questions**

151 Despite the knowledge gained during the first phase of AMMA-CATCH and the growing
152 awareness of the fragility of the West African societies in the context of global change (see
153 the recent World Bank report on climate migrations, Rigaud et al., 2018), West Africa is
154 still badly lacking adequate *in situ* measurements at the appropriate scales to document the
155 ongoing environmental changes and to grasp possible indications of tipping trajectories. The
156 challenge is all the more difficult as the actual trajectories will depend not only on natural
157 factors but also on future policy choices, most notably those chosen for agricultural
158 intensification (Lambin et al., 2014; Rockström et al., 2017). Moreover, considerable
159 uncertainties in future simulations by climate models remain, particularly concerning the
160 water cycle and precipitation. These uncertainties are higher in the inter-tropical zone,
161 considered as one of the hotspots of climate research (Toreti et al., 2013; IPCC, 2014).
162 Maintaining good quality observations over this region is thus a responsibility that falls on
163 the shoulders of the research community, and this is the central motivation for the continued
164 commitment of AMMA-CATCH in providing good quality data to the academic world and
165 to the socio-economic actors' altogether.

166 AMMA-CATCH has three main goals: (i) provide appropriate data for studying the impacts
167 of global change on the West African critical zone; (ii) federate a large community of

168 researchers from different countries and disciplinary backgrounds to analyze these data with
169 the aim of better understanding the dynamics of the system over a range of scales and to
170 detect significant changes in its key components; (iii) disseminate data and associated
171 results outside of the academic community. The observatory is consequently organized into
172 three thematic axes which drive the observation and instrumentation strategy, namely: (1)
173 analyze the long-term evolution of the eco-hydro-systems within a regional framework; (2)
174 better understand the critical zone processes and their variability; (3) link with decision
175 makers and end-users, so that the knowledge gained from the AMMA-CATCH data can be
176 used to meet the socio-economic and development needs based on proper mastering of
177 environmental conditions.

178 This involves a systemic approach that AMMA-CATCH is sharing with the Critical Zone
179 community, and it is thus part of the French network of Critical Zone Observatories
180 (OZCAR¹) (Gaillardet et al., this issue) and of the international network "Critical Zone
181 Exploration Network" (CZEN), (Brantley et al., 2017).

182

183 **3. Sites characteristics**

184 West Africa is characterized by a latitudinal climatic gradient that induces a staging of
185 vegetation. In the southern part, the coast of the well-watered Gulf of Guinea is covered
186 with dense vegetation; rainfall gradually decreases from south to north, until the limit of the
187 Sahara, which is arid and covered by scattered vegetation. The AMMA-CATCH

¹ OZCAR: Observatoires de la Zone Critique Application et Recherche – Critical Zone Observatories Application and Research

188 observatory gathers data from four densely instrumented mesoscale sites (with surface areas
189 ranging between 14,000 and 30,000 km²) located at different latitudes to sample the regional
190 eco-climatic gradient. Hereinafter, the term “mesosite” will be used to refer to these
191 mesoscale sites. From south to north we find (i) the Sudanian site (Benin) where rainfall is
192 ~1200 mm per year, (ii) the cultivated Sahelian site (Niger) with ~500 mm of annual
193 rainfall, and (iii) the pastoral Sahel site distributed in two locations (Mali and Senegal) with
194 an average annual rainfall of ~300-400 mm. Thus annual rainfall is roughly divided by a
195 factor of two when shifting from one site to the next along a South to North axis.

196

197 *3.1. The Sudanian site (Benin)*

198 The southernmost site of the observatory lies in the center of Benin (1.5 – 2.5°E, 9 – 10°N,
199 Figure 1) and coincides with the upper watershed of the Oueme river (14,000 km²) which
200 flows southwards to the Atlantic Ocean. It is located in the Sudanian climate regime, with
201 an average rainfall of about 1200 mm yr⁻¹ falling in a single rainy season extending from
202 April to October and with a mean annual temperature of ~25°C. Mean potential
203 evapotranspiration is ~1,500 mm yr⁻¹.

204 The geology of the area is made of metamorphic and crystalline rocks of various types, with
205 predominant schist and gneiss in the western and central part of the site and granitic rocks in
206 the east (Office Béninois des Mines, 1984). The weathered hard rock substratum constitutes
207 a heterogeneous groundwater reservoir, conceptually described as a two-layer system, in
208 which the unconsolidated, 15-20 m thick, saprolite top layer overlies the fissured, bottom
209 layer, with a smooth transition between the two (Vouillamoz et al., 2015). The tropical,

210 ferruginous soils are mainly classified as ferric Acrisols with frequent hard-pan outcropping
211 (Faure and Volkoff, 1998).

212 The topography of the area is gently undulating with elevations ranging from 630 m to 225
213 m asl, and a general slope to the South-East. The landscape is a mixture of forest clumps,
214 woodlands (as described by White, 1983) and rainfed crops including maize, sorghum, yam
215 and cassava. Except for the town of Djougou (NW of the basin, 268,000 inhab. in 2013), the
216 socio-economic activity is primarily rural, based on rainfed crops and herding. Population
217 density is 48 inhab. km⁻² (RGPH-4, 2013).

218 River flow starts one to two months after the first rain events, near the end of June and stops
219 between October and January depending on the watershed area. During the flowing period,
220 river discharge is made of a slow component (base flow) and of rapid components following
221 rainfall events. Contrarily to the two other sites, surface runoff is rarely observed, and river
222 base flow mainly originates from the discharge of seasonal, perched, shallow water tables.
223 The permanent water-table, lying 5-15 m below the ground surface in the saprolite, exhibits
224 an annual recharge-discharge cycle. It is recharged by infiltration during the rainy season,
225 and transpiration by deep rooted trees is currently considered the main driver of
226 groundwater discharge (Séguis et al., 2011; Richard et al., 2013; Getirana et al., 2017). In
227 the absence of large scale irrigation, water extraction for human domestic needs is
228 negligible in groundwater dynamics (Vouillamoz et al., 2015).

229 The observational set-up was built in 1996 on an existing network of 6 stream gauges,
230 managed by the national water authority, and surveying the Upper Oueme river since 1952
231 (Le Barbé et al., 1993). The long-term observation network has now been reinforced and
232 completed for a comprehensive water cycle documentation (see section 4). Since 2015, most
233 of the stream gauge stations are equipped with teletransmission, in order to contribute to the

234 early flood warning system. Teletransmission has been extended to soil moisture and
235 meteorological data for real-time monitoring and optimization of operation costs.

236

237 *3.2. The Sahelian site (Niger)*

238 The ~20,000-km² Central Sahelian mesosite (roughly 1.6-3°E, 13-14°N) is located in the
239 South-West of the Republic of Niger. It includes the capital city of Niamey (~1.3 M. inhab.,
240 2017), close to the Niger River (Figure 1). The area has a typical semiarid tropical climate,
241 with a long dry season (October to May) and a single wet season, from June to September
242 and peaking in August. The mean annual temperature over 1950-2010 at Niamey Airport is
243 29.2°C, with an increase of approximately 1°C over the six-decade period (Leauthaud et al.,
244 2017). Daily maximum temperatures are between 40 to 45°C from mid-March to mid-June.
245 Mean potential evapotranspiration is ~2,500 mm yr⁻¹. The mean post-drought annual
246 rainfall (1990–2007) is 520 mm in Niamey, still below the long-term (1905–2003) average
247 of 560 mm yr⁻¹. Annual rainfall is typically produced by fifteen to twenty “squall lines”
248 (Mathon et al., 2002), and many smaller mesoscale convective systems, with very large
249 space-time event variability.

250 The landscape consists of scattered, flat lateritic plateaus separated by large sandy valleys,
251 with a relief of less than one hundred meters (elevations in the range of 177 to 274 m asl)
252 and gentle slopes of a few percent at most. The largest fraction of the mesosite, to the north
253 and east of the Niger River, belongs to the large Iullemeden sedimentary basin. It is
254 characterized by endorheic hydrology, with small catchments feeding depressions or ponds
255 scattered along ancient river beds. The top sedimentary layer is the Continental Terminal
256 aquifer, partly covered with aeolian deposits in the northern part of the area in particular.

257 The water table depth varies spatially from >70 m below the plateaus to <5 m very locally,
258 with increasing outcropping in some valleys, resulting in localized soil salinization
259 processes. In contrast, the right bank of the Niger River at the south-west of the mesosite
260 belongs to the plutonic Liptako Gourma massif and is exorheic, draining to the Niger River.

261 Soils are essentially sandy and weakly structured, ferruginous and poor in organic matter
262 (0.5–3%) with little fertility. They are highly prone to rain-induced surface crusting and to
263 water and wind erosion. The woody savannah landscape of the mid-20th century has now
264 turned into a patchwork of rainfed millet and fallow fields of shrubby savannah, alternating
265 in an agropastoral rotation system. More or less degraded tiger bush, a banded contracted
266 vegetation, typical of the arid zones (Valentin and d'Herbès, 1999; Galle et al., 2001),
267 subsists on plateau areas. Population density, which reached ~30 inhab. km⁻² at the turn of
268 the century, is increasing at rates close to 3% yr⁻¹.

269 The first field observations at the Niger site date back to 1988, with the SEBEX (Sahelian
270 Energy Balance Experiment) and EPSAT (Estimation of Precipitation by SATellite)
271 experiments. The landmark HAPEX-Sahel experiment was conducted at this site in 1992
272 (Goutorbe et al., 1997), and basic long-term agro-ecological and hydrological observations
273 were subsequently made perennial. Intensive instrumentation of small pilot catchments was
274 deployed as of 2004, during the AMMA international program (Lebel et al., 2011). The
275 observing system deployed at different nested scales over the Niger site is presented in
276 section 4, and is further detailed, together with the site characteristics, in Cappelaere et al.
277 (2009).

278

279 3.3. *The Pastoral Sahelian sites (Mali and Senegal)*

280 3.3.1. The Mali site

281 The northernmost AMMA-CATCH site is located in North-East Mali, in the Gourma
282 pastoral region, which stretches from the loop of the Niger River southward down to the
283 border region with Burkina-Faso (30,000 km², Figure 1). It is a scarcely populated area,
284 with a population density of less than 7 inhab. km⁻² (RGPH, 2009).

285 The climate is warm tropical semi-arid, with a unimodal precipitation regime. The rainy
286 season extends from mid-June to mid-September, and is followed by a long dry season. The
287 long-term annual rainfall mean is 370 mm at Hombori and the mean annual temperature is
288 30.2°C. The main vegetation types are tree savannah on deep sandy soils, open forest on
289 clayed soils in depressions and scattered trees on erosion surfaces, covering respectively
290 56%, 12% and 30% of the area. Crops, mainly millet, installed on sandy soils, only
291 represents 2.4% of the Gourma supersite (Nguyen, 2015).

