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Dear Dominik,

I would like to submit the revised version of the manuscript entitled "NALPS19: Sub-orbital scale climate variability recorded in Northern Alpine speleothems during the last glacial period" for re-evaluation in Climate of the Past. The comments from both of the reviewers were extremely helpful and justified and have helped greatly to improve the manuscript. Each of the comments are addressed in turn below.

General Comments of Reviewer 1

- Section 2.1 presenting the cave sites and speleothems could be shortened. Instead of a long and tedious text to read, it would be helpful to have an associated table in the main manuscript that summarizes at least some of the information provided in the text e.g. cave name, coordinates, elevation, air temperature and precipitation rate, associated sample acronyms, length of the samples...).

AC: This has been done. The information can now be found in table 1. Additionally we shortened the lengthy U-Th dating results section and put this information in a new summary table 2.

- The discussion is also difficult to follow in Section 4.3, and the take-home messages hard to identify. The authors are investigating and discussing the roles of the different potential control factors on the calcite δ18O records from the different caves. However, I feel that we are left without clear conclusions or discussion of the implications when no firm conclusion can be drawn. This section needs to be written in a more concise and structured way (the authors should consider breaking the text into sub-sections), with a better highlight of the take-home messages. When reorganising the discussion, he authors could have in mind the following key questions to structure the text: (1)what is investigated and on what scientific ground? (2) what is observed? Is it significant or not? (3) What are the implications and how to go further?

AC: This has been greatly simplified and a short summary section added to the end to highlight the take home message.

- I find the Section 4.1 on the coherence and updates to NALPS19 versus NALPS unsatisfying. I believe that more specific justifications for selecting one speleothem rather than another to build the new composite calcite δ18O record are missing. For instance, it would be useful to provide a quantitative comparison (in a table?) for at least one or two periods (if not all) where there is overlap between "old" and "new speleothems" to better illustrate that the new ones are better dated and hence, more appropriate than the ones already published to constitute the new composite curve.

AC: This has been done and we now give a step by step approach as to why some speleothems are included and others are excluded. A table was not possible for this, hence the comparison is in the text. One can also see the comparison of the records in SI Fig. 5 (which was always the case).

My second general comment is that I find that many formulated statements, whether it is in the abstract or in the main manuscript, are too vague and/or miss some short background information. It renders the text sometimes hard to follow, especially for non-specialist readers. For instance, in multiple places, the authors state the good agreementofthedifferentchronologiesfromthespeleothemandicecorerecordwithin the dating uncertainties, without ever explicitly attached to their statement quantitative estimates of what those uncertainties are (pluridecadal-scale? centennial-scale?). Another example is the lack of a short sentence providing basic information regarding the different ice core timescales discussed in the text. In the section 2 of my review, C3

AC: This has been altered now so that quantitative statements are used throughout the manuscript to support the statements.

Specific Comments of Reviewer 1

- While it is relatively long, I find that several statements in the abstract are too vague and should be reformulated to be more specific:

Line 14: "...with highly similar shifts": this is vague, spell out clearly that you are referring to abrupt changes observed in the water isotopic profiles from Greenland ice core. I think also that one should be careful with the use of "highly similar", they are not the same proxy. If such comparison is kept, it should be specified in which sense they are highly similar.

AC: this has been revised to 'enabling direct chronological comparisons', P1 L15-16

Line 18: It is necessary to specify in which term(s) the major transitional events between stadials and interstadials agree i.e. timing of the transitions and/or amplitude of the transitions? In the same sentence, it is necessary to provide also a quantitative average estimate of the uncertainties that are referred to here.

AC: This has been updated accordingly to ….."Where speleothems grew synchronously, the timing of major transitional events in $\delta^{18}O_{calc}$ between stadials and interstadials (and vice versa) are all in agreement on multi-decadal timescales." P1 L20-21

Line 19: "...a good agreement between the NALPS19 speleothem δ18O record, the GICC05modelextNGRIP ice-core δ18Orecord and...." First, my comment is the same as previously, it is important to make it clear in which term the good agreement is.

AC: This has been updated accordingly to ….."Ramp-fitting analysis further reveals that, with the exception of stadial-20, the timing of $\delta^{18}O$ transitions occurred synchronously within centennial-scale dating uncertainties between." P1 L 21-23

Second, "GICC05modelext NGRIP ice core δ18O record" should be reformulated. It needs to be clearer here that GICC05modelext refers to an ice core age model (it might not be necessarily obvious to all CP readers). It could be reformulated such as "the NGRIP ice core δ18O record displayed on the GICC05modelext age scale".

AC: This has been updated accordingly so that the first mention of the chronology explains it clearer ….." Greenland Ice Core Chronology (GICC) 05modelext and Antarctic Ice Core Chronology (AICC) 2012" P1 L26-27

Line 21: "...too young" and "...a longer duration". By how much? Please be quantitative here and provide at least an order of magnitude.

AC: This has been revised to …." transitions in the AICC2012 chronology occurred up to 3,000 years later than in NALPS19." P1 L28-29

- For clarity purposes, I think it is important that throughout the manuscript, the authors specify "calcite δ18O" when mentioning the δ18O records from the different speleothems and "ice δ18O" and referring to the δ18O from ice cores. They do it in places, but I think this should appear systematically to avoid any confusion.

AC: This has been updated accordingly apart from where d18O is talked about in general in both ice and speleothems.

- P2, line 40: While for further details, the reader can certainly be referred to the Erhardt et al. (2019), a few sentences need to be added to describe the added value of performing such analysis and the general principle and method used for the ramp-fitting of the transitions.

AC: These finer details are now removed from the introduction. We have, however, addressed the point as follows… "The ramp-fitting function is similar to the one used by Mudelsee (2000), but instead uses probabilistic inference to define a transition via a linear ramp between two constant levels. Such an approach enables the accurate chronological quantification of climate transitions (Mudelsee, 2000), as well as the consistent treatment of records, unlike the more subjective approach of taking the first data-point that deviates from the baseline of the previous climate state (e.g. Capron et al., 2010a; Moseley et al., 2014; Rasmussen et al., 2014), which is often not so ambiguous. „ P7, L25-30

- From P5, line 25: "Results" section: SI Table 1 could appear in the main manuscript and information could be removed from the section. I found the information provided in the text very technical and from a non speleothem expert view, I feel that this should better be the supplementary material. Instead the results section could be focused on the description of the different records and a detailed comparison of the timing inferred for the transitions in the paleoclimatic records using the statistical tool of Erhardt et al. (2019).

AC: We have removed this data and placed it in a summary table that still belongs in the main manuscript (Table 2). Additionally we have greatly expanded the discussion and provided a detailed comparison of the timing as defined by the ramp fitting. See section 5.2, P7-8

The authors discuss the relationship between calcite δ18O and calcite δ13C and perform Hendy test. Again, from a non-expert point of view, I would find it very useful to have a few of sentences explaining why they are performing such exercise, what they expect to be able to decipher from such investigation and finally what are the implications of the results of their test.

AC: This was already included in the manuscript but we have expanded with the following….

"In addition to the main isotope track along the central axis, Hendy tests (Hendy, 1971) were also prepared for each sample as a first-order assessment of whether the respective stalagmite was deposited under conditions of isotopic equilibrium, though the preferred approach in recent years has been to reproduce the data in a second stalagmite (Dorale and Liu, 2009). Under the 'Hendy test' criteria, $\delta^{18}O_{calc}$ values should remain constant along a single growth layer, and there should be no correlation between $\delta^{18}O_{calc}$ and $\delta^{13}C_{calc}$ that might otherwise indicate kinetic fractionation." P.5 L.6-11

- P8, line 13: sentence starting with "Furthermore, despite...". Is there any explanation why the St Beatus records would record a signal that is different from the Gassel samples? It would be useful to provide more information on this.

AC: Ultimately we do not know why they would be different. This would require a completely different study and extensive monitoring. We have added some explanation that is it likely due to local effects as follows….

"Furthermore, the pattern of $\delta^{18}O_{calc}$ shifts across the whole interstadial 24 to 23 period is remarkably similar in the new speleothems analysed here to the pattern of events in NGRIP $\delta^{18}O_{ice}$ across the same period. This suggests the new speleothem samples are capturing a bigger-scale climate signal, unlike EXC3 and EXC4 from St. Beatus cave (Boch et al., 2011), which show a distinctly different pattern in $\delta^{18}O_{calc}$ across this time period. The reason for the difference is unknown, and is likely due to some local influence or control at the cave site." P7, L6-11

- P9, line 5: The paragraph regarding the durations of GS-22 and the precursor event is difficult to follow. It would be very helpful if the authors could provide a table that summarises the different existing and new estimates of the durations of GS-22, GS21.2 and GI-21.2 in the discussed paleoclimatic records. Implications from their new NALPS composite curve should be expressed more explicitly.

AC: The text has now been revised so that it is clearer (P9, L11-32) and the data is available in table 4.

- The numbering of the different sections needs to be revised. There should not be a sub Section1.1 if there is no Section 1.2 within the introduction section. I have a similar comment with the sub section 3.2.1, 3.3.1 and 3.3.4.

AC: The sub-sections are now removed.

Figure 3.c. A sentence to explain the shift in calcite δ18O values between the Asian monsoon composite records and the original data from which it was constructed need to be added.

AC: We don't think it is necessary to go into details of what other authors have done in their studies. Nevertheless, we have added "In Cheng et al., (2016), the Dongge and Hulu $\delta^{18}O$ values are reduced by 1.6 ‰ in the composite record to match the Sanbao record of Wang et al., (2008)." to the caption for figure 3..

- Figure 3. In the last sentence of the caption, "NGRIP nomenclature" should be replaced by "the latest INTIMATE event stratigraphy scheme".

AC: this has been done and the INTIMATE event stratigraphy scheme is also referred to more explicitly in the main text.

- Figure 4. This figure needs to be reworked to improve its readability. A y axis scale is missing. Transitions should be numbered following the INTIMATE event stratigraphy scheme and it should probably also show the reference curves in the background the reference curves onto which they have performed the analysis. Also, it needs to be clarified what are the three panels in (c), which speleothem records have been used to perform the transition analyses. Again, this would be straightforward if the original curves were shown underneath or in parallel.

AC: Figure 4 has been completely reworked and is now more readable. The transitions are available in the supplementary information as fig. 7 (as in the original manuscript)

- Figure 6. This figure is hard to read. Efforts must be made to improve its clarity. For instance, a triangle symbol should not be used to represent different parameters e.g. in (a), the catchment elevation relative to longitude and in the other panels some stadial δ18O values. For panels (e) and (g), "specific time periods" is vague, they should be specified. As far as I understand the caption for panel (f) is incorrect as only the mean δ18O values for the speleothems covering some selected GI and GS are being shown relative to the catchment elevation and not all. Finally, the expression "Colours are the same as in (a)" doesn't need to appear after the description of every panel. The authors could simply write the colour code at the start of the caption stating that it is the same on all the panels of the figure.

AC: With the simplification of the discussion we have been able to remove three of the sub-graphs which has greatly improved its clarity. We now have the same symbols in each graph and also a legend.

- Figure 7. The authors should be explicit on which type of δ18O values they are showing on the title of the axis e.g. ice δ18O for (a), calcite δ18O for (b) benthic δ13C and planktic δ18O.

AC: This has been added accordingly

-Figure S7. More information must be given to understand clearly what is represented: Titles for the two y axes should be provided as well as a description in the caption of the different curves that are represented e.g. δ18Odata, uncertainty ranges, probability density plots about the onset, mid-point and end of transition etc.

AC: This has been added accordingly

P1, line 16: a space is missing between “using,” and “eleven “.

AC: addressed, P1 L18

P1, line 21: Since it is not mentioned previously, it is important here to specify that AICC2012 refers to an ice core chronology i.e. “NGRIP ice δ18O when displayed on the AICC2012 ice core chronology “, or alternatively, the acronym can be spelt out.

AC: addressed, P1 L26

P1, line 28: “precursor” instead of “pre-cursor”.

AC: addressed, P1 L40

P1, line 29: to write “GS-24.2 COOLING event”.

AC: addressed, P2 L1

P1, line 29: “...occurred shortly”. Please be more specific so we have an idea from the abstract if you are talking about a few decades, or a few centuries, etc.

AC: addressed as follows....”$\delta^{18}O$ depletions occurred in the decades and centuries following rapid rises in sea level” P2, L2

P1, line 35: write “orbital-“.

AC: addressed, P2 L9

P2, line 2: “...have been shown to be synchronous within dating uncertainties”, please provide a reference to support this statement.

AC: addressed, P2, L17

P2, line 7: There is no need for higher resolved ice δ18O profile to identify the decadaland centennial-scale variability, it was already visible from the δ18O profile published in NGRIP project members 2004. Only that no one had provided a specific description before the study by Capron et al. (2010). Hence, I think that the sentence should be rephrased.

AC: addressed as follows “In total, 25 such cycles of rapid warming and gradual cooling, as well as many other smaller centennial- and decadal-scale events, are recognised as having occurred during the last glacial period (Dansgaard et al., 1993; NGRIP Project members, 2004; Capron et al., 2010a).“ P2, L23-25

P2, line 9: write “centennial-“.

AC: addressed P2, L24

P2, line 14: “GICC05....” Add information regarding the time interval covered by each of the timescales.

AC: addressed, P2, L31

P2, line 32: the authors are correct about the age differences between the different chronologies and they should provide a quantitative estimate of them (at least an order of magnitude).

AC: we consider the preceding discussion to be a sufficient explanation of the differences in chronologies

P2, line 35: add a space between (ka) and (Boch et al. 2011).

AC: addressed P3, L16-17

P2, line42: “a good agreement”. Please be quantitative here regarding the agreement.

AC: This section is now removed entirely

P3, line 3: why 1.1 Regional climate while there is no 1.2 and it follows the long introduction that doesn’t have a sub -section heading.

AC: Regional climate is updated to its own heading 2. P3

P3, lines 17, 20 and 21: Northern Alps and Southern Alps.

AC: The northern Alps are not recognised as a regional therefore should be lowercase. The Southern Alps are recognised as a region and therefore should be capitalised.

P3, line 23: The formulation is awkward and should be rephrased with a more direct style.

AC: Addressed as follows “In particular, the phase of the North Atlantic Oscillation (NAO), which is especially pronounced in winter (Wanner et al, 1997), exhibits one of the strongest controls.” P4, L4-6

P3, line 32: space is missing between (2015) and (though.

AC: addressed, P4, L15

P5, line 26: for clarity purposes, please write instead “samples from Baschg Cave” and similarly in the titles of sub-sections 3.2, 3.3, 3.4 and 3.5.

AC: this information is now in table 2

P8, line 29: here and throughout the manuscript: Erhardt et al. 2019 (not 2018).

AC: addressed, P7, L24

P9, line 2: In the paper by Columbu et al. (2017), a well-dated Sardinian speleothem covering GI-25b and GI-25a is presented. The timing of the abrupt transitions is also discussed and compared relative to the timing of the same events when displayed on the different Greenland ice core timescales. This study also provides evidences that there is a good agreement between the transition timing in the speleothem record and when considering GICC05modelext timescale, but that when considering the AICC2012 chronology, ages are younger by several millennia. The authors should mention this study in their manuscript.

AC: There are many well-dated speleothems over this time range. We do not intend to provide a review of them all and accordingly also do not pick out a select one.

P9, line 3: The sentence should be completed: “...too young by about XX yrs”.

AC: We have added significantly more information as follows…” Elsewhere, the transitions in the NALPS19 chronology are consistently earlier than their counterparts in the AICC2012 chronology i.e. GS-20 (c. -400 years), GI-21.1 (c. -500 years), GI-23.1 (c. -1,900 years), GS-24.1 (c. -2,700 years), and GI-24.2 (c. -2,960 years) suggesting that some revision of the AICC2012 chronology may be needed.” P8, L31-34

P9, line 7: The formulation of the sentence starting by “This demonstrated....” is awkward. It needs to be reformulated.

AC: This sentence has been removed.

P9, line 13: I don’t find the information in brackets necessary, it can probably be removed.

AC: We do consider the datum to be very important, however, this has now been moved to the caption of table 4.

P9, line 22: I find the title of the section 4.3 quite vague and not really appropriate. The authors should try and be more specific.

AC: This has been updated to “5.3 NALPS $\delta^{18}O$ variability during the last glacial period (15-120 ka)“ P9, L33

P12, line 11: centennial

AC: Addressed, P11, L39

P12, line 14: space between (Fig. 7) and (Capron...).

