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Multi-speleothem record reveals tightly coupled climate between central Europe and Greenland during Marine Isotope Stage 3

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Notes

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ABSTRACT

The last glacial period was punctuated by abrupt, millennial-scale climate changes that contain useful information about the rate at which the climate can change from one state to another. Improvement in our knowledge of the temporal and spatial character of these rapid climate changes is important for understanding their causes and effects, and provides essential observational information for modeling studies. Here, we expand the coverage of terrestrial climate records during the last glacial period, and present a series of high-resolution stalagmite records from a cave in the northern Alps (central Europe) covering parts of the period 65–35 ka (before A.D. 1950). The climatic pattern revealed by the stalagmite temperature-controlled $\delta^{18}O$ profiles strongly resembles that of Greenland ice cores on millennial scales, and also corresponds to the detail of decadal-scale cooling events within interstadials. This demonstrates for the first time a strong climatic similarity and/or coupling between the two regions during Marine Isotope Stage 3 (MIS 3). Furthermore, an overall long-term agreement between the northern European Alps stalagmite chronology (NALPS) presented here, and the Greenland Ice Core Chronology 2005 modelext (GICC05modelext), suggests that the central value of the Greenland chronology may be slightly too young, possibly as a result of an undercounting of layers in a younger section of the core, and that the uncertainty on the Greenland chronology may be overestimated. The synchronicity displayed here between Greenland and central Europe, especially during the period 65–49 ka, is crucial for our understanding of climate-system teleconnections that existed during the last glacial period, and will be important for developing mechanisms of abrupt climate events.

INTRODUCTION

The climate of the last glacial period, and in particular Marine Isotope Stage 3 (MIS 3, ca. 60–29 ka [before A.D. 1950]), was characterized by large-amplitude, millennial-scale cycles of abrupt temperature rise followed by gradual cooling, thus providing an ideal opportunity to study the character and chronology of naturally forced rapid climate change. The expression of these so-called Dansgaard-Oeschger (DO) cycles was first recognized in Greenland ice cores (Johnsen et al., 1992; Dansgaard et al., 1993), but has since been identified in both hemispheres (e.g., Clement and Peterson, 2008), and in marine and terrestrial records (e.g., Voelker et al., 2002). However, the scarcity of precisely dated, high-resolution terrestrial proxy records has meant that the onset, duration and sequence of these changes remain poorly understood. We reconstruct decadal- to millennial-scale climate changes from the stable-isotope composition of stalagmites deposited during MIS 3 in the northern European Alps (NALPS). These new data extend the previous NALPS speleothem record (120–60 ka; Boch et al., 2011).

CAVE SITE AND PRECIPITATION CHARACTERISTICS

The European Alps, herein referred to as the Alps, are a climatically sensitive region where the amplitude of temperature change was twice the mean Northern Hemisphere amplitude during the past century (Auer et al., 2007). Today, the Alps are situated in the direct path of the Westerlies, in a transition zone between the Azores high and Icelandic low, between oceanic and continental climates, and between Mediterranean and North Atlantic climates (Wanner et al., 1997). Processes operating over the North Atlantic and its sea-ice system, in particular, have an effect on northern Alpine climate (Wanner et al., 1997), with ~44% and ~5% of mean annual precipitation originating in the North Atlantic and Arctic, respectively, compared to ~17% from the Mediterranean and ~20% from land sources (Sodemann and Zubler, 2010). Sites located to the north of the main Alpine ridge thus share a common origin with air masses precipitating in Greenland. Furthermore, similar to Greenland, the $\delta^{18}O$ composition of precipitation has been shown to be highly correlated to changes in air temperature (Kaiser et al., 2002), thus providing an ideal opportunity to investigate climatic connections between Greenland and central Europe.

We analyzed four ~30-cm-long stalagmites (Höl-7, Höl-16, Höl-17, and Höl-18) from Hölloch cave situated on the northern rim of the Alps (47.38°N, 10.15°E) at an altitude of 1240–1438 m above sea level (asl) (see Figs. DR1 and DR2 in the GSA Data Repository[1]). The stalagmites were located in a stable environment (±0.2 °C) within 25 m of one another, and were identified by coring studies as being synchronously active during MIS 3. Similar to modern conditions, westerly atmospheric circulation dominated during MIS 3, and advection of moist air masses from the North Atlantic to the northern Alps resulted in increased precipitation following MIS 4 (Florineth and Schlüchter, 2000). Modeling results show that interstadials in particular were warmer and moister than stadials (Claussen et al., 2003), but that storm activity was higher during stadials (Renssen and Bogaart, 2003) as a result of movement of the storm track from a location over the Nordic Seas in warm phases, to over northwest Europe during cold phases (Rousseau et al., 2007).

