The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger: investigating water cycle response to a fluctuating climate and changing environment


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The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger – Investigating water cycle response to a fluctuating climate and changing environment


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Introduction

In the semiarid Sahelian belt, the generalised rainfall deficit of the 1970s and 1980s reached 25–50%, and continued almost unabated until the end of the 20th century (Lebel and Ali, this issue). This drought had especially severe consequences in the cultivated Sahel (roughly the 400–800 mm yr⁻¹ rainfall band stretching east-west across Africa, acknowledging that mean isohyet locations fluctuate over time and that different criteria could be used), which is one of the most densely populated rural areas in West Africa (see Fig. 3 in Lebel et al., this issue). Relying mainly on traditional techniques, local rain-fed agriculture is very sensitive to highly variable precipitation patterns. The AMMA-CATCH¹ Niger mesoscale site (ACN), located at latitude 13–14°N in SW Niger (see Fig. 8 in Lebel et al., this issue, for a location map of the three AMMA-CATCH mesoscale sites), is typical of a large fraction of the cultivated Sahel. It is thus a highly appropriate area for documenting interannual variability and decadal-scale trends in climate, land use, ecosystem, and hydrological cycle, and for improving our understanding of the mechanisms of interaction between these factors in one of the most challenging regions in the world for sustainable development.

In contrast to the northern Sahel, where the AMMA-CATCH Gourma site (15–17.5°N) is located and where rangeland is the

¹ Please see list of acronyms and specific terminology in Appendix.
dominant land use (Mougin et al., this issue), the two major activities in the cultivated Sahel are mixed crop-livestock agriculture and wood harvesting for cooking fuel, which are rapidly modifying the land cover. As a consequence, the response of the terrestrial biophysical system to the variability of the monsoon system at different scales in space and time (decadal, interannual, seasonal and sub-seasonal), even though strong, is blurred at the long timescales by man-induced environmental changes. Separating the role of climate from that of local human activity in the drastic changes observed in the hydrological cycle over the past decades is thus a major issue for the cultivated Sahel.

While the main climate-induced difference between the ACN and Gourma sites is land use, the major such difference between the ACN area and the southern AMMA-CATCH site of Ouémé in Benin (Sudanian climate, 9.5–10.5°N) is the hydrological environment. The Ouémé catchment, like most of the Sudanian or Guinean catchments located south of 10°N, or like the very large rivers that combine hydro-climatic regimes (Guinean, Sudanian, Sahelian), such as the Rivers Senegal or Niger, had their discharges reduced by the drought in a higher proportion than rainfall (Olivry, 2002; Descroix et al., this issue). By contrast, in SW Niger, both surface and ground water resources have been increasing for several decades, despite the duration and intensity of the drought (Leblanc et al., 2008). While degradation of soils and land cover provides a logical qualitative explanation for this phenomenon (Favreau et al., 2009), there is still no consistent quantitative scheme able to account for this spectacular change at any significant scale. The long-term monitoring investment in this region has thus specific goals in terms of understanding and modelling the complex relationships between climate, environment and the water cycle in the cultivated Sahel.

The ACN benefits from a rich history of hydrological observations that began with the EPSAT-Niger (Lebel et al., 1992) and HAP-EX-Sahel (Goutorbe et al., 1997) experiments in the early 1990s.
Substantial background data and knowledge exist on rainfall distribution (Ali et al., 2003), runoff processes (Estèves and Lapetite, 2003; Cappelaere et al., 2003), aquifer replenishment (Favreau et al., 2002a), or bioclimatology and land–atmosphere exchanges (Dolman et al., 1997). In the ACN area, the River Niger roughly separates the regional domains of endorheic and exorheic hydrology, to the north-east and south-west, respectively (Fig. 1). Endorheic hydrology, with small-scale catchments mixing both highly runoff-prone and infiltration-prone surfaces, is typical of many arid to semiarid areas and raises challenging questions and difficulties for field observation as well as for modelling, thus making the ACN of particular interest to hydrologists. Beyond hydrology and associated bio-physical processes, a large corpus of data and knowledge exists in the ACN area from a great variety of past or current environmental studies, on such important topics as wind erosion (Rajot et al., 2008), soil fertility (de Rouw, 2004; Renard et al., 1997), ecosystems (e.g., Mahamane et al., 2007), as well as on agro-economic and social issues (e.g., La Rovere et al., 2005).

The overall objectives and strategy of the AMMA-CATCH observation programme are described by Lebel et al. (this issue), in the wider context of the AMMA studies (Redelsperger et al., 2006). The aim of the present paper is to provide a specific overview of the ACN study area (“Study area”), of the programme and rationale for recent data acquisition at this site (“ACN data acquisition and monitoring programme”), and of the current state of knowledge (“A short review of current knowledge”). Many results obtained on the area’s vegetation and hydrology are detailed in several other papers of this special issue.

Study area

The ACN observatory (Fig. 2) encompasses an area extending roughly 1.5° in longitude by 1.2° in latitude, surrounding the city of Niamey (Republic of Niger) and representing a total surface area in the order of 20,000 km². This area is an extension of the so-called square-degree of Niamey (2–3°E; 13–14°N) used for the HAPEX-Sahel experiment. This extension, mainly to the west and north, was dictated by hydrological considerations stemming from analysis of HAPEX-Sahel data, including characteristics of the aquifer in particular.

