A high-resolution speleothem proxy record of the Late Glacial in the European Alps: extending the NALPS19 record until the beginning of the Holocene

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ABSTRACT: Previous research has shown that speleothems from the northern rim of the European Alps captured submillennial-scale climate change during the last glacial period with exceptional sensitivity and resolution, mimicking Greenland ice-core records. Here we extend this so-called NALPS19 record across the Late Glacial using two stalagmites which grew continuously into the Holocene. Both specimens show the same high-amplitude 818O signal as Greenland ice cores down to decadal resolution. The start of the warming at the onset of the equivalent of Greenland Interstadial (GI) GI-1e at 14.66 ± 0.18 ka agrees with the North Greenland Ice Core Project (NGRIP) (14.64 ± 0.28 ka) and comprised a temperature rise of about 5–6 °C. The transition from the equivalent of GI-1a into the equivalent of Greenland Stadial (GS) GS-1 (broadly equivalent to the Younger Dryas) commenced at 13.02 ± 0.13 ka which is consistent with NGRIP (12.80 ± 0.26 ka) within errors. The onset of the Holocene started at 11.78 ± 0.14 ka (11.65 ± 0.10 ka at NGRIP) and involved a warming of about 4–5 °C. In contrast to δ18O, δ13C values show no response to submillennial climate shifts due to strong rock-buffering and only record a long-term trend of soil development starting with the rapid warming at 14.7 ka.

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KEYWORDS: Alps; Late Glacial; rapid climate change; speleothems; Younger Dryas

Introduction

The European Alps are the cradle of Quaternary climate change research associated with pioneers including Giovanni Arduino and Louis Agassiz. Sedimentary archives in the foreland and partly also inside this mountain range preserve a fragmentary record of the waxing and waning of the Alpine glaciers on orbital timescales. Established by two other pioneers (Pencz & Brückner, 1909), this framework, although initially lacking an absolute chronology, has proven uniquely successful even after more than a century and has served as a reference for other formerly glaciated regions.

Modern palaeoclimate research has shown that the Alps are also a sensitive region for climate change on millennial down to decadal timescales. A milestone in this respect was the study of sediment cores from Ammersee, a lake in the northern foreland of the Alps, whose main catchment is located in the mountains on the rim of the Alps. Oxygen isotope data of benthic ostracods provide evidence of rapid temperature changes at the onset and end of the equivalent of Greenland Interstadial (GI) GI-1 as well as at the onset of the Holocene, including short-term coolings within GI-1 and during the so-called 8.2 ka event (von Grafenstein et al., 1999; ages in this paper are reported in ka (thousands of years) relative to the year AD 1950, unless otherwise noted). This pattern is highly reminiscent of the climate evolution in the circum-Atlantic realm, best illustrated by oxygen isotope data of Greenland ice cores (Rasmussen et al., 2014). While lacustrine sediment archives in the peri-Alpine region are mostly confined to the Late Glacial and Holocene and often lack robust age control prior to the Holocene, speleothems provide proxy records extending much further back in time and offer excellent chronologies based on 230Th dating. These cave records underscore the high sensitivity of the Alps, in particular along their northern rim – facing the westerlies – to millennial and shorter term climate variations. The Northern Alps speleothem (NALPS) record (Boch et al., 2011), recently updated and extended (NALPS19; Moseley et al., 2020), combines a series of Pleistocene stalagmites from cave sites along the northern part of the Alps and reinforced the striking similarity of the oxygen isotope pattern with that of Greenland ice cores for the last glacial period. This is unlike other regions in Europe, including the southern part of the Alps facing the Mediterranean where the relationship between δ18O and climate is more complex (e.g. Genty et al., 2003, 2006; Belli et al., 2013; Columbu et al., 2018; Budsky et al., 2019). The NALPS19 record ends with a marked rise in δ18O at 14.7 ka, registered by stalagmites from Sieben Hengste Cave in Switzerland (Luetscher et al., 2015). The goal of this study was to extend the Alpine speleothem record until the early Holocene, including the equivalents of GI-1 and Greenland Stadial (GS) 1 (broadly equivalent to the Younger Dryas, YD). Using a 230Th-constrained chronology we find that the northern Alps experienced centennial-scale climate variability between about 16 and 11 ka which is identical, within uncertainties, to the well-known pattern recorded by northern high-latitude ice cores.

