

Supplementary Materials

Multi-proxy records reveal rapid atmospheric reorganization during Dansgaard–Oeschger events

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Supplementary text

Text S1. Bayesian ramp-fitting framework

Each transition is modeled as the sum of a deterministic components $\hat{x}_i(\theta)$ (Eq. 2) and a stochastic error term ϵ_i that follows an AR(1) process (Eq. 3). The model is therefore defined by the parameter set $\theta = [t_0, x_0, \Delta t, \Delta x, s_{GS}, s_{GIS}, \sigma, \tau]$. Given a transition dataset $\mathcal{D} = [(t_i, x_i)]_{i=1}^n$, Bayesian inference is used to estimate the posterior distribution of model parameters as follows,

$$p(\theta|\mathcal{D}) = \frac{p(\mathcal{D}|\theta)p(\theta)}{p(\mathcal{D})} \quad (\text{Eq. S1})$$

While $p(\mathcal{D}|\theta)$ represents the likelihood of the model with parameter set θ to reproduce the dataset $\mathcal{D}$; $p(\theta)$ is the priori distribution of model parameters based on a priori knowledge or assumptions. $p(\mathcal{D})$ is the marginal likelihood (normalization constant).

Following the previous studies^{1,2}, the priors $p(\theta)$ are defined as follows,

$$p(t_0) = \mathcal{N}(0, 50^2) \quad (\text{Eq. S2})$$

$$p(\Delta t) = \text{Gamma}(2.0, 0.2) \quad (\text{Eq. S3})$$

$$p(x_0) = 1 \quad (\text{Eq. S4})$$

$$p(\Delta x) = 1 \quad (\text{Eq. S5})$$

$$p(\sigma) = 1 \text{ for } 0 < \sigma \leq |\Delta x| \quad (\text{Eq. S6})$$

$$p(\tau) = \text{Gamma}(1.5, 0.05) \quad (\text{Eq. S7})$$

Here, $\mathcal{N}(\mu, \sigma^2)$ denotes a normal distribution and $\text{Gamma}(\alpha, \beta)$ denotes a gamma distribution:

$$\mathcal{N}(\mu, \sigma^2) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2\sigma^2}(x - \mu)^2\right) \quad (\text{Eq. S8})$$

$$\text{Gamma}(\alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x} \quad (\text{Eq. S9})$$

The prior for t_0 is centered around an initial guess. Gamma priors are assigned to Δt and τ to ensure that these parameters remain positive. A uniform prior is used for σ within the range $(0, |\Delta x|)$, and for x_0 and Δx , allowing the method to be applied consistently across variables with different units and magnitudes. The residuals are defined as: $\epsilon_i = x_i - \hat{x}_i(\theta)$, and are assumed to follow an autoregressive model of order one (AR (1)) with decorrelation timescale τ . The likelihood can therefore be written as:

$$p(\mathcal{D}|\theta) = p(\epsilon_1|\theta) \prod_{i=1}^{n-1} p(\epsilon_{i+1}|\epsilon_i, \theta) \quad (\text{Eq. S10})$$

The initial residual is assumed to follow the stationary distribution:

$$p(\epsilon_1|\theta) \sim \mathcal{N}(0, \sigma^2) \quad (\text{Eq. S11})$$

For subsequent points, the conditional distribution is:

$$p(\epsilon_{i+1}|\epsilon_i, \theta) \sim \mathcal{N}(\alpha_i \epsilon_i, \sigma^2(1 - \alpha_i^2)) \quad (\text{Eq. S12})$$

where the autoregressive coefficient α_i depends on the time interval between observations (Eq. 4).

Bayesian inference is performed using an ensemble Markov chain Monte Carlo (MCMC) sampler implemented in Python with the *emcee.EnsembleSampler* package. This approach is based on the affine-invariant ensemble sampler of Goodman and Weare (2010)³ and adapted from Erhardt et al². The sampler is run with 20 walkers for 40,000 steps, with the first 1,000 steps discarded as burn-in. The chains are thinned by a factor of 200 to reduce autocorrelation. The final posterior ensemble consists of approximately 4,000 samples for each fit.

Text S2. Synthetic data tests for calibration and bias evaluation

The MCMC sampling yields 4,000 posterior parameter sets for each case (i.e., for each proxy and D-O event combination). These posterior samples are used to generate synthetic datasets for evaluating the calibration and potential fitting bias of the method.

To generate synthetic data, the transition onset time is fixed at $t_0 = 380$ years after the start of the event window (Table S1), while the remaining parameters are randomly drawn from the 4,000 posterior samples. The final synthetic data are generated as the sum of deterministic ramp component and AR (1) noise term using the same ramp model (Eq. 1). A total of 1,000 synthetic datasets are generated for each test case.

Each synthetic dataset is subsequently fit using the same MCMC framework and prior uncertainty assumptions as applied to the original data. The difference between the mean fitted onset time and the prescribed true onset time (i.e., 380) is used to evaluate potential fitting bias under the parameter regime associated with each case (Table S16). The method is considered well calibrated if the true onset time falls within the 5th-95th percentile range of the fitted posterior onset times for approximately 90% of the synthetic realizations (Table S17).

Full calibration tests for all 7 events and 9 proxies would require $1,000 \times 7 \times 9$ synthetic datasets and corresponding MCMC fits, resulting in substantial computational cost. Therefore, calibration tests are performed for one representative event for each proxy. To further reduce computational expense, instead of applying MCMC fitting to all 1,000 synthetic datasets, 20 synthetic datasets are randomly selected for MCMC fitting in each trial, and the resulting fitted t_0 are combined to evaluate calibration and bias. This procedure is repeated 10 times to reduce sensitivity to random selection of the synthetic datasets.

The representative event for each proxy is selected based on a relatively high noise-to-signal ratio and larger gradual slopes before or after the abrupt transition, as these conditions are expected to produce larger fitting bias and greater sensitivity to the fitting framework¹. The selected events are highlighted in Table S5.

Text S3. Simplified aerosol transport and deposition model

We used a Clausius-Clapeyron-based simplified aerosol model following the model framework described in Markle et al. ⁴. In this earlier model, air parcels transported from aerosol source areas to the Greenland site undergo pseudo-adiabatic cooling during meridional transport, with excess water vapor condensing and forming precipitation. Aerosol species are deposited to the surface both by wet removal and dry deposition. The temperature gradient is determined by the zonal mean temperature at the source region T_{source} and the site temperature T_{site} . Here we calculated the relative difference of site temperature with respect to the present day value (ΔT_{site}) based on the stable water isotope $\delta^{18}\text{O}$ measurements using the calibration developed in *Cuffey and Clow* ⁵ for the GISP2 ice core, in which $\Delta T_{\text{site}} = 3.05 \cdot \Delta \delta^{18}\text{O}$, where $\Delta \delta^{18}\text{O}$ is the difference of $\delta^{18}\text{O}$ with respect to the present day baseline (-35.37‰). We assumed a smaller change of temperature at the equator to account for the polar amplification⁶, such that $\Delta T_{\text{equator}} = \Delta T_{\text{site}}/f$. We used $f=10$ based on climate model estimates between PI and LGM configurations⁷. The ΔT values at the aerosol sources and en route to the Greenland site were linearly interpolated between $\Delta T_{\text{equator}}$ and ΔT_{site} according to the latitude. The present-day baseline values were taken from the NCEP reanalysis data.

