*Application of Tracers in Arid Zone Hydrology* (Proceedings of the Vienna Symposium, August 1994). IAHS Publ. no. 232, 1995.

# Isotopic characterization and origin of rainwater on the Aïr massif (Niger)

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**Abstract** The isotopic compositions of rainfall events, sampled on the Aïr massif between 1988 and 1990, have contributed to the knowledge of both the characteristics and origins of humid air masses of this sub-desertic area. Isotopes permit, in particular, improved understanding of the anomalies in observed some years (inversion of both the altitudinal and latitudinal gradients), and also confirm the ground observation of METEOSAT images.

## STUDY FRAMEWORK

Situated in Niger between latitudes 17° and 20°N, the Aïr massif constitutes the extreme northern limit of penetration of the Guinea monsoon (Dubief, 1953) upon the African continent (Fig. 1). An area of natural refuge for local populations, the Aïr massif has been, since the end of the 1960s and the beginning of the dryness, a place of new demographic pressure, which has rapidly demonstrated the limits of the local water resources.

In the framework of its actions of aid for development, the ORSTOM institute has performed a continued hydrological programme in Aïr between 1975 and 1990. The three last campaigns of this programme constitute the base of this study. Precipitation, collected at four sites (Azel, Dabaga, Aoudéras, Abardok) between 1988 and 1990, was analysed for chemical and isotopic contents. The analyses were performed at the Laboratoire d'Hydrologie et de Géochimie Isotopique (LHGI).

## RAINFALL DISTRIBUTION

According to the inter-annual isohyet outlines (Fig. 2), precipitation appears to be more abundant in the western than in the eastern part of the massif. Thus, under equivalent latitude and altitude, the inter-annual mean for the period from 1978 to 1990, decreases from 125.3 mm in the western part at Aoudéras, to 53.6 mm in the eastern part (Tabelot). The value at Abardok, situated between Aoudéras and Tabelot, is 67.2 mm.

The latitudinal distribution appears less regular. Firstly, the mean rainfall increases from 99.8 mm at Azel (170°N, 826 m) to 125.3 mm at Aoudéras (17°38'N, 810 m), at the foot of the first important relief of the massif (Todgha, Bagzanes). This fact suggests

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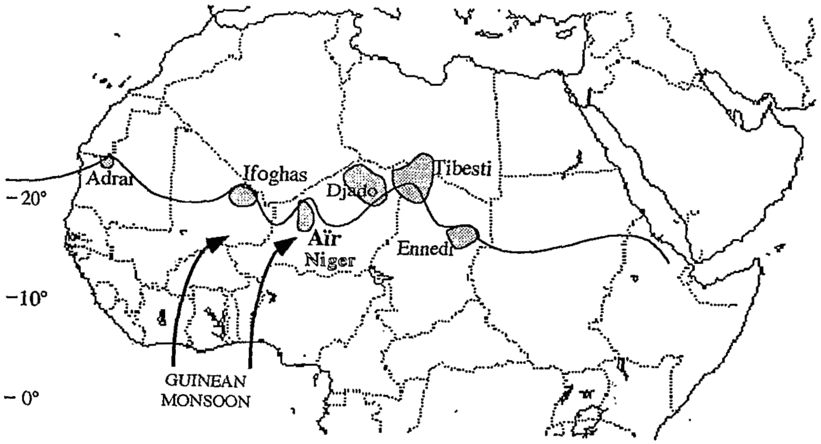
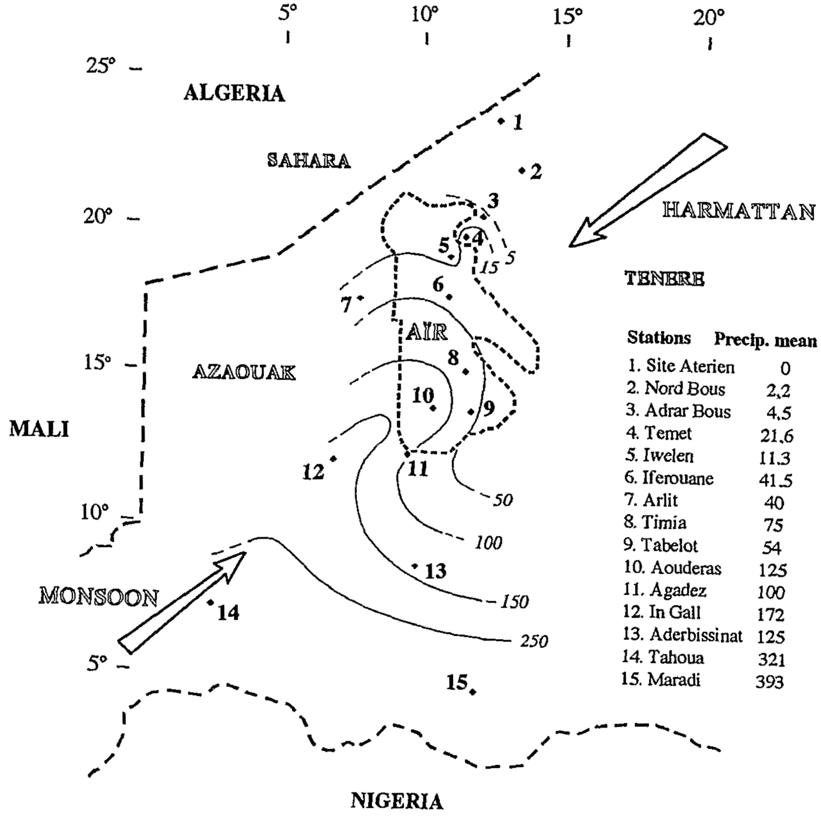