292 The landscape consists of an alternation of fixed sand dunes (endorheic system) and shallow
293 soils (erosion surfaces) associated to rock and iron pan outcrops, and low land fine-textured
294 soils. On the sandy soils, the endorheic system operates at short distances (some tens of
295 meters), with limited sheet runoff from dune slopes to inter-dune depressions. On the
296 shallow soils associated to rock and iron pan outcrops, and on low-land fine-textured soils,
297 the endorheic system operates over much larger distances (some kilometers) with
298 concentrated runoff feeding a structured web of rills ending in one or several interconnected
299 ponds (Gardelle et al., 2010; Gal et al., 2016).

300 Prior to the AMMA-CATCH monitoring, 37 vegetation sites were studied over ten years
301 between 1984 and 1993 by the International Livestock Centre for Africa, ILCA, and the

302 Institut d'Economie Rurale, IER. Since 2000 onwards, the monitoring was progressively
303 intensified under the AMMA project (Hiernaux et al., 2009b; Mougin et al., 2009). During
304 the AMMA experiment (2005-2010), the Gourma site extended also in the Haoussa region,
305 to the north of the Niger River (Mougin et al., 2009).

306 Since 2011, due to persistent security problems, the monitored sites have been restricted
307 within the 50 km x 50 km AMMA-CATCH supersite at the vicinity of the Hombori town
308 (15.3°N, 1.5°W). Besides, some equipment has been re-installed in Senegal, a pastoral area
309 with similar eco-climatic conditions.

310

311 3.3.2. The Senegal site

312 The Ferlo region in Senegal is extending to the North up to the Senegal River. The climate
313 is typical of the Sahelian area with a mean temperature at the Dahra site of 29°C, peaking in
314 May, and a mean annual precipitation of ~420 mm. The rainy season is mainly concentrated
315 within three months (July to September), during which herbaceous vegetation growth
316 occurs. Vegetation, like in the Gourma region, is dominated by annual grasses with a tree
317 cover of about 3%. Most water bodies in the Ferlo are temporary, except for a few
318 permanent ponds (Soti et al., 2010; Guilloteau et al., 2014).

319 Soil moisture, precipitation and dry herbaceous mass are monitored at two sites in the Ferlo
320 region (Kergoat et al., 2015) and extends the instrumentation set up since 2002 by the
321 University of Copenhagen, the Karlsruhe Technical Institute and the Lund University, in
322 collaboration with the University Cheikh Anta Diop and the Institut Sénégalais de
323 Recherche Agronomique (Dakar) at the Dahra local site (Fensholt et al., 2004; Tagesson et
324 al., 2016a).

325

326 **4. Long-term observations and observation strategy**

327 Long-term measurements began in 1990 with a different history for the three sites. In 2004,
328 during the AMMA international experiment (Redelsperger et al., 2006), the long-term
329 network was homogenized on three sites (Mali, Niger, Benin) and reinforced (Lebel et al.,
330 2011). It served as the ground component of the AMMA international experiment.

331 On all the four sites, the observation strategy is based on a multi-scale approach, associating
332 (i) a mesoscale site (typically 10^4 km²) to document the long-term water and energy cycles
333 (Figure 1, red outline); (ii) a so-called “super-site” (typically 10-100 km²) dedicated to
334 process studies at intra-seasonal to inter-annual time-scales on an integrating hydrological
335 domain (Figure 1, blue outline); and (iii) local sites (typically 1 km²) dedicated to the fine
336 documentation of the components of the water and energy cycles and the vegetation
337 dynamics. The mesoscale sites make the link with the regional scale. Nested sensor
338 networks, with decreasing resolution with domain size, allow linking processes across
339 scales.

340 This nested approach is illustrated for the Benin Sudanian site (Figure 2). The mesoscale
341 Benin site (Figure 2-a) gathers 16 stream gauge stations, 35 rain gauges and 12
342 wells/boreholes monitoring the dynamics of the water table. The Donga super-site, a ~600
343 km² sub-basin of the upper Oueme (Figure 2-b), includes denser rain gauges, piezometers
344 and stream gauges sub-networks. Within the Donga basin, three local sites were
345 instrumented. They are representative of the three main land use and land cover types
346 encountered in the area, which are marked by an increasing part of the woody layer: (i)
347 cultivated areas which include fallow and crops with isolated trees (Figure 2-c), (ii) wooded

348 savannah, and (iii) woodland. Each of these three local sites includes the monitoring of:
349 meteorological variables with a radiative budget; turbulent fluxes at eddy covariance flux
350 towers; vegetation dynamics (leaf area index, height); 0-1 m soil moisture, temperature and
351 suction profiles, located at the top, middle and bottom of a hillslope transect (700-1,000 m
352 long); permanent and perched water tables depths along the hillslope, using piezometers at
353 different depths. Similar nested approach is being deployed at the Niger and Mali sites
354 (Cappelaere et al. (2009); Mougin et al. (2009), respectively).

355 Besides the common setup illustrated above, supplemental instruments or networks have
356 been installed at each mesosite depending on its eco-hydrological context. In Benin, an
357 elementary watershed (0.15 km²) has been monitored to understand the origin of river flow
358 (Figure 2-c). A supra-conducting gravimeter monitors the local variations in total water
359 column and makes the link with the larger scales (Hinderer et al., 2012). In Niger, the ~2-
360 km² Wankama endorheic catchment gathers surface flux stations, soil moisture profiles,
361 vegetation plots, stream gauges, pond limnometry and an associated piezometry transect to
362 capture the water cycle from point to catchment scales. In Mali, the Agoufou pond (250 km²
363 watershed) water level, turbidity and suspended sediments are monitored to study the
364 dynamics of surface water.

365 Seven categories of variables are monitored with harmonized protocols and identical sensors
366 on the four sites: meteorology, surface water, groundwater, soil, surface-atmosphere fluxes,
367 vegetation and water quality. The measured variables in each of the seven categories as well
368 as the measurement periods are shown in Table 1. In 2018, a total of 290 stations (including
369 850 sensors) are in operation in the four countries (Table 1). The stations are grouped into
370 42 "instruments". An instrument aims to answer a scientific question and focuses on a
371 specific spatial and temporal scale. It may be either a group of identical sensors organized in

372 a network (e.g. a rain gauge/stream gauge networks), or a set of complementary sensors
373 located in the same place (e.g. a surface flux station composed of a flux tower with radiative
374 budget and soil heat flux). Each instrument is under the scientific responsibility of one or
375 two Principal Investigator(s) (PI). An instrument corresponds to a dataset of the observatory
376 database and is identified by a DOI. Currently 26 instruments are in operation, 12 are
377 stopped because they correspond to objectives that have been achieved (characterization,
378 process studies) and 4 are suspended for security reasons in Mali. At least one instrument in
379 each category of measurement is present in each ecoclimatic subregion (Table 1). This
380 observation system has continuously generated a coherent dataset over the last twenty five
381 years.

382

383 **5. Dedicated campaigns and experiments**

384 Besides the long-term observation system, specific field campaigns are organized to (i)
385 document the critical zone architecture, such as the geometry but also the hydrodynamic
386 properties of the groundwater reservoirs and soil layers, (ii) study fine processes, such as the
387 paths of water transfers between surface and ground water, and (iii) Calibration/Validation
388 (Cal/Val) of satellite missions, remote sensing being a key additional data source for our
389 large mesosites and for upscaling to the data-poor region. These campaigns allow in
390 particular to better characterize processes and to feed modeling approaches over the
391 AMMA-CATCH sites.

392

393 *5.1. Documenting the critical zone architecture*

394 Superficial soil properties have been characterized using tension-infiltrimeters at the Niger
395 and Benin sites (Vandervaere et al., 1997; Richard et al., 2013; Malam Abdou et al., 2015).
396 Particularly, the time evolution of surface conductivity in cultivated or fallow areas has been
397 shown to play a key role in Sahelian runoff generation processes (Malam Abdou et al.,
398 2015, see section 7.3.3).

399 Aquifer geometries, specific yield and permeabilities are not readily known in sedimentary
400 and hard-rock regions of West-Africa, but are nevertheless key parameters for the modeling
401 and use of groundwater resources (Vouillamoz et al., 2015). Geophysical techniques
402 provide useful tools to spatialize geophysical parameters linked with aquifer properties.
403 Electrical Resistivity Tomography (ERT), Magnetic Resonance Sounding (MRS), and time-
404 lapse gravity monitoring were implemented in Niger and Benin sites of AMMA-CATCH in
405 order to test their efficiency, and characterize aquifer parameters.

406 The ERT technique provides two dimensional electrical resistivity cross-sections. This is
407 suitable to characterize the aquifer and unsaturated zone 2D geometry, especially in the case
408 of highly heterogeneous sedimentary layers (Massuel et al., 2006) or hard rock areas (Alle
409 et al., 2018). In hard rock, from place to place, the aquifer system can deepen within
410 preexisting discontinuities as geological fault or tectonic fracture called “subvertical
411 fractures” (Figure 3-a, after Alle et al., 2018). Landscapes showing such high spatial
412 variability of the substrate are difficult to characterize by traditional methods.

413 MRS results (i.e. the MRS water content and MRS pore-size parameters) are found to be
414 well correlated with both specific yield and permeability/transmissivity calculated from long
415 duration pumping tests (e.g. Figure 3-b; Vouillamoz et al., 2014). MRS allowed estimating

416 the specific yield and the transmissivity in hard rock aquifers in Benin (Vouillamoz et al.,
417 2014; Legchenko et al., 2016) and in the unconfined sandstone aquifers of Niger site
418 (Vouillamoz et al., 2008; Boucher et al., 2009). Specific yield (Sy) and transmissivities (T)
419 are higher in Niger (Sy: 5% – 23%; T: 2×10^{-4} – 2×10^{-2} m² s⁻¹) than in Benin (Sy: 1% – 8%;
420 T: 2×10^{-5} – 4×10^{-4} m² s⁻¹). Time-lapse gravimetry surveys were also used for evaluating
421 the specific yield (Hinderer et al., 2009; Pfeiffer et al., 2011, Hector et al. 2013, 2014). These
422 results are in accordance with MRS water content and pumping test-derived specific yield.

423

424 *5.2. Exploring critical zone processes*

425 To detect specific hydrological processes such as water transfers between surface and
426 groundwater, the origin of the river discharge, or land-atmosphere exchanges,
427 hydrogeophysical and/or geochemical campaigns have been setup on each site, addressing
428 their specific scientific questions.

