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Rainfall characteristics ($\delta^{18}O$, δ^2H, ΔT and ΔH_r) in western Africa: Regional scale and influence of irrigated areas

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Abstract. A summary of previous isotopic studies of rainfall in western Africa (0°-17°N; 0°-15°E) together with the isotopic analyses of rainfall events from 15 stations in 1989 shows that (1) the Gulf of Guinea is the main source of water vapor in the Sudan-Sahelian zone (minimum of monthly mean of $\delta^{18}O$ contemporaneous with the heart of the monsoon), (2) the reevaporated water from previous local rainfalls is an important source of water vapor of subsequent rainfalls (lack of continental effect, where the majority of rain events present isotopic signature either evaporated or fed by evaporated water), and (3) no isotopic data support the Indian Ocean as a source of vapor. Isotopic ratios combined with variations of temperature and relative humidity associated with rain events in 1989 mirror the increasing aridity from south to north and from west to east. However, a Sahelian station, Birni N'Konni, presents all the features of a humid station with a large contribution of continental vapor (60% of rain events with d>10‰, -2 K<ΔT<2 K and ΔH_r<10%). This observation can be attributed to continental vapor originating from irrigated fields 100 km upstream of the dominant monsoon currents, in the Sokoto valley of Nigeria. This is corroborated by the difference in the evolution of rainfall amounts and relative humidity at Niamey and Birni N'Konni since 1951, signaling an important effect of land use changes on regional climate conditions.

1. Introduction

As reported by *Le Barbé and Lebel* [1997, p. 44] it might be said "that, during the 80s, opinions of the nature and the statistical significance of the Sahelian drought have fluctuated almost as much as the rainfall conditions themselves. As underlined by *Janicot and Fontaine* [1993], this may be partly attributed to the variety of mechanisms involved." In this context, it is interesting to examine what can be learned from isotopic signatures of rains, even if these results are initially qualitative, as argued by *Gong and Eltahir* [1996]. For example, continental vapor can contribute to meteoric precipitation through recycling by evapotranspiration, and this contribution can be identified by isotope analyses, particularly of the deuterium excess expressed as $d = \delta^2H - 8\delta^{18}O$ [*Dansgaard*, 1964; *Majoube*, 1971]. This parameter d has been extensively used [e.g., *Merlivat and Jouzel*, 1979; *Rindsberger et al.*, 1990; *Gat*, 1996; *Armengaud et al.*, 1998] in the characterization of hydrological systems (evaporation from falling rain droplets and contribution of evaporated moisture to rainfall) and also well as an indicator of paleoclimatological conditions in proxy materials such as ice cores.

According to the review by *Rozanski et al.* [1993], isotopic analyses of continental precipitation ($\delta^{18}O$ and δ^2H) have been performed in Europe and North America for ~ 40 years. By means of these analyses the origin of air masses and the processes that lead to precipitation can be characterized. Isotope data from the African continent are scarce, especially for the northern and western part of Africa (Figure 1). During the EPSAT-Niger program [*Lebel et al.*, 1996], rain events were sampled in Niger and Benin (Figure 2). The oxygen-18 and deuterium were analyzed in addition to the measurements of two air parameters, the temperature variation and the relative humidity variation associated with a rain event. The purpose of the present study is to obtain better answers concerning the sources of water vapor and the feedback between climate and surface water from these rainfall event measurements over a region of 1500 km x 1500 km on the African continent.

2. Main Climatological Features

The climate of western Africa is characterized by the succession of two seasons whose extreme conditions are summarized as follows after *Fontaine* [1991] and *Le Barbé et al.* [1993]:

1. During the boreal winter the subtropical anticyclone near the Azores favors a northerly wind component at the surface. Dry air masses (Harmatan) circulate toward the south, and the intertropical confluence zone (ITCZ) of wind cells from both hemispheres is situated close to the geographical equator.

2. During the boreal summer the North Atlantic subtropical anticyclone moves northward, and a low-pressure system develops over the Sahara because of the intense surface warming. The circulation of humid air masses is directed from the South Atlantic

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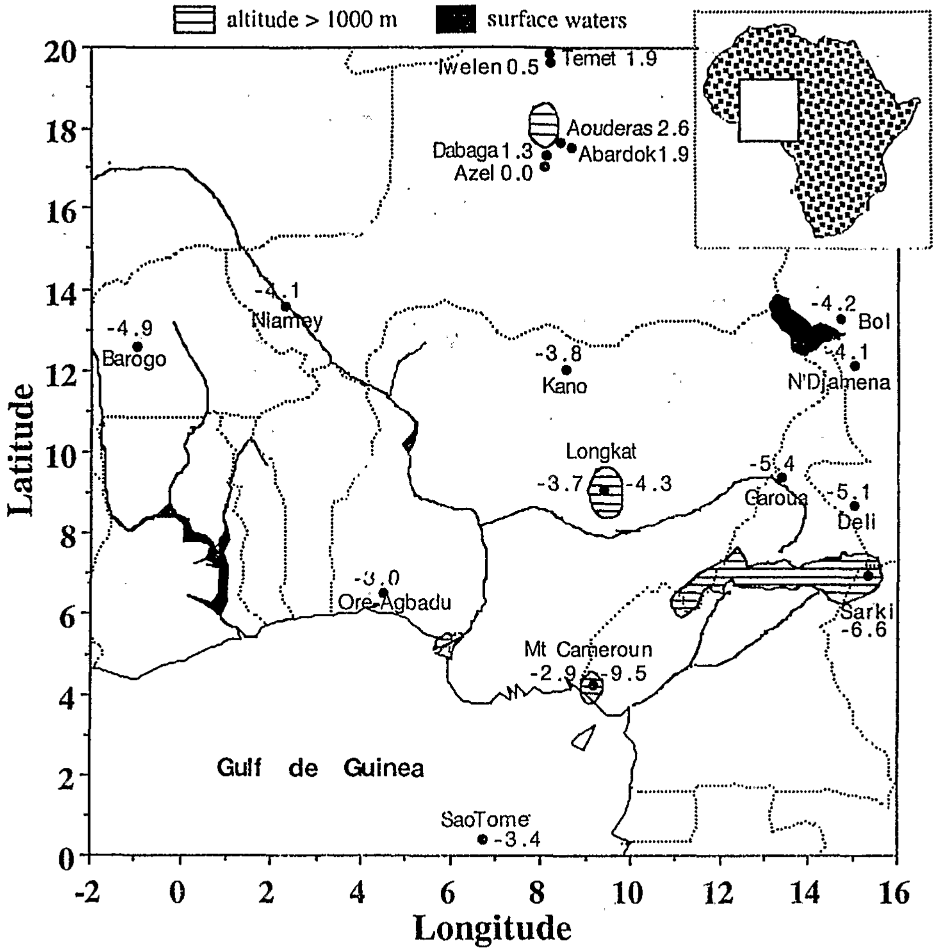

Figure 1. Location of stations where isotopic rainfall data were published in the region. Horizontal axis shows longitude in degrees. Vertical axis shows latitude in degrees north. Numbers are the weighted mean values of $\delta^{18}O$ in per mil at observation stations. For Longkat and Mount Cameroon each value corresponds to a different station at a different altitude (Table 1).

subtropical anticyclone toward the North, and the ITCZ extends up to ~ 13°N. The limit of the ITCZ in the lower layers is the intertropical front (ITF, 3 km high). The different thermal behaviors of ocean and continent induce a circulation from east to west (Tropical Easterly Jet at ~ 100 mbars and north-east African Jet at ~ 500 mbars).

The main features of the spatial evolution of rains according to *Charre* [1974] are as follows :

1. In the southern region (lower than 10°N) the rainy season has two maxima (spring and fall) corresponding to the period when the ITCZ crosses the region. Air masses from the subtropical anticyclone become laden with moisture when crossing the South Atlantic Ocean. These monsoon rains originate in a 200-km-wide band on both sides of the ITCZ where strong ascending occurs. The annual amount is ~ 1200 mm yr^{-1}.

2. In the northern region occupied by the ITF, currents from the eastern block cause the ascendance of humid air masses. Precipitation can occur if perturbations such as squall lines allow this structure to change. There is only one maximum in August, and the rainfall amount decreases to 130 mm yr^{-1} in Agadez. At the Sahelian latitude (13°N) the annual amount decreases from west (Niamey) to east (N'guigmi).

Evapotranspiration is an important source of water vapor in these regions as documented by micrometeorological data [*Monteny and Casenave*, 1989] and by the use of a mass balance model based on temperature, relative humidity, wind, and latent heat flux data [*Gong and Eltahir*, 1996]. However, the distribution of this flux between evaporation and transpiration is still poorly documented.

The Indian Ocean as a possible source of vapor at the latitude of the Sahel is still being debated [*Charre*, 1974; *De Felice et al.*, 1982; *Dhonneur*, 1985; *Fontaine*, 1991; *Joseph and Aranyossy*, 1989]. The challenge for future work is to understand the origin of the climatic variations such as, for example, the last 20-year drought over the region that is well characterized as to the rainfall data [e.g., *Le Barbé and Lebel*, 1997; *Paturel et al.*, 1997]. One way of addressing this question is to incorporate the isotopic cycles into a general circulation model (GCM) of the atmosphere [*Jouzel et al.*, 1987]. Considering the great heterogeneity of isotopic data regarding the continent, acquisition and publication of new data are of special importance.