Climate

The study area has a typical semiarid tropical climate, characterized by a long dry season (from October to May) followed by a single wet season of 4–5 months, peaking in August. Daily maximum temperatures run above 40°C from mid-March to mid-May, and remain continuously above 32°C except during the August monsoon peak. Daily minimum temperatures are always above 20°C, except in November-February when the dry Harmattan wind blows; temperatures can drop to 10–15°C in December–January. Rainfall generally varies in the 400–600 mm yr⁻¹ range in the Niamey region, and is typically produced by fifteen to twenty “squall lines” giving 15–40 mm of rainfall on average and around twenty smaller mesoscale convective events. The ACN site is located on one of the major westbound squall line routes across the central Sahel, most of which originate in the Air Mountains (17–19°N in North-Central Niger) and the Jos Plateau (12°N in Central Nigeria) (Shinoda, 2000; Mathon and Laurent, 2001). The regional climatology exhibits a negative northward gradient of 1 mm km⁻¹ in long-term mean annual rainfall (Fig. 3a), producing a difference of around 100 mm between the south (mean 1990–2007 rainfall of 575 mm yr⁻¹ at 13°N) and the north (465 mm yr⁻¹ at 14°N) of the ACN area (Fig. 3b). Over the 1970–1997 period, the rainfall deficit was about 30% relative to the 1950–1969 period (see Fig. 4b in Lebel and Ali, this issue).
Geology

Most of the ACN study area belongs to the large (600,000 km²) Iullemmeden sedimentary basin, while the western edge is part of the plutonic Liptako Gourma massif. The latter is part of the West African craton and consists of extensively weathered pre-cambrian gneisses, schists and granites. The boundary between the two formations roughly follows the River Niger (Fig. 1a). The upper part of the Iullemmeden basin is the Continental Terminal (CT series, 150,000 km²), composed of loosely cemented clays, silts and sands of continental origin from the Mio-Pliocene periods. The thickness of the Continental Terminal, which may reach 450 m, is ~250 m in our study area, overlapping the West African craton. The top layer (CT3, ~100–120 m thick) is the main aquifer of interest in the area, capped with dissected laterite plateaus (~27% of surface area) and carved along the eastern edge of the ACN domain by the large Dal-lol Bosso fossil valley. Quaternary alluvial sands (in valleys) and aeolian deposits (plateaus and valleys), dating back to former drier or wetter periods, cover some parts of the Continental Terminal.

Land morphology and soils

Fig. 4 gives a synthetic view of the landscape, showing a typical toposequence in the Niamey area. From top to bottom, it includes a piece of laterite plateau, with its steep edge, and the predominately sandy, gently-sloping hillslope, generally separated into

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two parts by a mid-slope indurated layer, and incised by a network of gullies. In the sandy valley bottom, a large fossil river bed ("kori"), dug during wetter periods of the Holocene, hosts a string of isolated ponds during the rainy season. Regional topography is illustrated by the 40-m resolution DEM of Fig. 5 (top-right), for a typical 1740-km² section of the ACN area.

Soils are essentially of the tropical ferrallitic type, sandy and weakly structured (D’Herbès and Valentin, 1997). On the generally hardly-cultivable laterite plateaus, thin acidic lithosols directly overlie the ferruginous ironpan. Hillslopes are covered by 0.5–8 m-thick sandy ferruginous soils, sometimes interlaid with other ironpan levels. Valley bottoms have weakly leached sandy ferruginous soils. All are rich in sesquioxides (Al₂O₃ and Fe₂O₃), poor in organic matter (0.5–3%), and have little fertility (low nitrogen and phosphate content). Their fragile structure makes them highly prone to rain-induced surface crusting and to water and wind

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**Fig. 4.** Land morphology in a typical toposequence of ACN, from plateau to valley bottom (after Massuel, 2005, modified in Leblanc et al., 2008).

**Fig. 5.** Change in land use/land cover over a 2-decade period in a typical 400-km² section of ACN (estimated by unsupervised classification of SPOT imagery of mid-september, 1986 and 2005). Top-right: shaded view of 40-m resolution DEM for 1740-km² section of ACN, with contours of supersite and of land use extract (after Elizondo et al., 2002). Wankama and Tondi Kiboro pilot catchments shown as ovals on land use maps.
erosion. These processes, generally favoured by land cultivation and fallowing cycles (Valentin and Bresson, 1992; Valentin et al., 2004), transform permeable soils into high runoff producing surfaces. Their hydrodynamic properties were analyzed by Vandervaere et al. (1997).

Vegetation, land cover/land use

The vegetation cover consists of a patchwork of three distinct basic units (D’Herbès and Valentin, 1997): tiger bush on the plateaus, fallow savanna and pearl millet fields on the sandy slopes. Tiger bush consists of alternating thickets and bare strips (Fig. 6a). The dense vegetation strips, which dominate in natural state (Ambouta, 1984), mainly consist of ligneous species such as Combretaceae (Combretum micranthum, Combretum nigricans, Combretum glutinosum, Guiera senegalensis). They are now extensively exploited for fuel wood (with considerable demand from the city of Niamey) and pasture, contributing to their severe degradation. Hillslopes and valleys were initially covered by open wooded savanna, with higher tree density in the valley bottoms. The savanna now remains only as fallow fields of various ages (Fig. 6b and c). The woody layer is dominated by the ubiquitous G. senegalensis shrub, with some remaining trees such as Combretaceae (see above), Pilostigma reticulata, Balanites aegyptiaca, Acacia spp, Faidherbia albida, and a few Prosopis africana. The grass stratum mostly consists of annual species, mainly Graminaceae (Cenchrus biflorus, Aristida mutabilis) and Dicotyledons (Zornia glochidiata, Mitracarpus scaber), with large annual variability (Hiernaux et al., this issue).

While crops used to cover only small acreages, clearing of the savanna over the recent decades has led to nearly all lands on hillslopes and in valleys being now either cultivated (with traditional rain-fed millet essentially, Fig. 6d), fallowed, or barren due to aeolian and hydric erosion after over-exploitation. In the valley bottoms, the original lush vegetation has largely disappeared and has been locally replaced by specific water-demanding crops (cassava, groundnut, or sorghum). The length of fallow periods has decreased considerably (Valentin et al., 2004), to ~2–5 years, threatening crop productivity in the absence of sufficient fertilizer input. In the whole Republic of Niger, millet productivity is estimated to have decreased by one-fifth since the 1950s (Fig. 7a), increasing food supply difficulties and cropped area requirements for the fast-growing population (Fig. 7b). As in many parts of the Sahel, crops and livestock are associated in a mixed system, through cohabitation of populations of farmers and pastoralists in particular, allowing fertilization of cropland by nutrient transfer from grazed land (Schlecht et al., 2004).