ANALYTICAL METHODS

The ^{230}Th dates (n = 59, datum = A.D. 1950) (Table DR1) obtained using state-of-the-art multicollector inductively coupled plasma–mass spectrometry (Cheng et al., 2013) are in stratigraphic order within 2σ uncertainty. Powders were micro-milled at a resolution of 0.1–0.25 mm from the central axis of each stalagmite and analyzed for $\delta^{18}O$ (n = 4875). Confidence that isotopic equilibrium was closely maintained during deposition is given by remarkable replication of the stable-isotope profiles between stalagmites (Fig. DR3) (Dorale and Liu, 2009). We can thus be confident that the large amplitudes in $\delta^{18}O$ shifts (between −8‰ and −11‰) observed in all samples are the results of changes in the $\delta^{18}O$ of precipitation and air temperature, rather than kinetic or vadose-zone processes. The temporal resolution of the final modeled stable-isotope interval averages 4 yr (range of <1–70 yr) and covers 10 of 13 stadial–interstadial transitions, plus two precursor events during MIS 3 (Fig. 1A).

$^{230}Th/^{232}Th$ ratios are highly variable (activity [act] = 3–1449) (Table DR1), making accurate correction for contaminant ^{230}Th important. Ten $^{230}Th/^{238}U$-$^{232}Th/^{238}U$ isochrons were constructed

[1]GSA Data Repository item 2014361, supplementary information related to the field site, samples, methods, and age models, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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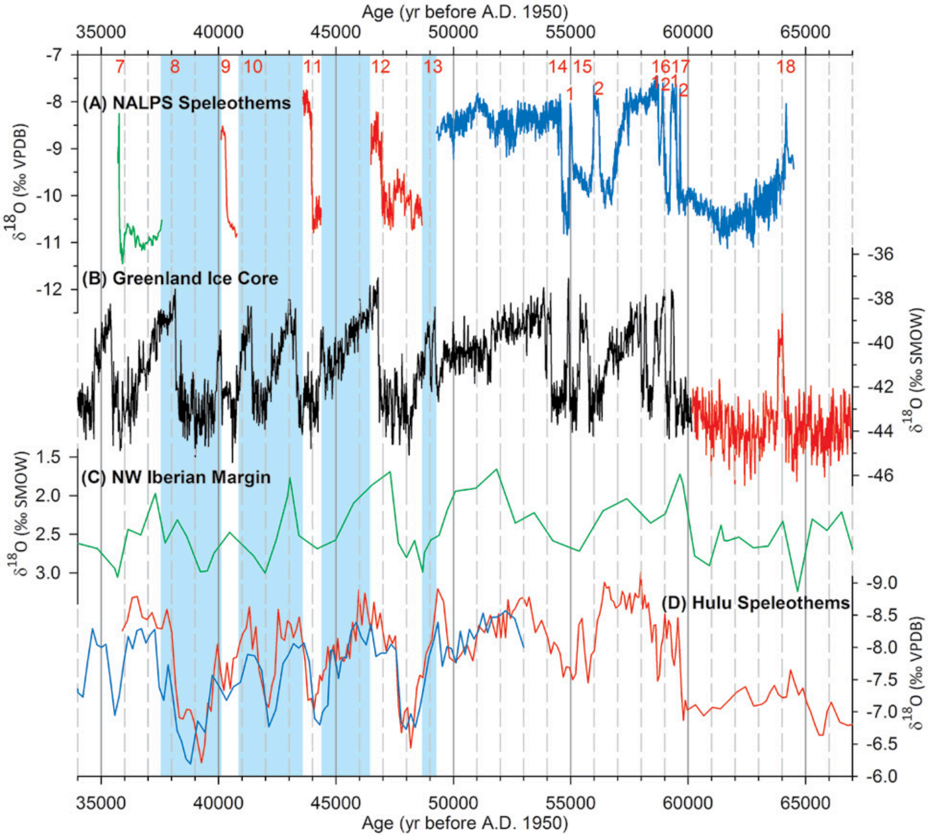

