Rapid ice-age warming events amplified by strong vegetation-albedo feedback: Supplementary Information

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This Supplementary contains the following figures and tables:

Supplementary Fig. 1: Changes in land-surface albedo during individual Dansgaard-Oeschger (D-O) cycles due to the combined effect of vegetation and snow. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).

Supplementary Fig. 2: Changes in land-surface albedo during individual Dansgaard-Oeschger (D-O) cycles due to the effect of vegetation. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).

Supplementary Fig. 3: Changes in land-surface albedo during individual Dansgaard-Oeschger (D-O) cycles due to the effect of snow. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).

Supplementary Fig. 4: Changes in land temperature during individual Dansgaard-Oeschger (D-O) cycles. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).

Supplementary Fig. 5: The relationship between global mean temperature and global mean land temperature as simulated by LOVECLIM.

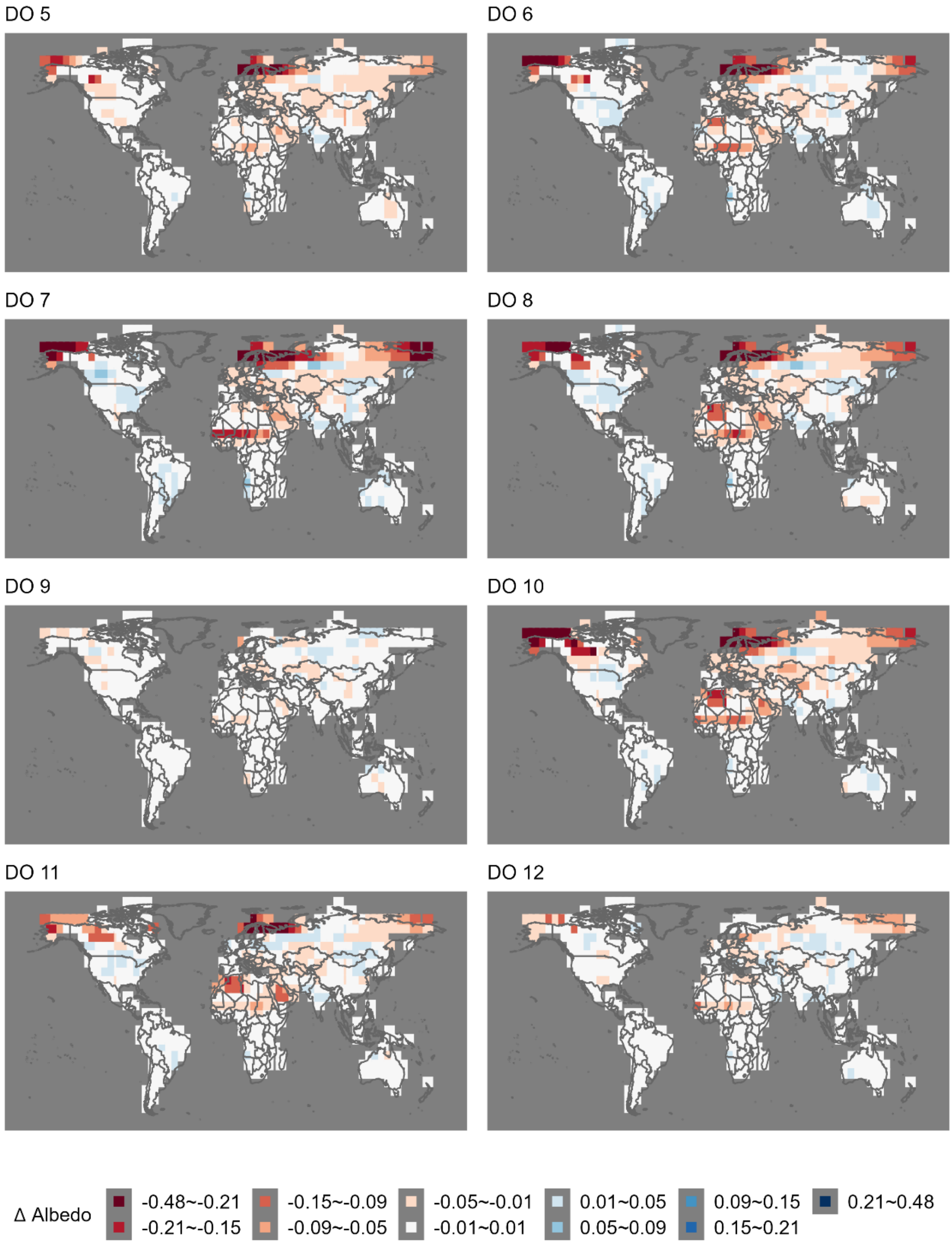
Supplementary Fig. 6: Performance of the seasonal snow conversion model. The *x* axis is the modern seasonal snow depth water equivalent and the *y* axis is the modern seasonal snow cover. The red line shows the fitted conversion model.

