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Evidence for periods of wetter and cooler climate in the Sahel between 6 and 40 kyr BP derived from groundwater

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[1] Concentrations of noble gases, stable isotopes and ^{14}C in samples from the Continental Terminal groundwaters of Niger provide evidence for more humid and cooler climate phases in West Africa in the Holocene and the late Pleistocene. During humid phases, even within the Holocene, the soil temperature was up to 5.5°C cooler than today, which is partly attributed to atmospheric cooling, but also to a change in the relationship between air and soil temperature due to increased vegetation. Intense rainfall events and increased groundwater recharge are consistently indicated by stable isotope data and excess air concentrations, i.e., the component of dissolved atmospheric gases in excess of solubility equilibrium. This finding encourages the use of excess air as an additional, humidity-related climate indicator. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1854 Hydrology: Precipitation (3354); 1833 Hydrology: Hydroclimatology; 1829 Hydrology: Groundwater hydrology. **Citation:** Beyerle, U., J. Rueedi, M. Leuenberger, W. Aeschbach-Hertig, F. Peeters, R. Kipfer, and A. Dodo, Evidence for periods of wetter and cooler climate in the Sahel between 6 and 40 kyr BP derived from groundwater, *Geophys. Res. Lett.*, *30*(4), 1173, doi:10.1029/2002GL016310, 2003.

1. Studied Area

[2] The studied area is located in south-western Niger, Africa, between 12.5–14.5°E and 2.5–4.5°N (Figure 1) dominated by semi-arid climate conditions. The average annual rainfall is 565 mm [*Leduc et al.*, 2001] in the capital Niamey and decreases in north-eastern direction. Most of the rain falls during the wet season in summer when the Intertropical Convergence Zone (ITCZ) reaches the area from the south. The investigated regional Continental Terminal (CT) aquifer system is divided into three layers (CT3, CT2, CT1) of similar lithology consisting of late Tertiary sequences of sands, sandstones and silts. Groundwater recharge into the CT3 aquifer occurs only during strong rainfall events (>20 mm) [*Leduc et al.*, 2001]. The CT3 is mostly unconfined, whereas CT2 and CT1 are confined downstream of the recharge area. Poorly permeable sediments mainly consisting of clays separate the CT aquifers from each other and from the underlying Continental Intercalaire aquifer (CI) [*Andrews et al.*, 1994]. The separation of the aquifers disappears towards the discharge zone in the south-west close to the river Niger [*Greigert*, 1966] (Figure 1). The hydraulic heads are generally highest in the CI followed by the CT1, CT2 and CT3, limiting the recharge from upper to lower compartments of the aquifer system.

2. Methods

[3] Groundwater samples were analyzed for stable isotope ratios (δ^{18}, δ^2H), carbon isotopes ($\delta^{13}C$ and ^{14}C), noble gas isotopes, and hydrochemistry. The noble gas temperature (NGT) and the excess air component (supersaturation above solubility equilibrium due to dissolution of entrapped air bubbles) are calculated according to *Aeschbach-Hertig et al.* [2000]. The chronology of the climate record is based on $^3H/^3He$ dating of the CT3 samples, ^{14}C dating of selected samples from the deeper aquifer compartments, and ^4He concentrations. Further details of the applied methods as well as all measured data and calculated ages are provided in the auxiliary material.[1]

3. Results and Discussion

3.1. Groundwater Age

[4] Besides the modern samples from the CT3 aquifer, our record contains samples from the recharge area of the CT2 aquifer with ages around 6 kyr, samples from the confined part of the CT2 with ages between 6 and 15 kyr, and samples from the CT1 aquifer with ages above 26 kyr (Figure 2). These ages closely correspond to known humid phases in the region. Before 4.5 kyr BP, the African climate was characterised by several humid phases during the Holocene with an optimum in the Sahara region at around 8.5–6.5 kyr BP, interrupted by short dry periods [*Gasse*, 2000]. In the Sahelian belt the monsoon reactivation after the dry and cold

