

Temperature-sensitivity of water stable isotopes in global precipitation: a groundwater noble gas-based, paleoclimate perspective

David V. Bekaert¹, Alizé Longeau¹, Camille Risi², Gabriel Fénisse¹, Charlotte Prud'Homme¹, Roi Ram^{3,4,5}, Jian Zhang⁶, Dominique Genty⁶, Alan M. Seltzer^{7,8}, Werner Aeschbach^{4,5}, Thomas Müller⁹, Roberto Kirchheim¹⁰, Sylvia Dee¹¹, Kanon Kino¹², Kei Yoshimura¹², Alexandre Cauquoin¹², Hayoung Bong¹³, Allegra N. LeGrande¹³, Pierre-Henri Blard^{1,14}.

¹Université de Lorraine, CNRS, CRPG, F-54000 Nancy, France

²Laboratoire de Météorologie Dynamique, IPSL, CNRS, École Normale Supérieure, Sorbonne Université, PSL Research University, Paris, France

³Geological Survey of Israel, 9692100 Jerusalem, Israel

⁴Institute of Environmental Physics, Heidelberg University, Heidelberg, Germany

⁵Heidelberg Center for the Environment (HCE), Heidelberg University, Heidelberg, Germany

⁶Université de Bordeaux, CNRS, Bordeaux INP, I2M, UMR 5295, F-33400 Talence, France

⁷Marine Chemistry and Geochemistry Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

⁸School of Earth Sciences, University College Dublin, Dublin, Ireland

⁹GEOMAR Helmholtz Centre for Ocean Research Kiel, RD2/Marine Geosystems, Germany

¹⁰Hydrology and Territorial Management Directory (DHT), The Geological Survey of Brazil (CPRM-SGB), São Paulo (SP), Brazil

¹¹Department of Earth, Environmental, and Planetary Sciences, Rice University, Houston, TX, USA,

¹² Institute of Industrial Science (IIS), The University of Tokyo, Kashiwa, Japan

¹³NASA Goddard Institute for Space Studies, New York, NY, USA

¹⁴Laboratoire de Glaciologie, Département de Géosciences, Environnement et Société, ULB, Brussels, Belgium

Supplementary Information

Supplementary Information contains several parts and files.

A) References used for fossil groundwater data compilation (Bekaert et al. (2026), <https://doi.org/10.60520/IEDA/114589>).

Abouelmagd, A., Sultan, M., Sturchio, N. C., Soliman, F., Rashed, M., Ahmed, M., ... & Chouinard, K. (2014). Paleoclimate record in the Nubian sandstone aquifer, Sinai Peninsula, Egypt. *Quaternary Research*, 81(1), 158-167. DOI: 10.1016/j.yqres.2013.10.017

Aeschbach-Hertig, W., Stute, M., Clark, J. F., Reuter, R. F., & Schlosser, P. (2002). A paleotemperature record derived from dissolved noble gases in groundwater of the Aquia Aquifer (Maryland, USA). *Geochimica et Cosmochimica Acta*, 66(5), 797-817. DOI: 10.1016/S0016-7037(01)00804-3

Andrews, J. N., & Lee, D. J. (1979). Inert gases in groundwater from the Bunter Sandstone of England as indicators of age and palaeoclimatic trends. *Journal of Hydrology*, 41(3-4), 233-252. DOI: 10.1016/0022-1694(79)90064-7

Andrews, J. N., Goldbrunner, J. E., Darling, W. G., Hooker, P. J., Wilson, G. B., Youngman, M. J., ... & Stichler, W. (1985). A radiochemical, hydrochemical and dissolved gas study of groundwaters in the Molasse basin of Upper Austria. *Earth and Planetary Science Letters*, 73(2-4), 317-332. DOI: 10.1016/0012-821X(85)90080-9

Andrews, J. N., Fontes, J. C., Aranyossy, J. F., Dodo, A., Edmunds, W. M., Joseph, A., & Travi, Y. (1994). The evolution of alkaline groundwaters in the continental intercalaire aquifer of the Irhazer Plain, Niger. *Water Resources Research*, 30(1), 45-61. DOI: 10.1029/93WR02226

Arslan, S., Yazicigil, H., Stute, M., Schlosser, P., & Smethie Jr, W. M. (2015). Analysis of groundwater dynamics in the complex aquifer system of Kazan Trona, Turkey, using environmental tracers and noble gases. *Hydrogeology Journal*, 23(1), 175-194. DOI: 10.1007/s10040-014-1188-z