429 In hard rock aquifers in Benin, the groundwater recharge has been investigated. During
430 three years, the major, as well as trace elements, and stable isotopes of water were sampled
431 in the surface and underground waters of the Donga basin (600 km²). Their analysis shows
432 that groundwater recharge occurs by direct infiltration of rainfall and accounts for 5% to
433 24% of the annual rainfall (Kamagaté et al., 2007). ERT time-lapse survey along the
434 hydrological season confirm a direct recharge process, but also a complicated behavior of
435 groundwater dilution, as well as the role of hardpans for fast infiltration (Wubda et al.,
436 2017).

437 The origin of the flows of the Donga basin (600 km², Benin) was investigated using
438 geochemical campaigns and gravimetry. Geochemical campaigns have shown that the

439 seasonal perched groundwaters are the major contributors to seasonal streamflow while the
440 permanent groundwater in the saprolite almost never drains to rivers (Séguis et al., 2011).
441 Episodic contribution of permanent water was revealed, using gravity measurements:
442 locally, deep-seated (>2m deep) clayey areas exhibit lower seasonal water storage changes
443 than elsewhere, suggesting favored lateral transfers above the clay units. This observation
444 contributed to evidence the higher contribution of such clayey areas to the total streamflow
445 (Hector et al., 2015). For the larger Ouémé basin (12,000 km²), the electrical conductivity
446 (EC) of base flow was below 70 $\mu\text{S cm}^{-1}$ until the river dried up. As this EC is far below that
447 of the permanent groundwater (from 150 to 400 $\mu\text{S cm}^{-1}$), a contribution of more
448 mineralized permanent groundwater has to be ruled out.

449 On the Sahelian sites, rainfall, surface water and groundwater isotopic sampling (¹⁸O, ²H,
450 and/or ³H, ¹⁴C, ¹³C) was performed to characterize the relationship between surface water
451 and ground water recharge on about 3,500 km² of the Niger site (Taupin et al., 2002;
452 Favreau et al., 2002), and in wells around the Mali Hombori supersite (Lambs et al., 2017).
453 On the Niger site, it has been found that land clearing increased ground water recharge by
454 about one order of magnitude (Favreau et al., 2002, 2009). Using MRS, localized recharge
455 beneath expanding valley ponds was evidenced as a key process. Through a combination of
456 vadose zone geophysical and geochemical surveys and of surface and subsurface
457 hydrological monitoring, substantial deep infiltration was also shown to occur below sandy
458 alluvial fans and channels on the hillslope, contributing to the recent groundwater recharge
459 increase (Massuel et al., 2006; Descroix et al., 2012b; Pfeffer et al., 2013).

460 In the Senegal Ferlo, soil biogeochemical analysis, and surface atmosphere exchanges of
461 nitrogen compounds campaigns showed that changes in water availability in semi-arid

462 regions have important non-linear impacts on the biogeochemical nitrogen cycle (Delon et
463 al., 2017).

464 Upscaling of turbulent fluxes from single ecosystem plots to mosaics of ecosystems at the
465 landscape scale was unraveled by complementing the permanent eddy covariance stations
466 with large-aperture scintillometry campaigns in both the Sahelian (Ezzahar et al., 2009) and
467 Sudanian (Guyot et al., 2009, 2012) settings.

468

469 *5.3. Providing in situ datasets for Calibration/Validation of satellite missions*

470 Satellite missions require *in situ* measurements to calibrate and validate their products for
471 various climates and continents. The AMMA-CATCH observatory provides a unique
472 opportunity for the so called Cal/Val activities in Sahelian and Sudanian climates. Indeed
473 the AMMA-CATCH sites are often the only Cal/Val sites in West Africa. To match the
474 requirement of Cal/Val activities, the setup of some *in situ* sensors has been specially
475 designed or reinforced (Kergoat et al., 2011).

476 Several studies have used the AMMA-CATCH rain gauge networks to evaluate satellite
477 rainfall products. The network density over these sites (especially the Niger and Benin sites
478 with about 40 gauges within a $1^{\circ} \times 1^{\circ}$ area) is unique in Africa and even in the Tropics. It
479 provides an unprecedented opportunity to analyze the ability of satellites to detect and
480 quantify rainfall within tropical convective systems. Within the Megha-Tropiques mission
481 ground validation program (Roca et al., 2015), Kirstetter et al. (2013) evaluated instant
482 rainfall retrievals based on the BRAIN algorithm (Viltard et al., 2006) evidencing the failure
483 in detecting the lightest rains. Guilloteau et al. (2016) demonstrated the ability of several
484 high resolution satellite rainfall products to reproduce the diurnal cycle of precipitation.

485 Gosset et al. (in press) confirm the good performances of the Global Precipitation
486 Measurement (GPM) era products in West Africa and the key role of the additional
487 sampling provided by the Megha-Tropiques satellite.

488 The SMOS mission (Soil Moisture and Ocean Salinity) soil moisture level 3 product
489 (SMOS-L3SM) was evaluated through comparison with ground-based soil moisture
490 measurements acquired in Mali, Niger and Benin from 2010 to 2012 (Louvet et al., 2015). It
491 was found that, over the three sites, the SMOS-L3SM product provided good coefficients of
492 correlation (from 0.70 to 0.77) with a RMSE lower than $0.033 \text{ m}^3 \text{ m}^{-3}$ in Niger and Mali.
493 However, the RMSE score in the Benin site was larger ($0.076 \text{ m}^3 \text{ m}^{-3}$), mainly due to the
494 presence of a denser vegetation cover (Louvet et al., 2015). More recent sensors such as
495 SMAP (Soil Moisture Active Passive, launched in 2015) products were controlled close to
496 their expected performance thanks to a network of 34 sites, including the AMMA-CATCH
497 sites (Colliander et al., 2017). The effort to compare SMAP soil moisture products will
498 continue beyond the intensive Cal/Val phase.

499 The AMMA-CATCH sites have also contributed to the validation of vegetation products
500 like the leaf area index (LAI) provided by the VEGETATION instrument and by the
501 moderate resolution imaging spectroradiometer (MODIS) sensor in the pastoral Sahel
502 (Morisette et al., 2006; Camacho et al., 2013; Mougouin et al., 2014), as well as MODIS gross
503 primary production (Sjöström et al., 2013).

504 In the near future, AMMA-CATCH will contribute to the Cal/Val of other missions, such as
505 the *ECOSTRESS* (ECOsysteM Spaceborne Thermal Radiometer Experiment on Space
506 Station) mission (plant response to water stress), to be launched by NASA in 2018 (Cawse-
507 Nicholson et al., 2017) and the SWOT (Surface Water Ocean Topography) mission

508 (Biancamaria et al., 2016), aiming at estimating water volumes and discharge over terrestrial
509 water bodies and rivers.

510 Beyond participation to Cal/Val phases of specific satellite missions and products, AMMA-
511 CATCH *in situ* measurements are intensively used for the development and evaluation of
512 new satellite-based methods: for the estimation of surface fluxes and evapotranspiration
513 (Ridler et al., 2012; Marshall et al., 2013; García et al., 2013; Allies et al., *subm.*), soil
514 moisture by passive and active microwave sensors or space altimeter (Pellarin et al., 2009;
515 Gruhier et al., 2010; Baup et al., 2011; Fatras et al., 2012), soil heat flux (Verhoef et al.,
516 2012; Tanguy et al., 2012), gross primary production (Sjöström et al., 2011; Tagesson et al.,
517 2017; Abdi et al., 2017), LAI and aboveground biomass (Mangiarotti et al., 2008), dry-
518 season vegetation mass (Kergoat et al., 2015), suspended sediments in ponds and lakes
519 (Robert et al., 2017) or soil moisture assimilation to improve rainfall estimates (Pellarin et
520 al., 2008, 2013; Román-Cascón et al., 2017).

521

522 **6. Data management and policy**

523 AMMA-CATCH is the result of long-term and joint work between researchers from
524 universities, research institutes and national operational networks in Benin, Niger, Mali,
525 Senegal and France. They work together to produce quality-controlled datasets. The data
526 acquisition instruments are generally isolated and need electric autonomy. They are
527 regularly collected by the technical teams and transmitted to the scientific Principal
528 Investigator (PI) of the dataset. The PIs are responsible for calibration, quality check and
529 annual transmission of the datasets to the database manager who makes them available
530 online on the web portal: <http://bd.amma-catch.org/>. This portal includes a geographical

531 interface which allows navigation across locations and datasets, and to retrieve the
532 metadata. It fosters data discovery by describing the dataset with standardized metadata
533 (ISO 19115², DataCite³), and interoperability with other information systems by
534 implementing the OGC⁴ standard exchange protocols (CSW⁵, SOS⁶). Soil moisture data are
535 also available from the International Soil Moisture Network (ISMN) portal (Dorigo et al.,
536 2011) and some of the surface fluxes data are part of the global network of
537 micrometeorological tower sites FLUXNET (Falge et al., 2016). This deliberate open, data
538 policy is a contribution to the dissemination of climatic and environmental datasets, which
539 is specially challenging in Africa (Dike et al, 2018). In 2017, 44% of the requests concerned
540 soil moisture, 24% rainfall, 9% surface fluxes and surface waters, 8% meteorology and 6%
541 other data. The users come from all continents: 7% Africa, 47% Europa (10% France), 33%
542 North America and 13% Asia.

543 All the AMMA-CATCH datasets are published under the Creative Common Attribution 4.0
544 International Licence⁷ (CC-BY 4.0). For any publication using AMMA-CATCH data,
545 depending on the contribution of the data to the scientific results obtained, data users should
546 either propose co-authorship to the dataset Principal Investigators or at least acknowledge
547 their contribution.

² ISO 19115: Geographic information – Metadata standards, <https://www.iso.org/standard/53798.html>

³ DataCite: Locate, identify, and cite research data, <https://www.datacite.org/>

⁴ OGC: Open Geospatial Consortium, <http://www.opengeospatial.org/>

⁵ CSW: Catalog Service for The Web, <http://www.opengeospatial.org/standards/cat>

⁶ SOS: Sensor Observation Service, <http://www.opengeospatial.org/standards/sos>

⁷ The following sentence should appear in the acknowledgments of the publication: "The AMMA-CATCH regional observing system (www.amma-catch.org) was set up thanks to an incentive funding of the French Ministry of Research that allowed pooling together various pre-existing small scale observing setups. The continuity and long term perennity of the measurements are made possible by an undisrupted IRD funding since 1990 and by a continuous CNRS-INSU funding since 2005".

548

549 **7. New insights and novel scientific findings**

550 A major set of scientific advances from the AMMA-CATCH observatory was presented in
551 2009, in a special issue of Journal of Hydrology (vol. 375(1-2)), see Lebel et al. (2009). This
552 section summarizes the main recent insights gained from the AMMA-CATCH observatory,
553 making a synthesis for each of the three research axes: long-term dynamics, process studies,
554 meeting the society needs.

