

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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B. Cappelaere, Luc Descroix, Thierry Lebel, N. Boulain, D. Ramier, et al.. The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger : investigating water cycle response to a fluctuating climate and changing environment. Journal of Hydrology, 2009, 375 (1-2), pp.34-51. 10.1016/j.jhydrol.2009.06.021 . ird-02153387

HAL Id: ird-02153387
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Journal of Hydrology xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

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

B. Cappelaere [a,*], L. Descroix [b], T. Lebel [b], N. Boulain [a], D. Ramier [a], J.-P. Laurent [b], G. Favreau [a], S. Boubkraoui [b], M. Boucher [a], I. Bouzou Moussa [c], V. Chaffard [b], P. Hiernaux [d], H.B.A. Issoufou [c], E. Le Breton [e], I. Mamadou [e], Y. Nazoumou [c], M. Oi [a], C. Ottlé [f], G. Quantin [b]

[a] IRD, UMR HydroSciences, BP 64501, 34394 Montpellier cedex 5, France
[b] IRD, L.T.H.E., BP 53, 38041 Grenoble Cedex 09, France
[c] Université A. Moumouni, Niamey, Niger
[d] CESBIO, 18 Avenue Edouard Belin, bpi 2801, 31401 Toulouse cedex 9, France
[e] CNRS, L.G.P., 1, Place Aristide Briand, 92195 Meudon, France
[f] CNRS, L.S.C.E., Centre d'Etudes de Saclay, 91191 Gif-sur-Yvette, France

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Land cover change
Semiarid
Water resources
Ecohydrology
Savanna vegetation
Observation system

SUMMARY

Among the three sites distributed along the West African latitudinal gradient in the AMMA-CATCH observation system, the experimental setup in the Niamey area of south-west Niger samples the cultivated Sahel environment, for hydrological, vegetation and land surface processes. The objective is to investigate relationships between climate, land cover, and the water cycle, in a rapidly changing semiarid environment. This paper first presents the main characteristics of the area, where previous research, including the EPSAT and HAPEX-Sahel experiments, had evidenced a widespread decadal increase in water resources, concurrently with severe drought conditions. The specifics of AMMA-CATCH research and data acquisition at this site, over the long-term (~2001–2010) and enhanced (~2005–2008) observation periods, are introduced. Objectives and observation strategy are explained, and the main characteristics of instrument deployment are detailed. A very large number of parameters – covering rainfall, vegetation ecophysiology, phenology and production, surface fluxes of energy, water vapour and CO_2, runoff and sediment, pond water, soil moisture, and groundwater – were monitored at local to meso scales in a nested structure of sites. The current state of knowledge is summarized, connecting processes and patterns of variation for rainfall, vegetation/land cover, and the terrestrial hydrologic cycle. The central role of land use and of its spectacular change in recent decades is highlighted. This paper provides substantial background information that sets the context for papers relating to the south-west Niger site in this AMMA-CATCH special issue.

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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-CATCH[1] 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

* Corresponding author. Tel.: +33 4 67 14 90 17; fax: +33 4 67 14 47 74.
E-mail address: bernard.cappelaere@mpl.ird.fr (B. Cappelaere).

[1] Please see list of acronyms and specific terminology in Appendix.

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doi:10.1016/j.jhydrol.2009.06.021

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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 HAPEX-Sahel (Goutorbe et al., 1997) experiments in the early 1990s.

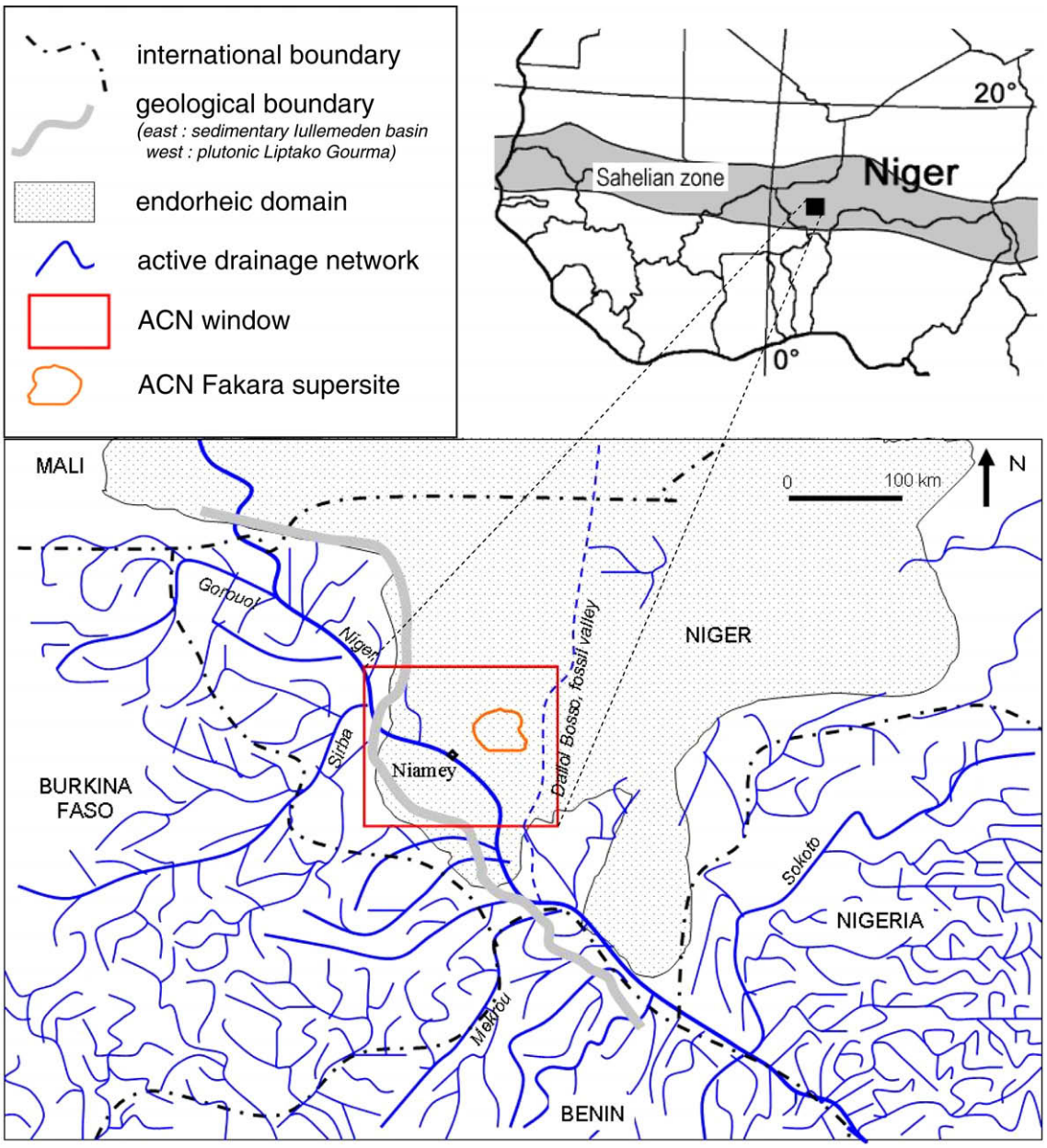


Fig. 1. Geographical, geological and hydrological setting of AMMA-CATCH Niger (ACN). (Limits of the Sahelian strip – top right – are merely indicative, using the 200 and 700 mm mean annual isohyets of 1951–1989).

