https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past Discussions

A global analysis of reconstructed land climate changes during Dansgaard-Oeschger events

Mengmeng Liu[1,2,*], Iain Colin Prentice[1], Sandy P. Harrison[2]

1: Georgina Mace Centre for the Living Planet, Department of Life Sciences, Imperial College London, Silwood Park Campus, Buckhurst Road, Ascot SL5 7PY, UK

2: Department of Geography and Environmental Science, University of Reading, Reading, RG6 6AB, UK

*** Corresponding author: m.liu18@imperial.ac.uk**

Abstract

Dansgaard–Oeschger (D–O) warming events are comparable in magnitude and rate to the anticipated 21st century warming. As such, they provide a good target for evaluation of the ability of state-of-the-art climate models to simulate rapid climate changes. Despite the wealth of qualitative information about climate changes during the D-O events, there has been no attempt to date to make quantitative reconstructions globally. Here we provide reconstructions of seasonal temperature changes and changes in plant-available moisture across multiple D-O events during Marine Isotope Stage 3 based on available pollen records across the globe. These reconstructions show that the largest changes in temperature occurred in northern extratropics, especially Europe and Eurasia. The change in winter temperature was not significantly different from the change in summer temperature, and thus there is no evidence that the D-O events were characterised by a change in seasonality. Although broadscale features of the temperature changes were consistent across the eight D-O events examined, the spatial patterns of temperature changes vary between events. Globally, changes in moisture were positively correlated with changes in temperature, but the strength and the sign of this relationship vary regionally. These reconstructions can be used to evaluate the spatial patterns of changes in temperature and moisture in the transient simulations of the D-O events planned as part of the Palaeoclimate Modelling Intercomparison Project.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

1. Introduction

Dansgaard–Oeschger (D–O) events are characterised in Greenland by a transition from cold Greenland Stadial (GS) to warmer Greenland Interstadial (GI) conditions (Dansgaard et al., 1993). The surface air temperature in Greenland increased by 10–15° C during the warming phases; these warming events occur over an interval of between 50 and 200 years (Huber et al., 2006; Kindler et al., 2014). Thus, the D-O events offer a parallel in terms of speed to projected future warming, although both the baseline state and the mechanism inducing this warming differ from anticipated 21st century climate changes. D-O events could therefore provide an opportunity to determine how well climate models that are used for future projections can simulate rapid climate changes (Malmierca-Vallet et al., 2023).

D-O events are registered globally (Voelker, 2002; Sánchez Goñi and Harrison, 2010; Harrison and Sánchez Goñi, 2010; Sánchez Goñi et al., 2017; Adolphi et al., 2019; Corrick et al., 2020). Shifts in vegetation types between GI and GS states have been interpreted as primarily a temperature signal in the extratropics and a moisture signal in the tropics (Harrison and Sánchez Goñi, 2010). Speleothem records provide a good time-control on the synchroneity of climate changes globally with the D-O events registered in Greenland (Adolphi et al., 2019; Corrick et al., 2020), but the driver of this signal can either be temperature or precipitation depending on the region. There are quantitative climate reconstructions based on pollen records from La Grande Pile (Guiot et al., 1993), Lago Grande di Monticchio (Huntley et al., 1999), Padul (Camuera et al., 2022), El Cañizar de Villarquemado (Wei et al., 2021; Camuera et al., 2022) and Lake Ohrid (Sinopoli et al., 2019), diatom assemblages at Les Echets, France (Ampel et al., 2010), bacterial membrane lipid records from the Eifel region (Zander et al., 2023), isotopic measurements of earthworm calcite from the Rhine Valley (Prud'homme et al., 2022) and clumped isotope measurements on snails in Hungary (Újvári et al., 2021). Aside from the lack of comparable quantitative estimates from outside Europe, differences in the methodology employed and in the specific climate variables reconstructed in each of these studies limits their usefulness for model evaluation. In particular, given that there is still uncertainty as to whether the D-O cycles are characterised by changes in seasonality such that warming events are primarily driven by changes in winter (Flückiger et al., 2008; Zander et al., 2023), in the regional strength of the warming (Harrison and Sánchez Goñi, 2010) and how warming relates to changes in moisture (Wei et al., 2021), there is a need for more systematic reconstruction of seasonal climate changes.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

In the paper, we provide reconstructions of seasonal temperature changes and changes in plant-available moisture across multiple D-O events during Marine Isotope Stage 3 based on available pollen records globally. We employ a standard methodology to construct age models for these records, as well as a standard regression-based approach to make the reconstructions. We analyse the regional patterns to identify key targets for model evaluation.

2. Methods

2.1. Data sources

Modern pollen data were obtained from version 2 of the SPECIAL Modern Pollen Data Set (SMPDSv2: Villegas-Diaz and Harrison, 2022). This global data set contains 24649 modern pollen records from 17827 sites. The dataset contains relative abundance records for 4816 pollen taxa, created after removing taxa that are not climatically diagnostic (e.g. obligate aquatics, carnivorous species, cultivated plants). The data set provides several levels of taxonomic aggregation; here we use the most aggregated level, where woody species were generally combined at genus level and herbaceous species at sub-family or family level unless they were palynologically distinctive, occupied distinctive ecological niches and were sufficiently geographically widespread. This "amalgamated" data set contains relative abundance information for 1338 taxa. These samples were aggregated by longitude, latitude and elevation in order to remove duplicates. Counts for *Quercus*, *Quercus* (deciduous) and *Quercus* (evergreen) were combined because of inconsistent differentiation of *Quercus* pollen in different regional records. Taxa with <10 occurrences were removed to avoid the problem of rarity (Liu et al., 2020). After this filtering, the data set contains 17547 sites (Figure 1) with 591 taxa.

The SMPDSv2 also provides climatic information at each pollen site, specifically the mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA), and a moisture index (α) calculated as the ratio of actual evapotranspiration to equilibrium evapotranspiration. These bioclimate variables reflect mechanistically distinct controls on plant growth.

The fossil pollen data were obtained from the Abrupt Climate Changes and Environmental Responses (ACER) database (Sánchez Goñi et al., 2017), which includes 93 records from the last glacial period (73-15 ka) with sufficient resolution and dating control to detect sub-

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions

millennial scale variability. Here we focus on the 73 records covering most of Marine Isotope Stage 3 (50-30 ka); 54 of these records are from terrestrial sites and 19 from continental-shelf marine sites (Figure 1; Table 1). The fossil data were taxonomically harmonised to be consistent with the SMPDSv2.

