Special Section: Hydrological Observatories

AMMA-CATCH, a Critical Zone Observatory in West Africa Monitoring a Region in Transition

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West Africa is a region in fast transition from climate, demography, and land use perspectives. In this context, the African Monsoon Multidisciplinary Analysis (AMMA)–Couplage de l'Atmosphère Tropicale et du Cycle eco-Hydrologique (CATCH) long-term regional observatory was developed to monitor the impacts of global change on the critical zone of West Africa and to better understand its current and future dynamics. The observatory is organized into three thematic axes, which drive the observation and instrumentation strategy: (i) analyze the long-term evolution of eco-hydrosystems from a regional perspective; (ii) better understand critical zone processes and their variability; and (iii) meet socioeconomic and development needs. To achieve these goals, the observatory has gathered data since 1990 from four densely instrumented mesoscale sites ($\sim 10^4$ km^2 each), located at different latitudes (Benin, Niger, Mali, and Senegal) so as to sample the sharp eco-climatic gradient that is characteristic of the region. Simultaneous monitoring of the vegetation cover and of various components of the water balance at these four sites has provided new insights into the seemingly paradoxical eco-hydrological changes observed in the Sahel during the last decades: groundwater recharge and/or runoff intensification despite rainfall deficit and subsequent re-greening with still increasing runoff. Hydrological processes and the role of certain key landscape features are highlighted, as well as the importance of an appropriate description of soil and subsoil characteristics. Applications of these scientific results for sustainable development issues are proposed. Finally, detecting and attributing eco-hydrological changes and identifying possible regime shifts in the hydrologic cycle are the next challenges that need to be faced.

Abbreviations: ALMIP, AMMA Land Surface Model Intercomparison Project; AMMA, African Monsoon Multidisciplinary Analysis; AMMA-CATCH, AMMA-Couplage de l'Atmosphère Tropicale et du Cycle eco-Hydrologique (Coupling the Tropical Atmosphere and the Eco-Hydrological Cycle); Cal/Val, calibration/validation; ERT, electrical resistivity tomography; HAPEX-Sahel, Hydrologic Atmospheric Pilot Experiment in the Sahel; IDF, intensity–duration–frequency; MRS, magnetic resonance sounding.

Core Ideas

- AMMA-CATCH is a long-term critical zone observatory in West Africa.
- Four sites sample the sharp ecoclimatic gradient characteristic of this region.
- Combined measurements of meteorology, water, and vegetation dynamics began in 1990.
- Intensification of rainfall and hydrological cycles is observed.
- The strong overall re-greening may hide contrasted changes.

West Africa is a hot spot of global change in all its components, with drastic consequences for the equilibrium of the critical zone. The critical zone extends between the rocks and the lower atmosphere—it is "critical" for life that develops there. On the one hand, regional warming has reached 1.5°C (IPCC, 2014), almost the double the global average. On the other hand, West Africa is home to 5% of the world's population, reaching 372 million inhabitants in 2017 (UN Department of Economic and Social Affairs, 2017). Its fivefold increase since 1950, when 73 million people lived in the region, makes the West African population the fastest growing worldwide. As a direct consequence, the increase rate of cultivated areas is also the highest for the whole of Africa, from a 22% coverage of the landscape in 1975 to 42% in 2000 (Eva et al., 2006), with considerable associated deforestation and land degradation. Prospect for the decades to come is a continuation—if not a reinforcement—of this sharp transitional phase, with a population that may double by 2050 (UN Department of Economic and Social Affairs, 2017) and a further temperature increase of 1.5 to 2°C, both figures corresponding to median scenarios. This would mean a total increase of roughly 3°C and a 10-fold multiplication of the population during the period 1950 to 2050. In such a context, the critical zone is more under threat here than anywhere else on the planet.

However, there is considerable uncertainty regarding the exact trajectory of this transition, since both climatic (e.g., Bony et al., 2013) and demographic (e.g., Bello-Schünemann, 2017) scenarios may deviate from a linear extrapolation of current tendencies in the presence of tipping elements. In their seminal study, Lenton et al. (2008) identified West Africa as a region where ongoing perturbations could qualitatively alter the future fate of the system, especially because the land–atmosphere coupling is extremely strong (Koster et al., 2004; Wolters et al., 2010; Taylor et al., 2011; Maurer et al., 2015; Mande et al., 2015): land degradation, as it affects soil moisture and vegetation, may feed back on rainfall occurrence and intensity, generating further land changes. Furthermore, the atmospheric circulation of the intertropical band is at the heart of the redistribution of energy and atmospheric water at the global scale; a change in its functioning will probably have an impact on the circulation and climate of the extratropical zones (Hu and Fu, 2007; Seidel et al., 2008; Bony et al., 2013; Voigt and Shaw, 2015).

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

Over the years, AMMA-CATCH has grown from a rainfall observatory to a holistic observing system, documenting most of the continental water cycle at high frequency thanks to the momentum gained from the setup of the AMMA program in 2002 (Redelsperger et al., 2006; Lebel et al., 2011). We start here by summarizing the motivations for maintaining such a complex observing system and by describing the main eco-climatic characteristics of the sites instrumented in AMMA-CATCH. We then detail the long-term observation strategy, some specific campaigns embedded in the AMMA-CATCH framework, and data management. Some new findings obtained from the Observatory are presented, and we conclude with the perspectives for the future.

Motivation and Science Questions

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

AMMA-CATCH has three main goals: (i) provide appropriate data for studying the impacts of global change on the West African critical zone; (ii) unite a large community of researchers from different countries and disciplinary backgrounds to analyze these data with the aim of better understanding the dynamics of the system across a range of scales and to detect significant changes in its key components; and (iii) disseminate data and associated results outside of the academic community. The observatory is consequently organized into three thematic axes that drive the observation and instrumentation strategy, namely: (i) analyze the long-term evolution of the eco-hydro-systems within a regional framework; (ii) better understand the critical zone processes and their variability; and (iii) link with decision makers and end users, so that the knowledge gained from the AMMA-CATCH data can be used to meet the socioeconomic and development needs based on proper mastering of environmental conditions.

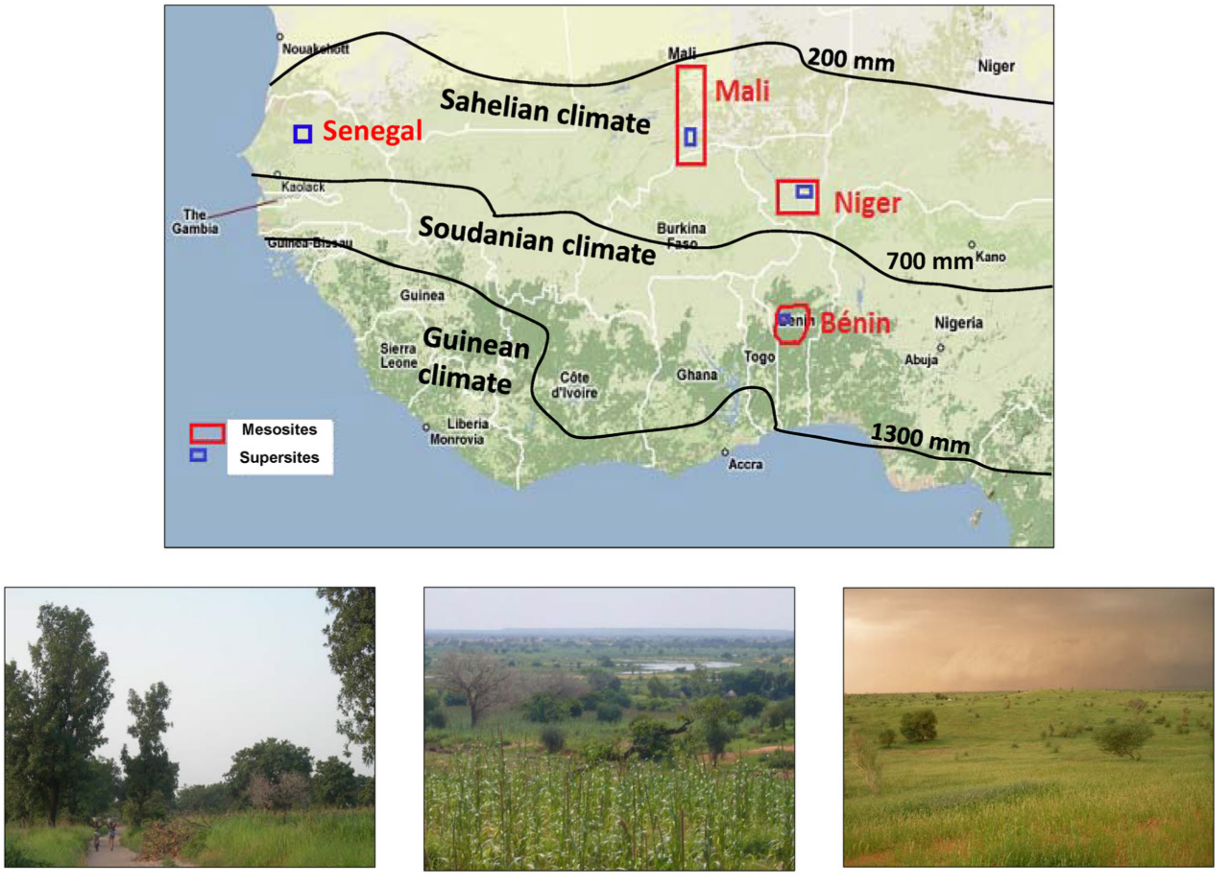
This involves a systemic approach that AMMA-CATCH is sharing with the critical zone community, and it is thus part of the French network of critical zone observatories (Observatoires de la Zone Critique Application et Recherche or OZCAR) (Gaillardet et al., 2018) and of the international Critical Zone Exploration Network (Brantley et al., 2017).