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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 run-off-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), ecosytems (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 km^2. 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 Aïr 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).

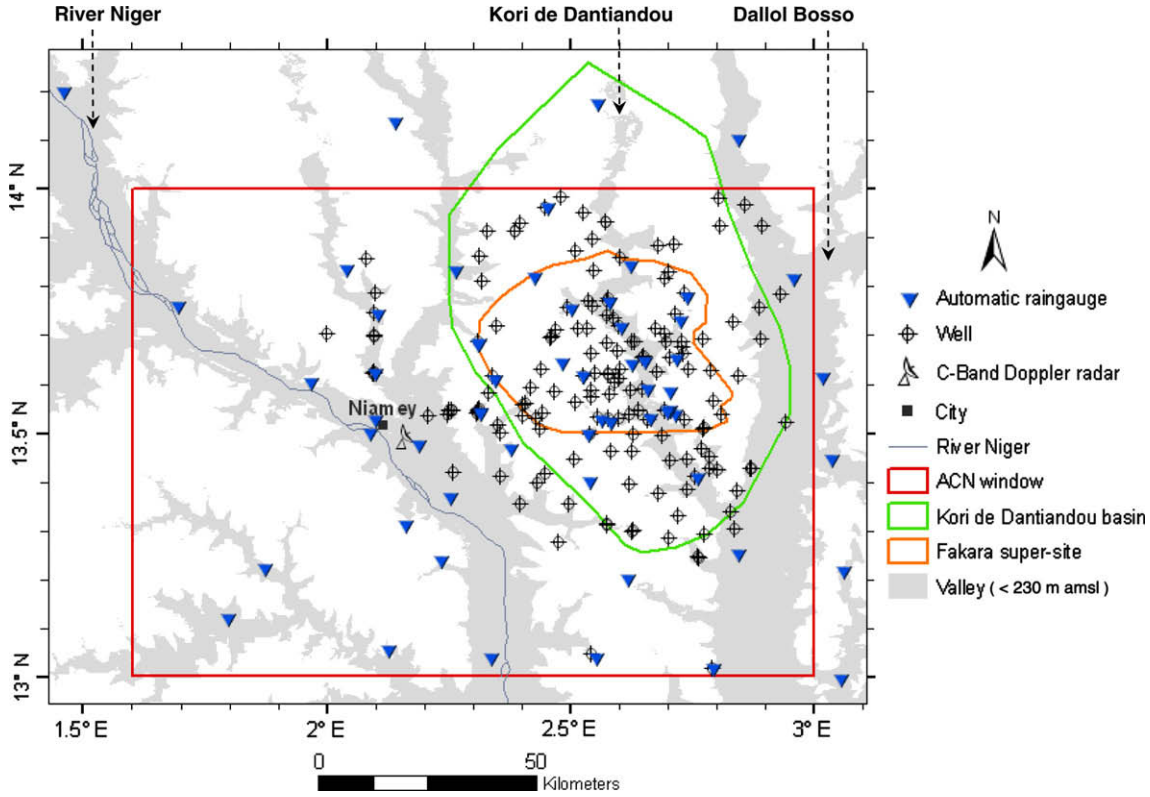


Fig. 2. General map of AMMA-CATCH Niger (ACN) observation system, showing limits of two mesoscale sites (ACN window, in red; Kori de Dantiandou basin, in green) and of Fakara supersite (orange), with networks of automatic rain gauges and village wells.

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Geology

Most of the ACN study area belongs to the large (600,000 km^2) *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 km^2), 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 Dallol 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 predominantly sandy, gently-sloping hillslope, generally separated into