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Study Area and Samples
We examined two stalagmites from Hölloch (47.38°N, 10.15°E), a cave site which is part of the NALPS19 record and extends from Germany across the border to Austria (Fig. 1). The cave comprises 11.3 km of passages and its main entrance is a 77 m-deep pit that opens at 1438 m a.s.l. (Stautz & Wolf, 2006). Parts of the cave are located in the epiphreatic zone. The host rock is a karstified Cretaceous limestone (Schrattenkalk Formation) which is underlain by marls of the Drusberg Formation which act as an aquiclude (Goldscheider & Hötzl, 1999). The air temperature in the interior parts of Hölloch varies between 5.6 ± 0.1° and 5.8 ± 0.1°C (2007–2016), which is close to the mean annual air temperature outside the cave at this elevation (Fig. 1). The timberline is located at about 1550 m a.s.l.; above this elevation dwarf pine thickets and higher up karrenfields dominate the landscape, reaching up to about 2000 m a.s.l.

The main focus of the present study was stalagmite HÖL22, collected in situ at Schwarzes Loch in the central part of the cave in the proximity of stalagmites which formed between about 65 and 35 ka (Moseley et al., 2014; Spötl et al., 2011). The rock overburden at Schwarzes Loch is about 71 m (surface elevation about 1210 m a.s.l.). Here we report data from the Late Glacial part of this 365 mm-tall stalagmite, whose growth continued throughout the Holocene. The second stalagmite, HÖL1, was removed some 20 years ago from Herkulessaal in the northernmost part of the cave, where the rock overburden...
is about 69 m (surface elevation about 1500 m a.s.l. – Fig. 1). This 29.2 cm-tall specimen was studied by Wurth (2002) and Wurth et al. (2004) who reported low-resolution stable isotope data. We re-examined the lower, Late Glacial, part of this stalagmite using high-resolution stable isotope data combined with new $^{230}$Th dates.

**Methods**

HÖL22 was first drilled *in situ* in the cave using a small-diameter drill to establish its basal age and then later removed, cut along the growth axis and polished. 27 powder samples with a weight of 60–100 mg each were drilled using a handheld drill. Four powder samples, 23 to 100 mg each, were drilled from the basal part of HÖL1. The samples were prepared and $^{230}$Th-dated at the Isotope Laboratory of Xi’an Jiaotong University, using standard chemistry procedures (Edwards et al., 1987) to separate U and Th. Uranium and Thorium isotopes were measured using a multi-collector inductively coupled plasma mass spectrometer (ThermoFinnigan NEPTUNE Plus) equipped with a MasCom multiplier behind the retarding potential quadrupole in peak-jumping mode. Instrumentation and standardisation are described in Cheng et al. (2000, 2013). Uranium–Thorium ages were calculated using the decay constants from Jaffey et al. (1971) and Cheng et al. (2013). Age uncertainties are reported at the 2σ level. The depth-age models were established using OxCal and a Poisson deposition model (P-sequence) was selected to simulate the speleothem precipitation process (Bronk Ramsey, 2008). No hiatus was set in the two speleothems.

Stable isotope data were obtained along the growth axis of both stalagmites by micromilling at 0.20 mm (HÖL22) and 0.15 mm increments (HÖL1) and analysing the powders (typically 0.05–0.15 mg) using a ThermoFisher DELTA-V Plus isotope ratio mass spectrometer equipped with a Gasbench II (Spötl, 2011). Calibration of the instrument was accomplished using international reference materials and the results are reported relative to VPDB. Long-term precision on the 1-sigma level is 0.06‰ and 0.08‰ for δ$^{13}$C and δ$^{18}$O, respectively. Eight Hendy tests (Hendy, 1971) were performed along one side of the stalagmite half, from the apex down the flank, following macroscopically visible laminae.