Bekaert, D. V., Blard, P. H., Raoult, Y., Pik, R., Kipfer, R., Seltzer, A. M., ... & Marty, B. (2023). Last glacial maximum cooling of 9° C in continental Europe from a 40 kyr-long noble gas paleothermometry record. *Quaternary Science Reviews*, 310, 108123. DOI: 10.1016/j.quascirev.2023.108123

Beyerle, U., Purtschert, R., Aeschbach-Hertig, W., Imboden, D. M., Loosli, H. H., Wieler, R., & Kipfer, R. (1998). Climate and groundwater recharge during the last glaciation in an ice-covered region. *Science*, 282(5389), 731-734. DOI: 10.1126/science.282.5389.731

Beyerle, U., Rueedi, J., Leuenberger, M., Aeschbach-Hertig, W., Peeters, F., Kipfer, R., & Dodo, A. (2003). Evidence for periods of wetter and cooler climate in the Sahel between 6 and 40 kyr BP derived from groundwater. *Geophysical Research Letters*, 30(4). DOI: 10.1029/2002GL016310

Blaser, P. C., Kipfer, R., Loosli, H. H., Walraevens, K., Van Camp, M., & Aeschbach-Hertig, W. (2010). A 40 ka record of temperature and permafrost conditions in northwestern Europe from noble gases in the Ledo-Paniselian Aquifer (Belgium). *Journal of Quaternary Science*, 25(6), 1038-1044. DOI: 10.1002/jqs.1391

Broers, H. P., Sültenfuß, J., Aeschbach, W., Kersting, A., Menkovich, A., de Weert, J., & Castelijn, J. (2021). Paleoclimate signals and groundwater age distributions from 39 public

water works in the Netherlands; insights from noble gases and carbon, hydrogen and oxygen isotope tracers. *Water Resources Research*, 57(7), e2020WR029058. DOI: 10.1029/2020WR029058

Brown, G. A., Love, A. J., Banks, E. W., Broadley, M. W., Tyne, R. L., Chambers, T. E., ... & Seltzer, A. M. (2026). Integrated groundwater noble gas and isotope tracers constrain hydroclimate variability and subsurface volatile sources. *Earth and Planetary Science Letters*, 690, 120173. DOI: 10.1016/j.epsl.2026.120173

Clark, J. F., Stute, M., Schlosser, P., Drenkard, S., & Bonani, G. (1997). A tracer study of the Floridan aquifer in southeastern Georgia: Implications for groundwater flow and paleoclimate. *Water Resources Research*, 33(2), 281-289. DOI: 10.1029/96WR03017

Clark, J. F., Davisson, M. L., Hudson, G. B., & Macfarlane, P. A. (1998). Noble gases, stable isotopes, and radiocarbon as tracers of flow in the Dakota aquifer, Colorado and Kansas. *Journal of Hydrology*, 211(1-4), 151-167. DOI: 10.1016/S0022-1694(98)00233-9

Corcho Alvarado, J. A., Leuenberger, M., Kipfer, R., Paces, T., & Purtschert, R. (2011). Reconstruction of past climate conditions over central Europe from groundwater data. *Quaternary Science Reviews*, 30(23-24), 3423-3429. DOI: 10.1016/j.quascirev.2011.09.003

De Melo, M. C., Paquete, P. C., & Da Silva, M. M. (2001). Evolution of the Aveiro Cretaceous aquifer (NW Portugal) during the Late Pleistocene and present day: evidence from chemical and isotopic data. *Geological Society, London, Special Publications*, 189(1), 139-154. DOI: 10.1144/GSL.SP.2001.189.01.09

Edmunds, W. M., & Smedley, P. L. (2000). Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. *Applied Geochemistry*, 15(6), 737-752. DOI: 10.1016/S0883-2927(99)00079-7

Edmunds, W. M., Ma, J., Aeschbach-Hertig, W., Kipfer, R., & Darbyshire, D. P. F. (2006). Groundwater recharge history and hydrogeochemical evolution in the Minqin Basin, North West China. *Applied geochemistry*, 21(12), 2148-2170. DOI: 10.1016/j.apgeochem.2006.07.016

Heine, F., Zosseder, K., & Einsiedl, F. (2021). Hydrochemical zoning and chemical evolution of the deep upper jurassic thermal groundwater reservoir using water chemical and environmental isotope data. *Water*, 13(9), 1162. DOI: 10.3390/w13091162