The change of atmospheric aerosol concentration C_{air} (aerosol mass per unit air volume) with latitude ϕ owing to wet deposition can be expressed as⁴:

$$\left(\frac{dC_{\text{air}}}{d\phi}\right)_{\text{wet}} = -PC_{\text{precip}}\rho_{\text{air}} = \frac{dr_s}{dT} \frac{dT}{d\phi} \omega(d_p)C_{\text{air}} \quad (\text{Eq. S13})$$

where C_{precip} is the aerosol concentration in precipitation (aerosol mass per unit precipitation mass), $-P$ (precipitation mass per unit air mass) is the precipitation, and r_s is the saturation mixing ratio. We calculated the size-resolved mass scavenging ratio $\omega(d_p) = \frac{C_{\text{precip}}}{C_{\text{air}}} \rho_{\text{air}}$ with units of (aerosol mass per unit precipitation mass)/(aerosol mass per unit air mass), which allows us to consider below-cloud scavenging⁸, in-cloud scavenging⁹, and cloud droplet nucleation. These processes generally remove large particles more efficiently than smaller ones for particles larger than 30 nm (Fig. S13).

Similarly, the dry deposition term is written as:

$$\left(\frac{dC_{\text{air}}}{d\phi}\right)_{\text{dry}} = C_{\text{air}}v_{\text{dry}}(d_p)\frac{dt}{d\phi} = \frac{C_{\text{air}}v_{\text{dry}}(d_p)}{w(\phi)} \quad (\text{Eq. S14})$$

where $v_{\text{dry}}(d_p)$ is the size-dependent dry deposition rate (d^{-1}), and $w(\phi)$ is meridional wind velocity ($^\circ \text{d}^{-1}$). To couple the dry deposition process with wet scavenging, we assumed a meridional air parcel velocity

of $w(\phi) = 2^\circ \text{ d}^{-1}$, corresponding to a hemispheric mixing time of 45 days¹⁰. Combining wet deposition and dry deposition, the atmospheric aerosol concentration across latitude is:

$$C_{air}(\phi) = C_{air}(\phi_0) \exp\left(\int_{\phi_0}^{\phi_s} \left(\omega(d_p) \frac{dr_s}{dT} \frac{dT}{d\phi} + \frac{v_{dry}(d_p)}{w(\phi)}\right) d\phi\right) \quad (\text{Eq. S15})$$

where ϕ_0 and ϕ_s are source and site latitudes, respectively. $C_{air}(\phi_0)$ is the atmospheric aerosol concentration at the source region. The resulting aerosol concentration in precipitation at the ice core site considering both the wet and dry deposition en route can be calculated as:

$$C_{precip}(\phi_s) = \left. \frac{\left(\frac{dC_{air}}{d\phi}\right)_{wet} + \left(\frac{dC_{air}}{d\phi}\right)_{dry}}{\frac{dr_s}{dT} \frac{dT}{d\phi} \rho_{air}} \right|_{\phi=\phi_s} = \left[\omega + \frac{v_{dry}(d_p)}{w(\phi)} / \left(\frac{dr_s}{dT} \frac{dT}{d\phi}\right) \right] \cdot \frac{C_{air}}{\rho_{air}} \Big|_{\phi=\phi_s} \quad (\text{Eq. S16})$$

Eqs. S15 and S16 can be numerically solved to derive the relationship between the aerosol concentration in air $C_{air}(\phi_0)$ and the aerosol concentration in precipitation $C_{precip}(\phi_s)$, and the $C_{precip}(\phi_s)$ value can be compared with and validated by ice core measurements and climate model simulations (Fig. S12). The simplified model was also used to estimate residual aerosol variability after accounting for modeled transport and removal, providing an upper level of the reconstructed source strength $C_{air}(\phi_0)$ based on the ice core data.

Supplementary Figures

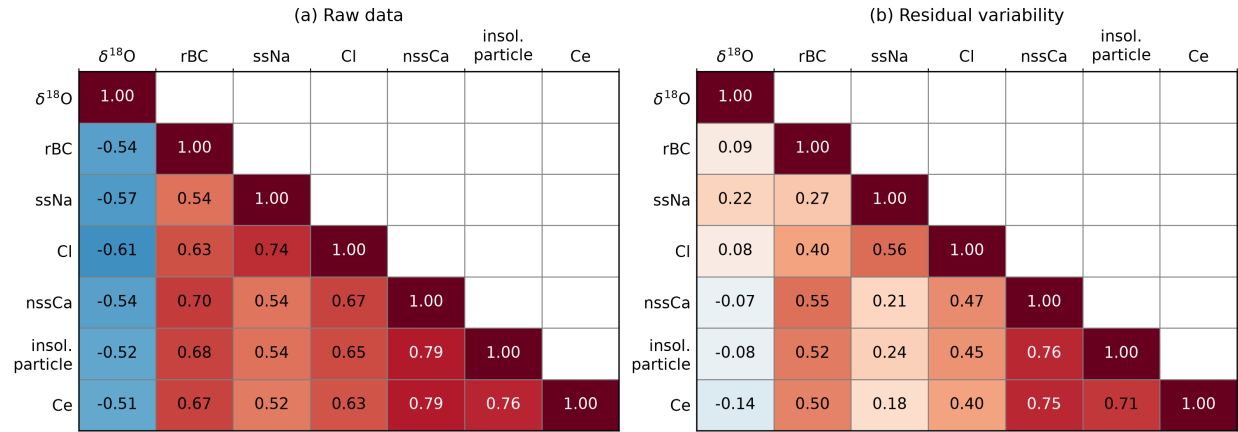


Figure S1. Correlation matrices for (a) ice core $\delta^{18}\text{O}$ and aerosol concentrations, and (b) ice core $\delta^{18}\text{O}$ and residual aerosol variability after removing the model-simulated transport and the contributions from wet and dry deposition. Colors indicate the Kendall's τ coefficients.