2.2. Climate reconstruction method

We used tolerance-weighted Weighted Averaging Partial Least Squares (*fx*TWA-PLS: Liu et al., 2020; Liu et al., 2023) regression to model the relationships between taxon abundances and individual climate variables in the SMPDSv2 modern training dataset and then applied these relationships to reconstruct past climate using the fossil assemblages from the ACER database (Figure 2). *fx*TWA-PLS reduces the tendency of regression methods to compress reconstructions towards the centre of the sampled climate range by applying a sampling frequency correction to reduce the influence of uneven sampling of climate space and weighting the contribution of individual taxa according to their climate tolerances (Liu et al., 2020). Version 2 of *fx*TWA-PLS (*fx*TWA-PLS2, Liu et al., 2023) uses P-splines smoothing to derive the frequency correction and applies this correction both in estimating the climate optima and tolerances, and in the regression itself, producing a further improvement in model performance compared to version 1 (Liu et al., 2020).

We evaluated the *fx*TWA-PLS models by comparing the reconstructions with observations using leave-out cross-validation, where one site at a time was randomly selected as a test site and geographically and climatically similar sites were removed from the training set to prevent redundancy in the climate information from inflating the cross-validation goodness of fit. We selected the last significant number of components (p-value ≤ 0.01) and assessed model performance using the root mean square error of prediction (RMSEP). Compression was assessed using linear regression and local compression was assessed by loess regression (*locfit*). Reconstructions of MTCO, MTWA and α were made for every sample in each fossil record. Sample specific errors were estimated via bootstrapping, as described in Liu et al. (2020). We corrected for the effect of changes in atmospheric CO_2 on plant water-use efficiency, and hence the reconstructions of α (Figure S1), following Prentice et al. (2022). Appropriate values of CO_2 were taken from the WAIS Divide ice core record (Bauska et al., 2021).

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past Discussions

2.3. Age modelling

Although the ACER database provides age models for each pollen record, the resolution of the individual records is variable (mean resolution 474 years) and these models are often imperfectly aligned with the dating of D-O events as recorded in the Greenland ice core. To create a better alignment, we used dynamic time warping (DTW: Belman and Kalaba, 1959; Burstyn et al., 2021) to adjust the age scale for each individual record (Figure 2). Dynamic time warping optimises the similarity between two sequences by stretching or compressing one sequence in the time dimension to match the other. Here, we use simulated mean annual temperature from a transient simulation of the interval 50-30 ka made with the LOVECLIM model (Menviel et al., 2014) as the reference sequence. We used the mid-point between the start dates of each D-O event (Wolff et al., 2010; converted into AICC2012 timescale) to sub-divide each record into discrete intervals. For each site in each interval, we modify the time scale of the reconstructed mean annual temperature series in each ACER record to match the reference, after having normalised both sequences to remove the influence of differences in absolute values and the amplitude of changes. To remove the influence of the variable temporal resolution of the pollen records we interpolated the reconstructions from individual samples to provide estimates at regular intervals (25 years) through each record. The adjusted age model for each site was then applied to the reconstructions of MTCO, MTWA, and α for that site.

2.4. Assessment of changes during D-O events

To estimate the magnitude of climate changes over the D-O events, we used a third-order polynomial to fit the reconstructions during the interval from 300 years before to 600 years after the official start date of each event (Wolff et al., 2010; converted into AICC2012 timescale) to obtain the sign of changes (increase or decrease). We used the ages corresponding to the minimum and maximum in the fitted polynomial ($t_{min\ polynomial}$, $t_{max\ polynomial}$) but, since the smoothed polynomial may underestimate the amplitude of change, we used the reconstructed minimum or maximum value within the period $t_{min\ polynomial} \pm 100$ years or $t_{max\ polynomial} \pm 100$ years respectively.

In cases where no change was registered for all of the three climate variables, we assume that the event was not registered at the site. As a measure of the accuracy of the DTW method to identify D-O events, we compared the number of identified events with the number of D-O events that occurred during the time covered by each record (Table 1). To assess whether events

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past Discussions

were missed in a particular record due to low sampling resolution, we examined the number of samples present in the 900-year interval covering the sampled D-O (i.e. 300 years before to 600 years after the official start date of each event), where low resolution was defined as ≤ 3 samples in this 900-year interval. Reconstructions covering intervals where a signal was not identified were not used in subsequent analyses.

3. Results

*fx*TWA-PLS reproduces the modern climate reasonably well (Table 2). The performance is best for MTCO (R^2 0.75, RMSEP 6.51, slope 0.85) but is also good for MTWA (R^2 0.59, RMSEP 3.68, slope 0.71) and α (R^2 0.65, RMSEP 0.18, slope 0.71). Assessment of the variance inflation factor scores shows that there is no problem of multicollinearity so that it is possible to reconstruct all three climate variables independently (Liu et al., 2023).

The use of dynamic time-warping made it possible to identify D-O events robustly (Table 1). Across the 73 sites, we identified 204 out of the 210 individual D-O events that occurred during the intervals covered by the records. In the majority of cases where a D-O event should have been registered but could not be identified in an individual record (5 out of 6 cases), the resolution of that part of the record was extremely poor (≤ 3 samples in the 900-year interval starting 300 years before to 600 years after the official start date of the event).

Changes in both MTCO and MTWA were generally largest in the extratropics and were more muted in the tropics (Figure 3). The change in MTCO was larger, but not significantly larger, in the northern extratropics when considered across all D-O events and sites; the change in MTCO was smaller, but not significantly smaller, in the southern extratropics; the changes in MTCO are not correlated with the changes in MTWA in the tropics (Table 3). There is a significant positive relationship between the change in α and the change in MTWA in all regions (Figure 4; Table 4).

The spatial patterns of changes in MTCO and MTWA show consistent features across multiple D-O events (Figure 5), most noticeably that the largest warming occurs in the extratropics of Europe and Eurasia, while western North America and the southern extratropics are characterised by cooling. The anti-phasing between the northern and southern extratropics is consistent across D-O events. Nevertheless, both the magnitude of the changes and the spatial patterns vary between the D-O events (Figure S2; Figure S3). Changes in α broadly follow the

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions

changes in temperature, with increased α in regions characterised by warming (Figure 5) but show more variability both spatially and between D-O events (Figure S4). This is particularly true for Europe, which is characterised by a mixed signal of drying and wetting.

4. Discussion and Conclusions

We have presented a first attempt to map the spatial patterns of quantitative changes in seasonal temperature and plant-available moisture during D-O events globally, using a consistent methodology and a single data source. These analyses show that there is an anti-phasing between changes in the northern extratropics and the southern extratropics, with warming in the north and cooling in the south. The largest and most consistent warming during D-O events occurs in Europe and Eurasia. There is no indication of a significant difference in the temperature change during winter and summer, and thus no indication of a large shift in seasonality as inferred from some site-based reconstructions (e.g. Zander et al., 2023). Globally, there is a positive relationship between the change in temperature and plant available moisture, as indicated by α. This is consistent with more qualitative interpretation of palaeo-records from specific regions, where many regions are characterised by both warming and wetting (e.g. western Europe: Sánchez Goñi et al., 2008; Fletcher et al., 2010; eastern Europe: Fleitmann et al., 2009; Stockehecke et al., 2016; central Siberia: Grygar et al., 2006; the Great Basin USA: Denniston et al., 2007; Jiménez-Moreno et al., 2010). However, according to our reconstructions, the nature of this relationship varies between regions: there are some regions that are characterised by warming and wetting, others are characterised by warming and drying. Previous studies have also indicated drier conditions during D-O events, particularly in parts of the USA such as the Pacific Northwest (Grigg and Whitlock, 2002) and Florida (Grimm et al., 2006; Jiménez-Moreno et al., 2010) Although there is some consistency in the broadscale patterns of changes across D-O events, the magnitude of the changes as well as the spatial patterning varies between events.