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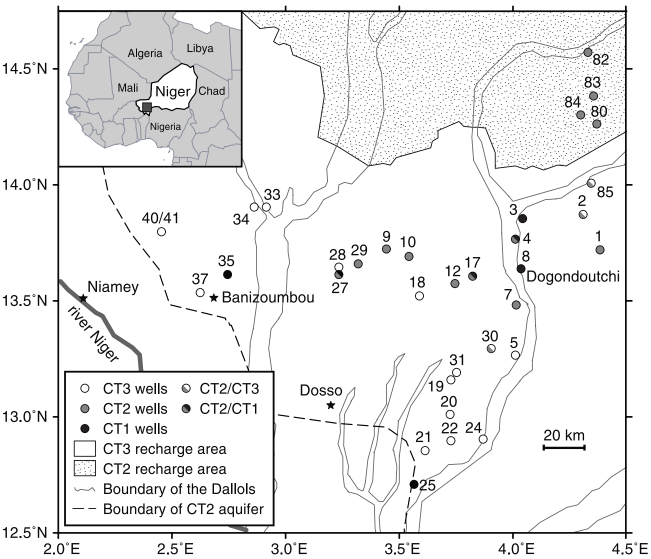

Figure 1. Map of the investigated area. Sampling locations are identified with numbers. The sequence of aquifer layers is CT3 (top), CT2 (middle) and CT1 (bottom). The CT2 disappears south-west of the dashed line [*Greigert*, 1966]. Samples from certain CT2 wells contain a significant amount of CT1 (wells 4, 17 and 27) or CT3 (wells 2, 30 and 85) groundwater due to open well screens at different depths. The altitude of the area shows a slight gradient in north-eastern direction from 200 m a.s.l. for the CT3 recharge area to about 300 m for the CT2 recharge area and about 350 to 400 m for the CT1 and CI recharge areas even further to the north-east or east.

Last Glacial Maximum (LGM, 23–18 kyr BP) took place in two steps at around 15 and 11.5 kyr BP [*Gasse*, 2000], separated by a return to drier conditions coincident with the Younger Dryas. Paleoclimate records from Africa that extend beyond the LGM indicate that before 23 kyr BP humid climate conditions alternated with arid phases while the average temperature remained lower than today [*Gasse*, 2000]. Apparently the CT2 aquifer was prominently recharged during humid periods up to 4.5 kyr ago. The fact that no groundwater was sampled with an age between 15 and 26 kyr suggests that there was no significant recharge during the LGM, in agreement with other paleorecords indicating dry conditions in the Sahel zone during the LGM [*Edmunds et al.*, 1999; *Gasse*, 2000]. Most likely the samples older than 26 kyr originate from humid phases before the LGM.

3.2. Noble Gas Temperature (NGT)

[5] The NGTs of the young CT3 samples are not significantly different from the respective water temperatures (T_{sample}, Table 1), confirming that both closely reflect the soil temperature. Compared to the mean modern air temperature of around 29°C, both groundwater and noble gas temperatures are elevated by about 3°C (Table 1, Figure 2). In temperate climate regions the soil temperature and hence the NGT tends to be slightly (about 1°C) higher than the annual mean air temperature [*Smith et al.*, 1964; *Stute and Schlosser*, 1993], but in arid zones with hardly any vegetation this difference can be larger [*Smith et al.*, 1964]. The HAPEX-Sahel data set from Banizoumbou of 1991 and 1992 shows an average difference of 3.6°C between soil and air temperature. The observed 2–4°C difference between the NGT of the CT3 samples and the modern air temperature is therefore to be expected. Although groundwater temperatures in the CT2 recharge area are similar to those observed in the CT3, the NGTs are significantly lower (Table 1). Compared to the modern CT3 samples, the NGTs of the samples from the CT2 recharge area (age around 6 kyr) are cooler by about 2°C, whereas for the older CT2 samples between 10 and 14 kyr BP the cooling increases up to 5.5°C (Figure 2). The mean NGT of all samples from the confined part of the CT2 and CT1 aquifers is about 5°C lower than the mean NGT of the CT3 samples.

