Re: C283: 'Review', Reviewer 1

We thank Reviewer 1 for commenting on our manuscript and for their pointing out potential usefulness of the data compiled in this study. We will take the following steps to improve our manuscript:

Jasechko et al. present a compilation of 88 sets of d18O isotope data. By bringing a large range of dated groundwater measurements together with speleothem and ice core data, they provide a global picture of the difference in d18O between the ice age (19,500 to 50,000 years ago) and the late Holocene (0 to 5000 years ago). This new compilation should prove a valuable resource for both isotopic modellers and observationalists. The paper is generally well structured and well written. It presents a convincing global and regional picture of the isotopic change. However the extended descriptions of the isotopic data can read more like an figure caption than a scientific investigation. Generally, there is a lack of physical explanations provided, more particularly , there is no meaningful use of the model results in helping the authors interpret/understand the compiled d18O measurements. To help alleviate this problem, Figures S1, S2, and S3 should be moved into the main text – and equivalent model plots to Figure S1b should also be provided. This would enable the authors to provide more by way of model-data interpretation.

We thank the reviewer for their suggestions and we will move the supplemental figures into the revised main text. We agree that further model-data inter-comparison would benefit from diagnosing model intricacies, focusing on regions where inter-model and model-observation precipitation isotope compositions diverge. The primary contribution of this study is the exploration in the spatial patterns of isotopic change from the latter half of the last glacial time period to the late-Holocene. Future climate model work could use these synthesized records to further diagnose global and regional model performance, focusing on regions where most models diverge from the measured $\Delta^{18}O_{late\text{-}glacial}$ values. We add the figures previously shown in the Supplement to the main text.

Finally, since the data compilation is the main point of the work, the data could usefully also be put into a more accessible form. Alongside Table S3, S4, and S5, a text or excel file, with these table info and also uncertainties (wherever possible) would be useful.

We thank the reviewer for their comment and agree that there may be scientists who would benefit from such a data repository. We will include an excel spreadsheet in our revised submission.

Terminology: The 'ice age' tends to be a rather loosely defined term. The authors could usefully switch to using the 'latter half of the last glacial period'. And define this as an average from 19,500 to 50,000 years ago. 'Ice age' is currently used throughout the text and figures.

We agree that we analyse isotope data spanning the latter half of the last glacial time period. However, this description is rather lengthy and leads to longer sentences that may complicate our efforts to communicate the findings of this study. We revise our manuscript to instead

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refer to "late-glacial" and explicitly state how we use this terminology by adding the following text:

"For brevity, we refer herein to the time period representing the latter half of the last glacial period (~20,000 to ~50,000 years before present) as the late-glacial (e.g., $\delta^{18}O_{late-glacial}$)."

The current title could be more precise, given that it does not really deal with glacial-interglacial shifts (plural). Perhaps could replaced with something like: "Global and regional d18O in precipitation during the latter half of the last glacial period". }

We revise the manuscript title to convey our examining only the most recent glacial-interglacial shift: *"Late-glacial to late-Holocene shifts in global precipitation $\delta^{18}O$"*

'In general, these models were the versions submitted to the CMIP5 archive and participating in PMIP3'. If three of the five model simulations are not from CMIP5-PMIP3 this sentence should be revised/removed, since 'in general' in not accurate.

We revise the manuscript to convey model participation in the CMIP5-PMIP3 inter-comparisons: *"GISSE2-R was submitted to the CMIP5 archive and participated in PMIP3. LMDZ4 was submitted to the CMIP3 archive. ECHAM5 and CAM3iso did not participate in CMIP5, while IsoGSM uses different boundary conditions than proposed for CMIP5 (Yoshimura et al., 2008)."*

P840 L8, and all other similar instances: 'reconstructed'. It would seem more accurate to use the term 'measured'. Reconstructed is usually used when inferring a quantity from a measurement e.g. reconstructed temperature (from d18O). In this case these d18O values seem to be measured quantities.

We agree with the reviewer's comment to use "measured" rather than "reconstructed" and make this change throughout the manuscript.

subsection 3.1 It would be useful to include a brief analysis/discussion of inter-archive differences here, i.e. do speleothem measurements show the same pattern as groundwater measurements?

There are limited locations where both speleothem and groundwater archives covering similar time spans exist in close proximity. We have added a new paragraph to section 3.1 comparing measured $\Delta^{18}O_{late-glacial}$ values obtained from different types of proxy records located near to one another in China, Israel and Turkey.

P842, L842 It is unlikely that the d18O simulation differences are primarily due to differences in ocean d18O. Most of the differences are instead likely to be due to differences in the simulated climates: e.g. humidity, temperature, precipitation etc. This should be described and discussed in 3.2.

Inter-model differences in simulated seawater $\delta^{18}O$ values may impact simulated precipitation $\delta^{18}O$ (LeGrande and Schmidt, 2006). We agree with the reviewer that most of the inter-model differences are likely due to differences in simulations of physical processes between the latter

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half of the last glacial period and the late-Holocene. We update the manuscript to point out that inter-model differences in simulated seawater $\delta^{18}O$ are likely of lesser importance than simulated atmospheric processes. We add: *"different seawater $\delta^{18}O$ specifications cannot account for all inter-model differences in simulated $\Delta^{18}O_{late\text{-}glacial}$ values."*

LeGrande, A. N., and Schmidt, G. A.: Global gridded data set of the oxygen isotopic composition in seawater, Geophys. Res. Lett., 33, L12604, 2006.

It seems odd to show the glacial-to-modern changes in land temperature S1 from reconstructed temperatures, without any similar discussion/plots of the model results. See also 'general comments' above.

We show a recently published map of temperature changes from the last glacial maximum to pre-industrial temperature change published (Annan and Hargreaves, 2013). We do not show individual atmospheric temperatures simulated by each model, instead providing references to publications describing the individual models for readers interested in examining inter-model differences in simulated hydro-climates.

Annan, J. D., and Hargreaves, J. C.: A new global reconstruction of temperature changes at the Last Glacial Maximum. Clim. Past, 9, 367–376, 2013.

P843 "Simulated precipitation d18O values either show little change (0.1 ‰ or show increases of up to 1.5 ‰ when modern spatial heterogeneous of surface ocean d18O values are included (LeGrande and Schmidt, 2006)." This is confusing – should it not be one or the other?

We reword to clarify how homogenous versus heterogeneous simulated seawater $\delta^{18}O$ impacts land precipitation $\delta^{18}O$: *"Including surface ocean $\delta^{18}O$ heterogeneities in model simulations impacts land precipitation $\delta^{18}O$ by up to ~1.5 ‰ relative to simulations with homogenous seawater $\delta^{18}O$ (LeGrande and Schmidt, 2006)."*

P846 L10-11 "mechanisms driving this extra-tropical/tropical difference remain elusive and can be examined through future inter-model or model-reconstruction comparative studies." Not a very useful statement – suggest removing it.

We remove this statement from the revised manuscript.

P849, L19 'during the Pleistocene' – rather non-specific!

We revise all cases to: *"during the late-glacial"*

P850, L2, 'subglacial recharge' – clarify please.

We reference previous publications describing subglacial recharge. We reword "subglacial recharge" to *"groundwater recharge that took place beneath the Laurentide ice sheet."*

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P852, L12 "Differences in simulated precipitation isotope composition changes amongst the models might be linked to different parameterizations of seawater d18O, glacial topography and convective rainfall, however, this hypothesis requires further testing." These would seem to be three hypotheses.

We revise to *"these hypotheses"*

The abstract should also be tightened up.

The abstract has been revised.

Figure 1 There are a lot of odd straight lines in my printed version of F1 – could these be removed?

We will inquire with journal typesetters to avoid the lines showing up on the current version of Figure 1.

Figure 2 It would be helpful if different colours were used for the groundwater versus the cave (speleothem?) measurements.

Speleothem records are now displayed in green.

Figure 3 This figure is much too small to be able to see anything. Perhaps it could be spread over two or three pages.

We will request that the multi-model precipitation isotope composition figure be displayed in large format in the revised manuscript. We will also submit the figure in vector format so that readers who are interested in specific model outputs will be able to zoom in to regions of interest without sacrificing image resolution.

S1, S2, and S3 would seem better off in the main text, accompanied by a new figure showing modelled temperature (and precipitation?) anomalies too.

We move current figures S1-S3 into the main text. We also revise the regional maps to show $\Delta^{18}O_{late\text{-}glacial}$ values as text to complement the colour scale.

P845 L17-18 i.e. or e.g. – consistency.

We revise the manuscript for consistency of "i.e.," and "e.g.,"

Supporting Information; Supplement; Supplementary Information – not used consistent throughout text.

We revise to "Supplement."

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Re: C294: 'comments', Ph. Négrel

We thank Ph. Négrel for his positive comments on our manuscript and for his fair and useful suggestions that helped us to improve our manuscript.

Jasechko et al. present a set of literature data regarding stable isotopes in different supports (groundwater, speleothems, ice…). They investigated the glacial-interglacial periods between 50-20ky and 5-0 ky. The compilation, even not fully complete but still impressive, will help using the stable isotopes as a supplementary constraint for investigating the climate and its evolution. The ms. is well written and do not need substantial changes. There is however a need for a more convincing demonstration by adding in the main text several items. Among this, the two mains are: - Define in the main text what is the D18O ice age (SS2 supplementary material for giving the readers the complete view of this parameter used in the discussion.

In the main text we define $\Delta^{18}O_{late\text{-}glacial}$ as *"Proxy-based meteoric water $\delta^{18}O$ changes from the latter half of the last glacial time period to the late-Holocene are described herein as measured $\Delta^{18}O_{late\text{-}glacial}$, where measured $\Delta^{18}O_{late\text{-}glacial} = \delta^{18}O_{late\text{-}glacial} - \delta^{18}O_{late\text{-}Holocene}$."* The time intervals are described in the preceding paragraph.

Add figure S2 in the main text and corresponding description.

We include current Figure S2 in the main text of the revised manuscript.

p837, line 10 please be careful. Here it is stated that the study is conducted using groundwater, ground ice, glacial ice and cave calcite records while p835, line 0-5 it is said that this study focused primarily on groundwater. Clarify and/or homogenize.

We revise our previous statement to make clear that our study focuses on groundwater isotope records due to their relative density compared to speleothem and ice core isotope records: *"This study examines speleothem, ice core and groundwater isotope records, focusing primarily on the groundwater isotope records due to their relative density in the published literature in comparison to the more limited number of published speleothem and ice core records."*

P838, line 20 it is said that some studies/samples have been removed; a plot of the d2H-d18O would be useful for the reader. It may define the range between the different systems and would enable to view the variations related to the climatic period.

We agree that plots of $\delta^{18}O$-$\delta^{2}H$ are useful for visualizing simultaneous changes to $^{18}O/^{16}O$ ratios and to $^{2}H/^{1}H$ ratios. We point future readers to the original published works referenced in our manuscript that each show $\delta^{18}O$-$\delta^{2}H$ plots. Data removed on the basis of possible evaporative isotope effects are included in a series of supplemental figures that show the groundwater age versus $\delta^{18}O$ or deuterium excess for each aquifer.

P840, line 7, the differences between the reconstructed and simulated must be pointed out more precisely. It is crucial for the rest of the reading.

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We include a stand-alone paragraph that clarifies "measured $\Delta^{18}O_{late\text{-}glacial}$" describes proxy-based values, and "simulated $\Delta^{18}O_{late\text{-}glacial}$" describes model-based values: *"For clarity, empirical $\Delta^{18}O_{late\text{-}glacial}$ values that are based on measured isotope contents of groundwater, speleothem, ground ice or ice core records are referred to herein as measured $\Delta^{18}O_{late\text{-}glacial}$; simulated precipitation isotope compositions obtained from general circulation model results are referred to as simulated $\Delta^{18}O_{late\text{-}glacial}$. We acknowledge that the general circulation models explicitly analyse the last glacial maximum and the pre-industrial climate conditions (i.e., simulated $\Delta^{18}O_{late\text{-}glacial} = \delta^{18}O_{last\ glacial\ maximum} - \delta^{18}O_{pre\text{-}industrial}$), whereas proxy record reconstructions of $\Delta^{18}O_{late\text{-}glacial}$ integrate hydroclimatology over multi-millennial time scales that are different from the model simulations."*

P840, line16, undeniably no results in this ms, only a discussion of published results from the literature, delete results from §3 title.

While we agree with the Reviewer that the data shown in this study have been presented in previous studies, we feel that our reanalysis of these synthesized datasets, sometimes derived from multiple publications for a single aquifer, warrants presentation of a "results" section for the following reasons: 1) few of the compiled publications explicitly describe the magnitude of $\delta^{18}O$ change from the late-glacial to the late-Holocene, especially in light of other regional records, 2) several of the compiled works do not focus on $\delta^{18}O$ changes from the late-glacial to more recent times, instead focusing on other uses of the data (e.g., Larsen et al., 2002), meaning that this study is the first to examine these data through a paleoclimate lens.

Larsen, F., Owen, R., Dahlin, T., Mangeya, P., Barmen, G. (2002), A preliminary analysis of the groundwater recharge to the Karoo formations, mid–Zambezi basin, Zimbabwe, Physics and Chemistry of the Earth, 27, 765–772.

P844, §3.3 I think Fig S3 would be useful in the main text to illustrate this §. May be this regional description can be compacted more.

We will add the previous supplemental figures to the main text in our revised manuscript. We thank the reviewer for their suggestion.

P851, Conclusions. I would like to see a more consistent "perspectives" description to put ahead the results of this work in the wider context of studies on climate change

We have added new text to the conclusions to place the synthesized isotopic data into context, pertaining specifically to ongoing climate change: *"Regionally-divergent precipitation $\delta^{18}O$ responses to the ~4°C of global warming occurring between the late-glacial and the late-Holocene suggest that continued monitoring of modern precipitation isotope contents may prove a useful for detecting hydrologic changes due to ongoing, human-induced climate change."*

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Re: C338: 'interactive discussion', Reviewer 3

We thank Reviewer 3 for their thorough review of our paper and for their pointing out the usefulness of model-data comparisons of late-glacial and late-Holocene precipitation isotope compositions.