AC: Addressed, P12, L2-3

P12, lines 13 and 27 and P13, lines 17, 18, 20 and 22: The use of the word “termination” should be avoided in this context and replaced by e.g stadial-interstadial transition. Indeed, as the authors know the word “termination” is classically used in paleoclimatology to refer to glacial-interglacial transitions and I think for clarity purposes, it is preferable to avoid introducing this term in a different context and to refer to a different climatic event.

AC: Addressed, termination has been removed in this context and replaced with “a stadial-interstadial transition“

P12, line 19: “Changes IN Ca^{2+}” rather than “Changes TO Ca^{2+}”.

AC: Addressed, P12, L8

Also, I don’t find the reference to Rasmussen et al. (2014) appropriate in this context. Instead I would suggest referring to the studies by Ruth et al. (2007). U. Ruth et al., Geophys. Res. Lett. 34, L03706, 10.1029/2006GL027876 (2007).

AC: Addressed, P12, L9-10

P12, line 25: “the NGRIP nomenclature” should be replaced by “the INTIMATE event stratigraphy scheme”.

AC: Addressed, P12, L16

P13, line 13: space between (Wang et al. 2004) and (Fig. 7).

AC: Addressed, P13, L8-9

REFERENCES:

Boch et al. Clim. Past, 7, 1247-1259, https://doi.org/10.5194/cp-7-1247-2011, 2011.

Capron et al. Clim. Past, 6, 345-365, https://doi.org/10.5194/cp-6-345-2010, 2010.

Columbu et al. QSR, 169, 391-397, 2017.

Erhardt et al. Clim. Past, 15, 811-825, https://doi.org/10.5194/cp-15-811-2019, 2019.

Ruth et al., Geophys. Res. Lett. 34, L03706, 10.1029/2006GL027876, 2007.

Wolff et al. QSR, 29, 2828-2838, 2010.

AC: We are not sure what the reviewer intends us to do as these references are all included in the manuscript

General Comments of Reviewer 2

My main point of critique is in the sometimes lengthy discussion, which can be difficult to follow for non-experts in both ice cores and speleothem science. I therefore suggest the authors provide moderate revisions (see specific and technical comments) to the manuscript before it can be accepted for publication

AC: We have removed two major sections and replaced them as Table 1 and Table 2

Specific Comments of Reviewer 2

Discussion of chronology (section 4.2): This section is in parts difficult to follow, especially for readers not overly familiar with the ice core literature. Some studies are cited, but the reasoning for this is not explained, and this can be confusing. I suggested some instances where some more background would be beneficial to improve overall clarity (see technical comments).

AC: We have added background details to the different chronologies as follows.

"For this study, ramp fitting was applied to: (1) δ18Ocalc of the new NALPS19 record (this study); (2) δ18Ocalc of the Asian monsoon composite speleothem record (Cheng et al., 2016); (3) NGRIP δ18Oice on the GICC05modelext chronology, which is comprised of a composite layer-counted chronology to 60 ka (Svensson et al., 2008) followed by splicing of the ss09sea-modelled chronology (Johnsen et al., 2001) between 60 to 122 ka onto the younger annual-layer counted chronology (Wolff et al., 2010); (4) NGRIP δ18Oice on the AICC2012 chronology, which is constructed using glaciological inputs, relative and absolute gas and ice stratigraphic markers, and Bayesian modelling (Veres et al., 2013), and; (5) NGRIP δ18Oice on the AICC2012 chronology updated by aligning δ18O of the atmosphere as measured in EPICA Dome C with δ18Ocalc of Chinese speleothems (Extier et al., 2018)."

P7, L31-40

This is especially the case for the discussion of GS-22. I think it would be worthwhile to restructure this paragraph and clarify the main message, i.e., NALPS19 allows to reevaluate conflicting results from different ice core age modelling techniques, and this is especially clear for the interval between GS-22-GS-21.2.

AC: This paragraph has been completely re-written and a table also added for clarity (Table 4). P9, L11-32

Discussion of palaeoclimate and d18O (section 4.3): I am a bit confused with the treatment of the Siebenhengste record. At the beginning of the section, the authors exclude the LGM part of the record from Siebenhengste from their discussion on the range in d18O, because of the influence from different moisture sources previously inferred for this time period. Here I was hoping the authors could provide some more background as to why this moisture source effect is only seen in the 7H LGM record: is it due to the time period covered or is the location of the cave the likely reason for this? Why are the authors certain that changes in moisture source were not an issue for any of the other records in the compilation?

AC: Siebenhengste is not excluded on the ground of moisture source but on the grounds of a different transport pathway. Full details are given in the cited manuscript as to why this occurred so there is no need to repeat it here. Furthermore, Leutscher et al, claim that the different transport pathway only affected the LGM and not other parts of the record thus our records are not affected in the time periods we are dealing with. The strong synchronicity between Greenland and NALPS is further support that the moisture source and wider North Atlantic climate remained the same during our period of interest.

Further along in the text, there is a lengthy discussion of why the Siebenhengste record is anomalous, but there is no more mention if the source effect. I think it would greatly benefit the flow of the manuscript if the authors could elaborate a bit more on their reasoning for this, and link it back to the beginning of the section and the discussion on source changes during the LGM.

AC: The reviewer completely misses the point that the lengthy discussion is related to two caves at the same location but different elevations. Moisture source changes cannot be responsible for local variations because ultimately the moisture source would have been the same for both caves.

Discussion of stadial-level centennial-scale cold events (section 4.4): I think these events need to be more clearly pointed out in the figure 7, or even in a separate, zoomed-in figure, as it is not particularly clear what is meant now.

AC: These are already marked on figure 7 but extra text has been added to the caption accordingly "Centennial-scale cold reversals of 16.2, 17.2, 21.2, 23.2 and 24.2 are highlighted as vertical dashed yellow bars."

Technical Comments of Reviewer 2

Page 1: - line 21: The meaning of AICC2012 needs to be specified, otherwise this sentence is very confusing for non-experts.

AC: Addressed, P1, L26-27

- line 37: please add "oxygen" to "isotopic records" to clarify what is meant.

AC: Addressed, P2, L11

Page 2: - lines 31 and following: I think here the authors must clearly state that this chronological issue is also present in the ice cores and not only between the NALPS record and the ice cores.

AC: There is already a discussion about the chronological issues in the ice cores. P3, L3-7

Page 3: - line 2: "controlling the d18O of precipitation in this region" would be more precise.

AC: this section is now removed.

- line 20: "the northern Alps receive" (instead of receives)

AC: Addressed, P4, L1

Page 4: The description of the sites and stalagmites is a bit lengthy and confusing in parts. I wonder if it would be better for the flow of the manuscript to summarise these details in a table, and streamline the text?

AC: Addressed, Table 1

Page 5: Lines 28 and following throughout the sample description: U concentrations should be in ng/g (not ug/g) according to Table 2.

AC: Addressed, this data is now in table 2

Page 6: For the caves with only one stalagmite analysed, it would be better to merge the two headings into one.

AC: Addressed, this data is now in table 2

Page 8: Lines 27 and following: please add some context here regarding the chronologies GICC05modelext and AICC2012, otherwise it is difficult to follow for readers less familiar with ice cores.

AC: Addressed as follows:

"For this study, ramp fitting was applied to: (1) δ18Ocalc of the new NALPS19 record (this study); (2) δ18Ocalc of the Asian monsoon composite speleothem record (Cheng et al., 2016); (3) NGRIP δ18Oice on the GICC05modelext chronology, which is comprised of a composite layer-counted chronology to 60 ka (Svensson et al., 2008) followed by splicing of the ss09sea-modelled chronology (Johnsen et al., 2001) between 60 to 122 ka onto the younger annual-layer counted chronology (Wolff et al., 2010); (4) NGRIP δ18Oice on the AICC2012 chronology, which is constructed using glaciological inputs, relative and absolute gas and ice stratigraphic markers, and Bayesian modelling (Veres et al., 2013), and; (5) NGRIP δ18Oice on the AICC2012 chronology updated by aligning δ18O of the atmosphere as measured in EPICA Dome C with δ18Ocalc of Chinese speleothems (Extier et al., 2018)."

P7, L31-40

Page 9: Lines 2-4: Please provide a brief explanation of what the findings of Extier are for the readers not familiar with this study.

AC: The discussion is Extier is now extended. We have applied additional ramp fitting to Extier and include discussion on P8, L34-39

Line 5: Please add the ages of the GS-22 interval here for context.

AC: The point is that this is a discussion about the different ages for GS-22, so it does not make sense to add ages here because which ones should be chosen? The ages follow in the proceeding text and new table 4.

Also, given that this is discussed at length over the next section, I would appreciate if the authors could point out this interval (and GI-GS21.2) in Fig. 3 or 5.

AC: Addressed, the nomenclature is now on Fig. 3

Lines 6-7: "Vallelonga et al. (2012) proposed the duration of GS-22 to be 2,894±198 years and GI-21.2 - GS-21.2 to be 350 ± 19 years (together 3,244 ± 199 years, two sigma error)." This sentence reads confusingly to me: I assume the authors mean that the duration of the transition between GI-21.2 and GS-21.2 to be 350 years, while the entirety of the interval is 3244 years?

AC: The text has now been revised so that it is clearer (P9, L11-32) and the data is available in table 4.

Line 9: NGRIP-EDML should be explained.

AC: Addressed, P9, L27-28

Page 10: Line 10: "The highest and lowest δ18O values for stadials and interstadials also both come from the same caves." I find this sentence confusing: the highest and lowest in general? Which cave are these values from

AC: Addressed as follows….

"the $\delta^{18}O_{calc}$ range in mean interstadial values is 5.0 ‰ (Klaus Cramer (-7.9 ‰) and Siebenhengste (-7.9 ‰) to Kleegruben (-12.9 ‰)), whilst the range in mean $\delta^{18}O_{calc}$ stadial values is slightly larger (but comparable) at 5.4 ‰ (Siebenhengste (-9.5 ‰) to Kleegruben (-14.9 ‰)) (Fig. 7a)." P10, L23-26

Line 27: I would rephrase “mean d18O” to “mean d18O of an entire record” or similar.

AC: this will make the following discussion extremely wordy, we do not think it is necessary

Line 35: “For a given location, however, Ambach et al. (1968) argued that the altitude effect cannot be the result of a difference in condensation temperature, because the condensation level should be approximately the same.” I find this sentence confusing, and would also appreciate some more details on why the condensation level is the same.

AC: As it already states in the text, the caves are in the same location therefore they receive the same rain which must have condensed at the same level. P11, L18-19

Page 13: Line 32-35: “Furthermore, we suggest that the highly-debated GS-22 - GI21.2 - GS-21.2 interval had a duration of 3,857 ± 249 years, which is in closer agreement with the 4,121 ± 325 years of NGRIP-EDML (Capron et al., 2010b) and the3,793 ±805 years of the Asian monsoon composite (Kelly et al.,2006; 35 Kelly, 2010; Cheng et al., 2016).” Closer agreement than what?

AC: Addressed as follows…

Additionally, we propose that the duration of the highly-debated GS-22 - GI-21.2 - GS-21.2 interval was 3,993 ± 155 years, which is in closer agreement **to the duration of** 4,122 ± 650 years in NGRIP-EDML (Capron et al., 2010b) and the 4,489 ± 960 years of the Asian monsoon composite record (Kelly et al., 2006; Kelly, 2010; Cheng et al., 2016).

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Figure 3: In the caption, I believe there is some information missing. For c) only the Dongge data is referenced, and there is no mention of Hulu. There is also a repetition at f)“for(e)colour-coded the same”.

AC: Addressed. Details have been added to say that the revised Hulu record comes from Cheng et al., 2016. The repetition has been removed.

Figure 4: I think this figure would benefit from some additional work. For example, it would be clearer if the different ice cores (b) and stalagmites (c) for which the ramp-fitting was done were indicated in the figure with labels. Also, possibly adding labels for the transitions identified in the Greenland records would help.

AC: This figure has been completely revised.

Figure 5: Here it would be helpful to the reader if the records were labelled, as in figure 2.

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Figure 6: I think it would be helpful to have a legend in the figure showing which symbol belongs to which cave.

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Yours faithfully,

Gina Moseley, Email. gina.moseley@uibk.ac.at

NALPS19: Sub-orbital scale climate variability recorded in Northern Alpine speleothems during the last glacial period

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Abstract. Sub-orbital-scale climate variability of the last glacial period provides important insights into the rates that the climate can change state, the mechanisms that drive such changes, and the leads, lags and synchronicity occurring across different climate zones. Such short-term climate variability has previously been investigated using $\delta^{18}O$ from speleothems ($\delta^{18}O_{calc}$) that grew along the northern rim of the Alps (NALPS), enabling direct chronological comparisons with $\delta^{18}O$ records from Greenland ice cores ($\delta^{18}O_{ice}$). In this study, we present NALPS19, which includes a revision of the last glacial NALPS $\delta^{18}O_{calc}$ chronology over the interval 118.3 to 63.7 ka using eleven, newly-available, clean, precisely-dated stalagmites from five caves. Using only the most reliable and precisely dated records, this period is now 90 % complete and is comprised of 16 stalagmites from seven caves. Where speleothems grew synchronously, the timing of major transitional events in $\delta^{18}O_{calc}$ between stadials and interstadials (and vice versa) are all in agreement on multi-decadal timescales. Ramp-fitting analysis further reveals that, with the exception of stadial-20, the timing of $\delta^{18}O$ transitions occurred synchronously within centennial-scale dating uncertainties between the NALPS19 $\delta^{18}O_{calc}$ record and the Asian Monsoon composite speleothem $\delta^{18}O_{calc}$ record. Due to the large millennial-scale uncertainties in the ice-core chronologies, a comprehensive comparison with the NALPS19 chronology is difficult. Generally, however, we find that the absolute timing of transitions in the Greenland Ice Core Chronology (GICC) 05$_{modelext}$ and Antarctic Ice Core Chronology (AICC) 2012 are in agreement on centennial-scales. The exception to this is during the interval 100 to 115 ka, where transitions in the AICC2012 chronology occurred up to 3,000 years later than in NALPS19. In such instances, the transitions in the revised AICC2012 chronology of Extier et al. (2018) are in agreement with NALPS19 on centennial scales, supporting the hypothesis that AICC2012 appears to be considerably too young between 100 to 115 ka. Ramp-fitting further shows that $\delta^{18}O$ shifts took place on multi-decadal timescales in the North Atlantic-sourced regions (N. Alps and Greenland), whereas shifts in the monsoon were on multi-centennial timescales. Given the near-complete record of $\delta^{18}O_{calc}$ variability during the last glacial period in the northern Alps, we also offer preliminary considerations regarding the controls on mean $\delta^{18}O_{calc}$ for given stadials and interstadials. We find that as expected, $\delta^{18}O_{calc}$ values became increasingly lighter with distance from the oceanic source regions, and increasingly lighter with increasing altitude. Exceptions were found for some high-elevation sites that locally display $\delta^{18}O_{calc}$ values that are heavier-than-expected in comparison to lower-elevation sites, possibly caused by a summer bias in the recorded signal of the high-elevation site, or a winter bias in the low-elevation site. Finally, we propose a new mechanism for the centennial-scale stadial-level depletions in $\delta^{18}O$ such as 'precursor' events GS-16.2, GS-17.2, GS-21.2, and GS-23.2, as

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well as the 'within-interstadial' GS-24.2 cooling event. Our new high-precision chronology shows that each of these $\delta^{18}O$ depletions occurred in the decades and centuries following rapid rises in sea level associated with increased ice-rafted debris and southward shifts of the Intertropical Convergence Zone, suggesting that influxes of meltwater from moderately-sized ice sheets may have been responsible for the cold reversals causing the Atlantic Meridional Overturning Circulation to slow down similar to the Preboreal Oscillation and Older Dryas deglacial events.

