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Isotopic study of rainfall in the Sahelian zone (Niger) along two sections, east-west (Lake Chad-Niamey) and north-south (Agadez-Niamey)

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Abstract During two years (1988, 1989) a study of rainfall isotopic content (^{2}H, ^{18}O) was carried out in Niger. This study aimed at analysing the average oxygen-18 and deuterium contents of rainfall at the time scale of a storm at six stations in 1988 and 12 stations in 1989, spread out along two sections: east-west (Lake Chad-Niamey) which is the prevailing direction of the mesoscale convective systems (MCS) circulation and north-south (Agadez-Niamey). These intersections are representative of the different rainfall regimes of the Sahel (100-800 mm). The oxygen-18 content of rainfall varies by more than 12‰. The isotopic composition at the beginning of the season seems to be more enriched with heavy isotopes, which can be directly connected to the low rainfall amounts and the significant evaporation of water drops when falling through the atmosphere characterizing this period. The most depleted values are reached in August, the wettest month, when the vertical development of clouds is likely to be the strongest. The isotopic content of rainfall at the limit of the Sahelian zone is influenced by the evaporation during the whole rainy season. The isotopes have also been used in order to follow the isotopic composition of the MCS during their travel over Niger, so as to check on the one hand the hypothesis of an opposite continental effect, and on the other the process of water vapour feeding the system.

INTRODUCTION

The air mass circulation in Niger and in Sahelian Africa is mainly influenced by the anticyclone of the Azores in the north, which engenders hot and dry air called "Harmattan" upon Sahara, and the anticyclone of Saint Helen to the south of the Equator, which generates a fresh and wet air mass called the "Guinean Monsoon". The annual latitudinal oscillation of the zone of confrontation between these two flows causes the alternation of dry seasons (October-March) and humid seasons (April-October), which is characteristic of the dry tropical climate. The Inter Tropical Front (ITF) symbolizes at ground level the limit between these two air masses. Precipitations in that region depend almost solely on the position of the ITF and on its structure, which can be distinguished by a vertical discontinuity of wind and wetness fields. Due to such a structure, 80% of rains in the Sahel have a convective origin, either in the form of isolated thunderstorms, or in the form of coherent cloudy accumulations which move from east to west at a speed that can reach 60 km h^{-1} called squall lines.

METHODOLOGY

The zone studied is situated between 12° and 17°N and 1° and 14° E. The sampling (Fig. 1) has been made at six stations in 1988 (Niamey, Brini N'Konni, Tahoua, Agadez, Maradi and Zinder) in a partial way. In 1989, a systematic sampling at the scale of an event has been made from June to October in these stations and in six others (Tillabéri, Gaya, Chikal, Gouré, Diffa, N'Guigmi). The isotopic analysis of oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) have been made that year on more than 90% of rainfalls in each station, except those of Tillabéri and Gaya, not yet analysed. Temperatures and relative humidity have been measured before and just after each rainy event.

RESULTS

The first results of the study show that the isotopic contents range from −9.33 to +5.15‰ in the case of oxygen-18 and from −65.5 ‰ to +32.0 ‰ for deuterium. The most positive values, which show an enrichment in $\delta^{18}O$, are due to rain evaporation during its fall through an unsaturated atmosphere. In Fig. 2, which describes the distribution of isotopic contents of oxygen-18 during the rainy season at five stations, it can be noted that at the beginning of the season, values are not much negative or even posi-