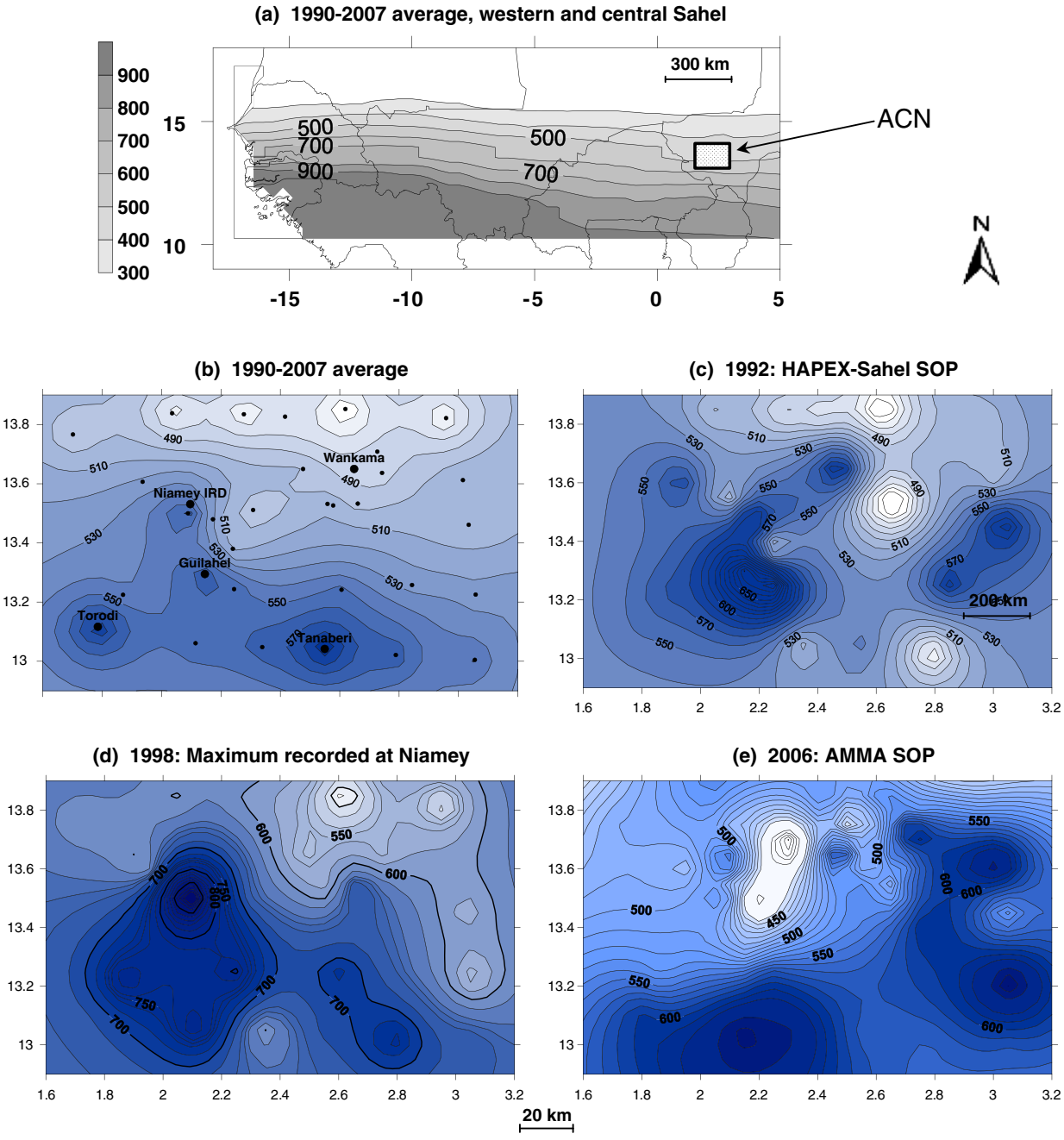


Fig. 3. Annual rainfall maps (mm) (a) over western and central Sahel, 1990–2007 average; (b)–(e) over the ACN window: (b) 1990–2007 average, (c)–(e) sample years (1992, 1998, 2006). While the climatological latidudinal gradient (a) is clearly visible on the ACN 18-year average map (b) (albeit local highs/lows), this gradient does not show up on the annual maps (c)–(e). Coordinates in decimal degrees; isohyets in mm computed from: (a) the operational daily rain gauge network, (b)–(e) the ACN 30-raingauge long-term monitoring network (*SOP = special observation period*).

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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-km^2 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 (Al_2O_3 and Fe_2O_3), 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

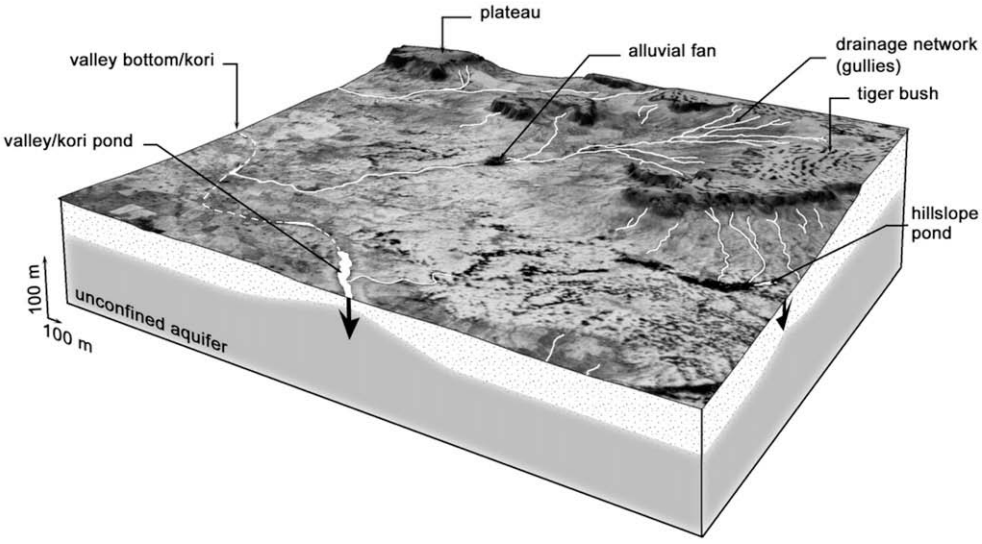


Fig. 4. Land morphology in a typical toposequence of ACN, from plateau to valley bottom (*after* Massuel, 2005, *modified in* Leblanc et al., 2008).

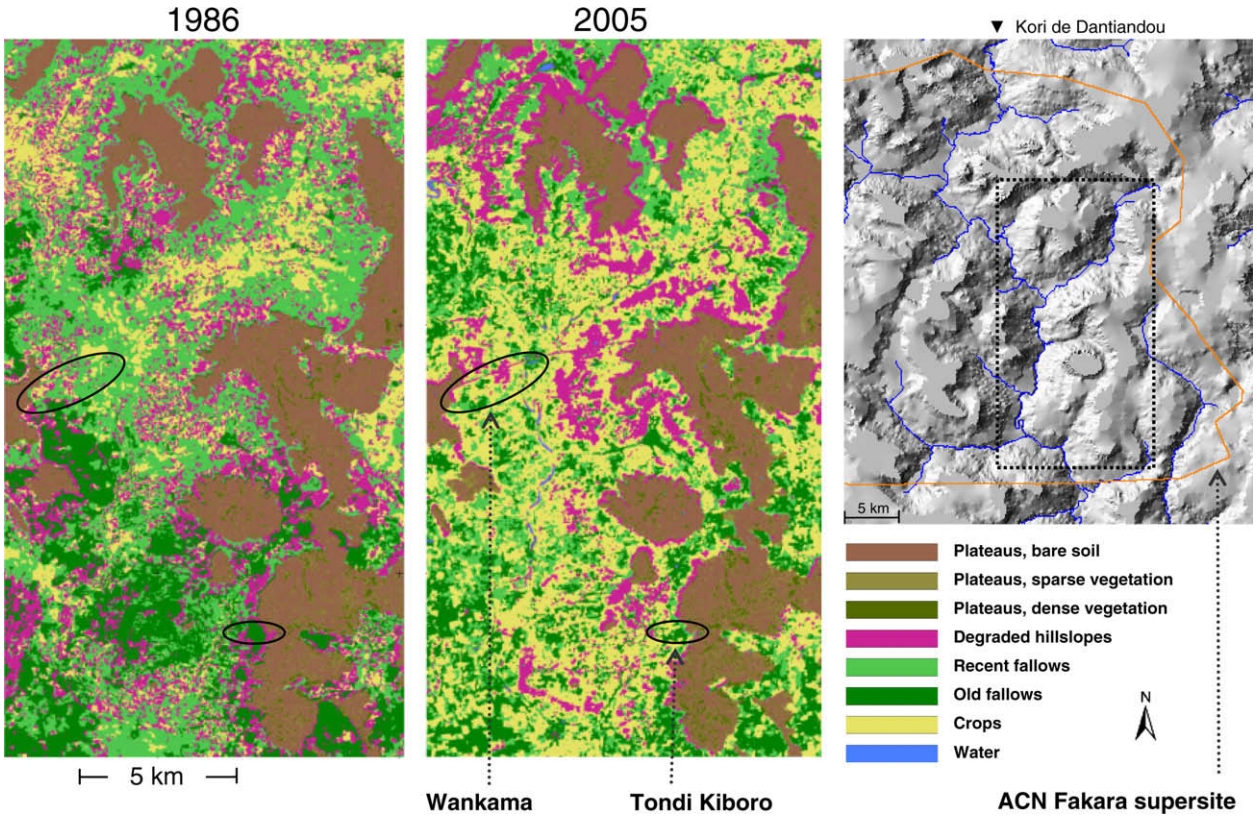


Fig. 5. Change in land use/land cover over a 2-decade period in a typical ~400-km^2 section of ACN (estimated by unsupervised classification of SPOT imagery of mid-september, 1986 and 2005). Top-right: shaded view of 40-m resolution DEM for 1740-km^2 section of ACN, with contours of supersite and of land use extract (*after* Elizondo et al., 2002). Wankama and Tondi Kiboro pilot catchments shown as ovals on land use maps.