555

556 *7.1. Regional long-term dynamics*557 7.1.1. Rainfall intensification

558 At the beginning of the 1990's, scientists mainly focused on the causes (atmospheric,
559 oceanic) and the impacts (hydrological, agricultural, food security) of the 1970's-1980's
560 drought. At that time, regional studies (Le Barbé and Lebel, 1997; Le Barbé et al., 2002)
561 showed that the Sahel region could be considered as a unique entity that records a unique
562 signature in terms of rainfall regime changes between the wet (1950-1969) and the dry
563 (1970-1990) periods (

564 Figure 4): the mean annual rainfall decreased by roughly 200 mm (corresponding to 20% to
565 50% of annual rainfall), mainly due to a decrease in the number of wet days and to a lesser
566 extent to a decrease of wet day intensity.

567 Since the beginning of the 1990's, the annual rainfall increased slowly, marking the end of
568 the Sahelian great drought. Behind this general statement, new aspects in the rainfall regime

569 are hidden. In fact, as first observed by Lebel and Ali (2009), some contrast appeared
570 between the West and the East Sahel (annual rainfall increased earlier in the East than in the
571 West). This result is confirmed by Panthou et al. (2018) who analyzed more deeply the East-
572 West contrast in terms of wet days (number and intensity), hydro-climatic intensity
573 (Trenberth, 2011; Giorgi et al., 2011) and extreme events. The main result found is that the
574 Western Sahel experiences slight increases of both number and intensity of wet days (and
575 thus annual rainfall). In contrast, the East Sahel is experiencing a slight increase in the
576 number of wet days, but a strong increase of wet days intensity, particularly the most
577 extremes. This strong intensification in the Central and East Sahel was early observed in
578 Mali by Frappart et al., (2009) and confirmed at the Sahelian scale (Panthou et al., 2014a;
579 Sanogo et al., 2015). The Standardized Precipitation Index for annual totals and annual
580 maxima follow a similar pattern since 1950 (

581 Figure 4). The main difference between both variables is that during the recent period (since
582 1990), annual maxima index has increased faster than annual totals. This is one of the
583 *manifesto* of the recent intensification of the rainfall regime recorded in the region.

584 The recent study of Taylor et al. (2017) provided some insight on the atmospheric
585 mechanisms that could explain this strong increase of extreme rainfalls. They found that the
586 frequency of rainy systems (Mesoscale Convective Systems – MCS) responsible for
587 extreme rainfalls in the Sahel has dramatically increased. Different mechanisms (such as
588 wind shear and Saharan dry air intrusion in the Sahelian mid-level atmospheric column),
589 linked to the increase of Saharan temperature and meridional temperature gradient (between
590 Guinean coast and Sahara) seem to explain the increasing frequency of extreme Mesoscale
591 Convective Systems. Since the increasing meridional temperature gradient is a robust

592 projection of Global Circulation Models, the authors argue that the ongoing intensification
593 in the Sahel is expected to pursue in the coming decades.

594 These results provide a new vision of the evolution of the rainfall regime at the regional
595 (Sahelian) scale. However, none of these studies have documented the evolution of fine-
596 scale rainfall intensities, mainly due to method and data limitations. This issue is pressing in
597 such a semi-arid context where rainfall intensities at short timescales (sub-hourly) drive
598 many surface processes (i.e. runoff, soil crusting, erosion). Very novel results come from
599 the AMMA-CATCH Niger network on that aspect. Despite its limited spatial extent and
600 monitoring period, Panthou et al. (2018) showed that this network was able to record the
601 sub-regional intensification, and found that the increase of sub-hourly intensities were
602 similar (between 2 and 4% per decade) to the increase of daily intensities. This result is
603 appreciable since detecting changes in sub-hourly intensities face methodological issues
604 (low signal-to-noise ratio), and long-term tipping bucket rain gauges data are very rare.
605 These difficulties have been tackled thanks to the presence of a long-term and dense tipping
606 bucket network, which provides quality-controlled series, in a region that records a very
607 strong signal of change. Note that such a detection of fine-scale rainfall changes is quite
608 unique in the literature.

609

610 7.1.2. Re-greening Sahel

611 The Sahelian vegetation has been shown to follow the precipitation recovery after the major
612 droughts of the 1970'-1980's. A general "re-greening" has been observed over the 1981-
613 2010 period by satellite data (Figure 5-a, from Dardel et al., 2014b). The NDVI
614 (Normalized Difference Vegetation Index) local trend is confirmed by *in situ* measurements

615 of herbaceous vegetation mass in Mali and Niger (Figure 5-b, 5c). Over the Gourma and
616 more generally over the Sahel, tree cover tends to be stable or slightly increasing over 2000-
617 2010 (Hiernaux et al., 2009a; Brandt et al., 2016a). However, the Sahelian re-greening is not
618 uniform in space: in Mali Gourma region, an increasing trend is observed (Figure 5-b) while
619 the Fakara region in the Niger mesoscale site has witnessed a decrease in vegetation
620 production (Figure 5-c). Moreover, even in some « re-greening » areas, vegetation
621 degradation can occur at a small spatial scale, which is difficult to observe using coarse
622 resolution satellite data (Dardel et al., 2014a). A detailed study carried out on the Agoufou
623 watershed in the Gourma region highlighted important changes in vegetation and soil
624 properties between 1956 and 2011 (Gal et al., 2017). The most relevant changes concerned
625 (i) the degradation of vegetation growing on shallow soils and tiger bush formations, and (ii)
626 a marked evolution of soil properties with shallow sandy sheets being eroded and giving
627 place to impervious soils. Trichon et al. (2018) highlighted the persistent decline of tiger
628 bush in the Gourma, following the major droughts of the 1970's and 1980's. These land
629 cover changes occurring at the local scale have important consequences on the hydrological
630 system operating at a larger scale and are responsible for the spectacular increase in surface
631 water and runoff in this region (see below). Regional spatial variability of Sahelian
632 ecosystem production was derived from carbon fluxes at six eddy covariance stations across
633 the Sahelian belt, including the four AMMA-CATCH stations in Niger and Mali. All sites
634 were net sinks of atmospheric CO₂ but gross primary productivity (GPP) variations strongly
635 affected the sink strength (Tagesson et al., 2016b).

636

637 7.1.3. Paradoxes and contrasts of the hydrological cycle

638 Despite the long Sahelian drought period, a general increase in surface water was observed
639 in different areas. This phenomenon is often referred to as the "Sahelian paradox". An
640 increase in the runoff coefficient on tributaries of major rivers in the Sahel has been reported
641 since 1987 and synthesized by Descroix et al. (2012a) and Mahe et al. (2013). The annual
642 runoff volume has shown a three-fold or even a four-fold increase since the 1950's (e.g.
643 Dargol river, Figure 6-b), but at the same time the flow duration has been shortened
644 (Descroix et al., 2012a).

645 A steady rise in the water table in Niger was also observed since the 1950's (Leduc et al.,
646 2001; Favreau et al., 2009; Nazoumou et al., 2016) (Figure 6-b), as a consequence of
647 increased recharge by surface waters concentrated in ponds and gullies (Massuel et al.,
648 2011). The network of gullies and ponds has considerably developed over the past decades
649 (Leblanc et al., 2008). An important increase in pond areas and surface runoff has also been
650 observed in the Gourma region in Mali (Gardelle et al., 2010; Gal et al., 2016, 2017) (Figure
651 6-a). Moreover Robert et al. (2017) have reported an increase in suspended sediments in the
652 Agoufou lake over the 2000-2016 period, which is likely linked to increased erosion within
653 the lake watershed.

654 The causes for the Sahelian paradox are still debated. For the Niger area, modifications of
655 surface characteristics (soil crusting and erosion) due to the increase in cropping activities
656 and/or land clearing and increased runoff over plateaus have been put forward as an
657 explanation (Séguis et al., 2004; Leblanc et al., 2008; Amogu et al., 2015), while in the
658 Malian pastoral site, where crops are very limited, the drought-induced vegetation
659 degradation over shallow soils plays a crucial role on surface runoff modifications (Gal et
660 al., 2017; Trichon et al., 2018). In the same time, the Sahel is experiencing an intensification

661 of extreme events, recently detected and quantified (Panthou et al., 2014a). More generally,
662 the intensification of precipitation favors groundwater replenishment in the tropics
663 (Jasechko and Taylor, 2015). Nevertheless, the processes that transmit intensive rainfall to
664 groundwater systems and enhance the resilience of tropical groundwater storage in a
665 warming world, remain unclear. Water table rise subsequent to land clearing has been
666 reported elsewhere in the world (Brown et al., 2005; Scanlon et al., 2006; Taylor et al.,
667 2013). However, a more diverse combination of processes, producing both diffuse and
668 concentrated recharge, appears to be at play in the Sahel. The attribution of the increase of
669 surface runoff and water table level to rain and / or to the modification of the land cover and
670 their relative contribution is a question under discussion (Aich et al., 2015), being a major
671 stake in order to predict the future evolutions of the eco-hydro system (Roudier et al., 2014).

672 In the Sudanian zone, the runoff more classically decreases with rainfall. However, the
673 relationship is not linear, and a 20% decrease in annual rainfall resulted in a much greater (>
674 60%) decline in flows (Le Lay et al., 2007; Descroix et al., 2009; Peugeot et al., 2011)
675 (Figure 6-c), which can have significant consequences for human populations. Conversely,
676 an increase in rainfall is amplified in the flows. Observations over the AMMA-CATCH eco-
677 climatic gradient highlighted the break between "Sahelian" behaviors, where an increase in
678 flows despite the drought is observed, and "Sudano-Guinean" where the decrease in flows is
679 greater than that of rain (Descroix et al., 2009; Amogu et al., 2010).

680 The increase in Sahelian stream flows, observed since the beginning of the drought in West
681 Africa, seems to be exacerbated by the modest rise in annual totals of rainfall since the mid-
682 1990's and/or by the intensification of the precipitation regime. Since the middle of the
683 decade 2001-2010, there has been an acceleration in the increase in volume of annual floods
684 and an upsurge of floods in West Africa (Descroix et al., 2012a; Sighomnou et al., 2013;

685 Yira et al., 2016). These floods are causing increasing damage in West Africa. Human
686 losses have increased by an order of magnitude since 1950 (Di Baldassarre et al., 2010).
687 This is partly explained by demographic growth, particularly urban growth, which in turn
688 induces a sharp increase in the vulnerability of societies. Therefore flood forecasting is
689 becoming an increasing priority for West African governments.