Supplementary Fig. 7: The spatial distribution of sites covering one or more Dansgaard-Oeschger (D-O) cycles during Marine Isotope Stage 3 (MIS3) from the Abrupt Climate and Environmental Responses (ACER) database (Sánchez Goñi et al., 2017) used in this study.

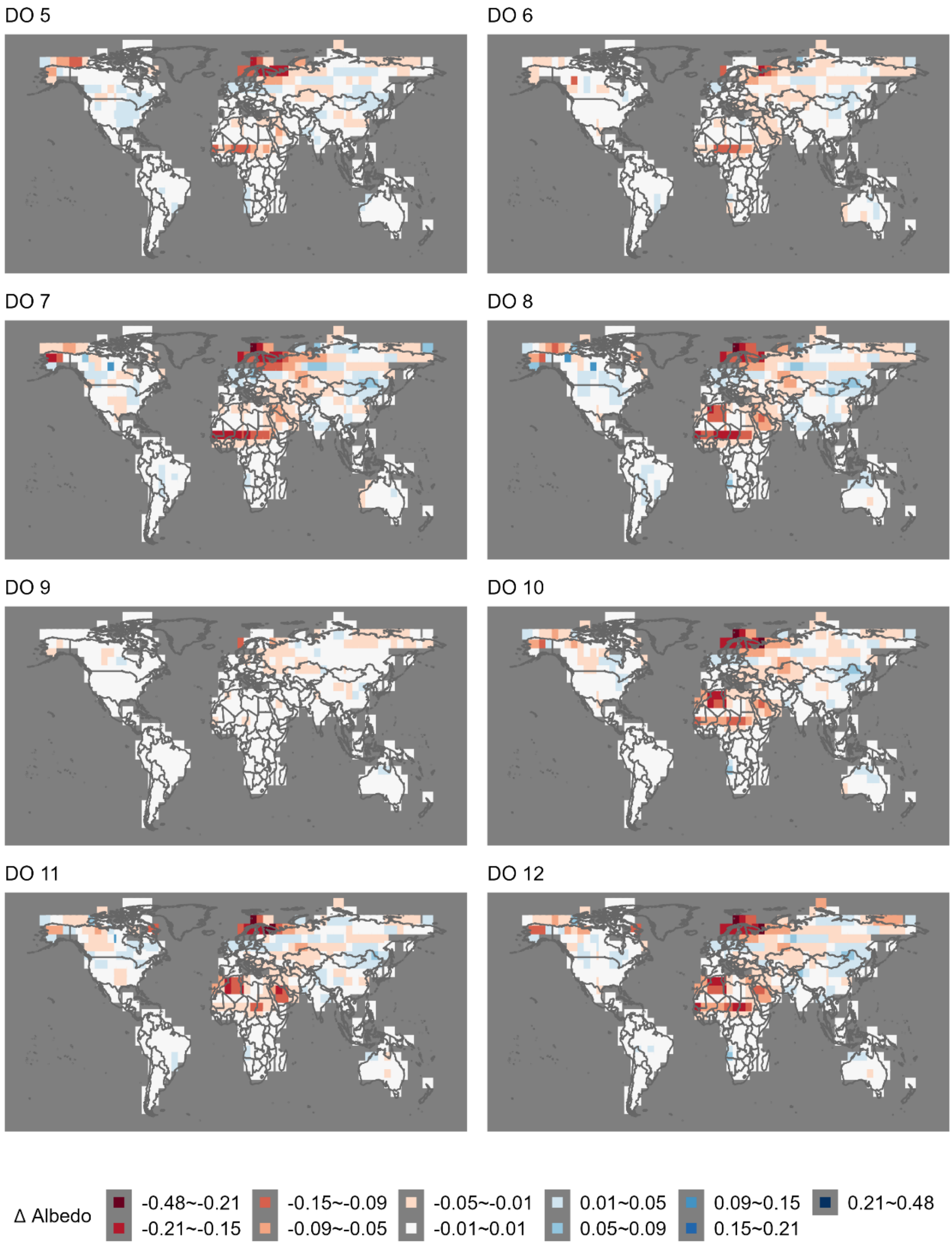
Supplementary Table 1: Modern data information. All data are aggregated at 5.625° × 5.625° resolution.