1 Introduction

Speleothems from the northern rim and central European Alps have provided a number of important, high-resolution, precisely ^{230}Th-dated records of both orbital- and millennial-scale climate variability during the last glacial and interglacial periods (Spötl and Mangini, 2002; Spötl et al., 2006; Boch et al., 2011; Moseley et al., 2014; Luetscher et al., 2015; Moseley et al., 2015; Häuselmann et al., 2015). The oxygen isotopic signature of such records (herein referred to as $\delta^{18}O_{calc}$) has helped improve fundamental understanding of the effect that changes in atmospheric (Luetscher et al., 2015) and North Atlantic circulation (Moseley et al., 2015) have on European climate, whilst the robust chronologies have provided important information about the timescales upon which the climate can change in this well-populated region (Boch et al., 2011; Moseley et al., 2014). Furthermore, the pattern and timing of excursions in $\delta^{18}O_{calc}$ of northern Alpine speleothems during the last glacial cycle have been shown to be synchronous within dating uncertainties (Boch et al., 2011; Moseley et al, 2014) with the sawtooth-pattern of changes in the $\delta^{18}O$ of Greenland ice cores (herein referred to as $\delta^{18}O_{ice}$) (known as Dansgaard-Oeschger cycles; Johnsen et al., 1992; Dansgaard et al., 1993), thus reflecting the shared North Atlantic moisture source and integrated climate system (Boch et al., 2011). The sawtooth pattern of $\delta^{18}O$ is generally interpreted in both Greenland and the northern Alps as being caused by a rapid increase in temperature and humidity leading into a mild climate state (interstadial), followed by a gradual cooling leading into a cold and dry glacial state (stadial). In total, 25 such cycles of rapid warming and gradual cooling, as well as many other smaller centennial- and decadal-scale events, are recognised as having occurred during the last glacial period (Dansgaard et al., 1993; NGRIP Project members, 2004; Capron et al., 2010a). This has resulted in a new stratigraphic framework (INTIMATE event stratigraphy) for abrupt climate changes in Greenland, in which shorter-scale events that occur within the 25 main stadials and interstadials are designated "a to e" (Rasmussen et al., 2014). This nomenclature will be used in the remainder of this article.

When considering the timing of the transitions in $\delta^{18}O$ between stadial and interstadial states, the largest offsets between the northern Alps speleothem chronology (NALPS) and Greenland Ice Core Chronology (layer-counted GICC05, 0 to 60 ka; Svensson et al., 2008 and modelled GICC05$_{modelext}$, 60 to 122 ka; Wolff et al., 2010) are 767 years in Marine Isotope Stage (MIS) 3 (Moseley et al., 2014) and 1,060 years in MIS 5 (Boch et al., 2011). The former is associated with the warming transition into Greenland Interstadial-16.1c (GI-16.1c), and the latter with the cooling transition into Greenland Stadial-22 (GS-22; Rasmussen et al., 2014). The timing for both of these transitions in the NALPS chronology was constrained from speleothems high in detrital thorium (Boch et al., 2011; Moseley et al., 2014). Since one of the prerequisites for reliable ^{230}Th dating is that minimal ^{230}Th is incorporated into the calcite at the time of deposition (Ivanovich and Harmon, 1992; Dorale et al., 2004), it is reasonable to question the accuracy of the age of these two transitions. In the case of the MIS 3 sample (Moseley et al., 2014), the correction for the initial incorporation of daughter nuclides was well constrained by isochron

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methods (Ludwig and Titterington, 1994; Dorale et al., 2004), however, in the case of the MIS 5 sample (Boch et al., 2011), the detrital Th was corrected for using an *a priori* assumption that the contaminant phase had the same composition of the silicate bulk earth (Wedepohl, 1995). Furthermore, the accuracy of the $GICC05_{modelext}$ chronology is questionable in the vicinity GI-22 to 21 (Capron et al., 2010b; Vallelonga et al., 2012). Specifically, the duration of GS-22 appears to be underestimated, probably as a result of an overestimation of the annual layer thickness by the ss09sea06bm ice flow model (Johnsen et al., 2001) upon which $GICC05_{modelext}$ is based in the portion of the record older than 60 ka (Wolff et al., 2010; Vallelonga et al., 2012). Vallelonga et al. (2012) thus revised the duration of GS-22 from 2,620 years to 2,894 ± 99 years using annual layer-counting of seasonal cycles in the chemical impurities in the ice. Given the uncertainties in the chronologies for both the NALPS speleothems and NGRIP ice core during GI-22 to GI-21, it is thus difficult to determine the reliability and extent of the leads, lags and synchronicity at this time. In addition to the complexities around GS-22, the chronology of events between GI-25 to 23 are also poorly constrained. This is visible when comparing the $GICC05_{modelext}$ chronology (Wolff et al., 2010) with the Antarctic Ice Core Chronology (AICC)2012 chronology (Veres et al., 2013), which differ by up to 2,700 years, and also when comparing the pattern of the $\delta^{18}O$ shifts during GS-24 in NALPS and NGRIP (Boch et al., 2011).

Here, we revisit the NALPS speleothem chronology over the interval 63.7 to 118.3 thousand years ago (ka) (Boch et al., 2011) using new samples that are low in detrital thorium and/or have a more pronounced $\delta^{18}O_{calc}$ signal, with the aim of improving the chronology such that better informed conclusions about leads/lags and synchronicity in the climate system may be made. The original record was discontinuous, with coverage of 76 % of the 54.6 ka interval. Gaps in the record were present between 111.6 and 110.0, 94.5 and 89.7, 84.7 and 83.0, 77.5 and 76.0, 75.5 and 72.0 ka (Boch et al., 2011). With the addition of new speleothems, we extend the coverage to 90 %, improve the accuracy and precision of some climate transitions, and designate the revised chronology “NALPS19”.

2 Regional Climate

The European Alps, situated between 44 and 48 °N, are a 950 km-long mountain range running ENE-WSW located close to the southern fringe of the European mainland. The highest peaks, reaching over 4,000 m in elevation, are situated in the Western Alps of France and Switzerland, whilst the Eastern Alps, located in Austria, are on average 1,000 m lower. Across the whole of the Alps, the average elevation is c. 2,500 m above sea level (a.s.l.), thus this mountain range forms a major topographic barrier between the North Atlantic and Mediterranean climate zones (Wanner et al., 1997). Today, the Alps are located to the south of the extra-tropical westerlies, which bring precipitation sourced from the North Atlantic to the northern and western flanks, particularly during winter and spring (Wanner et al., 1997; Sodemann and Zubler, 2010). Lagrangian back-trajectory studies have shown that for the period 1995-2002, the North Atlantic contributed c. 40% of the annual mean moisture to the Alps, whilst the Mediterranean contributed 23%, the Arctic, Nordic and Baltic seas 16%, and the European land masses 21% (Sodemann and Zubler, 2010). Contributions to the northern versus southern side of the Alps, however, displayed considerable seasonal differences. Throughout the year, the North Atlantic contributes more moisture to the northern Alps as compared to the Southern Alps, and this is especially pronounced in winter and spring (Sodemann and Zubler, 2010). During summer, Central European land masses are the dominant moisture source across the entire Alps, though the North Atlantic still makes some contribution

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Furthermore, the near-complete record of $\delta^{18}O_{calc}$ variability along the northern rim of the Alps during the last glacial period enables a deeper consideration of the main factors controlling the $\delta^{18}O$ of precipitation in this region. We also consider a meltwater-triggered mechanism for the centennial-scale cold reversals of GS-16.2, GS-17.2, GS-21.2, GS-23.2 and GS-24.2 similar to those already recognised for the deglacial period.

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to the northern flanks, and the Mediterranean to the southern flanks. In autumn, the northern Alps receive comparable quantities of moisture from both the North Atlantic and Mediterranean, whilst the Southern Alps are dominated by moisture from the Mediterranean (Sodemann and Zubler, 2010). On longer, multi-decadal timescales, moisture sources and trajectories to the Alps have been shown to be highly variable. In particular, the phase of the North Atlantic Oscillation (NAO), which is especially pronounced in winter (Wanner et al, 1997), exhibits one of the strongest controls. During the positive phase, when positive sea-surface temperature and air-pressure anomalies build up in the southwestern North Atlantic, and negative ones in the north, the associated temperature gradient across the western North Atlantic is high. This leads to an intensification of the North Atlantic polar front jet stream, which creates a high pressure zone over the Alps and Mediterranean causing higher temperatures and less precipitation (Wanner et al., 1997). Conversely, during a negative NAO phase the air pressure decreases over the Alps and Mediterranean leading to lower air temperatures and higher precipitation.

3 Methods

3.1 Cave Sites and Speleothems

Previous NALPS studies include MIS 2 in Luetscher et al. (2015) (though this was not branded as 'NALPS'), MIS 3 in Moseley et al. (2014), and MIS 4 to MIS 5 in Boch et al. (2011). The MIS 4/ MIS 5 chronology (which is the part revised here), was constructed from seven speleothems from four cave sites including St. Beatus caves, Große Baschg cave (Baschg cave for short), Klaus-Cramer cave and Schneckenloch (Boch et al., 2011). In this study, two additional samples from Baschg cave and one from Schneckenloch were analysed, plus one sample from Hölloch im Mahdtal (Hölloch cave for short), one from Grete-Ruth-Shaft, and six from Gassel Tropfsteinhöhle (Gassel cave for short). All cave sites are located on the northern rim of the European Alps (Fig. 1) and have small catchments of less than a few km^2. The distance between the most westerly and easterly caves is c. 475 km. Details of the speleothems analysed in this study and their respective caves are given in Table 1 whereas images of the respective samples are given in SI Fig. 1.

3.2 Analytical Methodology

The eleven stalagmites were cut in half along their growth axis and polished by a professional stone mason. Pilot dating studies guided the sample size that was needed for high precision ages. Sub-samples of between 20 to 150 mg were hand-drilled using a handheld-drill fitted with carbide burr-tipped drill bits of diameter 0.5 to 0.8 mm in a laminar-flow hood. The cleanest, densest growth layers were targeted for sampling.

Chemical procedures and aliquot measurements were undertaken in the Trace Metal Isotope Geochemistry Laboratory at the University of Minnesota. Separation and purification of U and Th aliquots from the sub-samples was undertaken using standard methods (Edwards et al., 1987) in a clean air environment. Samples were spiked with a dilute mixed ^{229}Th-^{233}U-^{236}U tracer to allow for correction of instrumental fractionation and calculation of U and Th concentrations and ratios. Procedural chemistry blanks were on the order of 5 – 83 ag for ^{230}Th, 2 – 523 fg for ^{232}Th, 73 to 171 ag for ^{234}U, and 0.2 to 1.6 pg for ^{238}U. Aliquots of U and Th were analysed on a ThermoFisher Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) in peak-jumping mode on the secondary electron multiplier (Shen et al., 2012).

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Moving from west to east and considering the new samples analysed in this study, Baschg cave (47.2501 N, 9.6667 E) is a 300 m-long cave with a single-known entrance located at 785 m a.s.l.. The cave air temperature is c. 10 °C and the mean annual precipitation 1,360 mm (recorded between 1981-2010 at the Feldkirch meteorological station located c. 5 km WNW from the cave at 438 m a.s.l. (ZAMG, 2018)). The nearest GNIP station is located 20 km SW at Sevelen where $\delta^{18}O$ ranges between -6.3 in July to -15.8 ‰ in November (IAEA, 2018). Samples from Baschg cave analysed in this study include BA-5 and BA-7 (Supplementary Information (SI) Fig. 1). Both are honey-brown coloured stalagmites c. 70 mm and 200 mm in length respectively. BA-5 and BA-7 were collected from the rear of the cave, c.180 m from the entrance. BA-5 was found buried in loam above the streamway, and BA-7 was found broken above the streamway. The base of BA-7 remains in situ.¶
Schneckenloch (47.3745 N, 10.0680 E), Klaus-Cramer (47.3559 N, 10.1064 E), and Hölloch (47.3779 N, 10.1505 E) caves are located within 10 km of one another. Schneckenloch is a 3.5 km-long cave with an entrance at an elevation of 1,285 m a.s.l. (Klampfer et al., 2017). The cave air temperature is c. 6 °C and the mean annual precipitation 2,073 mm (recorded at the Schoppernau meteorological station located c.7 km SSW from the cave at 839 m a.s.l. (ZAMG, 2018)). The nearest GNIP station is located 50 km WNW at St. Gallen where $\delta^{18}O$ ranges between -6.9 in July to -15.0 ‰ in February (IAEA, 2018). In Schneckenloch, speleothem deposition takes place today in the form of stalactites and active stalagmite and flowstone deposition is rare. For this study, a honey-brown coloured stalagmite (SCH-6), c. 235 mm in length was recovered from the end of a small, well-decorated side passage, 350 m from the entrance.¶
Hölloch is a 10.9 km-long cave located c. 10 km to the east of Schneckenloch. It has two known entrances at elevations of 1,240 m and 1,438 m a.s.l. (Wolf, 2006). The cave air temperature in the lower part is 5.6 ± 0.2 °C (Spötl et al., 2011). Mean annual precipitation is the same as for Schneckenloch. Hölloch is located c. 57 km ESE to the St. Gallen GNIP station, and 70 km WSW to the Garmisch-Partenkirchen GNIP station. At Garmisch-Partenkirchen $\delta^{18}O$ ranges between -6.7 in July to -14.7 ‰ in November (IAEA, 2018). From Hölloch we analysed HÖL-19, which is a 415 mm-long candlestick-type stalagmite (SI Fig. 1) that grew adjacent to HÖL-7, a stalagmite that was deposited during MIS 3 in the northern part of the Hölloch system (Moseley et al., 2014), c. 800 m from the northwestern entrance and 600 m from the southern entrance (Wolf, 2006). HÖL-19 has a variable internal structure that alternates between dark brown calcite, opaque white calcite, and cemented loam layers. opaque white calcite only Grete-Ruth-Shaft (47.5429 N, 12.0272 E) is a small cave, 142 m in length and 39 m deep, that opens to the surface at the top of a shaft 1,435 m a.s.l. (Rittig, 201 ...

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Stable isotopes ($\delta^{18}O_{calc}$ and $\delta^{13}C_{calc}$) were typically micro-milled at a spatial resolution of 250 µm (with the exception of GAS22=200 µm and BA7=500 µm) from the central axis of each sample (SI Fig. 2). In total 5,000 new measurements were made for this study at the University of Innsbruck on a ThermoFisher Delta^{plus}XL isotope ratio mass spectrometer linked to a Gasbench II. Analytical precisions are 0.08‰ and 0.06‰ for $\delta^{18}O_{calc}$ and $\delta^{13}C_{calc}$, respectively (1σ) (Spötl, 2011). All isotope results are reported relative to the Vienna PeeDee Belemnite standard. In addition to the main isotope track along the central axis, Hendy tests (Hendy, 1971) were also prepared for each sample as a first-order assessment of whether the respective stalagmite was deposited under conditions of isotopic equilibrium, though the preferred approach in recent years has been to reproduce the data in a second stalagmite (Dorale and Liu, 2009). Under the 'Hendy test' criteria, $\delta^{18}O_{calc}$ values should remain constant along a single growth layer, and there should be no correlation between $\delta^{18}O_{calc}$ and $\delta^{13}C_{calc}$ that might otherwise indicate kinetic fractionation. Bayesian age models were constructed for all eleven samples using OxCal version 4.2 for Poisson-process depositional models ('p sequence') and a variable 'k parameter' of 0.001 to 10 mm a-1 (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013).

4 Results

The results of the U-Th MC-ICPMS measurements and associated age calculations can be found in SI Table 1. Age modelling results including growth rates can be seen in SI Fig. 3. The correlation between $\delta^{18}O_{calc}$ and $\delta^{13}C_{calc}$ is shown in SI Fig. 4, whereas the results of Hendy tests are shown in SI Table 2. The key features of all of these results are summarised in Table 2 and will be discussed briefly here. Generally, all speleothems have ^{238}U concentrations of c. 250 to 1,500 ng g^{-1}, which are values typical of common alpine dripstones. The cleanest samples, as indicated by high $^{230}Th/^{232}Th$ ratios, are from Grete-Ruth Shaft (HUN14) and Gassel cave (GAS12, 13, 22, 25, 27, 29). Correction of final ages for detrital Th contamination in these samples is therefore negligible (SI Table 1). The samples from Baschg, Schneckenloch, and Hölloch caves are all variably contaminated with detrital Th. In the case of BA5, this results in corrections to younger ages of 57-135 years, which are within the levels of dating uncertainty (c. 300 to 400 years) (SI Table 1). BA-7 is the 'dirtiest' of the samples analysed here. Of the 16 U-Th ages used in the age model, nine are shifted less than 1,000 years to younger ages (SI Table 1). SCH6 has varying levels of detrital Th contamination, being very clean in the older part between c. 75.9 to 77.9 ka, but moderately dirty in the younger section between 74.4 to 75.5 ka (SI Table 1). The majority of the age models is thus constructed from clean samples. The internal morphology of HÖL19 is variable and contains sections of clean calcite, dirty calcite, and calcified loam layers (SI Fig. 1). The youngest part of the stalagmite dates to the late Holocene and the late glacial (SI Table 1) and thus is outside the time frame for this study. Between c.95 mm and c.160 mm from the top, the stalagmite is rich in calcified loam layers and thus is not suitable for dating. Below 160 mm there are a number of sections of clean and dirty calcite. Here we have concentrated on the cleanest part between 187.25 and 226.75 mm from the top. Correction of these ages for detrital Th results in a shift to younger ages of 64 to 213 years, which is within the c. 300-400 years range of dating uncertainty (SI Table 1). Linear regression analysis between $\delta^{18}O_{calc}$ and $\delta^{13}C_{calc}$, which is used as a test for isotopic equilibrium (Hendy, 1971; Dorale and Liu, 2009), yields extremely low R^2 values below 0.3 for the majority of samples (Table 2) suggesting that kinetic fractionation did not occur. Only GAS22 has an R^2 of 0.4 and GAS27 an R^2 of 0.6 indicating a minor correlation. Variation in $\delta^{18}O_{calc}$ across single growth layers is also generally low, with the exception of one out of five tests in GAS27 yielding a range of 0.8 ‰ (Table 2).