These reconstructions can be used as targets for model evaluation, specifically the two transient D-O experiments planned for the next phase of the Palaeoclimate Modelling Intercomparison (see Malmierca-Vallet et al., 2023 for the experimental protocol). The first of these experiments is a baseline simulation starting at 34 ka, a time with low obliquity, moderate MIS3 greenhouse gas values, and an intermediate ice sheet configuration, which appears to be most conducive to generating D–O-like behaviour in climate models. The second experiment involves the addition of freshwater, to examine whether this in necessary to precondition a state conducive

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

to generating D–O events. The observed anti-phasing in temperature changes between the northern and southern hemispheres is a general feature of climate model experiments. However, most models show larger warming in winter than in summer in the northern hemisphere (e.g. Flückiger et al., 2008; Van Meersbeeck et al., 2011; Izumi et al., 2023), which is not consistent with our reconstructions. Models generally show an intensification of the northern hemisphere monsoons during D-O events (e.g. Menviel et al., 2020; Izumi et al, 2023), but there is less consistency about changes in plant-available moisture in the extratropics. Our reconstructions of α suggest an intensification of the monsoon over northern South America but there are no records from other northern hemisphere monsoon regions. However, the records do provide an opportunity to evaluate moisture changes over the extratropics.

Identifying D-O events in pollen records is often problematic, particularly in regions where warming (especially if accompanied by dryer conditions) leads to a reduction (or an hiatus) in sedimentation as reflected in the variable resolution of the available pollen records (e.g. Sinopoli et al., 2019; Wei et al., 2021; Camuera et al., 2022; Pini et al., 2022). Interpolation of the reconstructed climate between more sparsely spaced samples goes some way to improving the identification of potential D-O events using dynamic time warping, as does the use of shorter periods (Alshehri et al., 2019). However, it is likely that some of the variability in the reconstructed changes between different D-O events reflects imperfect identification of specific events because of the comparatively modest resolution of the records. Several new high-resolution records covering MIS3 have become available since the compilation of the ACER database (e.g. Wei et al., 2021; Camuera et al., 2022; Pini et al., 2022) and including these newer records could help to improve the reliability of the global reconstructions presented here. Nevertheless, this first compilation of quantitative climate reconstructions through multiple D-O events during MIS3 provides an opportunity for evaluation of the transient D-O simulations planned as part of the next phase of the Palaeoclimate Modelling Intercomparison Project (Malmierca-Vallet et al., 2023).

Data and code availability. All the data used are public access and cited here. The code used to generate the reconstructions and figures is available at https://github.com/ml4418/DO-climate-reconstruction-paper.git

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past Discussions
Open Access

Author contributions. ML, SPH and ICP designed the study. ML made the reconstructions and produced the figures and tables. ML and SPH carried out the analyses. SPH wrote the first draft of the paper and all authors contributed to the final draft.

Competing Interests. The authors declare not competing interests.

Acknowledgements. ML acknowledges support from Imperial College through the Lee Family Scholarship. ICP acknowledges support from the ERC under the European Union Horizon 2020 research and innovation programme (grant agreement no.: 787203 REALM). SPH acknowledges fruitful discussions with colleagues from the D-O community working group.

References

Adolphi, F., Bronk Ramsey, C., Erhardt, T., Edwards, R. L., Cheng, H., Turney, C. S. M., Cooper, A., Svensson, A., Rasmussen, S. O., Fischer, H., and Muscheler, R.: Connecting the Greenland ice-core and U / Th timescales via cosmogenic radionuclides: testing the synchroneity of Dansgaard–Oeschger events, Clim. Past, 14, 1755–1781, https://doi.org/10.5194/cp-14-1755-2018, 2018.

Alshehri, M., Coenen, F., and Dures, K.: Effective sub-sequence-based dynamic time warping. In: Bramer, M., Petridis, M. (eds) Artificial Intelligence XXXVI. SGAI 2019. Lecture Notes in Computer Science, 11927. Springer, Cham. https://doi.org/10.1007/978-3-030-34885-4_23, 2019.

Ampel, L., Bigler, C., Wohlfarth, B., Risberg, J., Lotter, A.F., and Veres, D.: Modest summer temperature variability during DO cycles in western Europe, Quat. Sci. Rev., 29, 1322–1327, https://doi.org/10.1016/j.quascirev.2010.03.002, 2010.

Bauska, T. K., Marcott, S. A. and Brook, E. J.: Abrupt changes in the global carbon cycle during the last glacial period, Nat. Geosci., 14(2), 91–96, doi:10.1038/s41561-020-00680-2, 2021.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Bellman, R., and Kalaba, R.: On adaptive control processes, Automatic Control, IRE Transactions, 4, 1–9, http://ieeexplore.ieee.org/xpls/abs all.jsp? arnumber=1104847, 1959.

Burstyn, Y., Gazit, A., and Omri Dvir, O.: Hierarchical Dynamic Time Warping methodology for aggregating multiple geological time series, Comp. & Geosci., 150, 104704, https://doi.org/10.1016/j.cageo.2021.104704, 2021.

Camuera, J., Ramos-Román, M.J., Jiménez-Moreno, G. *et al.*: Past 200 kyr hydroclimate variability in the western Mediterranean and its connection to the African Humid Periods, Sci. Rep., 12, 9050, https://doi.org/10.1038/s41598-022-12047-1, 2022.

Corrick, E.C., Drysdale, R.N., Hellstrom, J.C., Capron, E., Rasmussen, S.O., Zhang, X., Fleitmann, D., Couchoud, I., and Wolff, E.: Synchronous timing of abrupt climate changes during the last glacial period, Science, 369, 963–969, https://doi.org/10.1126/science.aay5538, 2020.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, https://doi.org/10.1038/364218a0, 1993.

Denniston, R.F., Asmerom, Y., Polyak, V., Dorale, J.A., Carpenter, S.J., Trodick, C., Hoye, B., and González, L.A.: Synchronous millennial-scale climatic changes in the Great Basin and the North Atlantic during the last interglacial. Geology 35, 619-622, 2007.

Fleitmann, D., Cheng, H., Badertscher, S., Edwards, R.L., Mudelsee, M., Göktürk, O.M., Fankhauser, A., Pickering, R., Raible, C.C., Matter, A., Kramers, J., and Tüysüz, O.: Timing and climatic impact of Greenland interstadials recorded in stalagmites from northern Turkey, Geophys. Res. Lett., 36, 2009.