Fig. 1 Geographical location of the south saharian massifs (northern position of the InterTropical Front, after Dubief, 1953).



| Stations | Precip. mean |
|---|---|
| 1. Site Aterien | 0 |
| 2. Nord Bous | 2,2 |
| 3. Adrar Bous | 4,5 |
| 4. Temet | 21,6 |
| 5. Iwelen | 11,3 |
| 6. Iferouane | 41,5 |
| 7. Arlit | 40 |
| 8. Timia | 75 |
| 9. Tabelot | 54 |
| 10. Aouderas | 125 |
| 11. Agadez | 100 |
| 12. In Gall | 172 |
| 13. Aderbissinat | 125 |
| 14. Tahoua | 321 |
| 15. Maradi | 393 |

Fig. 2 Yearly mean precipitation (1978-1990) on the Aïr mountains.

that the altitude effect is more important than the continental effect. Because of the orographic effect, the rain-generating masses appear less important northward, both quantitatively (thickness) and qualitatively (humidity). The mean annual rainfall therefore decreases regularly with the latitude: 75 mm at Timia (18°08′N) and 41.5 mm at Iférouane (19°58′N). Up to this latitude, the gradient increases more rapidly: 21.6 mm at Témet (19°58′N), 4.8 mm on the Adrar Bous (20°21′N), 2.2 mm at the north of Bous (21°10′N) and 0 mm on the Atérian site (21°40′N). These four latter values represent, nevertheless, a mean over 9 years (Table 1). The continental effect dominates at latitudes up to 18°N. However, the orographic effect exists again locally. The annual rainfall on the Tamgak mountains (mean altitude 1500 m) is up to 90 mm, whereas that at Iférouane (650 m) is only 56 mm.

## ISOTOPIC BEHAVIOUR OF RAINFALL AT TELOUA

The good relationship between oxygen-18 and deuterium (Fig. 3) of all the rain events in the basin ($r^2 = 0.83$) suggests the same origin of vapour and the same processes of condensation. The value of oxygen-18 of the intercept (−5‰) of this relationship with the global meteoric water line (GMWL) suggests the origin is probably the Gulf of Guinea (Dansgaard, 1964; IAEA, 1992):