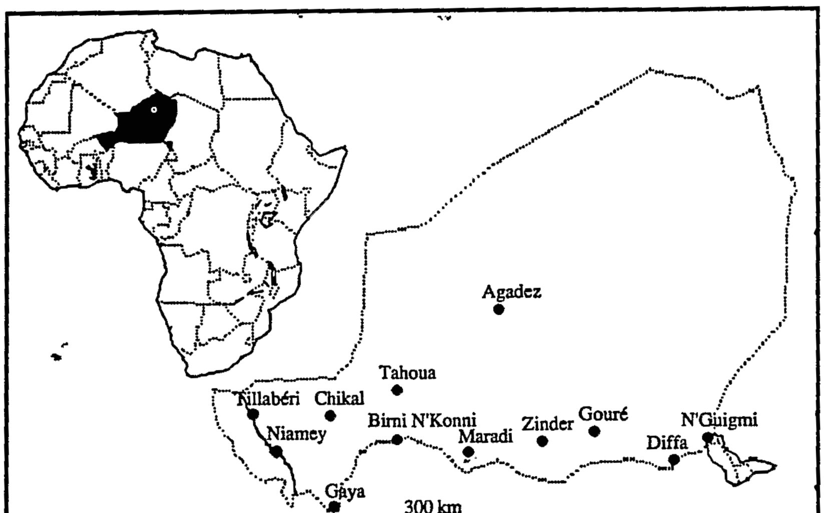

Fig. 1 Location of research area.

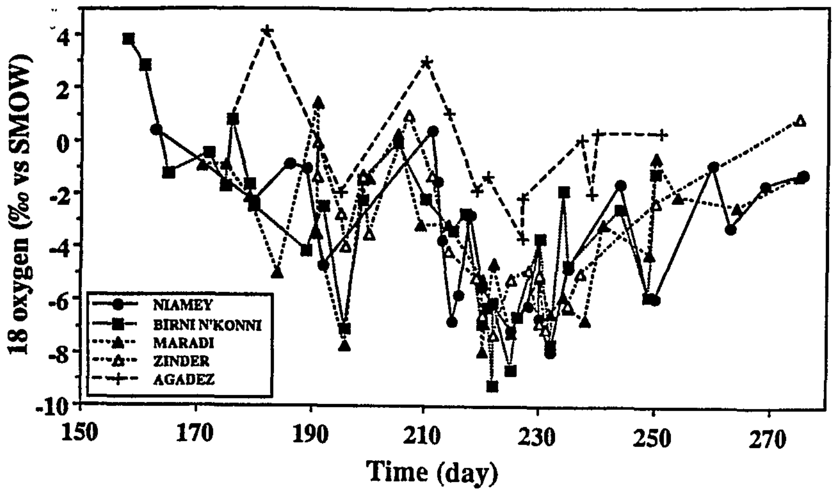

Fig. 2 Evolution of the oxygen-18 contents of rainfall during the 1989 rainy season.

tive. Such a phenomenon can sometimes be observed at the end of the season. At the mid-season (July and August), values are a lot more depleted in oxygen-18. That can be directly linked to the growth and raising of the monsoon flow to the north. At the beginning of the season, the monsoon is not yet well installed, bringing conditions which do not ease rainfalls; on one hand rainfalls are weak and on the other hand the atmosphere, generally unsaturated, is a factor of re-evaporation. This process of re-evaporation is particularly important in the most northern stations (Agadez and Tahoua) and in the most eastern ones (Diffa, Gouré and N'Guigmi), where annual rainfalls are the weakest, because the conditions of saturation are rarely obtained during the whole rainy season. In Fig. 2, the isotopic tendency of the station at Agadez is linked to that of the other stations: enriched isotopic contents at the beginning and at the end of the season and depleted isotopic contents during the mid-season, but isotopic contents are always more enriched, compared to the other stations. The same process, although less remarkable, can be noted in the case of the eastern stations. In Table 1, showing the weighted mean annual isotopic composition of precipitation for each station, a very clear enrichment to the south-north transact (Birni N'Konni, Tahoua, Agadez) can be noted, from −3.72‰ to −0.30‰ in oxygen-18. The east-west section also tends to enrich to the east, between Niamey and Diffa, from −4.54‰ to −1.82‰. But the station of N'Guigmi, the most eastern one, whose annual rainfall is 109 mm, has a particularly depleted weighted mean annual isotopic composition of precipitation (−4.54‰ in oxygen-18). That unusual content can be linked to three exceptional events, very depleted in oxygen-18, in August, bringing more than 60% of the total rainfall. Of course the weighted mean annual isotopic composition of precipitation in that station might be important; so the isotopic content cannot be considered as an average inter-annual content.