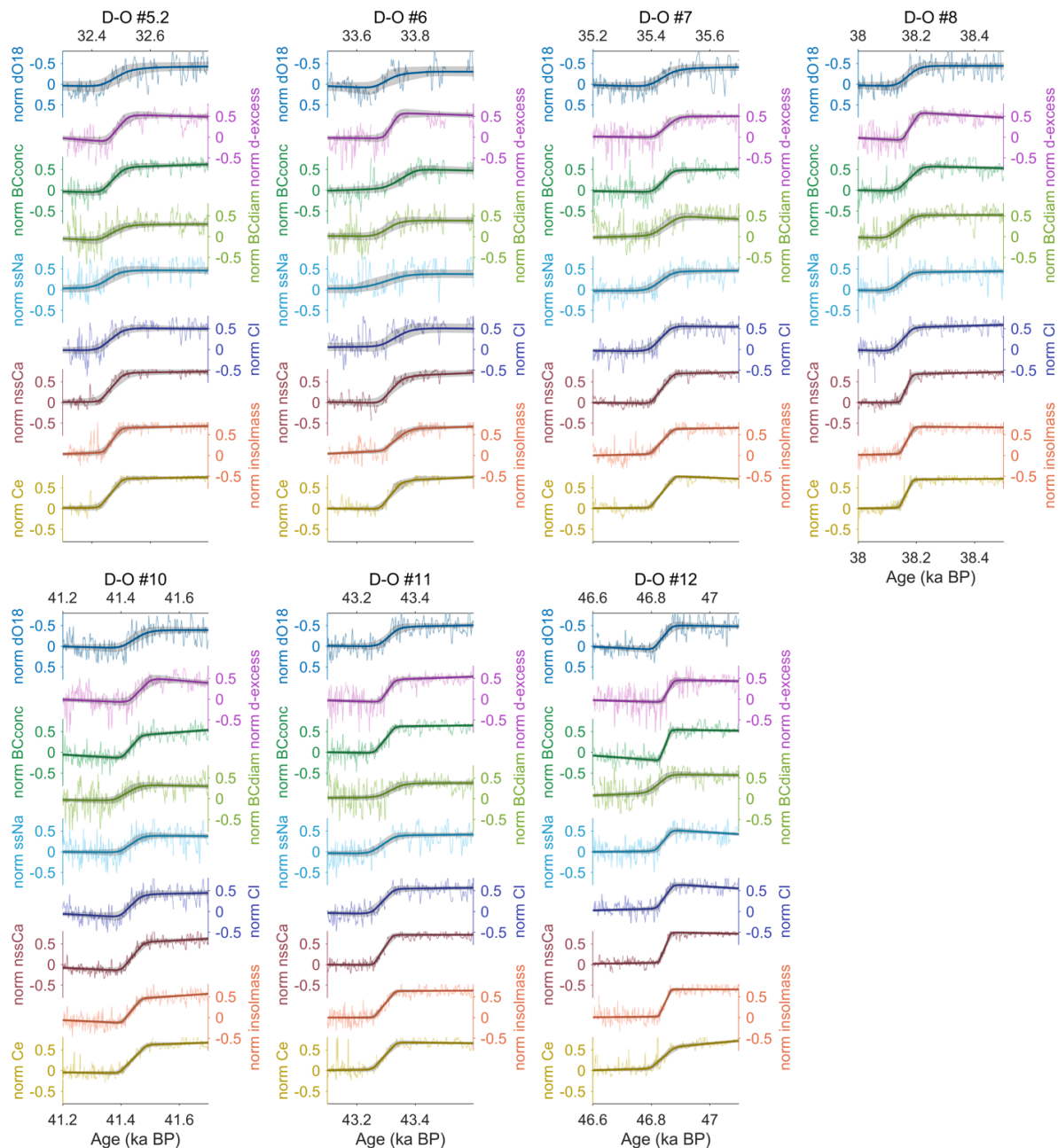


Figure S2. Normalized ice-core records for the seven D-O transition periods (Table S1) and the associated ramp-fitting results. Lighter-colored lines show the annual-resolution ice-core records. Darker-colored line and grey shaded areas show the median and 5th-95th percentile ranges of the ramp-fitting results from MCMC sampling. Note that D-O event #9 was covered by the observational record but was not included in the transition timing analysis.

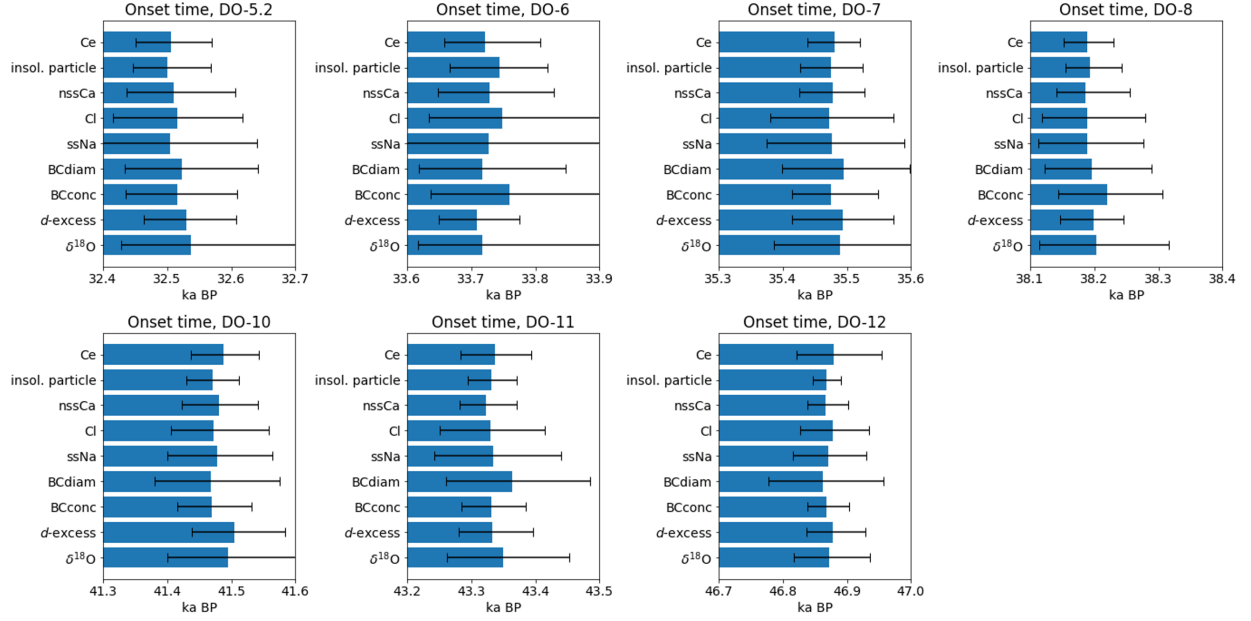


Figure S3. Transition onset times for the seven D-O events derived from the ramp-fitting results. Blue bars show the median estimates, and error bars indicate the 5th - 95th percentile ranges.

