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Persistent influence of the North Atlantic hydrography on central European winter temperature during the last 9000 years

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[1] A prominent feature of the N. Atlantic's Holocene climate is a series of centennial and millennial shifts in ocean surface hydrography (Bond et al., 2001; Oppo et al., 2003). Here, we compare a climate reconstruction from the Central Alps for the last 9,000 years derived from the oxygen isotope record in stalagmites with the percentage of hematite-stained-grains in N. Atlantic sediments, an indicator for the proportion of ice-bearing surface water from north of Iceland. The excellent match between the two curves proves that meteorological conditions in the Alpine region responded synchronously to changes in the hydrography of the N. Atlantic during winter. In addition, the speleothem record suggests significant multi centennial and millennial variability of N. European winters throughout the past 9,000 years that might have been incompletely recorded in tree-ring archives. **Citation:** Mangini, A., P. Verdes, C. Spötl, D. Scholz, N. Vollweiler, and B. Kromer (2007), Persistent influence of the North Atlantic hydrography on central European winter temperature during the last 9000 years, *Geophys. Res. Lett.*, *34*, L02704, doi:10.1029/2006GL028600.

1. Introduction

[2] The data base of proxy information from N. Atlantic sediments contains evidence of repeated large and regionally extensive changes in atmospheric and oceanic temperatures throughout the Holocene. From the percentages of hematite-stained-grains (HSG) in N. Atlantic sediments, a proxy for the amount of ice rafted debris, and their correlation to centennial and millennial cycles of both atmospheric ^{14}C and of the ^{10}Be-flux in the Greenland ice cores during the Holocene, *Bond et al.* [2001] concluded that the N. Atlantic hydrography was influenced by variations in the solar output through the entire Holocene. A correlation between the amount of winter precipitation and the intensity of the Sun during the late Holocene was also inferred from the correlation between the degree of kinetic enrichment of ^{18}O in stalagmites from N. Germany and $\Delta^{14}C$ [*Niggemann et al.*, 2003a, 2003b]. But despite a growing number of data pointing at a solar influence on Holocene climate, the mechanisms that govern the spatial and temporal patterns of variability of N. Hemisphere climate are not well understood [*Bard and Frank*, 2006]. The decadal and centennial ^{14}C cycles may be precisely related to measured and reconstructed cycles of the variability of the intensity of the sun during the last centuries. Atmospheric ^{14}C and ^{10}Be concentrations derived from measurements in ice cores covary during much of the Holocene and are generally ascribed to solar changes. However, the variations of atmospheric ^{14}C could as well be a response to variable North Atlantic Deep Water production [*Broecker*, 2004; *Hughen et al.*, 1998; *Oppo et al.*, 2003]. During periods of weaker deep water formation atmospheric ^{14}C would increase until ocean mixing starts again. For example, during the Younger Dryas atmospheric ^{14}C climbed by 5% in 200 years [*Broecker*, 2004; *Hughen et al.*, 1998].

[3] A large uncertainty also remains in the proxy estimates of mean annual N. Hemisphere temperature during the Holocene, particularly during the so called Medieval Warm Period (MWP) and the subsequent Little Ice age [*Bard and Frank*, 2006; *Broecker*, 2001]. For example, the centennial to millennial cycles of HSG in the N. Atlantic are, if at all, only weakly reproduced in the reconstruction of N.H. temperature by multi proxy stacks of the last millennium and the last 2,000 years [*Mann and Jones*, 2003]. This question was recently addressed by Moberg et al. [*Moberg et al.*, 2005], who reconstructed a larger variability of N. Hemisphere temperatures for the past 2,000 years after separating high and low resolution archives. They concluded that the low resolution archives show larger multi-centennial variability than most previously published multi-proxy reconstructions because the low frequency curve agrees better with the MWP temperatures reconstructed from borehole measurements in Greenland and with temperatures obtained with a general circulation model than with reconstructions from tree-ring stacks. This conclusion is supported by *von Storch et al.* [2004], who suggested that the centennial variability of N. Hemisphere temperature is probably underestimated by regression-based methods and that past variations may have been at least a factor of two larger than indicated by empirical reconstructions. Recently, a precisely dated oxygen isotope signal of a speleothem from Spannagel Cave in the Central Alps was converted into a temperature record for the last 2000 yr [*Mangini et al.*, 2005]. This record shows (i) the occurrence of several periods lasting 20–50 yr during the MWP with temperatures higher than the mean, (ii) that the temperature compared best to Luterbacher's et al. reconstruction of the winter temperature in the Alps [*Luterbacher et al.*, 2001], and (iii) that the reconstructed temperature is highly correlated to $\Delta^{14}C$ underlining the important role of solar forcing as a driver for N. Hemisphere climate during the last two millennia. The amplitude of the temperature variations in Spannagel, with an estimated range of 2.7 °C, largely exceeds the temperature reconstructions based on multi proxy record stacks as well as those from low resolution archives [*Mann et al.*, 1998, 1999; *Mann and Jones*, 2003].