Hssaisoune, M., Bouchaou, L., Matsumoto, T., Araguas, L., Kraml, M., & Aggarwal, P. (2019). New evidences on groundwater dynamics from the Souss-Massa system (Morocco): Insights gained from dissolved noble gases. *Applied Geochemistry*, 109, 104395. DOI: 10.1016/j.apgeochem.2019.104395

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

Kreuzer, A. M., von Rohden, C., Friedrich, R., Chen, Z., Shi, J., Hajdas, I., ... & Aeschbach-Hertig, W. (2009). A record of temperature and monsoon intensity over the past 40 kyr from groundwater in the North China Plain. *Chemical Geology*, 259(3-4), 168-180. DOI: 10.1016/j.chemgeo.2008.11.001

- Kulongoski, J. T., Hilton, D. R., & Selaolo, E. T. (2004). Climate variability in the Botswana Kalahari from the late Pleistocene to the present day. *Geophysical Research Letters*, 31(10). DOI: 10.1029/2003GL019238
- Kulongoski, J. T., Hilton, D. R., Izbicki, J. A., & Belitz, K. (2009). Evidence for prolonged El Nino-like conditions in the Pacific during the Late Pleistocene: a 43 ka noble gas record from California groundwaters. *Quaternary Science Reviews*, 28(23-24), 2465-2473. DOI: 10.1016/j.quascirev.2009.05.008
- Saltel, M., Rebeix, R., Thomas, B., Franceschi, M., Lavielle, B., & Bertran, P. (2019). Paleoclimate variations and impact on groundwater recharge in multi-layer aquifer systems using a multi-tracer approach (northern Aquitaine basin, France). *Hydrogeology journal*, 27(4), 1439-1457. DOI: 10.1007/s10040-019-01944-x
- Stute, M., & Deak, J. (1989). Environmental isotope study (^{14}C , ^{13}C , ^{18}O , D, noble gases) on deep groundwater circulation systems in Hungary with reference to paleoclimate. *Radiocarbon*, 31(3), 902-918. DOI: 10.1017/S0033822200012522
- Seltzer, A. M., Stute, M., Morgenstern, U., Stewart, M. K., & Schaefer, J. M. (2015). Mean annual temperature in New Zealand during the last glacial maximum derived from dissolved noble gases in groundwater. *Earth and planetary science letters*, 431, 206-216. DOI: 10.1016/j.epsl.2015.09.032
- Seltzer, A. M., Ng, J., Danskin, W. R., Kulongoski, J. T., Gannon, R. S., Stute, M., & Severinghaus, J. P. (2019). Deglacial water-table decline in Southern California recorded by noble gas isotopes. *Nature communications*, 10(1), 5739. DOI: 10.1038/s41467-019-13693-2
- Seltzer, A. M., Tyne, R. L., Musan, I., Langman, J. B., Amaya, D. J., Karnauskas, K. B., ... & Bekaert, D. V. (2025). Past aquifer responses to climate recorded by fossil groundwater. *Science Advances*, 11(24), eadu7812. DOI: 10.1126/sciadv.adu7812
- Stute, M., & Talma, A. S. (1998). Glacial temperatures and moisture transport regimes reconstructed from noble gases and $\delta^{18}\text{O}$, Stampriet aquifer, Namibia. In *Isotope techniques in the study of environmental change* (pp. 307-318). IAEA proceedings.
- Trabelsi, R., Matsumoto, T., Zouari, K., Trabelsi, M., & Kumar, B. (2020). Investigation of paleoclimate signatures in Sfax deep groundwater (Southeastern Tunisia) using environmental isotopes and noble gases. *Quaternary International*, 547, 208-219. DOI: 10.1016/j.quaint.2019.04.001
- Túri, M., Saadi, R., Marah, H., Temovski, M., Molnár, M., & Palcsu, L. (2020). Paleotemperature reconstruction using environmental isotopes and noble gases in groundwater in Morocco. *Hydrogeology Journal*, 28(3), 973-986. DOI: 10.1007/s10040-020-02121-1
- Varsányi, I., Palcsu, L., & Kovács, L. Ó. (2011). Groundwater flow system as an archive of palaeotemperature: Noble gas, radiocarbon, stable isotope and geochemical study in the Pannonian Basin, Hungary. *Applied Geochemistry*, 26(1), 91-104. DOI: 10.1016/j.apgeochem.2010.11.006
- Walraevens, K., Fernández-Lagunas, A., Blaser, P., Aeschbach, W., Vandenbohede, A., & Van Camp, M. (2021). Understanding the mechanisms of groundwater recharge and flow in periglacial environments: New insights from the Ledo-Paniselian aquifer in Belgium. *Journal of Contaminant Hydrology*, 241, 103819. DOI: 10.1016/j.jconhyd.2021.103819