Fletcher, W.F., Sánchez Goñi, M.F., Allen, J.R.M., Cheddadi, R., Combourieu-Nebout, N., Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V., Müller, U.C., Naughton, F., Novenko, E., Roucoux, K., Tzedakis, P.C.: Millennial-scale variability during the last glacial in vegetation records from Europe, Quat. Sci. Rev., 29, 2839-2864, https://doi.org/10.1016/j.quascirev.2009.11.015, 2010.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Flückiger, J., Knutti, R., White, J.W.C., and Renssen, H.: Modeled seasonality of glacial abrupt climate events, Clim. Dyn., 31, 633–645, https://doi.org/10.1007/s00382-008-0373-y, 2008.

Grigg, L.D., and Whitlock, C.: Patterns and causes of millennial-scale climate change in the Pacific Northwest during Marine Isotope Stages 2 and 3, Quat. Sci. Rev., 21, 2067-2083, 2002.

Grimm, E.C., Watts, W.A., Jacobson, G.L., Hansen, B.C.S., Almquist, H., and Dieffenbacher-Krall, A.C.: Evidence for warm wet Heinrich events in Florida, Quat. Sci. Rev., 25, 2197-2211, 2006.

Grygar, T., Kadlec, J., Pruner, P., Swann, G., Bezdicka, P., Hradil, D., Lang, K., Novotna, K., and Oberhänsli, H.: Paleoenvironmental record in Lake Baikal sediments: environmental changes in the last 160 ky, Palaeogeogr. Palaeoclimatol. Palaeoecol., 237, 240-254, 2006.

Guiot, J., de Beaulieu, J. L., Cheddadi, R., David, F., Ponel, P., and Reille, M.: The climate in Western Europe during the last Glacial/Interglacial cycle derived from pollen and insect remains, Palaeogeogr., Palaeoclimatol., Palaeoecol., 103, 73–93, https://doi.org/10.1016/0031-0182(93)90053-L, 1993.

Jiménez-Moreno, G., Anderson, R.S., Desprat, S., Grigg, L.D., Grimm, E.C., Heusser, L.E., Jacobs, B.F., López-Martínez, C., Whitlock, C.L., and Willard, D.A.:Millennial-scale variability during the last glacial in vegetation records from North America, Quat. Sci. Rev., 29, 2865-2881, https://doi.org/10.1016/j.quascirev.2009.12.013, 2010.

Harrison, S.P., and Sánchez Goñi, M.F.: Global patterns of vegetation response to millennial-scale variability during the last glacial: A synthesis. Quat. Sci. Rev., 29, 2957-2980, 2010.

Huber, C., Leuenberger, M., Spahni, R., Flückiger, J., Schwander, J., Stocker, T.F., Johnsen, S., Landais, A., and Jouzel, J.: Isotope calibrated Greenland temperature record over Marine Iso- tope Stage 3 and its relation to CH_4, Earth Planet. Sci. Lett., 243, 504–519, 2006.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Huntley, B., Watts, W.A., Allen, J.R.M., Zolitschka, B.: Palaeoclimate, chronology and vegetation history of the Weichselian Lateglacial: comparative analysis of data from three cores at Lago Grande di Monticchio, southern Italy, Quat. Sci. Rev.,18: 945-960, https://doi.org/10.1016/S0277-3791(99)00007-4, 1999.

Kindler, P., Guillevic, M., Baumgartner, M., Schwander, J., Landais, A., and Leuenberger, M.: Temperature reconstruction from 10 to 120 kyr b2k from the NGRIP ice core, Clim. Past, 10, 887–902, https://doi.org/10.5194/cp-10-887-2014, 2014.

Liu, M., Prentice, I.C., ter Braak, C.J.F, and Harrison, S.P.: An improved statistical approach for reconstructing past climates from biotic assemblages, Proc. Royal Soc., Math. A, 476, 20200346, 20200346, https://doi.org/10.1098/rspa.2020.0346, 2020.

Liu, M., Shen, Y., González-Sampériz, P., Gil-Romera, G., ter Braak, C.J.F. Prentice, I.C., and Harrison, S.P.: Holocene climates of the Iberian Peninsula, Clim. Past 19, 803-834, https://doi.org/10.5194/cp-19-803-2023, 2023.

Malmierca-Vallet, I., Sime, L.C., and the D–O community members: Dansgaard–Oeschger events in climate models: review and baseline Marine Isotope Stage 3 (MIS3) protocol, Clim. Past, 19, 915–942, https://doi.org/10.5194/cp-19-915-2023, 2023.

Menviel, L., Timmermann, A., Friedrich, T., and England, M. H.: Hindcasting the continuum of Dansgaard–Oeschger variability: mechanisms, patterns and timing, Clim. Past 10, 63–77, 2014.

Menviel, L.C., Skinner, L.C., Tarasov, L., and Tzedakis, P.C.: An ice–climate oscillatory framework for Dansgaard–Oeschger cycles, Nat. Rev. Earth Environ., 1, 677–693, https://doi.org/10.1038/s43017-020-00106-y, 2020.

Pini, R., Furlanetto, G., Vallé, F., Badino, F., Wick, L., Anselmetti, F.S., Bertuletti, P., Fusi, N., Morlock, M.A., Delmonte, B., Harrison, S.P., Maggi, V., Ravazzi, C.: Linking North Atlantic and Alpine Last Glacial Maximum climates via a high-resolution pollen-based subarctic forest steppe record, Quat. Sci. Rev., 294, 107759, https://doi.org/10.1016/j.quascirev.2022.107759, 2022.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Prentice, I. C., Villegas-Diaz, R. and Harrison, S. P.: Accounting for atmospheric carbon dioxide variations in pollen-based reconstruction of past hydroclimates, Glob. Planet. Change, 211, 103790, doi:10.1016/j.gloplacha.2022.103790, 2022.

Prud'homme, C., Fischer, P., Jöris, O., Gromov, S., Vinnepand, M., Hatté, C., Vonhof, H., Moine, O., Vött, A., and Fitzsimmons, K. E.: Millennial-timescale quantitative estimates of climate dynamics in central Europe from earthworm calcite granules in loess deposits, Commun. Earth Environ., 3, 1–14, https://doi.org/10.1038/s43247-022-00595-3, 2022.

Sánchez Goñi, M.F., and Harrison, S.P.: Millennial-scale climate variability and vegetation changes during the Last Glacial: Concepts and terminology, Quat. Sci. Rev., 29, 2823–2827, 2010.