Supplementary 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), annual maximum fraction of Absorbed Photosynthetically Active Radiation (*fAPAR*) and vegetation height (*hveg*), with *p*-spline smoothed *fx* estimation and bins of 0.02, 0.02, 0.01 and 1, respectively; *n* is the number of components used; 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 and is used to choose the last significant number of components (indicated in **bold**) to avoid over-fitting. 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 overall compression.

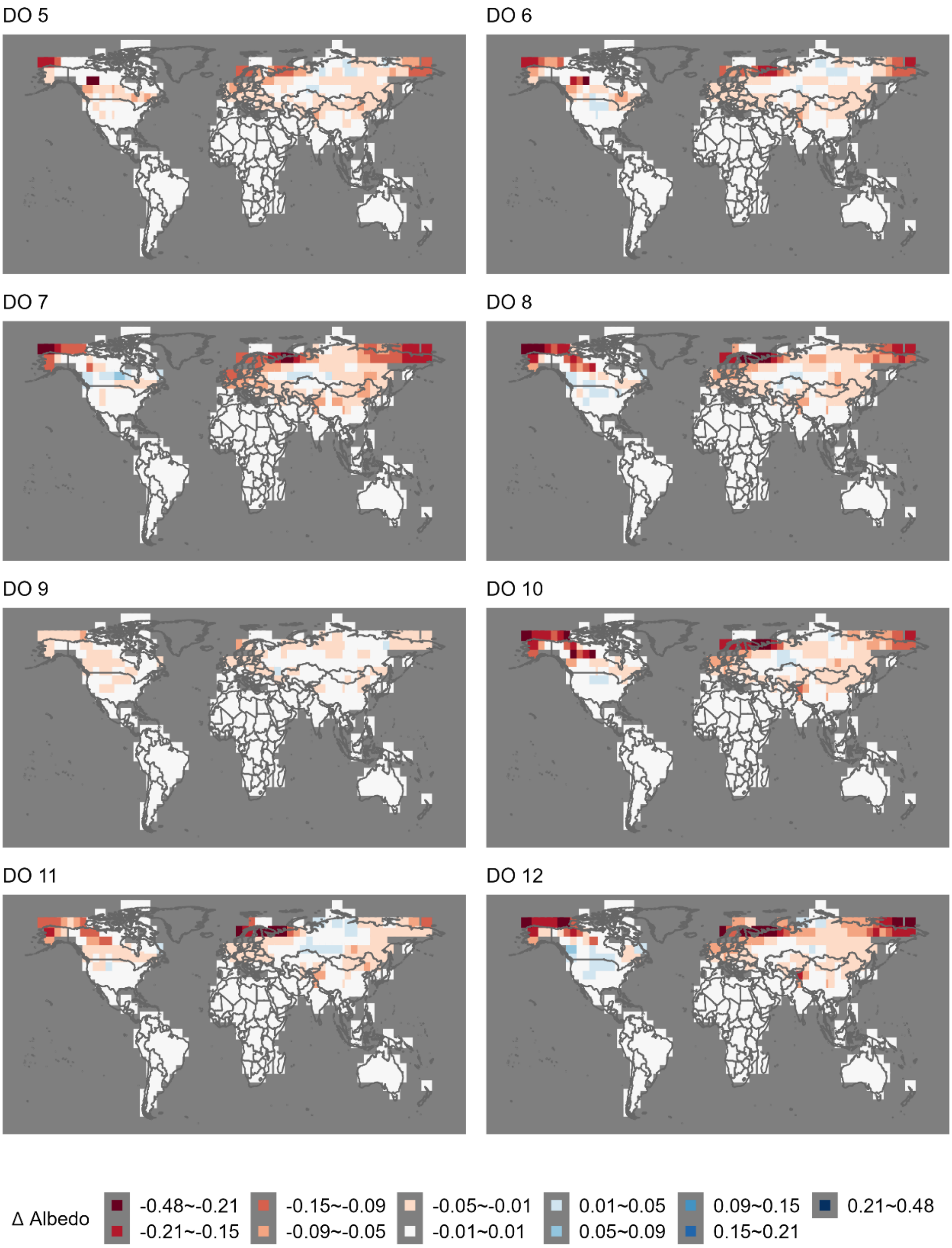
Supplementary Fig. 1: Changes in land-surface albedo during individual Dansgaard-Oeschger (D-O) cycles due to the combined effect of vegetation and snow. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).