Hydrology

Unlike the Liptako region (SW of the River Niger), the sedimentary basin (NE of the River) is characterized by endorheic surface hydrology, with no presently active large-scale hydrographic network (Fig. 1): small-sized catchments (generally limited to the few km$^2$ of a hillslope, up to a few tens of km$^2$ at most) feed surface runoff to short sandy gullies, which end up into temporary ponds or infiltrating areas. As in most of the Sahelian belt, streamflow is produced by Hortonian surface runoff, from short, intense rain-
ACN data acquisition and monitoring programme

Rationale and objectives

Initiated by specific studies in the late 80s–early 90s, such as EPSAT-Niger for mesoscale rainfall variability (Lebel et al., 1992) or SEBEX for surface energy balance (Wallace et al., 1991), research in the ACN area was gradually extended over the 90s to all components of the Sahelian water cycle. Spurred by the HAPEX-Sahel experiment, which centered on land–atmosphere interactions, hydrological studies rapidly focused on the puzzling dynamics of the water cycle accounting for the Niamey paradox. A substantial hydrological monitoring network, covering rainfall, pond water, and groundwater, had thus been operating in this area for several years when the AMMA-CATCH initiative was undertaken at the turn of the century. Several key questions needed further investigation to help understand and predict the variability of the Sahelian water cycle in relation to climate variability, vegetation change, and the overall dynamics of the coupled soil-vegetation–atmosphere system. Major pending issues were: (i) to refine estimates of the water balance, from point to meso and intraseasonal to interdecadal scales; (ii) to improve understanding of key processes that couple the different compartments of the hydrologic cycle, and more specifically interactions between water and vegetation; (iii) to develop, calibrate, validate and couple models of these processes and of their interactions, that take full account of the specifics of the Sahelian environment, and (iv) to understand scale transitions for the major processes and variables, and, in particular to analyze the space-scale non-linearities of hydrological processes when moving from the point or local scale to the endorheic unit, and up to the scale of the whole meso-site.

Table 1 further illustrates some of the key water cycle questions facing the ACN research community.

In this context, large benefits were anticipated from further observations and experiments at the SW Niger site, for the following reasons:

- combined with data collected over the previous decade, new data would allow further documenting the very large annual and decadal variability of biophysical processes and related variables, whether caused by climate or human activity;
- new field or remote sensing instruments and techniques were offering opportunities to gain more insights into – and develop models of – the processes that control the water cycle in the region, such as hydrology-vegetation coupling mechanisms or deep infiltration/aquifer recharge, and
- better time–space integration of physical and biological observation plans, over several full seasonal cycles, could greatly improve our knowledge of process interactions and their variability, and provide coherent, informative datasets needed for comprehensive model development.

Hence, a renewed field programme was initiated in 2001, with the aim of providing extended time series, denser time–space
sampling, observation of new variables not monitored previously, and more accurate measurements through a new generation of instruments. In addition to deployment of new instrument types, a large part of the AMMA-CATCH programme in Niger consisted in both intensifying and re-shaping the pre-existing network.

**Temporal and spatial strategy**

Following the wider AMMA agenda (Lebel et al., this issue), this new phase of field instrumentation was organized as a nesting of observation periods. A “LOP” (Long Observation Period, 2001–
hydrologic monitoring network was built in 2001, largely through the consolidation of pre-existing sets of ground instruments from HAPEX-Sahel and subsequent projects, to document the interannual variability of the mesoscale water cycle. The “EOP” (Enhanced Observation Period, 2005–2008) programme was set up to enable investigation of land processes over a range of scales both in space (from local to meso) and time (from event to seasonal). For this purpose, the LOP monitoring network was densified and extended to cover vegetation dynamics, catchment and erosion processes, and the energy budget, in order to capture the major physical and biological processes associated with the Sahelian water cycle. Linkages with recent – such as ADEOS, the A-TRAIN, GRACE and MSG – and future – such as SMOS and Megha-Tropiques – satellite missions were also part of this enhanced experimental design.

The ACN setup was designed as a spatially-nested structure of sites, including two meso-scale sites, a supersite, two elemental endorheic units, and the plot or point scale:

- at the mesoscale, a 16,000 km² rectangle (denoted as the ACN window, Fig. 2) is the support of continued and refined studies on the interannual and intraseasonal variability of rainfall, based on homogeneous long-term series at fine time resolution, with a spatial density unparalleled in West Africa;

![Fig. 9. Maps of Wankama (a) and Tondi Kiboro (b) local catchment sites.](image-url)
• a second mesoscale site, the Kori de Dantiandou (KD) basin (5650 km²), is mostly included in the ACN window (Fig. 2). Its boundaries were defined from the geometry of the aquifer and of its piezometric depression, in order to delineate a consistent hydrological entity that would facilitate modelling and the study of annual water balance closure (Massuel, 2005). Hence, while the “historical” ACN window is a reference in providing a homogeneous climatological framework for ACN studies, the KD basin is the reference domain for mesoscale water cycle and water budget studies;

• a supersite was defined as a composite of endorheic areas (Fig. 8) covering 1760 km² in the Fakara region, central to the KD basin. It was delimited so as to enable more detailed and accurate water cycle and water budget analyses, incorporating high-resolution satellite data, while representing a substantial sample of endorheic units;

• at the local scale, two typical endorheic gully catchments (the Wankama and Tondi Kiboro catchments, with areas of ~2 and 0.2 km², respectively; Fig. 9) were selected for detailed field studies of basic hydrological and vegetation processes. In SW Niger, such catchments, corresponding to typical catena units, represent the pivotal scale for surface and vadose zone processes, beyond which any direct spatial dependence can reasonably be neglected. Within these two pilot catchments, point- or plot-scale instruments provide hydrological and vegetation data at the smallest scale.