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3.1 Baschg Samples¶
3.1.1 BA-5¶
The ^{238}U concentration of the calcite in BA-5 ranges between c. 300 to 1,100 µng g^{-1}, and the $^{230}Th/^{232}Th_{atomic}$ ranges between c. 2000 x10^{-6} to 4500 x 10^{-6} (SI Table 2).

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Deleted: The resultant age model was constructed from seven U-Th ages and 279 stable isotope measurements (SI Table 1). It continuously covers the period 90.3 ± 0.3 to 85.0 ± 0.3 ka (SI Fig.3) with a resolution of 13-24 years (mean 19 years) per stable isotope measurement, and a growth rate of 10 – 20 mm ka^{-1} (mean 14 mm ka^{-1})(SI Table 1). $\delta^{18}O$ has a 4.3 ‰ range, between -7.9 to -12.2 ‰. The relationship between $\delta^{18}O$ and $\delta^{13}C$ is extremely low, as indicated by the minimal variation in $\delta^{18}O$ and $\delta^{13}C$ along two growth layers and linear regression analysis yielding an R^2 of 0.004 (SI Fig.4). Two Hendy tests reveal a range of 0.2 to 0.4 ‰ in $\delta^{18}O$ and 0.2 to 0.3 ‰ in $\delta^{13}C$ across single growth layers (SI Table 3).

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5 Discussion

5.1 Coherence and updates to NALPS19 versus NALPS

The new records produced in this study (Fig. 2b) comprise 5,000 $\delta^{18}O_{calc}$ measurements dated by 145 precise U-Th ages (SI Fig. 3, SI Table 1), which add to the NALPS chronology of Boch et al. (2011)(Fig. 2a) that comprised 7,141 $\delta^{18}O_{calc}$ measurements and 154 U-Th ages. Combined, the two chronologies cover the period 118.3 to 63.7 ka. Within this interval, the record is now 90 % complete, compared to 76 % in Boch et al. (2011). Where speleothems grew synchronously, major transitional events between stadials and interstadials (and vice versa) are all in agreement within uncertainty, which can be very clearly seen in SI Fig. 5. In the interest of completeness and transparency, we present all $\delta^{18}O_{calc}$ records here, however, some samples are cleaner than others as discussed in section 3 (i.e. low in detrital Th as indicated by a higher $^{230}Th/^{232}Th$ ratio) and thus deemed to be more reliably dated. The NALPS19 chronology is therefore constructed from only the most reliably dated records from this study and Boch et al. (2011) (Fig. 2c). Considering the construction of NALPS19 further and generally working from youngest to oldest: samples KC1 and HÖL19 are included on the basis that they are the only records available that cover the transitions into stadials-19 and 20. The transition into interstadial-20 is present in both SCH6 (this study) and BA1b (Boch et al., 2011). Both samples have comparable levels of detrital Th, and the dating precision of the transition in both samples is c. 200 to 250 years. Given the comparative cleanliness and dating precision, as well as the reproducibility of the timing of the transition to within c. 50 to 85 years (SI Fig. 5), both samples are included in NALPS19. Samples covering the transition into stadial-21 include GAS12 and 13 (this study) and BA1b (Boch et al., 2011). Samples from GAS12 and GAS13 are extremely clean with dating precisions of 250 to 300 years (Table 2), whereas those from BA1b are generally moderate to very clean. Critically though, GAS12 contains 6 ages and over 60 $\delta^{18}O_{calc}$ measurements within the transition, and GAS13, 3 ages and over 130 $\delta^{18}O_{calc}$ measurements (SI Fig. 2). On the other hand, BA1b has only three $\delta^{18}O_{calc}$ measurements in the transition, and one age which is quite dirty resulting in an age corrected to younger values by 760 years and a dating precision of 580 years (Boch et al. 2011). Based on the higher resolution and higher precision provided by GAS12 and GAS13, as well as the fact they are reproducible during the transition on sub- and decadal timescales, we therefore include GAS12 and GAS13 in NALPS19 and omit BA1b. EXC4 is then included for the interstadial-21 portion on the basis that it is clean. However, for this section it only contains the interstadial and no transitions, therefore it is excluded from the discussion on transition timing (Section 4.2). The transition into interstadial-21 is captured in BA1 (Boch et al., 2011), BA7 and GAS25 (this study). As discussed above, GAS25 is extremely clean, thus correction for detrital Th is negligible and the dating precision is on the order of 300 to 400 years (SI Table 2). In contrast, BA7 is the dirtiest of the samples with large corrections for detrital Th (SI Table 2), whereas BA1 is moderately dirty resulting in comparable shifts to younger ages (Boch et al., 2011). Ideally, the complete transition would be constrained only in GAS25 since this sample is the most reliable and best dated, but unfortunately this record is limited to growth mainly during and just after the transition. We therefore include GAS25 where it is applicable and omit BA1 and BA7, but then keep BA1 and BA7 for the parts of the record where there is no alternative available. The transition into stadial-22 is present in GAS25, BA5 (this study), and BA2 (Boch et al., 2011). The situation here is similar to the transition into interstadial-21, where GAS25 is the superior sample with higher dating quality. GAS25 therefore takes priority, whereas BA5 is included to complete the stadial part of the record. BA2 is completely omitted from NALPS19 on the basis that correcting for detrital Th causes shifts in ages of centuries (Boch et al., 2011) as compared to

Moved up [1]: The internal morphology of HÖL-19 is variable sections of clean calcite, dirty calcite, and calcified loam layers (SI Fig. 1). The youngest part of the stalagmite dates to the late Holocene and the late glacial (SI Table 2) and thus is outside the time frame for this study. Between c.95 mm and c.160 mm from the top, the stalagmite is rich in calcified loam layers and thus is not suitable for dating. Below 160 mm there are a number of sections of clean and dirty calcite. Here we have concentrated on the cleanest part between 187.25 and 226.75 mm from the top, which yielded eight U-Th dates with c.500 to 850 µg g^{-1} of ^{238}U, and an age model between 73.6 ± 0.3 and 74.4 ± 0.2 ka (SI Table 2). The final age model has a resolution of 4-5 years (mean 5 years) per stable isotope measurement, and a growth rate that varies between 46 to 68 mm ka^{-1} (mean 53 mm ka^{-1}). $\delta^{18}O$ has a 2.3‰ range between -8.3 to -10.6 ‰. A Hendy test at 211.75 mm from the top in the section of the speleothem analysed here reveals minimal variation in $\delta^{18}O$ and $\delta^{13}C$ along the respective growth layer (0.3 and 0.4‰, respectively)(SI Table 3), whilst linear regression analysis yields a medium R^2 of 0.3 (SI Fig. 4) indicating a weak relationship between $\delta^{18}O$ and $\delta^{13}C$.¶
3.4 Grete-Ruth Sample¶
3.4.1 HUN-14¶
The whole length of HUN-14, which contains two hiatuses, was analysed in this study. The calcite contains between 400 to 900 µg g^{-1} of ^{238}U and is extremely clean with $^{230}Th/^{232}Th_{atomic}$ ratios between 3,000 x10^{-6} to 110,000 x10^{-6}. The final age model, covering the period 111.3 ± 0.3 to 102.9 ± 0.2 ka was constructed from 34 U-Th ages. The model has a resolution of 4 to 24 years (mean 10 years) per stable isotope measurement and a growth rate that varies between 11 to 57 mm ka^{-1} (35 mm ka^{-1}). The R^2 between $\delta^{18}O$ and $\delta^{13}C$ is 0.2 thus indicating a negligible relationship between the two (SI Fig. 4). Four Hendy tests also show minimal variation ($\delta^{18}O$ is 0.2 to 0.4 ‰ and $\delta^{13}C$ is 0.3 to 0.9 ‰)(SI Table 3).¶
3.5 Gassel Samples¶
The six Gassel samples all display similar U-Th chemical characteristics with c. 200 to 500 µg g^{-1} of ^{238}U, and extremely clean calcite with high $^{230}Th/^{232}Th_{atomic}$ ratios (SI Table 2). Correction for detrital Th is thus negligible for the final ages of these samples.¶
3.5.1 GAS-12 and GAS-13¶
The age models for GAS-12 and GAS-13 were constructed from 12 and 13 high-precision U-Th ages respectively, covering the intervals 81.9 ± 0.2 to 77.0 ± 0.1 ka and 80.3 ± 0.2 to 76.9 ± 0.1 ka. GAS-13 thus grew synchronous with GAS-12 for the majority of the record presented here. The age models have a resolution of 4-17 years (mean 7 years) and 3-7 years (mean 5 years) per stable isotope measurement, respectively, and growth rates that vary between 26 to 61 mm ka^{-1} (mean 40 mm ka^{-1}) and 34 to 81 mm ka^{-1} (54 mm ka^{-1}), respectively (SI Table 1). $\delta^{18}O$ has a 2.3‰ range in GAS-12, between -8.0 to -10.3 ‰, whilst GAS-13 has a slightly lower range of 1.7‰ between -8.5 to -10.2 ‰. Hendy tests that were previously carried out on both samples reveal minimal

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decades in GAS25 (Table 2). The section of the record encompassing interstadial-23, stadial-24, and interstadial-24 is fully covered by GAS22, GAS27, GAS29 and HUN14, which are all extremely clean, well-dated records with typical dating precisions of 300 to 400 years (Table 2). Furthermore, the timing of the transition into interstadial-23 is reproducible to within 60 to 100 years between GAS27 and HUN14. The timing of the transition into stadial-24 is in agreement on the order of 40 to 60 years in GAS22, GAS29 and HUN14. Furthermore, the pattern of $\delta^{18}O_{calc}$ shifts across the whole interstadial 24 to 23 period is remarkably similar in the new speleothems analysed here to the pattern of events in NGRIP $\delta^{18}O_{ice}$ across the same period. This suggests the new speleothem samples are capturing a bigger-scale climate signal, unlike EXC3 and EXC4 from St. Beatus cave (Boch et al., 2011), which show a distinctly different pattern in $\delta^{18}O_{calc}$ across this time period. The reason for the difference is unknown, and is likely due to some local influence or control at the cave site. We acknowledge that there is still value in the St. Beatus records, but they are not ideal for investigations into leads, lags, and synchronicity when more comparable records exist, thus they are not included in NALPS19. Finally, the new record from HUN14 is used to complete the gap that existed previously at stadial-25.

In summary, important updates in the NALPS19 chronology (Figs. 2 and 3, SI Fig. 6) therefore include: (1) the addition of the cooling into GS-20: (2) a revision of the GI-20c/GS-21.1/ GI-21.1a period using multiple cleaner samples; (3) revision of the warming into GI-21.1e and cooling into GS-22, also using a cleaner sample; and (4), revision of the interval GI-23.1 to GI-25c, which includes the addition of the previously absent GI-25a and b and a more distinctive 'shape' to GS-24 in-line with NGRIP.

5.2 Chronological implications

Fig. 3 (split into 20,000 year time slices in SI Fig. 6) shows the NALPS19 $\delta^{18}O_{calc}$ record in comparison to other well-dated $\delta^{18}O$ records from distant Northern Hemisphere regions over the interval 60 to 120 ka. Comparison of NGRIP and NALPS19 shows that the broad-scale pattern of shifts in $\delta^{18}O$ was remarkably similar during this period, including down to centennial-scale events. Differences do, however, arise when considering the timing and duration of events, which we investigate further by applying the ramp-fitting function of Erhardt et al. (2019). The ramp-fitting function is similar to the one used by Mudelsee (2000), but instead uses probabilistic inference to define a transition via a linear ramp between two constant levels. Such an approach enables the accurate chronological quantification of climate transitions (Mudelsee, 2000), as well as the consistent treatment of records, unlike the more subjective approach of taking the first data-point that deviates from the baseline of the previous climate state (e.g. Capron et al., 2010a; Moseley et al., 2014; Rasmussen et al., 2014), which is often not so ambiguous. Adolphi et al. (2018) applied such a ramp-fitting method to the younger, late glacial portion of the NGRIP $\delta^{18}O_{ice}$ record (Adolphi et al., 2018), whereas Steffensen et al. (2008) applied another ramp-fitting method through the last deglacial. For this study, ramp fitting was applied to: (1) $\delta^{18}O_{calc}$ of the new NALPS19 record (this study); (2) $\delta^{18}O_{calc}$ of the Asian monsoon composite speleothem record (Cheng et al., 2016); (3) NGRIP $\delta^{18}O_{ice}$ on the $GICC05_{modelext}$ chronology, which is comprised of a composite layer-counted chronology to 60 ka (Svensson et al., 2008) followed by splicing of the ss09sea-modelled chronology (Johnsen et al., 2001) between 60 to 122 ka onto the younger annual-layer counted chronology (Wolff et al., 2010); (4) NGRIP $\delta^{18}O_{ice}$ on the AICC2012 chronology, which is constructed using glaciological inputs, relative and absolute gas and ice stratigraphic markers, and Bayesian modelling (Veres et al., 2013), and; (5) NGRIP $\delta^{18}O_{ice}$ on the AICC2012 chronology updated by aligning $\delta^{18}O$ of the atmosphere as measured in EPICA Dome C with $\delta^{18}O_{calc}$ of Chinese speleothems (Extier et al., 2018).

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Results of the ramp-fitting are shown in Table 3, Figs. 4 and 5, and SI Fig. 7. Unfortunately, results are not available for some transitions because their shape is incompatible with the transition model, which requires stable periods before and after the transitions. Where multiple NALPS19 speleothems grew synchronously, excellent agreement is found in the absolute timing of transitions, which show differences from as low as 10 years between GAS12 and GAS13 during the endpoint of the transition into GS-21.1, up to a maximum of only 163 years difference between GAS22 and HUN14 during the endpoint of the transition into GS-24.1 (i.e., within the 318 years uncertainty of GAS22 at this point) (Table 3, Fig. 4). Similarly, for the NGRIP $\delta^{18}O_{ice}$ record on the $GICC05_{modelext}$ chronology, we find that the timing of the start of the respective transitions are in excellent agreement (2 to 119 years) between the ramp-fitting used in this study and the INTIMATE event stratigraphy scheme (Rasmussen et al., 2014) (Table 3). Comparison between the timing of the ramp-fitted transitions in NALPS19 and the Asian monsoon speleothem records also show excellent agreement within centennial-scale uncertainties, with the exception of GS-20, which is older in NALPS19 by c. 900 years (Table 3, Figs. 4 and 5). The NALPS19 age for GS-20 is, however, in very good agreement on a multi-decadal scale with the $GICC05_{modelext}$ chronology (details below). It should be noted that a comprehensive comparison of the timing of transitions between NALPS19 and NGRIP on the three ice-core chronologies is made difficult because of the large uncertainties associated with AICC2012 (c. 3,000 – 3,200 years; Veres et al., 2013) and even the absence of uncertainties associated with $GICC05_{modelext}$ (Wolff et al., 2010). To deal with the absence of uncertainties in $GICC05_{modelext}$, we take the approach of Abbott et al. (2012) and extrapolate the linear trend in ratio between age and uncertainty from the layer-counted 0-60 ka GICC05 chronology (Svensson et al., 2008), which yields an uncertainty of c. 4.5 % by 120 ka (Table 3, Fig. 4). In reality, the uncertainty is likely to be considerably less since well-dated markers exist in some places (e.g. Guillou et al., 2019). Nevertheless, if only the central age is considered (where + indicates the respective chronology is earlier=older than NALPS19, and – is vice versa), excellent agreement in the absolute timing of the transition is displayed between NALPS19 and $GICC05_{modelext}$ for GS-20, which is offset by c. -45 years, and GI-21.1, which is offset by c. +20 to +80 years (Table 3, Figs. 4 and 5). Depending on the speleothem to which the comparison is made, the transition into GI-23.1 is offset by c. +230 to +290 years (HUN14) or c. +340 to +390 years (GAS27). The other transitions into GI-20 (+560 to +650 years), GS-21.1 (+490 to +570 years), GS-24.1 (-440 to -460 years), and GI-24.2 (c. -550 years) display the largest of the offsets (Table 3, Fig. 4 & 5). Comparison between NALPS19 and NGRIP on AICC2012 shows good agreement in the timing of GS-21.1 (c. +8 to -40 years) and GI-20 (+50 to +140 years). The timing for GS-21.1 is further supported in this instance by the close agreement also of the Asian monsoon composite chronology (-70 to -150 years) (Fig. 5). Elsewhere, the transitions in the NALPS19 chronology are consistently earlier than their counterparts in the AICC2012 chronology i.e. GS-20 (c. -400 years), GI-21.1 (c. -500 years), GI-23.1 (c. -1,900 years), GS-24.1 (c. -2,700 years), and GI-24.2 (c. -2,960 years) suggesting that some revision of the AICC2012 chronology may be needed. Extier et al. (2018) have also proposed such a revision for the period 100 to 120 ka, which is the interval in which there is the greatest discrepancy between AICC2012 and NALPS19. Application of the ramp-fitting to the Extier et al. (2018) revised AICC2012 chronology ($AICC2012_{Extier}$) shows that there is much better agreement with NALPS19 during the 100 to 120 ka interval than existed for AICC2012 (Figs. 4 and 5). Specifically, the offset for GI-23.1 is c. +350 years, GS-24.1 is c. -400 years, and GI-24.1 is c. -700 years.