Sánchez Goñi, M.F., Desprat, S., Daniau, A.-L., Bassinot, F., Polanco-Martínez, J.M., Harrison, S.P., Allen, J.R.P., Anderson, R.S., Behling, H., Bonnefille, R., Burjachs, F., Carrión, J.S., Cheddadi, R., Clark, J.S., Combourieu-Nebout, N., Courtney-Mustaphi, C., Debusk, G.H., Dupont, L.M., Finch, J., Fletcher, W.J., Giardini, M., González, C., Gosling, W.D., Grigg, L.D., Grimm, E.C., Hayashi, R., Helmens, K., Heusser, L.E., Hill, T., Hope, G., Huntley, B., Igarashi, Y., Irino, T., Jacobs, B.F., Jiménez-Moreno, G., Kawai, S., Kershaw, P., Kumon, F., Lawson, I., Ledru, M.-P., Lézine, A.-M., Liew, P.-M., Magri, D., Marchant, R., Margari, V., Mayle, F., McKenzie, M., Moss, P., Müller, S., Müller, U.C., Naughton, F., Newnham, R.M., Oba, T., Pérez-Obiol, R., Pini, R., Ravazzi, C., Roucoux, K.H., Rucina, S., Scott, L., Takahara, H., Tzedakis, P.C., Urrego, D.H., Van Geel, B., Valencia, B.G., Vandergoes, M.J., Vincens , A., Whitlock, C.L., Willard, D. A., and Yamamoto, M.: The ACER pollen and charcoal database: a global resource to document vegetation and fire response to abrupt climate changes of the last glacial period, Earth Syst. Sci. Data 9: 679-695, 2017.

Sinopoli, G., Peyron, O., Masi, A., Holtvoeth, J., Francke, A., Wagner, B., and Sadori, L.: Pollen-based temperature and precipitation changes in the Ohrid Basin (western Balkans) between 160 and 70 ka, Clim. Past, 15, 53–71, https://doi.org/10.5194/cp-15-53-2019, 2019.

Stockhecke, M., Timmermann, A., Kipfer, R., Haug, G.H., Kwiecien, O., Friedrich, T., Menviel, L., Litt, T., Pickarski, N., and Anselmetti, F.S.: Millennial to orbital-scale

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions
Open Access
EGU

variations of drought intensity in the Eastern Mediterranean, Quat. Sci. Rev., 133, 77-95, 2016.

Újvári, G., Bernasconi, S. M., Stevens, T., Kele, S., Páll-Gergely, B., Surányi, G., and Demény, A.: Stadial-Interstadial Temperature and Aridity Variations in East Central Europe Preceding the Last Glacial Maximum, Paleoceanog. Paleoclim., 36, e2020PA004170, https://doi.org/10.1029/2020PA004170, 2021.

Van Meerbeeck, C.J., Renssen, H., Roche, D.M., Wohlfarth, B., Bohncke, S.J.P., Bos, J.A.A., Engels, S., Helmens, K.F., Sánchez-Goñi, M.F., Svensson, A., and Vandenberghe, J.: The nature of MIS 3 stadial-interstadial transitions in Europe: New insights from model-data comparisons, Quat. Sci. Rev., 30, 3618–3637, https://doi.org/10.1016/j.quascirev.2011.08.002, 2011.

Villegas-Diaz, R., and Harrison, S.P.: The SPECIAL Modern Pollen Data Set for Climate Reconstructions, version 2 (SMPDSv2). University of Reading. Dataset. https://doi.org/10.17864/1947.000389, 2022.

Voelker, A.H.: Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: a database, Quat. Sci. Rev., 21, 1185–1212, 2002.

Wei, D., González-Sampériz, P., Gil-Romera, G., Harrison, S.P., and Prentice, I.C.: Seasonal temperature and moisture changes in interior semi-arid Spain from the last interglacial to the Late Holocene, Quat. Res., 101, 143–155, https://doi.org/10.1017/qua.2020.108, 2021.

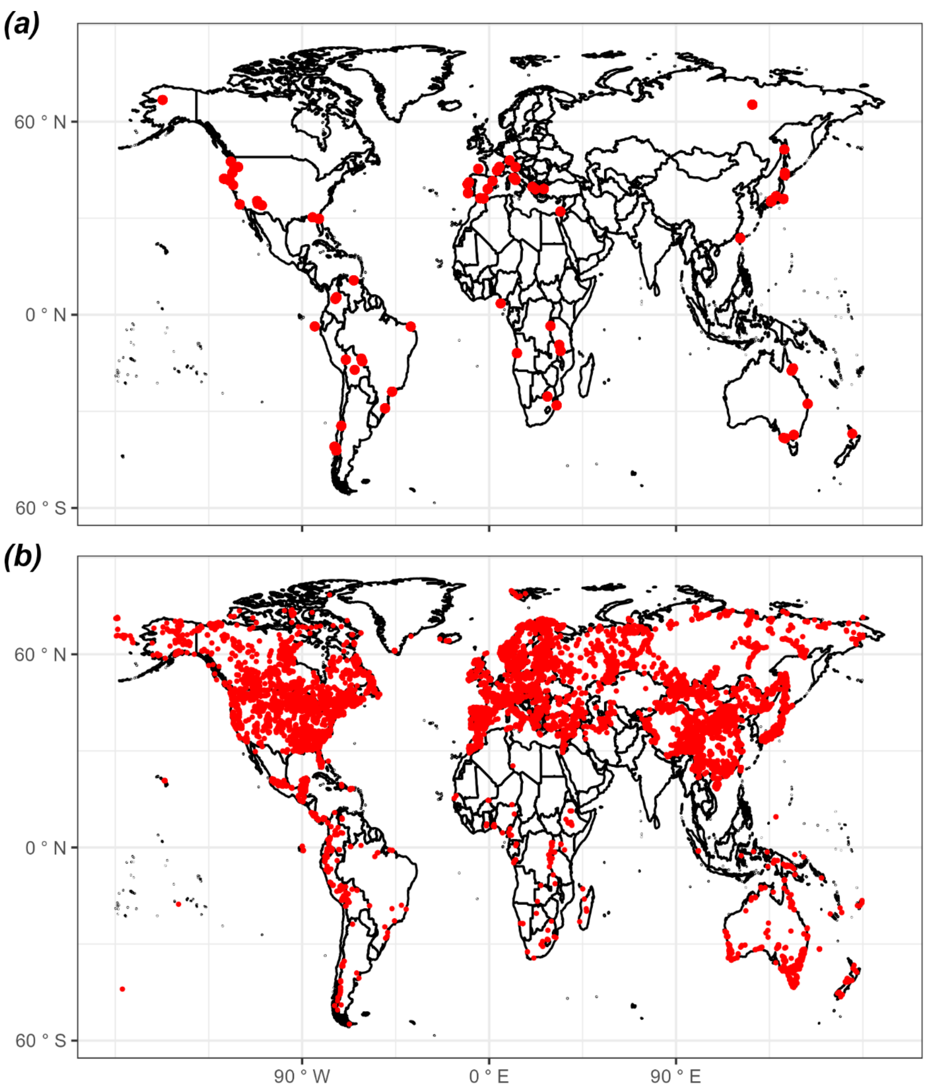
Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O. and Svensson, A.: Millennial-scale variability during the last glacial: The ice core record, Quat. Sci. Rev., 29(21), 2828–2838, doi:10.1016/j.quascirev.2009.10.013, 2010.

