What controls the isotopic composition of the African monsoon precipitation? Insights from event-based precipitation collected during the 2006 AMMA field campaign

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[1] The stable isotopic composition of the tropical precipitation constitutes a useful tool for paleoclimate reconstructions and to better constrain the water cycle. To better understand what controls the isotopic composition of tropical precipitation, we analyze the δ^{18}O and deuterium-excess of the precipitation of individual events collected in the Niamey area (Niger) during the monsoon season, as part of the 2006 AMMA field campaign. During the monsoon onset, the abrupt increase of convective activity over the Sahel is associated with an abrupt change in the isotopic composition. Before the onset, when convective activity is scarce, the rain composition records the intensity and the organization of individual convective systems. After the onset, on the contrary, it records a regional-scale intra-seasonal variability over the Sahel, by integrating convective activity both spatially and temporally over the previous days.
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1. Introduction

[2] The isotopic composition of the tropical precipitation (δD and δ^{18}O) constitutes a valuable tool to reconstruct past tropical climates and to better understand the atmospheric water cycle. An anti-correlation between precipitation amount and the heavy isotopes content of precipitation, called the amount effect, has long been observed at monthly or longer scales in the Tropics [*Dansgaard*, 1964; *Rozanski et al.*, 1993]. However, a variety of factors can actually affect the isotopic composition of precipitation. The goal of this study is thus to better understand what controls the isotopic composition of tropical precipitation. The African Monsoon Multidisciplinary Analysis (AMMA) campaign [*Redelsperger et al.*, 2006] that took place in West Africa in 2006 was an opportunity to investigate this question. We analyze the event-based isotopic composition (δD and δ^{18}O) of precipitation collected in the Niamey area (Niger) during the 2006 intensive observation period of the campaign. For this period, a large amount of atmospheric data is available and the synoptic, intra-seasonal and seasonal variability of convection has been thoroughly monitored and analyzed.

[3] Since the isotopic data are available only for the year 2006 so far, we focus on the intra-seasonal and seasonal time scales of variation. The total precipitation of the 2006 monsoon season is similar to previous years, despite a 10-day late onset of the monsoon in the Sahel compared to the climatology [*Janicot et al.*, 2008]. The large scale context of Niamey at the middle of the monsoon season (August) is illustrated in Figure 1a. At low levels, moisture is supplied mostly by the monsoon flow, and at mid-levels, by the African Easterly Jet (AEJ).

2. Data

[4] From June 9th to September 24th 2006, precipitation was collected on an event-based resolution at Wankama (13.65N, 2.65E) and Banizoumbou (13.53N, 2.66E). Precipitation was collected right after the end of each event (except on June 28th at Wankama and on June 17th and August 25th at Banizoumbou, when the collection was delayed), ensuring the quality of observations. We also collected precipitation at high frequency during the passage of convective systems over Niamey (13.53°N, 2.1°E) (C. Risi et al., Evolution of the isotopic composition (H2O18, HDO) of the rain sampled along Sahelian squall lines, submitted to *Quarterly Journal of the Royal Meteorological Society*, 2008) but present here the average composition over each event. In total, 30, 31 and 14 events were sampled at Banizoumbou, Wankama and Niamey respectively. All δ^{18}O and δD measurements are performed with an accuracy of ±0.05‰ and ±0.5‰ respectively leading to an accuracy of about ±0.7‰ on deuterium excess ($d = \delta D - 8 \cdot \delta^{18}O$ [*Dansgaard*, 1964]).

[5] Some of the measurements show small or negative *d*, especially before the monsoon onset (Figure 1b). Given our efforts to reliably collect precipitation, this probably arises from reevaporation of the precipitation in a dry atmosphere.