3. Previous Isotopic Studies of Rainfall in Western Africa

The results obtained in previous isotopic studies of the African region in question (0°-15°E, 0°-17°N) are summarized below and in Table 1 and Figure 1. The source of vapor from the Gulf of

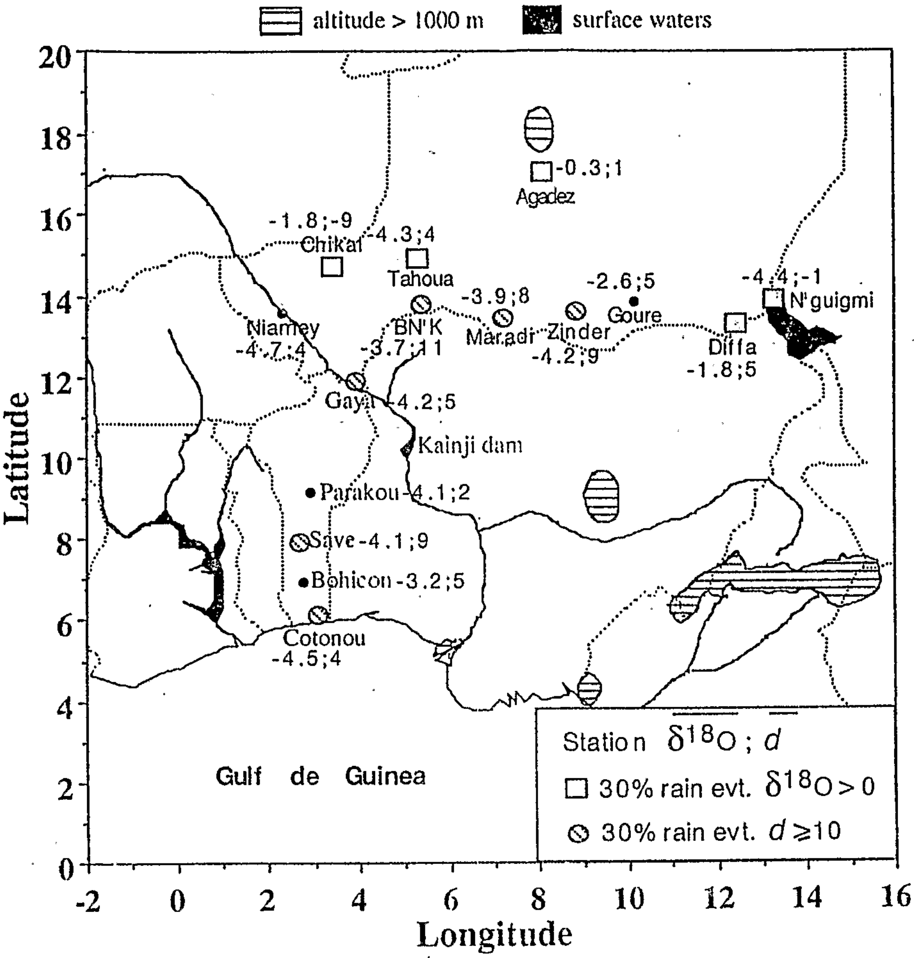

Figure 2. Location of stations sampled during the 1989 rainy season (EPSAT program). Numbers are the weighted mean values in per mil of $\delta^{18}O$ and deuterium excess for this period. Shaded squares are stations where more than 30% of rainfall events have $\delta^{18}O$>0‰ (numerous rainfall events affected by evaporation). Hatched circles are stations where more than 30% of rainfall events have a deuterium excess of more than 10‰ (contribution of vapor originating from evaporation over the continent).

Guinea is clearly the main source of water vapor according to climatic evidence. From the isotopical point of view, as moisture is gradually removed from air masses moving inland and condensation processes preferentially remove heavy isotopes more negative $\delta^{18}O$ should be observed with increasing distance from the coast. This feature known as the "continental effect" is observed over Europe and the Amazon basin [*Rozanski et al.*, 1993]. Over western Africa the tendency is, on the contrary, not at all clear at the regional scale (Figure 1) nor at the larger scale, along the trajectory of the Atlantic monsoon flow from Kano (12.03°N, 8.32°E) toward Khartoum (15.36°N, 32.33°E). An apparent increase of $\delta^{18}O$ with increasing distance from the coast is even observed from -3.8‰ at Kano to -2.1‰ at Khartoum [*Rozanski et al.*, 1993]. Locally, over the Aïr massif (from 17°N to 20°N) an increase in $\delta^{18}O$ is due to the increasing aridity toward the north [*Gallaire et al.*, 1995].

Disregarding the continental effect, what other isotopic arguments are in favor of an Atlantic source of water vapor in the rains between 0° and 17°N and 0° and 15°E? One argument is the V shape of the evolution over a year of the monthly mean $\delta^{18}O$ values. This type of graph is reported for stations located between 12°N and 17°N, Kano and N'djamena [*International Atomic Energy Agency* (*IAEA*), 1992], Barogo [*Mathieu et al.*, 1993], and Niamey [*Taupin et al.*, 1997]. Ranging between +4 and -8‰ the $\delta^{18}O$ values present their minimum values in August, which has the highest rainfall amount associated with the most northerly position of the ITCZ. Another argument is presented by *Mathieu et al.* [1993] for Barogo and by *Taupin et al.* [1997] for Niamey. The regional isotopic meteoric lines of these stations fitted on δ^2H versus $\delta^{18}O$ data (excluding rain events affected by evaporation) have almost the same equation for all stations, which argues for considerable amount of water vapor from a common source, the Gulf of Guinea. For the Aïr formation the same point of view is defended by *Gallaire et al.* [1995]. In that case, evaporation affects all the rainfalls, and the argument is that the $\delta^{18}O$ coordinate of the intersection between the fitted line on all data points and the World Meteoric Line is close to -5‰, which might indicate an oceanic source at the latitude of the Gulf of Guinea [*Rozanski et al.*, 1993].

The continental source of water vapor is propounded in several isotopic studies. On the basis of the data from the IAEA/World Meteorological Organization (WMO) network [*IAEA*, 1992], the apparent increase, quoted above, of the weighted mean value of $\delta^{18}O$ with increasing distance from the coast could be explained

Table 1. Available Weighted Mean Values of $\delta^{18}O$ in Western Africa (0°-17°N, 0°-15°E)

Name	Latitude, °N	Longitude, °E	Altitude, masl	Years	Reference	$\delta^{18}O$, ‰	Rain, mm
Abardok	17.31°	8.39°	830	1989-1990	*Gallaire* [1995]	2.0	55
Aouderas	17.38°	8.25°	810	1988-1990	*Gallaire* [1995]	2.6	149
Azel	17.03°	8.03°	526	1989-1990	*Gallaire* [1995]	0.1	157
Barogo	12.34°	-0.57°	280	1988-1989	*Mathieu et al.* [1993]	-4.8	655
Bol	13.28°	14.43°	<300	1967 and 1969	*Fontes et al.* [1970]	-4.2	306
Dabaga	17.19°	8.08°	650	1989-1990	*Gallaire* [1995]	1.3	101
Deli	8.43°	15.02°	<600	1967 and 1969	*Fontes et al.* [1970]	-5.1	1266
Garoua	9.23°	13.23°	<300	1991-1992	*Njitchoua et al.* [1995a]	-5.4	230
Gindiri	9.35°	9.13°	1050	1989	*Mbonu and Travi* [1994]	-4.6	725
Heipang	9.38°	8.52°	1000-1500	1989	*Mbonu and Travi* [1994]	-4.2	927
Iwelen	19.47°	8.25°	675	1988-1990	*Gallaire* [1995]	0.5	10
Jos (Fed. S.)	9.49°	8.50°	1280	1989	*Mbonu and Travi* [1994]	-4.8	791
Jos (Univ.)	9.56°	8.55°	1150	1988-1989	*Mbonu and Travi* [1994]	-4.3	833
Kano	12.03°	8.32°	476	1961-1966;1971-1973	*I.A.E.A.* [1992]	-3.8	763
Longkat	9.05°	9.22°	550	1989	*Mbonu and Travi* [1994]	-3.6	594
Mt Camer.	4.13°	9.10°	10	1972-1974	*Fontes and Olivry* [1976]	-2.9	6693
Mt Camer.	4.13°	9.10°	4050	1972-1974	*Fontes and Olivry* [1976]	-9.5	2188
N'Djamena	12.08°	15.02°	294	1964-1975;1977-1978	*I.A.E.A.* [1992]	-4.1	557
Niamey	13.36°	2.08°	222	1992-1995	*Taupin et al.* [1997]	-4.1	537
Ore-Agbabu	6.40°	4.58°	<200	1979	*Loehnert* [1988]	-3.0	1460
SaoTome	0.23°	6.43°	8	1962-1976	*I.A.E.A.* [1992]	-3.4	939
Sarki	6.57°	15.21°	<1500	1969	*Fontes et al.* [1970]	-6.6	1649
Temet	19.58°	8.25°	1050	1989-1990	*Gallaire* [1995]	1.9	14

Fed. S., Federal Secretariat; Univ., University; masl, meters above sea level.

by a continental vapor source [*Rozanski et al.*, 1993]. *Mathieu et al.* [1993] in the case of Barogo and *Taupin and Gallaire* [1998] for Sahelian stations point to the fact that deuterium excess (*d*) values overpass 10‰ to prove that the continental source is important for the rains at the edges of the rainy season. Values of *d* as high as 16.5‰ are also reported in May and June 1989 near Jos in Nigeria [*Mbonu and Travi*, 1994].