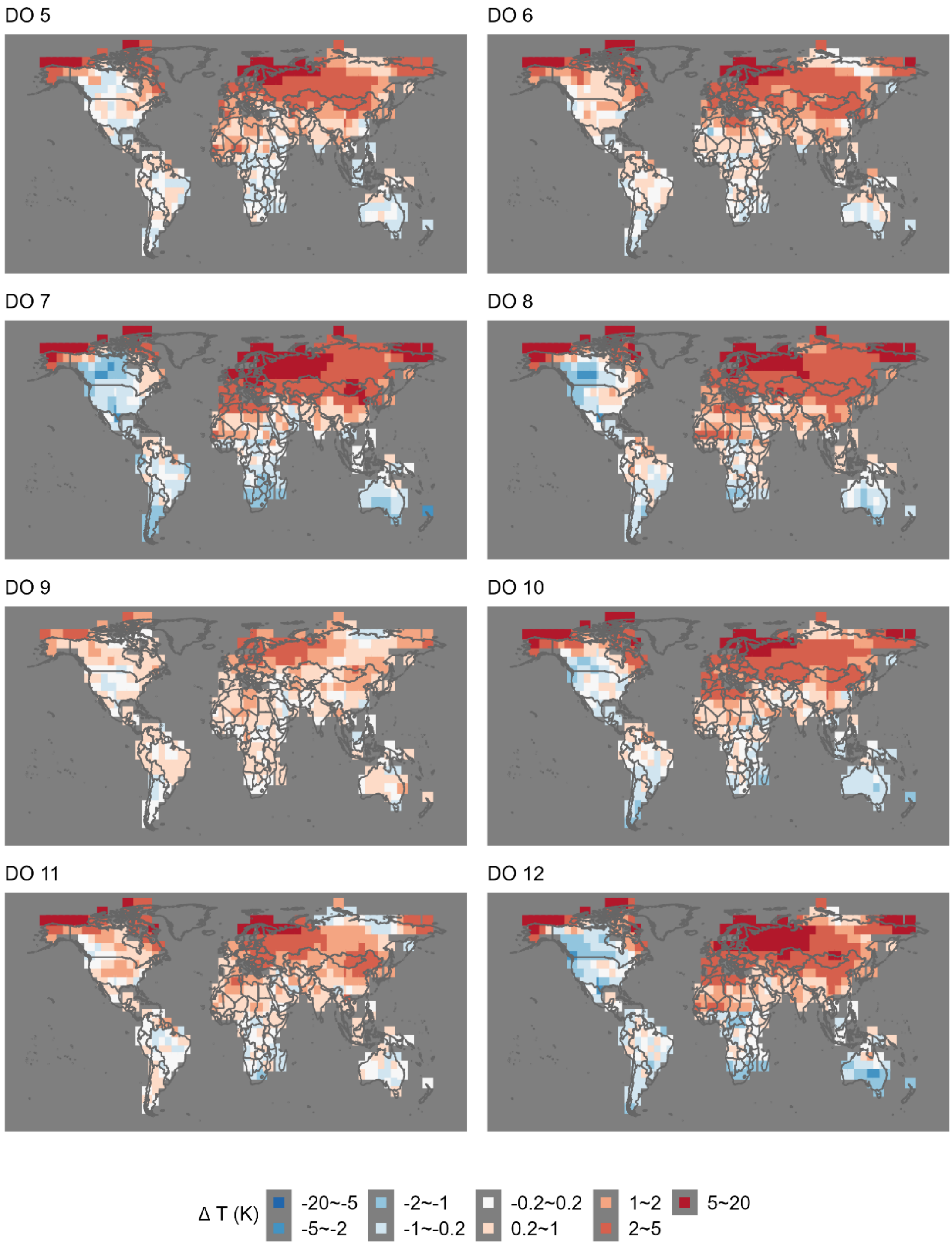
Supplementary Fig. 2: Changes in land-surface albedo during individual Dansgaard-Oeschger (D-O) cycles due to the effect of vegetation. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).