The LOP programme focuses primarily on the two mesoscale sites, whereas the EOP programme covers the range of scales from local to meso. Table 2 summarises the temporal and spatial structure of the ACN observation system. Note that, in addition to the EOP setup, the AMMA SOP (special observation period) programme in 2006 (AMMA-ICIG, 2006) included intensive monitoring of the atmosphere above the ACN area and the central Sahel, allowing for comprehensive concurrent observation of the free atmosphere, boundary layer and ground fluxes.

Hydrological observations

A summary presentation of the hydrological instruments deployed in the field in the framework of AMMA-CATCH Niger appears in Table 3. The LOP network essentially consists of 30 recording rain gauges and 174 village wells with monthly stage readings (Fig. 2), as well as continuous stage recording in five endorheic ponds (Fig. 8) and piezometric recorders in four aquifer boreholes in the vicinity of the Wankama pond (Fig. 9a). The rain gauges have been in operation since 1990, while the other observations began in 1992. The rain-gauge network was designed to provide good accuracy on the annual areal rainfall over the ACN window, as well as on the statistical properties of event rainfall at the mesoscale and at the sub-event/point scale (Lebel and Le Barbé, 1997). The network of wells yields the seasonal water table dynamics at the mesoscale over the KD basin. The pond stage recorders supply information on event catchment response at the scale of the elemental endorheic unit (Desconnets et al., 1997; Peugeot et al., 2003) and on intra-seasonal dynamics of infiltration from the ponds (Martin-Rosales and Leduc, 2003). The piezometric recorders were installed to investigate the local water table dynamics produced by a recharging pond. All pond and groundwater recorders are located within the supersite.

For the EOP, a very large set of additional hydrological instruments, detailed in Table 4, was introduced to sample the whole water cycle. With intensive and continuous field monitoring of rainfall and meteorology, surface–atmosphere exchanges and energy fluxes, surface flow and erosion, soil moisture, and groundwater, as well as geophysical and geochemical surveying, this part of the ACN observation system makes up the hydrologic core of the AMMA-CATCH experiment in Niger. In conjunction with the vegetation monitoring programme (“Vegetation observations”), most of these EOP instruments were located so as to best characterize the main surface and subsurface processes along the toposequences of the pilot gully catchments of Wankama and Tondi Kiboro (Fig. 9; Table 4). Densification of the rain-gauge network at supersite scale, together with installation of a C-band radar, completes this continuous field data acquisition programme (Figs. 2 and 8; Table 4).

Field surveys were conducted to determine subsurface physical properties. Soil characteristics (texture, porosity, bulk density) were sampled for each dominant type of land use/land cover in the 0–30 cm layer, in conjunction with TRMS (triple-ring infiltrometer at multiple suction) hydrodynamic tests. A combination of geophysical (electrical, electromagnetic, magnetic resonance) and hydrodynamic (pumping tests) methods was used to characterize the geometry and hydrodynamic properties of the aquifer at the supersite and meso scales (Boucher et al., in press). Deep infiltration pathways beneath the surface drainage network (gullies and alluvial fans of Wankama catchment, Fig. 9a) were analyzed by combining electrical tomography with geochemistry (Massuel et al., 2006). Since 2008, high-accuracy gravimetric measurements are regularly performed in coordination with the hydrologic monitoring of the vadose and saturated zones to further characterize seasonal and sub-seasonal mass variations in the different parts of the Wankama catchment, from plateau to bottom pond area (Hinderer et al., in press).

Methodologies were developed to derive surface soil moisture (SSM) fluctuations from satellite imagery. Time series of 1-km resolution maps showing sub-seasonal SSM dynamics were produced at supersite scale based on 2004–2005 ASAR/ENVISAT C-band data sets, with calibration/validation against dedicated simultaneous ground measurements (Zribi et al., 2007). Using ERS scatterometer data, Zribi et al. (this issue) produced such maps for the 1992–2006 period at 0.25° resolution over a 2 x 2° domain including the ACN site. AMSR microwave and MSG surface temperature data were combined with soil-vegetation–atmosphere and emission modeling to produce daily 5-km resolution SSM over the ACN window for the 2006 season, validated against field data (Pellarin et al., this issue). The ACN ground network will participate in the calibration/validation of the upcoming SMOS programme (http://www.esa.int/esaLP/UPsmos.html). In this environment, remote sensing is particularly looked forward to as a partial yet much needed alternative to distributed hydrologic field observations, including rainfall.

Vegetation observations

Under the EOP programme, comprehensive field monitoring of vegetation distribution and dynamics has been under way in the
Wankama catchment since 2005 (Boulain et al., this issue), including: (i) detailed field mapping of annual land use/land cover over the catchment; (ii) intensive monitoring, throughout the growing season, of key biological variables – vegetation density, biomass, leaf area index (LAI), phenology, allometry – in a set of eleven 50 × 50 m plots of fallow or millet cover (Fig. 9a), and (iii) mapping of all individual shrubs and trees in the vegetation plots. This vegetation programme is closely coordinated, both temporally and spatially, with monitoring of water and energy cycles by the eddy flux and soil moisture stations (Table 4 and Fig. 9a). Field measurements of photosynthetic characteristics and gas exchanges under controlled environment conditions (CO₂, light intensity, temperature, air humidity) were performed to determine leaf-scale response curves for the main vegetation species, using a LI-COR 6400 analyser.

In 2007, an exhaustive inventory and mapping of all trees and woody shrubs (except for G. senegalensis, which is distributed in thickets too dense for such a survey) was performed over the whole catchment. Biometric parameters (basal perimeter of trunk, total height, longest and orthogonal diameters) were measured for each single-trunk individual, as well as on multiple stems of basal perimeter greater than 6 cm (smaller stems were counted). The phenology of shrub and tree species (G. senegalensis, C. glutinosum, C. micranthum, P. reticulata) was monitored throughout the season. Density distribution, mass, total cover and diversity of grasses were estimated along three 1-km linear transects per-}

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Table 3
Summary of hydrological instruments of the AMMA-CATCH Niger observing system (for a description of instruments, see “Hydrological observations” for LOP, and Table 3 for EOP; color symbols used on site maps of Figs. 2, 8 and 9).