The central idea behind the work of Jasechko et al. was the reconstruction of climatically-induced shift in the isotopic composition of global precipitation between the last Glacial and the Holocene, and to confront it with the predictions of state-of-the art isotope-enabled general circulation models. The authors selected three different proxies of isotopic composition of past precipitation (groundwater, speleothem calcite, ice cores), conducted extensive literature search and came up with the reconstructed delta18O of precipitation for two time windows: (i) late Holocene (0 - 5000 calendar years), and (ii) Glacial (19500 - 50000 calendar years) at number of sites distributed globally. The resulting spatial distribution of the reconstructed Delta18O(ice age) was then compared with the modeled Delta18O(ice age) generated by five GCMs. This sort of global comparison was in fact long due and represents a valuable tool for assessing the performance of existing isotope-enabled GCMs. I highly appreciate the efforts and gigantic work done by the authors in compiling appropriate information. Still, when attempting this sort of comparison, a great care is needed in proper selection of the data in order to minimize the possibility of falling into "garbage in - garbage out" trap. Therefore, the proxy data selected for comparison should be carefully scrutinized. I do have a number of comments and suggestions which might assist the authors in improving the overall shape of the paper and which should be addressed in the revised version. They concern both the methodology used and the structure of the paper. Specific comments: 1. I would recommend adding a separate section in Chapter 2, where key characteristics of the selected proxies, of direct relevance to the presented model-data comparison, are discussed in depth. In particular, this discussion should highlight the following questions: (i) how well the given archive is preserving the (mean) isotopic composition of precipitation ? (ii) what are the potential biases? (iii) can reliable chronology of the given archive be established?. Some information on those issues is dispersed throughout the main text and in the Supplement but the paper would definitely gain in clarity if all this information is gathered in one place. While the authors address to some extend the question of establishing age of groundwater (see comment no. 3), they refrain from any comment on the uncertainties of the chronology of speleothem and ice core samples used in the comparison, which can be significant (see e.g. Landais e al., (2015) for ice cores).

We focus the majority of our revisions on this comment, pointing out potential biases linked to seasonality (e.g., Werner et al., 2000; Jasechko et al., 2014; James et al., 2015) and uncertainties in the chronologies of each proxy record. We have added a new paragraph to our manuscript highlighting the potential for such biases.

Jasechko, S., Birks, S. J., Gleeson, T., Wada, Y., Fawcett, P. J., Sharp, Z. D., McDonnell, J. J., and Welker, J. M.: The pronounced seasonality of global groundwater recharge, Water Res. Res., 50, 8845–8867, 2014.

James, E. W., Banner, J. L. and Hardt, B.: A global model for cave ventilation and seasonal bias in speleothem paleoclimate records, Geochem. Geophys. Geosyst., 16, 2015.

Werner, M., Mikolajewicz, U., Heimann, M., and Hoffmann, G.: Borehole versus isotope temperatures on Greenland: Seasonality does matter, Geophys. Res. Lett., 27, 723–726, 2000.

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2. It should be made clear that in view of significant uncertainties in establishing absolute chronologies of the archives selected for this work, particularly for the Glacial period, the boundaries of the selected time windows remain blurred. This is particularly true for the Glacial time window. Setting up a sharp lower boundary at 19500 calendar years does not make much sense in this context (should be rather ~19000 or ~20000 calendar years).

We change the lower age limit to ~20,000 years before present.

3. I have several objections with respect to the approach adopted by the authors to calculate groundwater ages, as described in the Supplement.

Below we show how we revise our groundwater ages following the suggestion of the reviewer. Including the changes made below has resulted in little change in our groundwater-based measured $\Delta^{18}O_{late\text{-}glacial}$ values. We agree with the reviewer that ^{14}C-based ages have uncertainty, however, the plateauing of $\delta^{18}O$ at each time interval and clear late-glacial to late-Holocene $\delta^{18}O$ shifts supports our interpretation of such $\delta^{18}O$ changes as records of late-glacial to late-Holocene climate change. We have added the following statement to the revised version of the manuscript: *"Further, the chronologies of groundwaters and ice core records have uncertainties on the order of thousands of years, meaning that the time intervals used to calculate measured $\Delta^{18}O_{late\text{-}glacial}$ values may be inaccurate. However, the plateauing of isotope content observed in most regional aquifers for 0-5,000 years before present and for >20,000 years before present supports our interpreting these data as records of late-glacial to late-Holocene isotopic shifts (see figures in the Supplement)."*

(i) to calculate groundwater age the authors use eq.(S1) which numerical factor (-8267) contains more recent value for 14C half-life (5730 years). Then, they convert ages derived using eq.(S1) to calendar ages using corrections based on the calibration curve proposed by Fairbanks et al., (2005). However, by definition the calibration curve relates conventional radiocarbon ages to calendar ages (cf. Fig. 2 of Fairbanks et al., 2005). Conventional radiocarbon ages are calculated on the basis of Libby's half-life (5568 years) which leads to numerical factor in eq.(S1) equal -8033, but not -8267. Besides, a more recent calibration curve (Reiner et al., 2013) synthesizing all available calibration data should be used rather than Fairbanks et al (2005) curve.

We update our calculations using the updated calibration curve using data presented in Reimer et al. (2013). We also use the half-life proposed by Libby following the reviewer's suggestion. This change led to the removal of a few samples that were previously used to calculate $\Delta^{18}O_{late\text{-}glacial}$ values. Overall, groundwater-based $\Delta^{18}O_{late\text{-}glacial}$ values changed little between our initial submission and this revised version.

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Reimer, P. J. et al. (2013), IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP, Radiocarbon, 55, 1869-1887.

(ii) Figures S4 - S62 have a horizontal axis labeled "Groundwater age (14C-years before present)". Are those indeed radiocarbon ages calculated on the basis of eq.(S1), or perhaps radiocarbon ages converted already to calendar ages ?. In any case, they contain number of data points showing unrealistically high finite ages going up to 62000 years.

The x-axis label for the supplemental figures is accurate (^{14}C years). We agree with the reviewer that ^{14}C ages exceeding ~30 thousand years are highly uncertain, we modify our groundwater age calculations to convey the limitations associated with these old ages. However, some of the compiled works report high-precision ^{14}C activities (e.g., 0.04 pmC in Larsen et al., 2002); we use the reported ^{14}C activities as our best estimate of ^{14}C content, but add an analytical uncertainty of ±1 pmC and propagate this added uncertainty through our age calculations.

Larsen, F., Owen, R., Dahlin, T., Mangeya, P., Barmen, G. (2002), A preliminary analysis of the groundwater recharge to the Karoo formations, mid–Zambezi basin, Zimbabwe, Physics and Chemistry of the Earth, 27, 765–772.

(iii) In their uncertainty analysis the authors apparently forgot to include the analytical uncertainty associated with the measured radiocarbon content in the given sample (quantity A in eq.(S1)) Large majority of the reported radiocarbon data (my guess would be that this is around 80-90) was obtained by laboratories using conventional (i.e. decay-based) analytical techniques. Typical analytical uncertainty of radiocarbon analyses in such laboratories (one sigma level) usually varies between ca. 0.5 and 1.0 pmc (percent of modern carbon). In addition, sampling of groundwater in the field for radiocarbon analyses introduces additional source of uncertainty (possible contamination with modern radiocarbon from the atmosphere). Therefore, a realistic value for the Limit of Detection (LoD) can be set in this case around 1 pmc. Modern AMS laboratories can do a bit better but still the problem of contamination during sampling remains open. This LoD of approximately 1 pmc leads to conventional radiocarbon age of ca. 35000 years, not accounting for any geochemical correction - just taking into account radioactive decay only. This age limit transfers to approximately 40000 calendar years. Consequently, all groundwater ages higher than ca. 35000 conventional radiocarbon years or ca. 40000 calendar years should not be reported as finite ages but rather as "> 35 ka BP or >40 cal. ka BP".

The additional uncertainty is now included in updated calculations. We report the best estimate of ^{14}C age and show that ^{14}C ages older than ~35,000 years often have very large uncertainties (updated supplemental figures for each aquifer).

(iv) The authors use so-called Pearson correction model to account for the dissolution of carbonate phases in the aquifer (eq.(S2)). However, it is well-known since long time that this model does not describe correctly all possible interactions between the TDIC reservoir which is dated by the radiocarbon technique and the aquifer matrix. Often, more complex models which merge evolution of carbon isotopes with the evolution of water chemistry along the flowpaths need to be applied in order to obtain realistic

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groundwater ages. More advanced correction schemes may result in radiocarbon ages differing by several thousand years from the ages returned by application of the simple Pearson correction model.

The reviewer is correct that ^{14}C groundwater ages calculated in many studies are imperfect and susceptible to a variety of complexities (e.g., non-linear averaging of ages due to mixing; Torgersen et al., 2013). More complex age correction models are not appropriate for use here because of the wide variability of data available amongst the compiled publications. For example, some studies do not report major ion chemistry or $\delta^{13}C$ values, whereas other publications report a more complete set of geochemical measurements.

Torgersen, T., R. Purtschert, F. M. Phillips, L. N. Plummer, W. E. Sanford, and A. Suckow (2013), Defining groundwater age, In: Isotope Methods for Dating Old Groundwater, International Atomic Energy Agency, Vienna, pp. 21-32.

Summarizing, the groundwater data need a major overhaul here. 4. In their compilation of groundwater data the authors do not refer to the IAEA database. This is by far the largest collection of isotope data for groundwater systems worldwide. Therefore, I would strongly recommend that three IAEA Atlases are consulted (Atlas of Isotope Hydrology - Africa, IAEA 2007; Atlas of Isotope Hydrology - Asia and the Pacific, IAEA 2008; Atlas of Isotope Hydrology - the Americas, IAEA 2009) and, if appropriate, additional data obtained from this source included in the global picture of reconstructed Delta18O(ice age) presented in the paper.

The Atlases provided by the International Atomic Energy Agency are a useful facility, which highlight the many aquifers investigated by IAEA coordinated research projects. However, these Atlases do not explicitly point out occurrences of paleowaters, instead providing ranges of isotope compositions observed for different samples (e.g., springs, groundwaters). We agree that these data could be used in future studies to further investigate spatial patterns of paleowater isotope compositions.

5. In Chapter 3.3 the discussion of each region should be accompanied by appropriate regional maps showing the locations of relevant sites, each labeled by two numbers: reconstructed and simulated Delta18O(ice age). Colors should be avoided because they hide to some extent the real differences. Such regional maps would guide the discussion and would help to identify regions which are most problematic with respect to the model-data comparison pursued in the paper. Figure S3 should be then removed from the Supplement.

Regional maps are added to the main text. We followe the reviewer's suggestion and labelled each measured $\Delta^{18}O_{late\text{-}glacial}$ value on the figure. Although we cannot match a single model simulated $\Delta^{18}O_{late\text{-}glacial}$ value to each because we report five different general circulation models. However, we display the multi-model ensemble median as a grid to aid the discussion of model-versus-measured $\Delta^{18}O_{late\text{-}glacial}$ values.

6. Figure S1 should be moved to the main text. Perhaps the authors may consider adding on the map presented in Fig. S1 the Holocene-Glacial noble gas recharge temperature

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differences reconstructed for number of aquifers which are included in the model-data comparison discussed in the text. Noble gas temperatures are considered excellent proxy of ground level air temperatures and it would be instructive to confront Annan and Hargreaves (2013) reconstructions with those derived from noble gas data. From this perspective, the 15 degree Celsius of temperature suppression for Hungary at the last glacial maximum, reported on page 848, line16, is clearly an exaggeration (noble gas data indicate only 8-9 degree Celsius - see e.g. Corcho Alvarado et al., 2011).

Global maps of surface temperature changes developed by Annan and Hargreaves (2013) will be added to the main text. We agree that future studies could compile and analyse the noble gas records, providing a useful set of paleo-temperature records that could be used to better understand the spatial patterns of late-glacial to late-Holocene temperature change. We have added reference to the temperature change for Hungary suggested by Deák et al. (1987) of 5-7°C, a lower value than proposed on the basis of geomorphic data (Fábián et al., 2014): *"Geomorphic evidence suggests permafrost covered portions of Hungary at the last glacial maximum, suggesting that land temperatures may have been up to 15°C cooler than present day (Fábián et al., 2014), a larger late-glacial to late-Holocene temperature shift than earlier, noble gas based reconstructions (5-7°C; Deák et al., 1987)."*

Deák, J., Stute, M., Rudolph, J., and Sonntag, C.: Determination of the flow regime of Quaternary and Pliocene layers in the Great Hungarian Plain (Hungary) by D, ^{18}O, ^{14}C and noble gas measurements, in: Isotope Techniques in Water Resources Development, International Atomic Energy Agency, Vienna, 335–350, 1987.

Fábián, S. Á., Kovács, J., Varga, G., Sipos, G., Horváth, Z., Thamó-Bozsó, E., and Tóth, G.: Distribution of relict permafrost features in the Pannonian Basin, Hungary, Boreas, 43, 722–732, 2014.

7. The conclusions should stress the fact that the compilation of reconstructed Delta18O(ice age) presented in the paper constitute a strong challenge for isotope enabled GCMs. Figure 3 makes it clear that the selected crop of isotope-enabled GCMs is not performing particularly well. The frustrating thing is that apparently not much progress has been made in this respect in the past twenty years or so. Perhaps the necessary first step towards improving the situation would be a comprehensive model-data comparison with the present-day spatial distribution of mean delta18O(delta2H) in global precipitation.

We agree with the reviewer that the models and observations do not agree in all locations. The compiled data presented here can be used to continue to improve isotope enabled general circulation models.

Re: Editor V. Masson-Delmotte's suggested revisions

We are thankful for the invitation from Editor Masson-Delmotte on behalf of Climate of the Past to resubmit this revised manuscript, and are grateful for the time devoted to considering our manuscript for publication. We now add an in-depth discussion of a multitude of processes and potential biases linked to the archive records, embedding a reminder for the reader of these biases into the model-measurement comparison sections.

Editor V. Masson-Delmotte suggests including reference to recent work showing that snow metamorphism impacts snow isotope content and may impact paleoclimate records based on ice cores.

The suggested addition made by Editor Masson-Delmotte is important and should be included in our manuscript. We do so by adding reference to Steen-Larsen et al., 2014 in a new discussion paragraph describing potential biases linked to each type of paleoclimate record: "Compiled ice core records may have be influenced by post-depositional exchanges of ice with atmospheric vapour (Steen-Larsen et al., 2014). The impact of atmospheric vapour exchanges on ice core isotope records remains poorly understood."