Under arid conditions the raindrops evaporate while falling toward the soil surface. This increases the high isotope contents so that points corresponding to evaporated rain are under the Global World Meteoric Line (GWML) in a δ^2H versus $\delta^{18}O$ graph, the deuterium excess is lower than 10‰. Such features are reported for Niamey [*Taupin et al.*, 1997] and for Barogo [*Mathieu et al.*, 1993] at the edges of the rainy season and for all the rains of the Aïr stations [*Gallaire*, 1995].

The altitude effect is well illustrated by the case of Mount Cameroon close to the ocean. The $\delta^{18}O$ values show an almost perfect gradient with respect to altitude [*Fontes and Olivry*, 1976] with a decrease of 0.15‰ of $\delta^{18}O$ per 100 m. This value is relatively small and could be explained after *Gonfiantini* [1998] by a liquid/vapor ratio increasing linearly with the altitude. At the Jos plateau a small value is also reported [*Mbonu and Travi*, 1994]. Farther inland, in the Aïr formation, the increasing aridity obliterates the altitude effect [*Gallaire et al.*, 1995].

The "amount effect" corresponds to an inverse relationship between the amount of monthly precipitation and its $\delta^{18}O$ composition [*Dansgaard*, 1964]. On tropical islands, covered by the IAEA/WMO network, a clear decrease is observed from values of 1‰ for small monthly amounts down to -6‰ for a monthly amount of ~ 350 mm [*Rozanski et al.*, 1993]. *Rozanski et al.* [1993] relate this phenomenon to the higher vertical velocity of ascending air masses during storms and to the smaller effects of exchanges between air and raindrops when the amount is higher. For the region under study, monthly data at Barago [*Mathieu et al.*, 1993] and Niamey [*Taupin et al.*, 1997] show a rather clear inverse relation where the first and last months of the rainy season show enriched isotopic ratios (>-4‰). However, the rainfall event data, when available, include some light rains with very negative $\delta^{18}O$ values and some heavy rains with high $\delta^{18}O$ values. This is the case for the Niamey region [*Taupin and Gallaire*, 1998; *Taupin et al.*, 1997], Barogo [*Mathieu et al.*, 1993], Garoua [*Njitchoua et al.*, 1995b], and the Aïr stations [*Gallaire*, 1995]. Small depleted rains might be explained by air masses ascending to very high/cold altitudes as corroborated by infrared Meteosat and radar data [*Taupin and Gallaire*, 1998]. Heavy rainfalls that are isotopically enriched might be related to a large continental source.

4. The Data Collected in 1989

The data were collected during the rainy season of 1989 as part of the EPSAT-Niger experiment designed to study the structure of Sahelian rain fields [*Lebel et al.*, 1996]. They were collected from meteorological stations chosen along a SSW-NNE line (Figure 2), from Cotonou (6°21'N) to Agadez (17°N), and an E-W line from N'guigmi (13°23'E) to Niamey (2°08'E). The first transect corresponds to the Guinean monsoon trajectory. The second corresponds to the movement of the convective systems that originate in central Africa and the Sahel.

Rainwater was collected from 15 meteorological stations (Figure 2 and Table 2). According to the statistical study by *Le Barbé and Lebel* [1997], the rain amounts over the Niger in 1989 were close to the mean values during the dry period of 1968-1990. For each station, isotope analyses were then made for a number of rain events whose total amount corresponds to 90% of the total rainfall over the period under consideration. The lower limit of analyzed rain events was 8 mm for the Sudanese region, 5 mm for the Sahel, and 1 mm for the subdesert region. There were 347 samples analyzed in oxygen-18 and deuterium. For hydrogen assay the water was first decomposed at 450°C using zinc metal to generate hydrogen gas. For oxygen isotope assay a gas preparation technique was used which relied on isotopic exchange of the

Table 2. Coordinates and Mean Values of the Parameters for the 15 Stations

Station				Rain			$\delta^{18}O_p$	δ^2H_p	d_p	ΔT	ΔH_r
Name	Latitude, °N	Longitude, °E	Elevation, masl	R_{im}	R_{89}	N_{89}	‰	‰	‰	K	%
Agadez	16.59°	7.59°	500	138	130	26	-0.3	-2	1	-7.1	23.6
Birni N'Konni	13.47°	5.22°	272	534	450	48	-3.7	-19	11	-1.8	7.7
Bohicon	7.10°	2.04°	167	1150	895	58	-3.2	-20	5	-2.5	8.2
Chikal	14.37°	3.26°	250		276	39	-1.7	-23	-9	-4.3	14.9
Cotonou	6.21°	2.23°	4	1250	913	45	-4.5	-38	4	-2.0	6.3
Diffa	13.14°	12.25°	350	288	221	22	-1.8	-10	4	-5.0	25.8
Gaya	11.53°	3.27°	180	819	576	50	-4.2	-30	5	-4.2	19.1
Gouré	13.49°	10.07°	451	335	289	33	-2.6	-15	5	-5.0	21.5
Maradi	13.29°	7.13°	388	541	587	36	-3.9	-22	8	-5.0	21.4
N'guigmi	13.51°	13.23°	289	218	109	16	-4.4	-35	0	-5.5	22.0
Niamey	13.36°	2.08°	222	566	600	31	-4.7	-35	4	-6.1	20.5
Parakou	9.21°	2.36°	320	1190	1171	64	-4.1	-31	2	-3.3	12.0
Savé	7.59°	2.28°	198	1100	740	57	-4.0	-24	9	-3.0	8.6
Tahoua	14.54°	5.21°	384	389	362	51	-4.3	-30	4	-5.1	20.2
Zinder	13.34°	8.54°	489	460	318	36	-4.2	-25	9	-4.7	19.7

R_{im} (mm yr^{-1}) is the yearly mean of annual rainfall amount (1925-1984 after *Le Barbé et al.* [1993] for the Benin and 1950-1989 after *Le Barbé and Lebel* [1997] for the Niger). R_{89} (mm yr^{-1}) is the rainfall amount during the rainy season in 1989. N_{89} is the number of studied rainfall events in 1989. Values $\delta^{18}O_p$, δ^2H_p and d_p are the mean values weighted by rainfall amounts for the analyzed rainfall events in 1989. Values ΔT and ΔH_r are the average variation of temperature and of relative humidity in the rainfall events of 1989.

oxygen in water with oxygen of known isotopic composition in carbon dioxide gases. Analysis was performed by using a VG-Micromass 602E mass spectrometer. The analytical errors were 0.2‰ for $\delta^{18}O$ and 2‰ for δ^2H.

Water samples were collected and stored in glass bottles of 20 mL kept in a cold and dark place until the analysis was performed in France at the University of Orsay. Isotopic data of one sample from Niamey and of six samples from Tahoua have been disregarded. They present d values of less than -50‰, which seems excessive and may correspond to samples evaporated after they were collected. For all other data the conformity has been checked by comparison with the measurements of temperature and relative humidity and, for Niamey, with the set of data on samples of 1992-1995 [*Taupin et al.*, 1997].

Temperature and relative humidity, which control the isotopic ratios of water [*Craig et al.*, 1963], were measured before and after each rain event. In tropical areas, saturation of the air is far from being reached, and the variation of the air parameters during a rainfall event is an integrating indicator of the exchanges between the raindrops and the air. If the air is almost saturated, the decrease in temperature and the increase in humidity should be small. On the contrary, if it is far from being saturated, exchanges are greater and lead to a large decrease in temperature and a strong increase in relative humidity.

5. Spatial Evolution of Rain Characteristics

5.1. The δ^2H, $\delta^{18}O$ and Deuterium Excess

The rain event values of $\delta^{18}O$ range between -11 and 4.2‰ when the d values range between 27 and 26‰. These ranges are smoothly lowered when the weighted mean values are considered (Table 3). The large range of monthly mean $\delta^{18}O$ values (-7.1 to 4.2‰) is especially noticeable for rainfalls of small amounts (<100 mm in Figure 3). This reflects either evaporation or convection up to high altitudes [*Taupin and Gallaire*, 1998]. When monthly or rain event data of $\delta^{18}O$ are plotted versus the rain amount for one particular station, no amount effect is observed. When all the monthly data from the 15 stations are considered, only a smooth trend is observed that mirrors the geographical variation: where an enriched isotopic ratio corresponds to a small amount of rain from more arid regions and lower values of the isotopic ratio correspond to greater amounts of precipitation from humid regions.