Figure 1. $\delta^{18}O$ variations between 67 and 34 ka. Red numbers (at top) denote Dansgaard-Oeschger (DO) events as defined in the Greenland ice cores (Rasmussen et al., 2014). Blue vertical bars indicate periods of speleothem growth cessation. A: Northern Alps (NALPS) speleothems (this study). Green: Höl-16–Höl-17composite; Red: Höl-7; Blue: Höl-7–Höl-16–Höl-17–Höl-18 composite. Höl—Hölloch cave. VPDB—Vienna Peedee belemnite. B: North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ on the Greenland Ice Core Chronology 2005 modelext time scale (GICC05modelext; Svensson et al., 2008; Wolff et al., 2010). SMOW—standard mean ocean water. C: Northwest Iberian Margin marine sediment core planktonic foraminifera $\delta^{18}O$ (MD99–2331; Sánchez Goñi et al., 2008). D: Chinese speleothems. Hulu Cave (Wang et al., 2001).

for both stadials and interstadials (Fig. DR4). $(^{230}Th/^{232}Th)_{(i)}$ (i is initial) remained unchanged within 2σ uncertainty between ca. 63 and 53 ka. However, between ca. 41 and 36 ka, $(^{230}Th/^{232}Th)_{(i)}$ was higher. We therefore employ a variable correction for detrital ^{230}Th derived from the weighted mean of the $(^{230}Th/^{232}Th)_{(i)}$ (Table DR2). For deposition between 48.7 and 35.7 ka, we use a $(^{230}Th/^{232}Th)_{act(i)}$ of 0.70 ± 0.35 (atomic ratio: 3.8 ± 1.9 ppm), and for deposition between 64.5 and 49.1 ka, 0.44 ± 0.22 (atomic ratio: 2.4 ± 1.2 ppm).

$\delta^{18}O$ was measured on a Thermo Fisher Finnigan Delta^{plus}XL isotope ratio mass spectrometer linked to a Gasbench II at the University of Innsbruck, Austria. Analytical precision is 0.08‰ (1σ). Hendy tests reveal minimal variation in $\delta^{18}O$ (typically 0.3‰) across 37 individual growth laminae (Fig. DR5). Where the samples show reproducible $\delta^{18}O$ shifts (Höl-16 and Höl-17 between ca. 37 and 35 ka, and all four samples between ca. 64 and 49 ka), single composite records were produced. This was achieved by identifying common features (tie-points) in each $\delta^{18}O$ profile, and transferring the depth scales of the other stalagmites onto that of Höl-16 (Figs. DR6 and DR7), or Höl-17 (Fig. DR9), using a cubic spline function. A three-point running mean was applied to the stacked $\delta^{18}O$ profile to produce composite isotope records (Figs. DR8 and DR9). Final age models were constructed using the StalAge Monte-Carlo simulation, and 95% confidence limits were calculated from the distribution of the simulated fits (Scholz and Hoffmann, 2011).

The onsets of DO events were defined in the same manner as the ice cores (Rasmussen et al., 2014); i.e., the first data point of the steep part that clearly deviates from the base level of the previous climate state (Fig. DR10). The end of each rapid climate transition was defined as the final data point of the steep part (Fig. DR10).

RESULTS

Speleothem growth occurred intermittently between 64.5 and 49.1 ka, 48.7 and 46.5 ka, 44.4 and 43.6 ka, 40.8 and 40.1 ka, and 37.6 and 35.7 ka (NALPS; Fig. 1A). Large-amplitude (~3‰) millennial-scale shifts in $\delta^{18}O$ are well expressed in the NALPS record, and mirror rapidly changing conditions in Northern Hemisphere climate archives. Higher $\delta^{18}O$ values in the NALPS stalagmites (reflecting warmer temperatures) correspond to higher temperatures in Greenland (Fig. 1B) (Svensson et al., 2008; Wolff et al., 2010), warmer sea-surface temperatures in the Northeast Atlantic Ocean (Fig. 1C) (Sánchez Goñi et al., 2008), as well as a strengthened summer Asian monsoon recorded in speleothems in China (Fig. 1D) (Wang et al., 2001).