Site Characteristics

West Africa is characterized by a latitudinal climatic gradient that induces a gradient of vegetation. In the southern part, the coast of the well-watered Gulf of Guinea is covered with dense vegetation; rainfall gradually decreases from south to north, until the limit of the Sahara, which is arid and covered by scattered vegetation. The AMMA-CATCH observatory gathers data from four densely instrumented mesoscale sites (with surface areas ranging between 14,000 and 30,000 km^2) located at different latitudes to sample the regional eco-climatic gradient. We use the term *mesosite* to refer to these mesoscale sites. From south to north we find (i) the Sudanian site (Benin) where rainfall is ~1200 mm yr^{-1}, (ii) the cultivated Sahelian site (Niger) with ~500 mm of annual rainfall, and (iii) the pastoral Sahel site distributed in two locations (Mali and Senegal) with an average annual rainfall of ~300 to 400 mm. Thus annual rainfall is roughly divided by a factor of two when shifting from one site to the next along a south to north axis.

The Sudanian Site (Benin)

The southernmost site of the observatory lies in the center of Benin (1.5–2.5° E, 9–10° N, Fig. 1) and coincides with the upper watershed of the Ouémé River (14,000 km^2), which flows southward to the Atlantic Ocean. It is located in the Sudanian climate regime, with an average rainfall of about 1200 mm yr^{-1} falling in a single rainy season extending from April to October and with a mean annual temperature of ~25°C. Mean potential evapotranspiration is ~1500 mm yr^{-1}.



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

Fig. 1. AMMA-CATCH Observatory sites in the pastoral Sahel (Mali, Senegal), cultivated Sahel (Niger), and Sudanian climate (Benin). Photos by E. Mougin (Mali), G. Favreau (Niger), and S. Galle (Benin).

The geology of the area is metamorphic and crystalline rocks of various types, with predominantly schist and gneiss in the western and central parts of the site and granitic rocks in the east (Office Béninois des Mines, 1984). The weathered hard rock substratum constitutes a heterogeneous groundwater reservoir, conceptually described as a two-layer system, in which the unconsolidated, 15- to 20-m-thick saprolite top layer overlies the fissured bottom layer, with a smooth transition between the two (Vouillamoz et al., 2015). The tropical, ferruginous soils are mainly classified as Ferric Acrisols with frequent hard-pan outcropping (Faure and Volkoff, 1998).

The topography of the area is gently undulating, with elevations ranging from 630 to 225 m asl, and a general slope to the southeast. The landscape is a mixture of forest clumps, woodlands (as described by White, 1983), and rainfed crops including maize (*Zea mays* L.), sorghum [*Sorghum bicolor* (L.) Moench.], yam (*Dioscorea alata* L.), and cassava (*Manihot esculenta* Crantz). Except for the town of Djougou (northwest of the basin, with 268,000 inhabitants in 2013), the socioeconomic activity is primarily rural, based on rainfed crops and herding. The population density is 48 inhabitants km^{-2} (Institut National de la Statistique et de l'Analyse Economique du Bénin, 2013).

River flow starts 1 to 2 mo after the first rain events, near the end of June, and stops between October and January depending on the watershed area. During the flowing period, river discharge is made of a slow component (base flow) and rapid components following rainfall events. Contrary to the two other sites, surface runoff is rarely observed and river base flow mainly originates from the discharge of seasonal, perched, shallow water tables. The permanent water table, lying 5 to 15 m below the ground surface in the saprolite, exhibits an annual recharge–discharge cycle. It is recharged by infiltration during the rainy season, and transpiration by deep-rooted trees is currently considered the main driver of groundwater discharge (Séguis et al., 2011; Richard et al., 2013; Getirana et al., 2017). In the absence of large-scale irrigation, water extraction for human domestic needs is negligible in groundwater dynamics (Vouillamoz et al., 2015).

The observational setup was built in 1996 on an existing network of six stream gauges, managed by the national water authority, and surveying the Upper Ouémé River since 1952 (Le Barbé et al., 1993). The long-term observation network has now been reinforced and completed for a comprehensive water cycle documentation (see below). Since 2015, most of the stream gauge stations are equipped with tele-transmission in order to contribute to the early flood warning system. Tele-transmission has been extended to soil moisture and meteorological data for real-time monitoring and optimization of operation costs.

The Sahelian Site (Niger)

The ~20,000-km^2 central Sahelian mesosite (roughly 1.6–3° E, 13–14° N) is located in the southwest of the Republic of Niger. It includes the capital city of Niamey (~1.3 million inhabitants in 2017), close to the Niger River (Fig. 1). The area has a typical semiarid tropical climate, with a long dry season (October–May) and a single wet season, from June to September and peaking in August. The mean annual temperature over 1950 to 2010 at Niamey Airport was 29.2°C, with an increase of approximately 1°C during the six-decade period (Leauthaud et al., 2017). Daily maximum temperatures are between 40 to 45°C from mid-March to mid-June. Mean potential evapotranspiration is ~2500 mm yr^{-1}. The mean post-drought annual rainfall (1990–2007) is 520 mm in Niamey, still below the long-term (1905–2003) average of 560 mm yr^{-1}. Annual rainfall is typically produced by 15 to 20 "squall lines" (Mathon et al., 2002), and many smaller mesoscale convective systems, with very large space–time event variability.

The landscape consists of scattered, flat lateritic plateaus separated by large sandy valleys, with a relief of <100 m (elevations in the range of 177 to 274 m asl) and gentle slopes of a few percent at most. The largest fraction of the mesosite, to the north and east of the Niger River, belongs to the large Iullemmeden sedimentary basin. It is characterized by endorheic hydrology, with small catchments feeding depressions or ponds scattered along ancient river beds. The top sedimentary layer is the continental terminal aquifer, partly covered with aeolian deposits in the northern part of the area in particular. The water table depth varies spatially from >70 m below the plateaus to <5 m very locally, with increasing outcropping in some valleys, resulting in localized soil salinization processes. In contrast, the right bank of the Niger River at the southwest of the mesosite belongs to the plutonic Liptako Gourma massif and is exorheic, draining to the Niger River.

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

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

The Pastoral Sahelian Sites (Mali and Senegal)

The Mali Site

The northernmost AMMA-CATCH site is located in northeast Mali, in the Gourma pastoral region, which stretches from the loop of the Niger River southward down to the border region with Burkina Faso (30,000 km^2, Fig. 1). It is a scarcely populated area, with a population density of fewer than 7 inhabitants km^{-2} (Direction Nationale de la Statistique et de l'Informatique, 2009).

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

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

Prior to the AMMA-CATCH monitoring, 37 vegetation sites were studied for 10 yr between 1984 and 1993 by the International Livestock Centre for Africa (ILCA) and the Institut d'Economie Rurale (IER). Starting in 2000, the monitoring was progressively intensified under the AMMA project (Hiernaux et al., 2009b; Mougin et al., 2009). During the AMMA experiment (2005–2010), the Gourma site extended also in the Haoussa region, to the north of the Niger River (Mougin et al., 2009).

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

The Senegal Site

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

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

Long-Term Observations and Strategy

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

On all four sites, the observation strategy is based on a multiscale approach, associating (i) a mesoscale site (typically 10^4 km^2) to document the long-term water and energy cycles (Fig. 1, red outline); (ii) a so-called "supersite" (typically 10–100 km^2) dedicated to process studies at intraseasonal to interannual time scales on an integrating hydrological domain (Fig. 1, blue outline); and (iii) local sites (typically 1 km^2) dedicated to the fine documentation of the components of the water and energy cycles and the vegetation dynamics. The mesoscale sites make the link with the regional scale. Nested sensor networks, with decreasing resolution with domain size, allow linking processes across scales.

This nested approach is illustrated for the Benin Sudanian site (Fig. 2). The mesoscale Benin site (Fig. 2a) gathers 16 stream gauge stations, 35 rain gauges, and 12 wells or boreholes monitoring the dynamics of the water table. The Donga supersite, an ~600-km^2 sub-basin of the Upper Ouémé (Fig. 2b), includes denser rain gauge, piezometer, and stream gauge sub-networks. Within the Donga basin, three local sites have been instrumented. They are representative of the three main land use and land cover types encountered in the area, which are marked by an increase in the woody layer: (i) cultivated areas, which include fallow and crops with isolated trees (Fig. 2c); (ii) wooded savannah; and (iii) woodland. Each of these three local sites includes the monitoring of: meteorological variables with a radiative budget; turbulent fluxes at eddy covariance flux towers; vegetation dynamics (leaf area index and height); 0- to 1-m soil moisture, temperature, and suction profiles located at the top, middle, and bottom of a hillslope transect (700–1000 m long); and permanent and perched water table depths along the hillslope, using piezometers at different depths. A similar nested approach is being deployed at the Niger and Mali sites (Cappelaere et al., 2009; Mougin et al., 2009, respectively).