The change points in each δ$^{18}$O profile obtained along the growth axis were objectively identified using RAMPFIT, a weighted-square method commonly used to determine a ramp between different states of a variable in a time series, and the

*Figure 2. Age models of HÖL22 and HÖL1. (A) Polished slab of the lower part of HÖL22 on the left side with yellow ruler showing the stable isotope track. OxCal-derived age model (blue) with 95% confidence interval (blue shaded band) shown on the right. Solid squares are $^{230}$Th dates with their 2σ errors. (B) Same for the basal part of HÖL1. The open square marks the $^{230}$Th date reported by Niggemann (2006). [Color figure can be viewed at wileyonlinelibrary.com].*
| Sample | Distance from Base (mm) | $^{234}$U* $^{230}$Th/238U $^{230}$Th Age (yr) | $^{230}$Th Age (yr) | $\delta$ (measured) | $\lambda$ (activity, corrected) |
|--------|-------------------------|-----------------------------------------------|-----------------------|---------------------|---------------------------------|
| HOL22-1 | 500 | 100.8 | 473.9 | 3.6 | 0.3 | 1156.2 |
| HOL22-2 | 410.0 | 38.4 | 87.2 | 0.3 | 1.2 | 96.0 |
| HOL22-3 | 320.0 | 35.8 | 91.9 | 0.3 | 1.2 | 95.5 |
| HOL22-4 | 230.0 | 31.8 | 81.3 | 1.1 | 0.1 | 1121.9 |
| HOL22-5 | 140.0 | 75.9 | 105.9 | 2.0 | 0.0 | 1486.8 |
| HOL22-6 | 60.0 | 65.7 | 105.9 | 2.0 | 0.0 | 1486.8 |
| HOL22-7 | 0.0 | 65.7 | 105.9 | 2.0 | 0.0 | 1486.8 |

*U decay constant: $\lambda_{234} = 1.55125 \times 10^{-10}$/yr (Cheng et al., 1991). $^{234}$Umeasured was calculated based on $^{234}$U* $^{230}$Th $^{230}$Th* $^{230}$Th, which is the ratio of $^{234}$Umeasured to $^{230}$Thmeasured.
uncertainties were obtained by 2000 times bootstrap resampling (Mudelsee, 2000). The reported ages for the onset and the end of climate transitions include these small uncertainties and the larger age-model uncertainties.

Results

Petrography

HÖL22 shows a brown colour in the polished slab, typical of speleothems from Hölloch. The stalagmite is macroscopically banded and lacks evidence of hiatuses. Under the microscope, the calcite shows a columnar crystal fabric. HÖL1 also shows a brown colour as well as macroscopic banding. Its petrography is also exclusively dominated by columnar calcite (Wurth, 2002).

Chronology

The depth-age model of HÖL22 is based on 27 $^{230}$Th ages between 15.11 ± 0.05 and 11.33 ± 0.10 ka, corresponding to a depth of 0 to 130 mm from the base (Fig. 2). The precision of the individual ages is compromised by variably low $^{230}$Th/$^{232}$Th ratios (Table 1), reflecting calcite containing clay and iron oxide/hydroxide particles. The OxCal age model suggests a rather uniform growth rate during the Late Glacial of about 26 µm/a. The depth-age model of the basal part of HÖL1 is based on four $^{230}$Th ages between 14.58 ± 0.13 and 11.66 ± 0.64 ka, corresponding to a depth of 0 to 30 mm from the base (Fig. 2). Dating this part of HÖL1 was challenging due to the low $^{230}$Th/$^{232}$Th ratios requiring relatively large corrections for the $^{230}$Th ages (Table 1). We also included one age that Wurth et al. (2004) reported for the lower part of this stalagmite, updated by Niggemann (2006; 12.89 ± 0.24 ka). The HÖL1 age model also suggests no major change in growth rate (mean 9 µm/a). The average resolution of the stable isotope data of HÖL22 and HÖL1 is 8.0 and 17.6 a, respectively.

Stable isotope composition

The $^{18}$O values of both stalagmites show a consistent pattern with low values of about -11 to -10‰ during the first few hundred years of growth followed by a sharp increase of 2.5‰ at the beginning of the equivalent of GI-1. This interstadial is characterised by a decreasing $^{18}$O trend interrupted by three marked lows that are best resolved in HÖL22 (Fig. 3). The equivalent of GS-1 is well expressed in both stalagmites by partly even lower values than prior to the onset of GI-1 (reaching as low as -12‰ in HÖL22) and a rapid start and end. Table 2 provides the ages and uncertainties of the three major climate shifts recorded in both stalagmites by their $^{18}$O values.