The spatial evolution of the seasonal weighted mean values of $\delta^{18}O$ (Figure 2) shows that from Cotonou to Niamey and between Zinder and Niamey the values are close to -4‰. This value corresponds to oceanic rains at these latitudes [*Craig and Gordon*, 1965; *Rozanski et al.*, 1993] and is corroborated by data from groundwater in Nigeria [*Loehnert*, 1988], Ghana [*Akiti*, 1980], and in the Niamey region [*Leduc and Taupin*, 1997]. This lack of continental effect with increasing distance from the Gulf of Guinea argues in favor of a continental source of vapor.

The main source of vapor in the region under study is obviously the Gulf of Guinea. In addition to climatological evidence, the isotopic data show that in most cases the minimum values of $\delta^{18}O$ are contemporaneous with the heart of the monsoon (Table 3 and Figure 4). The Sahelian stations between Niamey and N'guigmi, show a V shaped evolution of the event $\delta^{18}O$ value with the minimum values in August at the heart of the rainy season. At the edge of the rainy season the rainfall presents higher values because of the evaporation of the raindrops as they fall.

Joseph et al. [1992] developed an isotopic argumentation leading to an Indian Ocean source for the rains over the Sudan-Sahelian zone (10°N-15°N) in the whole African continent. Isotopic data on rainfall were then available for nine stations between the Indian Ocean and Dakar. These authors associated these scarce data with some others from shallow aquifers and presented a graph of an apparent decrease from east to west over 70° of longitude. They explained this by a major contribution of moisture from the Indian Ocean. Today, the 13 available data over only 20° of longitude (Figures 1 and 2) allow us to conclude that the weighted mean values of $\delta^{18}O$, ranging between , -4.9 and -1.8‰, do not present a decrease from east to west. Moreover, the

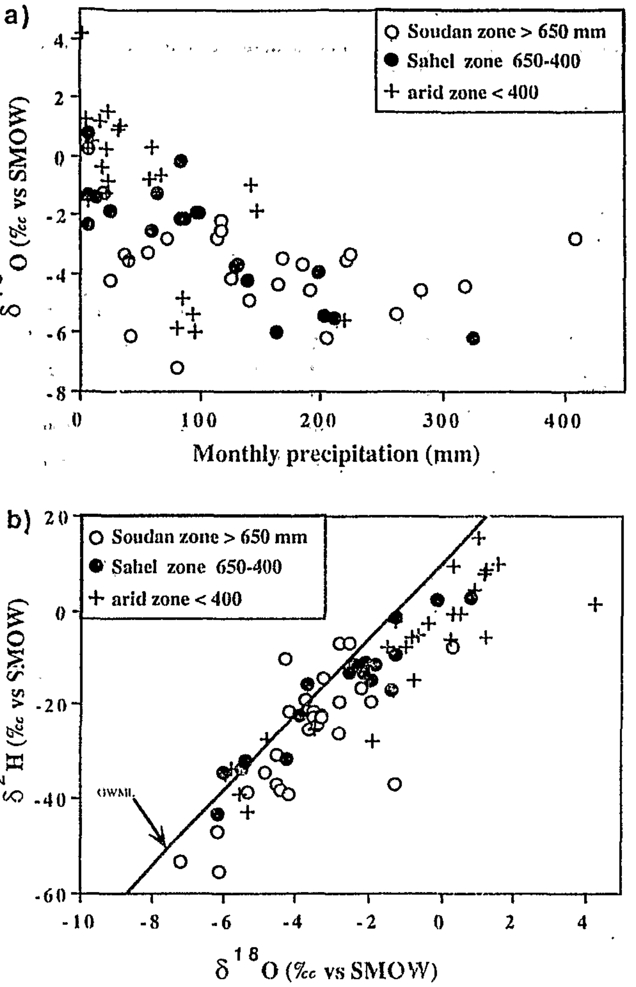

Figure 3. Monthly weighted mean values from rainfall event values from 1989: (a) $\delta^{18}O$ versus rain amount and (b) $\delta^{2}H$ versus $\delta^{18}O$. Sudanese zone includes Bohicon, Cotonou, Parakou, Save, and Gaya; Sahelian zone includes Birni N'Konni, Maradi, Niamey, and Zinder; and Arid zone includes Agadez, Chikal, Diffa, N'guigmi, Gouré, and Tahoua. SMOW, Standard mean ocean water.

relatively wide range of $\delta^{18}O$ in the phreatic aquifer in the region of Niamey, between -2.5 and -5.2‰ [*Leduc and Taupin,* 1997], demonstrates that an isolated value from an aquifer should not be used without a thorough hydrogeologic study. Finally, isotopic and chemical data on rain samples in Senegal [*Travi et al.,* 1987, 1993] show that the main source of vapor is the Atlantic Ocean. The previous argumentation of an Indian source of vapor feeding rainfall as far as Senegal is therefore no longer valid.

A continental source of vapor is related either to the nonfractionating transpiration from vegetation or to the fractionating evaporation from water bodies. Transpiration adds vapor to the atmosphere which tends to offset the continental effect by lowering the expected depletion of $\delta^{18}O$ values but not modifying the deuterium excess value. A source of vapor related to evaporation adds vapor to the atmosphere and tends to decrease $\delta^{18}O$ values and enhance d values (e.g. *Gat and Matsui* [1991] for the Amazon basin). In the region under study, water mass balance shows that a large amount of rainfall returns to the atmosphere, up to 90% in the Sahelian zone of Niger [*Leduc and Taupin,* 1997] and up to 70% in the Sudanese zone in Benin [*Le Barbé et al.,* 1993].

We shall now try to identify the rainfalls for which transpiration may be the major source of water vapor. Let us assume that these rainfalls have a $\delta^{18}O$ value ranging between -3 and -5‰ and a d value ranging between 8 and 12‰. Only a few data from Save and some other stations close to Birni N'Konni fit this criterion (Table 2 and Figures 2 and 4). Even Cotonou, Bohicon, and Parakou, where humid tropical vegetation exists, do not have rainfalls fitting the criterion. Hence the contribution of transpiration appears to be poorly inscribed in the isotopic data. Either this source is quantitatively weak, which is surprising in the forested region, or its contribution is masked by another process such as evaporation of raindrops.

We shall check the d>10‰ as a tentative criterion to characterize the rainfalls for which one source of vapor could be water evaporation on the continent. For the mean values of the season (Table 2), only Birni N'Konni fits the criterion. Considering the monthly values (Table 3), 12 of 70 data fit the criterion. They belong to nine stations mainly distributed in the Sudan-Sahelian zone. Considering the rainfall event data, all the

Table 3. Monthly Mean Values of $\delta^{18}O$ and d

	May		June		July		August		September		October		Percentage With d	
Stations (N)	$\delta^{18}O$ ‰	d ‰	$\delta^{18}O$ ‰	d ‰	$\delta^{18}O$ ‰	d ‰	$\delta^{18}O$ ‰	d ‰	$\delta^{18}O$ ‰	d ‰	$\delta^{18}O$ ‰	d ‰	<5‰	>10‰
Agadez (13)			0.9	-3	-0.7	4	-0.8	1	0.3	-7			69	8
Birni N'Konni (30)			-0.1	4	-3.7	14	-6.0	13	-2.5	7			30	60
Bohicon (27)	-2.5	8	-3.5	7	-2.8	13	-2.2	1	1.2	-27	-4.2	2	33	15
Chikal (22)			-0.4	0	-3.5	3	-1.8	[illegible]	[illegible]	-9			86	0
Cotonou (22)	-6.2	10	-2.8	-2	-3.3	13	-7.1	4	-2.8	3	-4.5	0	45	32
Diffa (16)			1.0	7	-0.6	0	-4.8	11	1.2	-2	1.2	-6	69	12
Gaya (20)			-0.9	-5	-5.9	11	-5.8	4					45	30
Goure (18)					-0.9	0	-4.4	11	-2.5	3			61	22
Maradi (26)			-1.2	8	-3.9	9	-5.5	10	-2.1	4	-1.3	3	42	35
N'guigmi (10)			4.2	-15	0.5	-5	-5.4	1			0.2	8	90	0
Niamey (24)			-1.8	3	-1.9	0	-6.2	5	-4.2	2	-1.3	1	65	12
Parakou (41)	-3.5	7	-3.3	4	-4.4	-3	-4.5	5	-3.6	2	-6.1	6	42	15
Save (25)	0.3	-10	-3.4	10	-3.2	10	-4.2	9	-4.3	20	4.9	5	36	52
Tahoua (25)	1.3	-3	1.6	-5	0.3	-3	-5.6	5	-1.5	4			64	12
Zinder (21)					-2.1	6	-5.4	11	-2.3	7	0.8	-3	48	33

Values are weighted by rainfall amount. N is the number of rainfall events analyzed for oxygen-18 and deuterium. The two last columns show the percentage [illegible]