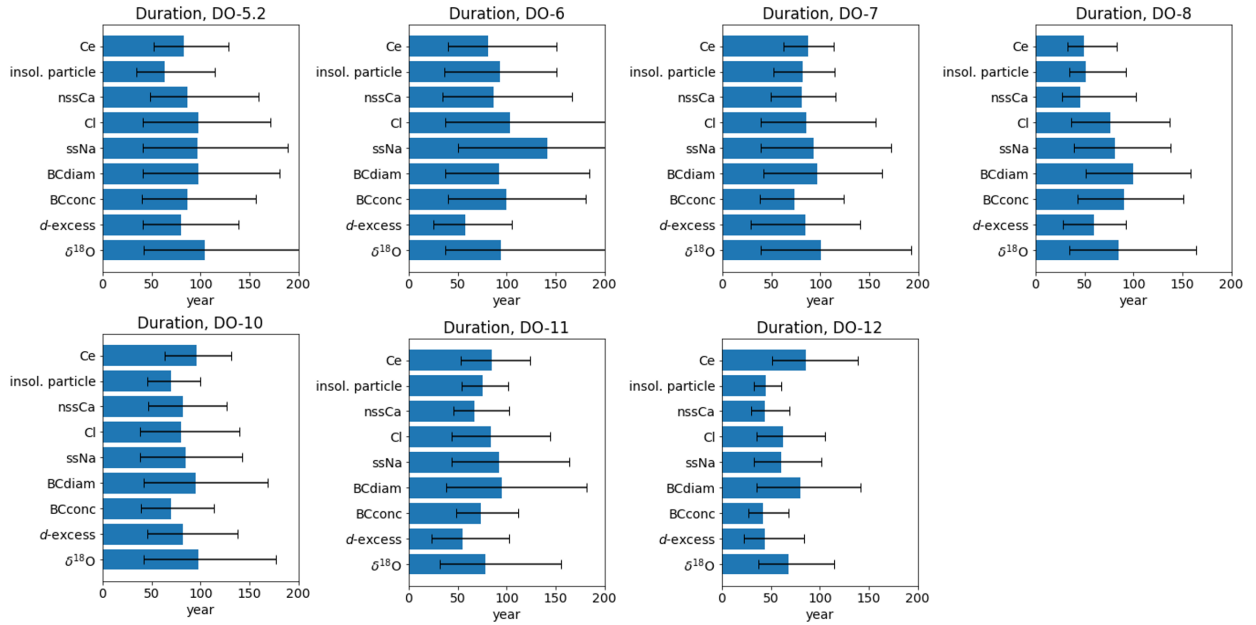


Figure S4. Transition durations for the seven D-O events derived from the ramp-fitting results. Blue bars show the median estimates, and error bars indicate the 5th - 95th percentile ranges.

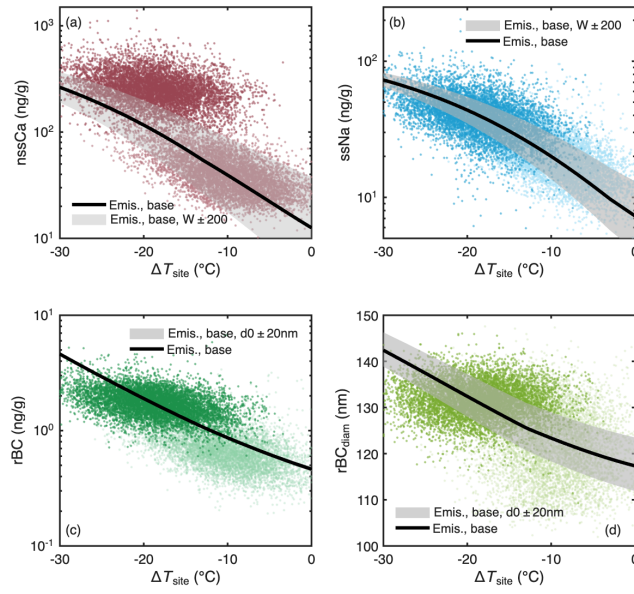


Figure S5. Same as Fig. 3, but showing the sensitivity of the modeled relationships to wet-scavenging efficiency for (a) nssCa and (b) ssNa, and to the assumed initial rBC geometric mean diameter at emission for rBC (c) concentration and (d) geometric mean diameter. Shaded areas indicate the range obtained by varying wet-scavenging efficiency by ± 200 for nssCa and ssNa, and the initial rBC diameter by ± 20 nm relative to the base-case values.

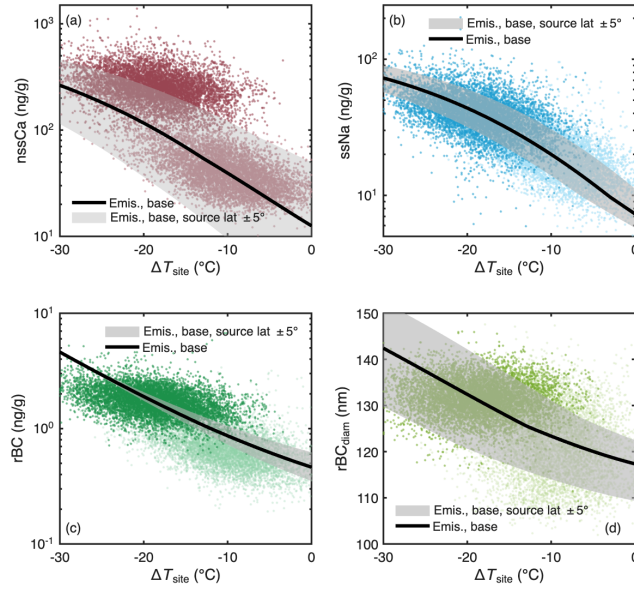


Figure S6. Same as Fig. 3, but showing the sensitivity of the modeled relationships to the assumed effective source latitude. Shaded areas indicate the range obtained by varying the source latitude by $\pm 5^\circ$ relative to the base-case value.