<table>
<thead>
<tr>
<th>Variable type</th>
<th>Instrument</th>
<th>Total number</th>
<th>Number per observ. period</th>
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<td></td>
<td></td>
<td>LOP (since 1990–1992)</td>
<td>EOP</td>
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<td>Rainfall</td>
<td>Recording rain gauges (5-min rainfall)</td>
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<td>30</td>
<td>Point/sub-event and meso (ACN window)/sub-seasonal</td>
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<td></td>
<td>Daily-read rain gauges</td>
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<td>24</td>
<td>Catchment and super-site/sub-event Catchment and super-site/daily</td>
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<td>1</td>
<td>Meso/sub-event</td>
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<td></td>
<td>Automatic weather station</td>
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<td>4</td>
<td>Point/event</td>
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<tr>
<td></td>
<td>Flux stations (energy and water budget, meteorology)</td>
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<td>1</td>
<td>Plot/30-min</td>
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<td>Scintillometers</td>
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<td>Plot/event</td>
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<td>54</td>
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<td>Pond stage recorders</td>
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<td>174</td>
<td>Meso (KD basin)/seasonal</td>
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<td>Recording groundwater piezometers</td>
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<td>Local (pond)/sub-seasonal</td>
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<td>Hydro-geophysical surveys</td>
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<td>Catchment/seasonal</td>
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</table>

A short review of current knowledge

Rainfall

Decadal – regional scale

After 30 years of rainfall deficit over the whole Sahel, wetter conditions have been recorded over the last decade in the central Sahel (see, e.g., Fig. 10a for Niamey airport), while the drought remains unabated in the western Sahel (Lebel and Ali, this issue). However, in a 5 × 5° box centred on the ACN area, the deficit of the current decade is still in the order of 15–20% with respect to the 1950–1969 average, to be compared to the 30% deficit that prevailed over 1970–1997. The August peak is still strongly dimin-
lished, corresponding to a lower frequency of occurrence of squall lines in the heart of the rainy season, which means an increased probability of intraseasonal droughts with respect to the wet 1950–1969 period. Contrary to unsubstantiated common belief, the length of the rainy season – defined by the 5-day moving average rainfall process, oriented according to the direction of convective systems travelling, as the average rainfall event process, oriented according to the direction of convective systems travelling, with 2-km and 1-km spacings in the travel and transverse directions, respectively. While the event process may be considered as isotropic, the probability of OCS significantly during these dry decades. While the ACN site is reasonably representative of the surrounding 5×5 km box as far as the 20-year average seasonal cycle and interannual variability are concerned, there are frequent discrepancies in the annual rainfall fields at the two scales, both in terms of average and of spatial pattern. These discrepancies reflect the high spatial variability of annual rainfall fields (see three sample years in Fig. 3c–e, and Ali et al., 2003).

**Event – meso scale**

Large organised mesoscale convective systems (OCS) account for ~80% of the annual rain total in the Niamey area (Mathon et al., 2002). The spatial structure of associated rain events is roughly isotropic with two characteristic scales at ~30 km and ~180 km, each accounting for about 50% (or 100 mm²) of the total spatial variance (200 mm²) at event scale (Ali et al., 2003). Studied over two sub-periods, one dry (1990–1995) and one wetter (1996–2000), this average spatial structure was found to be remarkably stable, i.e., not depending on the dryness/wetness of the period considered.

While the event process may be considered as isotropic, the probability of rain strongly anisotropic, since it is governed by the large scale meteorological structures that control the West African monsoon, implying a much stronger probability of OCS occurrence in the South of the Sahel than in the North. At the yearly scale, the spatial structure is thus a balance between the isotropic event scale structure and the anisotropic rain occurrence structure. Strong gradients may result, such as in 1992 when a rainfall difference of 270 mm (420 mm vs. 690 mm) was observed between two stations separated by only 9 km. These gradients are not necessarily North-South oriented (Fig. 3c–e). At the multi-year scale, the rain occurrence structure becomes increasingly dominant (variance divided by event number N, against N² for the event process), producing the familiar pattern of a fairly regular latitudinal structure (Fig. 3b).
was evidenced from SPOT imagery of the supersite (see, e.g., Fig. 5 for a typical ~400-km² excerpt). In the south of the supersite, this expansion was field-estimated at an average of ~3.6% yr⁻¹ over the second half of the 20th century (Fig. 7b; see also Fig. 6 in Descroix et al., this issue, reproduced from Loireau, 1998), continuing at a rate of ~2% yr⁻¹ since 1994 (Hiernaux et al., this issue). Over 1994–2006, herbaceous yields decreased in each land use type (cultivated and fallowed fields, rangeland) at an overall mean rate of 5% yr⁻¹, due to such factors as declining soil fertility and increasing grazing pressure, which also triggered changes in species composition (Hiernaux et al., this issue). Fig. 7a illustrates the decrease in local millet grain yield. Soil fertility and physical properties are jeopardized by continuous cropping and reduction of the fallow/field ratio, entailing the possibility of conversion of the ACN area from a dust sink into a dust source (Valentin et al., 2004). The protective role of soil crists is hampered by field weeding or cattle trampling, enhancing loss of fine particles. Animal manure input mitigates these effects (Gandah et al., 2003), but is very unevenly distributed (La Rovere et al., 2005) and cannot offer a long-term alternative to fallowing (de Rouw and Rajoit, 2004). Note that, despite decreasing yields in a given land use type, the shift to more herbaceous-productive types (in increasing order: old fallow, young fallow, millet including stalks) has led to an increasing trend in total herbaceous production, albeit with a reduction in biodiversity (Hiernaux et al., this issue). Whereas signs of “re-greening” were detected elsewhere in the Sahel (e.g., Olsson et al., 2005; Mougin et al., this issue), this does not appear to be the case in SW Niger where the human impact (land use change, increased grazing, wood cutting, decreased fertility) combines with drought persistence to curb leaf cover.