Evaporation is also well linked to the average relative humidity during rainfall (Fig. 3). It can be noted that, from an oxygen-18 content of about −2‰, the decreasing of the relative humidity is linked to the isotopic enrichment. The same analysis could have been applied to the temperature, which is linearly correlated to the relative

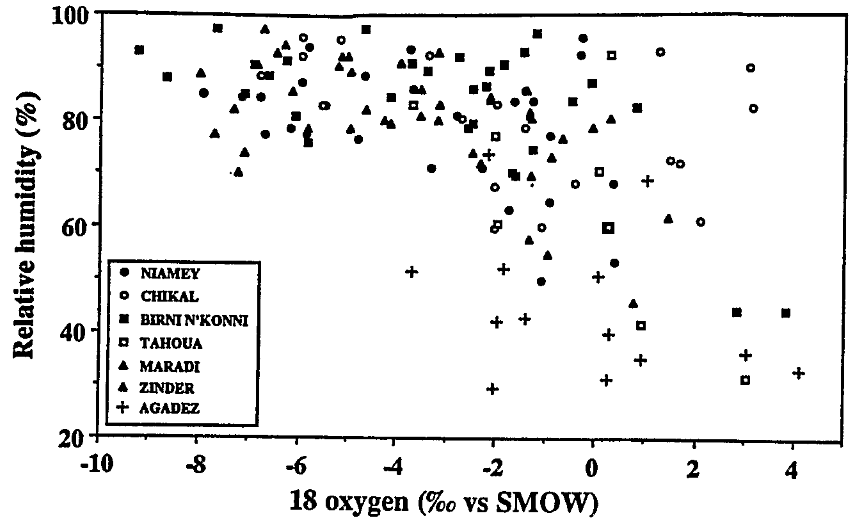

Fig. 3 Relationship between oxygen-18 content and the relative humidity during rainfall.

humidity (r^2 = 0.65 to 0.92, depending on the station). In the case of Agadez, the atmosphere under the cloud always keeps the air far from saturation, which explains the large dispersion of values.

The relation between oxygen-18 and rainfall (Fig. 4) shows the mass effect that can be observed in a tropical climate; but it can also be noted that some rainfalls are very depleted, though the rainfall depth is small. That can be linked to the mechanism of convection which, contrarily to what happens in the case of monsoon rainfalls, can have an important vertical development, to between 10 000 and 15 000 m high. Such heights bring very low condensation temperatures so very negative isotopic contents which do

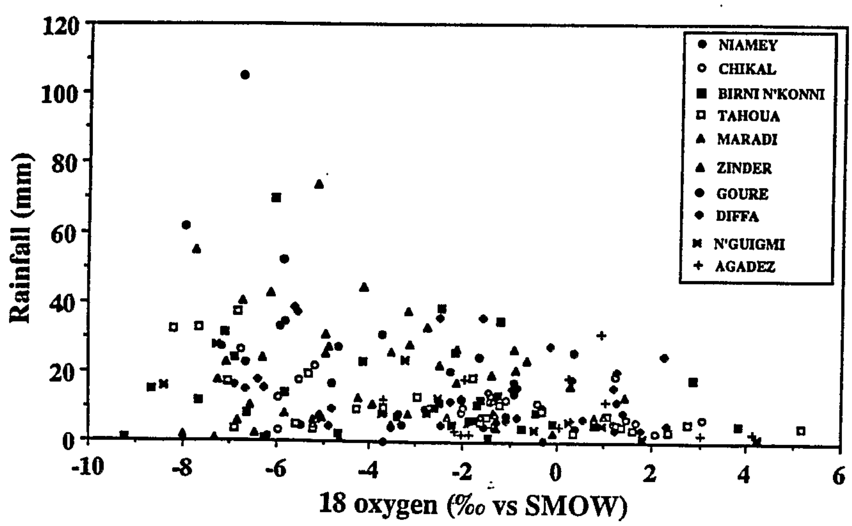

Fig. 4 Relationship between oxygen-18 contents and depth of rainfall.

not have time to re-equilibrate with the ambient temperature during the fall of raindrops. Such convective movements are particularly abundant in July and August, where climatological conditions are combined to allow the development of convection at a regional scale.