Zander, P.D., Böhl, D., Sirocko, F., Auderset, A., Haug, G., and Martínez-García, A.: Reconstruction of warm season temperatures in central Europe during the past 60,000 years from lacustrine GDGTs, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1960, 2023.

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

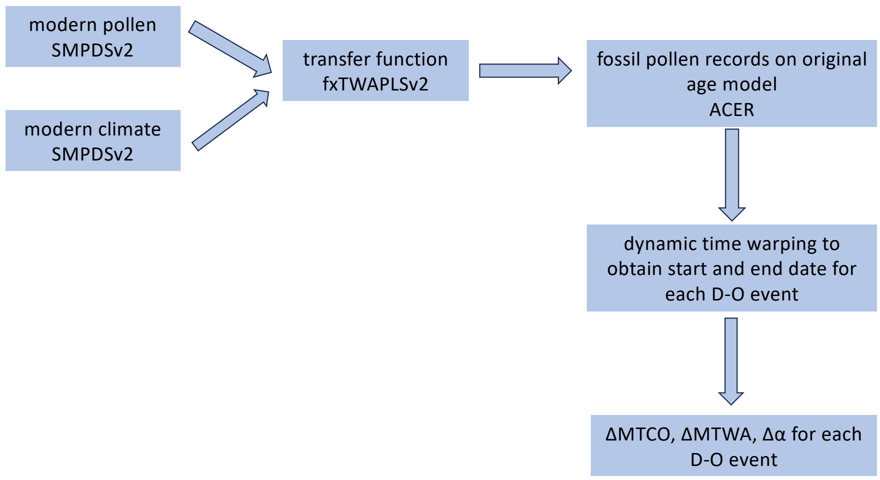
Figures and Tables

Figure 1: Map showing the locations of sites (a)from the Abrupt Climate Changes and Environmental Responses (ACER) database (Sánchez Goñi et al., 2017) covering the interval between 50 ka and 30 ka used for the reconstructions and (b) sites in version 2 of the SPECIAL Modern Pollen Data Set (SMPDSv2: Villegas-Diaz and Harrison, 2022) used to derive the transfer functions for these climate reconstructions.



https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

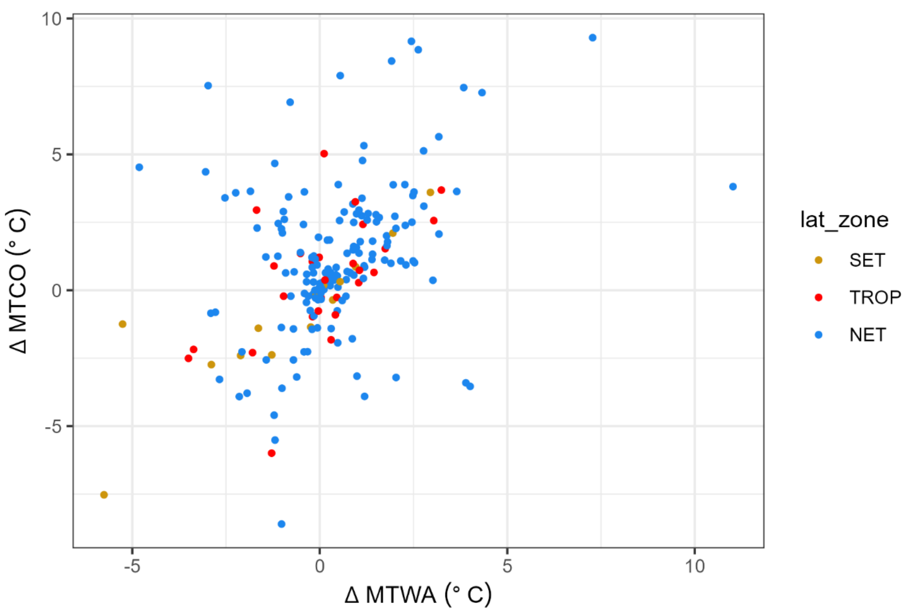
Figure 2: Flow chart showing the reconstruction methodology.



https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

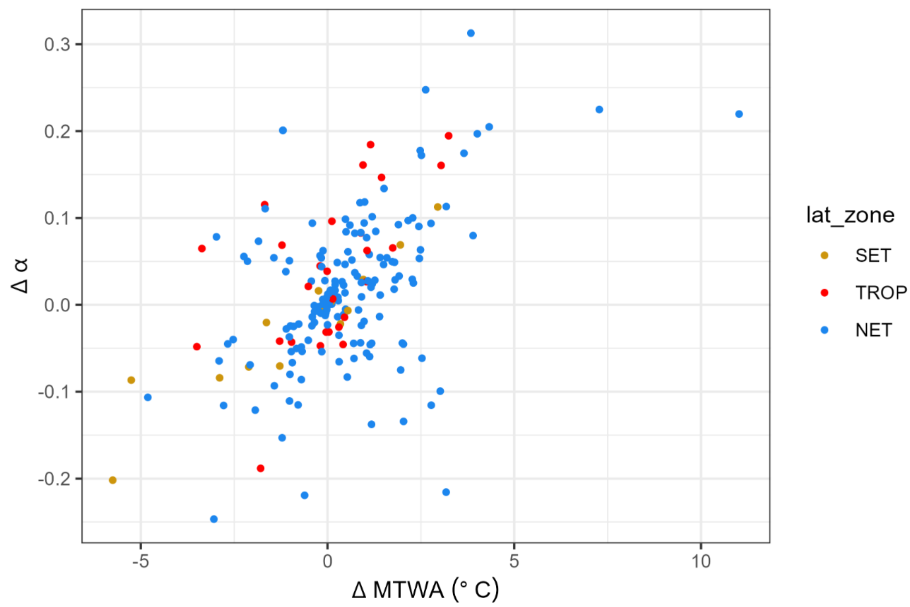
Climate of the Past
Discussions

Figure 3: Scatter plot of the change in mean temperature of the coldest month (ΔMTCO) versus the change in mean temperature of the warmest month (ΔMTWA) during individual Dansgaard-Oeschger (D-O) events at individual sites. The points are colour-coded to indicate whether the sites are from the northern extratropics (NET, north of 23.5°N), the tropics (TROP, between 23.5°N and 23.5°S) or southern extratropics (SET, south of 23.5°S).