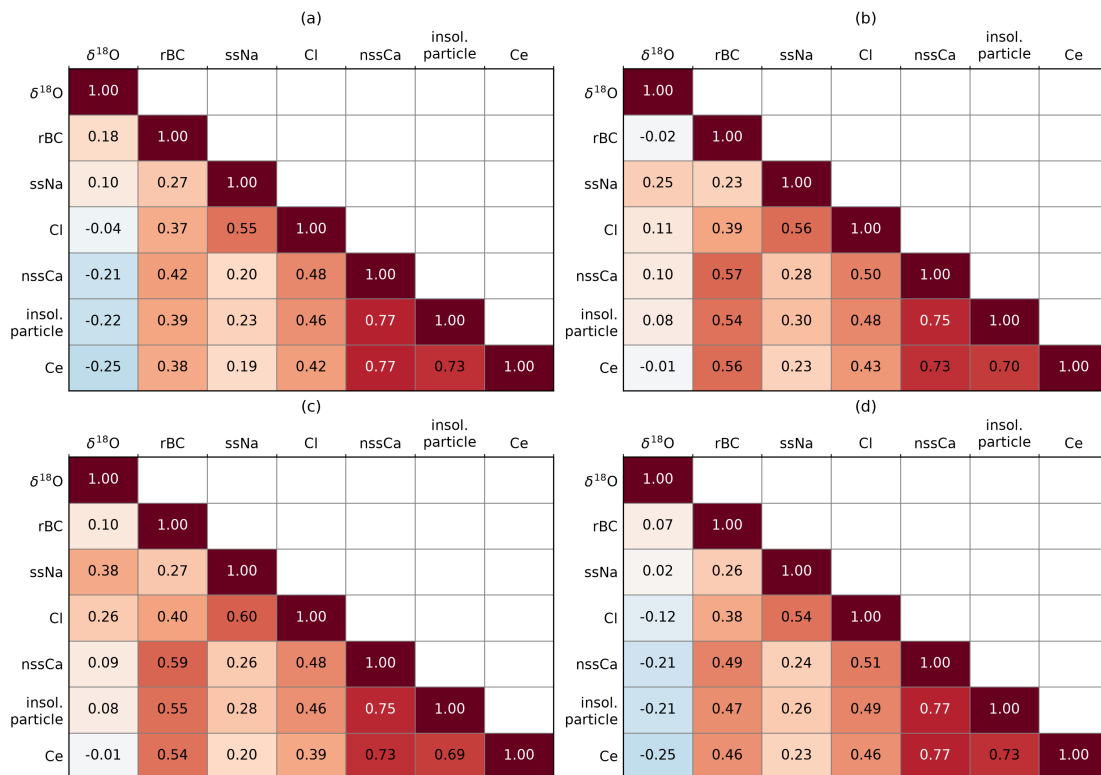


Figure S7. Same as Fig. S1b, but showing results obtained with alternative model parameter settings:
 (a) effective source latitude increased by 5° , (b) effective source latitude decreased by 5° , (c) initial rBC diameter increased by 20 nm and wet-scavenging efficiency increased by 200 for the other aerosol proxies, and (d) initial rBC diameter decreased by 20 nm and wet-scavenging efficiency decreased by 200 for the other aerosol proxies.

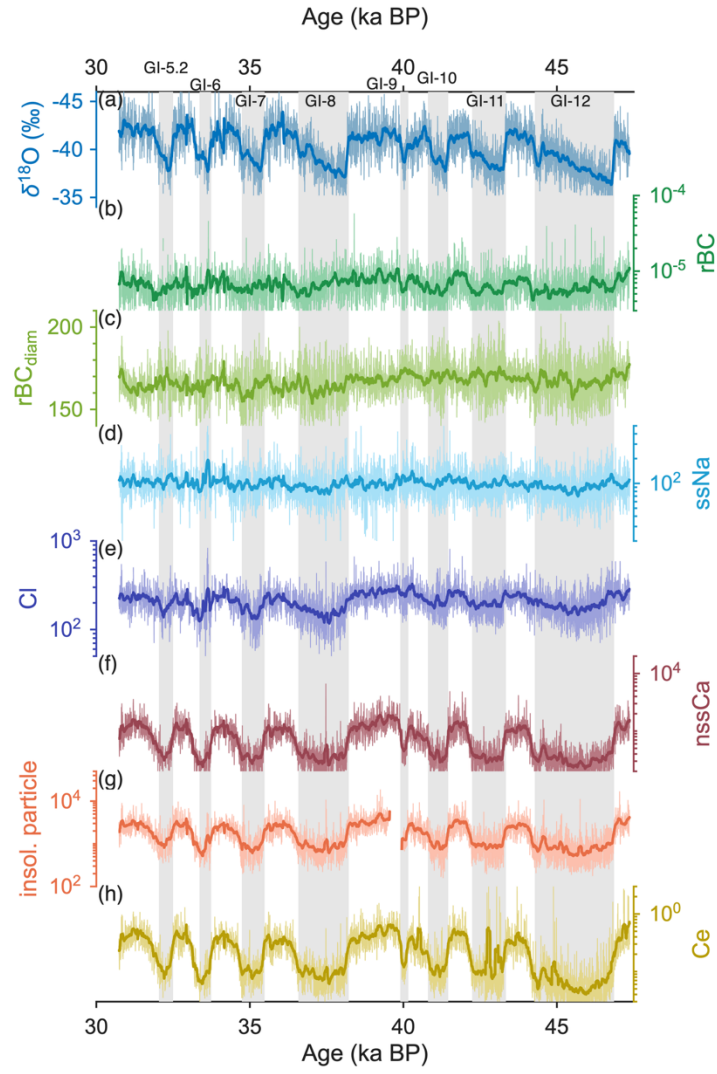


Figure S8. Same as Fig. 4, but showing results obtained with alternative parameter settings in the simplified model framework: effective source latitude increased by 5°

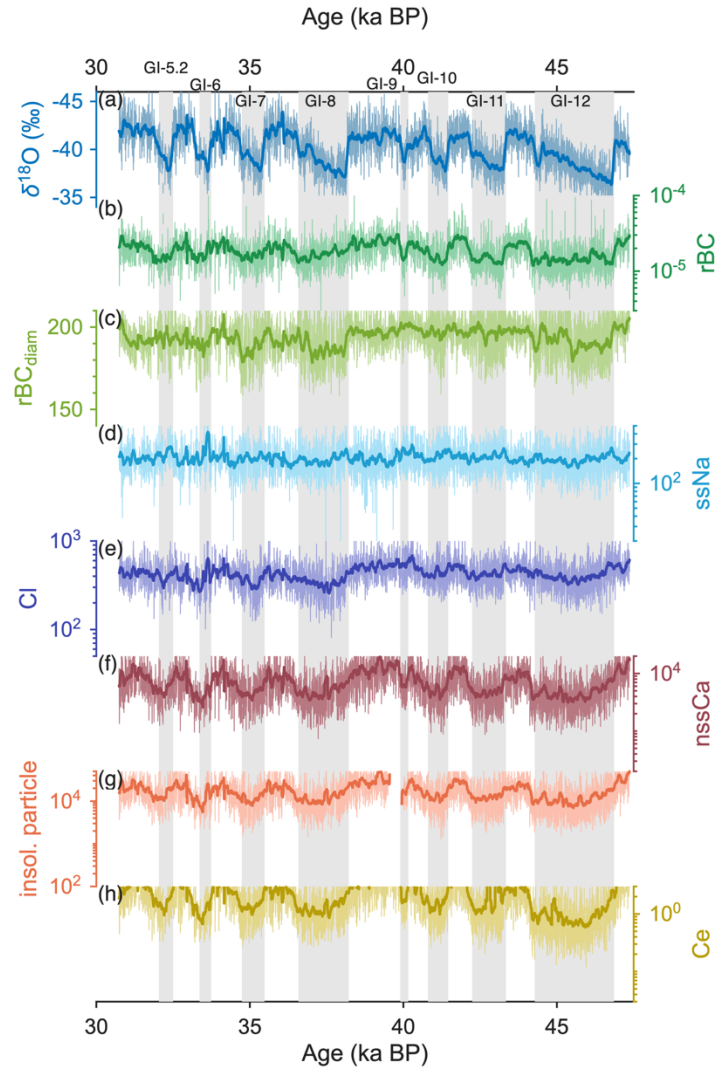


Figure S9. Same as Fig. 4, but showing results obtained with alternative parameter settings in the simplified model framework: effective source latitude decreased by 5°.