Besides the common setup illustrated above, supplemental instruments or networks have been installed at each mesosite depending on its eco-hydrological context. In Benin, an elementary watershed (0.15 km^2) has been monitored to understand the origin of river flow (Fig. 2c). A supra-conducting gravimeter monitors local variations in the total water column and makes the link with the larger scales (Hinderer et al., 2012). In Niger, the ~2-km^2 Wankama endorheic catchment gathers surface flux stations, soil moisture profiles, vegetation plots, stream gauges, pond limnimetry, and an associated piezometry transect to capture the

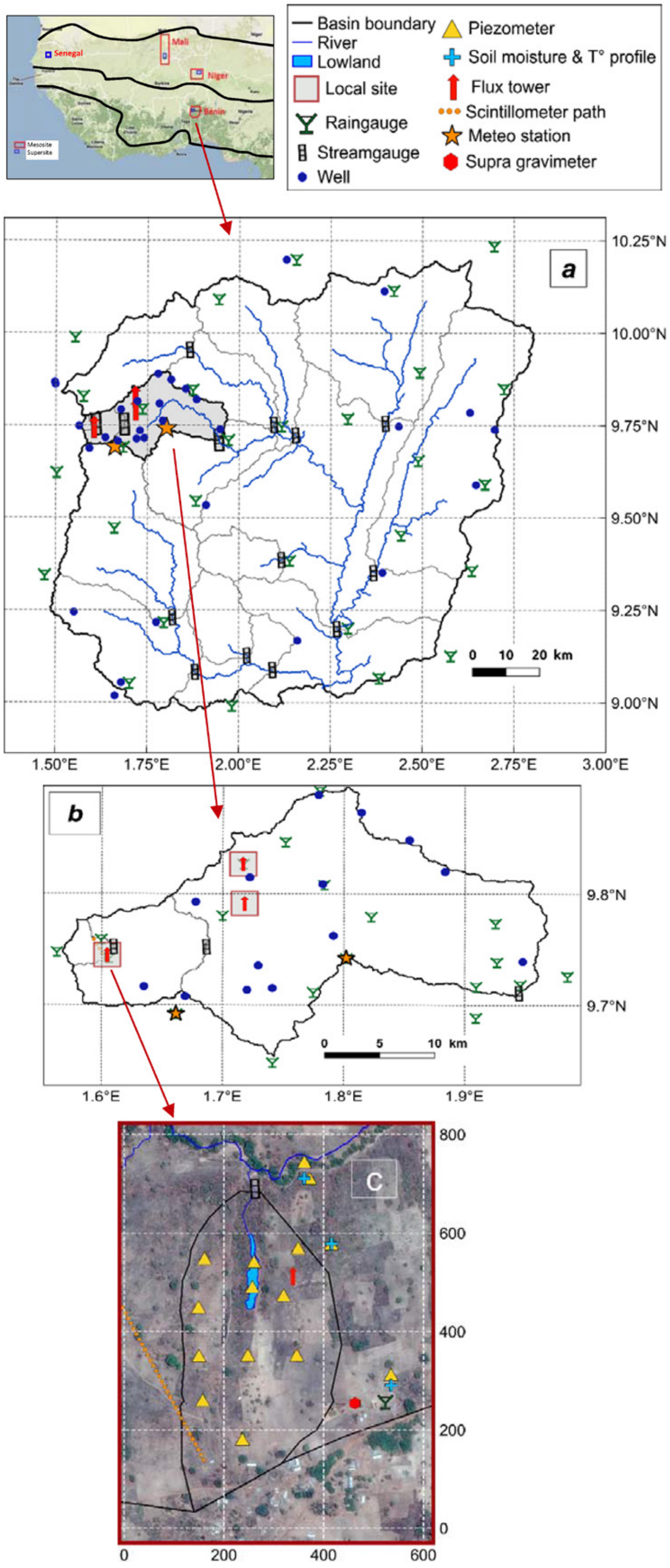


Fig. 2. Illustration of the multiscale experimental setup of the Sudanian site (Benin): (a) the Upper Ouémé mesoscale site; (b) a close-up of the Donga watershed supersite; and (c) the crop–fallow local site. Note that the Upper Ouémé mesoscale site contains two other local sites on two other types of land use characteristic of the region (woodland and wooded savannah).

water cycle from point to catchment scales. In Mali, the Agoufou pond (250-km^2 watershed) water level, turbidity, and suspended sediments are monitored to study the dynamics of surface water.

Seven categories of variables are monitored with coordinated protocols and identical sensors on the four sites: meteorology, surface water, groundwater, soil, surface–atmosphere fluxes, vegetation, and water quality. The measured variables in each of the seven categories as well as the measurement periods are shown in Table 1. In 2018, a total of 290 stations (including 850 sensors) are in operation in the four countries (Table 1). The stations are grouped into 42 "instruments." An instrument aims to answer a scientific question and focuses on a specific spatial and temporal scale. It may be either a group of identical sensors organized in a network (e.g., a rain gauge–stream gauge network) or a set of complementary sensors located in the same place (e.g., a surface flux station composed of a flux tower with radiative budget and soil heat flux). Each instrument is under the scientific responsibility of one or two principal investigators. An instrument corresponds to a dataset in the observatory database and is identified by a doi. Currently 26 instruments are in operation, 12 are stopped because they correspond to objectives that have been achieved (characterization or process studies), and four are suspended for security reasons in Mali. At least one instrument in each category of measurement is present in each eco-climatic subregion (Table 1). This observation system has continuously generated a coherent dataset for the last 25 yr.

Dedicated Campaigns and Experiments

Besides the long-term observation system, specific field campaigns are organized to (i) document the critical zone architecture, such as the geometry but also the hydrodynamic properties of the groundwater reservoirs and soil layers, (ii) study fine processes, such as the paths of water transfers between surface and groundwater, and (iii) calibration/validation (Cal/Val) of satellite missions, remote sensing being a key additional data source for our large mesosites and for upscaling to the data-poor region. These campaigns allow, in particular, better characterization of processes and inputs to modeling approaches across the AMMA-CATCH sites.

Documenting the Critical Zone Architecture

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

Aquifer geometries, specific yield, and permeabilities are not readily known in sedimentary and hard-rock regions of West Africa but are nevertheless key parameters for the modeling and use of groundwater resources (Vouillamoz et al., 2015). Geophysical techniques provide useful tools to spatialize

Table 1. Measurement categories, measured variables, and number of stations monitored at each of the four AMMA-CATCH observation sites.

		No. of monitored stations and operating period			
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, leaf area index, plant area index, sap flow	3 (2010–)	2 (2005–)	3 (2005–)	–
Water quality	turbidity, physico-chemical parameters, major and trace ions	20 (2002–2006)	–	1 (2014–)	–

† The operating period available in the database is indicated in parentheses (ending date is blank if ongoing).

geophysical parameters linked with aquifer properties. Electrical resistivity tomography (ERT), magnetic resonance sounding (MRS), and time-lapse gravity monitoring were implemented in the Niger and Benin sites of AMMA-CATCH in order to test their efficiency and characterize aquifer parameters.

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

The MRS results (i.e., the MRS water content and MRS pore-size parameters) have been found to be well correlated with both specific yield and permeability or transmissivity calculated from long-duration pumping tests (e.g., Fig. 3b; Vouillamoz et al., 2014). Magnetic resonance sounding allowed estimation of the specific yield and the transmissivity in hard rock aquifers in Benin (Vouillamoz et al., 2014; Legchenko et al., 2016) and in the unconfined sandstone aquifers of the Niger site (Vouillamoz et al., 2008; Boucher et al., 2009). Specific yield (Sy) and transmissivities (T) are higher in Niger (Sy: 5–23%; T: 2×10^{-4}–2×10^{-2} $m^2\ s^{-1}$) than in Benin (Sy: 1–8%; T: 2×10^{-5}–4×10^{-4} $m^2\ s^{-1}$). Time-lapse gravimetry surveys were also used for evaluating the specific yield (Hinderer et al., 2009; Pfeffer et al., 2011; Hector et al. 2013). These results are in accordance with MRS water content and pumping-test-derived specific yield.

Exploring Critical Zone Processes

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

In hard-rock aquifers in Benin, the groundwater recharge has been investigated. For 3 yr, the major as well as trace elements and stable isotopes of water were sampled in the surface and underground waters of the Donga basin (600 km^2). Their analysis shows that groundwater recharge occurs by direct infiltration of rainfall and accounts for 5 to 24% of the annual rainfall (Kamagaté et al., 2007). An ERT time-lapse survey during the hydrological season confirmed a direct recharge process but also a complicated behavior of groundwater dilution as well as the role of hardpans for fast infiltration (Wubda et al., 2017).

The origin of the flows of the Donga basin (600 km^2, Benin) was investigated using geochemical campaigns and gravimetry. Geochemical campaigns have shown that the seasonal perched groundwaters are the major contributors to seasonal stream flow while the permanent groundwater in the saprolite almost never drains to rivers (Séguis et al., 2011). Episodic contribution of permanent water was revealed using gravity measurements: locally, deep-seated (>2 m deep) clayey areas exhibit lower seasonal water storage changes than elsewhere, suggesting favored lateral transfers above the clay units. This observation contributed to evidence of the higher contribution of such clayey areas to the total streamflow (Hector et al., 2015). For the larger Ouémé basin (12,000 km^2), the electrical conductivity of the base flow was <70 µS cm^{-1} until the river dried up. Because this electrical conductivity is far below that of the permanent groundwater (150–400 µS cm^{-1}), a contribution of more mineralized permanent groundwater has to be ruled out.