Editor V. Masson-Delmotte points out that some records are "continuous," whereas others are integrate precipitation, potentially selectively due to climate variations (e.g., interstadials):

The representatively of the paleoclimate records remains unconfirmed. We agree that this important point should be added to the manuscript. We add: *"Similarly, groundwater isotope records are unlikely to represent constant and continuous recharge fluxes during the late-Holocene or the late-glacial (McIntosh et al., 2012). Modern groundwater recharge fluxes are highest in humid climates (Wada et al., 2010). Groundwater δ18O records only represent precipitation that recharges aquifers, meaning that groundwater-based Δ18Olate-glacial values could be biased to subintervals (e.g., interstadials, pluvial periods) within the late-Holocene and late-glacial intervals when recharge fluxes were at local maxima."*

More broadly, we point out after a discussion of many processes that may obscure values, that *"Potential biases in the preservation of precipitation δ18O differ among groundwater, glacial ice, and speleothem records, meaning that co-located records of differing type may yield different Δ18Olate-glacial values under similar climate conditions."*

Editor Masson-Delmotte points out the importance of highlighting these potential biases when discussing both inter-archive differences as well as model-measurement differences

We agree with Editor Masson-Delmotte that these points should be included in both the inter-archive comparison (new text shown above) and model-data comparison sections. We add the following point to our comparison of measured and simulated Δ18Olate glacial values to remind the reader that the measured isotope records are susceptible to biases: *"Further, as previously discussed in section 3.1, the measured Δ18Olate glacial values are susceptible to a number of potential biases that may obscure the magnitude and direction of late-glacial to late-Holocene precipitation δ18O changes."*

~~Glacial-interglacial~~Late-glacial to late-Holocene shifts in global ~~and regional~~ precipitation $\delta^{18}O$

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Abstract

~~Previous analyses~~Reconstructions of ~~past~~Quaternary climate ~~changes have~~are often ~~been~~ based on ~~site-specific~~ the isotopic content of paleo-precipitation preserved in proxy records. While many paleo-precipitation isotope records ~~from speleothems, ice cores, sediments and groundwaters. However, in most~~are available, few studies have synthesized these dispersed records ~~have not been integrated and synthesized in a comprehensive manner~~ to explore ~~the~~

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spatial patterns of late-glacial precipitation ~~isotope changes from the last ice age to more recent times~~$\delta^{18}O$. Here we ~~synthesize 88~~present a synthesis of 86 globally-distributed groundwater~~,~~ (n=59), cave calcite~~,~~ (n=15) and ice core (n=12) isotope records spanning the ~~last ice age~~late-glacial (defined as ~50,000 to ~20,000 years ago) to the late~~-~~-Holocene~~. Our data-driven review shows~~ (within the past ~5,000 years). We show that ~~reconstructed~~ precipitation $\delta^{18}O$ changes from the ~~last ice age~~late-glacial to the late~~-~~-Holocene range from −7.1 ‰ (~~ice age $\delta^{18}O$ < late-~~$\delta^{18}O_{late\text{-}Holocene}$ ~~$\delta^{18}O$~~> $\delta^{18}O_{late\text{-}glacial}$) to +1.~~8 ‰ (ice age $\delta^{18}O$ > late-~~7 ‰ ($\delta^{18}O_{late\text{-}glacial}$ > $\delta^{18}O_{late\text{-}Holocene}$ ~~$\delta^{18}O$~~)), with ~~wide regional variability. The~~ the majority (~~75~~77%) of ~~reconstructions have~~records having lower ~~ice age~~late-glacial $\delta^{18}O$ ~~values~~ than late~~-~~-Holocene $\delta^{18}O$ values. High-magnitude, negative ~~glacial-interglacial~~ precipitation $\delta^{18}O$ shifts ~~(ice age $\delta^{18}O$ < late-Holocene $\delta^{18}O$ by more than 3 ‰)~~ are common at high latitudes, high altitudes and continental interiors~~.~~ ($\delta^{18}O_{late\text{-}Holocene}$ > $\delta^{18}O_{late\text{-}glacial}$ by more than 3 ‰). Conversely, ~~lower~~low-magnitude, positive ~~glacial-interglacial~~ precipitation $\delta^{18}O$ shifts ~~(ice age $\delta^{18}O$ > late-~~are concentrated along tropical and subtropical coasts ($\delta^{18}O_{late\text{-}glacial}$ > $\delta^{18}O_{late\text{-}Holocene}$ ~~$\delta^{18}O$~~ by less than 2 ~~‰) are most common along subtropical coasts.~~ ‰). Broad, global patterns of late-glacial~~-interglacial~~ to late-Holocene precipitation $\delta^{18}O$ shifts ~~are consistent with~~suggest that stronger-than-modern isotopic distillation of air masses prevailed during the ~~last ice age~~late-glacial, likely impacted by larger global temperature differences between the tropics and the poles. Further, to ~~complement our synthesis of proxy-record~~test how well general circulation models reproduce global precipitation $\delta^{18}O$ shifts, we compiled simulated precipitation $\delta^{18}O$ shifts from five isotope enabled general circulation ~~model simulations of~~models simulated under recent and last glacial maximum climate states. ~~Simulated precipitation $\delta^{18}O$ from five general circulation models~~ Climate simulations generally show better inter-model and model-~~observation~~measurement agreement in ~~the sign of $\delta^{18}O$ changes from the last ice age to present day in~~ temperate ~~and polar~~ regions than in the tropics~~. Further model precipitation $\delta^{18}O$~~, highlighting a need for further research ~~is needed~~ to better understand ~~impacts of~~how inter-model spread in ~~simulated precipitation fluxes and parameterizations of~~ convective rainout, seawater $\delta^{18}O$ and glacial topography ~~on~~parameterizations impact simulated precipitation $\delta^{18}O$. Future research on paleo-precipitation ~~proxy record~~ $\delta^{18}O$ ~~research~~records can use ~~new~~the global maps of ~~glacial $\delta^{18}O$ reconstructions~~measured and simulated late-glacial precipitation isotope compositions to target and prioritize ~~regional investigations of past climate states~~field sites.

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1 Introduction

~~Reconstructed isotope~~Isotopic compositions of ~~Pleistocene~~late-glacial precipitation can be preserved in groundwaters, cave calcite, glacial ice, ground ice and lake sediments. These records have been used to better understand past climate changes for more than a half century (e.g., Münnich, 1957; Thatcher et al., 1961; Münnich et al., 1967; Pearson and White, 1967; Tamers, 1967; Gat et al., 1969). Each type of isotopic proxy record is distinguished by its temporal resolution, preservation of one or both $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios, and frequency ~~of records~~ on land surface. For example, groundwater records contain both $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios with widespread global occurrence, but have a coarser temporal resolution than other paleoclimate proxies (Rozanski et al., 1985; Edmunds and Milne, 2001; Edmunds, 2009; Corcho Alvarado et al., ~~2010~~2011; Jiráková et al., 2011). Speleothem records, in contrast, have high temporal resolution but usually only report calcite $^{18}O/^{16}O$ ratios (without fluid inclusion $^{2}H/^{1}H$ data) and are less common than groundwater records (e.g., Harmon et al., 1978; 1979). ~~Pleistocene glacier~~ Late-glacial ice core and ground-ice records have high temporal resolution, can be ~~analyzed~~analysed for $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios, but are rare on non-polar lands (Dansgaard et al., 1982; Thompson et al., 1989; 1995; 1997; 1998). Lake sediment records can have a high temporal resolution, can preserve $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios and are available for a multitude of globally-distributed locations (e.g., Edwards et al., 1989; Eawag et al., 1992; Menking et al., 1997; Wolfe et al., 2000; Anderson et al., 2001; Beuning et al., 2002; Sachse et al., 2004; Morley et al., 2005; Tierney et al., 2008). However, some lake water proxy isotope records may be impacted by paleo-lake evaporative isotope effects that obscure the primary meteoric water signal and mask paleo-precipitation isotope compositions (e.g., lake sediment calcite, diatom silica; Leng and Marshall, 2004).

This study ~~focuses~~examines speleothem, ice core and groundwater isotope records, focusing primarily ~~upon~~on the groundwater isotope records due to ~~the~~their relative density ~~of groundwater records~~ in the published literature in comparison to the more limited number of published ~~isotopic~~speleothem and ice core records ~~from speleothems and ice cores~~ (compilations by Pedro et al., 2011; Stenni et al., 2011; Clark et al., 2012; Shah et al., 2013; Caley et al., 2014a). There exist roughly twice as many groundwater reconstructions of ~~ice age~~ late-glacial to late-Holocene precipitation $\delta^{18}O$ shifts (n ~~= 61~~=59) as the combined total of speleothem and ice core ~~precipitation $\delta^{18}O$~~ records ~~spanning the last ice age and late-Holocene time periods~~ (n ~~=~~=27; where $\delta^{18}O = (^{18}O/^{16}O_{sample}) / (^{18}O/^{16}O_{standard\ mean\ ocean\ water} - 1)\times1000$).

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A recent global synthesis of paired precipitation-groundwater isotopic data demonstrated that modern annual ~~amount-weighted~~ precipitation and ~~local,~~ modern groundwater ~~recharge~~ isotope compositions follow systematic relationships with some bias toward winter and wet-season precipitation (Jasechko et al., 2014). Systematic rainfall-recharge relationships shown by Jasechko et al. (2014) support our primary assumption in this study that groundwater isotope compositions closely reflect meteoric water. Because groundwater records can only identify climate change occurring over thousands of years due to hydrodynamic dispersion during multi-millennial residence times (e.g., Davison and Airey, 1982; Stute and Deak, 1989), we limit the focus of this study to meteoric water isotope composition changes from the latter half of the last ~~ice age~~glacial time period to the late~~-~~Holocene. The latter half of the last ~~ice age time~~glacial period is defined as ~~19,500~~ ~20,000 to ~50,000 years before present, ~~defined~~ using the end of the last glacial maximum as the more recent age limit ~~(19,500~~(~20,000 years before present; Clark et al., 2009~~),~~) and the ~~approximate~~ maximum age of groundwater that can be identified by ^{14}C dating as an approximate upper age limit (i.e., groundwater ages more recent than ~50,000 years~~).~~ old).

For brevity, we refer herein to the time period representing the latter half of the last glacial period (~20,000 to ~50,000 years before present) as the *late-glacial* (e.g., $\delta^{18}O_{late\text{-}glacial}$). We adopt a definition of the *late~~-~~Holocene* as occurring within the last 5,000 years following Thompson et al. (2006). Other work proposes the late~~-~~Holocene be defined as within the last 4,200 years (Walker et al., 2012), which is consistent with the 5,000 years before present definition (Thompson et al., 2006) within the practical uncertainty of ^{14}C-based groundwater ages (± ~10^3 years). Further, although precipitation isotope compositions have varied over the late~~-~~Holocene, groundwater mixing integrates this variability, prohibiting paleoclimate interpretation at finer temporal resolutions.

~~Pleistocene to~~ Late-glacial to late-Holocene changes in precipitation isotope compositions provide important insights into conditions and processes of the past. Perhaps the two best-constrained global-in-scale differences between the ~~last ice age~~late-glacial and the late~~-~~Holocene are changes to oceanic and atmospheric temperatures (MARGO Members, 2009; Shakun and Carlson, 2010; Annan and Hargreaves, 2013), and changes to seawater $\delta^{18}O$ (Emiliani, 1955; Dansgaard and Tauber, 1969; Schrag et al., 1996; 2002). Atmospheric temperatures have increased by a global average of ~4°C since the last glacial maximum, with greatest warming at the poles and more modest warming at lower latitudes (Figure ~~S1; e.g.,~~1;

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Shakun and Carlson, 2010; Annan and Hargreaves, 2013). Seawater $\delta^{18}O$ during the last glacial maximum was 1.0±0.1 ‰ higher than the modern ocean, as constrained by paleo-ocean water samples collected from pore waters trapped within sea floor sediments (Schrag et al., 2002).

~~Other~~Previous studies have proposed ~~other~~many different interpretations ~~for reconstructed~~of past changes to precipitation isotope compositions ~~of ice age and modern day precipitation.~~. Records of ~~past changes to~~ paleo-precipitation $\delta^{18}O$ have been used as a proxy for regional land surface and atmospheric temperature (e.g., Rozanski, 1985; Nikolayev and Mikhalev, ~~1999~~1995; Johnsen et al., 2001; Grasby and Chen, 2005; Akouvi et al., 2008; Bakari et al., ~~2011),~~2012); however, $\delta^{18}O$-based paleotemperatures can be complicated by past changes to a variety of other processes controlling precipitation $\delta^{18}O$, including moisture sources, upwind rainout, transport pathways, moisture recycling and in-cloud processes (Ciais and Jouzel, 1994; Masson-Delmotte et al., 2005; Sjostrom and Welker, 2009). Process-based explanations for observed meteoric water $\delta^{18}O$ variations in proxy records include changes to hurricane intensity (e.g., Plummer et al., 1993), large-scale atmospheric circulation (e.g., Rozanski et al., 1985; Weyhenmeyer et al., 2000; McDermott et al., 2001; Pausata et al., 2009; Asmerom et al., 2010; Oster et al., 2015), aridity (e.g., Wagner et al., 2010), monsoon strength (e.g., Denniston et al., 2000; Lachniet et al., 2004; Liu et al., 2007; Pausata et al., 2011a), local seawater $\delta^{18}O$ (Wood et al., 2003; Feng et al., 2014), precipitation seasonality (e.g., Fawcett et al., 1997; Werner et al., 2000; Cruz et al., 2005), moisture provenance (e.g., Sjostrom and Welker 2009; Lewis et al., 2010), storm tracks, climate oscillation modes (e.g., North Atlantic oscillation), moisture recycling (e.g., Winnick et al., 2013; 2014; Liu et al., 2014a; 2014b) and groundwater flow path architecture (Purdy et al., 1996; Stewart et al., 2004; Morrissey et al., 2010; Hagedorn, 2015). While ~~unraveling~~unravelling these mechanisms and delineating the primary and secondary processes can be rather challenging, the use of climate models in combination with robust and extensive precipitation isotope data can resolve many of these complexities with meaningful interpretations and insight.