$$\delta^2H = 4.63\,\delta^{18}O - 8.19 \qquad (1)$$

The low slope (4.63) and the position of data points below the GMWL suggest the

**Table 1** Average annual rainfall and weighted oxygen-18 in the Aïr region.

| Station | Location | | Annual rainfall | | Average isotopic composition | |
|---|---|---|---|---|---|---|
| | Lat. N | Alt. (m) | mm | (years of observation) | Oxygen-18 | (years of obser.) |
| Azel | 17° | 526 | 99.8 | (13) | − 1.55 | (2) |
| Dabaga | 17°10′ | 650 | 116 | (13) | + 0.55 | (2) |
| Aouderas | 17°38′ | 850 | 125 | (13) | + 2.92 | (2) |
| Abardok | 17°32′ | 830 | 67 | (3) | | |
| Tabelot | 17°34′ | 840 | 54 | (12) | | |
| Timia | 18°08′ | 1100 | 75 | (12) | | |
| Iferouane | 19°12′ | 650 | 41.5 | (13) | | |
| Iwelen | 19°46′ | 675 | 11.3 | (9) | + 0.34 | (2) |
| Temet | 19°58′ | 1050 | 21.6 | (9) | + 3.70 | (1) |
| Adrar Bous | 20°21′ | 760 | 4.8 | (9) | + 5.94 | (2) |
| Nord Bous | 21°10′ | 630 | 2.2 | (9) | | |
| Site Aterien | 21°40′ | 600 | 0 | (9) | | |

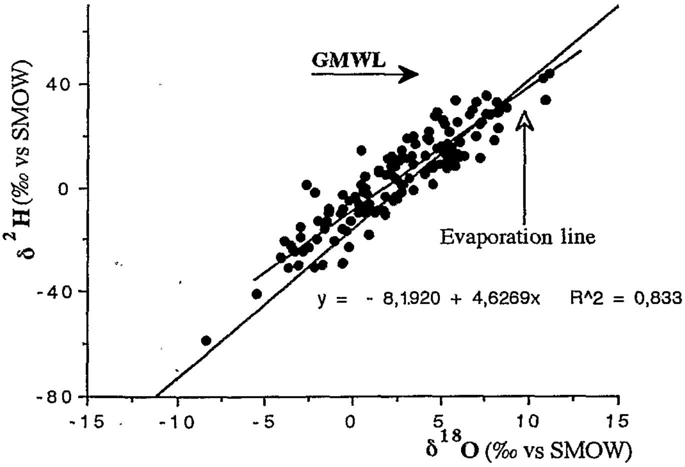


**Fig. 3** Correlation between deuterium and oxygen-18 of Aïr rainwater from 1988 to 1990.

influence of evaporation on the majority of rainfalls.

Figure 4 shows that isotopic variations of precipitations may also be controlled by the "mass effect". In fact, lighter precipitations display more enriched isotopic composition, whereas more depleted isotope values are observed in more important rainfalls. Such a variation may be related to evaporation in relation to the relative humidity at the time of rainfall. For this purpose, Dubief (1953) supposed that the number of rainfall events in the sub-desertic zone was not significantly different from that of the rest of the tropical region; nevertheless, falling through a strongly unsaturated atmosphere, a number of rain events in the sub-desertic areas did not reach the ground.

On the other hand, the oxygen-18 data display a temporal variation. The precipita-

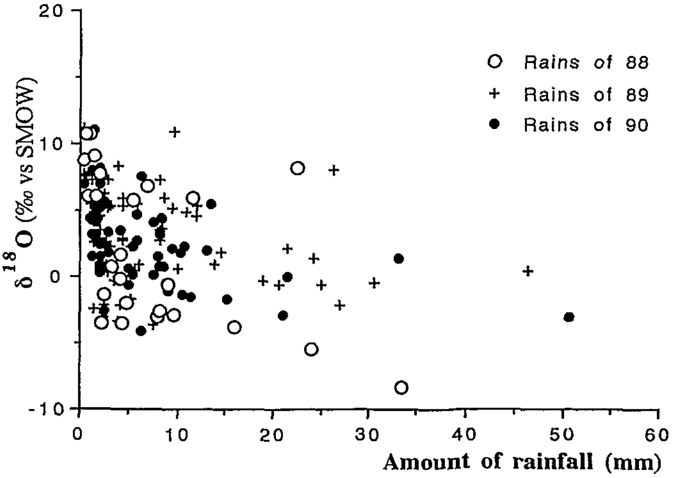


**Fig. 4** Oxygen-18 versus amount of precipitation from Aïr (1988-1990).

tions from the beginning (mid-June to mid-July) and end (mid-August to mid-September) of the rainy season are more enriched whatever the amount of rainfall, whereas important rainfalls at the heart of the rainy season (July to August) have more negative oxygen-18 values. However, some rain events with amounts less than 10 mm also appear depleted. Such an evolution may also be attributed to the saturation states of the atmosphere at the time of precipitation.