3. Relationship Between Isotopic Composition and Convection

[6] The coherent features between the 3 sites (Figure 1b) can be explained by the proximity of the 3 stations (within 60 km), which often receive precipitation from the same

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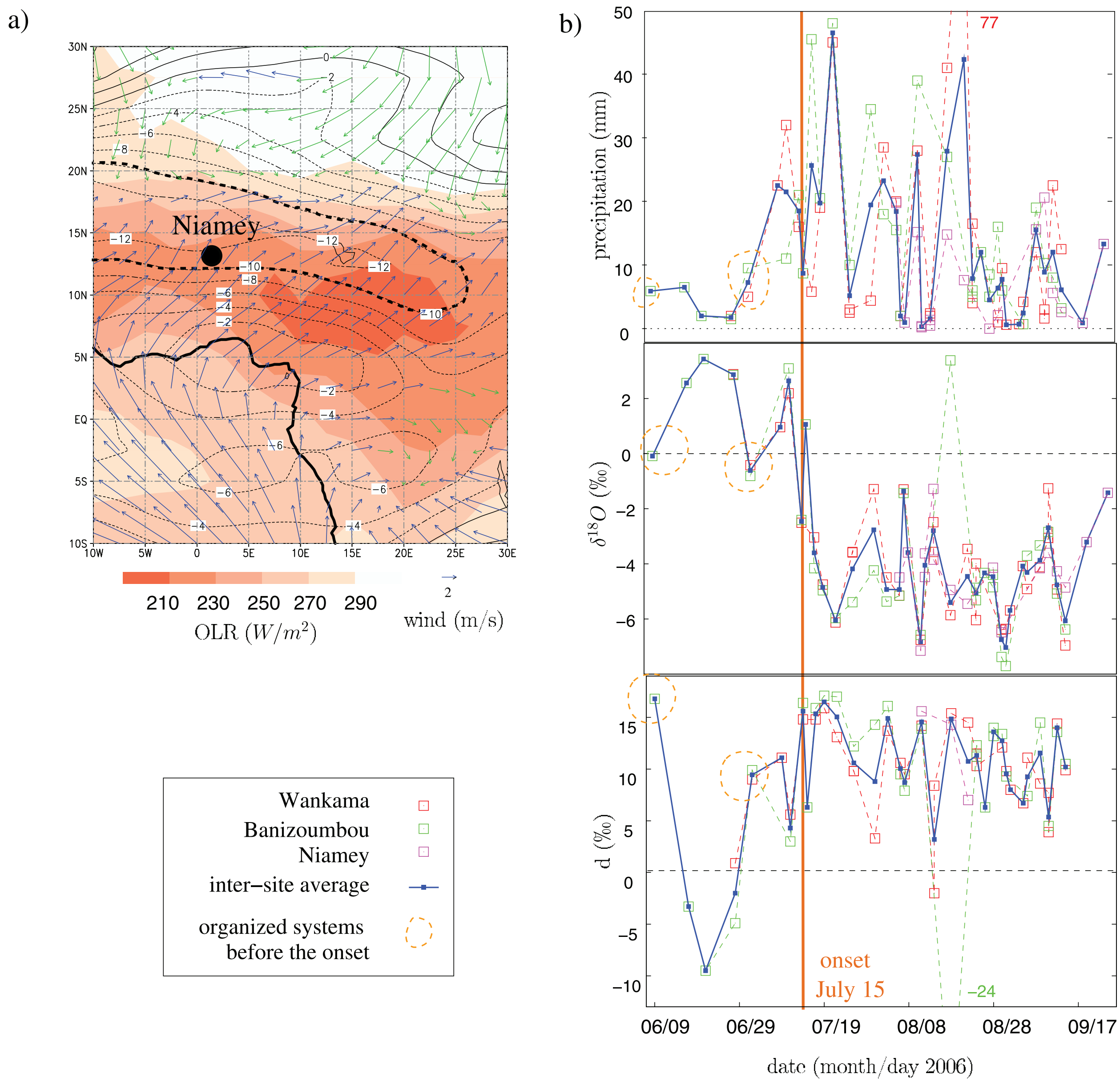

Figure 1. (a) August 2006 monthly mean OLR (shading) showing convective activity; 950 hPa wind vectors, indicating the monsoon flow; 600 hPa zonal wind (dashed contours), with the heavier isoline highlighting the AEJ. (b) Evolution of the cumulated precipitation, δ^{18}O and d-excess for events collected at each site (markers) and on average over the 3 sites (thick line).

large convective systems. This suggests that processes at the large-scale dominate over processes at the scale of convective systems in the control of the composition of the event-based precipitation. To highlight even better the influence of large-scale processes, we average the isotopic composition measured at the 3 sites to produce a single time series (blue lines on Figure 1b), analyzed below.