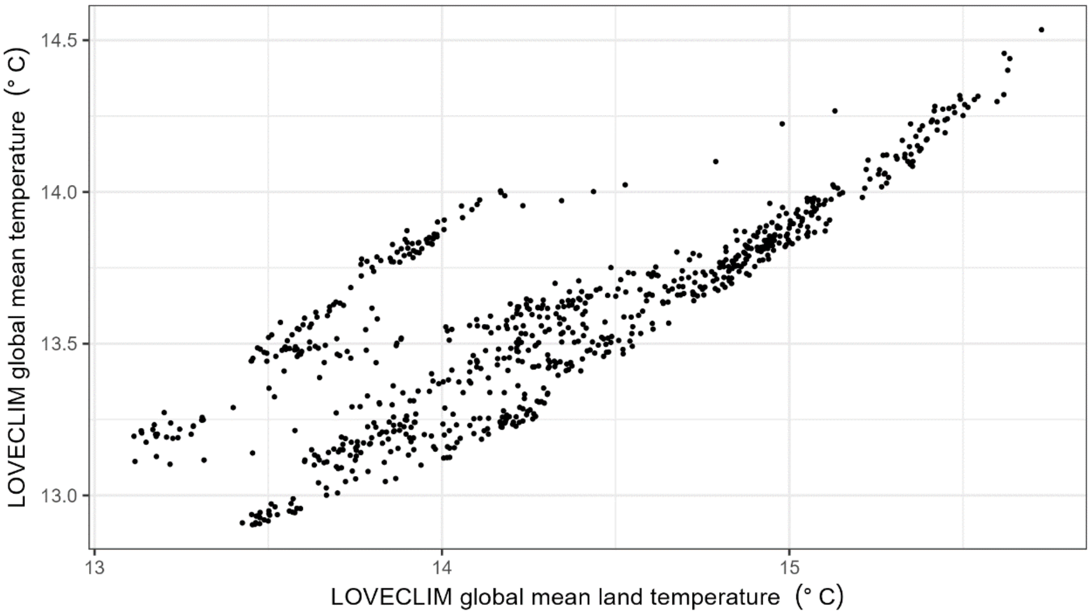
Supplementary Fig. 3: Changes in land-surface albedo during individual Dansgaard-Oeschger (D-O) cycles due to the effect of snow. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).