The variation of the annual weighted mean of $\delta^{18}O$ in 1988 and 1990 rainfalls (Fig. 5) points out the unusual role of both altitude and latitude, which produce an enrichment in both the southern and northern parts of the massif. The altitude effect (or continental in this case), which normally leads to a depletion of heavy isotopes in rainfalls owing to lower temperatures of condensation and little exchange during the fall, is observed here.

The isotopic depletion observed in Fig. 5 between Aoudéras and Iwelen, which constitutes a reverse of the usual scheme of continental variation, suggests: (a) that in the central part of the massif, evaporation may be less important; this fact is less pronounced, despite the altitude, taking into account the rapidly increasing dryness of air masses during their progression; and (b) the temperature of condensation may be lower, generating therefore more depleted isotope contents at the bottom of the clouds. The latter case appears more important where both the localized orographic and radiative effects (a dark patina of crystalline and volcanic surfaces which significantly diminish the albedo), may force the less wet air masses circulating in the central part of the massif to ascend and reach to high altitude . The extreme aridity observed on the northeastern border of the Aïr (Temet), and the transit in the desert of Tïnéré (Bous), may explain the reversal into the inverse scheme and the enriched values in oxygen-18.

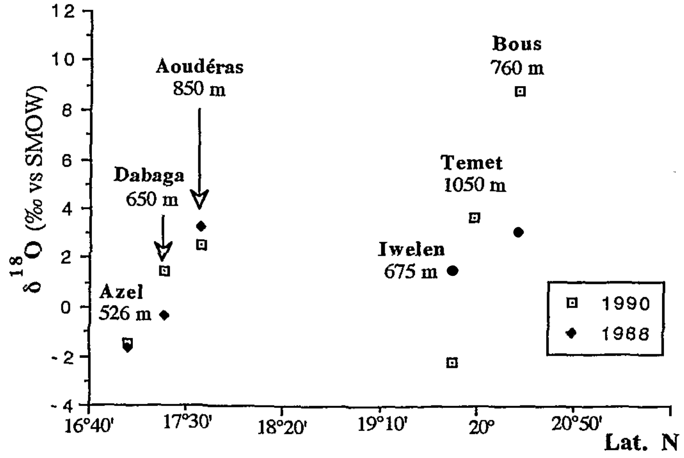


**Fig. 5** Annual variation of oxygen-18 in rainwater as a function of the latitude and altitude (1988-1990).

## TYPES OF RAINFALL IN THE AÏR MASSIF: COMPARISON OF 1988 AND 1990

The Aïr massif is geographically situated at the limit of influence of the Guinea monsoon, and normally, to the north of the route followed by the Sahelian squall lines (Joseph & Aranyossy, 1989). But some authors (Leroux, 1983; Rozanski *et al.*, 1994), suggest that the relief may give an undulatory character to the East African Jets (EAJ, = 500-800 mbar) which, in contact with the monsoon may lead to unstable zones, some of which are at the origin of squall lines. The METEOSAT infrared images (−40°C) show in fact the occasional formation of such instability lines on Azaouak, of which Aïr may have been the precursor (Guillot *et al.*, 1988).

It is more probable, in fact, that a majority of rain events in this area are generated by air masses from the Gulf of Guinea, in relationship with the more or less marked dynamic of the eastern jets, EAJ and the Eastern Tropical Jet (ETJ, = 200-300 mbar) (Lambergeon, 1981; Dhonneur, 1985; Fontaine, 1991; Janicot, 1989). The thesis of arrival at altitude with the EAJ of wet masses issued from the Indian monsoon (De Félice *et al.*, 1982; Joseph *et al.*, 1989; 1992) is still controversial (Rozański *et al.*, 1994) and still less probable at this latitude, regarding the obstacles encountered, such as the draining imposed by the crossing of the Rift barrier (up to 3000 m), or the aridity of large Sudano-Tchadian areas. On the contrary, the theory (Cadet & Nnoli, 1987) of a yield of humidity from the Central Africa (and thus from the Atlantic) via the EAJ, in relay with the Hadley meridian circulation, confirms Fig. 3 which suggests the same origin of condensable air masses of the Aïr.