[7] The isotopic composition does not exhibit any clear correlation with winds, air masses trajectories and relative humidity at different levels derived from the NCEP reanalysis [*Kalnay et al.*, 1996]. On the other hand, they are well correlated with proxies of convective activity, both local and large-scale: in-situ precipitation (data from Figure 1); large-scale ($1 \times 1°$) precipitation estimates from the Global Precipitation Climatology Project (GPCP) [*Huffman et al.*, 1997] or from the AMMA rain gauge network; $2.5 \times 2.5°$ Outgoing Longwave Radiation (OLR) [*Liebmann and Smith*, 1996]. This suggests that the convective activity is the main control of the isotopic composition of precipitation in this region, in agreement with the amount effect. The main reasons for the amount effect are the following. (1) When rainfall is more intense, the atmosphere gets moister and the reevaporation of the falling rain decreases, which leads to a lower δ^{18}O in the rain [*Dansgaard*, 1964; *Risi et al.*, 2008] and a higher *d* [*Bony et al.*, 2008]. (2) More frequent and more intense convective events deplete more efficiently the vapor at low-levels [*Lawrence et al.*, 2004; *Risi et al.*, 2008] which then feeds the subsequent convec-

tive systems with lower δ^{18}O. Hereafter, we will focus on the relationship between isotopic composition and convection and investigate at which time scales the amount effect operates.

3.1. Water Isotopes Record the Monsoon Onset

[8] The isotopic composition abruptly changes on July 15th: δ^{18}O drops by about 6‰ and *d* increases by about 7‰ on average (Figure 1b). This date coincides with the end of the monsoon transition period and the arrival of the Inter Tropical Convergence Zone in the Sahel [*Sultan and Janicot*, 2003; *Janicot et al.*, 2008]. The average precipitation rate increases from 1.7 to 5.3 mm/day. The abrupt drop of δ^{18}O is thus the signature of the amount effect at the seasonal scale. The data collected by *Taupin et al.* [1997] also featured such an amount effect at the seasonal scale (though the shift was smoother). The difference between the average δ^{18}O before and after the onset yields an amount effect of about −1.7‰/mm.day, more than twice that for the GNIP (Global Network for Isotopes in precipitation) tropical island stations (−0.6‰/mm.day [*Rozanski et al.*, 1993]). This likely results from the strong effect of rain reevaporation in dry conditions [*Risi et al.*, 2008] as is the case before the onset.

[9] The intensity of individual convective systems does not explain the shift in δ^{18}O: the rain before the onset is systematically more enriched than after the onset, even for systems having higher precipitation amounts before the onset. The abrupt isotopic shift is thus the signature of the increase of convection on average at the regional scale, or a change in large scale environmental conditions.

3.2. Before the Onset, Water Isotopes Record the Intensity and Organization of Individual Events

[10] Over tropical oceans, *Lawrence et al.* [2004] have shown an effect of the degree of organization of convective systems on the δ^{18}O of precipitation. Here, we use Meteosat infrared images to classify convective events into two classes: isolated (small events triggered in the Niamey area) or organized (large systems initiated over East Africa and propagating westward). Before the onset, the rain from organized systems is systematically more depleted (and has a higher *d*) than that from isolated systems, even for a similar cumulated precipitation, in agreement with *Lawrence et al.* [2004]: the 6 isolated systems have a positive δ^{18}O whereas the 2 organized systems have a negative δ^{18}O (Figure 1b).