The objective of this study is to ~~analyze~~analyse spatial patterns of ~~reconstructed~~measured late-glacial to late-Holocene precipitation $\delta^{18}O$ changes ~~since the last ice age~~ from published groundwater, ground ice, glacial ice and cave calcite records, and to compare these ~~observations~~measurements with output from five state-of-the-art isotope-enabled general circulation model simulations of last glacial maximum and ~~more recent~~pre-industrial or modern climate conditions. Synthesizing paleowater $\delta^{18}O$ records provides an important constraint for

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isotope-enabled general circulation model simulations of atmospheric and hydrologic conditions during glacial ~~meteorology and hydrology~~climate states (Jouzel et al., 2000). We combine a new global compilation of ~~ice age~~late-glacial groundwater and ground ice isotope data (n~~ = 61~~=59) with existing compilations ~~of speleothem~~for speleothems (n~~ = ~~=15; Shah et al., 2013) and ice ~~core~~cores (n~~ = 11~~=12; Pedro et al., 2011; Stenni et al., 2011; Clark et al., 2012; Caley et al., 2014a~~) isotope data.~~). This compilation of ~~ice age~~late-glacial groundwater isotope compositions builds from earlier reviews of European and African ~~ice age groundwater~~paleowater isotope compositions (Rozanski, 1985; Edmunds and Milne, 2001; Darling, 2004; Edmunds, 2009; Négrel and Petelet-Giraud, 2011; Jiráková et al., 2011).

2 Dataset and Methods

In order to examine spatial patterns of change to meteoric water $\delta^{18}O$ values we compiled $\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$ and ^{14}C data from 1713 groundwater samples collected from ~~61~~59 aquifer systems reported in ~~75~~76 publications (~~Supporting Information; Figure 1).~~data and primary references presented in the Supplement). $\delta^{13}C$, ^{3}H and ^{14}C data were used to ~~calculate ^{14}C-based modelled~~estimate groundwater ~~ages~~age (details within ~~Supporting Information~~Supplement). Changes to precipitation $\delta^{18}O$ values over time were determined by comparing groundwater isotope compositions of the late~~-~~ Holocene ($\delta^{18}O_{late\text{-}Holocene}$ defined here as less than 5,000 years before present; Thompson et al., 2006) and the latter half of the last ~~ice age ($\delta^{18}O_{ice\ age}$: 19,500~~ glacial time period ($\delta^{18}O_{late\text{-}glacial}$: 20,000 to ~50,000 years before present). We acknowledge that these two relatively long time intervals—necessarily long in order to examine groundwater isotope records—integrate precipitation $\delta^{18}O$ variability over the course of each time interval. The late~~-~~ Holocene time interval integrates known precipitation $\delta^{18}O$ variability~~,~~ (e.g., Aichner et al., 2015), and the ~~"last ice age"~~ late-glacial time interval ~~could incorporate precipitation occurring during Marine Isotope Stage 3 for groundwater records and multiple records~~ likely ~~incorporate~~incorporates groundwater preceding the last glacial maximum~~.~~, potentially during Marine Isotope Stage 3 or even older glacial time periods due to large uncertainties in ^{14}C-based groundwater ages (Supplement).

Proxy-based meteoric water $\delta^{18}O$ changes from the ~~last ice age~~latter half of the last glacial time period to the late~~-~~ Holocene are described herein as ~~*reconstructed $\Delta^{18}O_{ice\ age}$*~~*measured $\Delta^{18}O_{late\text{-}glacial}$*, where ~~reconstructed $\Delta^{18}O_{ice\ age}$ = $\delta^{18}O_{ice\ age}$ –~~ measured $\Delta^{18}O_{late\text{-}glacial}$ = $\delta^{18}O_{late\text{-}glacial} - \delta^{18}O_{late\text{-}Holocene}$. A minimum groundwater age of ~~19,500~~20,000 years before present was used to define the ~~last ice age~~late-glacial to remain consistent with the timing of

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the last glacial maximum ~~(see~~(~20,000 years before present; Clark et al., 2009). Samples having a deuterium excess of less than zero (deuterium excess = $\delta^2H - 8\times\delta^{18}O$; Dansgaard, 1964) and falling along regionally-characteristic evaporation $\delta^2H/\delta^{18}O$ slopes (Gibson et al., 2008) were removed from the analysis to avoid including groundwater samples impacted by partial evaporation. Further, studies reporting saltwater intrusion were avoided on the basis of groundwater $\delta^{18}O$ and salinities showing evidence of seawater mixing (e.g., Schiavo et al., 2009; Yechieli et al., 2009; Hamouda et al., 2011; Han et al., 2011; Wang and Jiao, 2012; Currell et al., 2013). The ~~61~~59 compiled groundwater ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values are unevenly distributed among western Europe (n~~ = ~~=10), eastern Europe and the Middle-East (n~~ = ~~=12), Africa (n~~ = 18~~=17), southeastern Asia (n~~ = ~~=6), Australia, Oceania and the Malay Archipelago (n~~ = 3~~=2), South America (n~~ = ~~=2), temperate and subtropical North America (n~~ = ~~=8) and the High Arctic (n~~ = ~~=2~~, ground ice records~~). Half of the compiled groundwater records are located in the tropics or subtropics (that is, within 35° of the equator; n=29) and half are located in the extra-tropics~~.~~ (n=30).

Speleothem and ice core isotope proxy records were also compiled. Lacustrine sediment $\delta^{18}O$ records are not considered in this study because these records may preserve meteoric waters impacted by evaporative isotope effects~~.~~ (Leng and Marshall, 2004). Speleothem and ice core ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values were calculated by subtracting average $\delta^{18}O$ values for each of the two time intervals defined for the groundwater records: the late~~-~~ Holocene (<5,000 years before present) and latter half of the last ~~ice age (19,500~~ glacial time period (20,000 to 50,000 years before present). This step effectively lowered the temporal resolution of speleothem and ice core precipitation isotope records to be consistent with the temporal resolution of the groundwater records. A correction factor was applied to speleothem $\delta^{18}O$ values to account for different H_2O-$CaCO_3$ isotopic fractionation factors during the ~~last ice age~~late-glacial and the late~~-~~ Holocene ~~imparted by the different~~because of differing land surface temperatures during each time period (details presented within ~~Supporting Information~~Supplement).

Simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values were compiled from five isotope-enabled general circulation models (simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ = $\delta^{18}O_{last\ glacial\ maximum} - \delta^{18}O_{pre\text{-}industrial}$): CAM3iso (e.g., Noone and Sturm, 2010; Pausata et al., 2011a), ECHAM5-wiso (e.g., Werner et al., 2011), GISSE2-R (e.g., Schmidt et al., 2014; LeGrande and Schmidt, 2008; 2009), IsoGSM (e.g., Yoshimura et al., 2003) and LMDZ4 (e.g., Risi et al., 2010a). ECHAM5-wiso

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and IsoGSM outputs are for modern climate rather than pre-industrial conditions~~,~~; however, the difference between the ~~isotope~~isotopic composition of pre-industrial and modern climate are expectedly small compared to late-glacial~~-interglacial~~ to late-Holocene $\delta^{18}O$ shifts. An offset factor was applied to simulated mean seawater $\delta^{18}O$ in all five models (Table S1) to account for known glacial-interglacial changes to seawater $\delta^{18}O$ (Emiliani, 1955; Dansgaard and Tauber, 1969; Schrag et al., 1996; 2002). Possible spatial differences in seawater $\delta^{18}O$ changes from the last glacial maximum to the pre-industrial time period are not incorporated into ~~forced~~ simulations with prescribed sea surface temperatures (CAM3iso, ECHAM5-wiso, ~~GISSE2-R~~IsoGSM, LMDZ4) but are simulated by the coupled ocean-atmosphere simulation of GISSE2-R (~~Supporting Information~~Supplement Table S1). ~~In general, these models were the versions~~GISSE2-R was submitted to the CMIP5 archive and participated in PMIP3. ~~Notable exceptions include IsoGSM using~~LMDZ4 was submitted to the CMIP3 archive. ECHAM5 and CAM3iso did not participate in CMIP5, while IsoGSM uses different boundary conditions than proposed for CMIP5 (Yoshimura et al., 2008~~), ECHAM5 not participating in CMIP5, and CAM3iso not participating in PMIP3.~~). The five models span a range of spatio-temporal resolutions and isotopic/atmospheric parameterizations described in detail in the above references. A selection of the inter-model similarities and differences are summarized in Table S1 (~~Supplementary Information~~Supplement).

For clarity, ~~data-based $\Delta^{18}O_{ice\ age}$~~ empirical $\Delta^{18}O_{late\text{-}glacial}$ values ~~from~~ that are based on measured isotope contents of groundwater, ~~speleothems~~speleothem, ground ice ~~and~~or ice ~~cores~~core records are referred to herein as ~~*reconstructed* $\mathit{\Delta^{18}O_{ice\ age}}$, whereas~~*measured* $\mathit{\Delta^{18}O_{late\text{-}glacial}}$; simulated precipitation isotope compositions obtained from general circulation ~~models~~model results are referred to as *simulated* ~~$\mathit{\Delta^{18}O_{ice\ age}}$~~$\mathit{\Delta^{18}O_{late\text{-}glacial}}$. We acknowledge that the general circulation models explicitly ~~analyze~~analyse the last glacial maximum and the pre-industrial climate conditions (i.e., simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ = $\delta^{18}O_{last\ glacial\ maximum} - \delta^{18}O_{pre\text{-}industrial}$), whereas proxy record reconstructions of ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ integrate hydroclimatology over multi-millennial time scales that are different from the model simulations~~ (i.e., reconstructed $\Delta^{18}O_{ice\ age} = \delta^{18}O_{ice\ age} - \delta^{18}O_{late\text{-}Holocene}$).~~.

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3 Results and Discussion

3.1 ~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values

~~Reconstructed~~Measured groundwater (n~~ = 61~~=59), speleothem (n~~ = ~~=15) and ice core (n~~ = ~~=12) ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values are presented in Figure ~~1~~2 (references presented in the ~~Supplementary Information). Reconstructed $\Delta^{18}O_{ice\ age}$~~Supplement). Measured $\Delta^{18}O_{late\text{-}glacial}$ values range from −7.1 ‰ (i.e., ~~$\delta^{18}O_{ice\ age}$ <~~ $\delta^{18}O_{late\text{-}glacial}$ < $\delta^{18}O_{late\text{-}Holocene}$) to +1.~~8~~7 ‰ (i.e., ~~$\delta^{18}O_{ice\ age}$ >~~ $\delta^{18}O_{late\text{-}glacial}$ > $\delta^{18}O_{late\text{-}Holocene}$). Three-quarters of the compiled records have negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values and one-quarter of compiled records have positive ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values. More than 80% of ~~reconstructed $\Delta^{18}O_{ice\ age}$~~records with positive measured $\Delta^{18}O_{late\text{-}glacial}$ values ~~of greater than zero~~ are located ~~in the~~ within 35° of the equator and within 400 km of the nearest coastline (e.g., Bangladesh ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ of +1.~~6~~5 ‰, less than 300 km from the coast; Figures ~~1 and~~ 2~~; Figure S2-~~4). In comparison, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values are found in both coastal regions and farther inland. Negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values of the greatest magnitude are located at high latitudes (e.g., northwestern Canada, latitude 64~~°: $\Delta^{18}O_{ice\ age}$~~°N: $\Delta^{18}O_{late\text{-}glacial}$ of −~~5.~~5.5 ‰; northern Russia latitude 72~~°: −5.~~°N: −5.4 ‰) and far from coastlines (e.g., Hungary: −3.7 ‰, ~500 km from Atlantic Ocean; Peru: −6.~~5~~3 ‰, ~2000 km from Atlantic Ocean, the modern moisture source to Peru~~,~~; Garreaud et al., 2009). Greenland and Antarctic ice cores have negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values that are of greater magnitude than non-polar ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values (Antarctic and Greenland ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values range from −3.6 ‰ to −7.1 ‰; Figure ~~2).~~3).

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Our synthesis shows that measured $\Delta^{18}O_{late\text{-}glacial}$ values ~~synthesized in this study generally show that tropical $\Delta^{18}O_{ice\ age}$ values~~ in the tropics are closer to 0 ‰ (i.e., no change) than $\Delta^{18}O_{late\text{-}glacial}$ values at high ~~latitude,~~ latitudes and continental ~~regions~~interiors that generally have high magnitude, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values. High magnitude, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values are most common where present day precipitation $\delta^{18}O$ values are at a minimum (e.g., Bowen and Wilkinson, 2002). This broad spatial pattern is consistent with the non-linear isotopic distillation of air masses undergoing progressive rainout (i.e., Rayleigh distillation). Because seawater $\delta^{18}O$ values were ~1 ‰ higher-than-modern during the last ~~ice age~~glacial maximum (Schrag et al., 1996; 2002), our finding that the majority of ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$

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values are negative suggests that isotopic distillation of air masses was greater during the ~~last ice age~~late-glacial than under present climate. This finding is consistent with land surface temperature reconstructions that show larger glacial-to-modern changes to land temperatures at high latitude and continental settings (~~Supplementary Figure S1; Annan and Hargreaves, 2013).~~Figure 1; Annan and Hargreaves, 2013). Tropical versus extratropical patterns of late-glacial/late-Holocene temperature change (Figure 1a) are broadly similar to measured $\Delta^{18}O_{late\text{-}glacial}$ values (Figure 3), where both temperature and isotope shifts are greater at high latitudes relative to the equator. Therefore, it is possible that the larger late-glacial to late-Holocene temperature shifts at the poles relative to the equator may have served to amplify the non-linear, Rayleigh relationship describing the heavy isotope depletion of air masses undergoing progressive rainout during transport from lower to higher latitudes. Further, the late-glacial was characterized by: (i) lower-than-modern atmospheric temperatures with larger coastal-inland gradients, and (ii) lower-than-modern eustatic sea level leading to longer overland atmospheric transport distances. Each of these late-glacial/late-Holocene changes favours stronger-than-modern isotopic distillation of air masses transported inland from the coast during the late-glacial (Dansgaard, 1964; Rozanski et al., 1993; Winnick et al., 2014), potentially contributing to the broad, global observation that most (77%) $\delta^{18}O_{late\text{-}Holocene}$ values exceed $\delta^{18}O_{late\text{-}glacial}$ values on continents.