While vegetation dynamics and carbon fluxes are tightly linked and strongly dependent on rainfall under this water-limited climate (Moncrieff et al., 1997), eco-hydrological modelling suggests that total seasonal rainfall may not be the main factor controlling biomass productivity (Boulain et al., 2006), as the timing of rainfall in the season appears to have a greater impact. Observed responses of vegetation (biomass, leaf area) and carbon dynamics to the time distribution of rainfall are quite different for fallow and millet plots (Boulain et al., this issue): whereas the pattern of distribution seems more important than its starting date for fallow vegetation, the starting date proves to be a major factor for millet development. Analysis of water use efficiency and of photosynthesis response to light at the leaf and plot scales shows that the low density of millet sowing is a limiting factor for carbon assimilation efficiency compared to fallow.

Surface exchanges

Ramier et al. (this issue) highlight the dominant role of water, through evapotranspiration, in the variability of the surface energy budget over time (seasonal, interannual) and space (land cover types). Rain-season evapotranspiration, which dominates the water balance (~60–85% of annual rainfall at catchment scale, after Boulain et al., in press), appears to be more sensitive to land use than to seasonal rainfall. It is lower from millet fields than from “natural” surfaces (Gash et al., 1997; Fig. 6 in Ramier et al., this issue). Less difference was found between fallow savanna and tiger bush, despite their quite different structure (Gash et al., 1997; Kabat et al., 1997). High sensible heat loss from the bare strips of tiger bush is partly transformed into enhanced transpiration from the vegetation bands (oasis effect). Lower rain-season evapotranspiration from millet fields appears to be due primarily to lower vegetation requirements rather than to infiltration/runoff properties (Ramier et al., this issue). Given the extent of exposed bare soil in these sparse canopy systems, soil evaporation appears to play a very significant role, e.g., in diurnal latent heat fluctuations (Dolman et al., 1997). In the historical time frame, changes in both land
use and climate presumably produced a reduction in rain-season evapotranspiration (Fig. 10b; Boulain et al., in press), with possible negative feedback on convective rainfall production.

Based on ACN data, new versions of existing land surface models (ISBA, Pellarin et al., this issue; SefS5, Saux-Picart et al., in press; WRF-NOAH, Decharme et al., submitted for publication) were developed to account for the specifics of Sahelian surfaces. Better representation of the top soil layer's control over infiltration and/or evaporation substantially improves simulations. Saux-Picart et al. (this issue) found that remotely-sensed MSG surface temperatures offer much more effective validation information than satellite-derived soil surface moisture.

Catchment hydrology

Processes

Due to high rainfall variability, strong evaporative demand, contrasts in transpiration requirements between land cover types and in infiltration/runoff properties depending on surface conditions, as well as to effect of location on the hillslope, soil moisture and percolation depth display very large time/space variability. These two parameters were found to be substantially higher under millet than under fallow savanna (Peugeot et al., 1997; Ramier et al., this issue), due at least in part to lower evapotranspiration (see “Land surface”). Gaze et al. (1997) observed infiltration varying spatially from 0.3 to 3.4 times the rainfall within the same millet field. In tiger bush, soil moisture fluctuates only in the top 30–50 cm of the bare strips, whereas the infiltration front penetrates more than 3–5 m deep in the vegetated portion (Cuenca et al., 1997; Galle et al., 1999). Soil surface conditions, including crusts and vegetation cover, are key determinants for Hortonian runoff generation. At point scale, infiltration is driven by hydraulic properties of crusts, which, where present, are in sharp contrast with the sandy soil. Man-induced soil and land cover degradation also strongly reduces infiltration capability. The combination of runoff/runon processes over spatially heterogeneous surfaces, together with topography-driven ponding, leads to considerable scale effects, that make runoff coefficients decrease with drainage area (Estèves and Lapetite, 2003). Such effects weaken and level off when rain intensity increases, with an increase in the effective contributing area. However, runoff yields remain nil at any scale above the endorheic gully catchment, due to infiltration in valley ponds (≈80–95% of total inflow, Descombes et al., 1997; Martin-Rosales and Leduc, 2003) as well as to substantial abstraction by the sandy conveying network. In this dry environment, spatial redistribution of rain-water provides important water-harvesting benefits to vegetation (Rockström et al., 1999; Valentim et al., 2004) and water resources (see “Groundwater”).

Historical perspective

As reported for some exorheic Sahelian watersheds (Albergel, 1987; Mahe et al., 2005; Descroix et al., this issue), the drought of the last few decades has coincided with increased surface runoff in the endorheic ACN environment, evidenced by spectacular development of ponds, in number, extension/volume and duration (Favreau, 2000; Leblanc et al., 2008). This sharp increase in surface runoff production has resulted in a new phase of active erosion, involving widespread soil degradation, silting up of valley bottoms, and significant modifications in the hydrological environment such as changes in the course and location of ravines, with the appearance of braided alluvial fans or mid-slope spreading areas (Massuel et al., 2006). The surface drainage network has developed considerably in lineage, density, and connectivity. Based on historical aerial photographs and field information, Leblanc et al. (2008) estimated an increase in drainage density by a factor of 2.5 from 1950 to 1992 (Fig. 10c) in a typical 500-km² area of the supersite, where ~80% of the savanna was cleared (up to 87% on hillslopes/valley bottoms). The considerable effect of land use change on the surface hydrology was evidenced in quantitative terms using Favreau et al. (2003)’s physically-based, distributed hydrological model of the Wankama catchment. An increase in cultivated area from 6% in 1950 to 56% in 1992 and in eroded land from 7% to 17% was estimated to have produced a nearly threefold increase in runoff to the valley pond (Fig. 10c), only partially dampened (~40%) by a simultaneous ~23% reduction in rainfall (Seguis et al., 2004). Analysis of the land use change effect on the scale transition from point to catchment for infiltration rates (Fig. 11) evidences a very large increase in concentrated infiltration outside the pond. The volume of water infiltrating with point intensity above 2 m yr⁻¹, essentially in the sandy hydrographic network (ravine and alluvial fan), increased by a factor of ~3; it is now higher for a typical dry year than it was for a wet year under initial land use. The simulated catchment water balance for the 1992–2000 period suggests equivalent orders of magnitude for infiltration from the drainage network and inflow to the pond (~12% of rainfall).