In the oxygen-18 versus deuterium graph (Fig. 5, Table 1) rainfalls are situated around the Waters Meteoric Line (WML), whose equation is: $\delta^2H = 8.\delta^{18}O + 10$. For different stations, the value of the slope A of the linear relation $\delta^2H = A.\delta^{18}O + B$ ranges from 5.1 to 7.1 for all rainfall. If only non-evaporated rainfalls are taken into consideration, the slope increases a little and ranges from 6.4 to 8.0. By taking only the stations with the most important rainfalls (Niamey, Birni N'Konni, Maradi and Zinder) where the evaporation process is less remarkable, the relation tends to that found by Joseph & Aranyossy (1989) established from the isotopic composition of the Sahelian band superficial groundwaters, which is: $\delta^2H = 7.5.\delta^{18}O + 4.8$. It can be noted that many points are substantially above the meteoric line, which concretizes by an excess of deuterium $d = \delta^2H - 8.\delta^{18}O$ superior to 10, due to the non-negligible contribution of recycled continental water to rainfalls.

The comparison between the years 1988 and 1989 shows the difference of the weighted mean annual isotopic composition of precipitation that can exist between a rainy season considered as normal (1988) and a season showing a deficit over the zone (1989). The consequence is, in the case of Birni N'Konni, a weighted mean annual isotopic composition of precipitation equal to −4.41‰ (546 mm) in oxygen-18 in 1988 and −3.72‰ (450 mm) in 1989. The annual isotopic characteristic will principally depend on the isotopic contents of August which associates the important rainfalls with the most depleted isotopic contents. That is what can be noted at Birni N'Konni where the important rainfalls in August 1988, 285 mm compared to 165 mm in 1989, will have a great annual influence (Fig. 6). Mathieu *et al.* (1993) tie the depletion of the isotopic composition to the maximum evolution of the monsoon further north in 1988, and to the presence of more numerous convective cells. Still, it can be noted that in 1989 the

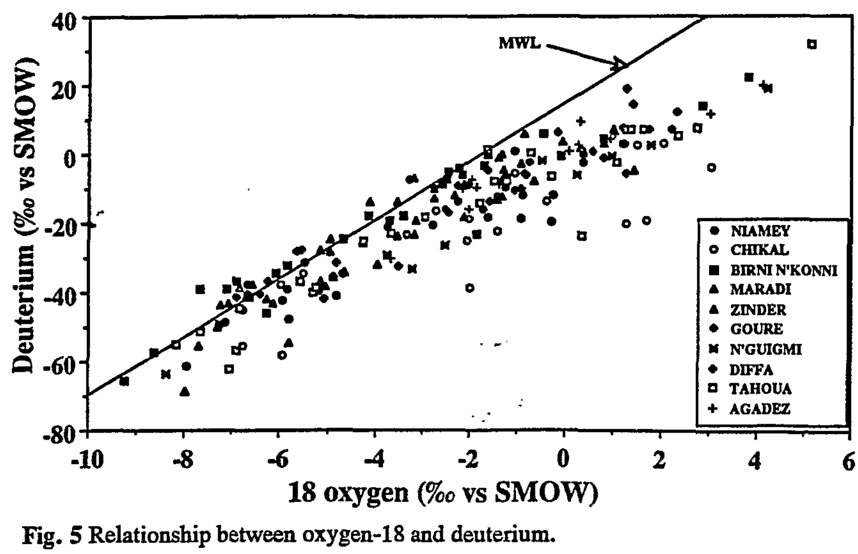

Fig. 5 Relationship between oxygen-18 and deuterium.