$^{13}$C shows a long-term declining trend in both speleothems starting with positive values and reaching the lowest values not before the earliest Holocene (Fig. 3). HÖL22 records a distinct first drop to values of about 0‰, which starts right at the end of the marked rise in $^{18}$O at the beginning of the equivalent of GI-1. The same drop is registered by HÖL1, which, however, starts with initial values of up to 6‰ compared with 1.8 to 3.3‰ in HÖL22 (Fig. 3). Both stalagmites reveal a long-term decrease during the first two thirds of GI-1, whereby HÖL22 is characterised by a second drop (by about 2.9‰, i.e. the equivalent of GI-1d). This drop is also recorded by HÖL1, albeit with a smaller amplitude. No major change in $^{13}$C occurred into and out of the equivalent of GS-1 (Fig. 3).

Discussion

Robustness of stable isotope proxy data

Stable isotope data of speleothems were evaluated using analyses along individual growth layers from the apex to the flank of a stalagmite, and using replication. The former, referred to as Hendy test, was performed on HÖL22 for those parts where the isotope record obtained along the growth axis revealed rather stable isotope values. The results show no significant lateral increase in $^{13}$C and $^{18}$O (Fig. 4). Wurth et al. (2004) reported three Hendy tests only for the Holocene section of HÖL1 also showing no evidence of kinetically enriched isotope values.

Figure 3. Stable isotope records of HÖL22 and HÖL1. The solid squares are $^{230}$Th dates with their 2σ errors. The open square marks the $^{230}$Th date reported by Niggemann (2006) for HÖL1. [Color figure can be viewed at wileyonlinelibrary.com].

Eight Hendy tests in the Late Glacial part of HÖL22 show no evidence of a strong increase in $^{18}$O values along growth laminae nor of a significant cross-correlation between $^{13}$C and $^{18}$O (Fig. 4). Wurth et al. (2004) reported three Hendy tests only for the Holocene section of HÖL1 also showing no evidence of kinetically enriched isotope values.
Table 2. Timing of major climate transitions obtained by ramp-fitting of the δ¹⁸O data of the two Hölloch stalagmites, NGRIP (Rasmussen et al., 2014) and the two north-Alpine lakes Ammersee (von Grafenstein et al., 1999) and Mondsee (Lauterbach et al., 2011). All uncertainties are 2 sigma. For details see text.

| Transition | Start (a) | Rampfit error (a) | Age model error (a) | Total error (a) | Transition age (ka) | End (a) | Rampfit error (a) | Age model error (a) | Total error (a) | Transition age (ka) |
|------------|-----------|-------------------|--------------------|----------------|-------------------|--------|-------------------|--------------------|----------------|-------------------|
| **GS-1 to Holocene transition (end of YD)** | | | | | | | | | | |
| HÖL22 | 11 775 | 17 | 123 | 140 | 11.78 ± 0.14 | 11 750 | 15 | 125 | 140 | 11.75 ± 0.14 |
| HÖL1 | 11 927 | 12 | 471 | 483 | 11.93 ± 0.48 | 11 851 | 11 | 482 | 493 | 11.85 ± 0.49 |
| NGRIP | 11 700 | 30 | 95 | 125 | 11.70 ± 0.13 | 11 600 | 29 | 95 | 124 | 11.60 ± 0.12 |
| Ammersee | 11 577 | 19 | | | | | | | | |
| Mondsee | 11 583 | 12 | | | | | | | | |
| **GI-1a to GS-1 transition (Allerød-YD transition)** | | | | | | | | | | |
| HÖL22 | 13 024 | 25 | 108 | 133 | 13.02 ± 0.13 | 12 803 | 22 | 76 | 98 | 12.80 ± 0.10 |
| HÖL1 | 13 165 | 29 | 364 | 393 | 13.17 ± 0.39 | 13 028 | 33 | 301 | 334 | 13.03 ± 0.33 |
| NGRIP | 12 800 | 126 | 136 | 262 | 12.80 ± 0.26 | 12 680 | 127 | 132 | 334 | 12.68 ± 0.33 |
| Ammersee | 12 695 | 23 | | | | | | | | |
| Mondsee | 12 740 | 13 | | | | | | | | |
| **GS-2.1 to GI-1e transition (Bolling onset)** | | | | | | | | | | |
| HÖL22 | 14 662 | 40 | 140 | 180 | 14.66 ± 0.18 | 14 609 | 53 | 157 | 210 | 14.61 ± 0.21 |
| HÖL1 | 14 642 | 124 | 121 | 245 | 14.64 ± 0.25 | 14 560 | 244 | 148 | 392 | 14.56 ± 0.39 |
| NGRIP | 14 640 | 93 | 185 | 278 | 14.64 ± 0.28 | 14 620 | 148 | 185 | 333 | 14.62 ± 0.33 |
| Ammersee | 14 792 | 53 | | | | | | | | |
| Mondsee | 14 625 | 8 | | | | | | | | |

except for a slightly larger uncertainty which takes into account the uncertainty of the ramp-fitting and of the age model (Table 2).