Groundwater

Recharge of the unconfined aquifer has been shown to be essentially indirect (Favreau et al., 2002b): rainfall concentration by runoff to preferential infiltration spots, such as endorheic ponds or sandy deposits, produces enhanced infiltration and deep drainage to the water table. The mesoscale (~10,000 km²) water table rise recorded since the mid-20th century is thus interpreted as a direct consequence of the simultaneous increase in surface runoff production (“Catchment hydrology”) and ensuing focused recharge. At local scale, seasonal piezometric mounds of up to a few meters high and a few hundred meters wide are observed below ponds and were found to be consistent with estimates of pond infiltration (Leduc et al., 1997; Favreau et al., 2009). Farther from the ponds, only long-term rises have so far been recorded. Water rise celerity increased from a mean of ~0.02 m yr⁻¹ in the 1960–70s to ~0.17 m yr⁻¹ in the 1990–2000s (spatial range of ~0.1–0.3 m yr⁻¹; Favreau et al., 2009), suggesting increasing recharge rates (Fig. 10d). The overall rise was ~4 m over the 1963–2007 period, representing an estimated increase in aquifer reserves of ~15% (Leblanc et al., 2008). The sharp amplification in the rate of rise in the 1980s was found to coincide with an enhanced dynamics in drainage network connectivity and in pond formation (Favreau et al., 2009), as well as with the transition from a declining to an increasing rainfall trend and an acceleration in runoff increase (Fig. 10; Boulain et al., in press).

While estimates of climate effects on catchment runoff/pond inflow (Séguis et al., 2004) and on groundwater recharge (Favreau et al., 2009) are quite similar (e.g., respectively ~40% and ~50% for runoff and recharge due to the 23% decline in rainfall between the periods before and after 1970), such is not the case for the effects of land use change. The threefold increase estimated for catchment runoff change in response to the multi-decadal land clearing (“Land surface”) contrasts with an estimated one-order-of-magnitude increase in aquifer recharge, from 1–4 mm yr⁻¹ in the pre-clearing 1950s (Favreau et al., 2002a, based on analytical modelling of radio-isotope data) to a present-day ~20–25 mm yr⁻¹ (Favreau et al., 2009, from groundwater level fluctuations and geophysical surveys). Estimation errors due to various types of uncertainty (e.g., models, aquifer hydrodynamic properties, etc.) may contribute to this discrepancy, which could also result in part from a possible change in recharging efficiency of pond water. However this large difference is also to be related to the development of new concentrated infiltration spots, such as new ponds or sandy gullies and alluvial fans (“Catchment hydrology”). For example, in the Wankama ravine and mid-slope fan, the combination of detailed
remain to be elucidated. For example, current models still fall short of reproducing the estimated one-order-of-magnitude increase in groundwater recharge, relative to the pre-drought period. Progress is needed towards a coherent assessment of all water fluxes, both at the surface and underground, with their variations in time, at intraseasonal to decadal scales, and in space over the ACN area. A consistent, comprehensive model of the land water cycle dynamics is required to achieve this goal.

Data analysis and modelling activities should not, however, dampen our commitment to observation. The value of such an observation system is to provide a view of the medium- to long-term dynamics of all components of the water cycle, in a context of changing climate and environment. As the rate of environmental changes has been increasing considerably and continuously in semiarid Africa over the recent decades, their hydrological effects are likely not yet fully perceptible, and forecasts on an eventual equilibrium state are highly uncertain, which strongly calls for pursuing the observational efforts. The fact that the climatic future of the region is very unclear – climate models produce largely conflicting scenarios for sub-Saharan Africa – is one more reason for keeping the AMMA-CATCH observing system in operation. In the short run, the LOP and most of the EOP setups of ACN will likely be maintained.

Making the best use of ACN data also means tackling the question of the regional representativeness of the knowledge gained from this pilot area. Contrasts between the cultivated Sahel and the pastoral Sahel are well reflected in this special issue, through the two sites in Niger and Mali located in these distinct domains. The extent to which the conclusions drawn from each site, such as the ACN, can be extended spatially within its own domain remains to be more fully investigated. Experimental programmes as elaborate and intensive as AMMA-CATCH cannot reasonably be replicated in other areas of West Africa in the near future. However lighter field studies are planned or under way east and west of the AMMA-CATCH sites within the Sahelian belt, for example in the Lake Chad basin (see, e.g., Favreau et al., 2008), which will help in building a more comprehensive regional picture. For instance, the spatial extent of rising aquifer reserves and the mapping of the intensity of this rise need to be clarified. Spatial delineation, with time variations due to climate and land use changes, of the hydrological sub-domains (Sahelian vs. Sudanian, endorheism vs. exorheism, Hortonian vs. Hewlettian runoff, increasing vs. decreasing runoff coefficients, indirect vs. diffuse groundwater recharge, differences in characteristic scales) needs to be refined (Descroix et al., this issue). A preliminary approach to the issue of the representativeness of ACN processes over the African continent was discussed by Favreau et al. (2009), with regard to the response to land clearing of runoff and/or groundwater recharge.

Outlook and conclusion

The data and knowledge gathered through the AMMA-CATCH programme in SW Niger indicate that land use change has had a larger – though indirect – impact on the terrestrial water balance than the direct influence of the long-lasting Sahelian drought. Even during the peak drought period (1970–1997), surface runoff and aquifer recharge increased. Now that the region seems poised to return to wetter conditions, with demographic pressure on the environment that will keep growing, this shift in the water cycle could further amplify. With the prospect of a possibly sharp rise in Sahelian temperatures (Christensen et al., 2007), the future of water and food resources, and the extent to which they can satisfy, in both quantity and quality, the needs of a growing population, thus remain challenging questions for the scientific community.