[11] For the 5 isolated systems before the onset, δ^{18}O is lower and *d* higher for more intense systems: the correlation between δ^{18}O and daily OLR in the 2.5 × 2.5° Niamey grid box is r = 0.9 (−0.6 for *d*). OLR and 1000 hPa relative humidity being strongly anti-correlated (r = −0.95), the correlations of δ^{18}O and *d* with relative humidity are the same as with OLR. For isolated systems occurring before the onset, the local convective intensity, and the associated relative humidity variations, thus control the isotopic composition of precipitation.

3.3. After the Onset, Water Isotopes Record Intra-seasonal Variability

[12] After the onset, the isotopic record exhibits a strong intra-seasonal variability, with δ^{18}O ranging from −1 to −8‰. The data from *Taupin et al.* [1997] also featured such large variations, with amplitudes up to 6‰. Contrary to the period before the onset, we find no significant correlation between convection and the isotopic composition at the scale of individual events. On the other hand, a good correlation between δ^{18}O and the OLR over Niamey is found after the onset when the OLR is averaged over the τ_m days preceding the events, with a maximum correlation for τ_m = 9 days (Figure 2a): the precipitation is more depleted when convective activity has been more intense over the 9 previous days. Thus, after the onset, δ^{18}O does not respond instantaneously to convection, but rather integrates convective activity over the previous days. This is in agreement with modeling studies by *Sturm et al.* [2007] and *Risi et al.* [2008]. Spatially, the correlation between δ^{18}O in precipitation and the OLR averaged over the 9 previous days is maximum North and East of Niamey (Figure 2b), suggesting that the δ^{18}O records a regional signal of convective variability.

[13] The property of δ^{18}O to integrate convection may be explained by each convective system depleting a little more the low-level vapor; the isotopic composition of the vapor feeding a convective system is thus influenced by the cumulative effect of the previous convective systems. In addition, the soil moisture may contribute to integrate convective activity on longer time scales, by storing the precipitation of convective events and reevaporating it later. If the integrative property of δ^{18}O is due to the accumulation of the convective effect in water reservoirs (low-level vapor or soil moisture), then the time constant over which δ^{18}O integrates convection could yield some information about the residence time of water in these reservoirs.

[14] δ^{18}O really integrates convection rather than just responding to it with delay, since correlations between δ^{18}O and averaged OLR are stronger than lag correlations: averaging allows use to select the low-frequency variability of OLR and discard the higher frequency variability to which water isotopes respond more weakly. Consistently, other proxies of convection feature a similar maximum of the correlation with δ^{18}O at 9 days, but faster varying proxies (e.g., precipitation from GPCP and pluviometers) need a longer averaging time or larger averaging domain to reach the maximum correlation (Figure 2a). This highlights the property of δ^{18}O to integrate temporally and spatially convection.

[15] To characterize the time scales of variability recorded by δ^{18}O, we perform correlations between δ^{18}O and averaged OLR for OLR filtered at different frequencies. Filtering between 6 and 18 days (Figure 2c) preserves the correlation pattern, whereas other filters erase it. The δ^{18}O thus records intra-seasonal time scales. In the Sahel, modes of variability at such time scales have been documented: the Sahelian [*Sultan et al.*, 2003; *Mounier and Janicot*, 2004] and Guinean [*Mounier and Janicot*, 2004] modes operate at the 15–20 days time scale. We calculated correlations between δ^{18}O and the time series of the 10–60 days filtered OLR projected on the Sahelian and Guinean modes [*Mounier and Janicot*, 2004] (Figure 2c): they reach maxima of 0.35 and 0.5 when averaged over 10 and 15 days respectively. δ^{18}O is thus a good recorder of these two modes of intra-seasonal variability, even better than the raw local OLR itself: the correlation between these modes and