The ramp-fitted transitions have also enabled an assessment of the duration of $\delta^{18}O$ transitions in the respective chronologies (Table 3, Fig. 5). The quickest shift of 21 years is displayed for the $AICC2012_{Extier}$ transition into

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GI-20, whereas the longest shift of 489 years is present in NALPS19 for the transition into GS-19.2. Consistency in the duration of transitions between NALPS19 and the Greenland chronologies is displayed in particular for GS-20 (211 to 236 years), GS-21.1 (204 to 243 years), GS-24.1 (73 to 96 years), and GI-24.2 (32 to 47 years) (Table 3, Fig. 5). The difference in durations for GI-21.1 (54 to 107 years) and GI-23.1 (68 to 138 years) is slightly larger but still comparable on multi-decadal timescales. The duration of GI-23.1 in the Asian monsoon is also comparable at 81 years. The greatest difference between NALPS19 and the Greenland chronologies is displayed for GI-20, which varies between 21 to 114 years. Interestingly, with the exception of GI-23.1, the duration of transitions in the Asian monsoon are considerably longer (on multi-centennial timescales) than for the North Atlantic–sourced NALPS19 and Greenland chronologies (on multi-decadal timescales) (Table3, Fig. 5).

The NALPS19 chronology also enables a new consideration of the duration of GS-22, which previously has been the subject of debate given the various different timescales presented in the literature (Boch et al., 2011; Vallelonga et al., 2012). Here, we use the same strategy as for the previous studies and define the duration of GS-22 as being from the mid-point of the $\delta^{18}O$ transition into GS-22 until the start of the $\delta^{18}O$ transition into GI-21.2 (Capron et al., 2010a; Vallelonga et al., 2012). The 'precursor event' is defined as the start of the $\delta^{18}O$ transition into GI-21.2 until the midpoint of the $\delta^{18}O$ transition into GI-21.1e. All uncertainties are at the 95% confidence interval. Based on multi-proxy annual layer-counting, Vallelonga et al. (2012) proposed the duration of GS-22 in the NGRIP ice to be 2,894 ± 198 years and the 'precursor event' to be 350 ± 19 years (together 3,244 ± 199 years, two sigma error; Table 4). The Vallelonga et al. (2012) layer-counted chronology thus indicated a longer duration for GS-22 than the GICC05$_{modelext}$ chronology (2,620 years) and a shorter duration for the precursor event (300 years) (together 2,920 years; Table 4) (Wolff et al., 2010). The ramp fitting function was not able to constrain the transition into the precursor event (GI-21.2), thus we consider here the duration of the full period from the cooling into GS-22 to the warming into GI-21.1e, which in the NALPS19 chronology is 3,993 ± 155 years (Table 4). This finding is in agreement with the duration from the previous NALPS chronology of 3,660 ± 526 years (Table 4), but is c. 1,000 years longer than in GICC05$_{modelext}$ and 750 years longer than in the layer-counted chronology (395 years if the uncertainties are considered). In contrast, a relatively long duration of 4,122 ± 650 years has been proposed for NGRIP on the EPICA Dronning Maud Land (EDML) Antarctic ice core chronology (Capron et al., 2010b; Vallelonga et al., 2012), which is in agreement with the duration from NALPS19. Additionally, the duration of the same period as estimated from the Asian monsoon composite record is 4,489 ± 960 years. The speleothem $\delta^{18}O_{calc}$ records from both the Alps and China therefore support a longer-duration GS-22 - GI-21.2 - GS-21.2 period in line with the NGRIP-EDML chronology (Capron et al., 2010b; Vallelonga et al., 2012).

5.3 NALPS $\delta^{18}O$ variability during the last glacial period (15-120 ka)

Speleothem deposits from the northern rim of the Alps now provide a near-complete record of $\delta^{18}O_{calc}$ variability during the last glacial period (Fig. 6; Boch et al., 2011; Moseley et al., 2014; Luetscher et al., 2015), which is remarkably similar to $\delta^{18}O$ variability recorded in the NGRIP Greenland ice core during the same period. It is hypothesised that the moisture source for both regions during the last glacial period was the North Atlantic, with the primary control on the $\delta^{18}O$ of precipitation in both Greenland and the Alps being temperature (Boch et al., 2011). Changes to the transport pathway have, however, been proposed for the northern Alpine speleothem record of the Last Glacial Maximum (LGM) between 26.5 and 23.5 ka induced by a southward shift in the North

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Atlantic storm track (Luetscher et al., 2015). The change to the transport pathway is, however, only considered to affect the LGM and not the remainder of the glacial (Luetscher et al., 2015).

We now consider the full glacial Alpine speleothem $\delta^{18}O_{calc}$ record in further detail. In addition to the NALPS records of Boch et al. (2011), Moseley et al. (2014) and NALPS19 (this study), we also consider an MIS 5 record from Siebenhengste (SI Fig. 9), a large cave system located on the northern rim of the Alps of Switzerland (Fig. 1), and a record from Kleegruben cave (Spötl et al., 2006), which is located in the Central Alps of Austria to the north of the main Alpine crest (Fig. 1). A thorough investigation of the controls on the $\delta^{18}O$ of precipitation would require a sophisticated modelling approach, which is beyond the scope of this paper, thus here we appreciate that our investigation is a first consideration only. Furthermore, given the many different factors that can influence the $\delta^{18}O$ of precipitation (Dansgaard, 1964; Rozanski et al., 1993; Clark and Fritz, 1997), it would be advantageous to have stable isotope information from fluid inclusions. Unfortunately, the speleothems presented here are largely devoid of fluid inclusions (Brandstätter, unpubl. data).

Today, temperature has been shown to have the most dominant control on the $\delta^{18}O$ of precipitation along the northern rim of the Austrian Alps (Kaiser et al., 2002; Hager and Foelsche, 2015), though other factors such as a changing moisture source, rain-out along the different transport pathways (continental effect), altitude (altitude effect), the North Atlantic Oscillation, and locally also the amount of rain (amount effect) all have some additional control (Ambach et al., 1968; Dray et al., 1998; Kaiser et al., 2002; Hager and Foelsche, 2015; Deininger et al., 2016). To consider the effects of these controls on the $\delta^{18}O$ of precipitation during the last glacial period, we have first removed from the speleothem records the variability in mean ocean $\delta^{18}O$ caused by et al. (2012).

Mean speleothem $\delta^{18}O_{calc}$ values for individual stadials and interstadials in the ice-volume corrected record have been calculated for each sample (Fig. 7a, SI Fig. 8, SI Table 3). Excluding the samples associated with the LGM because of the different transport pathway (Luetscher et al., 2015), the $\delta^{18}O_{calc}$ range in mean interstadial values is 5.0 ‰ (Klaus Cramer (-7.9 ‰) and Siebenhengste (-7.9 ‰) to Kleegruben (-12.9 ‰)), whilst the range in mean $\delta^{18}O_{calc}$ stadial values is slightly larger (but comparable) at 5.4 ‰ (Siebenhengste (-9.5 ‰) to Kleegruben (-14.9 ‰)) (Fig. 7a). We now consider the controls on $\delta^{18}O_{calc}$ during periods when more than one speleothem was deposited, specifically GI-23.1, GS-23.2, GI-24.1, and GS-24.1. Given the remarkable similarity with the $\delta^{18}O_{ice}$ record for Greenland, which is controlled predominantly by temperature variability (Johnsen et al., 2001), it is considered that the dominant control on the $\delta^{18}O$ of precipitation in the northern and central Alps during the last glacial period was temperature, and the dominant moisture source was the North Atlantic (as both are today). The correlation between both temperature and distance from the North Atlantic as compared to mean $\delta^{18}O_{calc}$ was investigated to identify potential continental and rainout effects. In all instances, mean $\delta^{18}O_{calc}$ became increasingly lighter with increasing distance from the North Atlantic; a medium correlation is displayed for GI-23.1 (r^2=0.64, n=4), GS-23.2 (r^2=0.63, n=3), GS-24.1 (r^2=0.57, n=4, two samples for Gassel), and a lower correlation during GI-24.1 (r^2=0.16, n=3). This trend of lighter mean $\delta^{18}O_{calc}$ with increasing distance from the source would be expected with progressive rainout and is consistent with present day observations.

Today, spatial variability of the $\delta^{18}O$ of precipitation in the Austrian Alps is highly dependent on altitude (Hager and Foelsche, 2015). We find that medium to strong correlations between catchment elevation and mean $\delta^{18}O_{calc}$ existed during GI-23.1 (r^2=0.49, n=4), GI-24.1 (r^2=0.67, n=3), GS-23.2 (r^2=0.79 n=3), and GS-24.1 (r^2=0.74, n=4 (Gassel has 2 samples)) (Fig. 7c). For GI-24.1, the relationship shows that mean $\delta^{18}O_{calc}$ becomes increasingly lighter with increasing elevation (as would be expected for altitudinal controls on $\delta^{18}O$ of

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precipitation). In contrast, the other examined time periods show an inverse relationship to what would be expected for altitudinal control, with mean $\delta^{18}O_{calc}$ becoming heavier with increasing elevation (Fig. 7c). Since GI-24.1 is the only event that does not contain the high-elevation Siebenhengste site, the mean $\delta^{18}O_{calc}$ of 7H-12 was removed from the linear regression analysis for the three time periods showing an inverse relationship (Fig. 7d). This resulted in a switch to increasingly lighter mean $\delta^{18}O_{calc}$ with increasing elevation for GI-23.1, GS-23.2 and GS-24.1 (Fig. 7d) (i.e. in line with an altitudinal control on $\delta^{18}O$ of precipitation).

Given that there is such limited availability of multiple speleothem $\delta^{18}O$ records covering the same time periods, it is difficult to make firm conclusions on the controls of $\delta^{18}O_{calc}$. Here though we offer some hypotheses based on the available data. We have shown that for a given time period $\delta^{18}O_{calc}$ trends towards lighter values with increasing distance from the North Atlantic (Fig. 7b). Despite this, there is some variability overprinted on top of this trend. For instance, even though Grete-Ruth is closer to the North Atlantic than Gassel cave, mean $\delta^{18}O_{calc}$ values for Grete-Ruth are consistently lighter than for Gassel (Fig. 7b). Since Grete-Ruth is located at a higher elevation than Gassel cave (Fig. 7c), the lighter mean $\delta^{18}O_{calc}$ values are likely a product of the altitude effect and associated cooler temperatures. In comparison, St. Beatus and Siebenhengste caves are located within 10 km of one another, and are the closest caves to the North Atlantic of all the caves investigated here. As expected, mean $\delta^{18}O_{calc}$ values are heavier for St. Beatus and Siebenhengste than for Grete-Ruth or Gassel caves (Fig. 7b). Closer investigation, however, shows that during GI-23.1, mean $\delta^{18}O_{calc}$ of the low elevation St. Beatus is lighter than the high-elevation Siebenhengste (Fig. 7b). Given the close proximity of the two caves, the condensation level (and therefore condensation temperature) would have been approximately the same, thus one must consider the reason for the difference in mean $\delta^{18}O_{calc}$ for these two caves. Since the three caves at lower elevation (St. Beatus, Gassel, Grete-Ruth) follow the expected altitude-induced trend of lighter mean $\delta^{18}O_{calc}$ with increasing elevation (Fig. 7d), it seems the anomaly lies with the high-elevation 7H-12 stalagmite from Siebenhengste. One reason for the heavier-than-expected mean $\delta^{18}O_{calc}$ at Siebenhengste could be that the full annual signal is better preserved at high-elevation sites that are less exposed to evapotranspiration effects during the summer season than in more vegetated catchments. Alternatively, a summer bias towards isotopically heavier $\delta^{18}O_{calc}$ at the high-elevation site could for instance be caused by wind erosion resulting in relocation of the isotopically-light winter snow, a process that has been well-documented at various Alpine sites (Ambach et al., 1968; Bohleber et al., 2013; Hürkamp et al., 2019). Eventually, if firn developed above Siebenhengste during GI-23.1, then this would also limit the input of isotopically-light precipitation causing a summer bias in the recorded signal. At present there is, however, no evidence to either support or reject the hypothesis of firn above Siebenhengste during MIS 5.

In summary, speleothems from the northern rim of the European Alps provide $\delta^{18}O_{calc}$ records for the majority of the last glacial period. As expected, the limited data set shows that mean $\delta^{18}O_{calc}$ for specific stadials and interstadials generally trends towards lighter values with increasing distance from the coast and with increasing altitude. An exception is the high-elevation 7H-12 stalagmite from Siebenhengste, which appears to record a stronger summer signal. Further investigation of the controls on $\delta^{18}O_{calc}$ in the northern Alps requires a more sophisticated modelling approach.

5.4 Stadial-level centennial-scale cold events

The recognition of centennial- to millennial-scale climate events, such as ‘precursors’ to interstadials and within-interstadial depletions in $\delta^{18}O_{ice}$ (Capron et al., 2010a), led to the designation of the INTIMATE event

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stratigraphy for the Greenland ice cores over the last glacial period (Rasmussen et al., 2014). Typically, a 'precursor-event' is a feature of a stadial-interstadial transition; this includes GS-16.2, 17.2, 21.2 and 23.2 (Fig. 8) (Capron et al., 2010a; Rasmussen et al., 2014). It is characterised in northern Alpine speleothems and Greenland ice cores by a rapid increase in $\delta^{18}O$ from stadial to interstadial conditions. The event is short-lived, lasting a maximum of a few centuries before $\delta^{18}O$ returns to near-stadial conditions for another few decades to centuries, followed by the main transition into the interstadial. $[Ca^{2+}]$ in the Greenland ice cores varies almost simultaneously with these $\delta^{18}O_{ice}$ changes, where increases in $[Ca^{2+}]$ are associated with depletions in $\delta^{18}O_{ice}$ and vice versa. Changes in $[Ca^{2+}]$ are interpreted to reflect changes in dust concentration caused by changes in dust source conditions and transport pathways indicative of regional-to-hemispheric-scale circulation changes (Ruth et al., 2007). In comparison, 'within-interstadial' climate perturbations are characterised in general by smaller-amplitude depletions in $\delta^{18}O_{ice}$ that typically do not reach stadial values, and are often of shorter duration than the reversals at stadial-interstadial transitions. $[Ca^{2+}]$ also varies in-tune with 'within-interstadial' $\delta^{18}O_{ice}$ fluctuations, but similarly does not reach full stadial values. Such characteristics appear to be consistent in $\delta^{18}O$ records from both Greenland ice cores and northern Alpine speleothems. The exception to such typical 'within-interstadial' cold perturbations is the event at 107.5 ka in the NALPS19 chronology, which is designated GS-24.2 in the INTIMATE event stratigraphy scheme (Rasmussen et al., 2014). This drop in $\delta^{18}O_{calc}$ to stadial values occurred 978 years after the start of the interstadial, thus firmly making it a 'within-interstadial' event rather than one associated with a stadial-interstadial transition. At present, the 107.5 ka-event (GS-24.2) is the only centennial-scale $\delta^{18}O$ event of such extreme amplitude occurring during an interstadial that is recognised in both Greenland and northern Alpine records. Because of this, it has been likened to the 8.2 ka cold event that occurred in the early Holocene (Alley et al., 1997; Capron et al., 2010a). Still, the $\delta^{18}O_{ice}$ excursion of the 8.2 ka event did not reach near-stadial values in NGRIP as GS-24.2 did, thus highlighting some differences between these two warm-interrupting cold reversals. In addition, Rasmussen et al. (2014) liken the 'within-interstadial' GS-24.2 cold perturbation to stadial-interstadial transition events GS-16.2 and GS-17.2. Both the similarities between GS-24.2 and the 8.2 ka event, as well as with GS-16.2 and GS-17.2, suggest that such abrupt climate variability is not critically influenced by the size of the Greenland ice sheet (Capron et al., 2010a; Rasmussen et al., 2014).