[4] One could argue that the larger temperature variability in Spannagel represents local conditions in the Central Alps,

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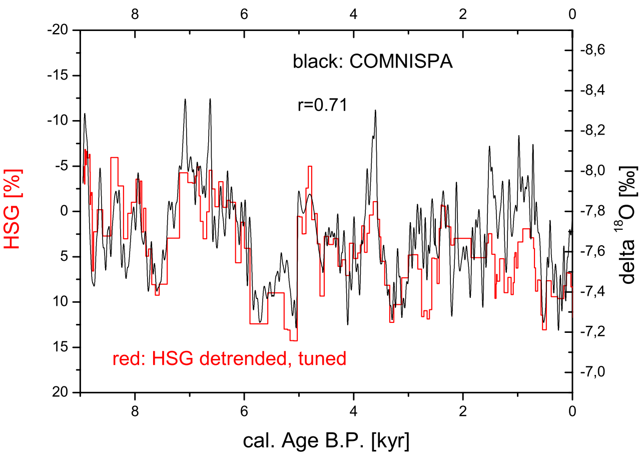

Figure 1. The combined oxygen isotope signal from Spannagel covering the past 9,000 years (black) together with the HSG curve from core V29-191 (red, reversed scale). The HSG curve from sediments in the N. Atlantic has been discussed earlier [*Bond et al.*, 2001]. For better comparison with COMNISPA, the HSG curve was detrended (−13%/9,000 yr) and tuned to the COMNISPA curve applying the program AnalySeries1.1 [*Paillard et al.*, 1996]. Tuning yields a correlation coefficient of r = 0.71, which is comparably high for geological data. The untuned curves are shown in auxiliary Figure S1[1]. The tuning of the peaks was performed within the range allowed by the uncertainty of the ^{14}C ages of the HSG record [*Bond et al.*, 2001] (auxiliary Figure S2).

which need not to be relevant for the N. Hemisphere mean. Recently, we have analyzed two further speleothems from this cave, sampled at close distance from stalagmite SPA 12, and by overlapping the dated records we built a composite curve (COMNISPA) that delivers a complete isotope record over the last 9,000 years [*Vollweiler et al.*, 2006]. Here we compare the COMNISPA curve with the HSG record from the N. Atlantic [*Bond et al.*, 2001]. The excellent match between the curves obtained from these two independent data sets gives evidence that the δ^{18}O signal recorded in Spannagel cave reflects the intensity of the warm N. Atlantic drift, disproving the assumption that the Spannagel isotope record is merely a local phenomenon. Furthermore, the very good age control of COMNISPA allows to test if the millennial cycles of atmospheric ^{14}C are a response to North Atlantic Deep Water production [*Oppo et al.*, 2003] or if they should be ascribed to solar variability.

2. Comparison of COMNISPA With the North Atlantic Record

[5] The data base for the COMNISPA curve are three Holocene stalagmites (SPA 12, SPA 128 and SPA 70) taken in Spannagel Cave within a distance of 50 m. The combined curve was acquired by extending the isotope record of SPA 12 to the interval from 2,000 yr to 5,000 yr and by shifting the baseline of the δ^{18}O values of the two new stalagmites (SPA 128 and SPA 70) to overlap the values of SPA 12 [*Mangini et al.*, 2005] in the interval between 2,000 and 5,000 years. The procedure is described in detail elsewhere [*Vollweiler et al.*, 2006]. Applying the calibration curve derived for SPA 12 [*Mangini et al.*, 2005], δ^{18}O of COMNISPA suggests temperatures between 0°C and +3.2°C during the last 9,000 years. However, because the isotopic composition of precipitation might have changed throughout the last 9,000 years, we refer to the δ^{18}O of COMNISPA in [*Vollweiler et al.*, 2006] as a meteorological record. First we compare COMNISPA with the HSG record from N. Atlantic sediments in Figure 1. The comparison is performed after detrending the HSG curve with a linear function that accounts for a late Holocene warming of the N. Atlantic current, especially during the last 6 kyr [*Moros et al.*, 2006]. Both curves show a very good agreement. This proves that the intensity of the N. Atlantic current controlled the isotope composition of precipitation in the Alps throughout the Holocene. Lower percentages of HSG in N. Atlantic sediments correspond to lighter isotopic composition of precipitation in the Central Alps, and vice versa. Our explanation for this relationship is that during periods of milder winter conditions in the N. Atlantic, Spannagel receives more winter precipitation from northern trajectories, which are lighter than those from the south (average values for precipitation in Stuttgart: −8.1‰, in Genoa: −5.6‰) [*International Atomic Energy Agency*, 1981; *Mangini et al.*, 2005]. The relationship between δ^{18}O of precipitation and temperature is based on the meteorological observation that NAO^{+} type conditions in winter favor northern trajectories of precipitation together with warmer