Wang, H., Mao, X., & Feng, L. (2015). Evidence of groundwater degassing in a deep confined aquifer: noble gas concentrations with hydrogen, oxygen and carbon isotope data. *Environmental Earth Sciences*, 74(5), 4439-4451. DOI: 10.1007/s12665-015-4482-8

Weyhenmeyer, C. E., Burns, S. J., Waber, H. N., Aeschbach-Hertig, W., Kipfer, R., Loosli, H. H., & Matter, A. (2000). Cool glacial temperatures and changes in moisture source recorded in Oman groundwaters. *Science*, 287(5454), 842-845. DOI: 10.1126/science.287.5454.842

Wieser, M., Aeschbach-Hertig, W., Schneider, T., Deshpande, R. D., & Gupta, S. K. (2011). A temperature and monsoon record derived from environmental tracers in the groundwater of northwest India. In *Isotopes in Hydrology, Marine Ecosystems and Climate Change Studies*, vol. I (pp. 7–14). Vienna, Austria: International Atomic Energy Agency. IAEA proceedings

Winter, T., Aeschbach, W., & Einsiedl, F. (2024). Reconstruction of the pleistocene paleoclimate from deep groundwater in southern germany from noble gas temperatures linked with organic radiocarbon dating. *Water Resources Research*, 60(1), e2023WR035644. DOI: 10.1029/2023WR035644

Zhu, C., & Kipfer, R. (2010). Noble gas signatures of high recharge pulses and migrating jet stream in the late Pleistocene over Black Mesa, Arizona, United States. *Geology*, 38(1), 83-86. DOI: 10.1130/G30369.1

B) Supplementary Figures (D-excess vs. T variations)

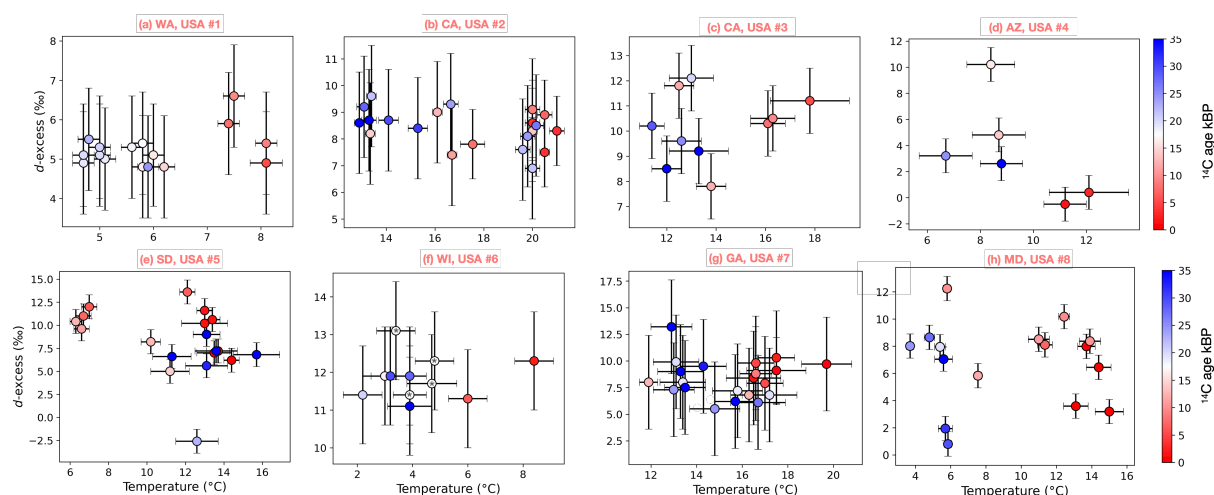


Figure S1: D-excess–Temperature (NGT) reconstructions from USA fossil groundwaters. Marker colors refer to ^{14}C ages, with blue shades representing the last glacial period. Data without available ^{14}C ages are marked with an asterisk. Numbers given as # correspond to site locations given on **Figure 1**. Reported uncertainties are 1 standard deviation.