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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), *Piliostigma 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-

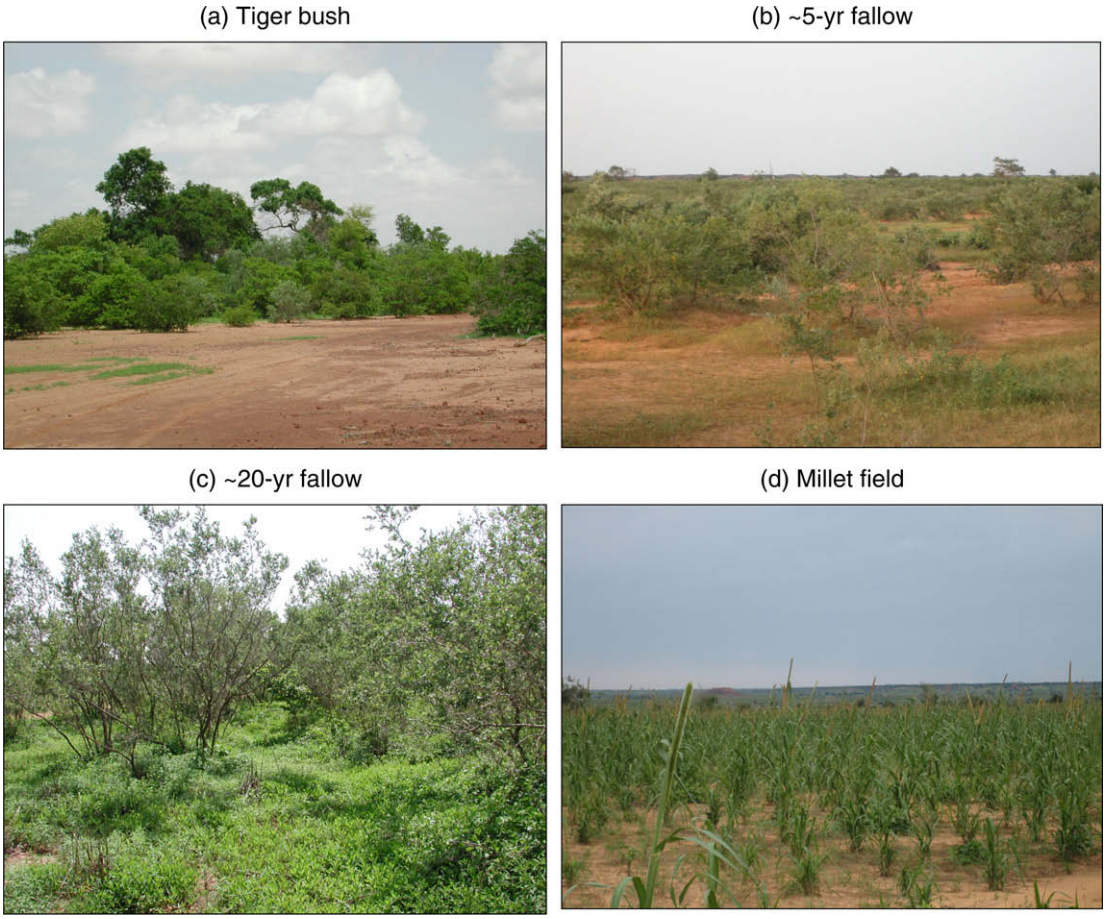


Fig. 6. Typical views of main vegetation cover types in ACN area: (a) tiger bush; (b) ~5-yr old fallow; (c) ~20-yr old fallow and (d) millet field.

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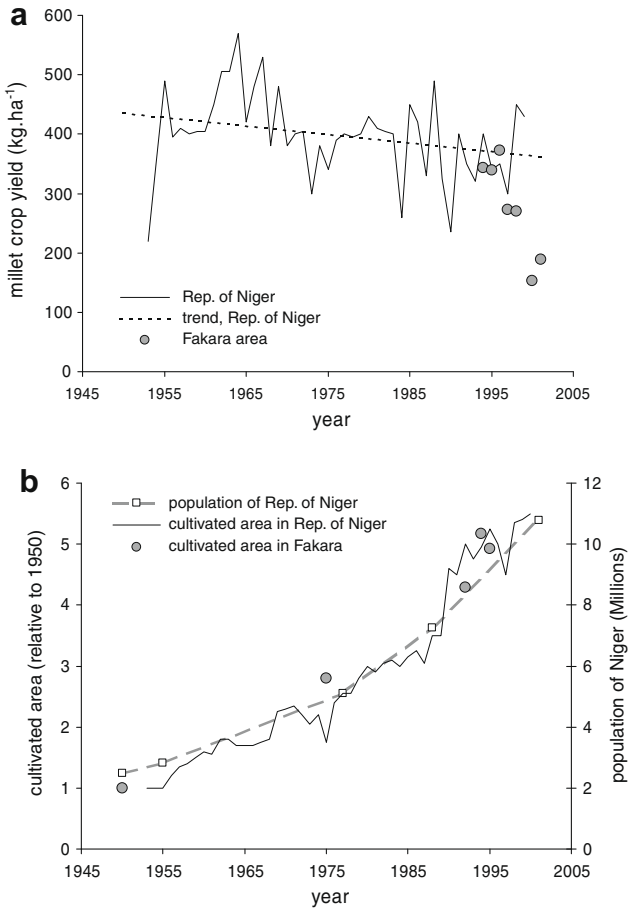


Fig. 7. Historical courses of: (a) crop grain yield in Rep. of Niger and Fakara area and (b) population of Republic of Niger, and cultivated surface area (relative to 1950) in Rep. of Niger and Fakara area. Thanks to slightly faster growth of cropped area than population (~3% yr^{-1}), national production per capita slightly increased in trend (~+10% in 50 years, with considerable annual variability) despite decreasing yields (*data for Rep. of Niger from* Guengant and Banoin, 2003).

fall events (Peugeot et al., 1997, 2003). Infiltration capacity is very small in the plutonic area, but strongly contrasted and potentially high in the sedimentary zone, with a combination of runoff/runon processes. Water resources are mostly provided by surface water in the former area and by groundwater in the latter, and are mostly used for human and cattle consumption. Depth to the water table ranges from ~10 to ~75 m in the CT3, except in the large Dallol Bosso valley where it outcrops locally. A continuous and generalised rise of the water table has been observed since the mid-20th century, with an average gain of ~0.1 m yr^{-1} for the 1963–1999 period (Leduc et al., 2001). This puzzling phenomenon of an increase in water resources in the context of a severe drought is commonly referred to as the Niamey paradox.

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 elemental 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

Table 1
Some of the overall water cycle research challenges of AMMA-CATCH Niger.