The transition from the equivalent of GI-1a (broadly equivalent to the Allerød) into GS-1 commenced at 13.02 ± 0.13 ka in HÖL22, which is slightly older than NGRIP (12.80 ± 0.26 ka; 12.85 ± 0.14 ka according to Rasmussen et al., 2014) but within the combined errors of HÖL22 and NGRIP (Table 2). Due to fewer data points and larger uncertainties, this transition is less precisely dated in stalagmite HÖL1 (13.17 ± 0.39 ka).

The last transition, the onset of the Holocene, started at 11.78 ± 0.14 ka in HÖL22 (11.93 ± 0.48 ka in HÖL1), consistent with NGRIP (11.70 ± 0.13 ka; 11.65 ± 0.10 ka according to Rasmussen et al., 2014; Table 2).

Benthic ostracods from sediment cores of Ammersee and Mondsee register a proxy signal for the Late Glacial, featuring sharp transitions very much like the Hölloch stalagmites (Fig. 5). Ammersee also records the very end of GS-2. The published Late Glacial age model of Ammersee (von Grafenstein et al., 1999) is based on one radiocarbon date in the early Holocene (11.58 ± 0.1 ka) and wiggle-matching to the GRIP δ¹³C record (Johnsen et al., 1992). This age model was verified by correlating δ¹⁸O minima to cold events recorded in the varved record of Meerfelder Maar (Eifel, Germany; Brauer et al., 1999), and the Laacher See tephra (12.88 ka BP) was used as a control point. The record from Mondsee, a lake 245 km east of Hölloch and 170 km east of Ammersee (Fig. 1), lacks radiometric age control for the Late Glacial part. Its age model was obtained by wiggle-matching to the NGRIP δ¹³C record (GICC05 timescale, Rasmussen et al., 2006) using six isotopic marker points as tie points and 65 a were subtracted following Muscheler et al. (2008) (Lauterbach et al., 2011).

We ran RAMPFIT calculations on the climate transitions of these two lake records and the timing of the major transitions is expectedly similar to NGRIP (Table 2).

Timing of major Late Glacial climate transitions

Both stalagmites register sharp changes in δ¹⁸O both into the first Late Glacial interstadial and into and out of the equivalent of GS-1. The overall shape of these transitions is very similar to those in the North Greenland Ice Core Project (NGRIP) δ¹³C record with the exception of the transition into the equivalent of GS-1 where Greenland shows a slightly less sharp drop and a smaller amplitude of change (Fig. 5).

In order to objectively identify the timing and its associated uncertainty we ran RAMPFIT calculations for both stalagmites as well as for NGRIP and two lake δ¹³C records from the northern part of the Alps (Ammersee, Mondsee – Table 2). The start of the warming at the onset of the equivalent of GI-1e in HÖL22 (14.66 ± 0.18 ka) and HÖL1 (14.64 ± 0.25 ka) agrees with NGRIP (14.64 ± 0.28 ka, timescale of Rasmussen et al. (2014) converted to yr). The onset of GI-1e in NGRIP as determined by RAMPFIT is in excellent agreement with the published age (Rasmussen et al., 2014, who used a different ramp-fitting routine) of 14.69 ± 0.19 ka (14.64 ± 0.19 ka)

High degree of correlation between the two stalagmites, in particular in δ¹⁸O. There are also some notable differences, however. While the δ¹³C values of both stalagmites agree well for the Last Glacial interstadial and the earliest Holocene, they are about 1% higher during the intervening cold episodes in HÖL1 compared with HÖL22. This, in conjunction with the significantly higher δ¹³C values in HÖL1, hints towards processes which led to higher C and O isotope values in HÖL1 during these cold periods and much less so during times of warmer climate. A possible explanation is prior calcite precipitation in the seepage water pathway that fed HÖL1. Prior calcite precipitation was likely enhanced during times of reduced recharge, such as cold and dry stadials, giving rise to calcite being deposited, e.g. on the ceiling of the chamber. This is consistent with the very slow growth rate of HÖL1 which is only about a third of that of HÖL22.
Climate interpretation based on oxygen isotopes