690

691 *7.2. Process studies*

692 7.2.1. The limits of models with global parameterization

693 The expertise acquired on land processes in this region and the availability of *in situ* data
694 motivated a specific model intercomparison exercise. The instrumentation deployed over the
695 AMMA-CATCH mesosites in Mali, Niger and Benin provided specific data for (i) forcing
696 the models and (ii) evaluating their capability to reproduce surface processes in this region.
697 About 20 state-of-the-art land-surface models participated to the AMMA Land-surface
698 Model Intercomparison Project phase-2 (ALMIP2), (Boone et al., 2009). Large differences
699 regarding the partitioning of the water budget components as well as the energy variables
700 were found among models over the Benin site (Figure 7). Concerning water fluxes, runoff
701 was found to be generally overestimated in the Oueme watershed (Figure 7) (Getirana et al.,
702 2017; Peugeot et al., *subm.*), but also in endorheic areas of the Mali site (Grippa et al.,
703 2017), where Hortonian runoff is the predominant mechanism. The soil description and
704 parameterization have been pointed out as a major issue to address in order to better
705 simulate water fluxes in this area. Concerning evapotranspiration, the multi-model average
706 compared relatively well with observations over the three mesoscale sites, although the
707 spread among models remained important (Grippa et al., 2017; Peugeot et al., *subm.*). Over

708 the Benin site, the actual evapotranspiration was underestimated during the dry season,
709 which is likely due to the underestimation of root extraction (see section below).

710 At a finer timescale, analysis of surface response - traced by the evaporative fraction - to
711 rain events at the three sites, showed that the ALMIP models generally produce poorer
712 results for the two drier sites (Mali and Niger). The recovery for vegetated conditions is
713 realistic, yet the response from bare soil is slower and more variable than observed (Lohou
714 et al., 2014).

715 More generally, differences in the water and energy partition among different models were
716 roughly the same over the three mesoscale sites, indicating that the signature of model
717 parameterizations and physics is predominant over the effect of the local atmospheric
718 forcing as well as soil and surface properties in the simulations.

719

720 7.2.2. Evapotranspiration of the main vegetation types

721 Evapotranspiration is the major term for water balance on the continents (65% on average)
722 yet it is still very poorly documented, especially in Africa. In West Africa, by far the main
723 sources of spatial variability in surface fluxes from a climatological perspective are the
724 regional eco-climatic gradient and the local ecosystem type. Hence, the flux station network
725 in the AMMA-CATCH observatory was designed to sample, with a manageable number of
726 stations (eight), these two main variability sources. The climatology of surface fluxes
727 captured by this dataset allowed to analyze their basic drivers, including for instance the role
728 of plant functional types on evapotranspiration dynamics (Lohou et al., 2014, see section
729 7.2.1), as well as to validate or develop remote sensing techniques and large-scale models

730 (Tagesson et al., 2017; Gal et al., 2017; Diallo et al., 2017, see section 7.2.1). These two
731 approaches provide ways to upscale observations regionally.

732 In Southern Sahel, during most of the year, evapotranspiration appears to be water-limited,
733 with the latent heat flux being tightly connected to variations in soil water and rainfall.
734 Direct soil evaporation dominates vapor flux except during the core of the rainy season
735 (Velluet et al., 2014). Depending on water availability and vegetation needs,
736 evapotranspiration preempts the energy available from surface forcing radiation, leading to
737 very large seasonal and inter-annual variability in soil moisture and in deep percolation
738 (Ramier et al., 2009). In Niger, vegetation development in fallow was found to depend more
739 on rainfall distribution along the season than on its starting date. A quite opposite behavior
740 was observed for crop cover (millet): the date of first rain appears as a principal factor of
741 millet growth (Boulain et al., 2009a). On a seven-year period, mean annual
742 evapotranspiration is found to represent ~82–85% of rainfall for the two systems, but with
743 different transpiration / total evapotranspiration ratio (~32% for fallow and ~40% for the
744 millet field), and different seasonal distribution (Figure 8). The remainder consists entirely
745 of runoff for the fallow (15-17% of rainfall), whereas drainage and runoff represents 40–60
746 % of rainfall for the millet field (Velluet et al., 2014). For the dominant shrub species in
747 Sahelian agrosystems (*Guiera senegalensis* J.F. Gmel), sensitivity to drought was found
748 significantly higher in mature shrubs than in resprouts from widespread yearly cuts, and
749 suggested that this species is likely to be vulnerable to projected drought amplification
750 (Issoufou et al., 2013).

751 In Northern Sahel, the magnitude of the seasonal cycle of the sensible heat, latent heat, and
752 net radiation fluxes measured above the Agoufou grassland in Mali can be compared to the
753 data from Niger (Tagesson et al., 2016b). The difference in latitude results in a shorter rainy

754 season in Mali and the presence of shrubs in the fallow sites around Niamey, which have a
755 longer leaf-out period than the annual grasses of the Agoufou grassland, where woody cover
756 is 2% only (Timouk et al., 2009). The maximum daily evapotranspiration rate is observed
757 for a flooded forest, which maintains losses in the order of 6 mm d^{-1} during the flood. In this
758 lowly extended cover ($\sim 5\%$ of the landscape), the annual evapotranspiration is more than
759 twice the precipitation amount, indicating substantial water supply from the hillslope.

760 In the Beninese Sudanian site, the period when water is limited is reduced. During the rainy
761 season, vegetation transpiration is limited by available radiation (Mamadou et al., 2014).
762 Evapotranspiration is weakly but consistently higher in Bellefougou woodlands than in
763 cultivated areas (Mamadou et al., 2016). The main difference between the two vegetation
764 types occurs in the dry season (Figure 9) when crops are harvested but woodlands are still
765 active (Seghieri et al., 2012). During the dry season, when soil water is exhausted in the first
766 upper meter of soil, the deeper roots of the trees allow them to transpire (Awessou et al.,
767 2017), producing an annual difference in evapotranspiration of about 20% (Mamadou et al.,
768 2016). On the same sites, the observed carbon flux of the woodland is twice that of the crop
769 (Ago et al., 2016). However, the impact of deforestation on the water cycle is a complex
770 issue to be assessed because transpiration of a specific tree varies according to its
771 environment in a woodland or in a fallow (Awessou et al., 2017).

772

773 7.2.3. Advances from field data – process models integration

774 Observational shortcomings (including time gaps, measurement representativeness,
775 accuracy issues or even the inability to simply observe a given variable of interest) limit the
776 field data potential for assessing energy and water budgets over time and space. Conversely,

777 field data are crucial to elaborate or evaluate process models, the only tool allowing to
778 assess unobserved components (soil evaporation, plant transpiration, drainage). Hence,
779 various developments or applications of ecohydrological and hydrogeological process
780 modeling were intricately constructed with AMMA-CATCH field data, of which only a few
781 can be presented here.

782 To better characterize the complex rainfall input signal, a stochastic, high spatial resolution
783 rainfield generator, conditioned to gauge observations, was developed for the Sahelian
784 context from the Niger site data (Vischel et al., 2009). Pertinence of this tool for the highly
785 sensitive runoff modeling was evidenced. Peugeot et al. (2003) showed how an uncalibrated
786 physically-based rainfall-runoff model can help to qualify and screen uncertain runoff
787 measurements. Velluet et al. (2014) proposed a data-model integration approach based on a
788 seven-year multivariable field dataset and the physically based soil-plant atmosphere
789 SiSPAT model (Simple Soil-Plant-Atmosphere Transfer model, Braud et al., 1995). They
790 estimate the long-term average annual energy and water budgets of dominant ecosystems
791 (i.e. millet crop and fallow) in Central Sahel, with their seasonal cycles (Figure 8). Results
792 underlined the key role played in the hydrological cycle by the clearing of savannah that
793 was observed these last decades at the scale of the agropastoral Sahel, especially for water
794 storage in the root zone, deep infiltration and potentially differed groundwater recharge, as
795 previously suggested by Ibrahim et al. (2014). This ecohydrological modeling approach was
796 also applied both to reconstruct past evolutions of the coupled energy and water cycles
797 during the last 60 years (Boulain et al., 2009b; Leauthaud et al., 2017) and to explore their
798 possible future changes (Leauthaud et al., 2015). In addition to these studies, constraining
799 groundwater modeling with complementary geophysical inputs, in particular from MRS,

800 reevaluated mesoscale recharge from 6 mm yr⁻¹ in the initial model to 23 mm yr⁻¹ (Boucher
801 et al., 2012).

802 On the other AMMA-CATCH mesosites, modeling studies supported by *in situ*
803 measurements revealed that some specific areas, even of limited extent, can play an
804 important role in the water cycle. In Mali, Gal et al. (2017) highlighted the role of bare soil
805 areas on increasing runoff, even if they remain very localized. In Benin, Richard et al.
806 (2013) simulated a hillslope water balance: water extraction by the riparian forest
807 transpiration captured all the water drained by the slopes for its benefit. Thus the hillslope
808 does not feed river flow, which is currently mainly supplied from waterlogged headwater
809 wetlands or “bas-fonds” (Hector et al., 2018). Such waterlogged head-water zones are very
810 common in the region and are considered to play a major role in the hydrological regimes of
811 Africa (Wood, 2006; Séguis et al., 2011). Although localized, it is of prime importance to
812 take into account riparian forest and waterlogged head-water zones in the models.
813 Moreover, Sudanian inland valleys carry an important agronomic potential for irrigation,
814 largely underexploited (Rodenburg et al., 2014; CILSS, 2016). Facing the strong
815 demographic rates, they are highly subject to undergo major land use land cover changes
816 (LULCC) that may thus drastically impact the hydrological cycle.

817

818 *7.3. Society applications*

819 In the context of research on subjects such as "hydrosphere", "critical zone" and "water
820 cycle" in the Anthropocene, eminently societal questions arise, as water is a resource for
821 human communities. This section attempts to make the transition from water as a physical
822 object, to water as a resource, i.e. how it is actually used by people (as blue or green water).

823 To do so it is necessary to integrate the idea that water resources are not only natural, but a
824 nature/culture co-production. We present below the work carried out by the AMMA-
825 CATCH observatory to contribute to these societal issues.

826

827 7.3.1. Characterization of the rainfall hazard

828 Flood hazard in West Africa is increasing (Descroix et al., 2012a; Wilcox et al., acc.), as a
829 result of various factors previously noted (demographic pressure, hydrological
830 intensification). In addition, urbanization and demographic growth have made West Africa
831 more vulnerable to hydrological hazards (Tschakert, 2007; Di Baldassarre et al., 2010;
832 Tschakert et al., 2010). Characterizing extreme hydrological hazards is becoming an urgent
833 request in order to design water related infrastructures (flood protection, dam, bridge, etc.).

834 Intensity Duration Frequency (IDF) curves and Areal Reduction Factor (ARF) aim at
835 describing how extreme rainfall distribution changes across space and time scales. Both
836 tools are regularly used for various applications (structure design, impact studies). As
837 climate is changing, the hydrological standard in West Africa must be revised (Amani and
838 Paturel, 2017).