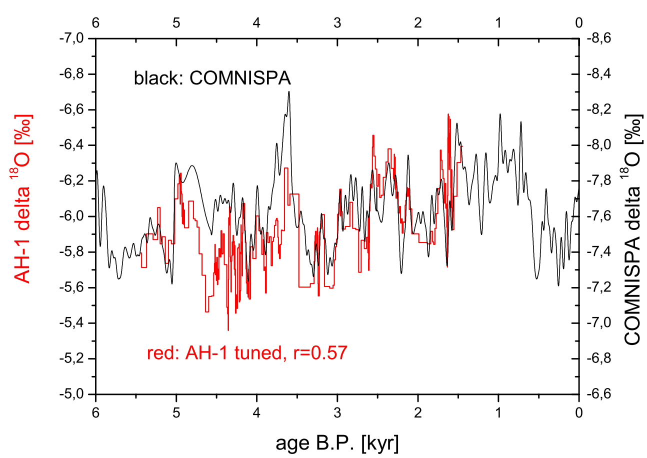

Figure 2. Comparison of the δ^{18}O in stalagmite AH-1 from Northern Germany with COMNISPA delivers an independent test for the ability to date central European climate variability with COMNISPA. The agreement of the position of the extrema in COMNISPA (reflecting the variable amount of precipitation from southern and northern trajectories), respectively, with those in stalagmite AH-1 (reflecting the variable intensity of winter precipitation in Northern Germany), confirms that a larger contribution of southern precipitation in the Alps was synchronous with colder and drier winters in central Europe. Both curves depict a warming trend since 6 kyr. The correlation coefficient of the untuned curves is r = 0.45.

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl028600. Other auxiliary material files are in the HTML.

winters in central Europe, and vice versa for NAO$^-$ type conditions with a larger southerly component and more rigid winters [*Mangini et al.*, 2005].

3. Comparison of COMNISPA With Record of Stalagmite AH-1

[6] Due to the supra-regional character of the meteorology, we expect the COMNISPA signal to agree with other winter-based precipitation records from central and northern Europe. We validate this hypothesis using the δ^{18}O record of the Th/U dated stalagmite AH-1 from N. Germany, that grew between 1.5 kyr and 5.5 kyr B.P., where cycles of kinetic enrichment of isotopes were ascribed to reduced ground water recharge during drier and colder winters and where a correlation to the HSG curve has already been observed [*Niggemann et al.*, 2003a, 2003b] (Figure 2).