The good correlation between, on one hand, the majority of annual rainfalls of Azel at the southern border of the massif and those of Aoudéras situated inside the massif, and on the other hand between oxygen-18 and deuterium (Fig. 3), seems to suggest that the rain-generating phenomena on the massif correspond, most of the time, to the same type. The usual relationship between the rainfall amounts at these two stations showed the importance of altitude prior to the continental ($Rainfall_{Azel} = 0.627\ Rainfall_{Aoudéras} - 6.99$). 1988 and even more 1990, showed an inverse trend. This similar behaviour seems to suggest that the rain mechanism during these two rainy seasons may be the same. This fact is supported by an identical number of events and precipitation levels at Azel. Neither the isotope nor the climatological parameters confirm this.

In Fig. 4, the oxygen-18 contents in rainfalls of 1988 appear more depleted than those of 1990. This phenomenon shows that if all the rain events were of the same origin, as suggested in Fig. 3, the conditions of precipitation, such as the processes of condensation, exchange during fall or recycling, were different during these two years.

The observations of the Azel meteorological station, in particular both thermograms and pluviograms, have permitted correlation of the oxygen-18 contents of rainfalls and the calculated temperature of equilibrium. These relationships (Figs 6 and 7) show that the conditions of condensation and/or exchange during the fall, are different. During 1988, the majority of precipitations, fairly depleted probably took place between 25° and 28°C. During 1990 there were more depleted rainfalls, and the temperatures at the ground − closely correlated with those of the bottom of rain-generating clouds (Dansgaard, 1964; Fontes, 1976; Gonfiantini, 1985) − were much lower, about 5°C lower than those of 1988. During 1990, the much lower temperatures at the ground imply a higher altitude of condensation and/or very important exchanges during the fall;

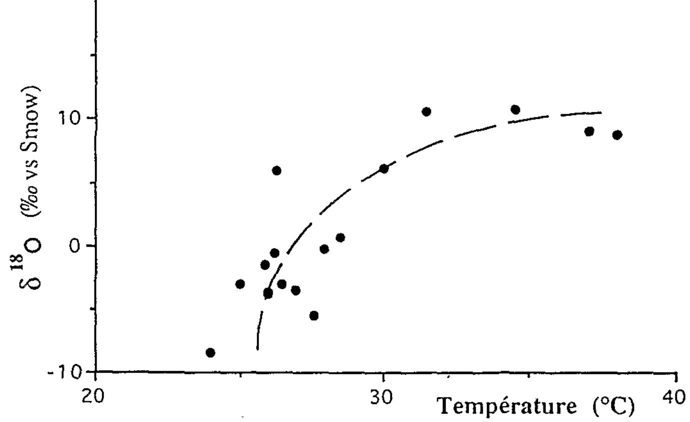


**Fig. 6** Relationship between oxygen-18 content and the equilibrium temperature at Azel station in 1988.

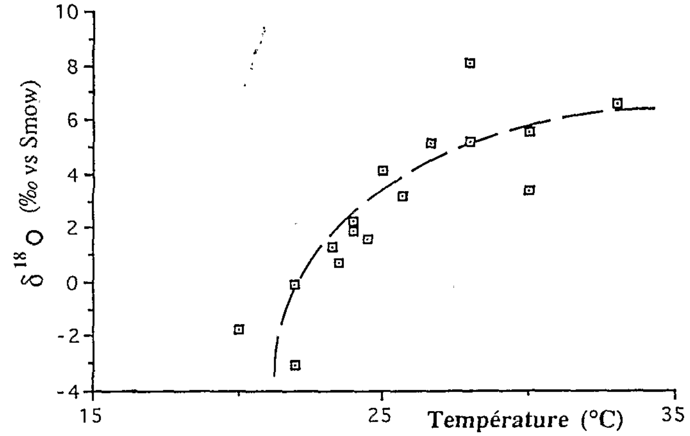


**Fig. 7** Relationship between oxygen-18 content and the equilibrium temperature at Azel station in 1990.

this implies a more marked under-saturation in the environment of precipitations during 1990. Similarly, the relationship between oxygen-18 and the ambient relative humidity, shows that during 1988 depleted rainfalls correspond to a range of relative humidity spread between 70 and 100%, whereas in 1990, depleted rainfalls, less important in number, correspond to relative humidity close to saturation, between 95 and 100%.