DISCUSSION

Comparison with a Central Alps Record

$\delta^{18}O$ shifts in the NALPS record agree within 2σ uncertainty with shifts in $\delta^{18}O$ recorded in speleothems from Kleegruben cave (Spötl et al., 2006)(2165 m asl) in the central Alps (Fig. 2). Small chronological differences are likely due to the use of alternative age modeling methods, half-life values, slight differences

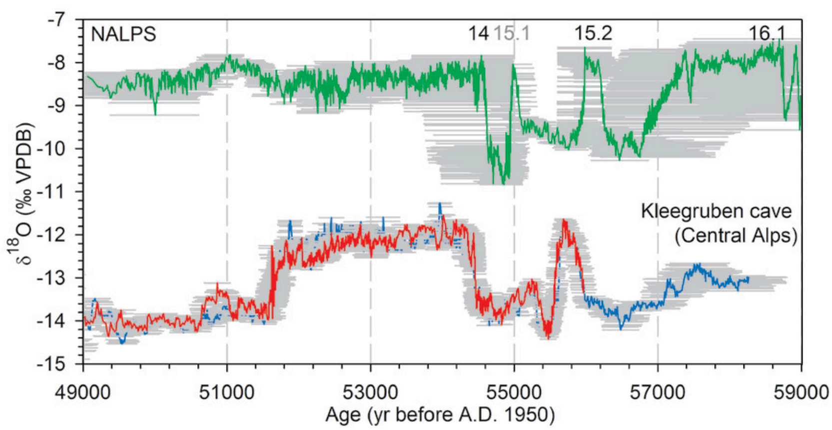

Figure 2. Comparison of $\delta^{18}O$ records from the northern Alps (NALPS) (this study) and Kleegruben cave (Spötl et al., 2006). Green represents NALPS; red and blue are two stalagmites from Kleegruben. Gray horizontal lines indicate 95% uncertainty on the respective age models. VPDB—Vienna Peedee belemnite.

in standardization, and analytical uncertainty. The timing of the transition into interstadial 14 was re-dated (Table DR3) at the same laboratory in which the ages for this NALPS study were produced in order to assess inter-laboratory differences; there was excellent agreement between the ages produced from the two different laboratories (Fig. DR11), thus enhancing confidence in the timing of the transition into interstadial 14 (Fig. 2).

By comparison to the NALPS record, the $\delta^{18}O$ record from Kleegruben is depleted by ~4‰ (reflecting the higher elevation and the location in the interior of the Alps), and event patterns differ slightly (reflecting the different moisture sources for the two regions). The greatest difference occurs at ca. 55 ka (interstadial 15.1) where $\delta^{18}O$ does not appear to reach full interstadial conditions at Kleegruben. Similarly, interstadial 15.1 appears to be absent from the Hulu monsoon record, or is blended into the long, ramped transition into interstadial 14 (Fig. 1D).

Chronology of Abrupt Climate Transitions

Remarkable similarities exist in the pattern of $\delta^{18}O$ shifts in the NALPS record and that of the North Greenland Ice Core Project (NGRIP) ice core on the Greenland Ice Core Chronology 2005 modelext time scale (GICC05modelext; Svensson et al., 2008; Wolff et al., 2010) (Figs. 1A and 1B). These analogous features so strongly resemble Greenland stadial-interstadial cycles and precursor events that it appears the climate of the high-elevation northern Alps was as responsive to DO forcing mechanisms as Greenland. The onset of 12 DO events (7, 9, 11, 12, 14, 15.1, 15.2, 16.1, 16.2, 17.1, 17.2, and 18; Rasmussen et al., 2014) are well preserved in the NALPS record as short sharp rises, reaching the highest $\delta^{18}O$ values at the beginning of the interstadial, followed by a gradual decrease throughout the interstadial-stadial to the point of the next sharp rise (Fig. 1A). The timing of the onset of these DO events consistently leads Greenland (Svensson et al., 2008; Wolff et al., 2010; Rasmussen et al., 2014) within the range of 118–767 yr (Fig. 3), which falls within the uncertainty of both chronologies. By comparison, specifically for the stadial-interstadial transitions considered here, the Hulu chronology also generally leads Greenland (by as much as 850 yr), with two nominal lags (up to 139 yr) (Fig. 3) (Wang et al., 2001), although defining the onset of abrupt climate transitions is less precise in the Hulu chronology because of the lower resolution of this version of the Hulu record. All three chronologies agree within quoted uncertainties.

