European climate variations over the past half-millennium reconstructed from groundwater

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[1] Temperature reconstructions for recent centuries are the basis of estimations of the natural variability in the climate system before and during the onset of anthropogenic perturbation. Here we present, for the first time, an independent and physically based reconstruction of mean annual temperature over the past half millennium obtained from groundwater in France. The reconstructed noble gas temperature (NGT) record suggests cooler than present climate conditions throughout the 16th–19th centuries. Periods of warming occur in the 17th–18th and 20th century, while cooling is reconstructed in the 19th century. A noticeable coincidence with other temperature records is demonstrated. Deuterium excess varies in parallel with the NGT, and indicates variation in the seasonality of the aquifer recharge; whereas high excess air in groundwater indicates periods with high oscillations of the water table.
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1. Introduction

[2] The reconstruction of past climate conditions is essential for placing recent observed climate changes in a longer term context. The lack of instrumental climate records before the mid 19th century, however, demands the use of natural climate archives to reconstruct past climates [*Mann et al.*, 2008]. Here we present the first temperature reconstruction of the past half-millennium obtained from noble gas concentrations in groundwater, which is a purely physical archive. The noble gas temperature (NGT), which is a direct measure of the soil temperature during infiltration and equilibration of groundwater with soil air, and the relative Ne excess (ΔNe), which is an indicator of humidity conditions, are derived from the noble gases [*Stute and Schlosser*, 1993; *Aeschbach-Hertig et al.*, 2000, 2001; *Klump et al.*, 2008a].

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[3] Most of the climatic reconstructions obtained from groundwater focus on the transition from the Pleistocene to the Holocene [*Stute et al.*, 1995; *Weyhenmeyer et al.*, 2000; *Aeschbach-Hertig et al.*, 2002; *Beyerle et al.*, 1998, 2003; *Klump et al.*, 2008b]. The lack of groundwater studies that focus on the millennial scale is explained by the high experimental demand to date groundwater on this timescale. Currently, the only reliable dating tool for the timescale of 100 to 1000 years is based on the radioisotope ^{39}Ar (half-life: 269 yrs) [*Loosli*, 1983; *Loosli et al.*, 1999; *Purtschert et al.*, 2001]. We applied ^{39}Ar to date groundwater samples from the Fontainebleau sands aquifer (FSA) in France, which is known to contain groundwater that infiltrated during the past few hundred years [*Corcho Alvarado et al.*, 2007].

[4] In the following, NGT and ΔNe in groundwater from the FSA are used to reconstruct a low frequency climate record for the past 500 years. Our record reveals new aspects of late Holocene climate variations in the Paris Basin. This is the first time that NGT, ΔNe and d-excess in groundwater are studied in such detail on this timescale.

2. Site Description

[5] The unconfined Oligocene FSA is located in a very homogeneous sandy formation (up to 99% pure unconsolidated quartz sands), in the shallow section of the Paris Basin (Figure 1). The formation has a thickness of 50 to 70 m and is constraint by two clayey layers. A thick unsaturated zone (UZ) of 3 to 45 m overlies the aquifer, which causes the precipitation to reach the water table after 1 to 3 decades [*Corcho Alvarado et al.*, 2007]. The wells are screened over a large depth interval and screens intercept the water table in most cases (Table 1). Despite high abstraction rates, water tables decreased only slightly because of the high yield and conductivity of the aquifer. The Paris basin has been characterized by a temperate climate over the past millennium, with an evolution similar to the one observed in the European climate [*Slonosky*, 2002; *Masson-Delmotte et al.*, 2005].

3. Methods

3.1. Field and Laboratory Methods

[6] Groundwater samples were collected in 2001 (7 deep long-screened wells) and 2007 (2 shallow short-screened wells). All the samples were analyzed for stable noble gases (^{3}He, ^{4}He, ^{20}Ne, ^{22}Ne, ^{36}Ar, ^{40}Ar, Kr, Xe), stables isotopes ^{18}O and ^{2}H, and ^{3}H activities. Noble gases were measured at the ETH Zurich (Switzerland, details by *Beyerle et al.* [2000]). ^{3}H was measured by liquid scintillation counting, at the University of Bern (Switzerland). The isotope ratios