The high degree of similarity of the $\delta^{18}$O pattern of Höllöch stalagmites, the lacustrine records and NGRIP is a strong argument for a common, North Atlantic-centred climate forcing during the Late Glacial on millennial to decadal timescales. This is consistent with the NALPS19 dataset which found that suborbital climate change was synchronous between Greenland and the northern part of the Alps within age uncertainties during the last glacial period (Moseley et al., 2020). The Höllöch stalagmites show that this pattern of rapid climate shifts recorded by NALPS19 continues into the Late Glacial. The age models suggest that the two major climate warmings at Höllöch occurred within a few decades. The transition into the equivalent of GS-1 was slightly slower and more stepwise, again consistent with the picture from Greenland ice cores (Fig. 5).

The HÖL22 stalagmite (and to a lesser degree also HÖL1) reveals a quadripartite structure of the Late Glacial interstadial which shows four intervals of rather high $\delta^{18}$O values separated by $\delta^{18}$O lows (Fig. 5). This structure is identical to NGRIP (Rasmussen et al., 2014) and has previously been

Figure 4. Hendy tests performed on HÖL22. The results are plotted versus distance from the central axis (starting point of sampling) and as O versus C isotope cross plots. Axes are identical on all distance plots and on all cross plots.
Response to these short large lakes Ammersee and Mondsee record only a muted (Rasmussen et al., 2014) and ostracod (Lauterbach et al., 2014) and termed Aegelsee Oscillation in ecological station within the lake’s catchment, von Grafenstein et al. (1999). Interestingly, benthic ostracod δ18O primarily reflects δ18O of meteoric precipitation (superimposed changes in air temperature), whereby the interior cave air temperature typically approaches the multi-annual air temperature of the atmosphere (Fig. 1). In contrast, benthic ostracods only record δ18O of precipitation given the constant temperature of the bottom water, which is close to 4°C throughout the year in sufficiently large and deep lakes. In this respect, it is interesting that, e.g. the rapid warming at the onset of the Late Glacial interstadial comprises nearly the same δ18O increase in Höllöch stalagmites as in benthic ostracods (approximately 2.7‰ – Fig. 5). The same holds true for the transition into the Holocene (approximately 2.0‰). Given that the calcite–water isotope fractionation in the cave (−0.24%/°C) counteracts the air temperature–δ18O relationship in the atmosphere (about 0.6%/°C for central Europe; Rozanski et al., 1993), the equivalent δ18O change for a given climate transition should be smaller for speleothems than for benthic ostracods. The observation that this is not the case suggests that either the speleothem records are biased towards slightly too high δ18O values in interstadials and/or slightly too low values in stadials. Hendy tests argue against significant non-equilibrium fractionation as a possible cause for anomalously high values during warm climate states. The comparison between the two Höllöch stalagmites revealed systematically higher δ18O for the slow-growing HöL1 specimen during cold climate intervals, which suggests that during such times speleothem δ18O are rather biased toward higher rather than lower values. Alternatively, the lacustrine δ18O values could be biased towards too high δ18O values during stadials or too low δ18O values during interstadials. Kern et al. (2014) pointed to a previously neglected bias in stable isotopes of precipitation in the Alps, whereby meteorological stations located above the planetary boundary layer show δ18O values that deviate from the linear altitude trend towards higher values. This is more pronounced during winter when the vertical mixing height is lower due to more pronounced stratification. This effect becomes significant for sites located close to and above about 2000 m a.s.l. (e.g. Sieben Hengste Cave, whose δ18O values are indeed anomalously high – Moseley et al., 2020). The average elevations of the catchment of the drip water at Höllöch and of the catchment of the Ammer river flowing into Ammersee are too low to be affected by this deviation trend (the same holds true for the catchment of Mondsee); in addition, the average elevation of the catchment of the Ammer river is higher than that of the Höllöch drip water. Irrespective of this unresolved issue, we use the magnitude of the δ18O change recorded by benthic ostracods in Ammersee, whose catchment is about 60 km ENE of the Höllöch site (Fig. 1), to assess the temperature change across major climate transitions of the Late Glacial.