839 The dense networks of tipping bucket rain gauges of the AMMA-CATCH sites, and the
840 required methodological developments (Panthou et al., 2014b) allowed to implement tools
841 such as IDF in different countries (see Panthou et al., 2014b for Niger; Agbazo et al., 2016
842 for Benin; Sane et al., 2017 for Senegal). The new IDF curves obtained for Niamey airport
843 (Figure 10-a) have already been requested by different organisms and end-users. These
844 curves have been obtained using the methods developed in Panthou et al.2014b and Sane et
845 al. 2018. Nonetheless, IDF and other indexes are implemented using a stationary hypothesis,

846 which is undermined by the recent results on the intensification of the rainfall regime. The
847 20-years return level for daily rainfall, estimated using the method developed in Panthou et
848 al. (2012), which was 90 mm in 1970 is now rising to 105 mm (+17%, see Figure 10-b).
849 Two consequences arise from this: (i) end-users must be aware of such changes and (ii)
850 scientists must develop tools taking into account climate non-stationarity.

851

852 7.3.2. Groundwater availability

853 Sustainable Development Goals such as SDG 6 for "clean and accessible water" suggest that
854 the mere presence of water in the subsoil is a necessary but not sufficient condition to
855 achieve this goal (Mertz et al., 2011).

856 **Reduce the rate of unsuccessfully drilled boreholes into hard rock aquifers in Benin**

857 In the past several decades, thousands of boreholes have been drilled in hard rocks of Benin
858 to supply human communities with drinking water. However, the access to drinking water is
859 still poor and it not improved significantly in the last years (e.g. 63 % in 2012 and 67% in
860 2015) despite a great effort put into drilling new boreholes by the community in charge of
861 water development.

862 The groundwater storage in the upper Oueme is 440 mm \pm 70 mm equivalent water
863 thickness (Vouillamoz et al., 2015a). As human abstraction (0.34 mm / year \pm 0.07 mm) is
864 far less than the natural discharge (108 mm / year \pm 58 mm), they conclude that increased
865 abstraction due to population growth will probably have a limited impact on storage as far
866 as water is used only for drinking and domestic uses. However, people have limited access
867 to groundwater because a significant number of drilled holes do not deliver enough water to

868 be equipped with a pump and hence are abandoned (i.e. 40% on average in Benin). This
869 high rate of drilling failure is mainly due to the difficulty of determining the appropriate
870 location to sit the drilling, because of the high geological heterogeneity of the hard rock.
871 Recent studies (Alle et al., 2018) showed that the approach currently used in Benin to sit
872 boreholes is not appropriate and can partly explain the high number of drilling failures. The
873 target to sit a borehole should be updated (i.e. from tectonic fractures to weathered units)
874 and the methods used to investigate the targets should be changed (i.e. 1D resistivity
875 techniques should be replaced by 2D Electrical Resistivity Tomography). Moreover, this
876 new approach could save money by reducing the number of unsuccessful drillings, even if it
877 improves the success rate by only 5%. This promising approach is already taught in
878 universities and hopefully soon applied by companies that drill wells.

879

880 **Taking advantage of the water table rise in Niger**

881 In Sahelian countries, the development of irrigated agriculture is one of the solutions to
882 avoid repetitive food crises. Nazoumou et al. (2016) demonstrated that increasing low-cost
883 groundwater irrigation represents a long-term solution, using shallow, unconfined perennial
884 groundwater, widely distributed in this region. The long-term rise of the water table
885 observed in Southwest Niger since the 1950's (see above section 7.1.3.) is such that it
886 outcrops in certain places, and is close to the surface in large areas (Torou et al., 2013). Data
887 analysis of AMMA-CATCH observatory and operational services (Nazoumou et al., 2016)
888 demonstrates that ~ 50,000 to 160,000 ha (3 to 9% of present-day cultivated areas) could be
889 turned into small irrigated fields using accessible shallow groundwater (water table depth \leq
890 20 m). A map of the potential irrigable lands as a function of the table depth has been
891 established (Figure 11) to help stakeholders to take decisions. The estimated regional

892 capacity for small scale irrigation, usually estimated with surface water, is doubled if
893 groundwater resources are also considered.

894

895 7.3.3. Sustainable land use

896 **Evaluation of different soil and water conservation practices**

897 Runoff increase causes problematic erosion of cultivated slopes in Niger (Bouzou Moussa et
898 al., 2011). In the framework of the AMMA-CATCH observatory, two techniques of soil and
899 water conservation works, widespread in Niger (benches and subsoiling), have been set up
900 and instrumented to quantify and analyze their impact on water flows (runoff, infiltration).
901 The comparison of the runoff coefficients observed before (Malam Abdou et al., 2015) and
902 after these layouts (Figure 12) shows that the benches and subsoiling favor infiltration (the
903 soil water content increases by a factor 3), and decreases the runoff coefficient (drop of 45%
904 to 10%) which results in a recovery of the vegetation cover in the areas with conservation
905 works (Boubacar Na'Allah et al., 2017; Bouzou Moussa et al., 2017). However the effect of
906 subsoiling on the runoff coefficient is temporary, as observed for cultivated areas (Peugeot
907 et al., 1997; Ndiaye et al., 2005; Malam Abdou et al., 2015), and must be restored regularly
908 while the effects of the benches are more durable.

909 To go further, a new type of soil and water conservation work was tested on the plateaus,
910 starting in 2016. The principle is to copy the natural water harvesting of the tiger bush
911 (Galle et al., 1999), defended by many authors (Ambouta, 1984; Torrekens et al., 1997;
912 Seghieri and Galle, 1999). These experiments are still ongoing and the impact of these soil
913 management practices will be assessed on the long-term.

914

915 **Joint evolution of forage and livestock production in the Sahel**

916 Livestock production systems in the Sahel are mostly pastoral, i.e. animals are getting the
917 bulk or all their feeds from grazing (Hiernaux et al., 2014). Sahel livestock graze on
918 communal lands: rangelands, but also fallows, cropland with weeds, stubbles and crop
919 residues after harvest. The herbaceous and woody biomass monitored by the observatory
920 was analyzed in terms of forage available for livestock. The short term impact of heavy
921 grazing during the growing season can only reduce production very locally, at worst by half
922 (Hiernaux et al., 2009b). On the longer term, grazing has little impact since the herbaceous
923 species are annuals and seeds that will grow the following year are already dispersed
924 (Hiernaux et al., 2016). Furthermore, livestock transform about half of forage intake into
925 manure, which stimulates vegetation production (Hanan et al., 1991; Rockström et al.,
926 1999), tends to favor the density of germinations (Miehe et al., 2010) and mitigate wind
927 erosion (Pierre et al., 2018). Woody plants tend also to be denser at the edge of these
928 concentration spots (Brandt et al., 2016b). These processes explain how the vegetation of
929 the pastoral areas has recovered from droughts, leading to the re-greening of the Sahel (see
930 above section 7.1.2).

931 The spatial heterogeneity in forage availability, and annual production (Hiernaux et al.,
932 2009b) justify the mobility of the herds as a major adaptation strategy of the pastoralists to
933 optimize livestock feed selection (Turner et al., 2014). Yet, the rapid expansion of the
934 cropped areas, the densification of roads and other infrastructures (dams) and the rapid
935 urbanization since the mid twentieth century has strongly reduced the area of rangeland and
936 multiplied the obstacles to livestock mobility, locally and regionally (Turner et al., 2014). It
937 weakens livestock productivity, close to the limit of technical viability, especially in the less

938 mobile agro-pastoralist herds (Lesnoff et al., 2012). The main way to enhance livestock
939 production at the height of the rapidly growing demand is thus to secure herd mobility and
940 access to common resources (Bonnet, 2013).

941

942 **8. Future perspectives**

943 West Africa as a whole is a region in transition, as highlighted by the reported changes: in
944 the rainfall regime, the hydrological intensification, and in some ecosystem components.
945 Climate change, indirect impacts of population growth (LULCC, urbanization, etc.), or a
946 combination of both have been put forward to explain the observed eco-hydrological
947 changes over the last 60 years. However, a clear, quantitative attribution of these changes to
948 climate versus the diverse human impacts largely remains to uncover. Moreover, the eco-
949 hydrological changes observed in the Sahel over the last decades (runoff intensification
950 despite rainfall deficit, subsequent re-greening with still increasing runoff) suggest that
951 some areas may pass tipping points and shift to new, ill-defined, regimes. The West African
952 monsoon system is identified as a possible tipping elements of the Earth System (Lenton et
953 al., 2008). In this context, several key science questions will have to be addressed in the
954 future, as described below.

955 **Detection of change in the eco-hydrological systems**

956 The term “change” as used here refers to any alteration of the forcing factors (e.g. rainfall,
957 incident radiation) and of the system response (e.g. groundwater recharge) which is not due
958 to natural variability. Since the signal-to-noise ratio in eco-hydro-meteorological series is
959 generally low due to the internal variability of climate (Hawkins and Sutton, 2009;

960 Hawkins, 2011; Deser et al., 2012), change detection requires long-term observations, at
961 space-time scales consistent with the process to detect. Despite the relatively low spatial
962 coverage in comparison to the regional West African system, AMMA-CATCH observations
963 have proven their usefulness to detect such changes (e.g. for vegetation, (Dardel et al.,
964 2014b); for fine-scale rainfall intensities, (Panthou et al., 2018); for runoff, (Amogu et al.,
965 2015; Gal et al., 2016). Indeed, these high resolution observations from a few seconds to
966 hours on dense networks fill a gap of measurements on fine space-time scales. Thus,
967 AMMA-CATCH datasets contribute to the documentation of regional trends when
968 combined with datasets from other observing systems, such as national measurement
969 networks, which measure the same variables with similar sensors or by using other sources
970 of data, such as remote sensing.

971 **Change attribution**

972 The attribution of a detected hydrological change to one or several factors, requires causal
973 models which must take into account the most relevant processes influencing the system
974 (Merz et al., 2012). These processes include the links between the different components of
975 the system (water tables, land cover, land use, etc.), as well as the main feedback loops
976 driving vegetation-hydrology processes. Irrespective of their nature, these models have to
977 give “good results for good reasons” and be robust (i.e. remain valid on a range of different
978 conditions). This implies that they must realistically represent the key processes based on
979 either physical principles, or process parameterizations, or a mixture of them; moreover they
980 must operate at the relevant spatio-temporal scales. These models must be able to simulate
981 system trajectories, in response to gradual changes in forcing, and disentangle the role of
982 forcing, initial conditions, and internal variability in the observed behavior. The

983 development of modeling tools dedicated to the attribution question in eco-hydrology is
984 clearly a challenge for the critical zone community in West Africa.