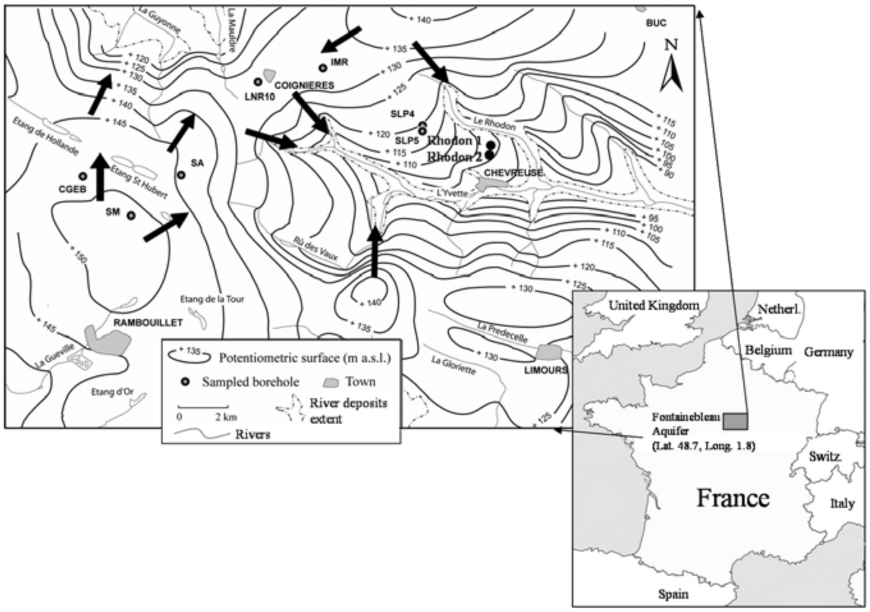

Figure 1. Map of a section of Europe with the location of the aquifer site south of Paris, France. Black arrows indicate the direction of the groundwater flow.

$\delta^{18}O$ and $\delta\ ^2H$ were measured by mass spectrometry at the University of Paris-Sud (France). In the deep wells, the radioactive noble gases ^{85}Kr and ^{39}Ar were also analyzed. These radioisotopes were measured by gas proportional counting at the University of Bern [*Corcho Alvarado et al.*, 2007].

[7] The concentrations of O_2, CO_2, H_2S and CH_4 in the UZ were measured at selected locations using an "*in situ*" airTOX gas analyser (Fresenius Umwelttechnik GmbH). In situ temperature loggers were installed in the shallow wells which continuously monitored water temperatures near the water table. The air temperatures (uncertainty ±0.2°C) were recorded at a local meteorological station (Station Trappes of Meteo France) and by temperature probes located at 1 m above the soil surface near the two shallow wells. The temperature data were averaged to mean annual water temperatures (MAWT, years 2004–2007) and mean annual air temperatures (MAAT).

3.2. Data Interpretation Approach

[8] The chronology of the shallow groundwater samples is based on $^3H/^3He$ dating [*Schlosser et al.*, 1989; *Kipfer et al.*, 2002]. The age structure of groundwater in the deep wells was previously published [*Corcho Alvarado et al.*, 2007] (Table 1).

[9] NGT and ΔNe are calculated from the stable noble gas concentrations using the inverse algorithm described by *Aeschbach-Hertig et al.* [1999], and the conceptual models for gas partitioning in groundwater [see *Aeschbach-Hertig et al.*, 2000]. High quality fits between the measured and modeled concentrations were obtained with the most simple model, assuming that the gas excess above solubility equilibrium (excess air) is pure atmospheric air (unfractionated air or UA-model) [*Corcho Alvarado et al.*, 2007]. The UA model produced the best fit for the shallow wells (Table 1). Depletion of O_2 due to biological activity in absence of an equivalent increase in CO_2 may increase the partial pressures of the noble gases in the UZ and thus bias the resulting NGTs to colder values [*Hall et al.*, 2005; *Castro et al.*, 2007]. However, measured O_2 and CO_2 concentrations in the UZ demonstrate that the small O_2 decrease of at most 4% is compensated or even overcompensated by a corresponding increase of the CO_2 partial pressure. Moreover, the concentrations of O_2 in groundwater (6–9 mg/l) are only slightly

Table 1. Characteristics of the Wells in the Fontainebleau Aquifer and Results of the Tracer Study