Fields	Issues
Rainfall (continuation of previous research)	Interannual variability and seasonal cycle in relation with large scale atmospheric forcing; extent to which mesoscale and local factors (vegetation, humidity) shape the 10-day to seasonal rain field patterns
Land surface–atmosphere exchanges (mostly new area of investigation)	Control of evapotranspiration and surface heat fluxes by energy forcing, soil water, vegetation type and seasonal cycle; surface fluxes scaling laws
Catchment hydrology (continuation of previous research)	Spatial redistribution processes along the catena and the endorheic gully system, and impact of land use and management practices
Groundwater (continuing previous research and new investigations on specific processes)	Spatial distribution of recharge and its relation to local surface and subsurface conditions; long-term dynamics and asymptotic state

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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–

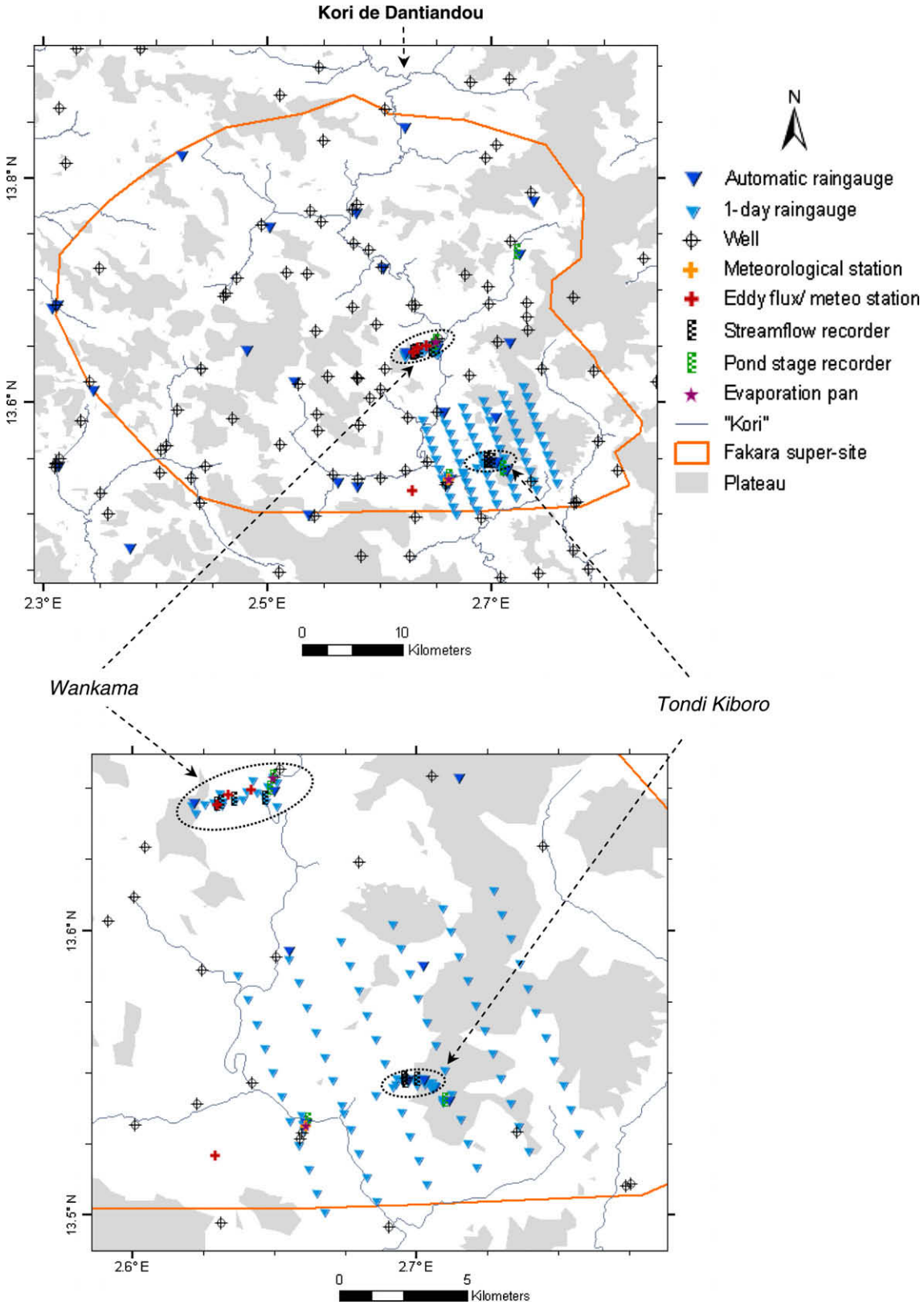


Fig. 8. Map of Fakara supersite in the ACN observation system.

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2010) 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 km^2 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;