Using a calibration dataset of ostracods from Ammersee and 200-year-long instrumental temperature data from a meteorological station within the lake’s catchment, von Grafenstein et al. (1996) obtained a relationship between δ18O of precipitation and the mean annual air temperature of 0.58±0.11%/°C. This is consistent with a slope coefficient of about 0.6%/°C for central Europe based on data from the Global Network of Isotopes in Precipitation (Rozanski et al., 1993). Under the assumption that this coefficient was also valid for the Late Glacial and correcting the Ammersee

Figure 5. Comparison between the oxygen isotope record of the NGRIP ice core (Rasmussen et al., 2014), speleothems HÖL22 and HÖL1 (this study), and ostracod-based records from the peri-Alpine lakes Mondsee (Lauterbach et al., 2011) and Ammersee (von Grafenstein et al., 1999). [Color figure can be viewed at wileyonlinelibrary.com].
data for the ice-volume effect (following Spratt and Lisiecki, 2016) suggests that the warming at the onset of the Late Glacial interstadial was about 4.7 °C (3.9–5.7 °C) and the warming at the onset of the Holocene comprised about 3.8 °C (3.2–4.7 °C). A study of a small aquifer in northern Switzerland which contains groundwater recharged since the Last Glacial Maximum yielded a slope of 0.49 ± 0.17‰/°C for the linear fit between groundwater δ18O (corrected for the ice-volume effect) and temperatures obtained from noble gas data (Beyerle et al., 1998). Using this coefficient, the warming for the Ammersee record at the onset of the Late Glacial interstadial and the onset of the Holocene was about 5.5 °C (4.1–8.4 °C) and 4.5 °C (3.3–6.9 °C), respectively. A similar coefficient was also suggested by a study of stalagmites from northern Switzerland (0.48‰/°C, Affolter et al., 2019).

These temperature amplitudes compare reasonably well to groundwater temperatures obtained from noble gas concentrations in fluid inclusions of stalagmites from Milandre Cave in the Swiss Jura Mountains, which suggest a warming towards the end of the YD of 6.3 ± 2.3 °C (Ghadiri et al., 2018). A similar temperature rise of about 7 °C was obtained from another stalagmite of the same cave using hydrogen isotope data of fluid inclusions and the above-mentioned gradient of 0.48‰/°C (Affolter et al., 2019).

Data from bio-proxies allow summer (July) temperature changes to be constrained during the Late Glacial. Pollen data for Gerzensee, a small lake on the Swiss plateau, suggest an approximately 4–5 °C increase in July temperatures at the onset of the Bolling, while chironomids imply only 2–3 °C (Lotter et al., 2012, later confirmed by Heiri et al., 2014). A more recent chironomid-based study of another small lake in central Switzerland (Burgrüschsee) yielded a July air temperature increase of about 3 °C for the onset of the Bolling (Bolland et al., 2020). Using a combination of ostracod, mollusc and charophyte data, von Grafenstein et al. (2013) obtained an increase of about 6 °C in mean annual air temperature for this warming at Gerzensee. The summer temperature rise associated with the onset of the Holocene was about 2–3 °C based on pollen (Lotter et al., 2000) and chironomid data (Heiri et al., 2014) from the Swiss plateau, while another chironomid study suggests about 4 °C warming for the inner-Alpine site Maloja Riegel at 1865 m a.s.l. (Ilyashuk et al., 2009). In conjunction with the isotope-based estimates of the mean annual air temperature change outlined above, this indicates a disproportionally large winter cooling during the YD and the stadial preceding the Late Glacial interstadial (cf. Denton et al., 2005; Broecker, 2006).

Soil and vegetation signal

The HÖL stalagmites record a gradual decrease in the C isotopic composition starting with positive values prior to the onset of the Late Glacial interstadial. These values overlap with those of the Cretaceous marine host rock and indicate negligible input of soil-derived carbon dioxide into the karst system. This lack of a soil cover and the existence of probably only sparse Alpine tundra-type vegetation above the cave is consistent with the cold and dry climate that prevailed prior to the onset of the Late Glacial interstadial. This includes Heinrich event H1 which was characterised by a summer temperature lowering in the eastern Alps of about 10 °C relative to mean 20th century values and precipitation lower by approximately 30% relative to the present day (Kerschner & Ivy-Ochs, 2007). The long-term δ13C trend starting at the onset of the Late Glacial interstadial reflects a rise in the timberline by several hundred metres, reforestation and subsequent soil formation in the catchment of Hölloch.