[6] A cooling of at least 5°C has been found in other tropical noble gas studies [*Andrews et al.*, 1994; *Edmunds et al.*, 1999; *Stute et al.*, 1995; *Stute and Talma*, 1998; *Weyhenmeyer et al.*, 2000] for full glacial conditions, but here the coldest NGTs occur clearly after the LGM even if uncorrected maximum ^{14}C ages are assumed. Such a large cooling is unexpected for the late glacial and early Holocene, although climate models suggest some cooling for these periods. *Jolly et al.* [1998] simulate about 2–3°C lower early to mid-Holocene air temperatures in Niger compared to today. The simulated cooling is more pronounced at 11 kyr BP than at 6 kyr BP. In addition, almost all models of the Paleoclimate Modelling Intercomparison Project (PMIP) [*Joussaume et al.*, 1999] show at 6 kyr BP a slight but significant atmospheric cooling over Niger (usually less than 2°C).

[7] In addition to atmospheric cooling, the large observed difference between modern and late glacial to early Holocene NGTs may also result from a change of the air/soil temperature relationship. An increase of the vegetation cover during humid phases could result in cooler soil temperatures due to reduced warming by solar irradiation and/or increased evaporative cooling. Groundwater formed in a temperate forest was found to have about 2°C cooler NGTs than groundwater formed in fields [*Stute and Sonntag*, 1992]. In view of the present day difference between NGTs and air temperature, a change in vegetation cover could account for a reduction of NGTs of about 3.5°C. A combination of this effect with about 2°C of atmospheric cooling could explain

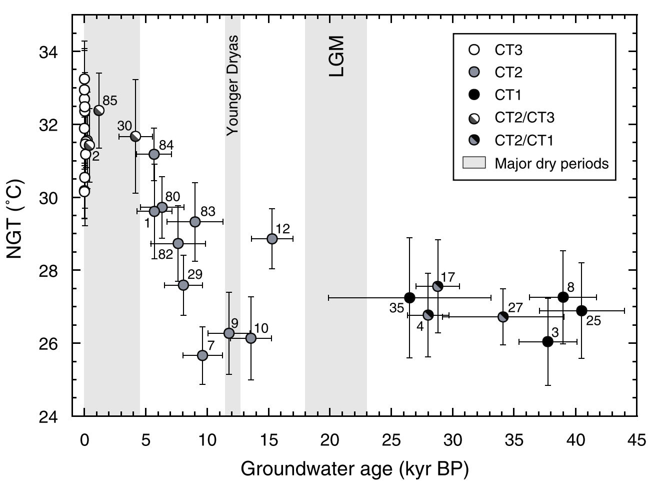

Figure 2. Calibrated groundwater age versus noble gas temperature (NGT).

Table 1. Mean Values[a] and Ranges of Measured and Calculated Quantities

		CT3	CT2 recharge	CT2 confined	CT1
$\delta^{18}O$	(‰)	−4.6 ± 0.4	−6.6 ± 0.2	−6.5 ± 0.2[c]	−7.2 ± 0.2
$\delta^{2}H$	(‰)	−29.3 ± 2.4	−45.3 ± 1.7	−44.8 ± 1.7[c]	−50.2 ± 1.4
T_{sample}	(°C)	32.3 ± 0.3	33.1 ± 0.2	32.9 ± 0.6[c]	34.8 ± 2.1
NGT	(°C)	31.6 ± 1.1	29.7 ± 1.0	26.4 ± 0.8[c]	26.9 ± 0.6
ΔNe	(%)	36 ± 14	73 ± 17	76 ± 12[c]	124 ± 10
$A(^4He)$[b]	(10^{-11} cc/g/yr)	>10	0.8 ± 0.2	2.9 ± 0.4	9.7 ± 2.4
TDIC	(mmol/l)	1.1–8.7	0.7–3.0	1.8–2.7	2.7–4.4
^{14}C	(pmc)	126–69[d]	40–35	42–17	0.9–0.5
$\delta^{13}C$	(‰)	−21 to −8[d]	−18 to −15	−20 to −16	−17 to −15
age	(kyr BP)	<1	6–8	6–15	26–40