On the Sahelian sites, rainfall, surface water, and groundwater isotopic sampling (^{18}O, ^{2}H, and/or ^{3}H, ^{14}C, and ^{13}C) was performed to characterize the relationship between surface water and groundwater recharge on about 3500 km^2 of the Niger site (Taupin et al., 2002; Favreau et al., 2002) and in wells around the Mali Hombori supersite (Lambs et al., 2017). On the Niger site, it has been found that land clearing increased groundwater recharge by about one order of magnitude (Favreau et al., 2002, 2009). Using MRS, localized recharge beneath expanding valley ponds was evidenced as a key process. Through a combination of vadose zone

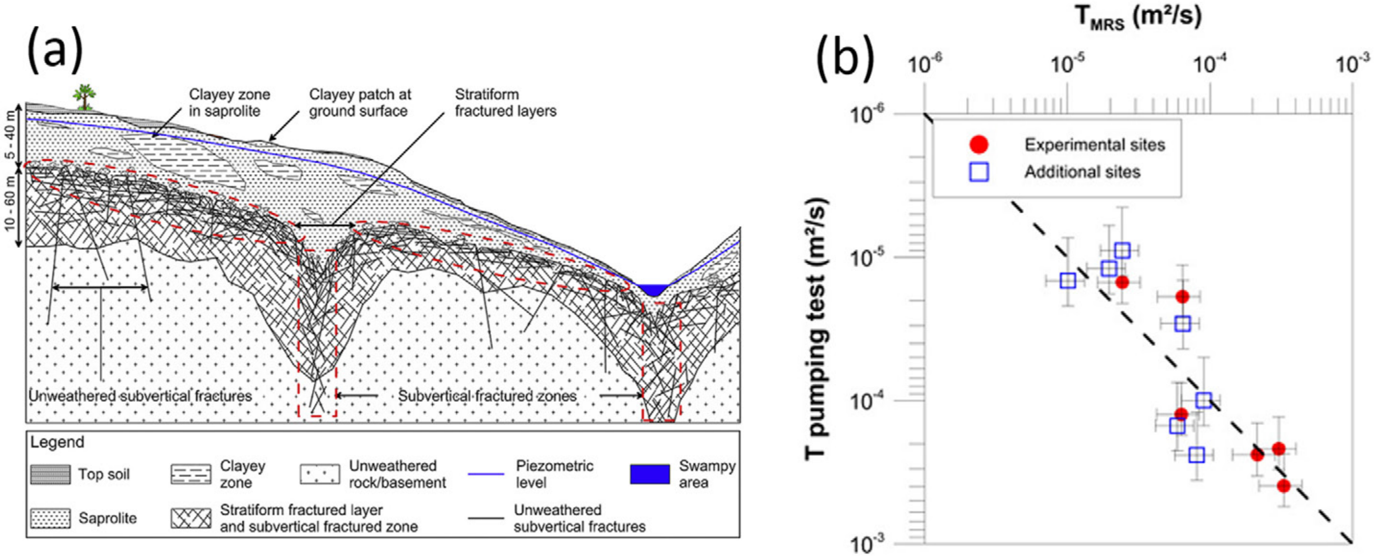


Fig. 3. (a) Hydrogeological model of weathered hard rock (after Alle et al., 2018), with higher hydraulic conductivities found in the stratiform fractured layer and in the subvertical fractured zones (area between the red dashes); (b) comparison of the transmissivity (*T*) estimated from magnetic resonance sounding (MRS) and calculated from a pumping test in hard rock in Benin (after Vouillamoz et al., 2014).

geophysical and geochemical surveys and of surface and subsurface hydrological monitoring, substantial deep infiltration was also shown to occur below sandy alluvial fans and channels on the hillslope, contributing to the recent groundwater recharge increase (Massuel et al., 2006; Descroix et al., 2012b; Pfeffer et al., 2013).

In the Senegal Ferlo, campaigns on soil biogeochemical analysis and surface atmosphere exchanges of nitrogen compounds showed that changes in water availability in semiarid regions have important nonlinear impacts on the biogeochemical nitrogen cycle (Delon et al., 2017).

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

Providing In Situ Datasets for Calibration/Validation of Satellite Missions

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

Several studies have used the AMMA-CATCH rain gauge networks to evaluate satellite rainfall products. The network density across these sites (especially the Niger and Benin sites with about 40 gauges within a 1 by 1° area) is unique in Africa and even in the tropics. It provides an unprecedented opportunity to analyze the ability of satellites to detect and quantify rainfall within tropical convective systems. Within the Megha-Tropiques mission ground validation program (Roca et al., 2015), Kirstetter et al. (2013) evaluated instant rainfall retrievals based on the BRAIN algorithm (Viltard et al., 2006), evidencing failure to detect the lightest rains. Guilloteau et al. (2016) demonstrated the ability of several high-resolution satellite rainfall products to reproduce the diurnal cycle of precipitation. Gosset et al. (2018) confirm the good performance of the Global Precipitation Measurement (GPM) era products in West Africa and the key role of the additional sampling provided by the Megha-Tropiques satellite.

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

The AMMA-CATCH sites have also contributed to the validation of vegetation products like the leaf area index provided by the VEGETATION instrument and by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor in the pastoral Sahel (Morisette et al., 2006; Camacho et al., 2013; Mougin et al., 2014), as well as MODIS gross primary production (Sjöström et al., 2013).

In the near future, AMMA-CATCH will contribute to the Cal/Val of other missions, such as the Ecosystem Spaceborne

Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission (plant response to water stress), to be launched by NASA in 2018 (Cawse-Nicholson et al., 2017), and the Surface Water Ocean Topography (SWOT) mission (Biancamaria et al., 2016), aimed at estimating water volumes and discharge over terrestrial water bodies and rivers.

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

Data Management and Policy

AMMA-CATCH is the result of long-term and joint work among researchers from universities, research institutes, and national operational networks in Benin, Niger, Mali, Senegal, and France. They work together to produce quality-controlled datasets. The data acquisition instruments are generally isolated and need electric autonomy. Their data are regularly collected by the technical teams and transmitted to the scientific principal investigator of the dataset. The principal investigators are responsible for calibration, quality check, and annual transmission of the datasets to the database manager, who makes them available online at http://bd.amma-catch.org/. This portal includes a geographical interface that allows navigation across locations and datasets and retrieval of the metadata. It fosters data discovery by describing the dataset with standardized metadata (ISO, 2014; DataCite [https://www.datacite.org/]), and interoperability with other information systems by implementing the Open Geospatial Consortium (OGC, http://www.opengeospatial.org/) standard exchange protocols (Catalog Service for the Web [CSW, http://www.opengeospatial.org/standards/cat] and Sensor Observation Service [SOS, http://www.opengeospatial.org/standards/sos]). Soil moisture data are also available from the International Soil Moisture Network portal (Dorigo et al., 2011), and some of the surface flux data are part of the FLUXNET global network of micrometeorological tower sites (Falge et al., 2016). This deliberate open data policy is a contribution to the dissemination of climatic and environmental datasets, which is specially challenging in Africa (Dike et al, 2018). In 2017, 44% of the requests concerned soil moisture, 24% rainfall, 9% surface fluxes and surface waters, 8% meteorology, and 6% other data. The users come from all continents: 7% Africa, 47% Europe (10% France), 33% North America, and 13% Asia.

All the AMMA-CATCH datasets are published under the Creative Common Attribution 4.0 International License (CC-BY 4.0). For any publication using AMMA-CATCH data, depending on the contribution of the data to the scientific results obtained, data users should either propose co-authorship with the dataset principal investigators or at least acknowledge their contribution.

New Insights and Novel Scientific Findings

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

Regional Long-Term Dynamics

Rainfall Intensification

At the beginning of the 1990s, scientists mainly focused on the causes (atmospheric and oceanic) and the impacts (hydrological, agricultural, and food security) of the 1970s to 1980s drought. At that time, regional studies (Le Barbé and Lebel, 1997; Le Barbé et al., 2002) showed that the Sahel region could be considered as a unique entity that records a unique signature in terms of rainfall regime changes between the wet (1950–1969) and the dry (1970–1990) periods (Fig. 4): the mean annual rainfall decreased by roughly 200 mm (corresponding to 20–50% of the annual rainfall), mainly due to a decrease in the number of wet days and to a lesser extent to a decrease in wet-day intensity.

Since the beginning of the 1990s, the annual rainfall has increased slowly, marking the end of the Sahelian great drought. Behind this general statement, new aspects in the rainfall regime are hidden. In fact, as first observed by Lebel and Ali (2009), some contrast appeared between the western and the eastern Sahel (annual rainfall increased earlier in the east than in the west). This result was confirmed by Panthou et al. (2018), who analyzed more deeply the east–west contrast in terms of wet days (number and intensity), hydroclimatic intensity (Trenberth, 2011; Giorgi et al., 2011), and extreme events. The main result found is that the western Sahel experiences slight increases in both number and intensity of wet days (and thus annual rainfall). In contrast, the eastern Sahel is experiencing a slight increase in the number of wet days but a strong increase in wet-day intensity, particularly the most extremes. This strong intensification in the central and eastern Sahel was observed early in Mali by Frappart et al. (2009) and confirmed at the Sahelian scale (Panthou et al., 2014a; Sanogo et al., 2015). The standardized precipitation index for annual totals and annual maxima has followed a similar pattern since 1950 (Fig. 4). The main difference between the two variables is that during the recent period (since 1990), the annual maxima index has increased faster than annual totals. This is one of the expressions of the recent intensification of the rainfall regime recorded in the region.

The recent study of Taylor et al. (2017) provided some insight into the atmospheric mechanisms that could explain this strong increase in extreme rainfalls. They found that the frequency of rainy systems (mesoscale convective systems) responsible for extreme rainfalls in the Sahel has dramatically increased. Different mechanisms (such as wind shear and Saharan dry air intrusion in the Sahelian mid-level atmospheric column), linked to the increase of Saharan temperature and the meridional temperature gradient (between the Guinean coast and the Sahara) seem to explain the increasing frequency of extreme mesoscale convective systems. Since the increasing meridional temperature gradient is a robust projection of global circulation models, they argue that the ongoing intensification in the Sahel is expected to continue in the coming decades.