985 **Improve physical processes' representations in land surface models**

986 Some components of the energy and water budgets remain insufficiently understood over
987 the area, such as the estimations of evapotranspiration, especially at scales larger than the
988 flux station footprint; the changes of groundwater processes (and hence of water resources
989 renewal) linked to land use land cover changes; 3D spatial variability of soil properties; the
990 mechanisms underlying rainfall intensification. Despite progress made in the last decade in
991 Earth System Models, some specific features of the critical zone in these tropical
992 hydrosystems are still poorly represented, leading to biases in simulations (e.g. ALMIP2
993 results): surface-groundwater interactions, evapotranspiration and its links with vegetation
994 through the representation of the root zone. This is all the more true in view of the current
995 developments of hyper-resolution modeling of the critical zone (Maxwell and Condon,
996 2016), which allow the simulation on fine, 3D grids, but for which the identification of
997 realistic parameter values remains an issue (Prentice et al., 2015).

998 **A new generation of satellite products**

999 Recent and future satellite missions will provide new opportunities with improved spatial
1000 and temporal resolutions (Sentinel, GPM, Ecostress, SWOT, Planet/RapidEye) and/or
1001 addressing new variables of the eco-hydro-systems (vegetation fluorescence: FLEX; global
1002 mass of trees: BIOMASS). *In situ* observation such as those by AMMA-CATCH provide
1003 the basis for calibration/validation activities for these new satellite products, but also a
1004 ground reference to evaluate the coherence of classical remote sensing products over a long
1005 time span (Hector et al., 2014; Dardel et al., 2014a). The AMMA-CATCH observations and

1006 community also contribute to the development of new satellite products and the innovative
1007 potential of the soil moisture-based rain product is now being tested on a global scale with
1008 European Space Agency (ESA) funding (Román-Cascón et al., 2017).

1009

1010 In this context, the strategy of the AMMA-CATCH community is to maintain consistent
1011 complete observations of the energy and water budget components, and document the
1012 ecosystems evolution on the long term, with four main objectives: (i) improve and update
1013 the existing data series to provide to the community long-term (ideally >30 years) high
1014 resolution (ranging from the minute to the day according to the needs) quality controlled
1015 datasets; (ii) detect trends, transitions and regime shifts; (iii) better understand and model
1016 the major processes at play in this region and (iv) address societal issues concerning the
1017 green and blue water resource, its accessibility and its sustainable management in a region
1018 where the populations are highly vulnerable and rapidly growing.

1019 An associated, crucial, issue is to secure, on the long term, the funding of observation
1020 systems. AMMA-CATCH location and geometry are unique but imply specific operation
1021 costs. The West African countries pledged to support climate and environmental monitoring
1022 in the Nationally Determined Contributions (NDCs) taken at COP21 in Paris, but the Green
1023 Climate Fund is not yet in place, while the climatic and anthropogenic changes are
1024 underway.

1025

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1045

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1656

1657 **Figure captions**

1658 Figure 1: AMMA-CATCH Observatory sites in Pastoral Sahel (Mali, Senegal), Cultivated
1659 Sahel (Niger) and Sudanian climate (Benin). Photos by: E. Mougin (Mali), G. Favreau
1660 (Niger) and S. Galle (Benin)

1661

1662 Figure 2: Illustration of the multi-scale experimental set-up of the Sudanian site (Benin): (a)
1663 the upper Ouémé mesoscale site; (b) a zoom over the Donga watershed super site; and (c)
1664 the crop/fallow local site. Note that the Upper Ouémé mesoscale site contain two other local
1665 sites on two other types of land uses characteristic of the region (woodland and wooded
1666 savannah).

1667

1668 Figure 3: (a) Hydrogeological model of weathered hard rock (After Alle et al., 2018). The
1669 higher hydraulic conductivities are found in the stratiform fractured layer and in the
1670 subvertical fractured zones (area between the red dashes); (b) Comparison of the

1671 transmissivity estimated from MRS and calculated from pumping test in hard rock in Benin
1672 (After Vouillamoz et al., 2014).

1673

1674 Figure 4: Standardized Precipitation Indices (SPI) throughout 1950-2018 for the total annual
1675 (blue) and the annual maxima (red); over the Sahelian box (-2E, 5W, 11N, 16N). Following
1676 the methodology developed in Panthou et al. (2014a).

1677

1678 Figure 5: (a) GIMMS-3g NDVI trends from 1981 to 2011 over the Sahel region; Temporal
1679 profiles of field observations of herbaceous mass over (b) the Mali Gourma region (blue
1680 rectangle) and (c) the Niger Fakara region (brown rectangle). After Dardel et al. (2014).

1681

1682 Figure 6: The hydrological response to global change since 1950 shows (a) an increase in
1683 the area of pools in the Malian pastoral site; (b) an increase in river runoff and a water table
1684 level rise over the Niger cultivated site; (c) a co-fluctuation of rainfall and flow indexes over
1685 the Upper Ouémé basin located in Benin Sudanian area. (Modified from Le Lay et al., 2007;
1686 Gardelle et al., 2010; Descroix et al., 2012; Nazoumou et al., 2016).

1687

1688 Figure 7: Annual water cycle main components simulated by 12 land surface models
1689 (ALMIP-2 experiment) and the measured runoff over the upper Oueme Basin (Benin).

1690

1691 Figure 8: Estimated mean seasonal courses of water cycle components, for fallow (solid
1692 lines) and millet (dashed lines) plots: fluxes and rate of storage change in the 0–4 m soil
1693 column. Means are computed across years and over a 30-day running window. Light-
1694 colored intervals show a variation of ± 1 standard estimation error. (After Velluet et al.,
1695 2014).

1696

1697 Figure 9: Midday evaporative fraction (EF) at Nalohou cultivated area (gray dots) and
1698 Bellefougou Woodland (black dots) during 2008-2010. Modified from Mamadou et al.
1699 (2016).

1700

1701 Figure 10: Characterizing extreme hydrological hazards at Niamey airport: (a) Intensity–
1702 duration–area–frequency curves for resolutions between 1 and 24 hours; (b) Estimation of
1703 the daily rainfall return level for different 20-years periods from 1950 to 2014.

1704

1705 Figure 11: Potential irrigable lands in the Niamey region (Niger) as function of the water
1706 table depth. After Nazoumou et al. (2016).

1707

1708 Figure 12: The subsoiling installation drastically limits runoff in Tondi Kiboro, Niger
1709 (Photo A. Ingatan Warzatan & A. Boubacar Na'allah).

1710

1711

1712 **Tables**

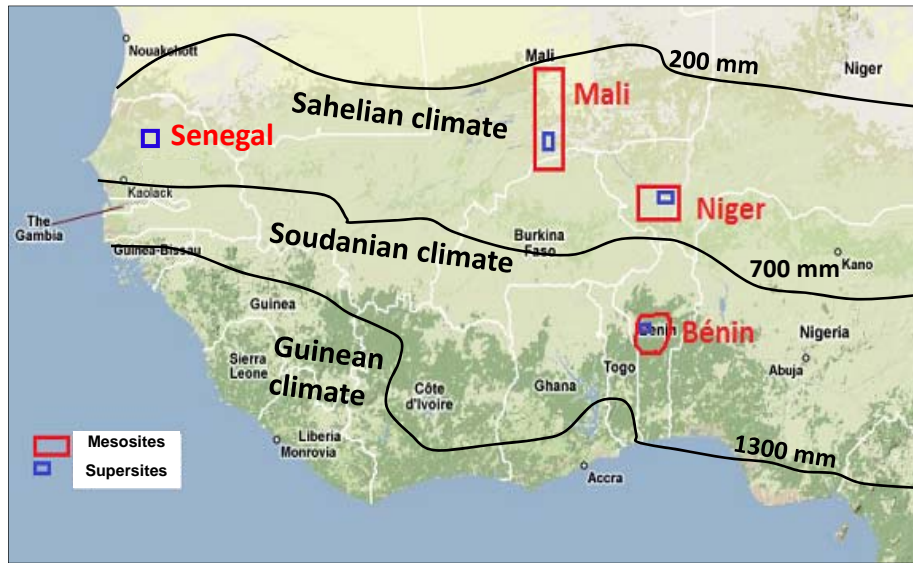
1713 [Table 1: Measurement categories, measured variables and number of stations monitored on](#)
 1714 [each of the four AMMA-CATCH observation sites. The operating period available in the](#)
 1715 [database is indicated in parentheses \(§ if ongoing\).](#)

Category	Measured variables	Benin site	Niger site	Mali site	Senegal Site
Meteorology	Rainfall	43 (1999-§)	55 (1990-§)	2-36 (2003-§)	2 (2013- §)
	Wind, Atmospheric pressure, Humidity, Radiative Budget	2 (2002-§)	2 (2005-§)	3 (2005-2011)	1 (2018- §)
Surface water	Runoff, pond level	15 (1996-§)	7 (2003-§)	1 (2011-§)	-
Groundwater	Water level in piezometers + domestic wells	20 + 28 (1999-§)	20 + 57 (2003-§)	-	-
Soil	Soil moisture, soil suction, soil temperature	9 (2005-§)	10 (2004-§)	12 (2004-2011)	2 (2013- §)
Surface fluxes	Latent and sensible heat, soil heat flux	3 (2005-§)	2 (2005-§)	3 (2005-2011)	1 (2018-§)
Vegetation	Biomass, LAI, PAI, Sap flow	3 (2010-§)	2 (2005-§)	3 (2005-§)	-
Water quality	Turbidity, physico-chemical parameters, majors ions and trace	20 (2002-2006)	-	1 (2014-§)	-

1716

1717

1718 **Figures**1719 [Figure1.pdf to Figure12.pdf](#)