[a]Values with errors are mean ±1σ.
[b]The ^4He accumulation rate $A(^4He)$ is given by the slope of a linear regression (forced through the origin) between the calculated groundwater age (either from ^{14}C or $^3H/^3He$ dating) and the radiogenic ^4He concentration.
[c]Only unmixed CT2 samples with cool NGTs (samples 7, 9, 10 and 29).
[d]Data from *Le Gal La Salle et al.* [2001].

the 5.5°C lower NGTs of the CT2 samples between 10 and 14 kyr BP. Possibly the CT2 samples at around 6 kyr BP, which have NGTs only 2°C cooler than the modern CT3 samples, infiltrated during periods in which the change in vegetation and/or air temperature was less pronounced. Alternatively, these samples from the CT2 recharge area may contain a certain amount of younger groundwater, i.e., infiltrated after the end of the last humid phase.

[8] The NGTs of the samples that infiltrated before the LGM are slightly warmer than those recharged between 10 and 14 kyr BP (Figure 2) arguing for similar climate conditions - most probably related to humid but relatively warm phases within the last glacial period. In summary, these findings suggest that in tropical paleogroundwater studies a drop in NGTs may not exclusively be interpreted in terms of atmospheric cooling. An increase in humidity and vegetation may also force cooler soil temperatures and hence cooler NGTs.

3.3. Stable Isotopes

[9] All groundwater samples have stable isotope compositions in the range of the present day regional and global meteoric water lines (see Figure in the E-Supplements), which suggests that the sampled groundwater was not significantly affected by evaporation during recharge or rock-water interactions. Along the meteoric water lines, the samples show a considerable spread of their isotope signals. The old CT2 and CT1 samples are depleted relative to the young CT3 samples by 2–2.5‰ in $\delta^{18}O$ and 15–20‰ in $\delta^{2}H$. A decrease in the stable isotope ratios of precipitation can be induced by [*Rozanski et al.*, 1993]: (1) decrease of average air temperature (temperature effect), (2) increased distance from the coast (continental effect), and (3) increased precipitation (amount effect).

[10] At tropical latitudes, there is no straightforward dependence between air temperature and stable isotopes in precipitation [*Rozanski et al.*, 1993]. Thus, a temperature effect can not explain the depleted stable isotope ratios of the Holocene CT2 samples. Since the recharge areas of the CT2 and CT1 are to the north-east of the CT3 recharge area, a continental effect may result in slightly lighter isotopic compositions. However, within the CT3 samples no geographical gradient in the isotopic composition is observed. Other studies also show a weak or not existing gradient of continentality in the region, which implies a considerable recycling of continental water [*Joseph et al.*, 1992].

[11] The amount effect provides a consistent explanation for the stable isotope data. Today, a correlation between rainfall intensity and stable isotope depletion is observed in most tropical stations [*Rozanski et al.*, 1993]. In the Sahel the correlation between monthly $\delta^{18}O$ values and the amount of rain is in the range of −1 to −2‰ per 100 mm [*Fontes et al.*, 1993]. Under present climate conditions, isotopically depleted showers, which are associated with the passage of the Intertropical Convergence Zone (ITCZ), occur during the wet season, which is more pronounced in the southern part of the investigated area. Several studies [*Cooperative Holocene Mapping Project*, 1988; *Joussaume et al.*, 1999] suggest that the ITCZ moved about 500 km further north during the green Sahara event, resulting in convective showers up to latitudes of 20°N. The depleted stable isotope signature of old CT2 and CT1 samples is therefore consistent with recharge during humid phases characterised by an increased frequency of heavy rain events associated with an intensification of northward movement of the ITCZ. Depleted isotopic compositions of early to mid-Holocene groundwater samples in northern Mali and Niger have also been explained by this effect [*Fontes et al.*, 1993].