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

Re-greening Sahel

The Sahelian vegetation has been shown to follow the precipitation recovery after the major droughts of the 1970s and 1980s. A general "re-greening" has been observed during the 1981 to 2010 period by satellite data (Fig. 5a, from Dardel et al., 2014b). The normalized difference vegetation index (NDVI) local trend is confirmed by in situ measurements of the herbaceous vegetation mass in Mali and Niger (Fig. 5b and 5c). Over the Gourma and more generally over the Sahel, tree cover tends to be stable or slightly increasing during 2000 to 2010 (Hiernaux et al., 2009a; Brandt et al., 2016a). However, the Sahelian re-greening is not uniform in space: in the Mali Gourma region, an increasing trend is observed (Fig. 5b), while the Fakara region in the Niger mesoscale site has witnessed a decrease in vegetation production (Fig. 5c). Moreover, even in some "re-greening" areas, vegetation degradation can occur at a small spatial scale, which is difficult to observe using coarse-resolution satellite data (Dardel et al., 2014a). A detailed study carried out on the Agoufou watershed in the Gourma region highlighted important changes in vegetation and soil properties between 1956 and 2011 (Gal et al., 2017). The most relevant changes concerned (i) the degradation of vegetation growing on shallow soils and tiger bush formations, and (ii) a marked evolution of soil properties, with shallow sandy sheets being eroded and giving place to impervious soils. Trichon et al. (2018) highlighted the persistent decline of tiger bush in the Gourma following the major droughts of the 1970s and 1980s. These land cover changes occurring at the local scale have important consequences on the hydrological system operating at a larger scale and are responsible for the spectacular increase in surface water and runoff in this region (see below). Regional spatial variability of Sahelian ecosystem production was derived from carbon fluxes at six eddy covariance stations across the Sahelian belt, including the four

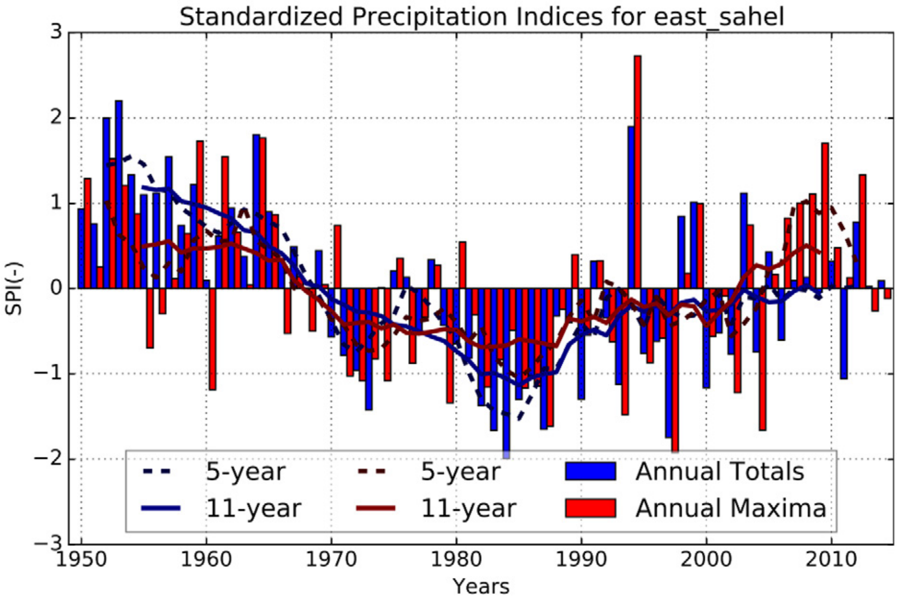


Fig. 4. Standardized precipitation indices (SPI) throughout 1950 to 2018 for the total annual (blue) and the annual maxima (red) over the Sahelian box (−2 E–5 W, 11–16 N) following the methodology developed by Panthou et al. (2014a).

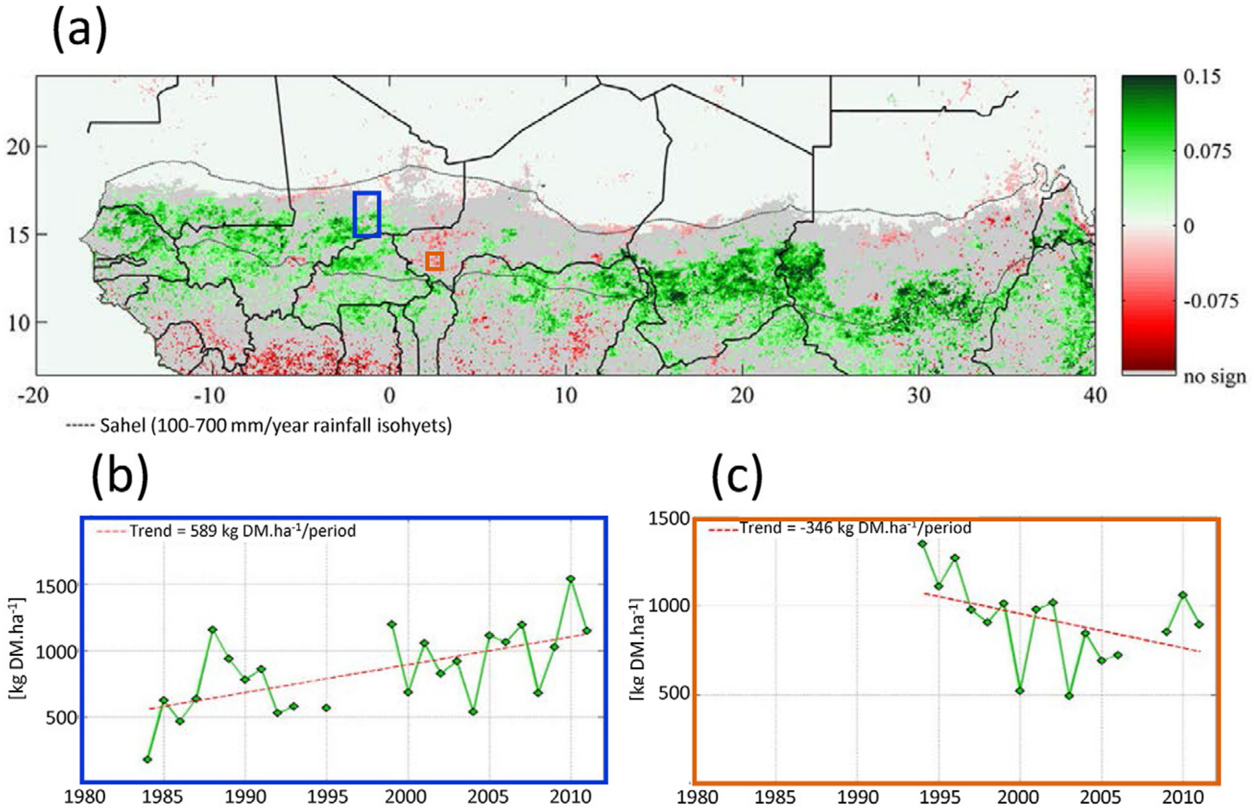


Fig. 5. (a) Global Inventory Monitoring and Modeling System (GIMMS) third generation normalized difference vegetation index (3g NDVI) trends from 1981 to 2011 over the Sahel region; temporal profiles of field observations of herbaceous mass over (b) the Mali Gourma region (blue rectangle) and (c) the Niger Fakara region (brown rectangle) (after Dardel et al., 2014b).

AMMA-CATCH stations in Niger and Mali. All sites were net sinks of atmospheric CO_2, but gross primary productivity variations strongly affected the sink strength (Tagesson et al., 2016b).

Paradoxes and Contrasts of the Hydrological Cycle

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

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

The causes for the Sahelian paradox are still debated. For the Niger area, modifications of surface characteristics (soil crusting and erosion) due to the increase in cropping activities and/or land clearing and increased runoff over plateaus have been put forward as an explanation (Séguis et al., 2004; Leblanc et al., 2008; Amogu et al., 2015), while at the Malian pastoral site, where crops are very limited, the drought-induced vegetation degradation over shallow soils plays a crucial role on surface runoff modifications (Gal et al., 2017; Trichon et al., 2018). At the same time, the Sahel is experiencing an intensification of extreme events, recently detected and quantified (Panthou et al., 2014a). More generally, the intensification of precipitation favors groundwater replenishment in the tropics (Jasechko and Taylor, 2015). Nevertheless, the processes that transmit intense rainfall to groundwater systems and enhance the resilience of tropical groundwater storage in a warming world remain unclear. A water table rise subsequent to land clearing has been reported elsewhere in the world (Brown et al., 2005; Scanlon et al., 2006; Taylor et al., 2013). However, a more diverse combination of processes, producing both diffuse and concentrated recharge, appears to be at play in the Sahel. The attribution of the increase in surface runoff and water table level to rain and/or to the modification of the land cover and their relative contributions is a question under discussion (Aich et al., 2015), being a major part of predicting the future evolution of the eco-hydrosystem (Roudier et al., 2014).