Pairings of groundwater and speleothem records are available within ~500 km of one another in the southwestern USA, central China and Israel. Southwestern USA speleothem and groundwater records ~400 km apart show similar $\Delta^{18}O_{late\text{-}glacial}$ values, with San Juan Basin groundwaters having a measured $\Delta^{18}O_{late\text{-}glacial}$ value of −2.5±1.0 ‰ (Phillips et al., 1986) and speleothems ~400 km to the south having measured $\Delta^{18}O_{late\text{-}glacial}$ values of −3.0±1.2 and −3.4±0.4 (Asmerom et al., 2010; Wagner et al., 2010). Central China speleothem and groundwater records ~200 km apart overlap within uncertainty margins (i.e., $\Delta^{18}O_{late\text{-}glacial}$ values of −1.1±1.7 ‰ and +0.3±2.1 ‰; Cai et al., 2010). Israeli speleothem and groundwater records ~100 km apart have different measured $\Delta^{18}O_{late\text{-}glacial}$ values. Two Israeli groundwater $\Delta^{18}O_{late\text{-}glacial}$ records were compiled; the coastal Israeli aquifer has a $\Delta^{18}O_{late\text{-}glacial}$ value of +0.3±0.4 ‰ (Yechieli et al., 2009), whereas groundwater of the Dead Sea Rift Valley has a $\Delta^{18}O_{late\text{-}glacial}$ value of −1.8±0.6 ‰ (Burg et al., 2013). Speleothem records have $\Delta^{18}O_{late\text{-}glacial}$ values close to +1 ‰ (Frumkin et al., 1999; Bar-Matthews et al., 2003). In northern Turkey, speleothem and groundwater separated by ~150 km have measured $\Delta^{18}O_{late\text{-}glacial}$ values that differ by ~3 ‰ (speleothem $\Delta^{18}O_{late\text{-}glacial}$ −5.7±0.4 ‰ versus groundwater $\Delta^{18}O_{late\text{-}glacial}$ of

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−2.8±1.0 ‰; Fleitmann et al., 2009; Arslan et al., 2013; 2015). While the locations of the groundwater and speleothem records differ, the compiled data suggests that groundwater and speleothem $\Delta^{18}O_{late\text{-}glacial}$ values may capture different $\Delta^{18}O_{late\text{-}glacial}$ values under similar climate conditions.

A number of potential processes could bias the preservation of precipitation isotope composition in ice core, speleothem or groundwater archives (Wang et al., 2001, Thompson et al., 2006; Edmunds, 2009). For example, groundwater and speleothem archives preserve only the isotope record of precipitation that traverses the vadose zone. Recent global analyses of paired precipitation-groundwater isotope compositions show that winter (extratropics) and wet season (tropics) precipitation contributes disproportionately to recharge (Jasechko et al., 2014), meaning that paleoclimate records may be more sensitive to changes to winter and wet seasons than summer or dry season (Vogel et al., 1963; Simpson et al., 1972; Grabczak et al., 1984; Harrington et al., 2002; Jones et al., 2002; Darling, 2004; Partin et al., 2012). Similarly, groundwater isotope records are unlikely to represent constant and continuous recharge fluxes during the late-Holocene or the late-glacial (McIntosh et al., 2012). Modern groundwater recharge fluxes are highest in humid climates (Wada et al., 2010). Groundwater $\delta^{18}O$ records only represent precipitation that recharges aquifers, meaning that groundwater-based $\Delta^{18}O_{late\text{-}glacial}$ values could be biased to subintervals (e.g., interstadials, pluvial periods) within the late-Holocene and late-glacial intervals when recharge fluxes were at local maxima. Speleothem records may be further complicated by processes impacting the timing of calcite precipitation. Recent modelling suggests that calcite precipitation in caves located outside of the tropics is greatest during the cool season and reduced during summer months due to changes in ventilation, meaning that higher latitude speleothems record oxygen isotope compositions biased to cool season climate change (James et al., 2015). Other recent work suggests that speleothem $\delta^{18}O$ data may be impacted by disequilibrium isotope effects (Asrat et al., 2008; Daëron et al., 2011; Kluge and Affek, 2012; Kluge et al., 2013) or by partial evaporation of drip waters resulting in ^{18}O-enrichment (e.g., Cuthbert et al., 2014a) and greater fractionation due to evaporative cooling (Cuthbert et al., 2014b), potentially obscuring the preservation of primary precipitation isotope contents in the speleothem record. Compiled ice core records may have be influenced by post-depositional exchanges of ice with atmospheric vapour (Steen-Larsen et al., 2014). The impact of atmospheric vapour exchanges on ice core isotope records remains poorly understood. Potential biases in the preservation of precipitation $\delta^{18}O$ differ among groundwater, glacial ice, and speleothem records, meaning that co-located records of differing record-type may preserve different $\Delta^{18}O_{late\text{-}glacial}$ values under similar climate conditions. Finally, all proxy records may be impacted by past changes in the seasonality of precipitation, which can substantially impact annual precipitation $\delta^{18}O$ values (e.g., Werner et al., 2000).

We cannot rule out the possibility that changes in seasonal biases of proxy record preservation occurred between the late-glacial and the late-Holocene and have impacted measured $\Delta^{18}O_{late\text{-}glacial}$ values. Further, the chronologies of groundwaters and ice core records have uncertainties on the order of thousands of years, meaning that the time intervals used to calculate measured $\Delta^{18}O_{late\text{-}glacial}$ values may be inaccurate. However, the plateauing of isotope content observed in most regional aquifers for 0-5,000 years before present and for >20,000 years before present supports our interpreting these data as records of late-glacial to late-Holocene isotopic shifts (see figures in the Supplement). Notwithstanding potential $\delta^{18}O$ preservation biases and chronology uncertainties, the global data synthesized here show patterns consistent with the enhanced distillation of advected air masses originating as (sub)tropical ocean evaporate and undergoing progressive, poleward rainout under cooler-than-modern late-glacial temperatures.

3.2 Simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values

Simulated precipitation ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values from five general circulation models are presented in Figure ~~3~~5. At least four of the five models agree on the sign of simulated ~~$\Delta^{18}O_{ice\ age}$ values~~ $\Delta^{18}O_{late\text{-}glacial}$ values—that is values consistently above or consistently below zero—for 68.8 % of grid cells covering Earth's surface (68.7 % of over-ocean areas and 68.9 % of over land areas; multi-model calculation completed using 3 of 4 models as a threshold at high-latitudes where IsoGSM data was ~~not available~~unavailable). Simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values are consistently negative over the North Atlantic Ocean and the Fennoscandian and Laurentide ice sheets and consistently positive over most of the tropical oceans, whereas ~~low~~poorer agreement is found over tropical land surfaces. The negative simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values over the northern hemisphere ice sheets and North Atlantic are likely driven by the difference in ice sheet topography and sea ice cover~~, respectively~~, between the ~~last ice age~~late-glacial and pre-industrial climate. The late-glacial~~-interglacial~~ to late-Holocene change in ice sheet topography and sea ice cover impacted surface temperatures~~.~~ ~~Surface temperatures~~, which were more than ~20°C cooler over most of present-day Canada during the last ~~ice age~~glacial maximum (Figure 1). Cooler temperatures in conjunction with ice

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sheet topography (>3000 m elevations; e.g., Peltier, 1994) enhanced Rayleigh distillation for air masses transecting Northern Hemisphere ice sheets, as evidenced by systematically low measured and ~~this temperature shift is likely to impact~~ simulated ~~$\Delta^{18}O_{ice\ age}$~~$\delta^{18}O_{late\text{-}glacial}$ values ~~(Figure S1~~in these regions (Figures 2, 3 and 5).

A comparison of simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values over tropical Africa, South America and Oceania shows inter-model disagreement (Figure ~~3~~5). Different tropical simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values ~~amongst~~among the models reflect the different isotopic parameterizations, inter-model spread in simulated precipitation ~~fluxes, glacial-interglacial shifts in seawater $\delta^{18}O$ (inter-model seawater $\delta^{18}O_{ice\ age}$ minus seawater $\delta^{18}O_{pre\text{-}industrial}$ ranges from +0.7 ‰ to +1.1 ‰)~~rates, and seawater $\delta^{18}O$ ~~heterogeneity~~specifications used in each model~~.~~ (Supplement). Inter-model spread in simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values in some regions highlights the importance of this global synthesis of ~~proxy record reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values as a constraint for isotope enabled climate ~~model simulated $\Delta^{18}O_{ice\ age}$ values~~simulations. Another potential source for the model disagreement is introduced by the different ice-sheet topography used in each model. CAM3Iso, IsoGSM and LMDZ4 ~~have~~ used Ice 5G (Peltier 1994) as advised for PMIP2 (Braconnot et al., 2007), whereas the GISSE2 replaces Ice 5G Laurentide ice with that of Licciardi et al. (1999) and ECHAM5-wiso uses ice topography from PMIP3 (Braconnot et al., 2007; 2012; PMIP3 follows ice sheet topography blended from multiple ice sheet reconstructions~~; e.g.,~~; Argus and Peltier, 2010; Toscano et al., 2011). ~~Glacial~~Ice sheet topography is an important driver of simulated temperature, precipitation and atmospheric circulation ~~at~~during the ~~Last Glacial Maximum~~last glacial maximum (e.g., Justino et al., 2005; Pausata et al., 2011b, Ullman et al., 2014). Therefore, it is likely that inter-model differences in paleo-ice sheet topographies impacts atmospheric circulation, and thus high~~-~~ latitude simulated ~~precipitation $\delta^{18}O$ at the Last Glacial Maximum, and thus simulated $\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values reported in this study (Figure ~~3~~5).

Differences in the specification of initial seawater $\delta^{18}O$ may also lead to inter-model differences in simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values. Seawater $\delta^{18}O$ is set to be globally-homogenous in CAM3Iso, IsoGSM and ~~LMDZ~~LMDZ4, and heterogeneous in ECHAM5-wiso (using modern gridded seawater $\delta^{18}O$ heterogeneity of LeGrande and Schmidt, 2006) and GISSE2-R (coupled atmosphere-ocean model; seawater $\delta^{18}O$ is calculated by the ocean model). ~~Simulated~~Including surface ocean $\delta^{18}O$ heterogeneities in model simulations impacts land precipitation $\delta^{18}O$ ~~values either show little change (±0.1 ‰) or show increases of~~by up to ~1.5 ~~‰ when modern spatial~~

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~~heterogeneous of surface ocean $\delta^{18}O$ values are included~~ ‰ relative to simulations with homogenous seawater $\delta^{18}O$ (LeGrande and Schmidt, 2006). ~~The incorporation of heterogeneous~~However, different seawater $\delta^{18}O$ ~~into~~ specifications cannot account for all inter-model ~~simulations can impact~~differences in simulated ~~$\Delta^{18}O_{ice\ age}$ values in cases where simulated moisture sources or simulated over-ocean meteorology change between the two climate states~~$\Delta^{18}O_{late\text{-}glacial}$ values.

The models also show deficiencies in simulating ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values in the tropics~~.~~, particularly over tropical Africa. This finding could, in part, ~~be related~~relate to the high sensitivity of precipitation $\delta^{18}O$ to convective parameterizations (Lee et al., 2009, Field et al 2014), although future research is required to test this. Another reason may ~~lie on the fact~~be that the ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ integrates the hydroclimatological signal over multi-millennial time scales, whereas the simulated ~~$\Delta^{18}O_{ice\ age}$~~ $\Delta^{18}O_{late\text{-}glacial}$ values explicitly ~~simulate the~~explore last glacial maximum and pre-industrial/present-day climate conditions. ~~The stronger extra-tropical agreement between the sign of~~ The smeared temporal resolution of groundwater-based measured $\Delta^{18}O_{late\text{-}glacial}$ values due to storage and mixing in the aquifer precludes an ideal comparison of measured versus simulated ~~and reconstructed $\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values. Further, as previously discussed in section 3.1, the measured $\Delta^{18}O_{late\text{-}glacial}$ values are susceptible to a number of potential biases that may obscure the magnitude and direction of late-glacial to late-Holocene precipitation $\delta^{18}O$ changes. Notwithstanding, models correctly simulate the sign of measured $\Delta^{18}O_{late\text{-}glacial}$ values (i.e., positive or negative) ~~relative~~in the extratropics more frequently than in the tropics. Better agreement in the sign of simulated versus measured $\Delta^{18}O_{late\text{-}glacial}$ values in the extra-tropics compared to the tropics is ~~most~~ likely linked to the substantial changes to extra-tropical ice-sheet topography and sea-ice cover between the two climate states in northern North America and Europe. ~~In this case the extreme temperature anomaly between last glacial and pre-industrial climate largely overwhelms a potential bias induced by smearing reconstructed $\delta^{18}O_{late\text{-}Holocene}$ values and reconstructed $\delta^{18}O_{ice\ age}$ values over multiple millennia~~Substantial changes to northern hemisphere ice volumes between the late-glacial and the late-Holocene likely enhanced upwind distillation of air masses leading to high-magnitude, negative $\Delta^{18}O_{late\text{-}glacial}$ values that are well captured by the climate simulations. However, simulated $\Delta^{18}O_{late\text{-}glacial}$ values over Antarctica and Greenland show large inter-model spread, suggesting that model-based interpretations of polar ice core records may vary widely among different atmospheric models.

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3.3 Regional ~~reconstructed~~measured and simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values

3.3.1 Australia and Oceania

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values from Australia and Oceania fall between −1 ‰ and +1 ~~‰ (Figures 1 and S3).~~ ‰ (Figure 2). Australian climate ~~at~~during the last ~~ice age~~glacial time period was more arid (Nanson et al., 1992), dustier (Chen et al., 1993) and cooler (Miller et al., 1997) than present day. Simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values across Australia are variable ~~amongst~~among the five models. ~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values across Oceania have been attributed to temporal changes in the strength of monsoons and convective rains (Aggarwal et al., 2004; Partin et al., 2007; Williams et al., 2010) potentially impacted by ~~ice age~~ late-glacial to late-Holocene shifts in the position of the intertropical convergence zone (Lewis et al., 2010; 2011).