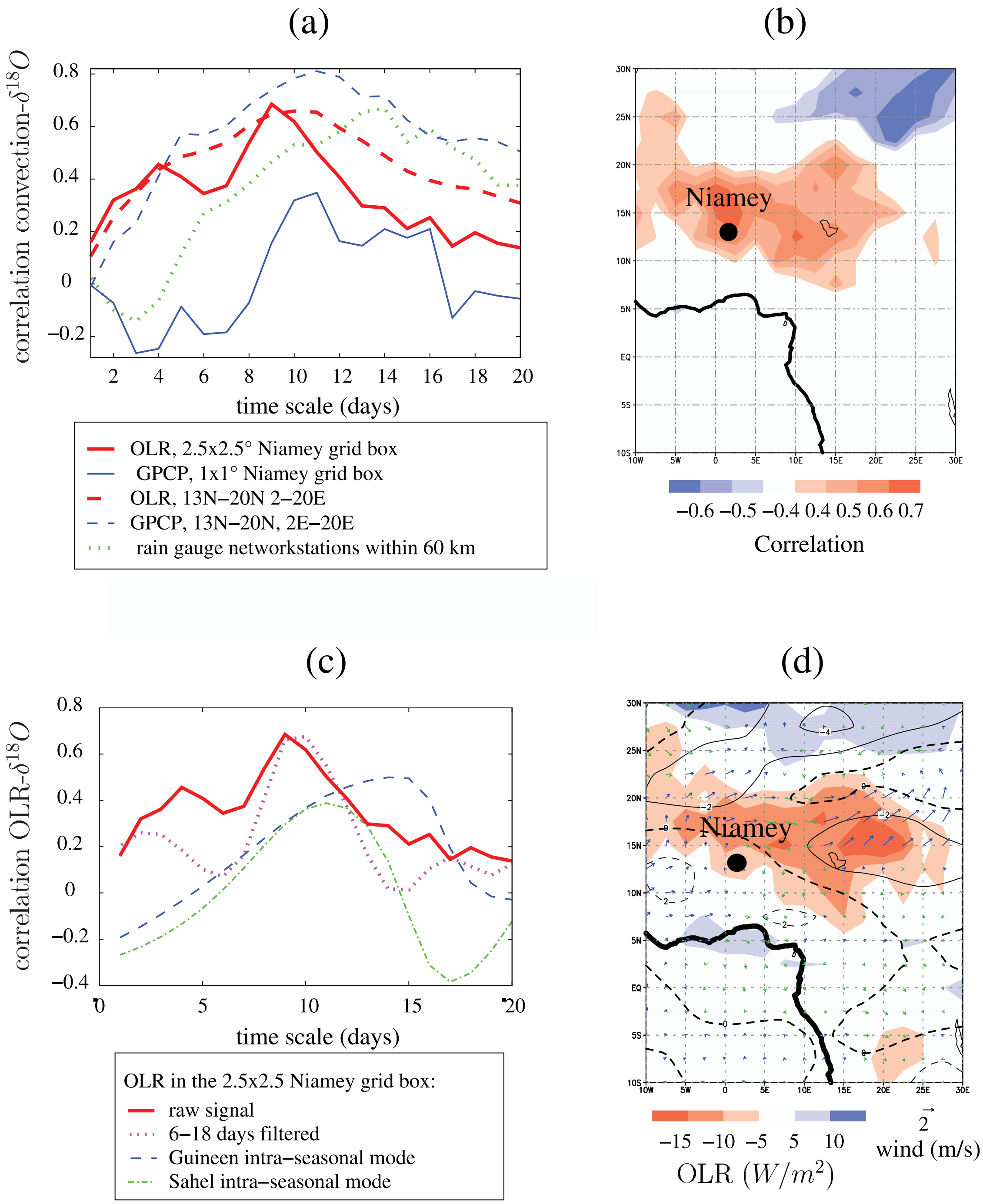

Figure 2. (a) Correlation between δ^{18}O of organized events after the onset and different proxies of convective activity averaged over the τ_m days preceding each rainy event, as a function of τ_m: OLR in the 2.5 × 2.5° Niamey grid box (thick solid red), GPCP precipitation in the 1 × 1° Niamey grid box (thin solid blue), OLR (thick dashed red) and GPCP precipitation (thin dashed blue) both averaged over the 13°N–20°N–2°E–20°E domain, precipitation averaged over the AMMA rain gauge network stations within 60 km of the 3 sites barycenter (dotted green). (b) Correlation between the δ^{18}O of the events and the OLR averaged over the 9 days preceding each event. (c) Solid red, same as heavy red line in Figure 2a; dotted magenta, same for 6–18 days filtered OLR; dashed blue and dash-dotted green, same for time series of 10–60 days filtered OLR projected on the Sahelian and Guinean modes of OLR variability [*Mounier and Janicot*, 2004]. (d) Difference between low δ^{18}O and high δ^{18}O composites, for organized events after the onset: difference of the composites of OLR averaged over the 9 previous days (shading), of 600 hPa zonal winds (contours, zero, positive and negative isolines in thick dashed, thin solid and thin dashed respectively) and of 950 hPa winds (vectors).