Table 1 Relationship between oxygen-18 (^{18}O) and deuterium (^{2}H) and weighted mean annual isotopic composition of precipitation for each station.

	Number of samples	A	B	r^2	Rainfall (mm)	Annual mean ^{18}O	Annual mean ^{2}H
Niamey	24	6.032 6.751	-4.663 -0.493	0.841 0.837	599.8	-4.54	-33.9
Chikal	20	5.136 6.712	-12.674 -5.172	0.732 0.827	275.5	-1.75	-22.9
Birni N'Konni	30	6.250 6.773	2.869 5.450	0.919 0.904	449.9	-3.72	-18.8
Tahoua	25	6.391 7.639	-3.709 3.133	0.710 0.926	362.4	-2.13	-24.6
Agadez	13	5.151 7.031	0.848 1.493	0.726 0.894	130.3	-0.3	-1.76
Maradi	26	7.194 8.078	3.010 7.301	0.852 0.887	586.7	-3.87	-22.6
Zinder	21	6.782 7.197	2.505 4.603	0.909 0.860	317.6	-4.24	-24.6
Gouré	18	5.840 6.455	-1.802 0.947	0.929 0.878	289.3	-2.58	-15.5
Diffa	16	6.137 6.520	-0.183 1.292	0.882 0.927	220.8	-1.82	-10.1
N'Guigmi	10	6.401 6.862	-6.958 -4.463	0.975 0.940	108.7	-4.38	-35.5
Niamey, Birni, Maradi, Zinder		7.281	4.982	0.870			

isotopic contents during the first two ten-day periods of August were a lot more depleted than in 1988, which can be due to high-altitude convection events that did not occur in 1988 at such an altitude. So, an important evolution of the monsoon to the north would block high-altitude convections. A study of temperature data at the top of clouds (infra-red satellite images) would permit one to confirm or invalidate that hypothesis.

The variation of the isotopic composition of squall lines during their movement from

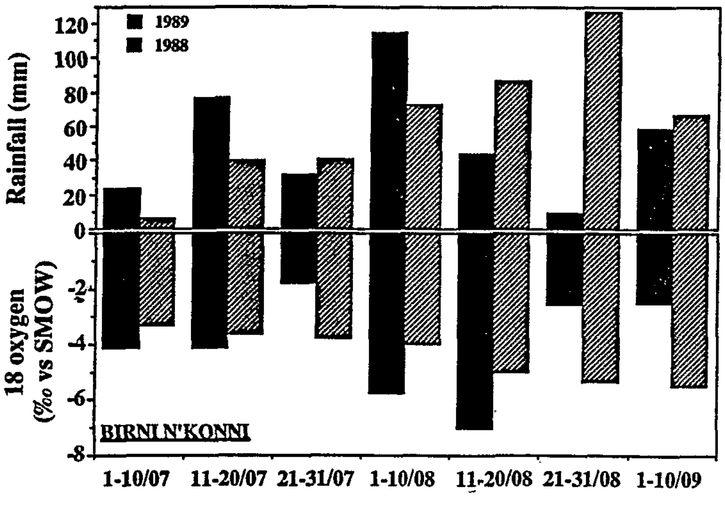

Fig. 6 Comparison of oxygen-18 contents of rainfalls in periods of 10 days between 1988 and 1989 in Birni N'Konni.

east to west has also been studied. In 1989, seven squall lines have been noted. A great depletion of isotopic contents of squall lines during their movement west in June and July can be noted (Fig. 7); in the case of August, it is a lot less noticeable. Figure 8 shows the evolution of deuterium excess from east to west over the four more complete squall lines. At the level of N'Guigmi, the excess of deuterium *d* is negative, which is the sign of an important evaporation abstracting; then the Zinder *d* tends to 10, which reveals an oceanic origin of the wet air mass. The evaporation sampling might be less and less important to the west, which is confirmed by a progressive increasing of the relative humidity. Then, between Maradi and Birni N'Konni, *d*, which appears to be a lot greater than 10 in the case of mid-season squall lines, could reflect a mixing of oceanic vapour and of recycled continental vapour coming from water reserves constituted by anterior rainfalls.

