

Response to editor

The editor's comments are given in normal text, our responses are given in italics, the modifications in the manuscript are given in normal text in blue.

1. Title: "A global analysis of reconstructed land climate changes during Dansgaard–Oeschger events". Could you add pollen in the title? For example: "A global analysis of pollen-inferred land climate changes during Dansgaard–Oeschger events."

We have now changed the title to:

A global analysis of pollen-based reconstructions of land climate changes during Dansgaard–Oeschger events.

2. Abstract: Please add a sentence at the end describing the method used, and clearly highlight the fact that CO₂ is taken into account, which represents a novelty compared to previous studies.

We have now modified the abstract to describe the reconstruction method and the CO₂ correction approach as follows:

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 use frequency-corrected Tolerance-weighted Weighted Averaging Partial Least Squares regression (fxTWA-PLS) to reconstruct mean temperature of the coldest month, mean temperature of the warmest month, and a plant-available moisture index across multiple D–O events between 50 and 30 ka based on available pollen records across the globe. The reconstruction of plant-available moisture is corrected for the impact of changing atmospheric CO₂ concentrations on plant water use efficiency. These reconstructions show that the largest warming occurred in northern extratropics, especially Eurasia, while western North America and the southern extratropics were characterised by cooling. The change in winter temperature was significantly larger than the change in summer temperature in the northern extratropics and the tropics, indicating that the D–O warming events were characterised by reduced seasonality, but there was no significant difference between the summer and winter temperature changes in the southern extratropics. The antiphasing between northern and southern extratropical changes, and the west-east pattern of cooling and warming in North America were generally consistent across the eight D–O events examined, although coherency is greatest during the strongest events. There was no globally consistent pattern between changes in moisture and changes in temperature. 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.

3. Introduction:

For the sentence “a standard regression-based approach to make the reconstruction”, please add the relevant reference, specify the name of the method, and include a brief sentence emphasizing that CO₂ is taken into account in the reconstructions, which is new compared to previous syntheses (e.g. Zumaque et al.).

We have now modified the final paragraph in the Introduction as follows:

In the paper, we provide reconstructed changes in seasonal temperatures and plant-available moisture during the intervals corresponding to D-O warming events in Greenland between 50 and 30 ka based on available pollen records globally, using a standard regression-based approach, \hat{x} -corrected Tolerance-weighted Weighted Averaging Partial Least Squares (\hat{x} TWA-PLS; Liu et al., 2020, 2023). We also correct the reconstructions of plant-available moisture to take account of the impact of lower CO₂ on plant water-use efficiency following Prentice et al. (2022a). We analyse the regional patterns to identify key targets for model evaluation.

4. For the following paragraph:

“Although D-O events are found throughout the last glacial period, the largest number and the most regular patterning occurred during Marine Isotope Stage 3 (MIS 3; 57 to 29 ka) when there were 11 separate events (D-O 15 to D-O 5), while earlier stages such as MIS 4 (71 to 57 ka) only had 3 separate events (D-O 18 to 16). The typical duration of a cycle as manifested in Greenland is ca. 1500 years and is characterised by an initial short slow warming, followed by an abrupt large warming in a matter of decades, followed by a long slow cooling over centuries to millennia, with a terminal phase of fast cooling (e.g. D-O 8, D-O 12). However, there are also cycles in which the warming and cooling phases took roughly the same time (e.g. D-O 5, D-O 6, D-O 9). The magnitude of changes also differs, with both strong events (e.g. D-O 8, D-O 12) and weak events (e.g. D-O 9).” Please add appropriate references.

We have modified this paragraph as follows:

Although D-O events are found throughout the last glacial period, the largest number and the most regular patterning occurred during Marine Isotope Stage 3 (MIS 3; 57 to 29 ka) when there were 11 separate events (D-O 15 to D-O 5), while earlier stage such as MIS 4 (71 to 57 ka) only had 3 separate events (D-O 18 to 16) (Kindler et al., 2014). The typical duration of a cycle as manifested in Greenland is ca. 1500 years and is characterised by an initial short slow warming, followed by an abrupt large warming in matter of decades, followed by a long slow cooling over centuries to millennia, with a terminal phase of fast cooling (e.g. D-O 8, D-O 12); however, there are also cycles in which the warming and cooling phases took roughly the same time (e.g. D-O 5, D-O 6, D-O 9) (Kindler et al., 2014). The magnitude of changes also differ, with both strong events (e.g. D-O 8, D-O 12) and weak events (e.g. D-O 9) (Kindler et al., 2014).

Reference:

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(2), 887–902, doi:10.5194/cp-10-887-2014, 2014.

5. Data sources: it would be preferable to divide this section into: 2.1.1. Modern pollen dataset and 2.1.2. Fossil pollen dataset

We have now divided section 2.1 into: 2.1.1. Modern pollen dataset and 2.1.2. Fossil pollen dataset.

6. In line 241, the sentence “Statistical reconstructions cannot take this into account since they are based on modern relationships between pollen assemblages and climate under recent CO₂ levels (Bartlein et al., 2011; Chevalier et al., 2020)” should be modified to cite the paper by Guiot on the inverse modelling approach, as follows: “Except for the method developed by Guiot et al. (1999), which is based on the inversion of a vegetation model, statistical reconstruction methods cannot take this into account since they are based on modern relationships between pollen assemblages and climate under recent CO₂ levels (Bartlein et al., 2011; Chevalier et al., 2020).”