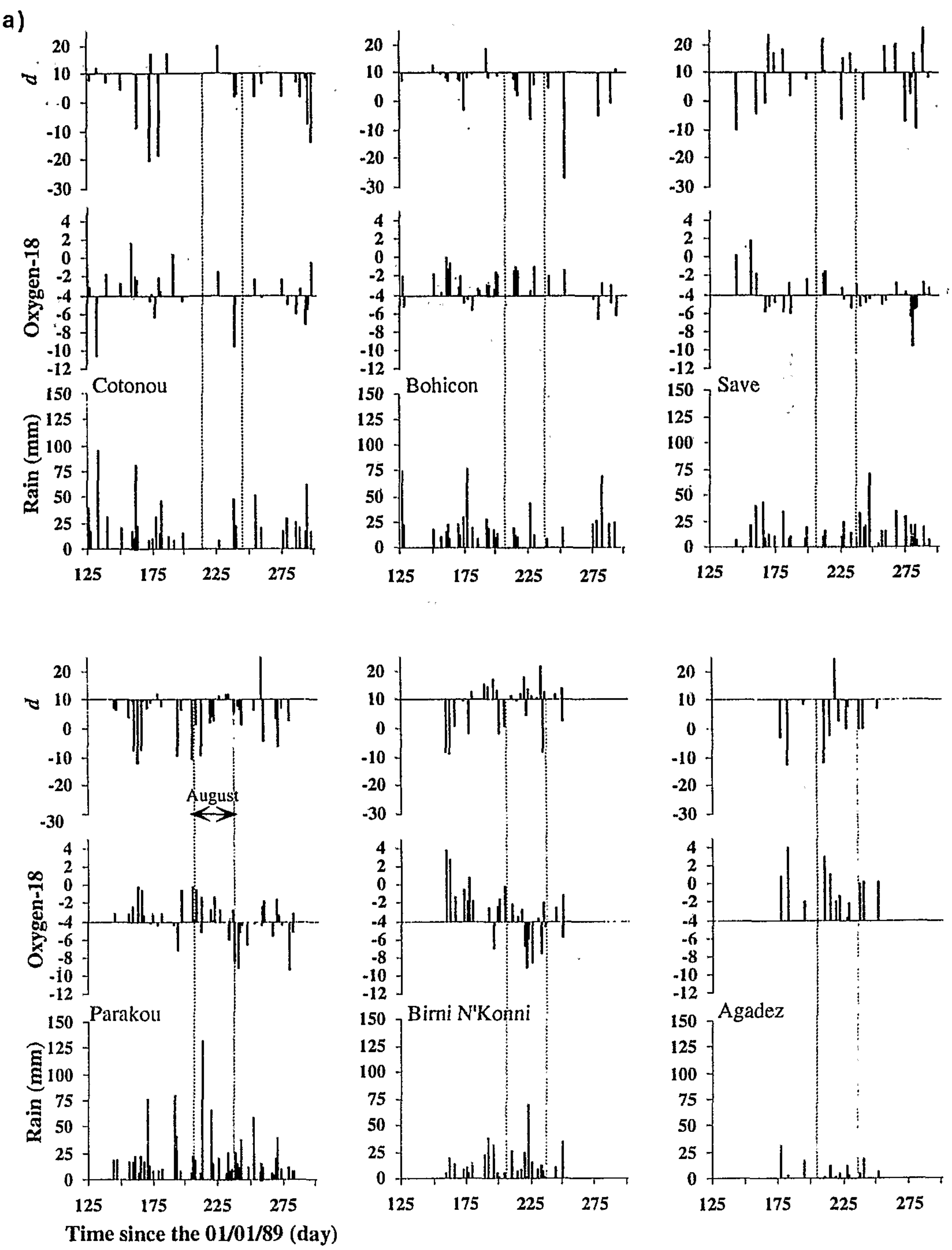

Figure 4. Rainfall event data from 1989, including rain amount, oxygen-18 and *d* versus time. (a) Stations from south (Cotonou) to north (Agadez). (b) Stations from west (Niamey) to east (N'guigmi) in the Sahelian zone.

stations except the very arid ones of Chikal and N'guigmi present events fitting the criterion. The percentage of rainfall events fitting the criterion (Table 3) is as high as 60% for Birni N'Konni and 30% for six other stations. It is very likely that everywhere in the region one important source of vapor is continental evaporation.

Now the question is: Where does this evaporated water come from? There are two large, open water bodies. One is lake Chad that can reach 20,000 km^2. This lake and the vapor above it were sampled in the late sixties [*Fontes et al.*, 1970]. Evaporation from the lake is evident from its $\delta^{18}O$ values ranging between 0 and 15‰ and from the slope of 5.2 in a δ^2H versus $\delta^{18}O$ graph. Vapor sampled between June and August shows high values of d (23‰) and low values of $\delta^{18}O$ (-15 to -12‰). Precipitations at N'guigmi are most probably related to a contribution of vapor from the lake that was not dry in 1989 [*Olivry et al.*, 1996]. However, they are not associated with *d* values exceeding 10‰; it is very likely that evaporation affected the falling raindrops. The other large, open water body is Kainji dam, but no station is sufficiently close to it to be able to characterize its specific influence. Finally, if vapor originating from evaporation is prevalent in the region, the source could be the soil water wetted by previous rainfall events or even water evaporated from these events.

The criterion for evaporation during rainfall is tentatively

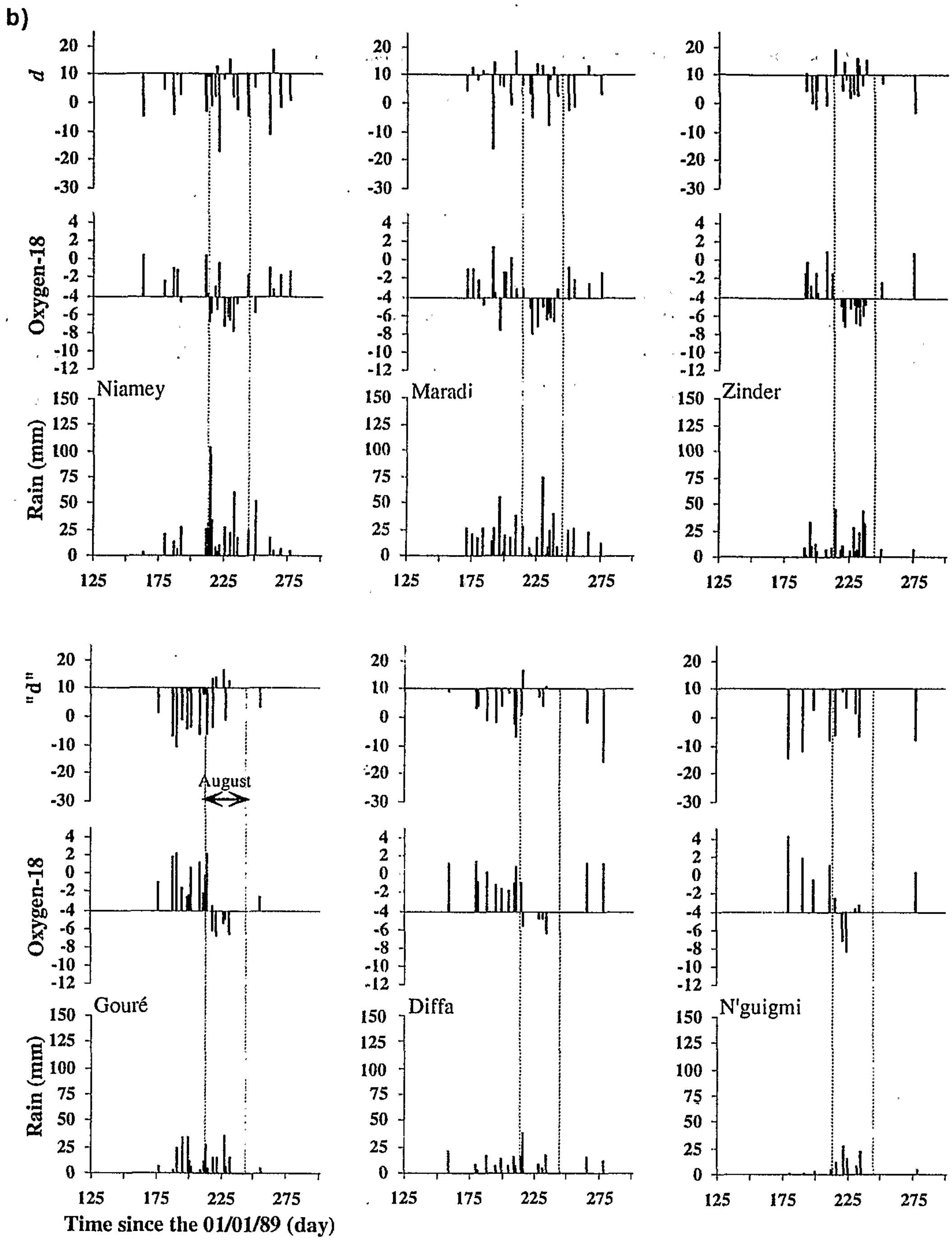

Figure 4. (continued)

chosen as d<5‰. At the seasonal scale, nine of the stations between Agadez and Cotonou and between N'guigmi and Niamey (Table 2) fit the criterion. At the monthly scale, 44 of the 70 data again fit the criterion (Table 3). At the event scale, 52% of the rainfall events would be affected by evaporation (40% in the Sudanese zone and 61% in the Sahelian zone). All the stations from Sahelian and arid zones present an evaporated signal at the beginning of the rainy season ($\delta^{18}O$>-4‰ and d<10‰, Figure 4). It is very likely that this phenomenon hides the isotopic signature of the vapor sources. Conversely, this process constitutes, on its own, a source of vapor that is able to feed the subsequent rainfalls. An argument in favor of this hypothesis comes from the study of the dry event between two rainfalls. For all the stations and the period under consideration the maximum duration ranges between 10 and 23 days. The maximum duration of the dry event preceding the rainfall events that present d values exceeding 10‰ is 2 days in Agadez, 5 days at Sahelian stations, and is unlimited in the Sudanese zone. In these semi-arid and arid regions the available water from previous rainfalls has "disappeared" after these 2 or 5 days. In the Sudanese zone there is no limit to the duration of the dry event, water is always available for evaporation.