Well	Aquifer Section	Depth Water Table (m)	Screen Size (m)	Water Age (yrs)	NGT (°C)	ΔNe (%)	d-Excess[a] (‰)
Rhodon 1A	Shallow	6–7	1	<5[b]	10.9 ± 0.2	9.3 ± 2	9.4 ± 1.1
Rhodon 2A	Shallow	6–7	1	<5[b]	10.8 ± 0.2	1.6 ± 2	9.2 ± 1.1
Rhodon 1B	Shallow	6–7	1	<5[b]	-	-	9.6 ± 1.1
Rhodon 2B	Shallow	6–7	1	<5[b]	-	-	9.4 ± 1.1
SM	Deep	20–25	32.5	103 ± 45[c]	9.7 ± 0.2	36.9 ± 2	6.2 ± 1.1
CGEB	Deep	26–31	11.1	144 ± 37[c]	9.8 ± 0.2	30.5 ± 2	7.1 ± 1.1
SA	Deep	26–31	11.2	174 ± 41[c]	10.1 ± 0.2	32.0 ± 2	7.8 ± 1.1
LRN10	Deep	35–40	22.5	116 ± 33[c]	9.6 ± 0.2	39.4 ± 2	6.9 ± 1.1
IMR	Deep	35–40	12.0	318 ± 65[c]	10.5 ± 0.2	58.9 ± 2	9.0 ± 1.1
SLP4	Deep	35–40	1.6	270 ± 56[c]	10.6 ± 0.2	44.2 ± 2	8.1 ± 1.1
SLP5	Deep	21–26	3.0	373 ± 76[c]	10.3 ± 0.2	39.6 ± 2	7.6 ± 1.1

[a]Deuterium excess is defined as d-excess = $\delta^2H - 8\delta^{18}O$.
[b]$^3H/^3He$ ages.
[c]Data taken from *Corcho Alvarado et al.* [2007]. "Water age": mean exponential residence time.

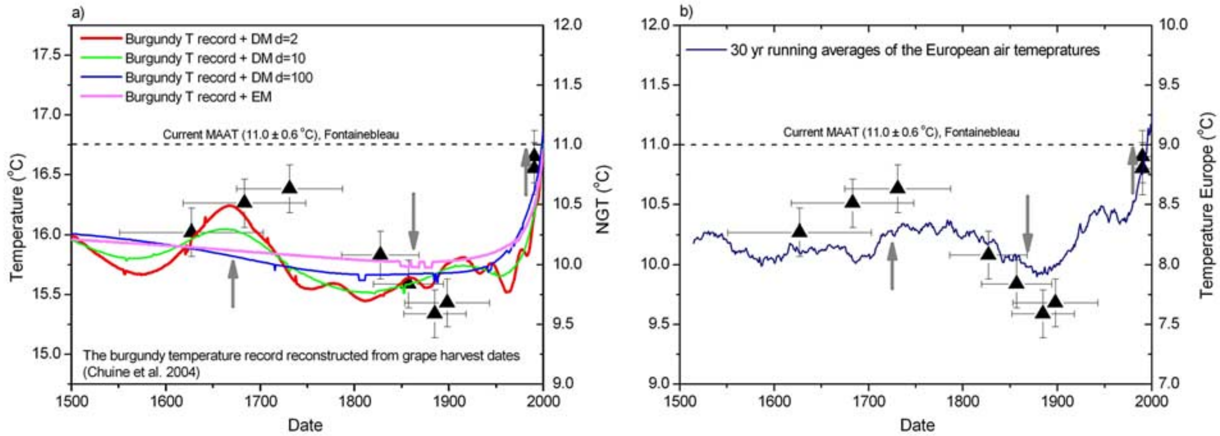

Figure 2. Temporal evolution of the *NGT* (triangles) in the FSA compared to (a) temperature records obtained by convoluting a Burgundy temperature record (spring-summer mean air temperatures), and (b) a 30-yr running average of the mean annual surface air temperature (line) for Europe. For Figure 2a, data are taken from *Chuine et al.* [2004] with the dispersion model (DM, dispersion parameters d: 2, 10 and 100 yrs) and the exponential model (EM). The convolution with the box-models accounts for the mixing of water within the aquifer and the well screen. The Burgundy region is located less than 200 km from the FSA (Figure 1). For Figure 2b, data are taken from *Luterbacher et al.* [2004] and *Xoplaki et al.* [2005]. The current MAAT in the recharge area of the aquifer is also shown in Figures 2a and 2b (11.0 ± 0.6°C).

depleted with respect to air saturated water at 10°C (about 11 mg/l of O_2). Significant changes of noble gas partial pressures in the UZ and related NGT biases due to O_2 depletion are therefore unlikely.