Considering that the central value of the GICC05modelext chronology consistently lags the NALPS chronology, and generally lags the Hulu chronology, it is possible that absolute ice-core ages may be too young during MIS 3 as a result

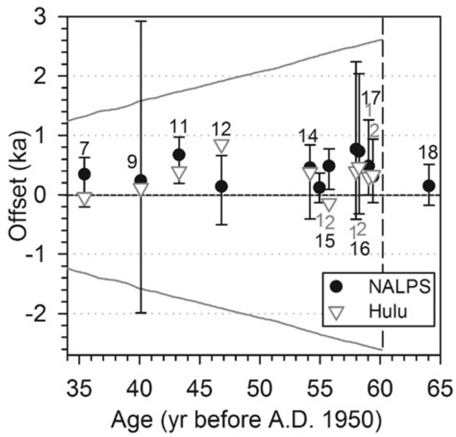

Figure 3. Difference in timing between the northern Alps (NALPS) (this study), Greenland (Svensson et al., 2008; Wolff et al., 2010), and Hulu, China (Wang et al., 2001) records for the onset of Dansgaard-Oeschger (DO) events. The age of the event in the Greenland Ice Core Chronology 2005 modelext (GICC05modelext) chronology is plotted along the *x*-axis, while the offsets with NALPS (filled circles) or Hulu (triangles) are on the *y*-axis. 95% uncertainty is given for the NALPS chronology, but is not available for each modeled age in the Hulu chronology. Positive values mean the onset of an event is older in the NALPS or Hulu chronology than in Greenland, and vice versa. The maximum counting error (MCE) of the GICC05modelext chronology (Svensson et al., 2008; Wolff et al., 2010) is shown as two solid gray lines. Dashed vertical line represents the end of the MCE. Numbers denote DO events.

of an undercounting of layers in a younger section of the core. However, when considering the timing of transitions in the NALPS chronology with the highest level of precision in the modeled ages, i.e., transitions into interstadials 15.1 (±0.5%) and 18 (+0.6, –0.5%), the lead before Greenland falls within the lower end of the range at 118 yr and 148 yr, respectively, thus showing a good agreement between the two absolute chronologies. This result is further supported by the more precise Kleegruben data showing that at interstadial 15.2, the NALPS record should sit toward the younger end of its uncertainty, and thus closer to the GICC05modelext chronology. In addition, given the overall long-term agreement in the pattern and timing of the NALPS and GICC05modelext chronologies, particularly in the interval DO14–18, it is possible that the uncertainty on the GICC05modelext chronology is overestimated.

Duration of Stadial-Interstadial Transitions

Over shorter intervals, such as the rapid transitions from stadials to interstadials (Fig. DR12), ice-core layer counting has excellent relative uncertainty. In the NGRIP GICC05modelext chronology (Svensson et al., 2008; Wolff et al., 2010), these rapid climate transitions vary in length on a 20 yr resolution from 20 to 100 yr. Although ^{230}Th ages of speleothems have much larger relative uncertainty than the ice cores over short durations, the NALPS chronology presented here suggests that rapid climate-change events in the high-elevation Northern Alps, and likely the wider central European area, occurred at roughly the same pace as in Greenland, with transitions ranging from 8 to 65 yr. The largest differences in the duration of transitions in the NALPS versus GICC05modelext chronology occur into interstadials 9 and 15.2 (Fig. DR12), and could be the product of sampling resolution.

Decadal-Scale Climatic Cooling Excursions

In detail, the NALPS $\delta^{18}O$ record displays decadal-scale climatic cooling excursions within interstadials, indicating a highly responsive high-elevation central European climate. Such shifts are very noticeable in the individual $\delta^{18}O$ profiles for each stalagmite (Fig. DR3), but unfortunately have become slightly dampened in the amalgamation of the composite record (Fig. 1). The shifts of up to 1‰ occur toward the start of interstadials 14, 16.1, and 17.1, as well as at the end of interstadial 16.1 (Figs. DR3 and DR10). The decadal-scale climatic cooling excursions at the beginning of interstadials are also present in Greenland (Fig. DR10). By contrast, the cooling event at the end of interstadial 16.1 is difficult to recognize in the Greenland record (Figs. DR3 and DR10F), but may be present at ca. 57 ka (Fig. 1). Furthermore, a mid-interstadial 14 cooling event in Greenland at 51.5 ka is difficult to identify in the NALPS record (Fig. DR10E) (Rasmussen et al.,2014), but may be present at ca. 51.8 ka. (Fig. 1). The NALPS record thus highlights a close coupling in temperature between high-elevation central Europe and Greenland not only on millennial time scales, but also at the decadal scale, when climatic cooling excursions occurred close to the beginning of an interstadial. Once the climate of the interstadials was established, any further short-term cooling events may have been restricted to one or the other region, indicating a possible occasional decoupling in temperature between the northern Alps and Greenland.

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