https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

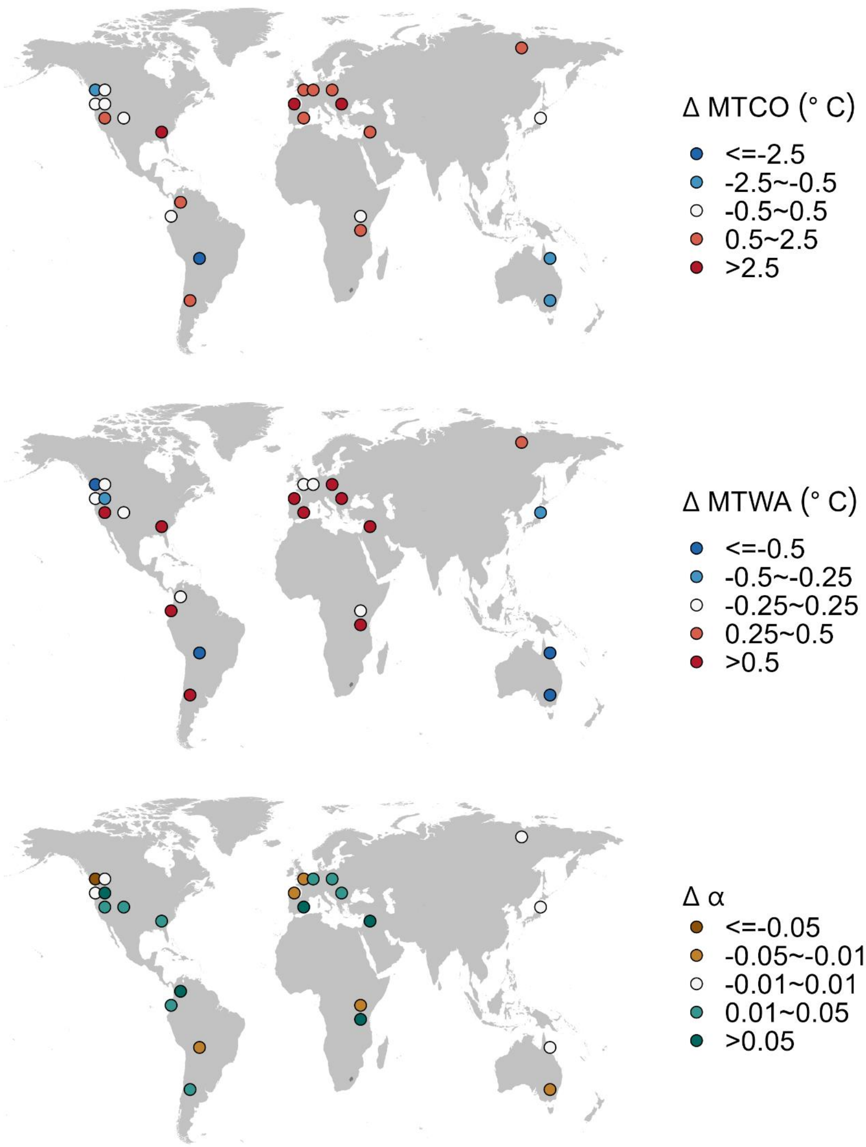
Figure 4: Scatter plot of the change in plant-available moisture (Δα) versus the change in mean temperature of the warmest month (ΔMTWA) during individual Dansgaard-Oeschger (D-O) events at individual sites. The points are colour-coded to indicate whether the sites are from the northern extratropics (NET, north of 23.5°N), the tropics (TROP, between 23.5°N and 23.5°S) or southern extratropics (SET, south of 23.5°S).



https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions
Open Access

Figure 5: Maps showing the median change of site-based reconstructions for Dansgaard-Oeschger (D-O) events.



https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Open Access
Discussions
EGU

443 Table 1: Details of the 73 sites from the Abrupt Climate Changes and Environmental Responses (ACER) database (Sánchez Goñi et al., 2017) covering the interval between 50 ka and 30 ka used for the climate reconstructions. n_{due} is the number of D-O events that should be found based on the time interval covered by the record. n_{miss} is the number of D-O events that were not identified. $n_{miss\_low\_res}$ is the number of D-O events missed because of low resolution of part of the record. Six of the D-O events out of the 210 that should have been registered were not identified, of which 5 are because of low resolution. Reconstructions based on samples where the D-O signal was not identified were not used in subsequent analyses. Some of the 73 sites (indicated by / in n_{due}, n_{miss} and $n_{miss\_low\_res}$) provide records for parts of the 50-30ka interval but not for the intervals of the D-O events.

Site name	Latitude	Longitude	Elevation (m)	Site type	n_due	n_miss	n_miss_ low_res
Abric Roman	41.53	1.68	350	TERR	/	/	/
Azzano Decimo	45.88	12.72	10	TERR	8	0	0
Caledonia Fen	−37.33	146.73	1280	TERR	/	/	/
Cambara do Sul	−29.05	−50.10	1040	TERR	/	/	/
Camel Lake	30.26	−85.01	20	TERR	3	1	1
Carp Lake	45.91	−120.88	720	TERR	8	0	0
Colnia	−23.87	−46.71	900	TERR	/	/	/
Core Trident 163 31B	−3.61	−83.96	−3210	MARI	1	0	0
Fargher Lake	45.88	−122.58	200	TERR	8	0	0
Framoos	47.98	9.88	662	TERR	/	/	/
Fundo Nueva	−41.28	−73.83	66	TERR	/	/	/
Fuquene	5.45	−73.46	2540	TERR	7	1	1
GeoB3104	−3.67	−37.72	−767	MARI	/	/	/
Hay Lake	34.00	−109.43	2780	TERR	6	1	1
Ioannina	39.75	20.85	470	TERR	8	0	0
Joe Lake	66.77	−157.22	183	TERR	/	/	/
Kalaloch - DIGI	47.61	−124.37	19	TERR	8	0	0

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past Discussions

Kamiyoshi Basin (KY01)	35.10	135.59	335	TERR	1	0	0
Kashiru Bog	−3.47	29.57	2240	TERR	8	1	1
Kenbuchi Basin	44.05	142.38	135	TERR	/	/	/
Khoe	51.34	142.14	15	TERR	/	/	/
Kohuora	−36.95	174.87	5	TERR	/	/	/
Kurota Lowland	35.52	135.88	20	TERR	/	/	/
KW31	3.52	5.57	−1181	MARI	/	/	/
La Laguna	4.92	−74.03	2900	TERR	2	0	0
Lac du Bouchet - DIGI	44.83	3.82	1200	TERR	/	/	/
Lagaccione	42.57	11.80	355	TERR	/	/	/
Laguna Bella Vista	−13.62	−61.55	600	TERR	/	/	/
Laguna Chaplin	−14.47	−61.07	600	TERR	/	/	/
Lake Billyakh	65.28	126.78	340	TERR	8	0	0
Lake Biwa (BIW95-4)	35.25	136.05	84	TERR	/	/	/
Lake Consuelo (CON1)	−13.95	−68.99	1360	TERR	/	/	/
Lake Malawi	−11.22	34.42	470	TERR	/	/	/
Lake Masoko	−9.33	33.75	840	TERR	2	0	0
Lake Nojiri	36.83	138.22	657	TERR	8	0	0
Lake Tulane	29.83	−81.95	36	TERR	/	/	/
Lake Wangoom LW87 core	−38.35	142.60	100	TERR	8	0	0
Lake Xinias	39.05	22.27	500	TERR	/	/	/
Les Echets G - DIGI	45.90	4.93	267	TERR	8	0	0
Little Lake	44.16	−123.58	217	TERR	5	0	0
Lynchs Crater	−17.37	145.70	760	TERR	8	0	0
MD01-2421	36.02	141.77	−2224	MARI	/	/	/
MD03-2622 Cariaco Basin	10.71	−65.17	−877	MARI	/	/	/
MD04-2845	45.35	−5.22	−4100	MARI	8	0	0