To conclude, isotopic data provide arguments for excluding the Indian Ocean as a noticeable source of vapor for Sahelian rainfall and including various other sources of vapor: the maritime one from the Gulf of Guinea transported by the monsoon and the continental one transpired (less) and evaporated (more) from soil

Table 4. Temperature and Relative Humidity Variation Associated With Rain Events

Name	N	Mean ΔT, K	Rainfall Events With ΔT<-2 K, small rains, %	Rainfall Events With ΔT>-2 K, %	Mean ΔH_r, %	Rainfall Events With ΔH_r>10% small rains, %	Rainfall Events With ΔH_r<10%, %
Agadez	13	-7.1	46	15	23.6	42	15
Birni N'Konni	50	-1.8	8	66	7.7	10	62
Bohicon	58	-2.5	17	36	8.2	19	55
Chikal	31	-4.3	26	29	14.9	16	48
Cotonou	45	-2.0	9	53	6.3	4	78
Diffa	21	-5.0	14	24	25.8	20	20
Gaya	48	-4.2	40	29	19.1	44	29
Gouré	17	-5.0	18	29	21.5	18	23
Maradi	27	-5.0	7	18	21.4	11	22
N'guigmi	16	-5.5	44	31	22.0	50	19
Niamey	30	-6.1	20	20	20.5	13	40
Parakou	64	-3.3	30	27	12.0	31	42
Savé	57	-3.0	25	40	8.6	14	63
Tahoua	33	-5.1	30	27	20.2	36	21
Zinder	15	-4.7	7	33	19.7	6	31

N is the number of rain events with recorded ΔT and ΔH_r values. Rainfall events with ΔT<-2 K, small rains are the percentage of rainfall events with a large decrease of temperature for rain with small amounts (less than 5 mm at the arid-Sahelian stations and less than 10 mm at the others). Rainfall events with ΔT>-2 K are the percentage of rainfall events with a small decrease of temperature for any amount of rain. Rainfall events with ΔH_r>10%, small rains are the percentage of rainfall events with large variations of relative humidity for rain with small amounts. Rainfall events with ΔH_r<10% are the percentage of the rain events with small variations of relative humidity for any amount of rain.

and rain. In the Sahelian zone the previous rainfall generally feeds the subsequent one when the dry event lasts less than 5 days. A dominant process in the region is the evaporation of raindrops.

5.2. Evolution of Climatic Parameters ΔT and ΔH_r

The difference in temperature (ΔT) and humidity (ΔH_r) measured at ground level between the end and the beginning of a rainfall event is presented in Table 4. During the 1989 rainy season in the studied area, the variations in temperature during rainfall events range between ~ 2 and -16 K (Figure 5). In the following text, large variations of temperature refer to ΔT values ranging between -2 and -16 K. Variations of relative humidity range between 50 and -10% (Figure 6), disregarding the probably erroneous value of -21% at Agadez. In the following, large variations of relative humidity refer to ΔH_r values ranging between 10 and 50%.

Over the period under consideration, the mean values of ΔT (Table 4) vary from -2 K at Cotonou to -7.1 K at Agadez. The mean values of ΔH_r (Table 4) vary similarly from 6% at Cotonou to more than 20% at Agadez and Diffa. This progressive increase in the variations of temperature and relative humidity during rainfall indicates an increase in the exchanges linked to a deficit of

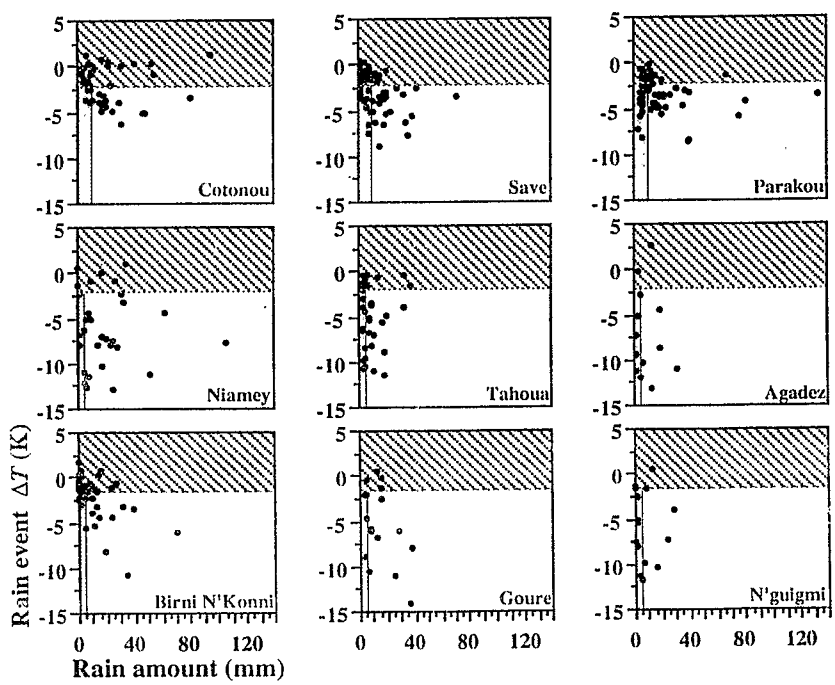

Figure 5. Variation of temperature ΔT versus rainfall amount for nine stations. In the upper hatched rectangles limited below by ΔT=-2 K, dots correspond to rains with low temperature variations for any rain amount. In the shaded left-hand rectangles, dots correspond to rains with small amounts and large temperature decreases.

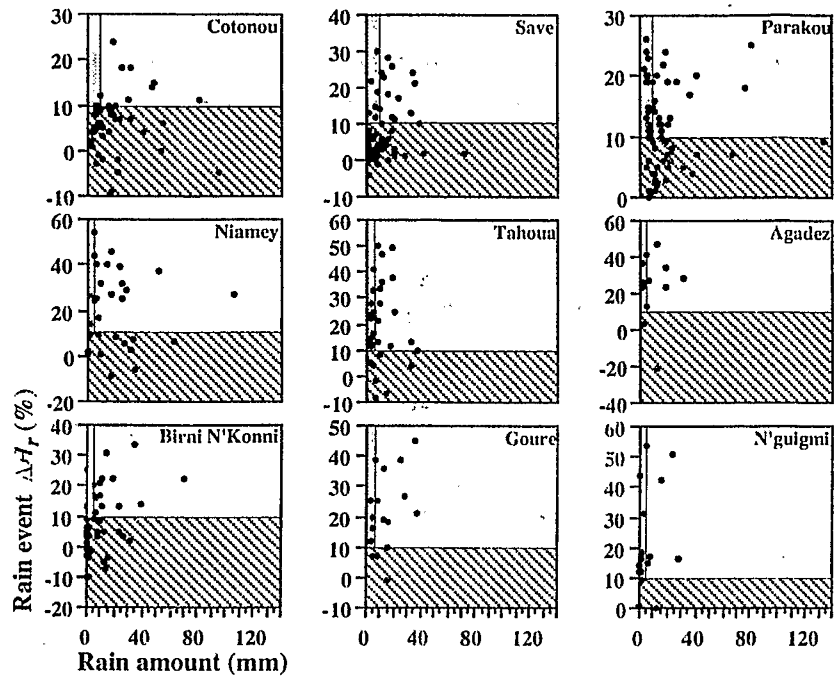

Figure 6. Relative humidity variation versus rainfall amount for nine stations. In the shaded left-hand rectangles limited by ΔH_r = 10%, dots correspond to rains with high variations of relative humidity and small amounts. In the lower hatched rectangles, dots correspond to rains with small variations of relative humidity for any rainfall amount.

atmospheric humidity. Over the Sahel zone the mean ΔT values range between -6 and -4 K except for Birni N'Konni, where the ΔT value (-2 K) is close to that of coastal stations. Similarly in this zone, the mean ΔH_r values range between 15 and 26% except for Birni N'Konni, where the ΔH_r value (8%) is also close to that of the coastal stations.