[10] In order to better constrain the temporal air and soil temperature variations in the studied site, the reconstructed NGT record is compared to other Northern Hemisphere (NH) temperature records [*Luterbacher et al.*, 2004; *Chuine et al.*, 2004; *Xoplaki et al.*, 2005; *Smith et al.*, 2006]. However, the water samples from the long-screened wells turned out to represent mixtures of water recharged at different times. As a consequence, the determined NGT represents a weighted mean over the years during which groundwater recharged. To account for this averaging, the NH temperature records were convoluted with simple box models [*Zuber and Maloszewski*, 2001] that describe mixing in the aquifer and within the well screen (see auxiliary material).[1]

4. Results and Discussion

4.1. Noble Gas Temperatures

[11] Air temperatures of the region oscillate around a MAAT of 11.0°C (standard deviation of 0.6°C, and seasonal amplitude ± 15°C). In the shallow wells, at 6 m depth, the MAWT is 11.4°C with a seasonal variation of 1.5°C. These results are in good agreement with the prediction of conductive heat transport through the soil, described by exponential damping of the annual temperature signal with depth [*Stute and Schlosser*, 1993; *Klump et al.*, 2007]. In the shallow wells, the NGTs (Table 1, 10.8–10.9°C) agree with the MAAT of the region and are only slightly lower than the MAWT. This agreement, in case of the young water (age < 5 yrs), is in line with the expectation that NGTs reflect soil temperatures during recharge, which for moderate climate zones as for the Paris basin closely follow MAAT [*Klump et al.*, 2007], if depletion of O_2 in the quasi-saturated zone [*Hall et al.*, 2005; *Castro et al.*, 2007] is not significant.

[12] Deep groundwaters from long-screened wells have mean residence times of a few hundred years (Table 1). Hence these waters recharged between the 16th and 20th centuries. The NGTs in these samples are lower than those in the young water (9.5–10.6°C, Table 1). The observed NGT shift points to cooler recharge conditions (soil temperatures) during the past five centuries compared to present day. As NGT is a good proxy for MAAT, the observed NGT difference most probably is the consequence of rising air temperatures over the past 150 to 200 years.

[13] The observed variability in the NGTs separates the record in distinguishable warmer and colder periods. A

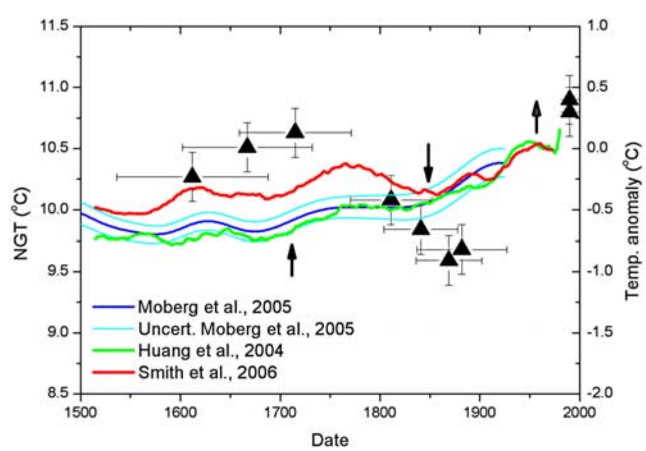

Figure 3. Temporal evolution of the *NGT* (triangles) in the FSA compared to three low frequency records of Northern Hemisphere temperatures reconstructed from borehole temperatures [*Huang et al.*, 2000], multiple proxy data [*Moberg et al.*, 2005] and speleothems data [*Smith et al.*, 2006].

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038826.