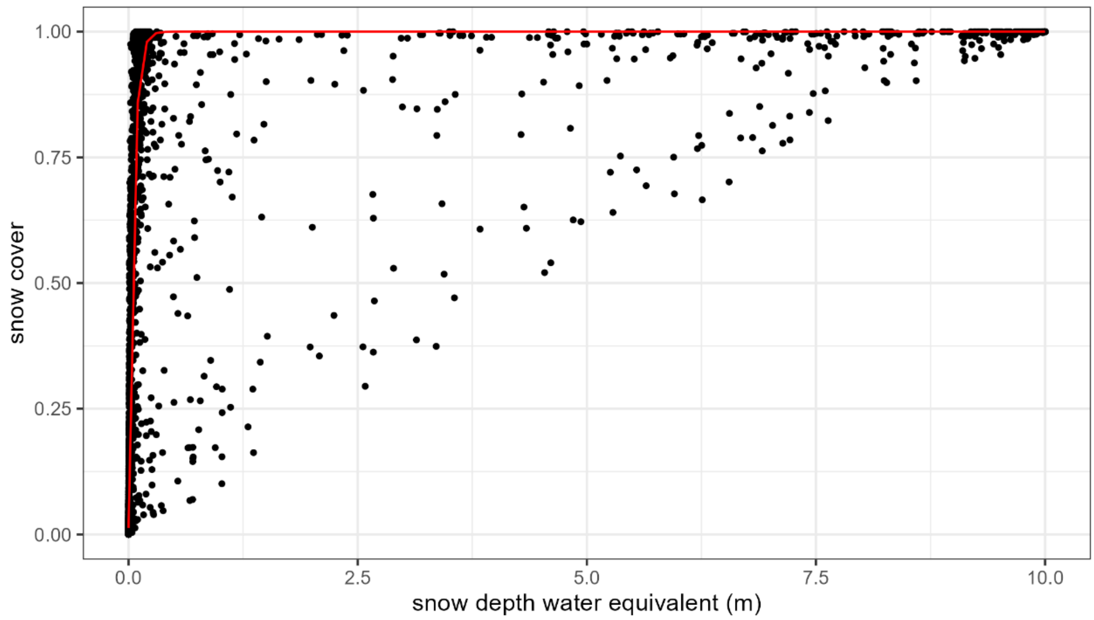
Supplementary Fig. 4: Changes in land temperature during individual Dansgaard-Oeschger (D-O) cycles. The site-based reconstructions have been extrapolated using 3D variational data assimilation (3D-var).



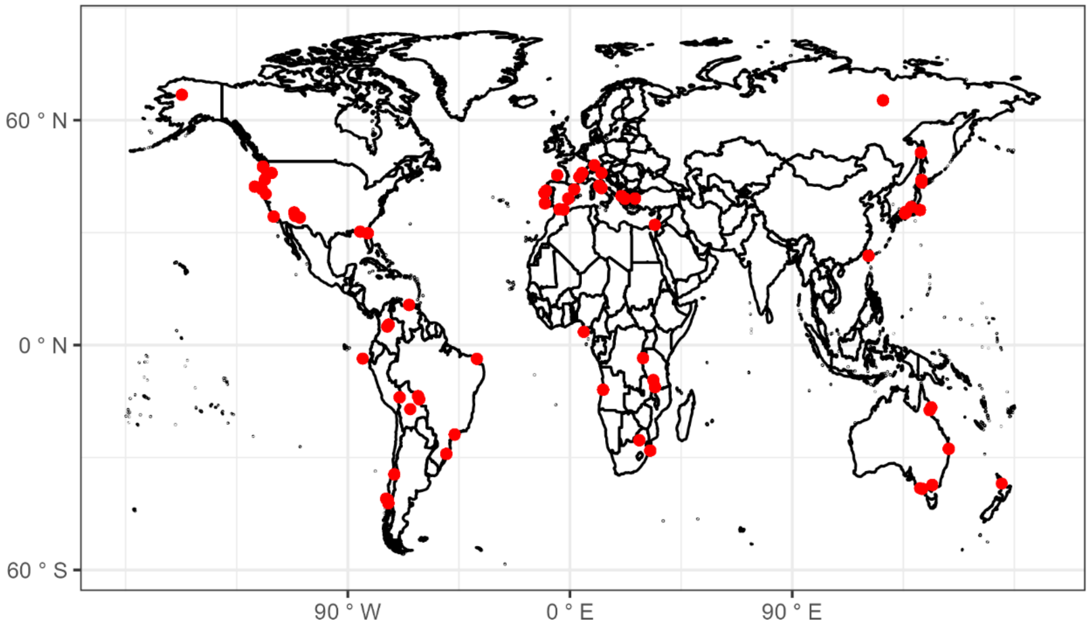
Supplementary Fig. 5: The relationship between global mean temperature and global mean land temperature as simulated by LOVECLIM.