During the deglacial and early Holocene, large-scale meltwater events are widely suggested as being responsible for causing some short-term climate reversals through the weakening of Atlantic meridional overturning circulation (AMOC) (e.g., Broecker et al, 1994; Teller et al., 2002; Clark et al., 2001, 2004). Such cold reversals thought to be triggered by meltwater events include the Older Dryas at 14 ka (GI-1d, Rasmussen et al., 2014), the Preboreal Oscillation at 11.4 ka (e.g., Johnsen et al., 1992; Björck et al. 1996; Fischer et al., 2002), the 9.3 ka event (Fleitmann et al., 2008; Yu et al., 2010), and the 8.2 ka event (Alley et al., 1997). In contrast though, not all freshwater injections led to cold events, and not all cold events were caused by freshwater injections (Stanford et al., 2006). For instance, both the Younger Dryas and Heinrich events occurred during times of already-colder sea surface temperatures and weakened AMOC, indicating that the input of freshwater from the iceberg armadas was not the initial cause of the AMOC slowdown (e.g., Hall et al., 2006; Henry et al., 2016).

In the case of the centennial-scale cold reversals of GS-16.2, GS-17.2, GS-21.2, GS-23.2 and GS-24.2 (Fig. 8), a possible mechanism for each of these events could be similar to the meltwater-triggered cold reversals of the deglacial. This hypothesis is supported when considering that events GS-17.2, GS-21.2, and GS-24.2 occurred shortly following episodes of rapid sea-level rise, which were in excess of 12 m ka^{-1} in the high-resolution record

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of Grant et al. (2012)(Fig. 8). Such rapid sea-level rise does not appear to have occurred prior to GS-23.2, though closer inspection of the sea-level curve shows that following the rise prior to GS-24.2, sea levels had remained elevated and underwent a series of rapid oscillations that are smoothed out in the rate-of-change curve (Fig. 8). Likewise, GS-16.2 did not occur coincident with an episode of sea-level rise, but did occur shortly after the rise associated with GS-17.2 (Fig. 8). Additionally, the rapid rises in sea level each began at times of increased ice-rafted debris (IRD) in the North Atlantic (McManus et al., 1999, on U-Th timescale), weakened AMOC and increased ice volume as indicated by high benthic $\delta^{13}C$ and $\delta^{18}O_{plantic}$ values, respectively, as well as pluvial periods in Brazil caused by a southward shift of the intertropical convergence zone (ITCZ) (Wang et al., 2004) (Fig. 8). In the late glacial, such episodes are associated with Heinrich events (Wang et al., 2004). Furthermore during glacial terminations, the sequence of events has been shown to include a Heinrich event, followed by short-lived warming, then a millennial-scale return to cold conditions, and finally the transition to the interglacial (Cheng et al., 2009). Though on shorter timescales, the pattern of events during these specific stadial-interstadial transitions is similar to the pattern of events during glacial terminations. The oscillations of GS-16.2, GS-17.2, GS-21.2 and GS-23.2 at stadial-interstadial transitions can therefore be considered as being akin to the meltwater-triggered Preboreal Oscillation, which occurred shortly following the warming at the end of the Younger Dryas stadial during a time when considerable volumes of ice still existed, similar to the early glacial. These reversals at stadial-interstadial transitions during the early glacial period are therefore not so much warming events that punctuate cold periods (Capron et al., 2010a), but rathermore small-scale terminations that failed due to freshwater influx. On the other hand, GS-24.2, which occurred nearly 1,000 years after warming occurred, is more similar to the Older Dryas in which a cold event punctuated a warm interval.

6 Conclusions

In this paper, we present the most recent chronology, named NALPS19, for $\delta^{18}O_{calc}$ variability as recorded in speleothems that grew during the last glacial period between c. 15 and 120 ka along the northern rim of the Alps. In particular, we have updated the record between 63.7 to 118.3 ka, using eleven cleaner, more accurately and precisely dated samples from five caves. Over the 63.7 to 118.3 ka interval, the record is now 90% complete. Ramp-fitting analysis of the transitions between stadials and interstadials shows that $\delta^{18}O$ shifts in the North Atlantic realm occurred on multi-decadal timescales, whereas transitions in the Asian monsoon occurred on multi-centennial timescales. Further, the absolute timing of shifts show good agreement between NALPS19 and Greenland ice core chronologies within the multi-millennial-scale ice core uncertainties, though absolute offsets are often on multi-decadal to multi-centennial scales. Major differences do, however, arise when comparing NALPS to NGRIP on AICC2012 between 100 to 120 ka, suggesting that the AICC2012 chronology is too young by c. 3,000 years in this time period. Additionally, we propose that the duration of the highly-debated GS-22 - GI-21.2 - GS-21.2 interval was 3,993 ± 155 years, which is in closer agreement to the duration of 4,122 ± 650 years in NGRIP-EDML (Capron et al., 2010b) and the 4,489 ± 960 years of the Asian monsoon composite record (Kelly et al., 2006; Kelly, 2010; Cheng et al., 2016). Preliminary investigation of the trends in mean $\delta^{18}O_{calc}$ as recorded in the NALPS speleothems for different interstadials and stadials reveals that for a given time period, as expected, $\delta^{18}O_{calc}$ becomes lighter with increasing distance from the source and increasing elevation. Exceptions are found at one high-elevation site, which appears to record a stronger summer signal. Finally, our accurate and precise chronology enables a deeper investigation of centennial-scale cold reversals

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that occurred either as ‘precursor events’ (i.e., GS-16.2, GS-17.2, GS-21.2, GS-23.2; Capron et al., 2010a) or during interstadials (i.e. GS-24.2). Each of these events occurred in the decades and centuries following rapid rises in sea level of over 12 m kyr^{-1} (Grant et al., 2012) that occurred coincident with IRD events (McManus et al., 1999) and shifts in the ITCZ causing speleothem growth in Brazil (Wang et al., 2004). We therefore propose that these centennial-scale cold reversals are products of freshwater discharge into the North Atlantic during times of moderate ice sheet size, which caused a slowdown of the AMOC and associated atmospheric cooling, similar to deglacial events such as the Preboreal Oscillation or Older Dryas.

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Data availability

The stable isotope data both on distance along growth axis and OxCal age models are available at both SISAL and the US National Oceanic and Atmospheric Administration (NOAA) data center for paleoclimate (speleothem site) at the following address: TBC

Author contribution

GM undertook the majority of the U-Th analyses, interpreted the data, and wrote the manuscript. CS conceived the project and carried out field work together with GM and partly SB. SB undertook additional U-Th analyses, prepared and ran Hendy tests and stable-isotope samples. TE developed and ran ramp-fitting models. ML provided data. RLE provided analytical U-Th facilities. All authors directly contributed to the manuscript through discussion or writing.

Competing interests

The authors declare that they have no conflict of interest.

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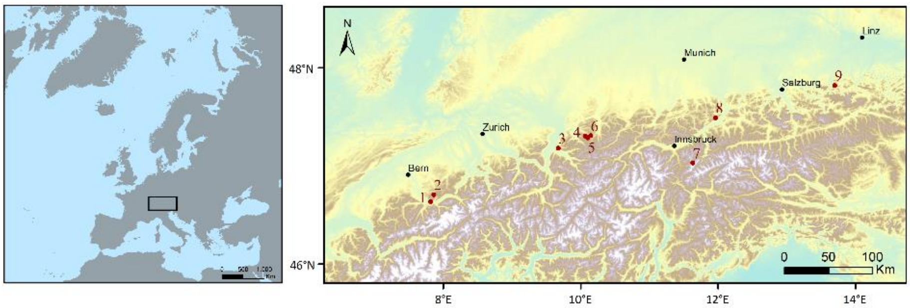

Figure 1: Map of cave sites discussed in text. 1. St. Beatus cave; 2. Siebenhengste cave; 3. Große Baschg cave; 4. Schneckenloch cave; 5. Klaus Cramer cave; 6. Hölloch cave; 7. Kleegruben cave (part of wider discussion on isotopic controls); 8. Grete-Ruth Shaft; 9. Gassel cave.

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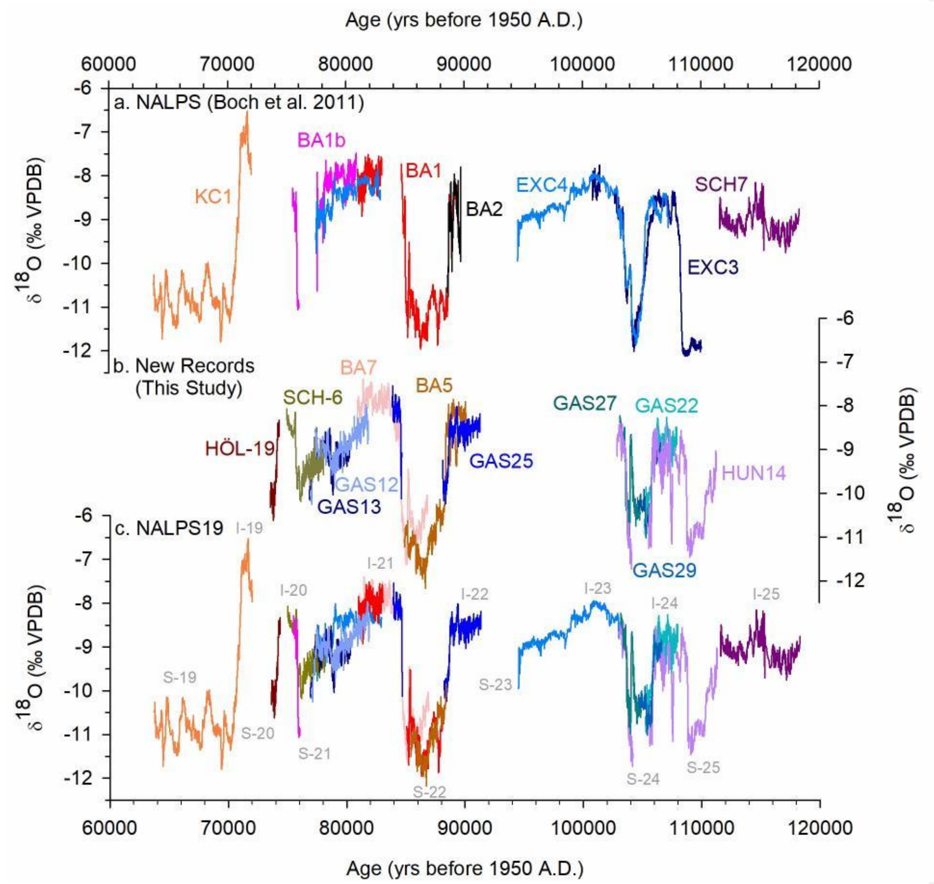

Figure 2: NALPS δ18O speleothem records a. Original NALPS record of Boch et al. (2011); b. new records from this study; c. the most reliable records of Boch et al. (2011) and this study combined to form NALPS19. Grey numbers in c indicate the stadial (S) and interstadial (I) nomenclature.

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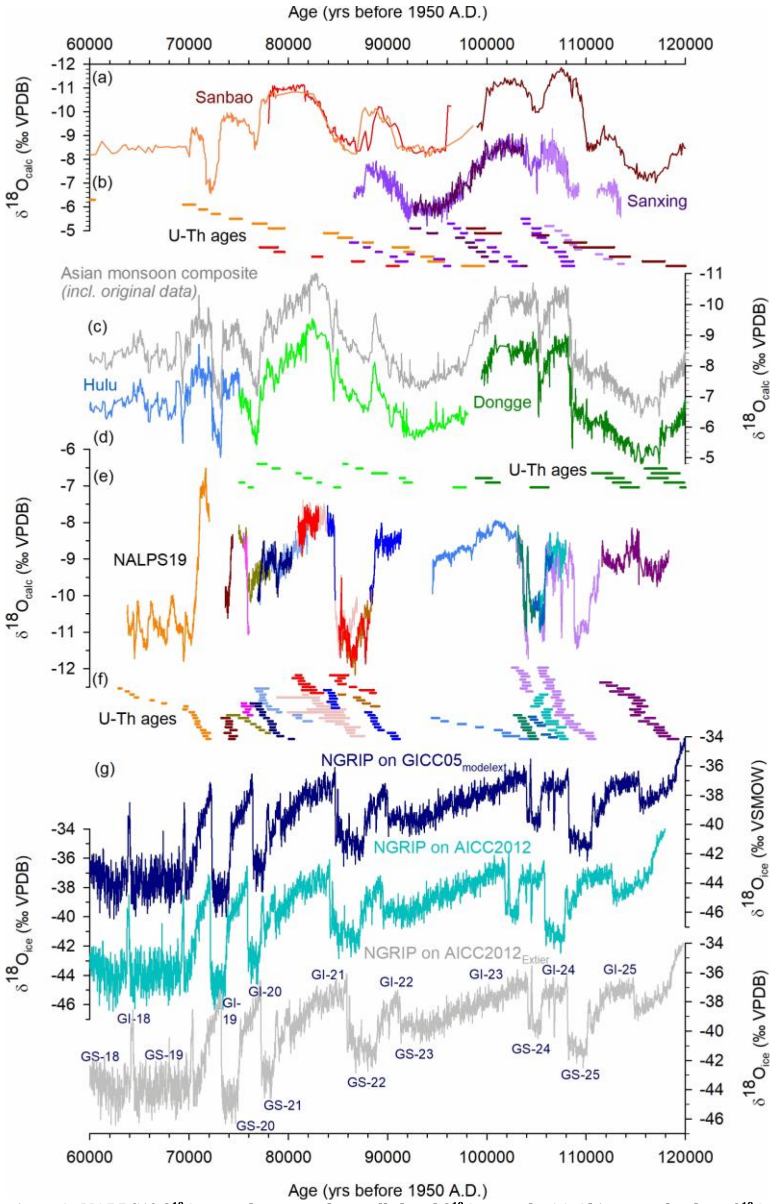

Figure 3: NALPS19 $\delta^{18}O$ record versus other well-dated $\delta^{18}O$ records. (a) Chinese speleothem $\delta^{18}O$ records from Sanbao (Wang et al., 2004) and Sanxing caves (Jiang et al., 2016). (b) 2σ range of U-Th ages used to produce (a) are colour-coded the same as (a). (c) Asian monsoon composite record (Cheng et al., 2016) as well as the original data from which it was constructed (revised Hulu record; Cheng et al., 2016; Dongge; Kelly et al., 2006; Kelly, 2010). In Cheng et al., (2016), the Dongge and Hulu $\delta^{18}O$ values are reduced by 1.6 ‰ in the composite record to match the Sanbao record of Wang et al., (2008). (d) 2σ range of U-Th ages used to produce (c) are colour-coded the same as (c). (e) NALPS19 record (this study). (f) 2σ range of U-Th ages used to produce (e) are colour-coded the same as (e). (g) NGRIP records on the GICC05$_{modelext}$ chronology (Svensson et al., 2008; Wolff et al, 2010), AICC2012 chronology (Veres et al., 2013), and AICC2012 revised according to Extier et al. (2018). To see this graph split into 20,000 year slices and with the INTIMATE event stratigraphy scheme (Rasmussen et al., 2014), see SI Fig. 6.