3.3.2 Southeast Asia

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values from ~~southeast~~southeastern Asia range from −2.~~4~~3 ‰ to +1.~~8~~7 ‰. The highest regional ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values are found in Bangladesh (~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ of +1.5±1.3 ‰; Aggarwal et al., 2000) and in central and southeastern China (~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ of +0.3 ‰ to +1.~~8~~7 ‰; Wang et al., 2001; Yuan et al., 2004; Dykoski et al., 2005; Cai et al., 2010; Yang et al., 2010). General circulation models have positive simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values near to the Chinese coasts, but are more variable across western and northern China (Figure ~~3~~5). Chinese speleothem records show near-zero or positive ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values interpreted to reflect the reduced strength of the East Asian (Wang et al., 2001; Dykoski et al., 2005; Cosford et al., 2008) or Indian monsoons (Pausata et al., 2011a). Further research ~~examining various time periods~~ suggests that Chinese speleothem $\delta^{18}O$ variations reflect changes to regional moisture sources and the intensity or provenance of atmospheric transport pathways (LeGrande and Schmidt, 2009; Dayem et al., 2010; Lewis et al., 2010; Maher and Thompson, 2012; Caley et al., 2014b; Tan, 2014).

~~Reconstructed $\Delta^{18}O_{ice\ age}$ from~~ North China Plain groundwaters ~~reveals a~~have high-magnitude, negative ~~value (reconstructed $\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values (measured $\Delta^{18}O_{late\text{-}glacial}$ of −2.~~4~~3±0.6 ‰; Zongyu et al., 2003) compared to coastal, more southerly counterparts.

Combining the negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ in northern China (Zongyu et al., 2003; Ma et al., 2008; Currell et al., 2012; Li et al., in press) with the positive ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values in central and southeastern China (Wang et al., 2001; Yuan et al., 2004; Dykoski et al., 2005; Cai et al., 2010; Yang et al., 2010) reveals a south-to-north decrease from positive (south) to negative (north) ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values (~~Figure 1~~Figures 2 and 6). Previous studies of modern precipitation have identified increasing precipitation $\delta^{18}O$ values from the coast ~~(i.e., Hong Kong)~~ to inland China ~~(e.g., Zhangye)~~ during the wet season, sharply contrasting spatial patterns expected from Rayleigh distillation (Aragúas-Aragúas et al., 1998). ~~More~~A more recent work suggests that low wet-season precipitation $\delta^{18}O$ values over southern China are controlled by the deflection of westerlies ~~from~~around the Tibetan Plateau, whereas precipitation $\delta^{18}O$ values over northern China are controlled by local-scale ~~precipitation fluxes~~rainfall and below-cloud raindrop evaporation (Lee et al., 2012). Therefore, ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values from southern China may reflect changes to atmospheric circulation at broader spatial scales, whereas ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values from northern China may indicate changes to more localized atmospheric conditions impacting processes such as raindrop evaporation in addition to meso- and synoptic-scale circulation changes.

3.3.3 Africa

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values from Africa range from −2.9 ‰ to +0.~~4 (Figure~~ 1~~). 14~~ ‰ (Figures 2 and 6). 16 of ~~18 reconstructed $\Delta^{18}O_{ice\ age}$~~17 measured $\Delta^{18}O_{late\text{-}glacial}$ values from Africa are negative. Near-zero ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values are generally found near to coasts (e.g., Senegal~~, $\Delta^{18}O_{ice\ age}$~~ $\Delta^{18}O_{late\text{-}glacial}$ of +0.~~3~~1±0.8 ‰; Madioune et al., 2014), whereas higher magnitude, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values in Africa are found farther inland (e.g., Niger~~, $\Delta^{18}O_{ice\ age}$ -~~ $\Delta^{18}O_{late\text{-}glacial}$ values of −2.3±2.0 ‰ and −2.9±0.9 ‰: ~800 ~~kilometers~~km from the Atlantic coast). General circulation ~~models~~model $\Delta^{18}O_{late\text{-}glacial}$ values show ~~poorer~~poor agreement with ~~reconstructed $\Delta^{18}O_{ice\ age}$ values~~ measured $\Delta^{18}O_{late\text{-}glacial}$ over tropical Africa compared to model-measured comparisons for Europe and North America (Figure ~~3), mechanisms driving this extra-tropical / tropical difference remain elusive and can be examined through future~~5), with positive simulated $\Delta^{18}O_{late\text{-}glacial}$ values predicted over large parts of Africa where negative $\Delta^{18}O_{late\text{-}glacial}$ values are measured. Figure 5 shows that Africa has the largest inter-model ~~or model-~~

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~~reconstruction comparative studies~~and model-measurement disagreements in the sign of $\Delta^{18}O_{late\text{-}glacial}$ values of the continents.

Northern African hydrological processes are influenced by ~~multiple~~ interlinked controls such as ~~the strength of Atlantic meridional overturning circulation (Mulitza et al., 2008) and~~ meridional shifts in the position of the intertropical convergence zone (Arbuszewski et al., 2013) and the strength of Atlantic meridional overturning circulation (Mulitza et al., 2008). Paleowater chemistry indicates that northern Africa was at least 2°C cooler than today (Guendouz et al., 1998) and that westerly moisture transport was stronger than the present during the ~~last ice age (Sultan et al., 1997; Abouelmagd et al., 2014). Paleowater isotope compositions of Northern Africa may have been impacted by higher-than-modern sea surface humidity as interpreted from lower-than-modern paleowater deuterium excess values (Rozanski, 1985). However, the deuterium excess of seawater during the last ice age may have been different from present day given that the Laurentide ice sheet had a deuterium excess value of ~10 ‰ to ~15 ‰ (e.g., Grasby and Chen, 2005; Ferguson et al., 2007~~late-glacial (Sultan et al., 1997; Abouelmagd et al., 2012).

Tropical Africa was 2°C to 4°C cooler and more arid than present day at the last glacial maximum (Powers et al., 2005; Tierney et al., 2008). Early- and late~~-~~Holocene ~~precipitation fluxes~~rainfall and isotope compositions were highly variable across Africa (Tierney et al., 2008; Schefuß et al., 2011; Tierney et al., 2013; Otto-Bliesner et al., 2014). Tropical African rainfall originates from both Indian and Atlantic sources, with Atlantic-sourced moisture travelling across the Congo rainforest (Levin et al., 2009). Lower-than-modern continental moisture recycling during the ~~last ice age~~late-glacial may partially explain negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values across some regions of inland tropical Africa (e.g., Risi et al., 2013). ~~Although negative reconstructed $\Delta^{18}O_{ice\ age}$~~Negative measured $\Delta^{18}O_{late\text{-}glacial}$ values in tropical Africa could also be interpreted to reflect higher-than-modern upwind rainout during the ~~last ice age~~late-glacial (see Risi et al., 2008; 2010b; Lee et al., 2009; Scholl et al., 2009; Lekshmy et al., 2014; Samuels-Crow et al., 2014~~),~~); however, this explanation necessitates stronger-than-modern convection during the ~~last ice age~~late-glacial, an explanation that would contradict the established cooler-than-modern land surface temperatures. Therefore, changes to atmospheric transport distances and ~~vapor~~vapour origins are more likely responsible for negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values across tropical Africa (Lewis et al., 2010).

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3.3.4 Europe and the Mediterranean

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values across Europe, the Middle-East and the eastern Mediterranean range from −5.7 ‰ to +1.3 ‰. 80% of ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values across these regions are negative. All five general circulation models ~~converge upon~~agree on negative simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values across Europe, consistent with the negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values across the majority of Europe. ~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values are generally higher in western Europe (0.0 ‰ to −1.0 ‰ ~~across~~in Portugal~~ and~~, the United Kingdom and France) than in eastern Europe (−1.80 ‰ to −5.7 ‰ in Poland, Hungary and Turkey~~)~~; Stute and Deak, 1989; Le Gal La Salle et al., 1995; Darling et al., 1997; Barbecot et al., 2000; Zuber et al., 2004; Galego Fernandes and Carreira, 2008; Celle-Jeanton et al., 2009; Varsányi et al., 2011; Samborska et al., 2012; Arslan et al., 2013). This spatial pattern of $\Delta^{18}O_{late\text{-}glacial}$ values is consistent with enhanced isotopic distillation of westerlies during the late-glacial due to cooler-than-modern final condensation temperatures.

~~The highest~~High magnitude, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$ value in Europe is~~measured $\Delta^{18}O_{late\text{-}glacial}$ values are located in Turkey ~~near to~~and Georgia south and east of the Black Sea (−2.8±1.0 to −5.7~~ ‰) and potentially reflects a change to regional moisture source (~~±0.4 ‰; Fleitmann et al., 2009; Arslan et al., 2013; Melikadze et al., 2014). Westerly air mass trajectories distal to the Fennoscandian ice sheet topography may not have ~~not~~ changed considerably since the ~~last ice age~~late-glacial over western and central Europe (Rozanski, 1985; Loosli et al., 2001). ~~Positive reconstructed $\Delta^{18}O_{ice\ age}$~~Therefore, higher, near-zero measured $\Delta^{18}O_{late\text{-}glacial}$ values in ~~the eastern Mediterranean (Frumkin et al.,~~ western Europe and lower~~, 1999; Bar-Matthews et al., 2003; Ayalon et al., 2013) differ from~~ negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values in ~~nearby groundwater aquifers (e.g., Burg et al., 2013), advocating for further comparative research to ensure speleothem and groundwater isotope compositions each capture meteoric water $\delta^{18}O$ unaltered by fractionating processes such as partial evaporation. Recent work suggests that speleothem $\delta^{18}O$ data may be impacted by disequilibrium isotope effects (Asrat et al., 2008; Daëron et al., 2011; Kluge and Affek, 2012; Kluge et al., 2013) or by partial evaporation of drip waters resulting in ^{18}O-enrichment (e.g., Cuthbert et al., 2014a) and greater fractionation due to evaporative cooling (Cuthbert et al., 2014b), potentially explaining a portion of the difference between groundwater and speleothem~~

~~reconstructed $\Delta^{18}O_{ice\ age}$ values~~eastern Europe indicate enhanced distillation of advected air masses during the late-glacial relative to the late-Holocene.

Changes to freeze-thaw conditions of the ground surface between the latter half of the last ~~ice age~~glacial time period and the modern climates may have impacted the seasonality of the fraction of precipitation recharging aquifers and thus ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ (Darling, 2004; Darling, 2011; Jasechko et al., 2014). Geomorphic evidence suggests permafrost covered portions of Hungary at the last glacial maximum, ~~suppressing~~suggesting that land temperatures ~~by as much as~~may have been up to 15°C cooler than present day (Fábián et al., 2014), a larger late-glacial to late-Holocene temperature shift than earlier, noble gas based reconstructions (5-7°C; Deák et al., 1987). European pollen records indicate that northern Europe was tundra-like and that southern Europe was semi-arid ~~at~~during the last glacial maximum (Harrison and Prentice, 2003; Clark et al., 2012). The European late-glacial~~-~~ to ~~-modern~~ late-Holocene transition from semi-arid deserts to temperate forests could have lowered ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values as groundwater recharge ratios transitioned from more extreme winter-biased ~~groundwater recharge ratios~~ (e.g., semi-arid lands during ~~last ice age~~the late-glacial) to less extreme ~~but still~~ winter-biased groundwater recharge ratios (e.g., forests during late~~-~~Holocene; Jasechko et al., 2014).

3.3.5 South America

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values across South America range from −6.~~2~~3 ‰ to +0.~~3 ‰ (Figure 1).~~6 ‰ (Figures 2 and 6). The highest-magnitude, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values ~~(~~are found in Andean ice cores ($\Delta^{18}O_{late\text{-}glacial}$ of −4.6±1.0 and −6.3±1.3; Thompson et al., 1995; 1998~~) are found in similar locations to the lowest present day precipitation $\delta^{18}O$ values across South America (Bowen and Wilkinson, 2002~~). Here the importance of upstream convection upon modern Andean precipitation $\delta^{18}O$ has been highlighted at inter-annual (~~e.g.,~~ Hoffmann et al., 2003; Vuille and Werner, 2005), seasonal (~~e.g.,~~ Vimeux et al., 2005, Samuels-Crow et al., 2014) and daily time scales (~~e.g.,~~ Vimeux et al., 2011). It is therefore possible that upstream convection controls past changes to Andean precipitation isotope compositions recorded in ice cores. ~~Further, upwind changes to continental moisture recycling driven by shifts in plant transpiration fluxes may have altered continental gradients in precipitation $\delta^{18}O$. Glacial-interglacial changes to the density of Amazonian vegetation are supported by oceanic pollen records (Haberle and Maslin, 1999).~~

~~Negative reconstructed $\Delta^{18}O_{ice\ age}$ values in parts of South America may have been driven in part by lower-than-modern continental moisture recycling during the last ice age.~~

The ~~reconstructed~~measured groundwater ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ value located in eastern Brazil is −2.7±1.3 ‰ (Salati et al., 1974). Eastern Brazil was 5°C cooler than today during the latter half of the last ~~ice age~~glacial period (Stute et al., 1995b). Four of the five general circulation models simulate positive ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values across eastern Brazil (Figure ~~3~~5), highlighting ~~differences~~a difference between simulated and ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values in parts of the tropics. The negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ value in eastern Brazil has been previously interpreted to reflect higher-than-modern precipitation during the ~~Pleistocene~~last glacial time period (Salati et al., 1974). Lewis et al. (2010) show that localized ~~precipitation fluxes govern~~rainfall governs precipitation $\delta^{18}O$ in ~~east~~eastern Brazil. Modern precipitation $\delta^{18}O$ values are lowest in eastern Brazil when precipitation rates are at a maximum~~; extending~~. Extending Lewis et al.'s interpretation linking local precipitation amount to precipitation $\delta^{18}O$ ~~suggests~~would suggest that the negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ value found in eastern Brazil may indeed record wetter-than-modern conditions ~~at~~during the ~~last ice age~~late-glacial as proposed by Salati et al. (1974). Further, disagreement between measured and simulated $\Delta^{18}O_{late\text{-}glacial}$ in eastern Brazil highlights the need to critically evaluate climate model performance in regions where the precipitation amount is closely correlated with precipitation $\delta^{18}O$.