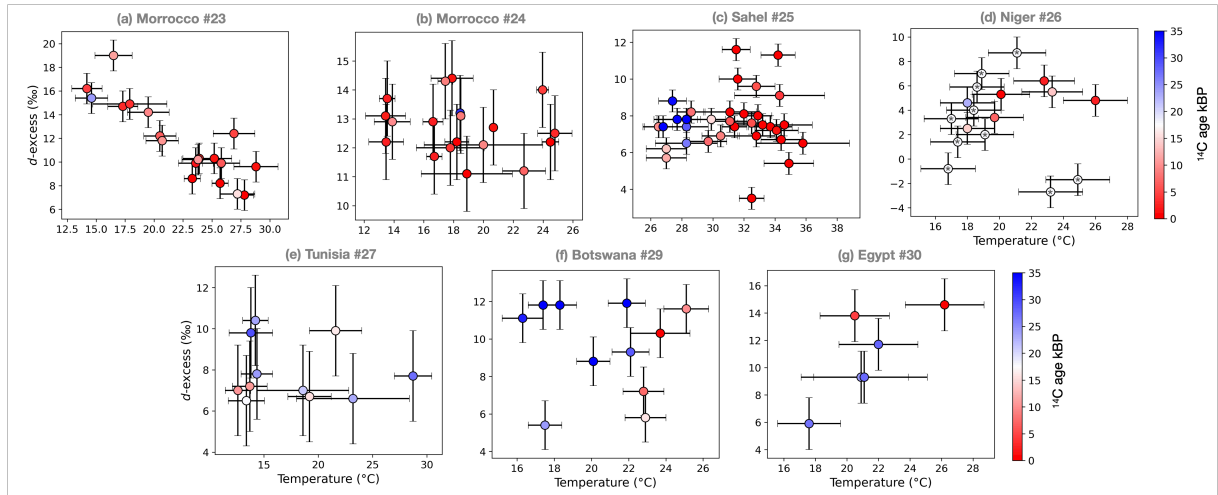


Figure S2: D-excess–Temperature (NGT) reconstructions from fossil groundwaters in Africa. Marker colors refer to ^{14}C ages, with blue shades representing the last glacial period. Data without available ^{14}C ages are marked with an asterisk. Numbers given as # correspond to site locations given on **Figure 1**. Reported uncertainties are 1 standard deviation.

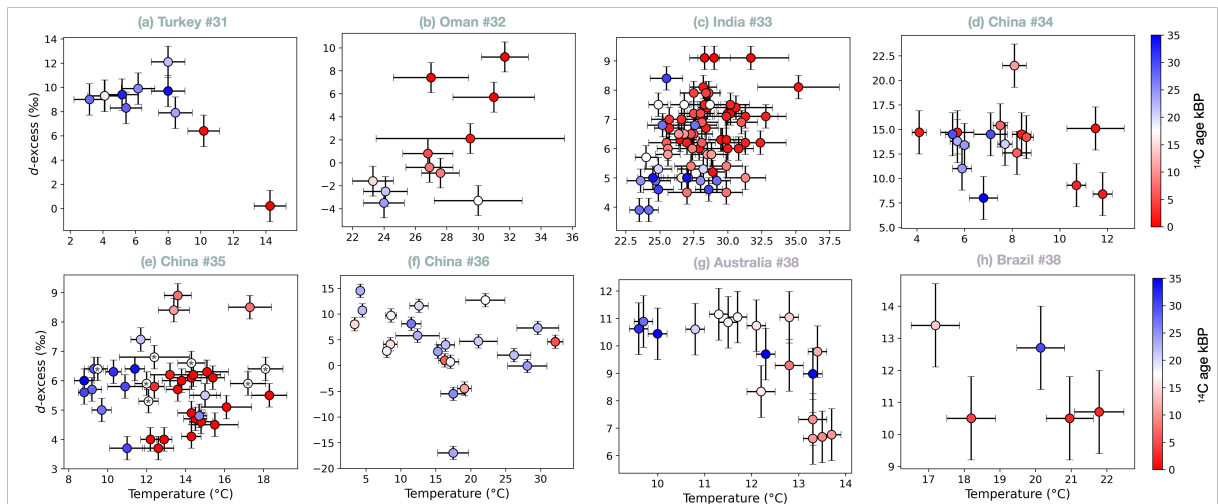


Figure S3: D-excess–Temperature (NGT) reconstructions from fossil groundwaters in Asia, Australia and Brazil. Marker colors refer to ^{14}C ages, with blue shades representing the last glacial period. Data without available ^{14}C ages are marked with an asterisk. Numbers given as # correspond to site locations given on **Figure 1**. Reported uncertainties are 1 standard deviation.