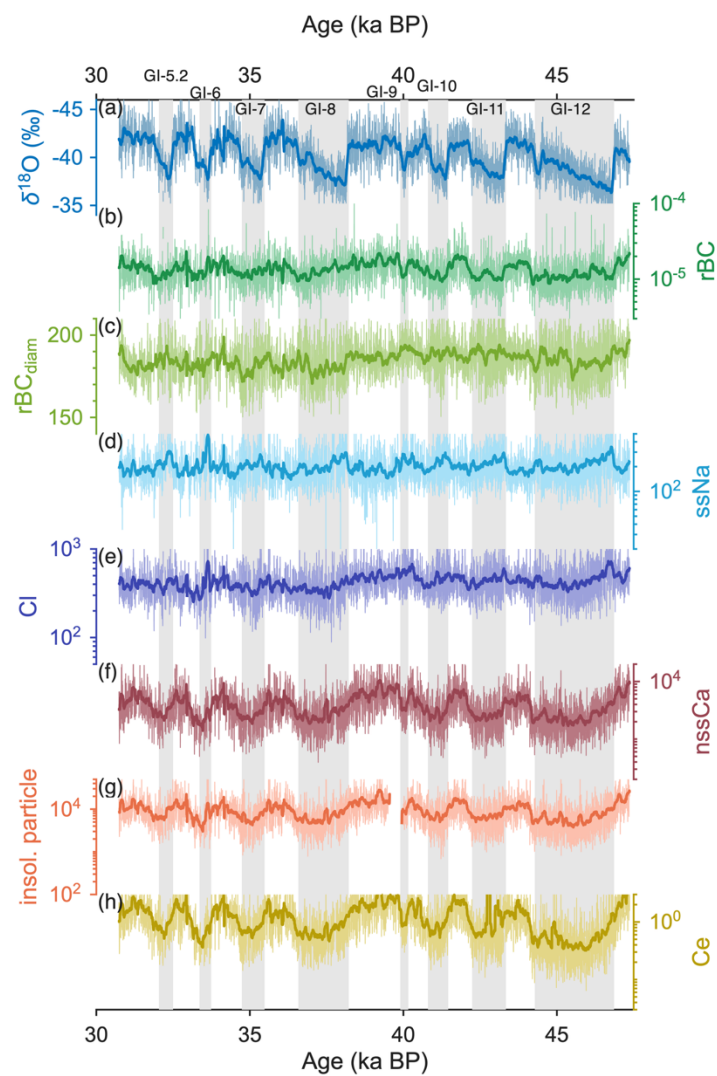


Figure S10. Same as Fig. 4, but showing results obtained with alternative parameter settings in the simplified model framework: initial rBC diameter increased by 20 nm and wet-scavenging efficiency increased by 200 for the other aerosol proxies.

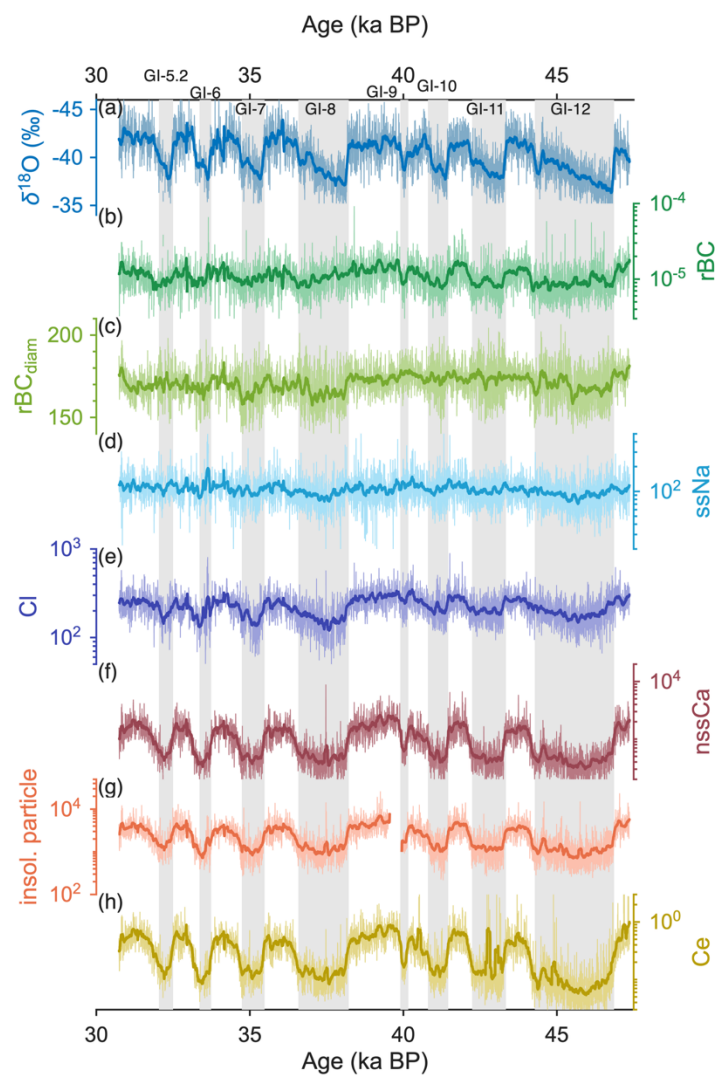


Figure S11. Same as Fig. 4, but showing results obtained with alternative parameter settings in the **simplified model framework**: initial rBC diameter decreased by 20 nm and wet-scavenging efficiency decreased by 200 for the other aerosol proxies