Stations in humid tropical areas (Cotonou, Bohicon, and Save) and the Sahelian station Birni N'Konni have small mean values (-3 K<ΔT<-2 K) and more than 30% of rainfall events (Table 4) with small temperature variations (-2 K<ΔT<2 K and ΔH_r<9%). More arid stations (Agadez, Tahoua, and N'guigmi) present greater temperature and relative humidity variations associated with rainfall events (-7 K<ΔT<-5 K in Figure 5 and ΔH_r>20% in Figure 6) and over 30% of these events are small rainfall events with large temperature or relative humidity variations (-15 K<ΔT<-2 K and ΔH_r>10% in Table 4).

The set of data of $\delta^{18}O$, deuterium excess, ΔT and ΔH_r shows very good correlation and can be used to characterize atmospheric processes. Evaporation is well defined at arid stations (Agadez, N'guigmi, and Tahoua) where 30% of the rainfall events present positive values of $\delta^{18}O$, and 30% also show small amounts with large decreases in temperature (-15 K<ΔT<-2 K) as well as large increases in relative humidity (10%<ΔHr<50%). Vapor recycling is well characterized for stations (Cotonou, Save, and Birni N'Konni) where reevaporation from the continent constitutes an important contribution to the precipitation. At these stations, 30% of rainfall events have large values of deuterium excess (d>10‰) and small variations in temperature and relative humidity. The different parameters are less well correlated for the other stations that are either subjected to intermediate climatic conditions or subjected to the influence of peculiar geographical characteristics.

6. Particularity of the Area of Birni N'Konni

The peculiar isotopic ratio and climatic data in the region of Birni N'Konni could be explained by regeneration of air masses through evapotranspiration from local free water bodies. The anomalies in the isotopic data of rain and air characteristics are corroborated by the vegetation index map based on satellite images in August 1989 which present higher relative values in the region of Birni N'Konni than in the surrounding areas at the same latitude [*Rigal*, 1989].

The geological map (Figure 7) shows outcrops of sedimentary formations overlying the crystalline bedrock of the Pan-African shield 150 km south of Birni N'Konni. The Sokoto valley is a zone of natural recharge of the sedimentary aquifers [*Geyh and Wirth*, 1980] and may constitute a potential source of water vapor during the rainy season.

The main land use change in the region is the Kainji dam (Figure 1) on the Niger River. Its water surface area is 1250 km^2; it was first filled in 1968 [*Beadle*, 1981] and is mainly used for the production of electrical power. A smaller but closer modification is the Bakolori Dam on the Sokoto River (Figure 7). It was filled in 1983 during the rainy season and has a water surface area of 80 km^2. About 230 km^2 of land are irrigated from this reservoir [*Adams*, 1996; *Bird*, 1985]. In the Sokoto valley, rice crops have been grown since a few years after the dam was built [*Larousse*, 1984] and seem to be continued [*Serryn*, 1988; *Serryn and Blasselle*, 1994].

If these land use changes have a real impact on the isotopic and climatic parameters in the Birni N'Konni region, what effects have been recorded? The data available to test whether or not these changes affect the climatic parameters are the relative humidity

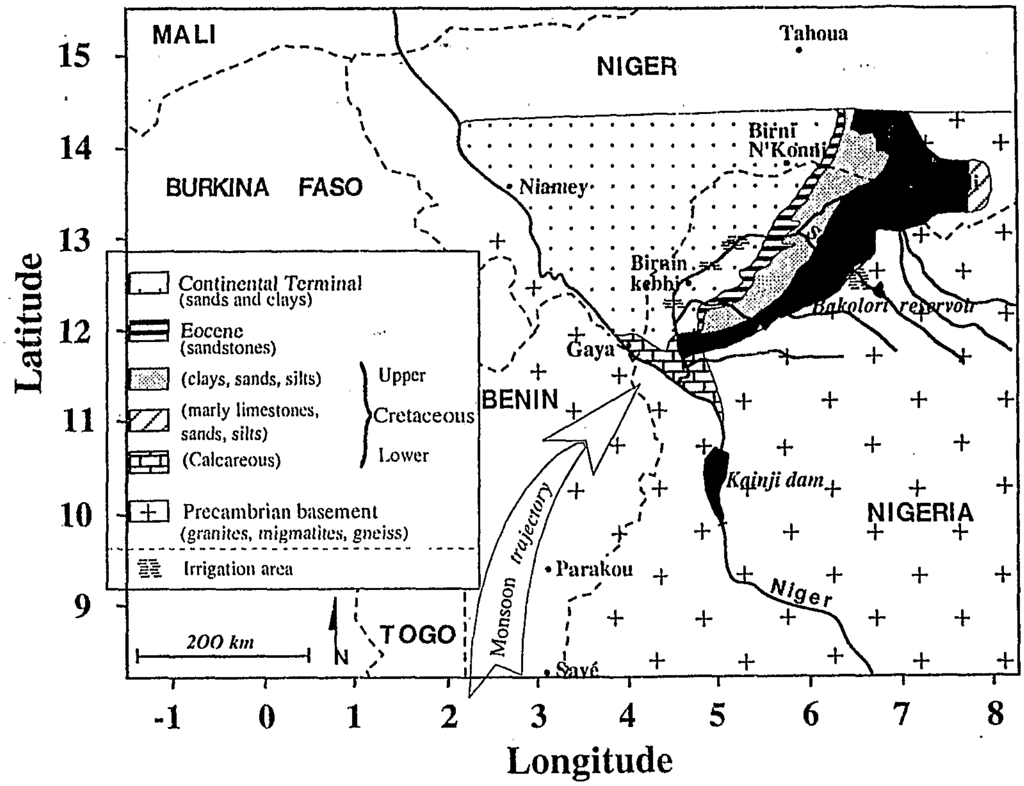

Figure 7. Regional geology and surface water management near Birni N'Konni. Air masses from the south may be recharged over the Kainji dam, the Bakolori reservoir, and the irrigated areas.

values at Niamey and Birni N'Konni recorded since 1951. These stations present a very similar mean evolution of the relative humidity over 1 year (Figure 8a). Maximum values are reached in August with a daily relative humidity ranging between 90 and 50%. Minimum values occur in February with a daily relative humidity ranging between 30 and 10%. The period between 1951 and 1967 was more humid [*Le Barbé and Lebel*, 1997]: the difference between the mean values over this humid period and the mean values over the 1951-1995 period is mainly positive (Figure 8b). The period between 1968 and 1983, after the Kainji reservoir was filled, corresponds to drier climatic conditions [*Le Barbé and Lebel*, 1997]: the difference between the mean values over this dry period and the mean values over the 1951-1995 period is mainly negative. Either the filling of the Kainji dam did not affect the relative humidity at Birni N'Konni or its influence was similar on both stations which are both situated ~ 400 km north of the Kainji dam. During the period between 1984 and 1995, after the development of irrigation in the Sokoto valley, the climate was even drier [*Le Barbé and Lebel*, 1997]. As expected, Niamey presents values of relative humidity lower than those during the previous period. On the contrary, Birni N'Konni shows mean values of the daily minimum relative humidity higher by 4% than those of the 1968-1983 period. This is probably a consequence of the evaporation from water bodies in the irrigated fields in the Sokoto valley situated ~ 100 km south of Birni N'Konni. This evaporation probably does not affect Niamey, situated to the northwest of the Sokoto valley, out of the path of major air mass fluxes.

Is this increase in relative humidity accompanied by an increase in rainfall amount? The mean values of the annual rainfall amount were studied for stations that are near and to the north of the Bakolori reservoir. Again, three periods were considered: the humid one from 1950 to 1967 and the dry ones from 1968 to 1983 and from 1984 to 1995, respectively, before and after the filling of the Bakolori reservoir. Table 5 shows that all five stations present a large rainfall decrease of more than 100 mm between the first humid period and the second one. From the second to the third period the different stations show different behaviors. The stations farthest from Birni N'Konni, Niamey and Zinder, show a decrease of 36 and 39 mm, respectively. On the contrary, at Birni N'Konni there is an increase of 19 mm, and at the stations nearest to it, Tahoua and Maradi, there is an increase of 7 and 10 mm, respectively.

The evaporation from the Bakolori reservoir and the rice paddies can be estimated. Potential evaporation from a Colorado tank is ~ 5 mm d^{-1} [*Griffiths*, 1972; *Le Barbé et al.*, 1993]. A coefficient of 0.8 [*Pouyaud*, 1986; *Riou*, 1975] should be taken into account to estimate actual evaporation from a reservoir. On the basis of the energy budget and a stable isotope composition of water vapor [*Brunel et al.*, 1992], evapotranspiration fluxes from rice paddies in tropical areas have been estimated to be ~ 6 mm d^{-1}. In the following, the first estimate corresponds to a maximum of 620 Mm^3 computed as follows, from the Bakolori reservoir and from the irrigated areas, successively:

$$80\ Mm^2 \times 0.005\ m\ d^{-1} \times 0.8 \times 365\ days = 116.8\ Mm^3$$

$$230\ Mm^2 \times 0.006\ m\ d^{-1} \times 365\ days = 503.7\ Mm^3$$

To obtain a minimum estimate, taking into account a smaller surface area of the reservoir and of the irrigated area and only 4 months of irrigation, the water volume available from this source would be 217 Mm^3.