3.4. Excess Air Component

[12] Higher excess air values in old groundwaters seem to be typical for aquifer systems in semi-arid, tropical regions [*Aeschbach-Hertig et al.*, 2002; *Andrews et al.*, 1994; *Heaton et al.*, 1983; *Stute et al.*, 1995]. According to the model used for the formation of excess air [*Aeschbach-Hertig et al.*, 2000], as well as laboratory column experiments [*Holocher et al.*, 2002], the amount of excess air, which can be expressed by the relative Ne excess (ΔNe, see Figure 3), is not constrained by the availability of entrapped air, but is strongly correlated to the over-pressure acting on the entrapped air during recharge [*Aeschbach-Hertig et al.*, 2002]. A rise of the water table can increase the hydrostatic pressure on the entrapped air in the quasi-saturated zone and thus increase ΔNe. A transition to a more humid climate may therefore result in a peak in the ΔNe record [*Stute and Talma*, 1998]. It has been speculated [*Heaton et al.*, 1983; *Stute and Talma*, 1998] that ΔNe may be interpreted in terms of increased recharge rates. Indeed in our study ΔNe shows a strong positive correlation with the stable isotopes (Figure 3). Sustained periods of high ΔNe values probably require periodic water table fluctuations with high amplitudes due to

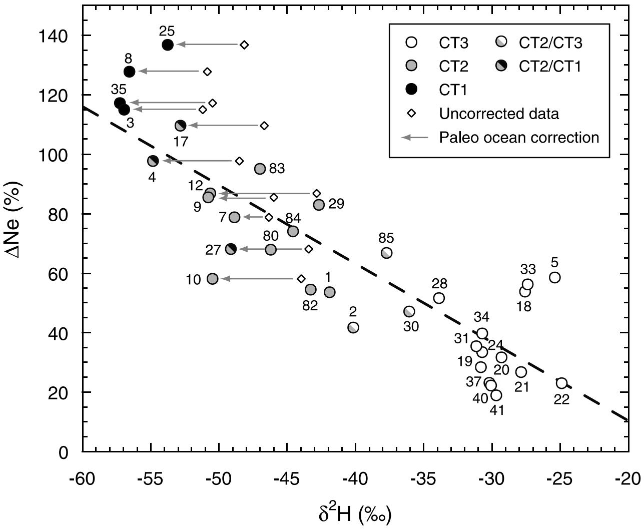

Figure 3. Correlation between δ^2H and excess air (ΔNe). ΔNe is the percentage of the measured Ne concentration in excess of atmospheric equilibrium in water ($\Delta Ne = (Ne_{meas.}/Ne_{eq.} - 1) \cdot 100\%$). Since evaporation and rock-water interaction would affect δ^{18}O more strongly than δ^2H, the latter is chosen to plot against ΔNe. The δ^2H values of samples older than 9 kyr BP were corrected for changes of the δ^2H value of the ocean using the temperature corrected δ^{18}O record of benthic foraminifera [*Sowers et al.*, 1993] and a $\delta^2H/\delta^{18}O$-slope of 8. Both corrected and measured data are shown. Linear regressions though the data show significant correlation (uncorrected $r^2 = 0.71$; corrected $r^2 = 0.75$, dashed line). A similar but slightly lower correlation is found between δ^{18}O and ΔNe (uncorrected $r^2 = 0.69$; corrected $r^2 = 0.74$).

intensive but intermittent rainfalls [*Heaton et al.*, 1983]. Such a scenario of intermittent strong recharge events is consistent with the strong seasonal convective precipitation inferred for humid periods in Niger from climate models and stable isotope depletion. In our study, two independent tracers (ΔNe and stable isotopes) consistently indicate periods of intense rainfall and high recharge rates between 6–15 kyr BP and before 26 kyr BP, in agreement with known humid phases and cooler soil temperatures inferred from the NGTs. This finding definitively encourages the use of excess air in paleogroundwater studies as an additional, humidity-related climate indicator, at least in arid regions.

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