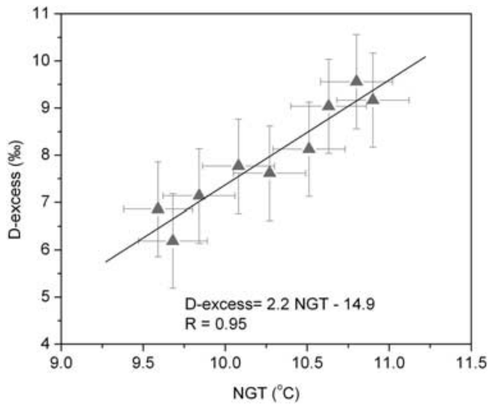

Figure 4. Correlation between *d-excess* and *NGT* for the Fontainebleau sands aquifer.

transition from warmer (10.6°C) to colder (9.8°C) temperatures occurred between the 16th and 19th century. After 1800–1900, NGTs increased by about 1°C until the present (10.8–10.9°C). This evolution of NGTs is fully consistent with data obtained from other NH records (Figures 2 and 3).

[14] Soil and, therefore, noble gas temperatures are also affected by soil cover [*Stute and Schlosser*, 1993; *Beyerle et al.*, 2003]. For the investigated area, historical documents identify intensive clearing of woods to reclaim agricultural land between two to three hundred years ago. This new distribution in land use remains approximately the same until now. Although caution has to be exercised in drawing final conclusions, the influence of soil properties on NGT seems to have been rather constant over the last 200 years and hence can not explain the observed increase in NGT, i.e. soil temperature.

[15] The NGT record has a low temporal resolution, and cannot resolve for example decadal variability; but provides an independent estimate of local low-frequency temperature variations. The NGT record is in some aspects comparable to borehole temperature reconstructions, which also measure soil temperatures with low temporal resolution [*Huang et al.*, 2000]; or to speleothem temperature reconstructions, which are obtained from mineral deposits formed from groundwater in caves [*Smith et al.*, 2006]. As can be seen in Figures 2b and 3, the evolution of the NGTs in general shows consistency with NH temperatures reconstructed from borehole temperatures and speleothems [*Huang et al.*, 2000; *Moberg et al.*, 2005; *Smith et al.*, 2006], although the centennial variation is more pronounced in our NGT record. This difference may reflect local variability that has been attenuated in the hemispheric low frequency records that represent averages over several individual records from different regions in the NH.

4.2. Excess Air Component

[16] Large differences are observed between the ΔNe amounts in shallow (1.6–9.3%) and deep groundwater (30.5–58.9%), indicating distinct recharge conditions. ΔNe reflects the amplitude of water table fluctuations [*Ingram et al.*, 2007; *Klump et al.*, 2008a]. The low ΔNe values found in the shallow samples indicate weak fluctuations in recent times. Over the past decades the aquifer was subject to significant abstraction which may have suppressed water table rises during recharge episodes. A continuous reduction of the recharge rate of the aquifer over the last centuries may also be part of the explanation of the large differences observed in ΔNe. This suggested reduction in recharge is in line with observations that the discharge of springs has declined between the 18th and first half of the 20th centuries.

4.3. Deuterium Excess

[17] The d-excess record is well correlated with the NGT record (Figure 4). Elevated temperatures in the recharge area cause higher evaporation rates; and therefore reduced d-excesses in the recharging water (or higher d-excess for locally cooler temperatures [*Araguas-Araguas et al.*, 2000]. Winter recharge will therefore have larger d-excess whereas in summer d-excess is reduced. Furthermore, the proportion of winter recharge increases with increasing temperature because summer recharge is reduced due to evaporation. A global temperature increase would therefore lead to higher d-excess in groundwater in agreement with our observation (Figure 4), assuming that the source region of precipitation remained the same over time [*Rozanski*, 1985].

5. Conclusions

[18] Strong relationships were observed between NGT, d-excess and ΔNe with the climate conditions that prevailed in the recharge area of the FSA over the past 500 years. The NGT reflects the soil temperature at recharge, which is strongly linked to the air temperature in the region. The reconstruction of the NGTs back to 1500 AD indicated cooler than present climate conditions throughout the 16th–19th centuries. Variations in air temperature over the past centuries induced changes in the seasonality of the aquifer recharge, which in turn produced changes in d-excess in groundwater. High ΔNe amounts in the older groundwater seem to reflect periods of higher variability of the water table. The climate reconstruction of the past half millennium obtained from groundwater data has a low temporal resolution. Nevertheless, groundwater provides climate information at multi-centennial timescales that may not be captured by high resolution data sets.

References

Aeschbach-Hertig, W., F. Peeters, U. Beyerle, and R. Kipfer (1999), Interpretation of dissolved atmospheric noble gases in natural waters, *Water Resour. Res.*, *35*, 2779–2792, doi:10.1029/1999WR900130.