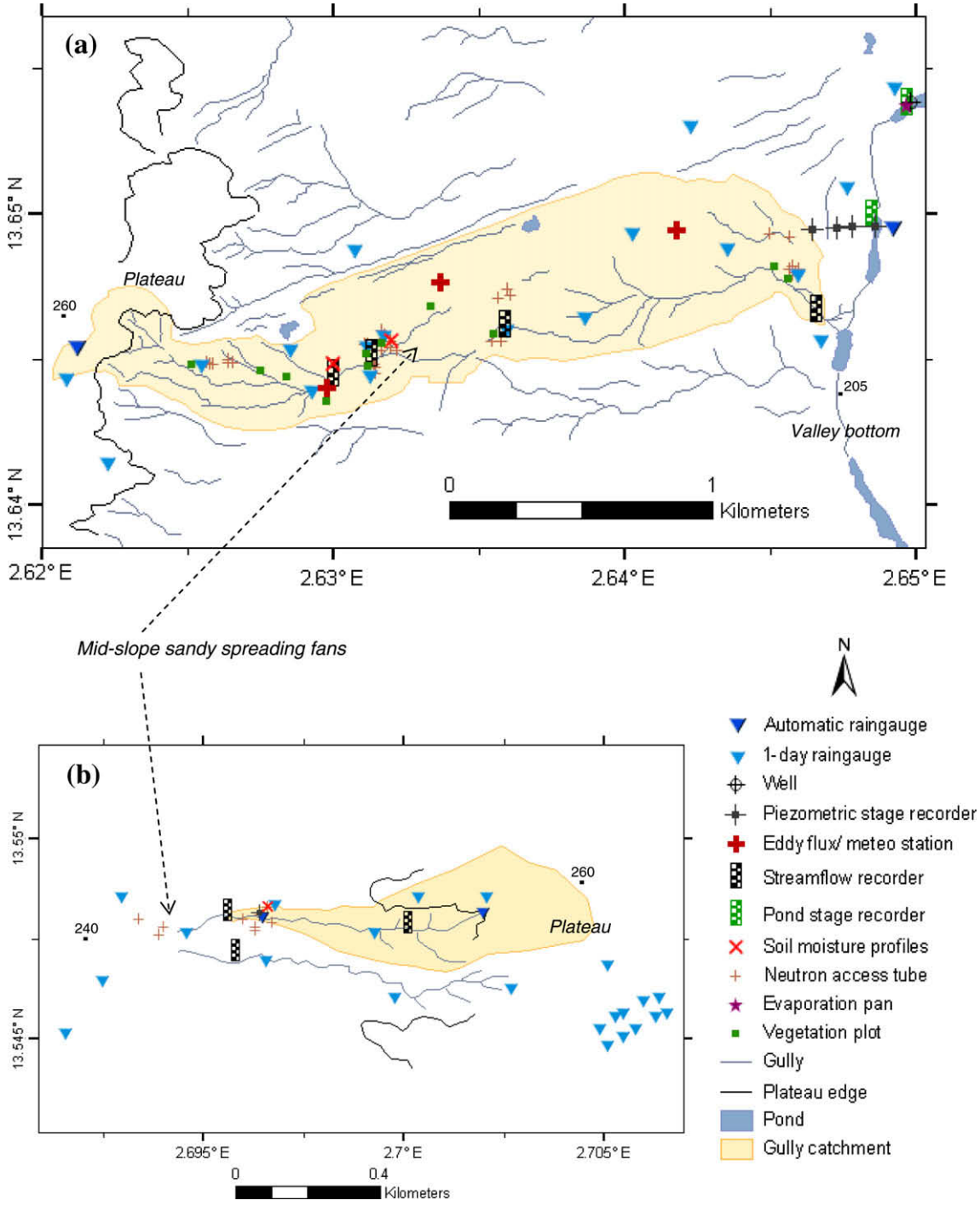


Fig. 9. Maps of Wankama (a) and Tondi Kiboro (b) local catchment sites.

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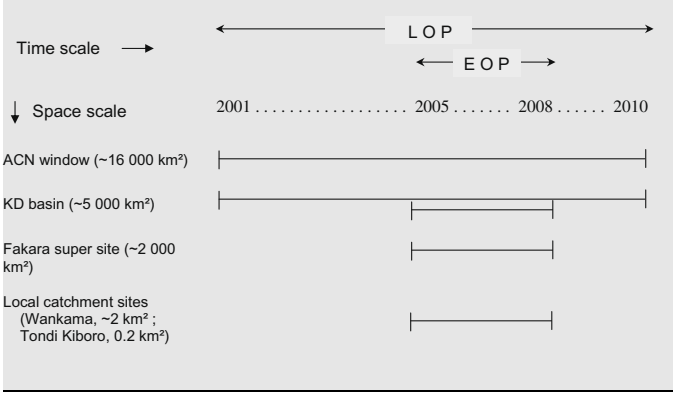
- a second mesoscale site, the *Kori de Dantiandou* (KD) basin (5650 km^2), is mostly included in the ACN window (Fig. 2). Its boundaries were defined from the geometry of the aquifer and of its piezometric depression, in order to delineate a consistent hydrological entity that would facilitate modelling 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 km^2 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 km^2, 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 reading (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.

Table 2
Temporal and spatial structure of AMMA-CATCH Niger observing system.



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 TRIMS (triple-ring infiltrometer at multiple suctions) 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 2×2° domain including the ACN site. AMSR microwave and MSG surface temperature data were combined with soil-vegetation–atmosphere and emission modelling 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/LPsmos.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

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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).

Variable type	Instrument	Total number	Number per observ. period		Target space/time scales
			LOP (since 1990–1992)	EOP	
Rainfall	Recording rain gauges (5-min rainfall)	54	30		Point/sub-event and meso (ACN window)/sub-seasonal
				24	Catchment and super-site/sub-event
	Daily-read rain gauges	153		153	Catchment and super-site/daily
	Radar (C-band)	1		1	Meso/sub-event
Surface fluxes and meteorology	Automatic weather station	1	1		Point/event
	Flux stations (energy and water budget, meteorology)	4		4	Plot/30-min
	Scintillometers	2		2	Catchment/30-min
Soil moisture	Profile recording (0–3 m)	13		13	Plot/event
	Neutron probe access tubes (1–12 m)	54		54	Catchment/sub-seasonal
Streamflow	Gully streamflow stations	7		7	Catchment/sub-event
Pond water	Pond stage recorders	5	5		Local (endoreism)/event
Groundwater	Wells (manual piezometric monitoring)	174	174		Meso (KD basin)/seasonal
	Recording groundwater piezometers	8	4		Local (pond)/sub-seasonal
				4	Catchment/seasonal
	Hydro-geophysical surveys	20		20	Local to meso

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 (CO_2, 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*, *F. albida* and *P. reticulata*) was monitored throughout the season. Density distribution, mass, total cover and diversity of grasses were estimated along three 1-km linear transects perpendicular to the slope, in the upper, middle, and lower parts of the catchment (Issoufou, 2008). A specific study on *F. albida* was performed in 2005–2006, including: mapping of individuals, monitoring of phenology and sub-daily variations in branch diameter, as well as oxygen isotope concentrations, in conjunction with deep soil moisture. The special interest of this inverted-phenology species lies in its possibly important role as a dry-season discharge pathway for deep subsurface and ground water to the atmosphere. At the end of each of the 2004–2008 rainy seasons, high-resolution aerial imaging of the two experimental catchments was performed with the PIXY, a small land-surveying drone. At the supersite scale, the seasonal, annual, and decadal dynamics of LAI and land cover were analyzed and documented from a bank of SPOT-HRV images since 1986, with calibration/validation against field data from the pilot catchments over the EOP period (Saux-Picart et al., this issue; Zin et al., submitted for publication).

Specific surveying was performed on the agricultural component of the ecosystem, in cooperation with specialized regional institutions. At the scale of the ACN window, millet phenology, development and yields, as well as farmers' practices, were monitored by AGRHYMET over a sample of ~300 fields throughout the EOP growing seasons. In the south of the Fakara supersite area, ILRI led a long-term field survey of the mixed crop-livestock farming system from 1994 to 2006 (Hiernaux et al., this issue). Vegetation and fodder resources were monitored in a set of 71 cropland and fallow-rangeland 2-ha fields, for seasonal yields, species composition, crop density and crop-fallow rotations. Land use and fodder resources were mapped over a 270-km^2 area, and household land and animal ownership, cropping activities, livestock herding and soil fertility management practices were surveyed (Hiernaux, 2004). Finally, it should be noted that the ACN observatory contributes directly to larger-scale programmes outside the AMMA sphere, such as the CARBOAFRICA project on carbon cycling in Africa (http://www.carboafrica.net; Merbold et al., 2009), and that several other observation programmes and networks have instruments in the ACN sites, e.g., for aerosols (AERONET, http://loaphotons.univ-lille1.fr/photons/; Li et al., 2007), atmospheric chemistry (IDAF, http://medias.obs-mip.fr/idaf/), or ecosystems (ROSELT/OSS, http://www.oss-online.org/).

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-

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Table 4
Description of hydrological instruments specific to EOP programme (color symbols used on site maps of Figs. 2, 8 and 9).