The volume of water corresponding to the increase in the rainfall may also be roughly estimated. The area affected by the

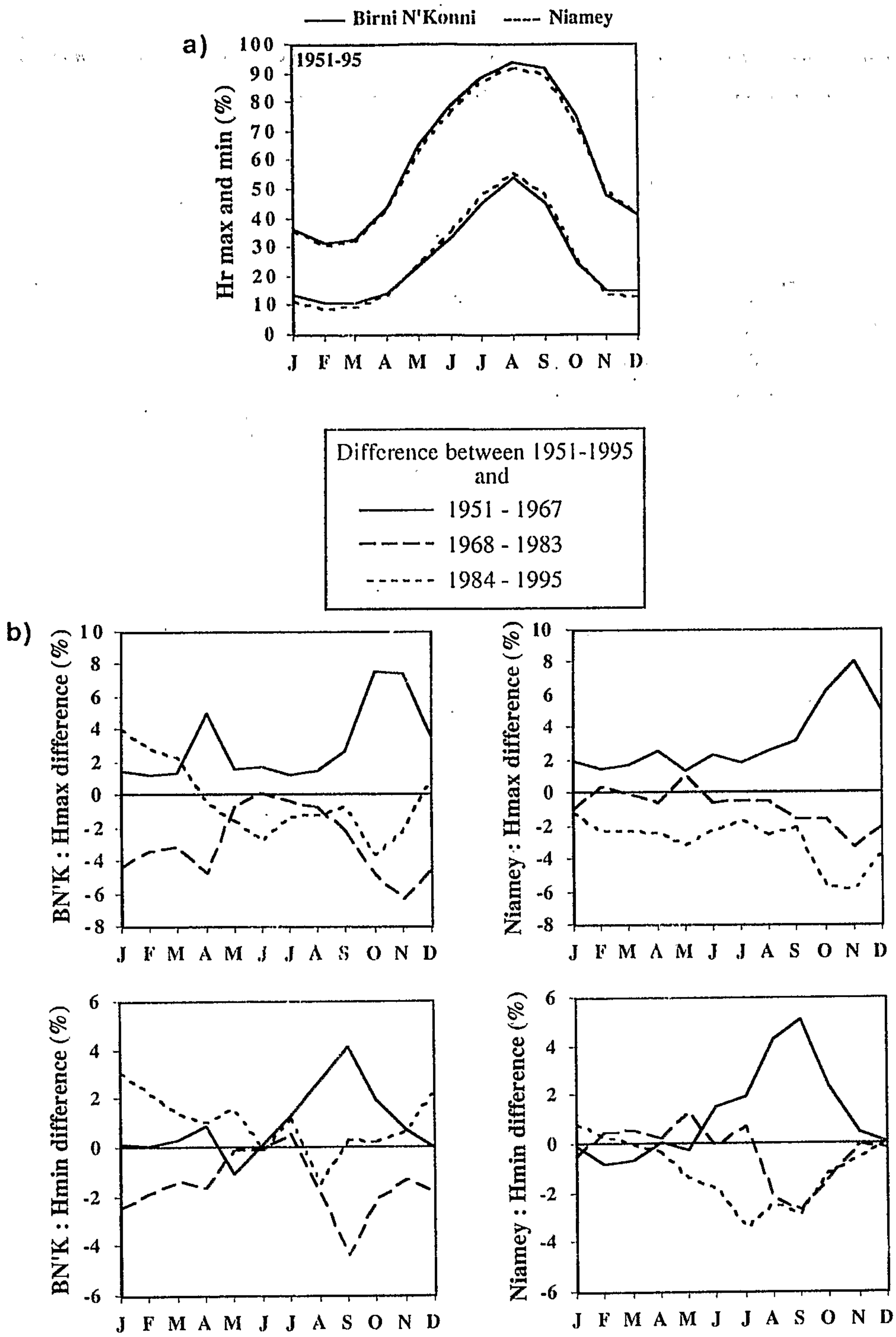

Figure 8. Relative humidity in Niamey and Birni N'Konni (BN'K) from 1951 to 1995. (a) Year-to-year monthly mean of daily maximum and minimum relative humidity. Niamey and Birni N'Konni show almost the same evolution. (b) Difference between the mean values over the period of 1951-1995 and the mean values over other periods. The upper plots show the difference in maximum relative humidity, and the lower plots show the difference in minimum relative humidity. For the humid period of 1951-1967 the difference is mainly positive for both stations. For the dry period of 1968-1983, differences are negative. For the dry period of 1984-1995, differences are negative for Niamey but positive for Birni N'Konni during the dry season, which could be linked to the irrigation in the Sokoto valley.

rainfall increase between Tahoua in the northern part, 50 km to the west of Birni N'Konni, Sokoto to the south in Nigeria, and Zinder ... is roughly 60,000 km^2. The increase in annual rainfall amount is, in this area, of the order of 10 mm yr^{-1}. The corresponding volume of water is then ~ 600 Mm^3, i.e., of the same order of magnitude as the upper value estimated for the evapotranspiration from the dam and the rice fields.

Finally, to settle the argument, it is interesting to see if the new irrigated area may change the d value of precipitation by several units as has been observed. Adding a new source of vapor, ~ 40

Table 5. Mean Values of Annual Rainfall Amounts Over Several Periods and for Stations Closest to the Bakolori Reservoir in the South and More Distant Stations

Period	Niamey	Tahoua	Birni N'Konni	Maradi	Zinder
1950-1995	562	391	535	533	445
1950-1967	654	463	633	653	541
1968-1983	518	343	463	451	400
1984-1995	482	349	482	461	362

Birni N'Konni is the station closest to the Bakalori reservoir. Niamey is a distant station to the west, and Zinder is a distant station to the east. In the Sahel, 1950-1967 is a humid period followed by a dry period. This dry period has become even more severe since 1989.

mm yr^{-1}, that has a higher deuterium excess (~ 20‰ similar to the maximum value recorded for the rainfall events at this latitude) to a mean annual rain amount of ~ 480 mm would increase the mean value of d in Birni N'Konni by about two units. Another, even more efficient process is the lowering of the raindrop evaporation as a consequence of the higher relative humidity of the air.

7. Conclusions

Concerning the Sudan-Sahelian zone (0°-17°N; 0°-15°E), a summary of previous isotopic studies of rains and the results of measurements (rain amount, $\delta^{18}O$, δ^2H, ΔT and ΔH_r) made at the scale of rainfall events during 1989 at 15 stations suggest the following:

1. The minimum of $\delta^{18}O$ (-10‰ at 6°N to -2‰ at 16°N) contemporaneous with the heart of the monsoon confirms the importance of the Gulf of Guinea as a source of water vapor in the Sudan-Sahelian zone. The lack of "continental effect" argues in favor of an additional continental source of water vapor.

2. In the whole region 50-90% of the rainfall events are either evaporated (most of them) or fed by reevaporated water from the continent (10‰ < d < 26‰). In the Sahelian zone, rainfall events are partly fed by previous rainfall events when the duration of the preceding "dry event" is less than 5 days.

3. The $\delta^{18}O$ mean values from 13 stations at the Sahelian latitude do not show a monotonous decrease from east to west, allowing us to exclude the possibility of the Indian Ocean as a source of vapor, which was previously suggested on the basis of limited data.

4. The wide range of isotopic data, between -7.2 and 4.2‰ for $\delta^{18}O$ at the monthly scale, shows how important it is that the modeling of precipitation over continents in tropical areas by general circulation models [e.g., *Jouzel et al.*, 1997] be based on path scales as small as 100 km.

5. Agadez, N'guigmi, and Tahoua, as expected, present characteristics of aridity, with 30% of evaporated rainfall events ($\delta^{18}O$>0‰) and more than 30% of rainfall events with strong variations in temperature and relative humidity although their amounts are small (-15 K<ΔT<-2 K and 10%<ΔH_r<50%). Two stations close to the Gulf of Guinea and, surprisingly, Birni N'Konni in the Sahelian zone (13°N, 5°E) present a conjunction of indicators of high air saturation and large contributions of reevaporated water from the soil. More than 30% of their rainfall events have deuterium excesses exceeding 10‰, and small variations of temperature and relative humidity (-2 K<ΔT<5 K and -10%<ΔH_r < 10).

The peculiar case of Birni N'Konni may be explained by the presence of the Bakolori reservoir and its associated irrigated fields that are ~ 100 km south of this station on the Sokoto River. The reasons are that the reservoir was first filled during the rainy season of 1983 and that since 1984, the relative humidity and the annual rainfall amount have increased at Birni N'Konni by several percent and ~ 20 mm yr^{-1}, respectively, while general drought continued to prevail in the region.

The reservoir and the irrigated area constitute a vapor source of approximately several hundred millions of cubic meters per year. The increase in rainfall in the region affects ~ 50,000 km^2 and corresponds to the same order of volume of water. This anomaly of Birni N'Konni demonstrates the importance of transboundary considerations in the sharing of water resources and the need, as already mentioned in Sahelian studies by *Savenije* [1995], to consider recycling to estimate the relationships between land use and water management. Conclusions of this study also point to the important feedback between climate and surface water as already inferred by the modeling of climatic variations during the last ten thousand years [*Coe and Bonan*, 1997].

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