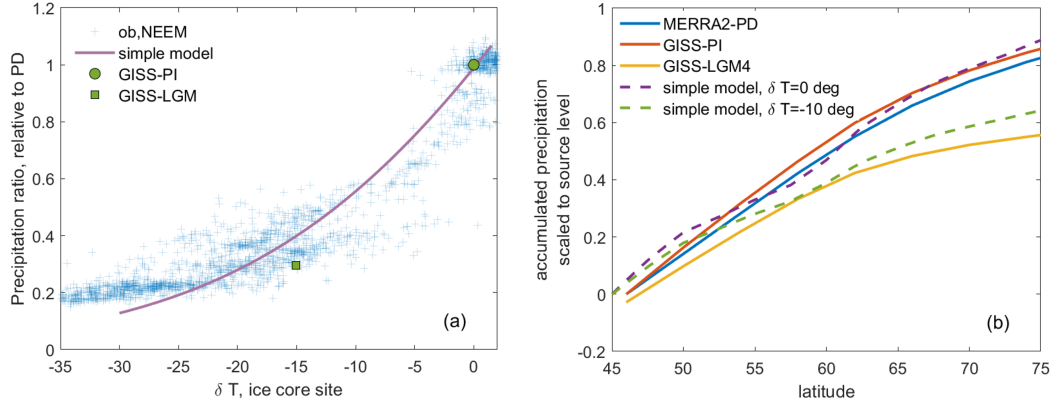


Figure S12. Validation of the precipitation-related assumptions in the simplified transport and removal model framework through comparison with observations and climate model simulations. (a) Relationships between precipitation change relative to the present day and ice-core site temperature anomaly, also relative to the present day. The results from the simplified model are shown by the purple line, reconstructions from NEEM ice-core records¹¹⁻¹³ by blue crosses, and GISS-E2.1 model simulations¹⁴ by green markers for the preindustrial (PI) and Last Glacial Maximum (LGM). (b) Comparison of accumulated precipitation from the prescribed source latitude (45°N) to the ice-core site. The different curves represent the simplified model simulations (with $\delta T = 0^\circ\text{C}$ and $\delta T = -10^\circ\text{C}$, roughly representing warm interstadials and cold stadials, respectively), GISS-E2.1 simulations¹⁴ for the PI and LGM climates, which differ by approximately 10°C at the ice-core site, and modern reanalysis data from MERRA2¹⁵. Despite its idealized treatment of temperature evolution, condensation, and precipitation, the simplified framework reproduces the broad nonlinear relationship between Greenland temperature and precipitation change and the large-scale latitudinal evolution of accumulated precipitation seen in the reconstructions and climate model simulations, supporting its use as a first-order representation of precipitation-related transport and removal processes.

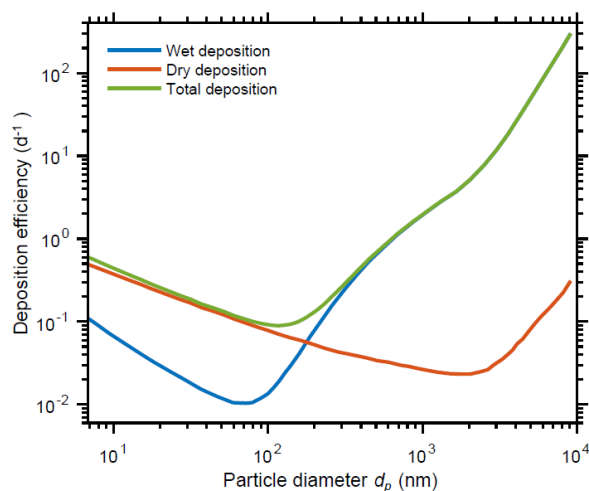


Figure S13. Size-resolved aerosol wet and dry removal efficiency used in the simplified model for biomass burning (BB) rBC particles. The wet removal was calculated assuming a precipitation rate of 2 mm d^{-1} .

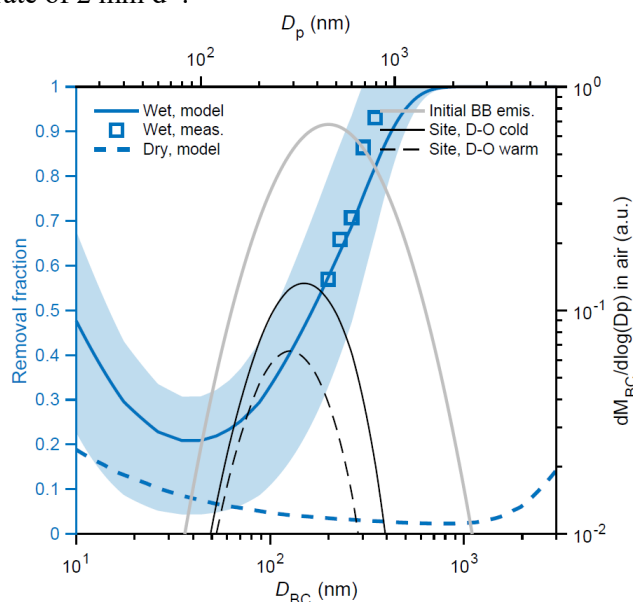


Figure S14. Modeled size-resolved removal fraction of rBC-containing aerosol particles over one day as a result of wet deposition and dry deposition. Measured size-resolved wet removal fractions of rBC by precipitation from Ohata et al.¹⁶ are plotted for comparison (blue squares). The geometric means of both rBC core diameter (D_{BC} , bottom axis) and coated particle diameter (D_p , top axis) are shown. The coated particle size is calculated assuming a coating-to-rBC mass ratio of 10. Wet removal was calculated assuming a precipitation rate of 2 mm d^{-1} . The blue shading represents uncertainty associated with different assumptions of precipitation (1 to 4 mm d^{-1}). Grey curve indicates the initial mass-diameter distribution of atmospheric aerosol particles in the model, and the modeled distributions at the Greenland site for cold stadial and warm interstadial stages over a D-O event are shown as black solid and dashed curves, respectively.

Supplementary Tables

Table S1. Time intervals selected around the seven D-O transitions for ramp fitting analysis.

	Start time (year BP)	End time (year BP)
D-O #5.2	32900	32100
D-O #6	34100	33300
D-O #7	35800	35000
D-O #8	38600	37800
D-O #10	41800	41000
D-O #11	43700	42900
D-O #12	47200	46400

Table S2. Median, 5th, and 95th percentiles of the posterior estimates of onset time (unit: year BP) for each ice-core proxy and in each D-O event.