Aeschbach-Hertig, W., F. Peeters, U. Beyerle, and R. Kipfer (2000), Palaeotemperature reconstruction from noble gases in ground water taking into account equilibration with entrapped air, *Nature*, *405*, 1040–1044, doi:10.1038/35016542.

Aeschbach-Hertig, W., U. Beyerle, J. Holocher, F. Peeters, and R. Kipfer (2001), Excess air in groundwater as a potential indicator of past environmental changes, in *International Conference on the Study of Environmental Change Using Isotope Techniques*, *C&S Pap. Ser.*, vol. 13, pp. 34–36, Int. At. Energy Agency, Vienna.

Aeschbach-Hertig, W., M. Stute, J. F. Clark, R. Reuter, and P. Schlosser (2002), A paleotemperature record derived from dissolved noble gases in groundwater of the Aquia Aquifer (Maryland, USA), *Geochim. Cosmochim. Acta*, *66*, 797–817, doi:10.1016/S0016-7037(01)00804-3.

Araguas-Araguas, L., K. Froehlich, and K. Rozanski (2000), Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture, *Hydrol. Processes*, *14*, 1341–1355, doi:10.1002/1099-1085(20000615)14:8<1341::AID-HYP983>3.0.CO;2-Z.

Beyerle, U., et al. (1998), Climate and groundwater recharge during the last glaciation in an ice-covered region, *Science*, *282*, 731–734, doi:10.1126/science.282.5389.731.

Beyerle, U., et al. (2000), A mass spectrometric system for the analysis of noble gases and tritium from water samples, *Environ. Sci. Technol.*, *34*, 2042–2050, doi:10.1021/es990840h.

Beyerle, U., J. Rueedi, M. Leuenberger, W. Aeschbach-Hertig, F. Peeters, R. Kipfer, and A. Dodo (2003), 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.

Castro, M. C., C. M. Hall, D. Patriarche, P. Goblet, and B. R. Ellis (2007), A new noble gas paleoclimate record in Texas—Basic assumptions revisited, *Earth Planet. Sci. Lett.*, *257*, 170–187, doi:10.1016/j.epsl.2007.02.030.

Chuine, I., et al. (2004), Grape ripening as a past climate indicator, *Nature*, *432*, 289–290.

Corcho Alvarado, J. A., et al. (2007), Constraining the age distribution of highly mixed groundwater using ^{39}Ar: A multiple environmental tracer (^{3}H/^{3}He, ^{85}Kr, ^{39}Ar, and ^{14}C) study in the semiconfined Fontainebleau Sands Aquifer (France), *Water Resour. Res.*, *43*, W03427, doi:10.1029/2006WR005096.

Hall, C. M., M. C. Castro, K. C. Lohmann, and L. Ma (2005), Noble gases and stable isotopes in a shallow aquifer in southern Michigan: Implications for noble gas paleotemperature reconstructions for cool climates, *Geophys. Res. Lett.*, *32*, L18404, doi:10.1029/2005GL023582.

Huang, S., H. N. Pollack, and P. Y. Shen (2000), Temperature trends over the past five centuries reconstructed from borehole temperatures, *Nature*, *403*, 756–758, doi:10.1038/35001556.

Ingram, R. G. S., K. M. Hiscock, and P. F. Dennis (2007), Noble gas excess air applied to distinguish groundwater recharge conditions, *Environ. Sci. Technol.*, *41*, 1949–1955, doi:10.1021/es061115r.

Kipfer, R., W. Aeschbach-Hertig, F. Peeters, and M. Stute (2002), Noble gases in lakes and ground waters, *Rev. Mineral. Geochem.*, *47*, 615–700, doi:10.2138/rmg.2002.47.14.

Klump, S., et al. (2007), Field experiments yield new insights into gas exchange and excess air formation in natural porous media, *Geochim. Cosmochim. Acta*, *71*, 1385–1397, doi:10.1016/j.gca.2006.12.006.

Klump, S., O. A. Cirpka, H. Surbeck, and R. Kipfer (2008a), Experimental and numerical studies on excess-air formation in quasi-saturated porous media, *Water Resour. Res.*, *44*, W05402, doi:10.1029/2007WR006280.