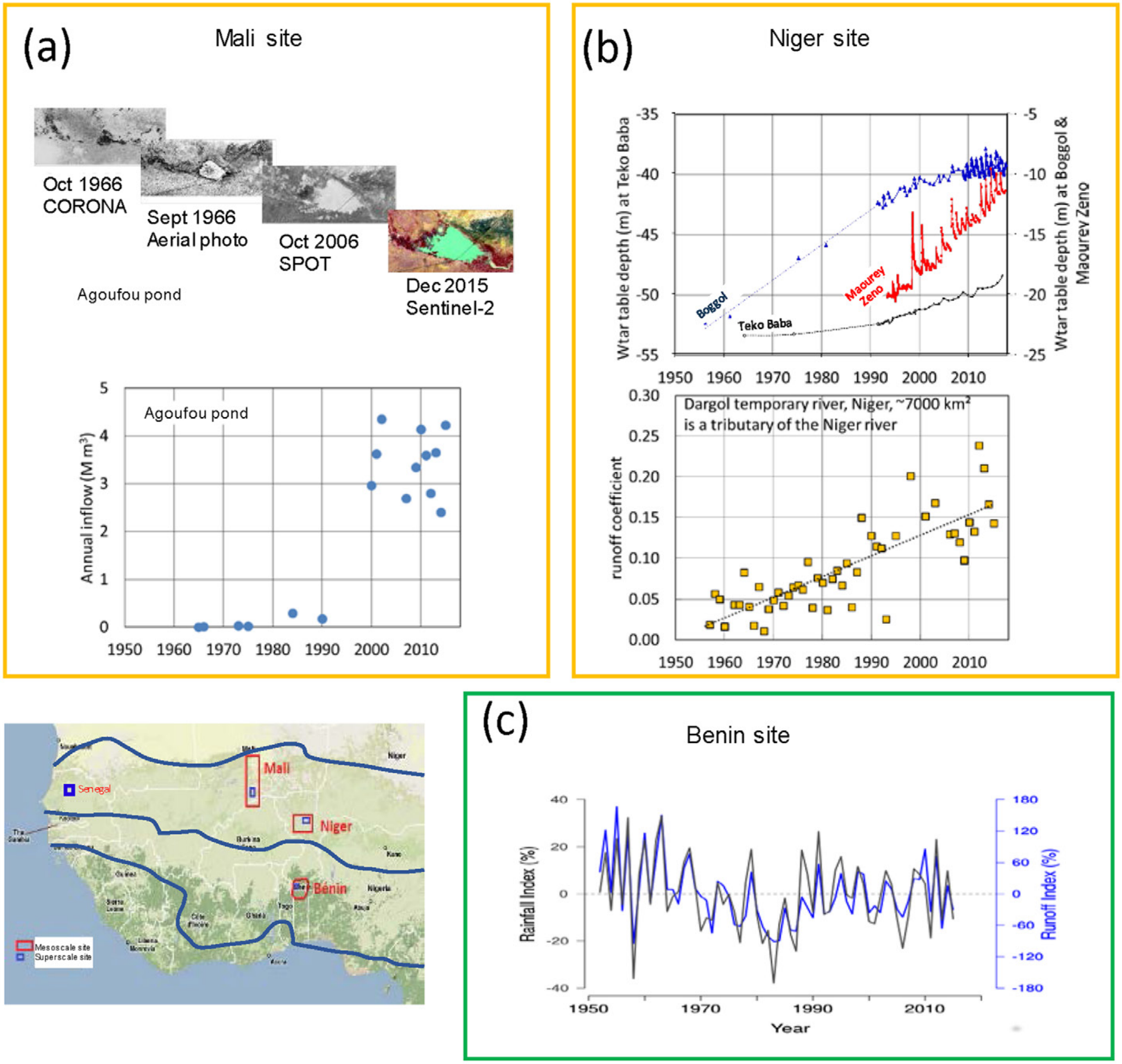


Fig. 6. The hydrological response to global change since 1950 shows (a) an increase in the area of pools at the Malian pastoral site; (b) an increase in river runoff and a water table level rise at the Niger cultivated site; and (c) a co-fluctuation of rainfall and flow indices in the Upper Ouémé basin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

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

The increase in Sahelian stream flows, observed since the beginning of the drought in West Africa, seems to be exacerbated by the modest rise in annual totals of rainfall since the mid-1990s and/or by the intensification of the precipitation regime. Since the middle of the decade 2001 to 2010, there has been an acceleration in the increase in volume of annual floods and an upsurge of floods in West Africa (Descroix et al., 2012a; Sighomnou et al., 2013; Yira et al., 2016). These floods are causing increasing damage in West Africa. Human losses have increased by an order of magnitude since 1950 (Di Baldassarre et al., 2010). This is partly explained by demographic growth, particularly urban growth, which in turn induces a sharp increase in the vulnerability of societies. Therefore, flood forecasting is becoming an increasing priority for West African governments.

Process Studies

The Limits of Models with Global Parameterization

The expertise acquired on land processes in this region and the availability of *in situ* data motivated a specific model intercomparison exercise. The instrumentation deployed over the AMMA-CATCH mesosites in Mali, Niger and Benin provided specific data for (i) forcing the models and (ii) evaluating their capability to reproduce surface processes in this region. About 20 state-of-the-art land-surface models participated to the AMMA Land-surface Model Intercomparison Project Phase 2 (ALMIP2), (Boone et al., 2009). Large differences regarding the partitioning of the water budget components as well as the energy variables were found among models over the Benin site (Fig. 7). Concerning water fluxes, runoff was found to be generally overestimated in the Ouémé watershed (Fig. 7) (Getirana et al., 2017), but also in endorheic areas of the Mali site (Grippa et al., 2017), where Hortonian runoff is the predominant mechanism. The soil description and parameterization have been pointed out as a major issue to address in order to better simulate water fluxes in this area. Concerning evapotranspiration, the multi-model average compared relatively well with observations over the three mesoscale sites, although the spread among models remained important (Grippa et al., 2017). Over the Benin site, the actual evapotranspiration was underestimated during the dry season, which is likely due to the underestimation of root extraction (see section below).

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

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

Evapotranspiration of the Main Vegetation Types

Evapotranspiration is the major term for water balance on the continents (65% on average) yet it is still very poorly documented, especially in Africa. In West Africa, by far the main sources of spatial variability in surface fluxes from a climatological perspective are the regional eco-climatic gradient and the local ecosystem type. Hence, the flux station network in the AMMA-CATCH observatory was designed to sample, with a manageable number of stations (eight), these two main variability sources. The climatology of surface fluxes captured by this dataset allowed to analyze their basic drivers, including for instance the role of plant functional types on evapotranspiration dynamics (Lohou et al., 2014, see section 7.2.1), as well as to validate or develop remote sensing techniques and large-scale models (Tagesson et al., 2017; Gal et al., 2017; Diallo et al., 2017, see section 7.2.1). These two approaches provide ways to upscale observations regionally.

In Southern Sahel, during most of the year, evapotranspiration appears to be water-limited, with the latent heat flux being tightly connected to variations in soil water and rainfall. Direct soil evaporation dominates vapor flux except during the core of the rainy season (Velluet et al., 2014). Depending on water availability and vegetation needs, evapotranspiration preempts the energy available from surface forcing radiation, leading to very large seasonal and inter-annual variability in soil moisture and in deep percolation (Ramier et al., 2009). In Niger, vegetation development in fallow was found to depend more on rainfall distribution along the season than on its starting date. A quite opposite behavior was observed for crop cover (millet): the date of first rain appears as a principal factor of millet growth (Boulain et al., 2009a). On a seven-year period, mean annual evapotranspiration is found to represent ?82–85% of rainfall for the two systems, but with different transpiration/total evapotranspiration ratio (∼32% for fallow and ∼40% for the millet field), and different seasonal distribution (Fig. 8). The remainder consists entirely of runoff for the fallow (15–17% of rainfall), whereas drainage and runoff represents 40

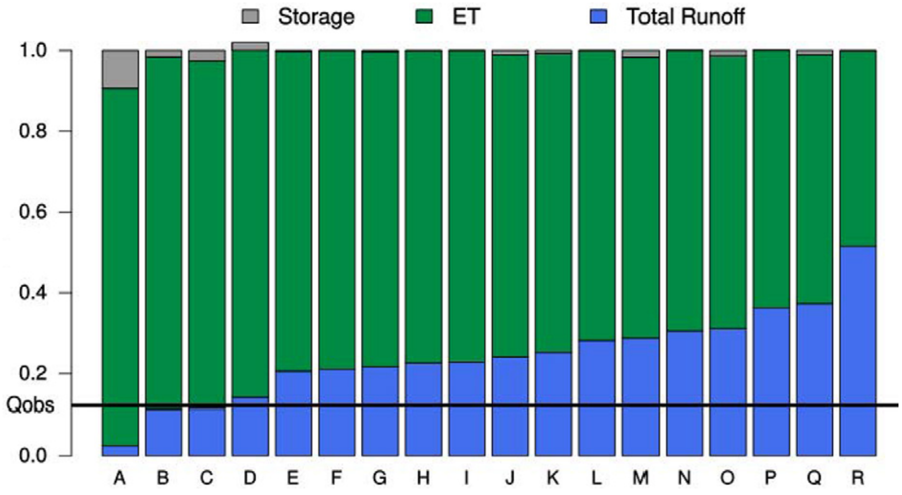


Fig. 7. Annual water cycle main components, including storage, evapotranspiration (ET), measured runoff, and total runoff) simulated by 12 land surface models (ALMIP2 experiment) for the Upper Ouémé basin (Benin) Simulated total runoff can be compared with observed runoff (Q_{obs}).

to 60% of rainfall for the millet field (Velluet et al., 2014). For the dominant shrub species in Sahelian agrosystems (*Guiera senegalensis* J.F. Gmel), sensitivity to drought was found significantly higher in mature shrubs than in resprouts from widespread yearly cuts, and suggested that this species is likely to be vulnerable to projected drought amplification (Issoufou et al., 2013).

In Northern Sahel, the magnitude of the seasonal cycle of the sensible heat, latent heat, and net radiation fluxes measured above the Agoufou grassland in Mali can be compared to the data from Niger (Tagesson et al., 2016b). The difference in latitude results in a shorter rainy season in Mali and the presence of shrubs in the fallow sites around Niamey, which have a longer leaf-out period than the annual grasses of the Agoufou grassland, where woody cover is 2% only (Timouk et al., 2009). The maximum daily evapotranspiration rate is observed for a flooded forest, which maintains losses in the order of 6 mm d^{-1} during the flood. In this lowly extended cover (~5% of the landscape), the annual evapotranspiration is more than twice the precipitation amount, indicating substantial water supply from the hillslope.