Instruments	Sites	Periods
Rainfall		
– 24 additional recording *rain gauges* (a) and 153 daily-read rain gauges; in particular, a sub-network of 66 daily rain gauges (b) was setup on a 6 × 11 rectangular grid (Fig. 8), oriented according to the direction of convective systems travelling, with 2-km and 1-km spacings in the travel and transverse directions, respectively	Fakara super-site (Fig. 8) and pilot catchments (Fig. 9)	(a) 2005–2008 (b) 2006–2008
– C-band *radar* installed at Niamey airport is operating since the 2006 rain season, and is associated to 20 new rain gauges since 2007 to help in the characterization of convective rainfields	Niamey airport, covering super-site (Fig. 2)	2006–2008
Surface exchanges		
– 4 *eddy covariance* stations, measuring 4-component radiation and eddy (sensible and latent heat, carbon) fluxes, as well as ground heat flux and temperature, together with met. variables (Ramier et al., and Boulain et al., this issue). Sample main land cover types, namely millet (2), fallow bush and degraded vegetation	all in Wankama catchment (Fig. 9a), except for a millet site (Fig. 8)	2005–2008
– a *scintillometry* experiment was conducted during the 2006 rain season, using two large-aperture scintillometers, to address the issue of upscaling from plot to catchment (Ezzahar et al., this issue)	Wankama catchment	July–October 2006
Soil moisture		
– 13 *continuously-monitored 0–3 m profiles* (4 of them being associated to eddy flux measurements, see above) with three to six water content sensors (TDR-type CS616 of Campbell Scientific) each, distributed over the following types of sites: millet (4), fallow (3), gully (2), spreading zone, degraded vegetation, tiger bush vegetation and bare strips; nine of these profiles also include ten matrix potential sensors (Watermark of Eijkelkamp) each	7 in Wankama c. (Fig. 9a), 5 in Tondi Kiboro c. (Fig. 9b), 1 isolated	2005–2008
– 54 *neutron-probe* access tubes drilled in the unsaturated zone down to 12 m depth, for monthly (dry season) or twice-monthly (monsoon season) profile probing	Wankama c. (Fig. 9a) and Tondi Kiboro c. (Fig. 9b),	2004–2008
Runoff production and erosion		
– 14 event-scale *runoff and erosion plots*, sampling the 4 main land use/land cover types (millet, fallow, degraded fallow with either algal or erosion crust)	Wankama c. (Fig. 9a): four 10-m^2 plots (one per land cover type) Tondi K. c. (Fig. 9b): eight 10-m^2 plots (two per land cover type) + two 100-m^2 plots (millet, fallow)	2004–2007 2005–2008
Streamflow and sediment transport		
– seven *discharge gauging* stations installed in Wankama and Tondi Kiboro gullies (the second allowing for comparison with 1992-1994 period before catchment clearing, see Estèves and Lapetite, 2003); each consists of a Parshall-type flume equipped with OTT Thalimedes stage recorder[a]; rating curves established by current-meter discharge measurements in observed discharge range	Wankama c. (4 stations, Fig. 9a) Tondi Kiboro c. (3 re-equipped stations[a], Fig. 9b)	2004–2008 1992–1994 + 2004–2008
– *suspended load* sampling (1 l.) at station above mid-slope alluvial fan in each catchment (see Fig. 9), every 2 min. during flood rise and 5 min. during flood recession	Wankama c. (Fig. 9a) and Tondi Kiboro c. (Fig. 9b),	2004–2008
Groundwater		
– four new *piezometers* (14–50 m deep) to further characterize groundwater response beneath key hydrologic objects such as ponds, gullies, or mid-slope alluvial fans, in pilot catchments	Wankama and Tondi Kiboro catchments (Fig. 9)	2004–2008
– series of *hydro-geophysical surveys* (20 sites) aimed at improving aquifer characterization (geometry, porosity and storativity, permeability and hydraulic conductivity), including electrical, TDEM (time domain electromagnetic) and MRS (magnetic resonance sounding; Vouillamoz et al., 2008) methods	Fakara super-site (Fig. 8), and KD basin (Fig. 2)	2006 and 2009

[a] One in small catchment just south of Tondi Kiboro c. to study effects of replanting of tree hedges (since 2007).

ished, 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 being larger than 1 mm day^{-1} – has not changed significantly during these dry decades. While the ACN site is reasonably representative of the surrounding 5×5° box as far as the 20-year average seasonal cycle and interannual variability are concerned, there are frequent discrepancies in the annual rainfields at the two scales, both in terms of average and of spatial pattern. These discrepancies reflect the high spatial variability of annual rain 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 ~90% 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 mm^2) of the total spatial variance (200 mm^2) 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 is 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 N^2 for the event process), producing the familiar pattern of a fairly regular latitudinal structure (Fig. 3b).

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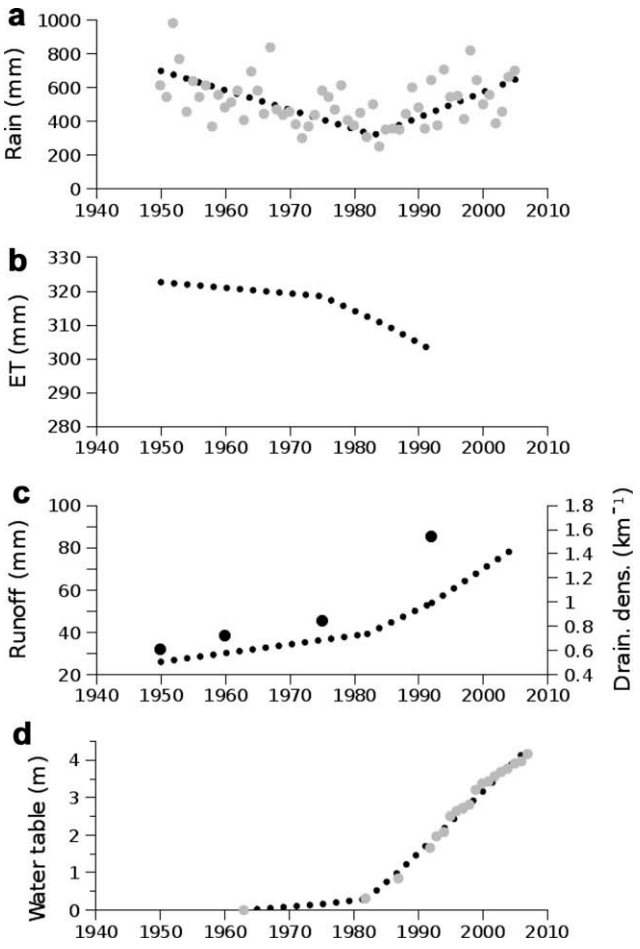


Fig. 10. Historical trends in annual water cycle: (a) rainfall; (b) rainy-season evapotranspiration (ET); (c) catchment runoff (line) and drainage density (dots), and (d) water table level. Dots correspond to field data: at Niamey airport for rainfall (*courtesy DMN Niger*); in a 500-km^2 section of supersite – encompassing the land-use domain of Fig. 5 – for drainage density (Leblanc et al., 2008); areal mean difference with 1963 over KD basin for water table (Massuel, 2005). Lines for evapotranspiration and runoff are simulations for Wankama catchment (Boulain et al., in press).