the daily OLR over Niamey reach maxima of 0.33 and 0.28 respectively.

[16] To further characterize the variability recorded by δ^{18}O after the onset, OLR and winds are composited as a function of δ^{18}O. The difference between the composites of low and high δ^{18}O (Figure 2d) shows that the most depleted events coincide with an increased convective activity East and North of Niamey, consistent with Figure 2b. This is compatible with the δ^{18}O response to a westward propagating disturbance of convective activity over the Sahel. During the same time, the AEJ is located northward and the monsoon flow is enhanced (Figure 2d). These features are consistent with the Sahelian mode of variability [*Sultan et al.*, 2003].

[17] Lower *d* correlates with higher convective activity integrated over the previous days: this is opposite to the relationship found at the seasonal scale or before the onset, and to the expected effect of convection on *d* (higher convective activity is expected to be associated with less rain reevaporation and thus higher *d* [*Bony et al.*, 2008; Risi et al., submitted manuscript, 2008]). Such a "reverse" relationship is also observed in South America. During this period, surface processes (e.g., the partition of evapotranspiration into transpiration and evaporation) may exert a control on *d* [*Taupin et al.*, 2000] strong enough to offset the effect of convection.

4. Conclusion and Perspectives

[18] At the seasonal scale, the increase in convective activity after the monsoon onset induces a strong drop in δ^{18}O (in agreement with the amount effect) and an increase in *d*. Before the onset, when the average convective activity is weak, the amount effect is observed at the scale of individual event: organized systems are systematically more depleted than isolated systems, and for the latter the intensity of convection is the major control on the isotopic composition. On the contrary, after the onset, δ^{18}O integrates convective activity over time and records the intra-seasonal variability of convection over the Sahel.

[19] The integrative property of δ^{18}O was also found in South America [*Sturm et al.*, 2007]. However, the isotopic composition collected in the Andes was found to be related to convection upstream of low-level trajectories [*Vimeux et al.*, 2005]. In Niger, no relationship is found with proxies of convection along the southerly monsoon flow trajectories, but rather North and East of Niamey. This feature may be tentatively explained by two elements: first, it is consistent with the westward propagation of intra-seasonal convective disturbances. Second, over the Sahel, a substantial part of the moisture (up to half, J.-Y. Grandpeix, personal communication, 2006) converging into convective systems comes from the AEJ that blows westward. This, combined with the fact that in convective atmospheres, water vapor δ^{18}O varies more in the mid-troposphere than at low levels [*Bony et al.*, 2008], may explain that convection occurring eastward of Niamey affects more the δ^{18}O of precipitation over Niamey than the convection occurring along the monsoon flow.

[20] To further disentangle the various atmospheric controls on the isotopic composition of precipitation, together with the potential impact of surface processes, we plan to use in the future the General Circulation Model developed at LMD (LMDZ) [*Hourdin et al.*, 2006] coupled to a land surface scheme, fitted with water stable isotopes and zoomed over West Africa.

[21] Although few paleoclimatic isotopic archives have been exploited so far in West Africa, we show that the δ^{18}O in this monsoon region records the monsoon onset and large-scale convective variability. However, what controls the inter-annual variability of the isotopic composition will be explored in the future when other years of data will be available. We show that the isotopic composition of precipitation constitutes a tracer of several characteristics of the African monsoon. A long-term and extended network of isotopic data over Western Africa would thus be useful for a better understanding of tropical monsoons, African water cycle and paleoclimates.

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