BENIN

1200-1300 mm/year
Crops (sorghum, yam...) and woodland



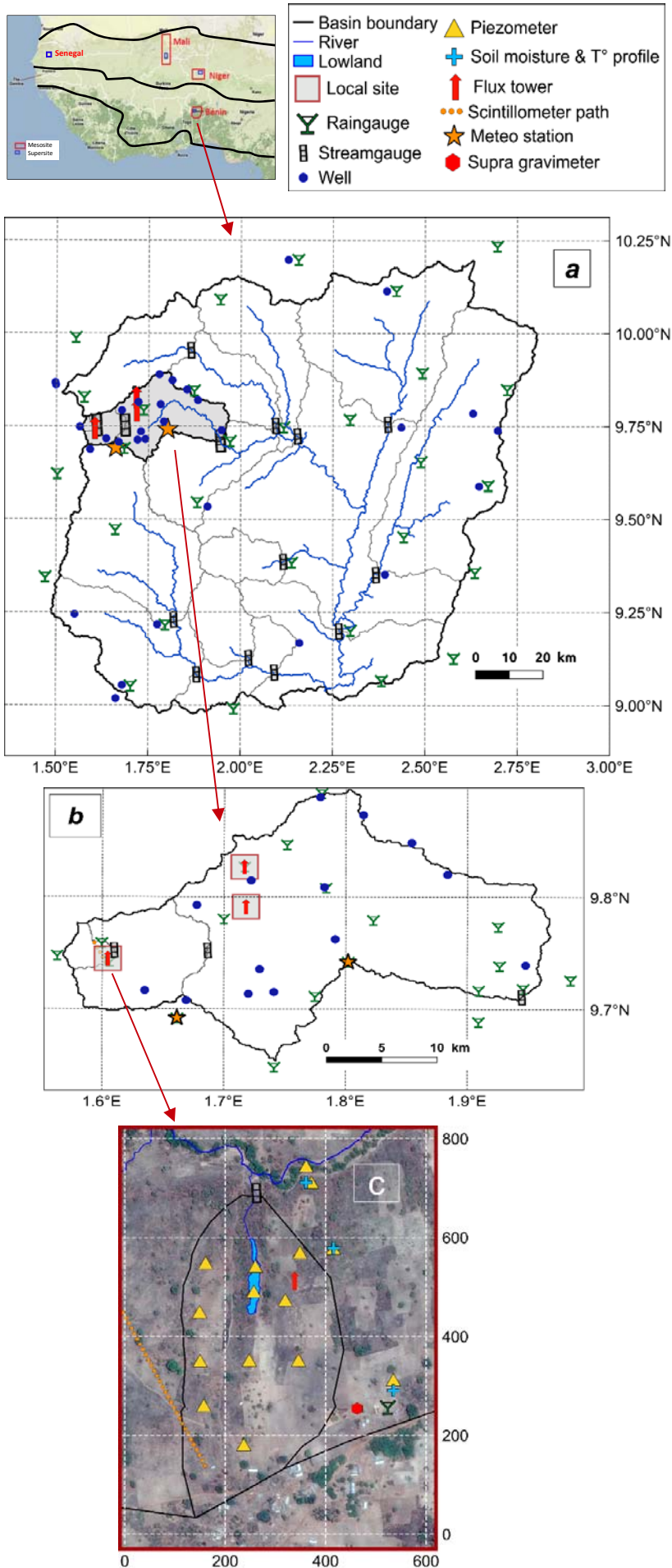
NIGER

450-600 mm/year
Pastoral and crop (millet)

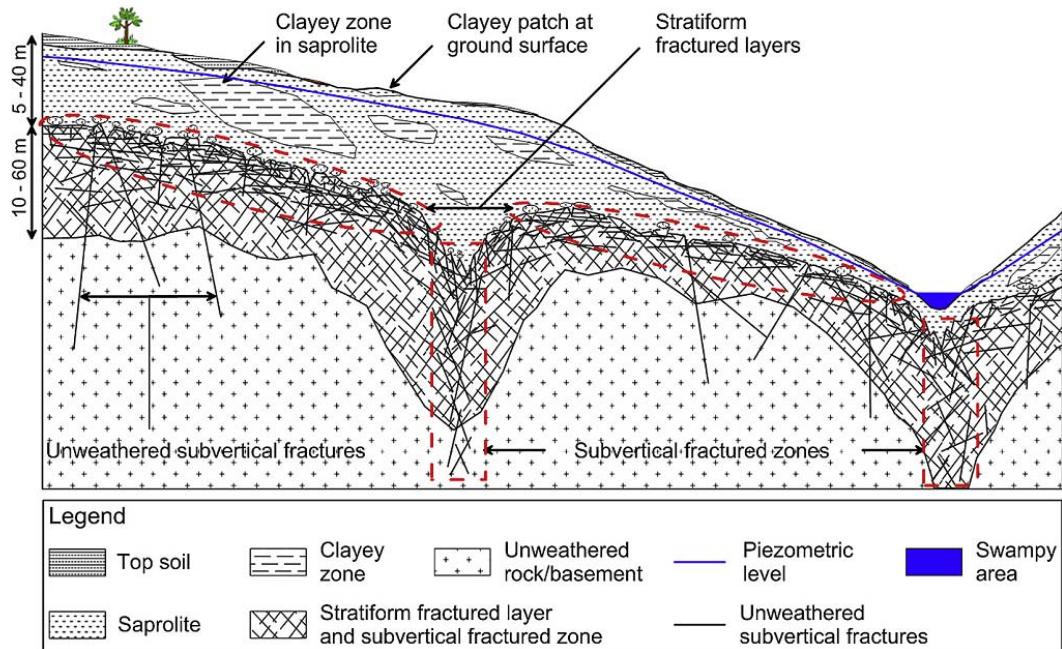


MALI / SENEGAL

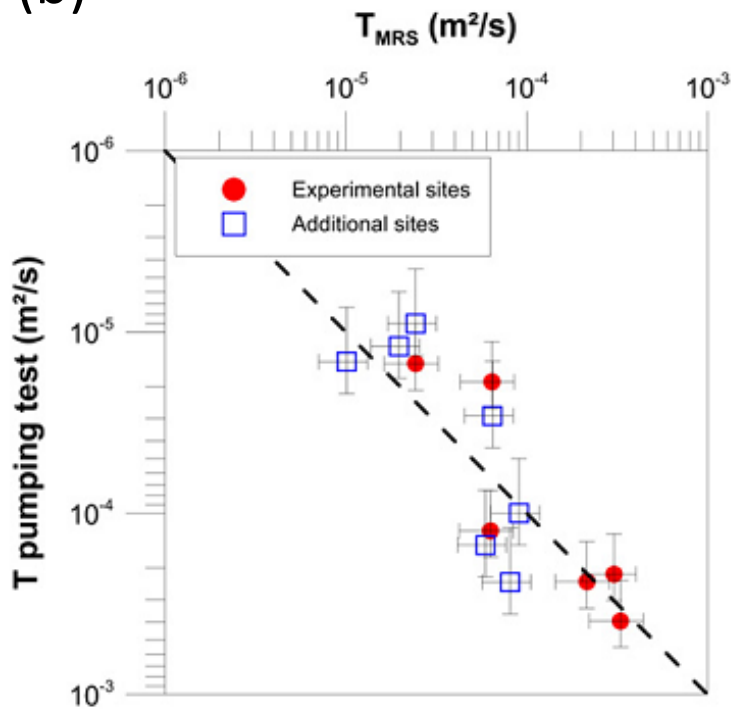
200-400 mm/year
Pastoral

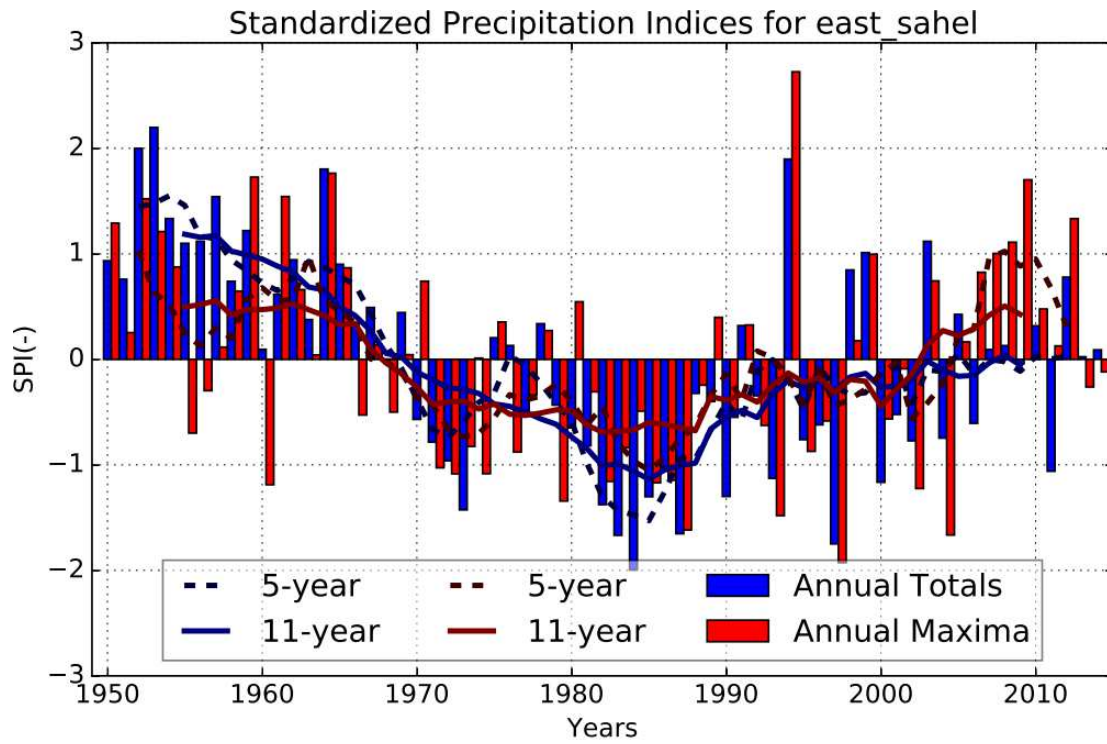


(a)

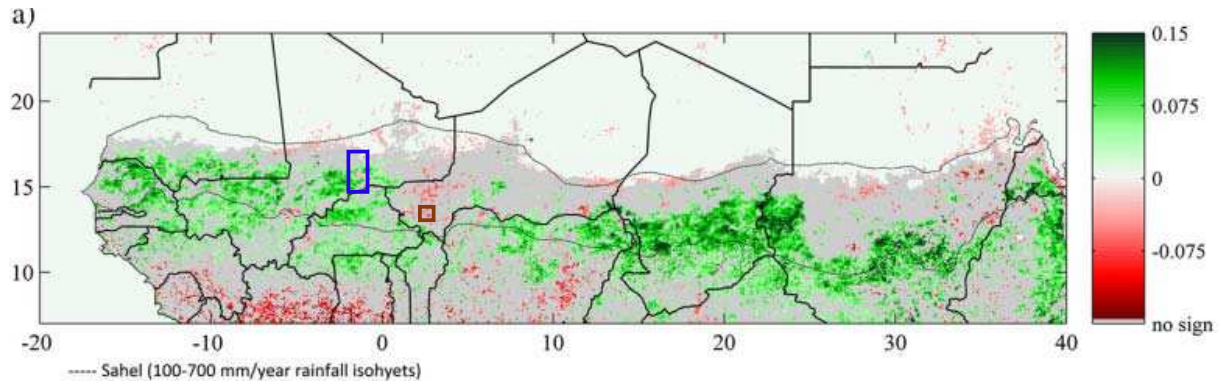


(b)

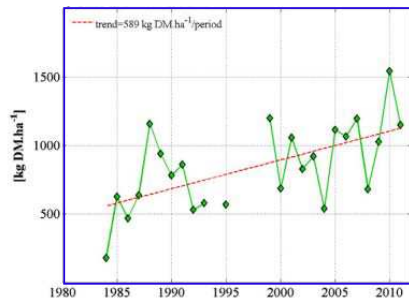




(a)



(b)



(c)