4. Discussion

[7] COMNISPA suggests large climate variations throughout the last 9,000 years and based on the arguments above, it can reasonably be assumed to reflect non-local conditions. Two questions then remain to be answered: First, why COMNISPA from the Central Alps displays larger variations for the last 2,000 years than the multi proxy record in Europe, which is mainly derived from tree-ring data [*Büntgen et al.*, 2005; *Mann and Jones*, 2003]. The most probable answer is that tree-rings rather record the climate conditions during spring and summer whereas both the HSG and COMNISPA curves mirror winter-like conditions, which are only poorly recorded in tree-rings. The comparison thus infers stronger seasonality. There are several indications for a stronger winter than summer variability during the Holocene: (i) the good correlation observed between the Spannagel record and Luterbacher's winter temperature reconstruction for the Alps during the last 500 years [*Mangini et al.*, 2005]. The winter-based explanation is also supported by instrumental and documentary proxy data back to 1500 AD, which suggest that the amplitude of spring temperature variations at decadal and multi-decadal scales doubles that of autumn and is most expressed in northeastern Europe [*Xoplaki et al.*, 2005]. (ii) The sea salt sodium flux and the chemical records from the Greenland Ice Sheet Project 2 (GISP 2) indicate winter-like conditions during deposition of high contents of HSG in the sediments [*O'Brien et al.*, 1995; *Oppo et al.*, 2003]. Finally, COMNISPA and the AH-1 stalagmite show a long-term warming trend during the last 6 kyr, in contrast to records from the N. Atlantic and N. Hemisphere, which show a decrease of temperature following the decreasing N. Hemisphere summer insolation during the Holocene [*Andersen et al.*, 2004; *Berger et al.*, 1998; *Fleitmann et al.*, 2003]. Thus, in summary, the record from Spannagel suggests significant multi centennial and millennial variability of N. European winter climate throughout the past 9,000 years. Our results further imply that multi proxy reconstructions from Europe, which rely heavily on tree-ring records, registering mainly summer signals, might have missed this winter variability. This explanation is corroborated by a recent spectral analysis of the variability of tree ring parameters of riverine Oaks from the Rhine, Danube and Main, in time intervals centered at 800 BC, 2,800 BC and 6,200 BC which show only a very small variability and insignificant correlation to solar parameters [*Latuske*, 2006]. These results support Moberg's et al. conclusions derived from high and low frequency records and recommend that future work should put more emphasis on the seasonal imprint in the records.

[8] The second question concerns the reason for the observed variability of Holocene N. Atlantic climate, and its relationship to surface forcing and deep water production. The extremely high correlation between the band-pass filtered COMNISPA and the ^{14}C records (see supplementary material) with correlation coefficients between 0.8 and 1, reinforces Bond's observations and suggests either a persistent solar influence on N. Atlantic climate during the Holocene [*Bond et al.*, 2001] or a strong impact of ocean circulation on the atmospheric ^{14}C concentration [*Broecker*, 2000, 2004]. As demonstrated in the supplementary material, COMNISPA shows the best agreement with the ^{14}C production curve after shifting the ^{14}C scale by 40 to 150 years towards younger ages on three analyzed bands. This phase lag lies in the range of 60 – 100 years estimated for Δ^{14}C using a box-model for a change in solar production [*Siegenthaler et al.*, 1980]. Together with the absence of large ventilation changes as deduced from Pa/Th in deep sea sediments [*McManus et al.*, 2004], this adds a further argument that the variations of atmospheric ^{14}C on the millennial scale are more probably a response to solar changes than to millennial changes of deep water production.

5. Conclusions

[9] In summary, the COMNISPA curve reveals that millennial cycles of colder and drier winters in N. Europe coincide with colder N. Atlantic winters. Thus, it serves as a very valuable, well dated archive of central European climate to which other, less precisely dated, N. Hemispheric geological archives may be tuned. Though not giving a final answer, it delivers additional evidence that the variability of atmospheric ^{14}C on the millennial scale is of solar origin.

[10] **Acknowledgments.** We dedicate this manuscript to the late Gerard Bond, whom we thank for his fantastic pioneering work on N. Atlantic sediments. We thank M. Wimmer and R. Eichstädter for their work in the stable isotope and TIMS laboratories. The funding was supplied by the DEKLIM program, FG 668 of the DFG (DAPHNE), and START Y122-GEO (FWF). P.V. has been supported by the Alexander-von-Humboldt Foundation.

References

Andersen, C., N. Koç, A. Jennings, and J. T. Andrews (2004), Nonuniform response of the major surface currents in the Nordic Seas to insolation forcing: Implications for the Holocene climate variability, *Paleoceanography*, *19*, PA2003, doi:10.1029/2002PA000873.

Bard, E., and M. Frank (2006), Climate change and solar variability: What's new under the Sun?, *Earth Planet. Sci. Lett.*, *248*, 1–14.

Berger, A., M. F. Loutre, and H. Gallée (1998), Sensitivity of the LLN climate model to the astronomical and CO_2 forcings over the last 200 ky, *Clim. Dyn.*, *14*, 615–629.

Bond, G., B. Kromer, J. Beer, R. Muscheler, M. N. Evans, W. Showers, S. Hoffmann, R. Lotti-Bond, I. Hajdas, and G. Bonani (2001), Persistent solar influence on North Atlantic climate during the Holocene, *Science*, *294*, 2130–2136.

Broecker, W. S. (2000), Was a change in thermohaline circulation responsible for the Little Ice Age?, *Proc. Natl. Acad. Sci. U. S. A.*, *97*, 1339–1342, doi:10.1073/pnas.97.4.1339.

Broecker, W. S. (2001), Was the Medieval Warm Period global?, *Science*, *291*, 1497–1499.