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions

MD84-629	32.07	34.35	−745	MARI	8	0	0
MD95-2039	40.58	−10.35	−3381	MARI	8	0	0
MD95-2042	37.80	−10.17	−3148	MARI	/	/	/
MD95-2043	36.14	−2.62	−1841	MARI	8	0	0
MD99-2331	41.15	−9.68	−2110	MARI	8	0	0
Megali Limni	39.10	26.32	323	TERR	/	/	/
Mfabeni Peatland	−28.15	32.52	11	TERR	/	/	/
Nakafurano	43.37	142.43	173	TERR	/	/	/
Native Companion Lagoon	−27.68	153.41	20	TERR	/	/	/
Navarrs	39.10	−0.68	225	TERR	3	1	0
ODP 1233 C	−41.00	−74.45	−838	MARI	/	/	/
ODP 820	−16.63	146.30	−280	MARI	/	/	/
ODP site 976	36.20	−4.30	−1108	MARI	8	0	0
ODP1019	41.66	−124.91	989	MARI	8	0	0
ODP1078C	−11.92	13.40	−426	MARI	/	/	/
ODP893A	34.28	−120.03	−577	MARI	8	0	0
Potato Lake	34.45	−111.33	2222	TERR	4	0	0
Rice Lake (Rice Lake 81)	40.30	−123.22	1100	TERR	/	/	/
Siberia	−17.09	−64.72	2920	TERR	2	0	0
Stracciacappa	42.13	12.32	220	TERR	/	/	/
Tagua Tagua - DIGI	−34.50	−71.16	200	TERR	6	0	0
Taiquemo	−42.17	−73.60	170	TERR	/	/	/
Toushe Basin	23.82	120.88	650	TERR	/	/	/
Tswaing Crater	−25.40	28.08	1100	TERR	/	/	/
Tyrrendara Swamp	−38.20	141.76	13	TERR	/	/	/
Valle di Castiglione	41.90	12.76	44	TERR	/	/	/
W8709-13 PC	42.11	−125.75	−2712	MARI	8	0	0
W8709-8 PC	42.26	−127.68	−3111	MARI	8	1	1

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions
Open Access

Walker Lake	35.38	−111.71	2500	TERR	/	/	/

453

454

Table 2. Leave-out cross-validation (with geographically and climatically close sites removed) using fxTWA-PLSv2 for mean temperature of the coldest month (MTCO), mean temperature of the warmest month (MTWA) and plant-available water (α) with P-splines smoothed *fx* estimation and bins of 0.02, 0.02 and 0.002, respectively. *n* is the number of components where the last significant number of components is indicated in **bold**. Avg.bias is the average bias; RMSEP is the root-mean-square error of prediction; and ΔRMSEP is the per cent change of RMSEP, which is 100 × ($RMSEP_n - RMSEP_{n-1}$)/$RMSEP_{n-1}$; when n = 1, $RMSEP_0$ is the RMSEP of the null model. *p* assesses whether using the current number of components is significantly different from using one component less. The degree of overall compression is assessed by linear regression of the cross-validated reconstructions on to the climate variable; b_1 and b_1.se are the slope and the standard error of the slope, respectively. The closer the slope (b_1) is to 1, the less the compression.

	n	R^2	Avg.bias	RMSEP	ΔRMSEP	*p*	b_1	$b_1.se$
MTCO (°C)	1	0.72	–1.11	6.83	–45.45	0.001	0.83	0.00
	2	0.74	–1.21	6.68	–2.25	0.001	0.84	0.00
	3	**0.75**	**–1.10**	**6.51**	**–2.48**	**0.001**	**0.85**	**0.00**
	4	0.75	–1.10	6.54	0.53	1.000	0.85	0.00
	5	0.75	–1.13	6.54	–0.07	0.188	0.85	0.00
MTWA (°C)	1	0.54	–0.33	3.89	–29.76	0.001	0.66	0.00
	2	0.58	–0.32	3.69	–5.10	0.001	0.71	0.00
	3	**0.59**	**–0.33**	**3.68**	**–0.14**	**0.001**	**0.71**	**0.00**
	4	0.59	–0.33	3.69	0.07	0.746	0.71	0.00
	5	0.59	–0.33	3.67	–0.39	0.001	0.71	0.00
α	1	0.62	–0.02	0.189	–37.73	0.001	0.66	0.00
	2	0.63	–0.022	0.188	–0.81	0.001	0.68	0.00
	3	0.63	–0.021	0.186	–0.87	0.001	0.68	0.00
	4	**0.65**	**–0.02**	**0.182**	**–2.11**	**0.001**	**0.71**	**0.00**
	5	0.65	–0.02	0.182	0.11	1.000	0.71	0.00

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions
Open Access
EGU

Table 3: Maximum likelihood estimates of the relationship between the change in mean temperature of the coldest month (ΔMTCO) and the change in mean temperature of the warmest month (ΔMTWA) by latitudinal bands for the northern extratropics (NET, north of 23.5°N), tropics (TROP, between 23.5°N and 23.5°S) and southern extratropics (SET, south of 23.5°S). The intercepts were set to zero since both variables are changes. Coefficients in bold mean both the lower 95% and upper 95% estimates are above 0.

Region		Coefficient	Standard error (SE)	Lower 95%	Upper 95%
NET	Slope	**2.129**	0.657	0.841	3.417
TROP	Slope	2.276	1.381	−0.431	4.983
SET	Slope	**0.979**	0.151	0.684	1.275

https://doi.org/10.5194/cp-2024-12
Preprint. Discussion started: 12 March 2024

Climate of the Past
Discussions
Open Access
EGU

475 Table 4: Maximum likelihood estimates of the relationship between the change in plant-available water (Δα) and the change in mean temperature of the warmest month (ΔMTWA) by latitudinal bands for the northern extratropics (NET, north of 23.5°N), tropics (TROP, between 23.5°N and 23.5°S) and southern extratropics (SET, south of 23.5°S). The intercepts were set to zero since both variables are changes. Coefficients in bold mean both the lower 95% and upper 95% estimates are above 0.

Region		Coefficient	Standard error (SE)	Lower 95%	Upper 95%
NET	Slope	**0.082**	0.022	0.039	0.124
TROP	Slope	**0.075**	0.026	0.024	0.127
SET	Slope	**0.031**	0.003	0.025	0.037