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

Advances from Field Data–Process Model Integration

Observational shortcomings (including time gaps, measurement representativeness, accuracy issues or even the inability to simply observe a given variable of interest) limit the field data potential for assessing energy and water budgets over time and space. Conversely, field data are crucial to elaborate or evaluate process models, the only tool allowing to assess unobserved components (soil evaporation, plant transpiration, drainage). Hence, various developments or applications of ecohydrological and hydrogeological process modeling were intricately constructed with AMMA-CATCH field data, of which only a few can be presented here.

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

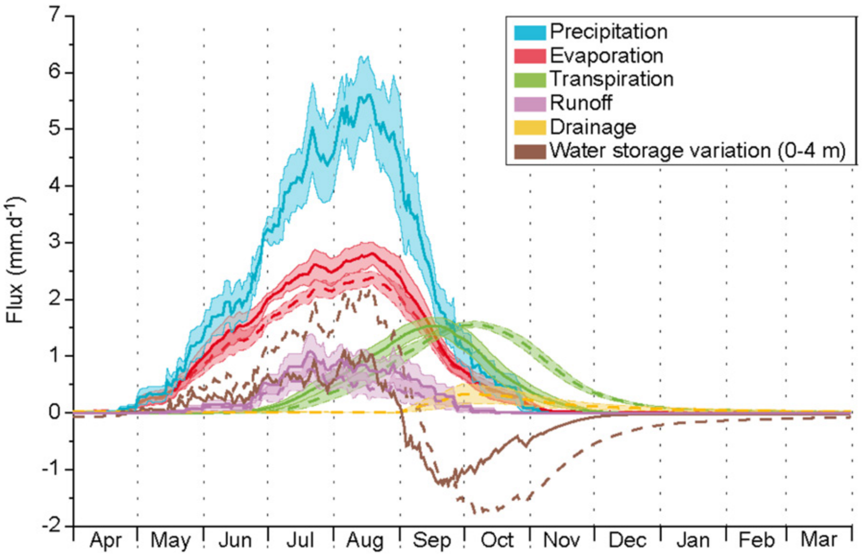


Fig. 8. Estimated mean seasonal courses of water cycle components for fallow (solid lines) and millet (dashed lines) plots: fluxes and rate of storage change in the 0- to 4-m soil column. Means are computed across years and for a 30-d running window. Light-colored intervals show a variation of ±1 standard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

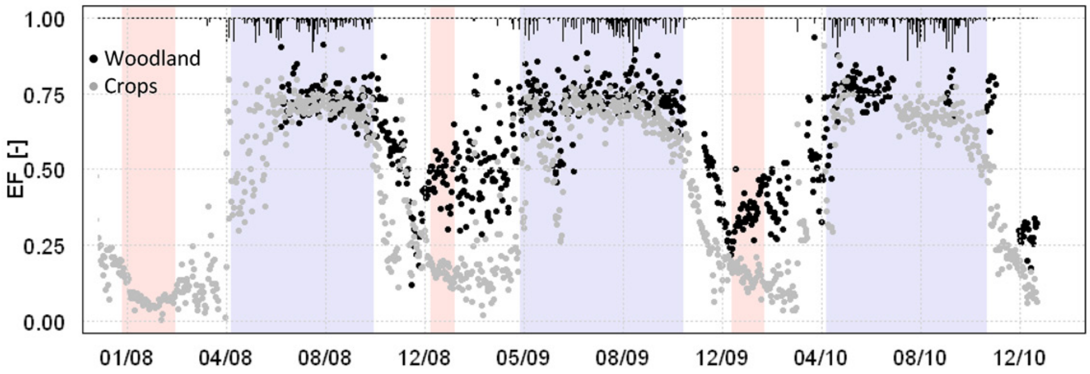


Fig. 9. Midday evaporative fraction (EF) at Nalohou cultivated area (gray dots) and Bellefoungou woodland (black dots) in Benin during 2008 to 2010 (modified from Mamadou et al., 2016).

reevaluated mesoscale recharge from 6 mm yr^{-1} in the initial model to 23 mm yr^{-1} (Boucher et al., 2012).

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

Society Applications

In the context of research on subjects such as "hydrosphere", "critical zone" and "water cycle" in the Anthropocene, eminently societal questions arise, as water is a resource for human communities. This section attempts to make the transition from water as a physical object, to water as a resource, i.e. how it is actually used by people (as blue or green water). To do so it is necessary to integrate the idea that water resources are not only natural, but a nature/culture co-production. We present below the work carried out by the AMMA-CATCH observatory to contribute to these societal issues.

Characterization of the Rainfall Hazard

Flood hazard in West Africa is increasing (Descroix et al., 2012a; Wilcox et al., 2018), as a result of various factors previously noted (demographic pressure, hydrological intensification). In addition, urbanization and demographic growth have made West Africa more vulnerable to hydrological hazards (Tschakert, 2007; Di Baldassarre et al., 2010; Tschakert et al., 2010). Characterizing extreme hydrological hazards is becoming an urgent request in order to design water related infrastructures (flood protection, dam, bridge, etc.).

Intensity–duration–frequency (IDF) curves and the areal reduction factor (ARF) aim at describing how extreme rainfall distribution changes across space and time scales. Both tools are regularly used for various applications (structure design, impact studies). As climate is changing, the hydrological standard in West Africa must be revised (Amani and Paturel, 2017).

The dense networks of tipping bucket rain gauges of the AMMA-CATCH sites, and the required methodological developments (Panthou et al., 2014b) allowed to implement tools such as IDF in different countries (see Panthou et al., 2014b for Niger; Agbazo et al., 2016 for Benin; Sane et al., 2017 for Senegal). The new IDF curves obtained for Niamey airport (Fig. 10a) have already been requested by different organisms and end-users. These curves have been obtained using the methods developed in Panthou et al.2014b and Sane et al. 2017. Nonetheless, IDF and other indexes are implemented using a stationary hypothesis, which is undermined by the recent results on the intensification of the rainfall regime. The 20-years return level for daily rainfall, estimated using the method developed by Panthou et al. (2012), which was 90 mm in 1970 is now rising to 105 mm (+17%, see Fig. 10b). Two consequences arise from this: (i) end-users must be aware of such changes and (ii) scientists must develop tools taking into account climate non-stationarity.

Groundwater Availability

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

Reducing the rate of unsuccessfully drilled boreholes into hard rock aquifers in Benin: In the past several decades, thousands of boreholes have been drilled in hard rocks of Benin

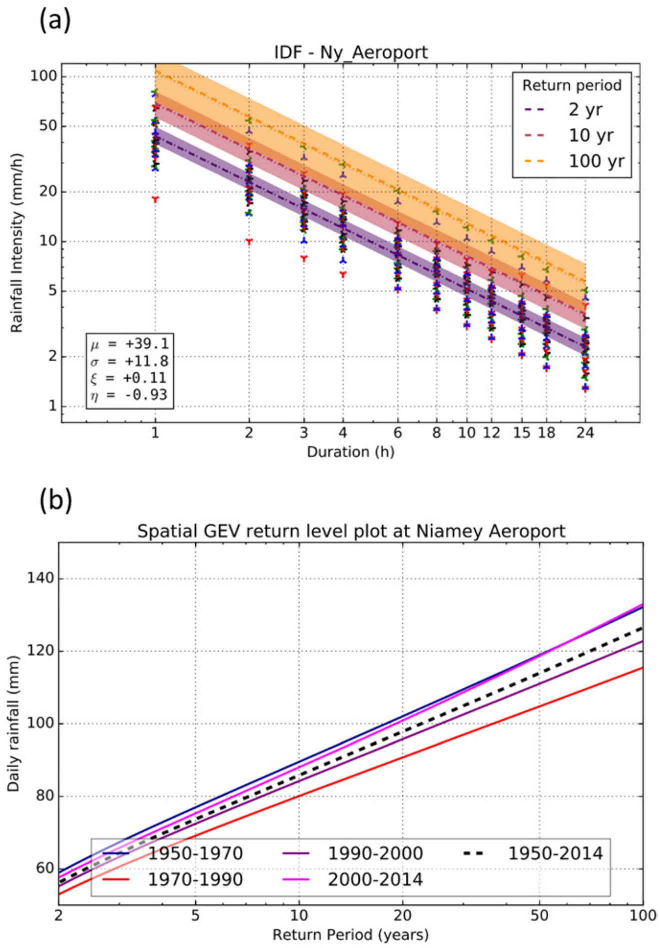


Fig. 10. Characterizing extreme hydrological hazards at Niamey (Ny) airport: (a) intensity–duration–area–frequency (IDF) curves for resolutions between 1 and 24 h, and (b) estimation of the daily rainfall return level for different 20-yr periods from 1950 to 2014; ξ is the shape parameter of the generalized extreme value (GEV) and η is the temporal scaling of the IDF curves.

to supply human communities with drinking water. However, the access to drinking water is still poor and it not improved significantly in the last years (e.g. 63% in 2012 and 67% in 2015) despite a great effort put into drilling new boreholes by the community in charge of water development.