3.3.6 North America

~~Reconstructions of $\Delta^{18}O_{ice\ age}$~~ Measured $\Delta^{18}O_{late\text{-}glacial}$ from North American proxy records range from −5.5 ‰ to +1.0 ‰. Canadian records of ~~subglacial~~groundwater recharge ~~from~~that took place beneath the Laurentide ice sheet ~~(e.g.,~~are not included in this synthesis ("subglacial recharge;" Grasby and Chen, 2005; Ferguson et al., 2007~~) are not included in this synthesis~~; McIntosh et al., 2012; Ferguson and Jasechko, in press). These records were excluded because ~~of possible transport along~~ the subglacial meltwaters that recharged aquifers likely reflect precipitation that fell elsewhere on the paleo-~~glacial flow paths in the Laurentide~~ ice sheet, potentially complicating the comparison of groundwater isotope compositions for the late-Holocene and last glacial time period.

~~Reconstructed $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values along the USA east coast show the highest, positive values in Georgia (latitude: 32°N; ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured

$\Delta^{18}O_{late\text{-}glacial}$ of +1.0 ‰; Clark et al., 1997), decreasing northward to near-zero ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values in coastal Maryland (latitude 39°N; ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ of −0.1±0.4 ‰; Aeschbach-Hertig et al., 2002). Decreasing ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values with increasing latitude along the USA east coast may be explained in part by the isotopic distillation of air masses advected northward from the subtropics under cooler-than-modern final atmospheric condensation temperatures. ~~The chemistry of~~ Indeed, paleoclimate records indicate that Maryland ~~groundwaters has been interpreted to show that the region~~ was more arid and as much as 9-12°C cooler during the ~~last ice age~~late-glacial relative to ~~modern climate conditions~~the late-Holocene (Purdy et al., 1996; Aeschbach-Hertig et al., 2002; Plummer et al., 2012). ~~This glacial~~ In addition to ~~modern~~ temperature change ~~is larger than most other temperature proxy records at similar latitudes (Annan and Hargreaves, 2013). Impacts of higher-than-modern ice age seawater $\delta^{18}O$ upon terrestrial~~, late-glacial precipitation ~~$\Delta^{18}O_{ice\ age}$ may have been offset~~isotope compositions along eastern USA coastline were likely impacted by the lower-than-modern late-glacial sea levels ~~that increased~~, which changed overland atmospheric transport distances ~~during the last ice age~~between the late-glacial and late-Holocene (Clark et al., 1997; Aeschbach-Hertig et al., 2002; Tharammal et al., 2012).

~~Reconstructions of $\Delta^{18}O_{ice\ age}$~~Measured $\Delta^{18}O_{late\text{-}glacial}$ values in the central and southwestern USA have the highest magnitude, negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values of temperate North America, ranging from −1.0~~.7~~ ‰ to −3.4 ‰. Central and southwestern USA ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values contrast the positive ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values found along the eastern USA coast at similar latitudes. Consistently negative ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values in central and southwest USA suggest that advected moisture to the region underwent greater upstream air mass distillation during the ~~last ice age~~late-glacial than under modern climate. Pollen, vadose zone and groundwater records show that ~~Pleistocene~~late-glacial southwestern USA was ~4°C cooler, had greater groundwater recharge fluxes, and had more widespread forests than present day (Stute et al., 1992; 1995a; Scanlon et al., 2003; Williams, 2003). Negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values found in the southwest USA have been ascribed to lower-than-modern summer precipitation (New Mexico, Phillips et al., 1986), latitudinal shifts in the positions of the polar jet stream and the intertropical convergence zone (New Mexico, Asmerom et al., 2010) and changes to over-ocean humidity, temperature or moisture sources (Idaho, Schlegel et al., ~~2009). USA reconstructed $\Delta^{18}O_{ice\ age}$ values could also be influenced by~~

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~~changes to groundwater recharge ratio seasonality as land surface conditions changed (Jasechko et al., 2014).~~2009). Wagner et al. (2010) interpret decreases to southwestern precipitation $\delta^{18}O$ to reflect cooler and more-humid conditions. Extending this interpretation to negative ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values found across the southwestern USA values supports earlier conclusions that the region was cooler and more humid than today during the ~~last ice age~~late-glacial, possibly linked to changes in air mass trajectories and moisture sources (Asmerom et al., ~~2010;~~ 2010; Wagner et al., 2010). Simulated $\Delta^{18}O_{late\text{-}glacial}$ values across North America closely match spatial patterns of measured $\Delta^{18}O_{late\text{-}glacial}$ synthesized in this study. Strong, multi-model agreement with measured $\Delta^{18}O_{late\text{-}glacial}$ patterns supports continued application of isotope enabled general circulation models when interpreting North American precipitation isotope proxy records.~~Wagner et al., 2010).~~

~~Simulated $\Delta^{18}O_{ice\ age}$ values across North America closely match spatial patterns of reconstructed $\Delta^{18}O_{ice\ age}$ synthesized in this study. The strong, multi-model agreement with reconstructed $\Delta^{18}O_{ice\ age}$ values support continued application of isotope enabled general circulation models when interpreting USA precipitation isotope proxy records.~~

4 Conclusions

~~Compiled~~While changes to the isotope content of precipitation between the last glacial time period and more recent times has been widely documented, few studies have synthesized these dispersed data to explore the global patterns of $\delta^{18}O$ change driven by past shifts to regional climate. In this study we compile groundwater, speleothem, ice core and ground ice records of $\delta^{18}O$ ~~changes~~shifts between ~~the last ice age and~~ the late-~~-~~glacial (20 to ~50 thousand years ago) and the late-Holocene (within the past 5,000 years). Late-glacial to late-Holocene $\delta^{18}O$ shifts range from −7.1 ‰ (i.e., ~~$\delta^{18}O_{ice\ age}$ <~~ $\delta^{18}O_{late\text{-}glacial} < \delta^{18}O_{late\text{-}Holocene}$) to +1.~~8~~7 (i.e., ~~$\delta^{18}O_{ice\ age}$ >~~ $\delta^{18}O_{late\text{-}glacial} > \delta^{18}O_{late\text{-}Holocene}$). Aquifers with positive ~~reconstructed $\Delta^{18}O_{ice\ age}$~~measured $\Delta^{18}O_{late\text{-}glacial}$ values (~~25~~23% of records) are most common along the subtropical coasts. ~~75% of reconstructed $\Delta^{18}O_{ice\ age}$~~The majority (77%) of measured $\Delta^{18}O_{late\text{-}glacial}$ values are negative, with the highest magnitude differences between ~~$\delta^{18}O_{ice\ age}$~~$\delta^{18}O_{late\text{-}glacial}$ and $\delta^{18}O_{late\text{-}Holocene}$ observed at high latitudes and far from coasts. This spatial pattern suggests ~~stronger~~that isotopic distillation of advected air masses was greater during the ~~last ice age~~late-glacial than under present climate ~~were able to override higher than~~, likely due to the non-linear nature of Rayleigh distillation, accentuated by larger glacial-interglacial atmospheric temperature changes at the poles relative to lower latitudes. Regionally-divergent precipitation $\delta^{18}O$

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responses to the ~4°C of global warming occurring between the late-glacial and the late-Holocene suggest that continued monitoring of modern ~~glacial seawater $\delta^{18}O$ values at most locations.~~precipitation isotope contents may prove a useful for detecting hydrologic changes due to ongoing, human-induced climate change. Future paleo-precipitation proxy record $\delta^{18}O$ research can use ~~this~~these new global ~~map~~maps of ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ records to target and prioritize ~~developing new records in certain regions and to compare $\Delta^{18}O_{ice\ age}$ shifts from different proxy records.~~field sites. In the near term, a global compilation of large lake sediment isotope records that accounts for paleo-evaporative isotope effects could enhance spatial coverage of interglacial-glacial $\delta^{18}O$ shifts.

General circulation models agree on the sign and magnitude of terrestrial precipitation ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values better in the extra-tropics than in the tropics. Differences in simulated precipitation isotope composition changes amongst the models might be linked to different parameterizations of seawater $\delta^{18}O$, glacial topography and convective rainfall, however, ~~this hypothesis requires~~these hypotheses require further testing. Future model research should focus on quantifying the relative roles of inter-model spread in the simulated climate versus the isotopic response to climate change on resulting simulated precipitation $\delta^{18}O$. This would provide guidelines to interpret model-data isotopic differences and to identify what aspects ~~of the ice age~~ climate ~~and hydrology~~ models have greatest difficulties ~~in~~ capturing.

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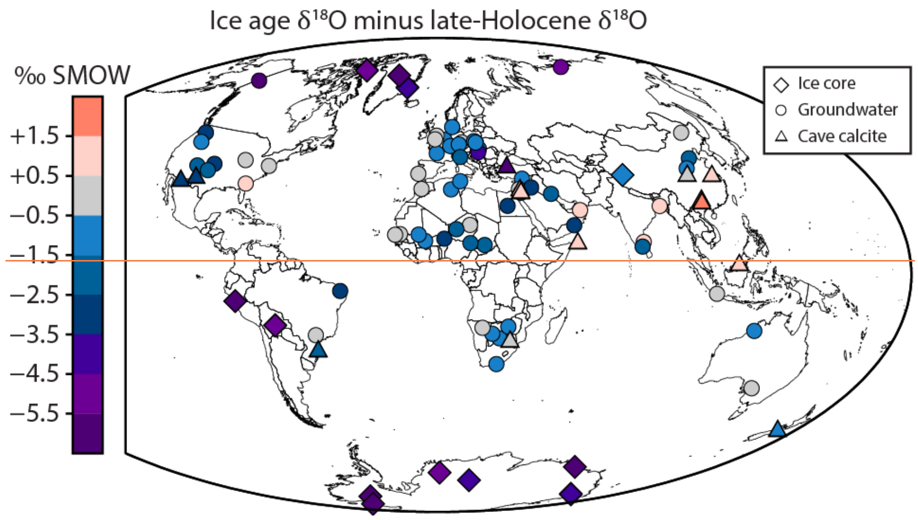

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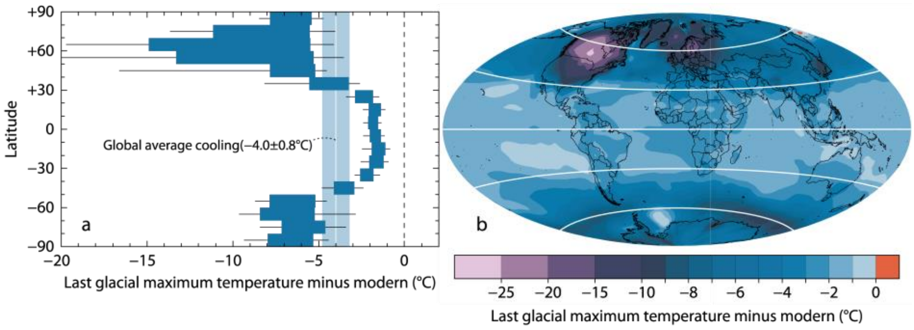

Figure 1. The change in surface air temperatures from the last glacial maximum to the preindustrial era (gridded data from Annan and Hargreaves, 2013). (a) Percentile ranges of temperature changes since the last glacial maximum for 10 degree latitudinal bands. Blue shading marks the 25th-75th percentile range; thin horizontal lines mark the 10th-90th percentile range. The grey band shows the globally-averaged estimate of temperature change since the last glacial maximum of −4.0±0.8 °C. (b) Gridded surface air temperature anomaly from the last glacial maximum to the preindustrial era (data from Annan and Hargreaves, 2013).

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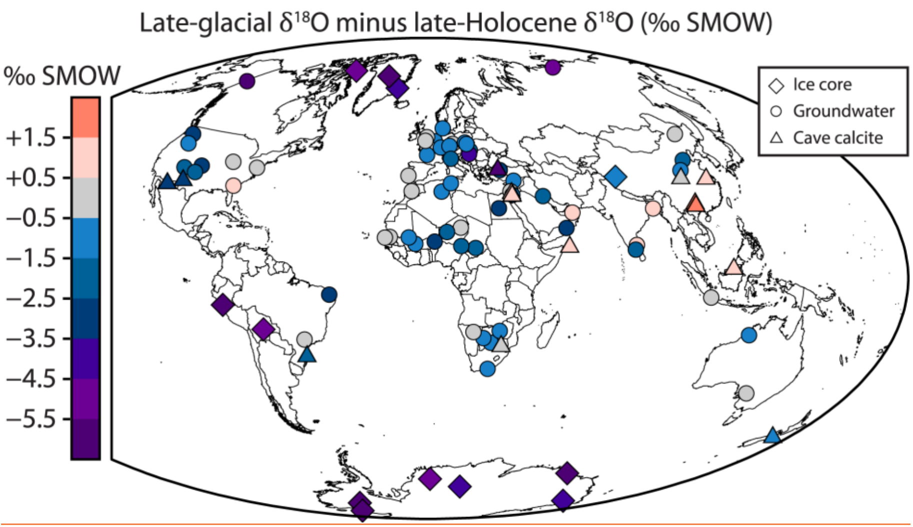

Figure 2. Meteoric water $\delta^{18}O$ change from the ~~latter half of the last ice age (19,500 to~~ late-glacial (20,000 to ~50,000 years ago) to the late~~-~~Holocene (within past ~5,000 years; average $\Delta^{18}O_{late\text{-}glacial}$ values shown, where $\Delta^{18}O_{late\text{-}glacial} = \delta^{18}O_{late\text{-}glacial} - \delta^{18}O_{late\text{-}Holocene}$). The low temporal resolution of groundwater records means that $\delta^{18}O$ variations within each time period are smoothed and likely represent unequal temporal weighting. References for ~~reconstructed~~measured meteoric water $\delta^{18}O$ changes for ice cores, groundwater and cave calcite are presented in the ~~Supplementary Information~~Supplement.