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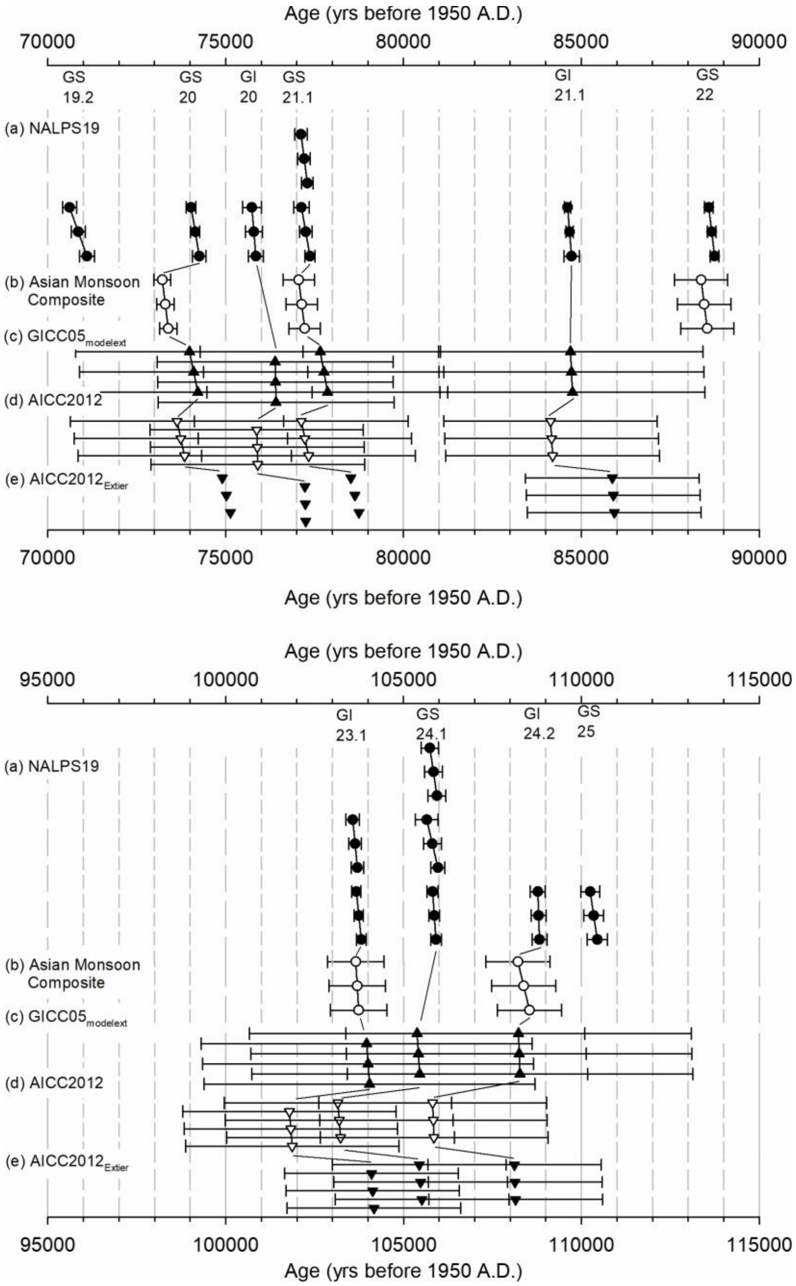

Figure 4: The timing of transitions as defined by the ramp-fitting model of Erhardt et al. (2019) in (a) NALPS19 $\delta^{18}O_{calc}$ record (this study); (b) Asian monsoon composite speleothem $\delta^{18}O_{calc}$ record (Kelly et al., 2006; Kelly, 2010; Cheng et al., 2016); (c) NGRIP $\delta^{18}O_{ice}$ record on GICC05$_{modelext}$ chronology (Wolff et al, 2010); (d) NGRIP $\delta^{18}O_{ice}$ record on AICC2012 chronology (Veres et al., 2013); NGRIP $\delta^{18}O_{ice}$ record on the Extier et al (2018) revised AICC2012 chronology. Each ramp-fit relative to its reference curve is given in SI Fig. 7. The GICC05$_{modelext}$ chronology does not contain uncertainties in this time period (Wolff et al., 2010) thus these errors are based on the

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maximum counting error of Svensson et al. (2008). Extier et al (2018) quote an uncertainty of 2,440 years (2 sigma) in MIS 5. Uncertainties are not given outside of MIS5.

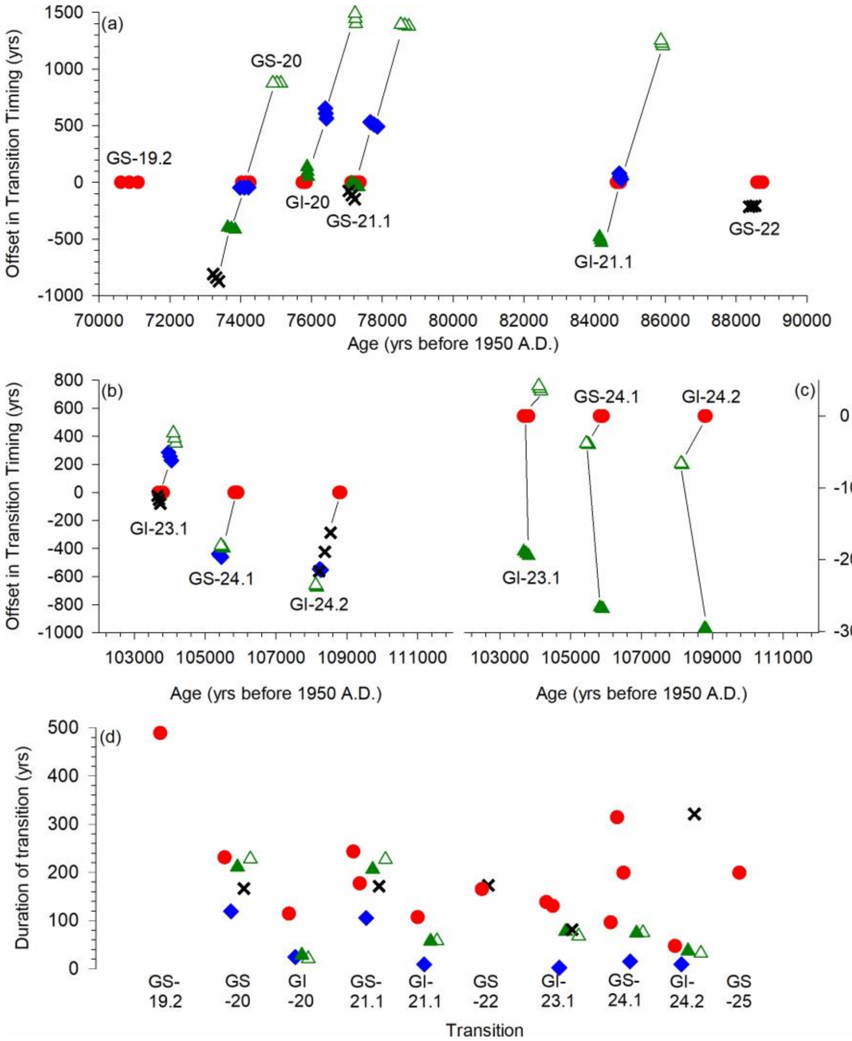

Figure 5: (a) (b) (c) Offsets in absolute chronology relative to NALPS19 of transitions into stadials and interstadials as defined by the ramp fitting applied in this study. (+) values indicate the timing in the respective chronology is older=earlier than in NALPS19. (-) values indicate the timing in the respective chronology is younger=later than in NALPS19. (d) Duration of transitions. NALPS19 (red circles, this study); NGRIP on GICC05$_{modelext}$ chronology (blue circles, Wolff et al, 2010); NGRIP on AICC2012 chronology (green triangle, Veres et al., 2013); NGRIP on Extier et al (2018) revised AICC2012 chronology (open green triangle); Asian monsoon composite speleothem (black crosses, Kelly et al., 2006; Kelly, 2010; Cheng et al., 2016).

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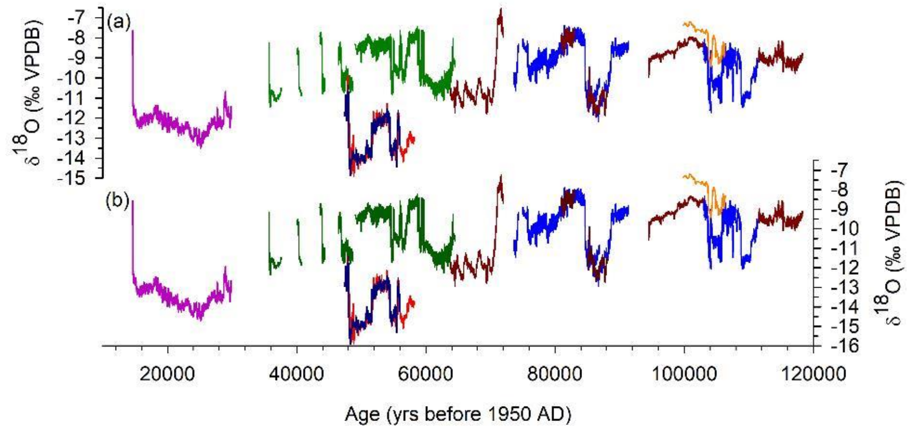

Figure 6: Speleothem $\delta^{18}O$ records from the northern rim and central European Alps. (a) Original records: pink (Luetscher et al., 2015), green (Moseley et al., 2014), red and dark blue (Spötl et al., 2006), dark red (Boch et al., 2011 contained in NALPS19), medium blue (new record in this study), orange (Luetscher see SI Table 4 and SI Fig, 10). (b) $\delta^{18}O$ records corrected for $\delta^{18}O$ variability as a result of changing ice volume. Colour codes the same as in (a).

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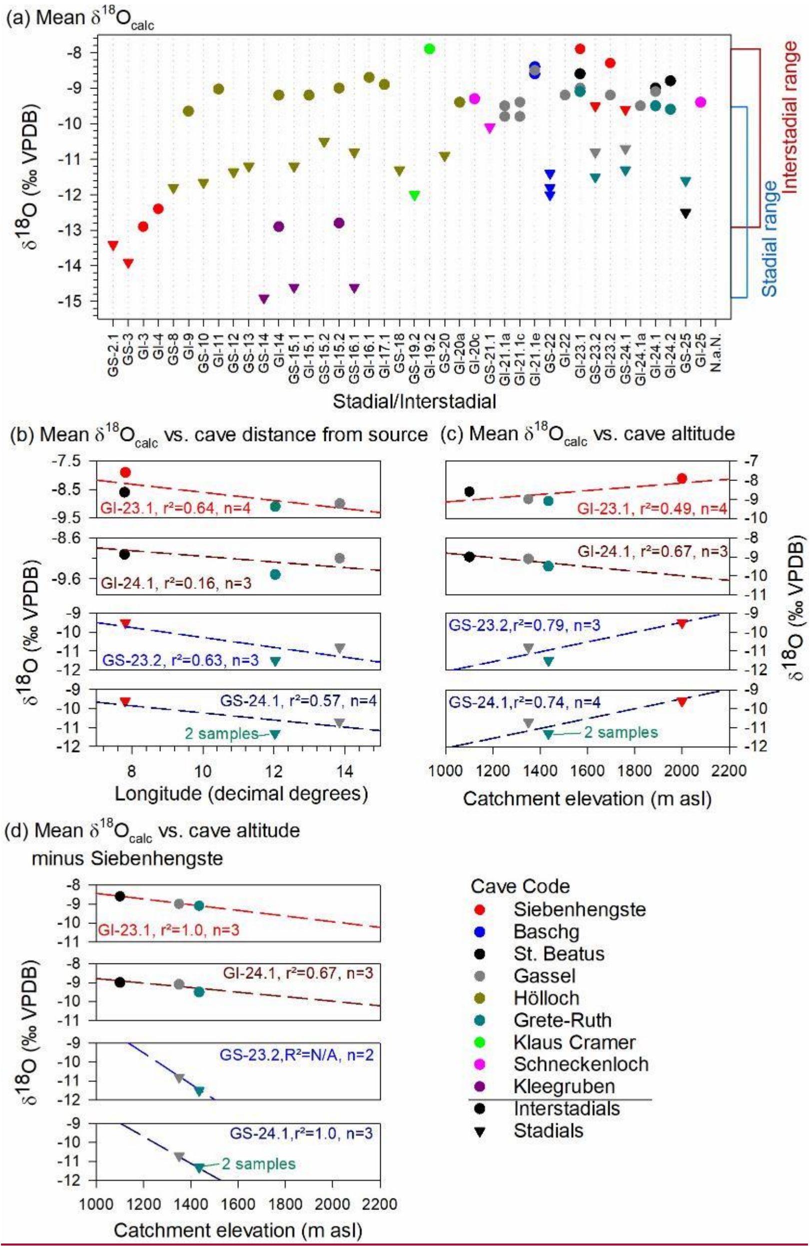

Figure 7: (a) Mean $\delta^{18}O_{calc}$ for individual caves during specific stadials (triangles) and interstadials (circles). (b) Mean $\delta^{18}O_{calc}$ values for specific time periods plotted relative to longitude. (c) Mean $\delta^{18}O_{calc}$ values for specific time periods plotted relative to catchment elevation. (d) Same as (c) minus the data for Siebenhengste.

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Deleted: Mean $\delta^{18}O$ values for specific interstadials and stadials (see SI Table 4 and SI Fig. 9). (a) Cave information. Catchment elevation (triangle). Sample location (cross). Cave depth range (vertical bar). Where cave depth is too small to see on this scale, the sample location is circled. Siebenhengste (red), St. Beatus (black), Baschg (blue), Klaus Cramer (green), Schneckenloch (pink), Hölloch (dark yellow), Kleegruben (dark pink), Grete-Ruth (cyan), Gassel (grey). (b) Cave temperature relative to elevation. Colours are the same as in (a). Black solid line represents the average lapse rate for the Eastern Alps based on instrumental data 1981-2010 (source: ZAMG).

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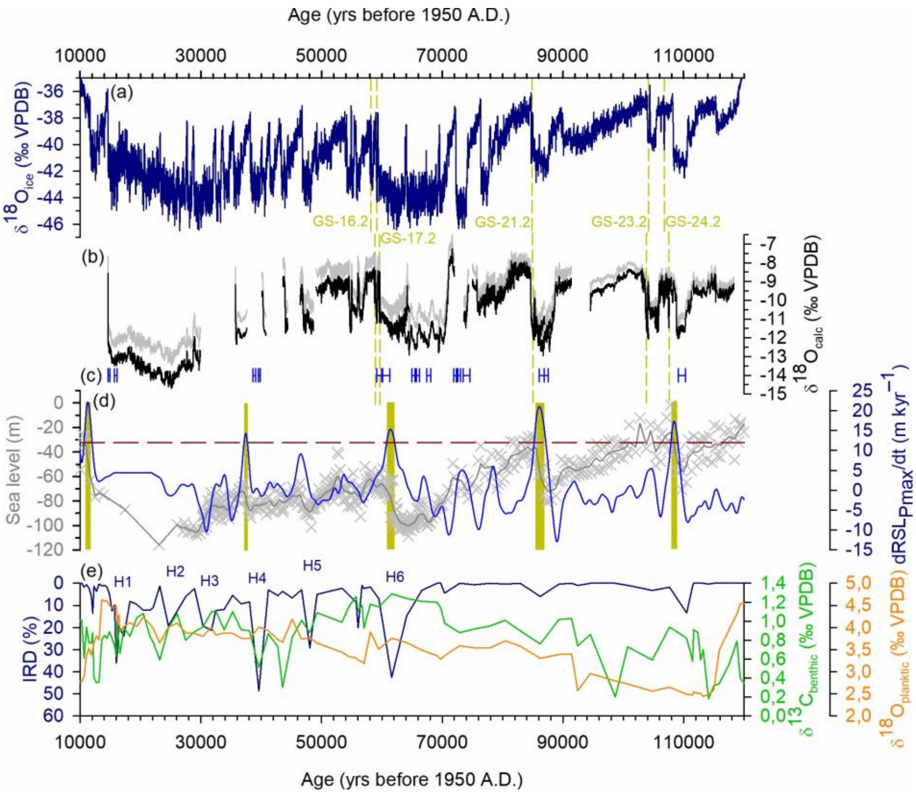

Figure 8: (a) NGRIP $\delta^{18}O_{ice}$ on GICC05$_{modelext}$ (Wolff et al., 2010). (b) NALPS19 $\delta^{18}O_{calc}$ uncorrected for variability in ocean $\delta^{18}O$ (grey), corrected for variability in ocean $\delta^{18}O$ (black). (c) Growth periods in Brazilian speleothem (Dark blue) (Wang et al., 2004). Centennial-scale cold reversals of 16.2, 17.2, 21.2, 23.2 and 24.2 are highlighted as vertical dashed yellow bars. (d) Sea-level variability (Grant et al., 2012). Relative sea-level data (grey crosses). Maximum-probability relative sea-level (grey line). Rate of sea-level change (blue line). Rate of 12 m kyr^{-1} indicated by horizontal red line. Peaks of sea-level change in excess of 12 m kyr^{-1} indicated by yellow bars. (e) Ice-rafted debris (dark blue), benthic $\delta^{13}C$ (green), and planktic $\delta^{18}O$ (orange) from ODP980 on Hulu U-Th age scale (McManus et al., 1999; Barker et al., 2011).