The groundwater storage in the upper Ouémé is 440 mm ± 70 mm equivalent water thickness (Vouillamoz et al., 2015). As human abstraction (0.34 mm yr^{-1} ± 0.07 mm) is far less than the natural discharge (108 mm yr^{-1} ± 58 mm), they conclude that increased abstraction due to population growth will probably have a limited impact on storage as far as water is used only for drinking and domestic uses. However, people have limited access to groundwater because a significant number of drilled holes do not deliver enough water to be equipped with a pump and hence are abandoned (i.e. 40% on average in Benin). This high rate of drilling failure is mainly due to the difficulty of determining the appropriate location to sit the drilling, because of the high geological heterogeneity of the hard rock. Recent studies (Alle et al., 2018) showed that the approach currently used in Benin to sit boreholes is not appropriate and can partly explain the high number of drilling failures. The target to sit a borehole should be updated (i.e. from tectonic fractures to weathered units) and the methods used to investigate the targets should be changed (i.e., one-dimensional resistivity techniques should be replaced by two-dimensional ERT). Moreover, this new approach could save money by reducing the number of unsuccessful drillings, even if it improves the success rate by only 5%. This promising approach is already taught in universities and hopefully will soon be applied by companies that drill wells.

Taking advantage of the water table rise in Niger: In Sahelian countries, the development of irrigated agriculture is one of the solutions to avoid repetitive food crises. Nazoumou et al. (2016) demonstrated that increasing low-cost groundwater irrigation represents a long-term solution, using shallow, unconfined perennial groundwater, widely distributed in this region. The long-term rise of the water table observed in southwestern Niger since the 1950s (see above) is such that it outcrops in certain places and is close to the surface in large areas (Torou et al., 2013). Data analysis of AMMA-CATCH observatory and operational services (Nazoumou et al., 2016) demonstrates that ∼50,000 to 160,000 ha (3–9% of present-day cultivated areas) could be turned into small irrigated fields using accessible shallow groundwater (water table depth ≤20 m). A map of the potential irrigable lands as a function of the table depth has been established (Fig. 11) to help stakeholders make decisions. The estimated regional capacity for small-scale irrigation, usually estimated with surface water, is doubled if groundwater resources are also considered.

Sustainable Land Use

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

To go further, a new type of soil and water conservation work was tested on the plateaus, starting in 2016. The principle is to copy the natural water harvesting of the tiger bush (Galle et al., 1999), defended by many researchers (Ambouta, 1984; Torrekens et al., 1997; Seghieri and Galle, 1999). These experiments are still

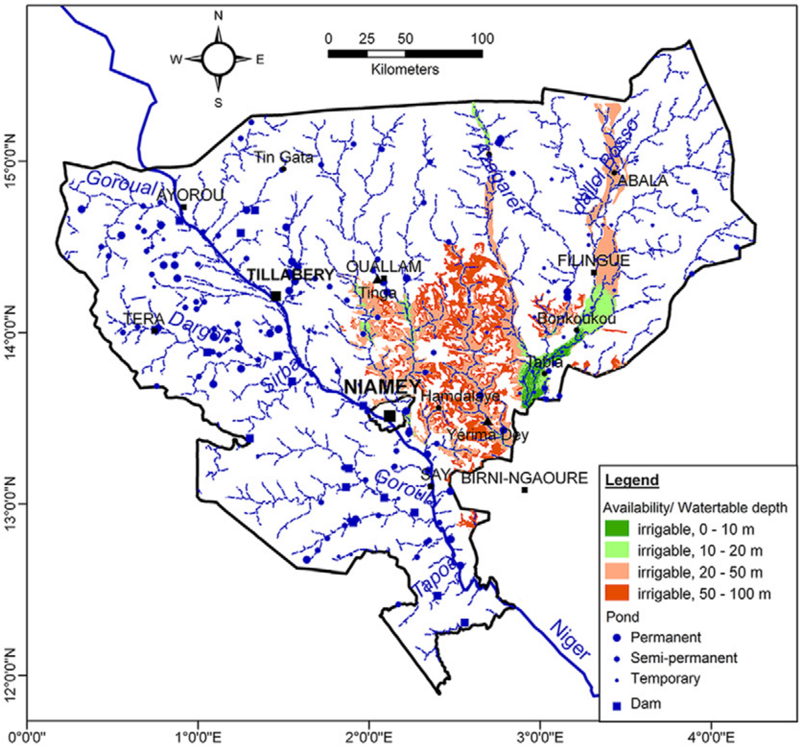


Fig. 11. Potential irrigable lands in the Niamey region (Niger) as function of the water table depth (after Nazoumou et al., 2016).

ongoing and the impact of these soil management practices will be assessed for the long term.

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

The spatial heterogeneity in forage availability and annual production (Hiernaux et al., 2009b) justify the mobility of the herds as a major adaptation strategy of the pastoralists to optimize livestock feed selection (Turner et al., 2014). Yet the rapid expansion of the cropped areas, the densification of roads and other infrastructures (dams), and the rapid urbanization since the mid-20th century has strongly reduced the area of rangeland and multiplied the obstacles to livestock mobility both locally and regionally (Turner et al., 2014). It weakens livestock productivity, close to the limit of technical viability, especially in the less mobile agro-pastoralist herds (Lesnoff et al., 2012). The main way to enhance livestock production at the height of the rapidly growing demand is thus to secure herd mobility and access to common resources (Bonnet, 2013).

Future Perspectives

West Africa as a whole is a region in transition, as highlighted by the reported changes—in the rainfall regime, the hydrological intensification, and in some ecosystem components. Climate change, indirect impacts of population growth (land use–land cover changes, urbanization, etc.), or a combination of both have been put forward to explain the observed eco-hydrological changes in the last 60 yr. However, a clear, quantitative attribution of these changes to climate vs. the diverse human impacts largely remains to be uncovered. Moreover, the eco-hydrological changes observed in the Sahel in the last decades (runoff intensification despite rainfall deficit, subsequent re-greening with still increasing runoff) suggest that some areas may pass tipping points and shift to new, ill-defined regimes. The West African monsoon system has been identified as a possible tipping element of the Earth system (Lenton et al., 2008). In this context, several key science questions will have to be addressed in the future, as described below.

Detection of Change in Eco-hydrological Systems

The term *change* as used here refers to any alteration of the forcing factors (e.g., rainfall or incident radiation) and of the system response (e.g., groundwater recharge) that is not due to natural variability. Since the signal/noise ratio in eco-hydro-meteorological series is generally low due to the internal variability of the climate (Hawkins and Sutton, 2009; Hawkins, 2011; Deser et al., 2012), change detection requires long-term observations at space–time scales consistent with the process to detect. Despite the relatively low spatial coverage compared with the regional West African system, AMMA-CATCH observations have proven their usefulness to detect such changes (e.g., for vegetation [Dardel et al., 2014b], for fine-scale rainfall intensities [Panthou et al., 2018], and for runoff [Amogu et al., 2015; Gal et al., 2016]). Indeed, these high-resolution observations from a few seconds to hours on dense networks fill a gap in measurements at fine space–time scales. Thus, AMMA-CATCH datasets contribute to the documentation of regional trends when combined with datasets from other observing systems, such as national measurement networks, which measure the same variables with similar sensors or by using other sources of data, such as remote sensing.

Fig. 12. The subsoiling installation drastically limits runoff in Tondi Kiboro, Niger (photo by A. Ingatan Warzatan and A. Boubacar Na'Allah).

Change Attribution

The attribution of a detected hydrological change to one or several factors requires causal models, which must take into account the most relevant processes influencing the system (Merz et al., 2012). These processes include the links between the different components of the system (water tables, land cover, land use, etc.), as well as the main feedback loops driving vegetation–hydrology processes. Irrespective of their nature, these models have to give "good results for good reasons" and be robust (i.e., remain valid across a range of different conditions). This implies that they must realistically represent the key processes based on either physical principles, process parameterizations, or a mixture of the two; moreover they must operate at the relevant spatiotemporal scales. These models must be able to simulate system trajectories in response to gradual changes in forcing, and disentangle the roles of forcing, initial conditions, and internal variability in the observed behavior. The development of modeling tools dedicated to the attribution question in eco-hydrology is clearly a challenge for the critical zone community in West Africa.

Improvement of Physical Process Representations in Land Surface Models

Some components of the energy and water budgets remain insufficiently understood across the area, such as the estimations of evapotranspiration, especially at scales larger than the flux station footprint, the changes in groundwater processes (and hence of water resource renewal) linked to land use land cover changes, three-dimensional spatial variability of soil properties, and the mechanisms underlying rainfall intensification. Despite progress made in the last decade in Earth system models, some specific features of the critical zone in these tropical hydro-systems are still poorly represented, leading to biases in simulations (e.g., ALMIP2 results): surface–groundwater interactions and evapotranspiration and its links with vegetation through the representation of the root zone. This is all the more true in view of the current developments of hyper-resolution modeling of the critical zone (Maxwell and Condon, 2016), which allows simulation on fine, three-dimensional grids but for which the identification of realistic parameter values remains an issue (Prentice et al., 2015).

A New Generation of Satellite Products

Recent and future satellite missions will provide new opportunities with improved spatial and temporal resolution (Sentinel, GPM, ECOSTRESS, SWOT, Planet/RapidEye) and/or addressing new variables of the eco-hydrosystems (vegetation fluorescence: FLEX; global mass of trees: BIOMASS). In situ observations such as those by AMMA-CATCH provide the basis for Cal/Val activities for these new satellite products but also a ground reference to evaluate the coherence of classical remote sensing products over a long time span (Hector et al., 2013; Dardel et al., 2014a). The AMMA-CATCH observations and community also contribute to the development of new satellite products, and the innovative potential of the soil-moisture-based rain product is now being tested on a global scale with European Space Agency funding (Román-Cascón et al., 2017).

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

An associated, crucial issue is to secure, in the long term, the funding of observation systems. The location and geometry of AMMA-CATCH are unique but imply specific operation costs. The West African countries pledged to support climate and environmental monitoring in the Nationally Determined Contributions (NDCs) taken at COP21 in Paris, but the Green

Climate Fund is not yet in place, while the climatic and anthropogenic changes are underway.

Acknowledgments

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