Addressing these questions will require both a finer understanding of elementary processes, and the development of integrated models that take better advantage of increasingly informative remote sensing data, goals to which the ACN data sets can offer substantial contributions. As the first phase of the AMMA-CATCH programme is coming to an end, several pivotal questions remain to be elucidated. For example, current models still fall short of the European Community’s Sixth Framework Research Programme. Detailed information on scientific coordination and funding is available on the AMMA International website http://www.ammainternational.org.

Fig. 11. Modelled point-to-catchment scale relationship for annual infiltration in Wankama catchment (pond excluded), before and after land use change. Each curve gives the catchment-scale flux (y-axis) infiltrated with point intensities above a given threshold (x-axis), for a given land use map (1950 or 1992) and rain season (dry or wet). Over the 42-year period, total catchment-scale infiltration decreased (top of curves), whereas concentrated infiltration (e.g., point rates greater than rainfall) increased spectacularly.

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programme over the recent years. They include technicians (H. Alassane, A. Alhassane, B. Hamani, A. Koné, B. Seyni), students (A. Bachir, S.M. Elhadj, O. Halilou, B. Ibrahim, M. Ibrahim, M.A. Moussa, K. Souley Yévo), international volunteers (C. Baillieu, F. Métayer, F. Mominin, M. Rabanit), and researchers (A. Boubaçar Hassane, G. Chehbouni, M. Descloitres, A. Diedhiou, J. Ezzahar, B. Gérard, J. Hoetjes, K. Lawan, C.R. Lloyd, A. Mahamane, T. Pellarin, S. Massuel, J.L. Rajot, J. Seghieri, L. Séguis, F. Timouk, S. Traoré, J.M. Vouillamoz, E. Williams). Their participation is gratefully acknowledged. M. Zribi, C. André, S. Saux-Picart and B. Decharme contributed to the remote sensing aspects. Many other people helped in various ways, including the French and Nigerian staff of the IRD office in Niamey for all logistics and administrative aspects, and are warmly thanked. All other participants to the AMMA-CATCH observing system, from CESBIO, HSM and LTHÉ labs, have contributed one way or another, including through fruitful discussion and inter-site collaboration. The referees are thanked for their helpful reviews.

List of acronyms and other specific terminology

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABN</td>
<td>Niger Basin Authority</td>
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<tr>
<td>ACN</td>
<td>AMMA-CATCH Niger (component of AMMA-CATCH regional observation system)</td>
</tr>
<tr>
<td>ADEOS</td>
<td>Advanced Earth Observing Satellite</td>
</tr>
<tr>
<td>AERONET</td>
<td>Aerosol Robotic Network</td>
</tr>
<tr>
<td>AGRHYMET</td>
<td>Regional center for agro-ecology in the Sahel, Niamey (Niger)</td>
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<tr>
<td>AMMA</td>
<td>African Monsoon Multidisciplinary Analyses</td>
</tr>
<tr>
<td>AMMA-CATCH</td>
<td>Coupling hydrological cycle with tropical atmosphere in AMMA</td>
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<tr>
<td>AMMA-ICIG</td>
<td>AMMA International Coordination and Implementation Group</td>
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<tr>
<td>AMSR</td>
<td>Advanced Microwave Scanning Radiometer</td>
</tr>
<tr>
<td>ASAR/Envisat</td>
<td>Advanced Synthetic Aperture Radar on board the Envisat Satellite</td>
</tr>
<tr>
<td>A-Train</td>
<td>A train of six satellites dedicated to documenting the water cycle and the radiative forcing</td>
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<tr>
<td>CT3</td>
<td>Surface geological layer of the Continental Terminal series in the ACN area</td>
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<tr>
<td>DEM</td>
<td>Digital elevation model</td>
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<tr>
<td>DMN</td>
<td>Direction of National Meteorology, Rep. of Niger</td>
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<tr>
<td>DRE</td>
<td>Direction of Water Resources, Rep. of Niger</td>
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<tr>
<td>EOP</td>
<td>Enhanced observation period</td>
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<tr>
<td>EPSAT</td>
<td>Rainfall estimation from satellite</td>
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<tr>
<td>HAPEX</td>
<td>Hydrological-Atmospheric Pilot Experiment (1992)</td>
</tr>
<tr>
<td>ICrisat</td>
<td>International Crop Institute for the Semi-Arid Tropics</td>
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<tr>
<td>ICAF</td>
<td>IGAC/DEBITS/Africa : Monitoring of Atmospheric Chemistry</td>
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<tr>
<td>ILRI</td>
<td>International Livestock Research Institute</td>
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<td>INRAN</td>
<td>National Institute of Agronomic Research, Rep. of Niger</td>
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<tr>
<td>KD</td>
<td>Kori de Dantandou</td>
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<tr>
<td>kori</td>
<td>Gully or fossil river bed</td>
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<td>LOP</td>
<td>Long observation period</td>
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<td>MSG</td>
<td>Meteosat Second Generation</td>
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<td>OCS</td>
<td>Organised mesoscale convective systems</td>
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<td>ROSETT/OSS</td>
<td>Réseau d’Observatoires de Surveillance Ecologique à Long Terme/Observatoire du Sahara et du Sahel</td>
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<tr>
<td>SEBEX</td>
<td>Surface Energy Balance Experiment</td>
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<td>SMOS</td>
<td>Soil Moisture and Ocean Salinity</td>
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<tr>
<td>SSM</td>
<td>Soil surface moisture</td>
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References


J.M. Vouillamoz, E. Williams). Their participation is gratefully acknowledged. M. Zribi, C. André, S. Saux-Picart and B. Decharme contributed to the remote sensing aspects. Many other people helped in various ways, including the French and Nigerian staff of the IRD office in Niamey for all logistics and administrative aspects, and are warmly thanked. All other participants to the AMMA-CATCH observing system, from CESBIO, HSM and LTHÉ labs, have contributed one way or another, including through fruitful discussion and inter-site collaboration. The referees are thanked for their helpful reviews.