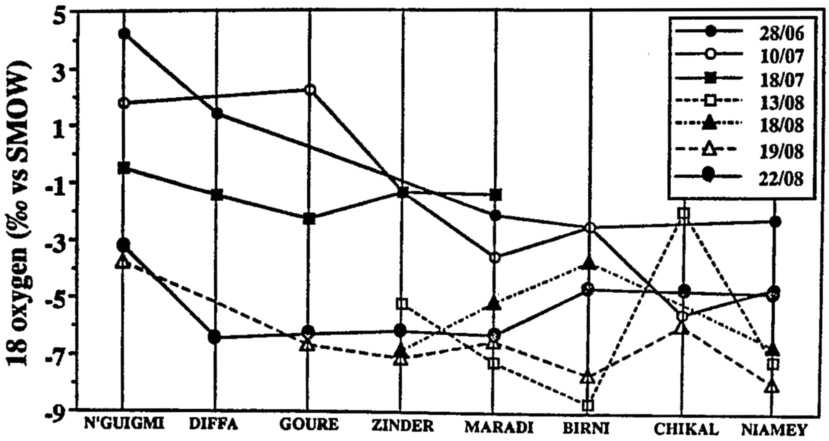

Fig. 7 Evolution from east to west of oxygen-18 contents of rainfall.

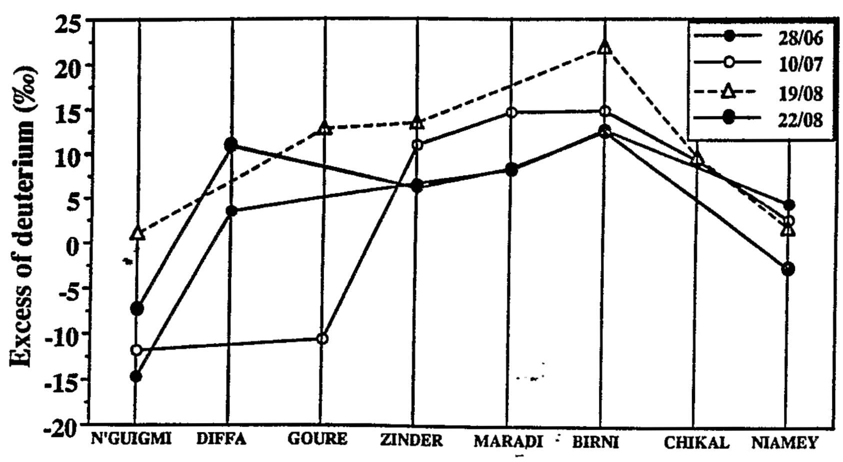

Fig. 8 Evolution from east to west of the excess of deuterium of rainfall.

CONCLUSION

The isotopic composition of rainfalls in the tropical zone can bring qualitative elements to the air mass circulation. Due to the complexity of that process, further information must be researched, using other techniques and working on:
- the analysis of infrared satellite data in order to separate the altitude of condensation;
- climatological maps to define air mass movements; and
- radio-samplings to discover the vertical differences between different air layers.

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REFERENCES

Joseph, A. & Arranyossy, J. F. (1989) Mise en evidence d'un gradient de continentalité inverse en Afrique de l'Ouest en relation avec les lignes de grain. *Hydrogeologie* 3, 215-218.

Mathieu, R., Bariac, T., Fouillac, C., Guillot, B. & Mariotti, A. (1993) Stable isotope variations in precipitations in 1988 and 1989 in Burkina Faso: contributions of regional meteorology. *Veille Climatique Satellitaire* 45, 47-64.