Despite the similar relative change in δ13C, the Hölloch stalagmites also reveal obvious differences in the absolute values (Fig. 3). While HÖL22 reaches values of about -5‰ at the onset of the Holocene, values of HÖL1 remain at about +1‰ across most of the Holocene (Wurth et al., 2004). This high intra-cave variability is most likely unrelated to the host rock, whose lithology does not change between the two sites, which are about 1.1 km apart (beeline). In addition, both sampling sites show a similar thickness of rock overburden. Part of this offset in δ13C may be related to the elevation of the local catchment of HÖL22, which is approximately 300 m lower than that of HÖL1 and hence probably characterised by a slightly better developed soil zone. Most likely, however, this difference reflects individual drip water sources, e.g. infiltration in a soil-covered doline versus a karst terrain largely devoid of soil; the latter being more likely closer to the timberline (i.e. at the HÖL1 site). The C isotope composition of HÖL22 and HÖL1 shows no correlation with δ13C at the onset and end of the equivalent of GS-1 (Fig. 3). This is surprising as this interval was associated with a drop of the timberline by several hundred metres (cf. Kerschner, et al., 2000), which is also recorded by pollen in lake sediments from Körbersee near Schröcken, 16 km SSW of Hölloch, located at 1656 m a.s.l. (Walde & Oeggl, 2004). This lack of a response of the C isotope system to this drastic vegetation change suggests that the drip sites of both stalagmites were rather insensitive to vegetation changes once a stable soil layer had developed. This is at least partly consistent with their δ13C values, which even during the early Holocene are significantly higher than values expected for speleothems fed by drip water in a catchment dominated by C3 plants (e.g. McDermott, 2004). This can be explained by significant rock-buffering and the presence of disseminated pyrite in the host rock (in particular in the marl beds near the base of the Schrattenkalk Formation) and was also observed for other stalagmites from this cave, which are part of the NALPS19 dataset (C. Spöl & G. Moseley, unpublished data).

Conclusions and Outlook

The new stalagmites from Hölloch provide the first high-resolution and replicated speleothem stable isotope record in the greater Alpine realm covering the entire transition from the onset of the Late Glacial interstadial to the onset of the Holocene. They replicate the iconic Ammersee ostracod-based isotope record, whose chronology, as for other Late Glacial lake sediment records in the Alps, is based largely on tuning. In contrast, the chronology of the two speleothems is independent and based on 31 13C dates.

The new stalagmites document that the pattern of rapid high-magnitude δ18O swings known from older stalagmites of the last glacial period (Moseley et al., 2020) extends all the way to the end of the Pleistocene and the major climate transitions are, within the combined errors, synchronous with Greenland ice-core records. For the Late Glacial interstadial the two speleothems reveal a quadripartite structure matching NGRIP data on multi-decadal resolution.

These new stable isotope records from Hölloch fill an important gap in the NALPS19 record, which previously ended with the rapid rise in δ18O at 14.7 ka captured by a stalagmite from Sieben Hengste Cave in Switzerland (Luetscher et al., 2015). Ongoing research aims at filling the remaining small gaps in this record, which now spans from the Last Interglacial to the onset of the current interglacial. Work to
extend this northern Alpine stable isotope record back into the penultimate glacial period in an advanced state (Fohlmeister et al., 2019; submitted) and the prospect of combining this with an updated version of a central-Alpine record of Marine Isotope Stage 7 (Spötl et al., 2008; Wendt et al., submitted) is high.

Acknowledgements. CS is grateful to DK Richter for providing stalagmite HOL1, to A Wolf, Y Dublyansky and G Moseley for logistic support during field work. The Austrian Science Fund (FWF grant P222780) and the National Natural Science Foundation of China (grants 41888101 and 41731174) partially supported this research. Helpful comments by S Lauterbach and a second reviewer are gratefully acknowledged.

Data availability statement
The stable isotope data that support the findings of this study are available on request from the corresponding author.

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