We assume that the editor is referring to the paper by Guiot et al. (2000) here. We acknowledge that inverse modelling, as proposed by Guiot et al. (2000), does take account of the impact of CO₂ on vegetation. However, the reconstructions are dependent on the quality of the vegetation model used and its sensitivity to CO₂, as pointed out by Guiot et al. in their review paper on inversion modelling in 2009. Furthermore, inverse modelling is a reconstruction method but not a statistical technique per se. We have modified the text to make this clearer, as follows:

However, the low CO₂ at glacial period could lead to potential bias between reconstructed and actual plant-available moisture. Atmospheric CO₂ concentration has a direct impact on plant physiological processes, by modulating water-use efficiency (WUE), that is the ratio of carbon uptake to water loss through the stomata (Hatfield and Dold, 2019). The low CO₂ during the glacial period led to reduced water use efficiency (Farquhar, 1997; Gerhart and Ward, 2010; Prentice and Harrison, 2009). Strictly statistical reconstructions cannot take this into account since they are based on modern relationships between pollen assemblages and climate under recent CO₂ levels (Bartlein et al., 2011; Chevalier et al., 2020). Reconstructions based on inversion of a vegetation model (e.g. Garreta et al., 2010; Guiot et al., 2000; Izumi and Bartlein, 2016; Wu et al., 2007) implicitly account for the impact of CO₂ on vegetation composition, but the reconstructions are dependent on the reliability of the vegetation model and its sensitivity to CO₂ changes (Chevalier et al., 2020; Guiot et al., 2009). The actual conditions under low CO₂ should be wetter than the vegetation-based reconstructions of moisture variables (Prentice et al., 2017, 2022a). Prentice et al. (2022a) provide a correction method to account for variations on CO₂ based on

combining eco-evolutionary optimality theory and experimental evidence on how the water-use efficiency as expressed by the ratio of leaf-internal to ambient CO₂ responds to variations in CO₂, as follows:

Added references:

Guiot, J., Torre, F., Jolly, D., Peyron, O., Boreux, J. J. and Cheddadi, R.: Inverse vegetation modeling by Monte Carlo sampling to reconstruct palaeoclimates under changed precipitation seasonality and CO₂ conditions: Application to glacial climate in Mediterranean region, *Ecol. Modell.* 127, 119–140, doi:[https://doi.org/10.1016/S0304-3800\(99\)00219-7](https://doi.org/10.1016/S0304-3800(99)00219-7) (2000).

Garreta, V., Miller, P.A., Guiot, J. *et al.* A method for climate and vegetation reconstruction through the inversion of a dynamic vegetation model. *Clim. Dynam.* 35, 371–389 (2010). <https://doi.org/10.1007/s00382-009-0629-1>

Wu, H., Guiot, J., Brewer, S., and Guo, Z.: Climatic changes in Eurasia and Africa at the Last Glacial Maximum and mid- Holocene: reconstruction from pollen data using inverse vegetation modelling, *Clim. Dynam.* 29, 211–229, 2007

Guiot, J., Wu, H., Garreta, V., Hatté, C., Magny, M. A few prospective ideas on climate reconstruction: from a statistical single proxy approach towards a multi-proxy and dynamical approach. *Clim. Past* 5, 571-583 (2009)

Izumi, K. and Bartlein, P., North American paleoclimate reconstructions for the Last Glacial Maximum using an inverse modeling through iterative forward modeling approach applied to pollen data, *Geophys. Res. Lett.*, 43, 10965–10972, <https://doi.org/10.1002/2016GL070152>, 2016.

7. Discussion:

Please move the following sentences to the Results section, within the part on alpha reconstruction, after line 416:

“We have applied a correction for low CO₂ values during the glacial period to plant-available moisture. The actual values ($\alpha_{\text{plant, corrected}}$) are generally higher than the vegetation-based reconstructed values (α_{plant}) (Figure S2-1). However, the correction does not have a significant impact on the spatial patterns during D-O events (Figure S2-2; Figure S7-3).”

We have now moved the sentences to the Results section, within the part on alpha reconstruction.

The changes in plant-available moisture are less spatially coherent than the changes in temperature (Figure 5). There is an increase in $\alpha_{\text{plant, corrected}}$ in some regions characterised by warming, for example, southeastern China and Japan; but there are mixed signals of drying and wetting in other regions characterised by warming, such as southern Europe. Furthermore, regions characterised by cooling, such as western North America and southern extratropics, can also show both drying and wetting.

Changes in $\Delta\alpha_{\text{plant,corrected}}$ also show more variability between D-O events than changes in temperature (Figure S7-4). We have applied a correction for low CO₂ values during the glacial period to plant-available moisture. The actual values ($\alpha_{\text{plant,corrected}}$) are generally higher than the vegetation-based reconstructed values (α_{plant}) (Figure S2-1). However, the correction does not have a significant impact on the spatial patterns during D-O events (Figure S2-2; Figure S7-3).

8. Please note that we have also taken the opportunity to modify the title of section 4.4 in the Discussion to clarify what we are discussing, as follows:

Implications of the use of dynamic time warping