Hydrological bearing

As intense rainfall is produced by convective cells of characteristic scales in the order of a few kilometres and a few minutes within the OCS, 50% of the annual rain falls in a total time of less than 4 h, with intensities greater than 35 mm/h (Balme et al., 2006). Vischel et al. (this issue) showed that, for rainfall–runoff ratios to be simulated realistically, these small-scale characteristics must be taken into account explicitly, as simulated runoff may be underestimated by a factor of up to 50% when using smoothed input rainfields (e.g., 25% for rain-gauge kriging). The importance of proper infra-daily disaggregation of rainfall was demonstrated by Messager et al. (2006) for the simulation of the Sirba catchment, the River Niger tributary closest to the ACN observatory (Fig. 1).

Land surface

Vegetation and land cover

While the drought has been the essential factor of environmental alteration in the Malian Gourma site (Mougin et al., this issue), ever-increasing human pressure (Fig. 7b; 1988–1996 population growth of ~3.2% yr^{-1} in Fakara) has been playing a dominant role in the considerable land cover changes in SW Niger since the mid-20th century. The extent of cropland encroachment on natural or fallow vegetation of sandy hillslopes through the last two decades was evidenced from SPOT imagery of the supersite (see, e.g., Fig. 5 for a typical ~400-km^2 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 crusts 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 Rajot, 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

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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; SetHyS, 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, Desconnets 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; Valentin et al., 2004) and water resources (see "Groundwater").

Historical perspective

As reported for some exorheic Sahelian watersheds (Albergel, 1987; Mahé 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-km^2 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 Cappelaere 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 (Séguis 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 km^2) 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 1990–2000 s (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

Please cite this article in press as: Cappelaere, B., et al. The AMMA-CATCH experiment in the cultivated Sahelian area of south-west Niger – Investigating water cycle response to a fluctuating climate and changing environment. J. Hydrol. (2009), doi:10.1016/j.jhydrol.2009.06.021

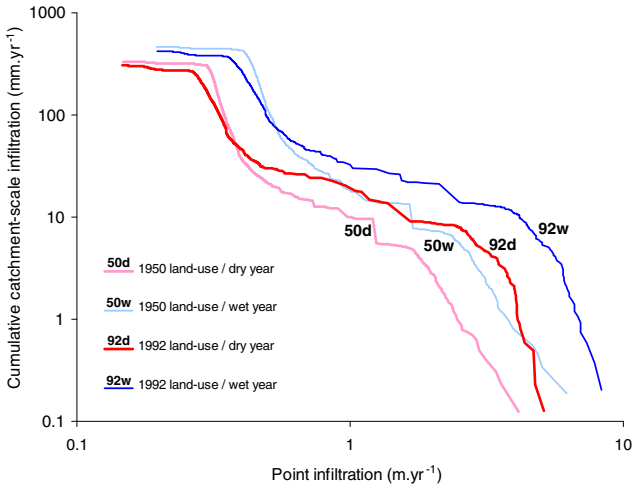


Fig. 11. Modelled point-to-catchment scale relationship for annual infiltration in Wankama catchment (pond excluded), before and after land use change. Each curve gives the catchment-scale flux (*y*-axis) infiltrated with point intensities above a given threshold (*x*-axis), for a given land use map (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.

vadose zone investigation (geophysics, geochemistry, neutron soundings), streamflow gauging, and hydrological modelling strongly suggests the occurrence of massive infiltration and deep percolation episodes. These results provide strong support for the hypothesized role of the hydrographic network as a significant contributor to aquifer recharge, in addition to the network of endorheic ponds, at least in wet years. Results from coupled surface-ground water modelling at the scale of the KD basin over 1992–2000 (Massuel, 2005) confirm that more recharge sources than those readily identified (i.e., valley ponds essentially), are needed to account for the observed water table rise. Note that a side effect of the land cover change and induced increase in recharge has been a marked degradation in groundwater quality with a rise in naturally-produced nitrates around valley ponds, where the unconfined aquifer is mainly tapped (Favreau et al., 2009).

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 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.

Acknowledgements

The AMMA-CATCH observation system in Niger was financed through the French and European AMMA[2] fundings, by the French ECCO-PNRH programme, by the ORE programme of the French Research Ministry, and by IRD. Cooperation with national institutions of Niger (DMN, DRE, INRAN, Univ. Abdou Moumouni) and regional organizations (ABN, AGRHYMET, ICRISAT, ILRI) is gratefully acknowledged. Many more people than the authors of this paper have contributed significantly, by their work in the field and/or in the lab or by their scientific inputs, to this large experimental

[2] Based on a French initiative, AMMA was built by an international scientific group and is currently funded by a large number of agencies, especially from France, the UK, the US and Africa. It has been the beneficiary of a major financial contribution from 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.

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 Yéro), international volunteers (C. Bailleul, F. Métayer, F. Monnin, M. Rabanit), and researchers (A. Boubacar 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 LTHE 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

ABN	Niger Basin Authority
ACN	AMMA-CATCH Niger (component of AMMA-CATCH regional observation system)
ADEOS	Advanced Earth Observing Satellite
AERONET	Aerosol Robotic Network
AGRHYMET	Regional center for agro-ecology in the Sahel, Niamey (Niger)
AMMA	African Monsoon Multidisciplinary Analyses
AMMA-CATCH	Coupling hydrological cycle with tropical atmosphere in AMMA
AMMA-ICIG	AMMA International Coordination and Implementation Group
AMSR	Advanced Microwave Scanning Radiometer
ASAR/Envisat	Advanced Synthetic Aperture Radar on board the Envisat Satellite
A-Train	A train of six satellites dedicated to documenting the water cycle and the radiative forcing
CT3	Surface geological layer of the Continental Terminal series in the ACN area
DEM	Digital elevation model
DMN	Direction of National Meteorology, Rep. of Niger
DRE	Direction of Water Resources, Rep. of Niger
EOP	Enhanced observation period
EPSAT	Rainfall estimation from satellite
ERS	European scatterometer missions: ERS-1 (1991–2000) and ERS-2 (1995–)
HAPEX	Hydrological-Atmospheric Pilot Experiment (1992)
ICRISAT	International Crop Institute for the Semi-Arid Tropics
IDAF	IGAC/DEBITS/AFrica : Monitoring of Atmospheric Chemistry
ILRI	International Livestock Research Institute
INRAN	National Institute of Agronomic Research, Rep. of Niger
KD	Kori de Dantiandou
kori	Gully or fossil river bed
LOP	Long observation period
MSG	Meteosat Second Generation
OCS	Organised mesoscale convective systems
ROSELT/OSS	Réseau d'Observatoires de Surveillance Ecologique à Long Terme/Observatoire du Sahara et du Sahel
SEBEX	Surface Energy Balance Experiment
SMOS	Soil Moisture and Ocean Salinity
SSM	Soil surface moisture

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