## INTERPRETATION

During 1988, the proportion of depleted rainfalls was up to 50%. These rainfalls pass through an atmosphere when the humidity appears less selective with respect to the isotope contents, and where temperatures are still elevated at equilibrium. These conditions correspond to those of the monsoon within which the altitudes of condensation and further vapour-liquid exchanges are relatively moderated. The METEOSAT IR images confirm the occurrence, during both the second and third ten-day periods of August, of higher convective activities up to 18°N on the Aïr; and as a result, elevated percentages (> 15%) of cold top (−40°C) cloud occurrences.

The 39°C isotherm, which is a good indicator of the position of the FIT, is moved, since July, to the heart of the massif, at the same latitude of 18°N. The convection front rises upward to 20°N during the third 10-day period of August. If the 39°C isotherm was found at an equivalent latitude in August 1990, the important occurrences of cold-top clouds were absent on the Aïr. The low temperatures at the time of rain events are an indication of condensations at higher altitude (Fig. 7). The percentage of depleted precipitations, clearly much lower (< 18%), as well as the relative humidity, show that during 1990 rainfalls have been submitted to evaporation within a less saturated atmosphere. These conditions correspond to isolated convective type phenomena.

If the position of FIT does not seem to constitute a selective condition of the event types (Citeau & Mahé, 1991), the dynamic of the monsoon, apparently linked to that of jets (EAJ and ETJ) which may result in Aïr from a wet region of more or less important thickness, might explain differences in the isotopic compositions. Under equivalent conditions of convergence, an important thick wet region will produce moderated ascendencies, resulting in a more elevated relative humidity which favours a rapid condensation process. These conditions seem to be those prevailing in 1988. A region of less importance should make the less saturated air masses rise higher before condensing. Evaporation will be important in the air column below at the time of precipitation. Despite these non-favourable conditions, 1990 was a distinctive year, suggesting other sources of moisture for rainfalls of years with low monsoon activities. The existence of advections of polar air, considered by some authors as a stimulant factor for the formation of squall lines, may be favoured by the occurrence of low pressures at the ground, followed by the ascendancy of radiative origin. These cold advections, by reducing the altitude of condensation, may optimize the capacity of weakened air masses.

The existence of a dynamic EAJ, corresponding to a deficient monsoon flux, may bring (Cadet & Nnoli, 1987) a noticeable contribution of central African air masses. Alternatively, this jet could regenerate the depleted air masses in the central part of the massif by canalizing the cold drops from the Indian ocean issuing from the pole through the Himalayas, but is vigorously carried to altitude by the radiative effect.

## CONCLUSIONS

The Aïr, as well as other northern Sahelian massifs, is situated at the limit of influence of the Guinea monsoon which seems to regenerate the air masses which are very weakened at this latitude. If the precipitated amounts are still noticeable in the south of the massif, responding to the altitude effect, the very rapid depletion with latitude of wet air masses may explain the abnormal isotopic composition which is observed in this part of the Aïr: both altitude and latitude producing an isotopic enrichment.

A reversal of the "classical" continent effect, at the heart of the massif, is not conceivable. This effect, already hidden to windward of the first relief by the evaporation phenomena, appears more weakened again under their shadow as a result of the foaling effect. The depletion observed is the result of condensation at much higher altitudes, due to the important radiative effect of both volcanic and altered metamorphic surfaces with low albedo.

The influence of evaporation, indicated by the plot of data points below the global meteoric water line, is noticeable for most of the rainfalls. The study of the oxygen-18 variation with respect to basic climatic parameters, both temperature and relative humidity, allows the recognition of two types of precipitation during the rainy season. Such a distinction was not possible either in the total amounts or in the distribution. The amounts of precipitation in Aïr do not seem to constitute a criterion for separation of rain types. The comparison of 1988 and 1990, which are characterized by identical rainfalls, despite different conditions of the air masses, shows that a mediocre monsoon flux may also be at the origin of a good pluviosity in Aïr, probably in relation to other factors such as the yields of EAJ from Central Africa, or advections of polar air at high altitude.

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