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Table 1. Details of caves and speleothem samples analysed in this study, presented from west to east. See Boch et al., (2011) for details of cave and samples from the previous NALPS study.

Cave	Location	Entrance Elevation (m a.s.l.)	Cave length (m)	Cave air temperature (°C)	Mean annual precipitation (mm)	$\delta^{18}O$ range (‰)	Sample	Sample length (mm)	Sample Notes
Großer Baschg	47.2501 N 9.6667 E	785	300	10	1,360[a]	-6.3 (Jul) to -15.8 (Nov)[1]	BA5	70	Honey-brown coloured stalagmite. Collected from the rear of the cave, c. 180 m from entrance, buried in loam above streamway.
							BA7	200	Honey-brown coloured stalagmite. Collected from the rear of the cave, c. 180 m from entrance, broken above streamway.
Schneckenloch	47.3745 N 10.0680 E	1,285[α]	3,500	6.0	2,073[b]	-6.9 (Jul) to -15.0 (Feb)[2]	SCH6	235	Modern stalactite and stalagmite deposition occurs in cave. SCH-6 is a honey-brown coloured stalagmite. Collected at the end of a small, well-decorated side passage, 350 m from the entrance.
Hölloch im Mahdtal	47.3779 N 10.1505 E	1,240 & 1,438[β]	10,900	5.6 ± 0.2[γ]	2,073[b]	-6.9 (Jul) to -15.0 (Feb)[3]	HÖL19	415	The cave is located 10km east of Schneckenloch. HÖL-19 was collected c. 800 m from the northwestern entrance and 600 m from the southern entrance. It has a variable internal structure alternating between dark brown calcite, opaque white calcite, and cemented loam layers. Only opaque white layers, which have a lower detrital Th content were analysed in this study.
Grete-Ruth	47.5429 N 12.0272 E	1,435[§]	142	4.5	1,327[c]	-6.7 (Jul) to -14.7 (Nov)[4]	HUN14	215	Honey-brown coloured stalagmite, 60 mm in diameter. Collected from the most northerly part of the system in a sheltered alcove at the base of the entrance shaft.
Gassel	47.8228 N 13.8428 E	1,225	5,000	5.2 ± 0.1	2,015[d]	-3.0 (Jul) to -21.5 (Dec)[5]	GAS12	530	Translucent white/greyish calcite stalagmites. All inactive at the time of collection from a chamber approximately 250 m from the entrance.
							GAS13	180	
							GAS22	110	
							GAS25	215	
							GAS27	210	
							GAS29	740	Same as for other Gassel samples except already broken in three parts. Here only the middle section is presented (135 mm long)

[a]recorded at the Feldkirch meteorological station located c. 5 km WNW from the cave at 438 m a.s.l. between 1981-2010 (ZAMG, 2018)
[b]recorded at the Schoppernau meteorological station located c.7 km SSW from the cave at 839 m a.s.l. (ZAMG, 2018)
[c]recorded at the Kufstein meteorological station located c.12 km ENE from the cave at 492 m a.s.l. (ZAMG, 2018)
[d]recorded at the Feuerkogel meteorological station located c. 10 km west from the cave at 1,618 m a.s.l. (ZAMG, 2018)

[1]nearest GNIP station is located 20 km SW at Sevelen (IAEA, 2018)
[2]nearest GNIP station is located 50 km WNW at St. Gallen (IAEA, 2018)
[3]nearest GNIP stations are located c. 57 km WNW at St. Gallen (-6.9 (Jul) to -15.0 (Feb) ‰) and 70 km ENE at Garmisch-Partenkirchen (-6.7 (Jul) to -14.7 (Nov) ‰) (IAEA, 2018)
[4]nearest GNIP station is located 73 km WSW at Garmisch-Partenkirchen (IAEA, 2018)

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[5]nearest GNIP station is located 10 km W at Feuerkögel (IAEA, 2018)

[α]Klampfer et al., (2017)
[β]Wolf (2006)
[γ]Spötl et al., (2011)
[§]Rittig (2012)

Table 2. Summary of the key features of the U-Th measurements, age modelling, and tests for isotopic equilibrium as presented in SI Tables 1 and 2, and SI Figs. 3 and 4.

Sample	^{238}U [ng g^{-1}]	^{230}Th / ^{232}Th (atomic $x10^{-6}$)	U-Th ages in age model	Stable isotopes in age model	Age model coverage (ka)	Resolution of age model (a), average in parentheses	Growth rate (mm ka^{-1}), average in parentheses	$\delta^{18}O$ range (‰)	$\delta^{18}O$ to $\delta^{13}C$ correlation (r^2)	Range of $\delta^{18}O$ across single growth layers (‰)	Range $\delta^{13}C$ across single growth layers (‰)
BA5	300 to 1,100	2,000 to 4,500	7	279	90.3 ± 0.3 to 85.0 ± 0.3	13 -24 (19)	10 – 20 (14)	-7.9 to -12.2	0.004	0.2 to 0.4	0.2 to 0.3
BA7	400 to 1,500	80 to 3,500	16	407	86.9 ± 0.3 to 80.9 ± 0.3	11 – 24 (15)	21 – 45 (34)	-7.4 to -11.6	0.3	0.3 to 0.4	0.4 to 0.5
SCH6	100 to 300	300 to 15,000	7	349	78.1 ± 0.4 to 75.0 ± 0.7	6 – 22 (9)	11 – 44 (32)	-8.1 to -10.2	0.0007	0.2 to 0.7	0.3 to 1.0
HÖL19	500 to 850	1,000 to 3,000	8	159	74.4 ± 0.2 to 73.6 ± 0.3	4 -5 (5)	46 – 68 (53)	-8.3 to -10.6	0.3	0.3	0.4
HUN14	400 to 900	3,000 to 110,000	34	707	111.3 ± 0.3 to 102.9 ± 0.2	4 – 24 (10)	11 – 57 (35)	-8.4 to -11.7	0.2	0.2 to 0.4	0.3 to 0.9
GAS12	200 to 500	10,000 to 400,000	12	751	81.9 ± 0.2 to 77.0 ± 0.1	4 – 17 (7)	26 – 61 (40)	-8.0 to -10.3	0.13	<0.5[1]	<1.0[1]
GAS13	100 to 500	7,000 to 230,000	13	692	80.3 ± 0.2 to 76.9 ± 0.1	3 – 7 (5)	34 – 81 (54)	-8.5 to -10.2	0.06	<0.5[1]	<1.0[1]
GAS22	200 to 400	25,000 to 420,000	16	530	108.0 ± 0.2 to 105.3 ± 0.1	2 – 16 (5)	13 – 100 (45)	-8.3 to -11.0	0.4	0.3 to 0.5	1.6 to 3.2
GAS25	250 to 450	6,000 to 420,000	17	630	91.4 ± 0.2 to 88.2 ± 0.09 84.7 ± 0.1 to 83.9 ± 0.2	4 – 8 (6)	30 – 61 (40)	-7.5 to -10.2	0.24	0.2 to 0.6	0.6 to 2.0
GAS27	250 to 600	50,000 to 560,000	9	240	104.9 ± 0.2 to 103.1 ± 0.2	6 – 9 (7)	29 – 39 (34)	-8.1 to -11.0	0.6	0.3 to 0.8	0.3 to 4.6
GAS29	250 to 350	13,000 to 240,000	6	256	106.6 ± 0.2 to 104.6 ± 0.1	7 – 9 (8)	28 – 36 (32)	-8.7 to -11.0	0.2	0.2 to 0.7	0.7 to 3.0

[1]Offenbecher (2004)

Table 3. Results of the ramp-fitting model runs for NALPS19 (this study), NGRIP on $GICC05_{modelext}$ (Wolff et al., 2010), AICC2012 (Veres et al., 2013), AICC2012 revised by Extier et al (2018), and the Asian monsoon composite (Kelly et al., 2006; Kelly, 2010; Cheng et al., 2016). All ages are reported relative to 1950 A.D. Uncertainties given are modelling uncertainties as marginal posterior standard deviations. Uncertainties in parentheses are associated uncertainties from the original chronologies.

	GS-19.2	GS-20	GI-20c	GI-20c	Δ[a]	GS-21.1	GS-21.1	Δ[b]	GI-21.1e	GS-22	GI-23.1	GI-23.1	Δ[c]	GS-24.1	GS-24.1	GS-24.1	Δ[d]	GI-24.2	GS-25
NALPS19[1]	**KC1**	**HÖL19**	**SCH6**	**BA1b**		**GAS12**	**GAS13**		**BA7-GAS25**	**GAS25**	**HUN14**	**GAS27**		**HUN14**	**GAS22**	**GAS29**		**HUN14**	**HUN14**
Start	71104 ±28 (210)	74262 ±18 (189)	75852 ±23 (213)	75901 ±8 (166)	**74**	77372 ±30 (146)	77296 ±41 (158)	**76**	84725 ±16 (216)	88747 ±17 (117)	103814 ±20 (136)	103705 ±22 (172)	**109**	105916 ±18 (149)	105971 ±28 (199)	105944 ±17 (252)	**55**	108825 ±6 (210)	110450 ±44 (284)
Mid-point	70859 ±19 (200)	74146 ±12 (130)	75795 ±11(240)	75857 ±4 (190)	**62**	77251 ±18 (177)	77207 ±22 (176)	**44**	84671 ±8 (100)	88664 ±14 (118)	103745 ±9 (129)	103640 ±9 (178)	**105**	105868 ±10 (154)	105814 ±23 (253)	105845 ±8 (248)	**54**	108801 ±8 (210)	110350 ±23 (274)
End	70615 ±34 (190)	74031 ±24 (138)	75738 ±10(266)	75812 ±6 (195)	**49**	77129 ±24 (217)	77119 ±27 (173)	**10**	84618 ±15 (90)	88582 ±32 (123)	103676 ±22 (131)	103575 ±19 (188)	**101**	105820 ±18 (159)	105657 ±47 (318)	105745 ±13 (240)	**163**	108778 ±8 (210)	110251 ±34 (263)
Duration	**489 ± (283)**	**231 ± (234)**	**114 ± (341)**	**89 ± (256)**		**243 ± (262)**	**177 ± (234)**	**66**	**107 ± (234)**	**165 ± (170)**	**138 ± (189)**	**130 ± (255)**	**8**	**96 ± (218)**	**314 ± (375)**	**199 ± (348)**	**218**	**47 ± (297)**	**199 ± (387)**
$GICC05_{modelext}$[2]																			
INTIMATE Start		74100	76440			77760			84760		104040			105440				108280	
Start		74219±23 (3208)	76417±14 (3315)			77865±27 (3385)			84751±10 (3718)		104042 ±15 (4652)			105455±37 (4720)				108271±12 (4856)	
Mid-point		74101±14 (3202)	76403±5 (3314)			77763±15 (3380)			84724±4 (3717)		104001±6 (4650)			105418±16 (4718)				108251±5 (4855)	
End		73984±22 (3197)	76390±10 (3313)			77661±27 (3375)			84697±6 (3715)		103961±11 (4648)			105382±17 (4716)				108231±6 (4854)	
Duration		**236 ± (4528)**	**25 ± (4687)**			**204 ± (4780)**			**54 ± (5256)**		**82 ± (6576)**			**73 ± (6672)**				**41 ± (6866)**	
Δ[e]		**119**	**24**			**105**			**9**		**2**			**15**				**9**	
AICC2012[3]																			
Start		73846±21 (3000)	75904±15 (3000)			77332±27 (3000)			84194±11 (3000)		101868±14 (3000)			103226±37 (3200)				105855±11 (3200)	
Mid-point		73741±13 (3000)	75890±6 (3000)			77229±16 (3000)			84166±4 (3000)		101829±5 (3000)			103189±16 (3200)				105839±4 (3200)	
End		73635±20 (3000)	75876±11 (3000)			77127±26 (3000)			84137±7 (3000)		101791±11 (3000)			103153±18 (3200)				105819±6 (3200)	
Duration		**211 ± (4243)**	**28 ± (4243)**			**206 ± (4243)**			**57 ± (4243)**		**77 ± (4243)**			**74 ± (4525)**				**37 ± (4525)**	
$AICC2012_{Extier}$[4]																			
Start		75136±23	77253±14			78749±29			85929±11 (2440)		104166±14 (2440)			105517±38 (2440)				108151±10 (2440)	
Mid-point		75022±14	77241±5			78636±18			85900±5 (2440)		104132±6 (2440)			105479±16 (2440)				108135±4 (2440)	
End		74908±21	77229±9			78522±29			85871±7 (2440)		104099±10 (2440)			105442±17 (2440)				108119±5 (2440)	
Duration		**228**	**21**			**227**			**58 ± (3394)**		**68 ± (3394)**			**75 ± (3394)**				**32 ± (3394)**	
Asian Monsoon Composite[5]																			
Start		73389 ±24 (240)				77224 ±45 (440)				88540 ±60 (750)	103734 ±153 (800)							108538 ±44 (900)	
Mid-point		73306 ±13 (240)				77138 ±27 (440)				88454 ±25 (750)	103694 ±149 (800)							108377 ±31 (900)	

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End		73222 ±20 (240)				77053 ±41 (440)				88367 ±39(750)	103653 ±150 (800)							108217 ±51 (900)	
Duration		**166 ± 399**				**171 ± 622**				**173 ± 1061**	**81 ± 1131**							**321 ± 1273**	

[a]Difference in the respective timing between SCH6 and BA1b
[b]Difference in the respective timing between GAS12 and GAS13
[c]Difference in the respective timing between HUN14 and GAS27
[d]Largest difference in the respective timing between HUN14, GAS22, and GAS29
[e]Difference in the respective timing for the start of transitions in $GICC05_{modelext}$ as defined by the INTIMATE event stratigraphy (Rasmussen et al., 2014) scheme and ramp-fitting (this study)

[1]This study
[2]Wolff et al., (2010)
[3]Veres et al., (2013)
[4]Extier et al., (2018)
[5]Cheng et al., (2016)

Table 4. The duration of GS-22 and the precursor event (GI-21.2) in various different chronologies. All ages given relative to 1950 A.D. and with two sigma uncertainty.

Chronology	**GI-21.1e midpoint**	**GI-21.2 onset**	**GS-22 midpoint**	**Duration GI-21.2 onset to GS-22 midpoint**	**Duration GI-21.2 onset to GI-21.1e midpoint**	**Duration GI-21.1e midpoint to GS-22 midpoint**
Annual layer counting[a]				2,894 ± 198	350 ±19	3,244 ± 199
GICC05modelext[b]	84,710	85,010	87,630	2,620	300	2,920
NGRIP-EDML[c]	83,634 ± 460	84,131 ± 460	87,756 ± 460	3,625 ± 650	496	4,122 ± 650
NALPS[d]	85,030 ± 410	85,440 ± 410	88,690 ± 330	3,250 ± 526	410	3,660 ± 526
NALPS19[This study]	84,671 ± 100		88,664 ± 118		705	3,993 ± 155
Asian Monsoon Composite[e]	*84,065 ± 600*		88,454 ± 750			4,489 ± 960

[a]Vallelonga et al., 2012
[b]Wolff et al., 2012
[c]Capron et al., 2010b; Vallenlonga et al., 2012
[d]Boch et al., 2011
[e]Cheng et al., 2016 with ramp fitting from this study. Italics indicates where a transition could not be ramp-fitted and is therefore manually assessed.

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