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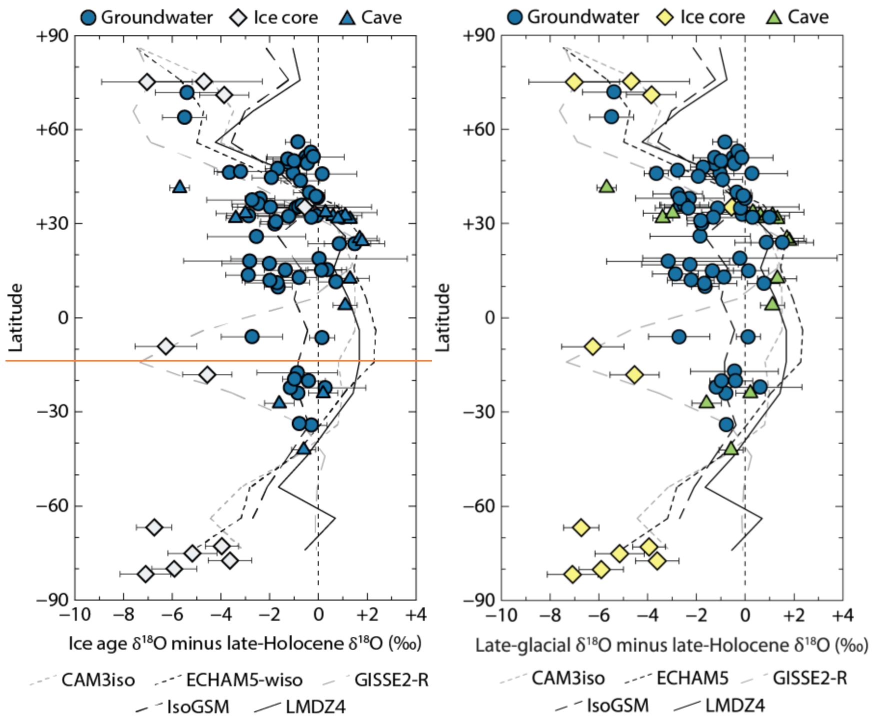

Figure ~~2~~3. Latitudinal variations of ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values of groundwater (circles, each circle is one aquifer), ice cores (diamonds) and cave calcite (i.e., ~~speleothems;~~ triangles~~).~~; where $\Delta^{18}O_{late\text{-}glacial} = \delta^{18}O_{late\text{-}glacial} - \delta^{18}O_{late\text{-}Holocene}$). Dashed lines mark 10° zonal mean simulated ~~$\Delta^{18}O_{ice\ age}$~~$\Delta^{18}O_{late\text{-}glacial}$ values from five different general circulation models: CAM3iso, ECHAM5-wiso, GISSE2-R, IsoGSM and LMDZ4 (Yoshimura et al., 2003; Legrande and Schmidt, 2008; 2009; Risi et al., 2010a; Noone and Sturm, 2010; Pausata et al., ~~2011~~2011a; Werner et al., 2011).

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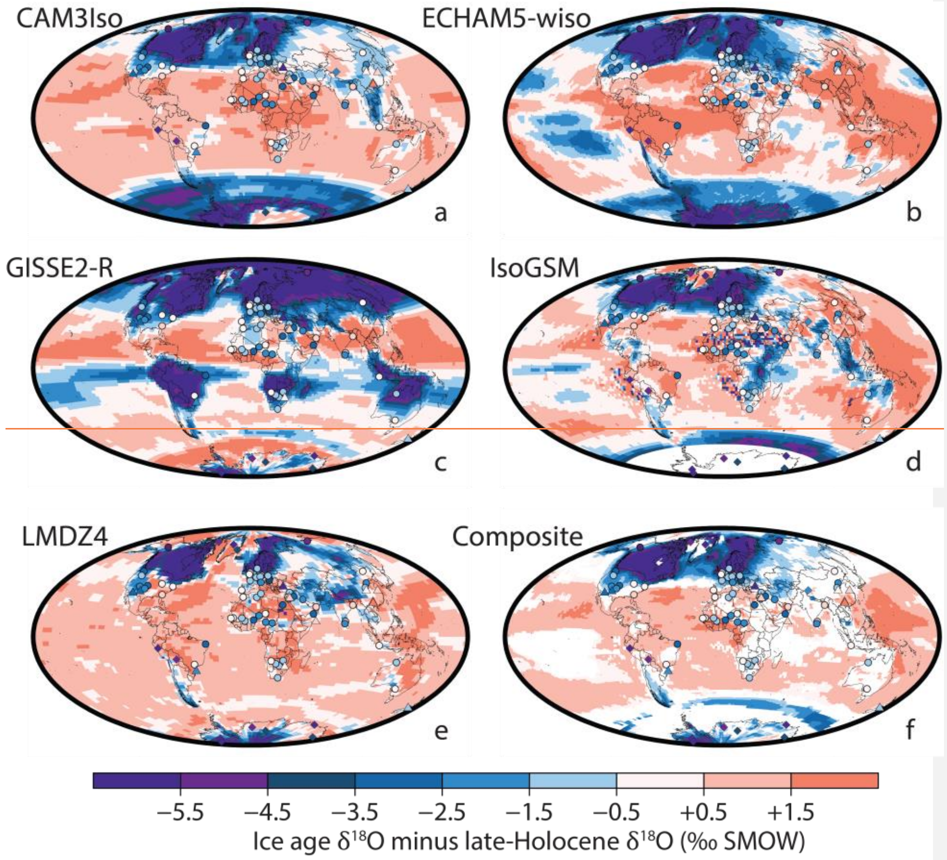
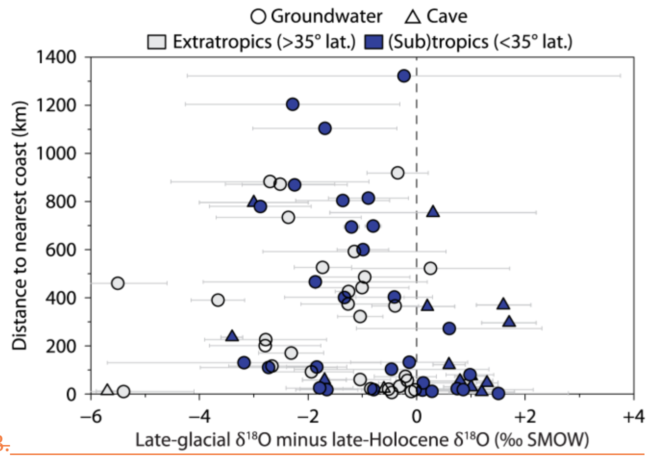

CAM3Iso
ECHAM5-wiso
a
b
GISSE2-R
IsoGSM
c
d
LMDZ4
Composite
e
f
−5.5
−4.5
−3.5
−2.5
−1.5
−0.5
+0.5
+1.5
Ice age δ18O minus late-Holocene δ18O (‰ SMOW)

2

Groundwater
Cave
Extratropics (>35° lat.)
(Sub)tropics (<35° lat.)
Distance to nearest coast (km)
1400
1200
1000
800
600
400
200
0
−6
−4
−2
0
+2
+4
Late-glacial δ18O minus late-Holocene δ18O (‰ SMOW)

~~Figure 3.~~

Figure 4. Measured $\Delta^{18}O_{late\text{-}glacial}$ value variability with distance to the nearest coast ($\Delta^{18}O_{late\text{-}glacial} = \delta^{18}O_{late\text{-}glacial} - \delta^{18}O_{late\text{-}Holocene}$). Tropical and subtropical locations are shown in deep blue (<35° absolute latitude), extra-tropical sites are shown in light grey (>35° absolute latitude). The shape of each point corresponds to groundwater and ground ice (circles) or cave calcite (i.e., speleothems; triangles). Error bars mark one standard deviation from the mean.

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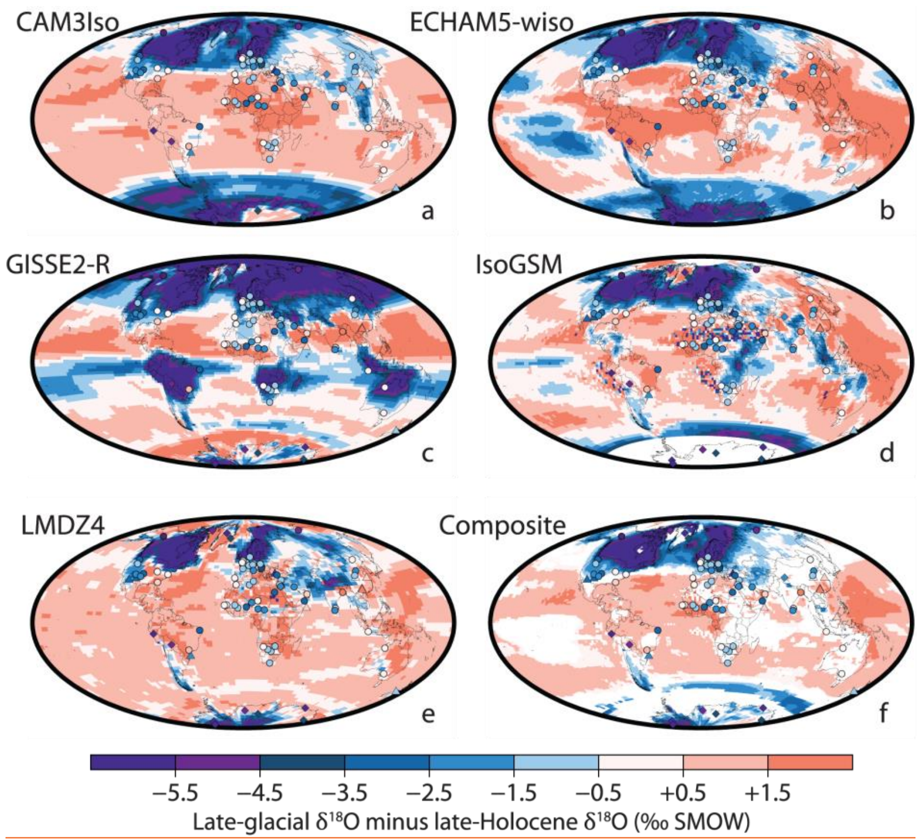

Figure 5. Simulated precipitation $\delta^{18}O$ differences between the last glacial maximum and pre-industrial time periods (i.e., $\delta^{18}O_{\text{last glacial maximum}} - \delta^{18}O_{\text{pre-industrial}}$) from five general circulation models: CAM3iso, ECHAM5-wiso, GISSE2-R, IsoGSM and LMDZ4 (Yoshimura et al., 2003; Legrande and Schmidt, 2008; 2009; Risi et al., 2010a; Noone and Sturm, 2010; Pausata et al., ~~2011~~2011a; Werner et al., 2011). Circles (groundwater), triangles (speleothems) and diamonds (ice cores) show ~~reconstructed $\Delta^{18}O_{\text{ice age}}$~~measured $\Delta^{18}O_{\text{late-glacial}}$ values from paleoclimate proxy records (Figure 1, original data presented in Tables S2–S5). The panel entitled "Composite" shows the multi-model ensemble median ~~$\Delta^{18}O_{\text{ice age}}$~~simulated $\Delta^{18}O_{\text{late-glacial}}$ value where at least four of the five models agree on the sign of simulated ~~$\Delta^{18}O_{\text{ice age}}$~~$\Delta^{18}O_{\text{late-glacial}}$ values (i.e., positive or negative; all five model simulations of $\delta^{18}O_{\text{last glacial maximum}} - \delta^{18}O_{\text{pre-industrial}}$ were used to calculate multi-model median shown in "Composite").

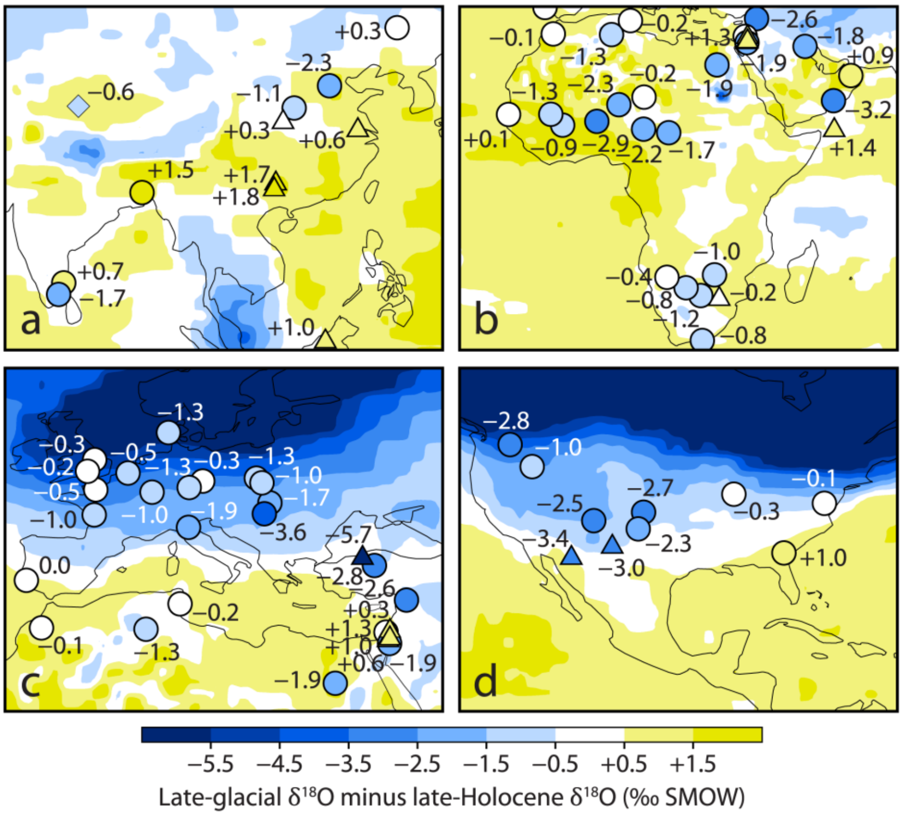

Figure 6. Regional proxy record $\Delta^{18}O_{late-glacial}$ values for (a) southeastern Asia, (b) Africa, (c) Europe, and (d) the contiguous United States of America (where $\Delta^{18}O_{late-glacial} = \delta^{18}O_{late-glacial} - \delta^{18}O_{late-Holocene}$). The multi-model ensemble median simulated $\Delta^{18}O_{late-glacial}$ value is shown as a grid (0.5 degree smoothing). Groundwater records are represented by circles, speleothems by triangles, and ice cores by diamonds, labels show measured $\Delta^{18}O_{late-glacial}$ values for each individual record.

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