Broecker, W. S. (2004), *The Role of the Ocean in Climate Yesterday, Today and Tomorrow*, 176 pp., Lamont-Doherty Earth Obs., Palisades, N. Y.

Büntgen, U., J. Esper, D. C. Frank, K. Nicolussi, and M. Schmidhalter (2005), A 1052-year tree-ring proxy for Alpine summer temperatures, *Clim. Dyn.*, *25*, 141–153.

Fleitmann, D., S. J. Burns, M. Mudelsee, U. Neff, J. Kramers, A. Mangini, and A. Matter (2003), Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman, *Science*, *300*, 1737–1739.

Hughen, K. A., J. T. Overpeck, S. J. Lehman, M. Kashgarian, J. Southon, L. C. Peterson, R. Alley, and D. M. Sigman (1998), Deglacial changes in ocean circulation from an extended radiocarbon calibration, *Nature*, *391*, 65–68.

International Atomic Energy Agency (Ed.) (1981), *Statistical Treatment of Environmental Isotope Data in Precipitation*, 255 pp., Vienna.

Latuske, N. (2006), Solar variability and climatic variations on time scales from decades to centuries in the Holocene, Ph. D. thesis, Univ. of Heidelberg, Heidelberg, Germany.

Luterbacher, J., et al. (2001), Extending North Atlantic oscillation reconstructions back to 1500, *Atmos. Sci. Lett.*, *2*(1), 114–124.

Mangini, A., C. Spötl, and P. Verdes (2005), Reconstruction of temperature in the Central Alps during the past 2,000 years from a δ^{18}O stalagmite record, *Earth Planet. Sci. Lett.*, *235*, 741–751.

Mann, M. E., and P. D. Jones (2003), Global surface temperatures over the past two millenia, *Geophys. Res. Lett.*, *30*(15), 1820, doi:10.1029/2003GL017814.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1998), Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, *392*, 779–787.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1999), Northern Hemisphere temperatures during the past millenium: Inferences, uncertainties and limitations, *Geophys. Res. Lett.*, *26*, 759–762.

McManus, J. F., R. Francois, J.-M. Gheradi, L. D. Keigwin, and S. Brown-Leger (2004), Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes, *Nature*, *428*, 834–837.

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

Moros, M., J. T. Andrews, D. D. Eberl, and E. Jansen (2006), Holocene history of drift ice in the northern North Atlantic: Evidence for different spatial and temporal modes, *Paleoceanography*, *21*, PA2017, doi:10.1029/2005PA001214.

Niggemann, S., A. Mangini, M. Mudelsee, D. K. Richter, and G. Wurth (2003a), Sub-Milankovitch climatic cycles in Holocene stalagmites from Sauerland, Germany, *Earth Planet. Sci. Lett.*, *216*, 539–547.

Niggemann, S., A. Mangini, D. K. Richter, and G. Wurth (2003b), A paleoclimate record of the last 17,600 years in stalagmites from the B7-cave, Sauerland, Germany, *Quat. Sci. Rev.*, *22*, 555–567.

O'Brien, S. R., P. A. Mayewski, L. D. Meeker, D. A. Meese, M. S. Twickler, and S. I. Whitlow (1995), Complexity of Holocene climate as reconstructed from a Greenland ice core, *Science*, *270*, 1962–1964.

Oppo, D. W., J. F. McManus, and J. L. Cullen (2003), Deepwater variability in the Holocene epoch, *Nature*, *422*, 277–278.

Paillard, D., L. Labeyrie, and P. Yiou (1996), Macintosh program performs time-series analysis, *Eos Trans. AGU*, *77*, 379.

Siegenthaler, U., M. Heimann, and H. Oeschger (1980), ^{14}C-variations caused by changes in the global carbon cycle, *Radiocarbon*, *22*, 177–191.

Vollweiler, N., D. Scholz, C. Mühlinghaus, A. Mangini, and C. Spötl (2006), A precisely dated climate record for the last 9 kyr from three high alpine stalagmites, Spannagel Cave, Austria, *Geophys. Res. Lett.*, *33*, L20703, doi:10.1029/2006GL027662.

von Storch, H., E. Zorita, J. M. Jones, Y. Dimitriev, F. Gonzalez-Rouco, and S. F. B. Tett (2004), Reconstructing past climate from noisy data, *Science*, *306*, 679–682, doi:10.1126/science.1096109.

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 millenium, *Geophys. Res. Lett.*, *32*, L15713, doi:10.1029/2005GL023424.

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