Klump, S., T. Grundl, R. Purtschert, and R. Kipfer (2008b), Groundwater and climate dynamics derived from noble gas, ^{14}C, and stable isotope data, *Geology*, *36*(5), 395–398, doi:10.1130/G24604A.1.

Loosli, H. H. (1983), A dating method with ^{39}Ar, *Earth Planet. Sci. Lett.*, *63*, 51–62, doi:10.1016/0012-821X(83)90021-3.

Loosli, H. H., B. E. Lehmann, and W. M. Smethie (1999), Noble gas radioisotopes: ^{37}Ar, ^{85}Kr, ^{39}Ar, ^{81}Kr, in *Environmental Tracers in Subsurface Hydrology*, edited by P. G. Cook and A. L. Herczeg, pp. 379–396, Kluwer Acad., Boston.

Luterbacher, J., D. Dietrich, E. Xoplaki, M. Grosjean, and H. Wanner (2004), European seasonal and annual temperature variability, trends and extremes since 1500, *Science*, *303*, 1499–1503, doi:10.1126/science.1093877.

Mann, M. E., et al. (2008), Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia, *Proc. Natl. Acad. Sci. U. S. A.*, *105*, 13,252–13,257, doi:10.1073/pnas.0805721105.

Masson-Delmotte, V., et al. (2005), Changes in European precipitation seasonality and in drought frequencies revealed by a four-century-long tree-ring isotopic record from Brittany, western France, *Clim. Dyn.*, *24*(1), 57–69, doi:10.1007/s00382-004-0458-1.

Moberg, A., D. M. Sonechkin, K. Holmgren, N. M. Datsenko, and W. Karlén (2005), Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, *Nature*, *433*, 613–617, doi:10.1038/nature03265.

Purtschert, R., U. Beyerle, W. Aeschbach-Hertig, R. Kipfer, and H. H. Loosli (2001), Palaeowaters from the Glatt Valley, Switzerland, in *Palaeowaters in Coastal Europe: Evolution of Groundwater Since the Late Pleistocene*, edited by W. M. Edmunds and C. J. Milne, *Spec. Publ. Geol. Soc. London*, *189*, 155–162.

Rozanski, K. (1985), Deuterium and oxygen-18 in European groundwaters—Links to atmospheric circulation in the past, *Chem. Geol.*, *52*, 349–363.

Schlosser, P., M. Stute, C. Sonntag, and K. O. Munnich (1989), Tritiogenic ^{3}He in shallow groundwater, *Earth Planet. Sci. Lett.*, *94*, 245–256, doi:10.1016/0012-821X(89)90144-1.

Slonosky, V. C. (2002), Wet winters, dry summers? Three centuries of precipitation data from Paris, *Geophys. Res. Lett.*, *29*(19), 1895, doi:10.1029/2001GL014302.

Smith, C. L., A. Baker, I. J. Fairchild, S. Frisia, and A. Borsato (2006), Reconstructing hemispheric-scale climates from multiple stalagmite records, *Int. J. Climatol.*, *26*(10), 1417–1424, doi:10.1002/joc.1329.

Stute, M., and P. Schlosser (1993), Principles and applications of the noble gas paleothermometer, in *Climate Change in Continental Isotopic Records*, *Geophys. Monogr. Ser.*, vol. 78, edited by P. K. Swart et al., pp. 89–100, AGU, Washington, D. C.

Stute, M., et al. (1995), Cooling of tropical Brazil (5°C) during the last glacial maximum, *Science*, *269*, 379–383, doi:10.1126/science.269.5222.379.

Weyhenmeyer, C. E., et al. (2000), Cool glacial temperatures and changes in moisture source recorded in Oman groundwaters, *Science*, *287*, 842–845, doi:10.1126/science.287.5454.842.

Xoplaki, E., J. Luterbacher, H. Paeth, D. Dietrich, N. Steiner, M. Grosjean, and H. Wanner (2005), European spring and autumn temperature variability and change of extremes over the last half millennium, *Geophys. Res. Lett.*, *32*, L15713, doi:10.1029/2005GL023424.

Zuber, A., and P. Maloszewski (2001), Lumped-parameter models, in *Environmental Isotopes in the Hydrological Cycle. Principles and Applications*, vol. 6, *Modelling*, *Tech. Doc. Hydrol.*, vol. 39, edited by W. G. Mook, pp. 5–35, U.N. Educ., Sci., and Cult. Organ., Paris.

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