Supplementary Fig. 6: Performance of the seasonal snow conversion model. The *x* axis is the modern seasonal snow depth water equivalent and the *y* axis is the modern seasonal snow cover. The red line shows the fitted conversion model.



Supplementary Fig. 7: The spatial distribution of sites covering one or more D-O cycles during Marine Isotope Stage 3 (MIS3) from the Abrupt Climate and Environmental Responses (ACER) database (Sánchez Goñi et al., 2017) used in this study.



Supplementary Table 1: Modern data information. All data are aggregated at 5.625° × 5.625° resolution.

Variable	Name	Source	Original resolution
Albedo Snow depth water equivalent Snow cover	ERA5-Land monthly averaged data at year 2005	Obtain the monthly data from Muñoz Sabater (2019) https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=overview and use the arithmetic mean as the seasonal data: season 1 = mean (month 12,1,2) season 2 = mean (month 3,4,5) season 3 = mean (month 6,7,8) season 4 = mean (month 9,10,11)	0.1° × 0.1 °
fAPAR	Annual maximum fraction of Absorbed Photosynthetically Active Radiation (use the mean over the period 1982 ~ 2016)	Obtain 15-day GIMMS 3g fPAR from Zhu et al. (2013) at 1/12 degree resolution, then select the maximum value through each year at each grid cell, and then aggregate into 0.5 degree resolution using 95 percentile of the value in each set of 6×6 1/12 degree grid cells	0.5° × 0.5 °

Vegetation height	Global 1km Forest Canopy Height at the year 2005	Simard et al. (2011) https://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=10023	0.5° × 0.5 °

Supplementary 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), both derived from Liu et al. (2024), annual maximum fraction of Absorbed Photosynthetically Active Radiation (*fAPAR*) and vegetation height (*hveg*), with P-splines smoothed *fx* estimation and bins of 0.02, 0.02, 0.01 and 1, respectively; *n* is the number of components used; 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 $100 \times (\text{RMSEP}_n - \text{RMSEP}_{n-1})/\text{RMSEP}_{n-1}$; 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 and is used to choose the last significant number of components (indicated in **bold**) to avoid over-fitting. 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 overall 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

fAPAR	1	0.44	–0.05	0.15	–20.54	0.001	0.51	0.00
	2	**0.46**	**–0.05**	**0.15**	**–1.15**	**0.001**	**0.52**	**0.00**
	3	0.46	–0.05	0.15	0.15	0.990	0.52	0.00
	4	0.47	–0.04	0.15	–2.12	0.001	0.55	0.00
	5	0.47	–0.04	0.15	–0.39	0.001	0.56	0.00
hveg	1	0.25	0.55	6.08	–10.15	0.001	0.35	0.01
	2	0.32	0.52	5.80	–4.63	0.001	0.44	0.01
	3	**0.32**	**0.51**	**5.77**	**–0.44**	**0.001**	**0.44**	**0.01**
	4	0.32	0.50	5.76	–0.20	0.032	0.44	0.01
	5	0.33	0.50	5.75	–0.20	0.001	0.44	0.01