	D-O #5.2	D-O #6	D-O #7	D-O #8	D-O #10	D-O #11	D-O #12
$\delta^{18}\text{O}$	32537 (32428, 32718)	33717 (33617, 33913)	35490 (35386, 35625)	38204 (38114, 38317)	41495 (41401, 41609)	43350 (43262, 43453)	46872 (46817, 46936)
<i>d</i> -excess	32530 (32463, 32607)	33708 (33649, 33775)	35493 (35414, 35572)	38199 (38147, 38245)	41505 (41439, 41584)	43332 (43280, 43396)	46878 (46838, 46929)
rBC	32515 (32436, 32609)	33760 (33637, 33901)	35476 (35415, 35549)	38220 (38144, 38306)	41470 (41416, 41532)	43332 (43284, 43385)	46868 (46839, 46903)
rBC _{diam}	32523 (32433, 32641)	33717 (33618, 33847)	35495 (35399, 35597)	38196 (38123, 38289)	41468 (41381, 41576)	43365 (43261, 43486)	46863 (46778, 46957)
ssNa	32505 (32395, 32641)	33727 (33563, 33932)	35477 (35375, 35590)	38189 (38112, 38277)	41477 (41401, 41564)	43334 (43242, 43441)	46871 (46816, 46930)
Cl	32516 (32415, 32617)	33748 (33634, 33908)	35473 (35380, 35572)	38190 (38118, 38280)	41473 (41406, 41558)	43330 (43251, 43415)	46878 (46828, 46934)
nssCa	32511 (32437, 32606)	33728 (33648, 33830)	35478 (35426, 35528)	38187 (38141, 38255)	41481 (41423, 41542)	43323 (43282, 43371)	46867 (46839, 46902)
Insol. particle	32501 (32466, 32568)	33745 (33667, 33819)	35475 (35427, 35524)	38193 (38155, 38242)	41471 (41430, 41512)	43332 (43295, 43371)	46868 (46847, 46890)
Ce	32506 (32451, 32570)	33721 (33658, 33807)	35481 (35439, 35520)	38189 (38152, 38230)	41487 (41437, 41542)	43337 (43284, 43394)	46880 (46821, 46955)

Table S3. Same as Table S2, but for posterior transition duration (unit: year) estimates

	D-O #5.2	D-O #6	D-O #7	D-O #8	D-O #10	D-O #11	D-O #12
$\delta^{18}\text{O}$	104 (42, 225)	94 (37, 224)	100 (39, 193)	85 (34, 164)	98 (42, 177)	78 (32, 156)	68 (37, 115)
<i>d</i> -excess	80 (41, 139)	58 (25, 105)	85 (29, 141)	60 (28, 93)	82 (45, 138)	55 (23, 103)	44 (22, 84)
rBC	87 (40, 156)	100 (40, 181)	74 (38, 124)	90 (43, 151)	70 (39, 114)	74 (48, 111)	42 (27, 68)
rBC _{diam}	98 (41, 181)	92 (37, 185)	97 (42, 163)	100 (51, 158)	95 (42, 169)	95 (39, 182)	80 (36, 142)
ssNa	97 (41, 189)	142 (51, 275)	93 (39, 172)	81 (39, 138)	85 (38, 142)	92 (44, 194)	61 (32, 102)
Cl	98 (41, 171)	104 (37, 206)	85 (39, 157)	76 (36, 137)	80 (38, 140)	84 (44, 144)	62 (36, 105)
nssCa	87 (48, 160)	87 (35, 167)	81 (50, 116)	45 (27, 102)	82 (47, 127)	67 (45, 103)	44 (29, 69)
Insol. particle	63 (35, 115)	93 (37, 150)	82 (52, 115)	52 (34, 92)	70 (46, 99)	75 (54, 102)	45 (32, 60)
Ce	83 (52, 129)	81 (40, 151)	88 (63, 114)	50 (33, 83)	96 (63, 131)	85 (53, 124)	85 (51, 139)

Table S4 Same as Table S2, but for posterior estimates of the autoregressive coefficients in the noise terms of the transition estimates (i.e., α in Eq. 4)

	D-O #5.2	D-O #6	D-O #7	D-O #8	D-O #10	D-O #11	D-O #12
$\delta^{18}\text{O}$	0.93 (0.90, 0.96)	0.93 (0.90, 0.96)	0.90 (0.87, 0.93)	0.90 (0.87, 0.93)	0.87 (0.83, 0.90)	0.86 (0.83, 0.89)	0.85 (0.82, 0.89)
$d\text{-excess}$	0.84 (0.80, 0.89)	0.84 (0.79, 0.89)	0.71 (0.66, 0.76)	0.75 (0.71, 0.79)	0.81 (0.78, 0.85)	0.73 (0.69, 0.77)	0.65 (0.60, 0.70)
rBC	0.79 (0.74, 0.83)	0.88 (0.85, 0.92)	0.80 (0.76, 0.84)	0.80 (0.76, 0.84)	0.75 (0.71, 0.80)	0.73 (0.69, 0.77)	0.77 (0.73, 0.82)
rBC _{diam}	0.77 (0.73, 0.82)	0.85 (0.81, 0.89)	0.81 (0.77, 0.85)	0.76 (0.72, 0.80)	0.75 (0.71, 0.79)	0.75 (0.71, 0.79)	0.79 (0.76, 0.83)
ssNa	0.81 (0.77, 0.85)	0.90 (0.861, 0.93)	0.84 (0.80, 0.87)	0.76 (0.72, 0.80)	0.76 (0.72, 0.80)	0.81 (0.78, 0.85)	0.72 (0.67, 0.76)
Cl	0.86 (0.82, 0.90)	0.92 (0.89, 0.95)	0.85 (0.81, 0.89)	0.83 (0.79, 0.86)	0.86 (0.82, 0.90)	0.85 (0.82, 0.88)	0.81 (0.77, 0.84)
nssCa	0.90 (0.86, 0.93)	0.94 (0.91, 0.97)	0.91 (0.88, 0.94)	0.87 (0.84, 0.91)	0.87 (0.83, 0.90)	0.87 (0.83, 0.90)	0.85 (0.82, 0.89)
Insol. particle	0.74 (0.70, 0.79)	0.77 (0.72, 0.81)	0.65 (0.60, 0.70)	0.64 (0.59, 0.69)	0.61 (0.56, 0.66)	0.56 (0.51, 0.61)	0.56 (0.51, 0.61)
Ce	0.80 (0.76, 0.85)	0.85 (0.81, 0.89)	0.81 (0.78, 0.86)	0.74 (0.70, 0.78)	0.78 (0.74, 0.83)	0.71 (0.66, 0.75)	0.78 (0.74, 0.82)

Table S5. Same as Table S2, but for posterior estimates of the noise-to-signal ratio. The noise-to-signal ratio is defined as the amplitude of the AR(1) noise divided by the transition amplitude (i.e., $\sigma/\Delta x$ in Eqs. 2-3). Events selected for estimating the MCMC fitting bias (Text S2) are highlighted.

	D-O #5.2	D-O #6	D-O #7	D-O #8	D-O #10	D-O #11	D-O #12
$\delta^{18}\text{O}$	0.495 (0.326, 0.835)	0.571 (0.338, 0.920)	0.456 (0.320, 0.770)	0.392 (0.281, 0.640)	0.485 (0.342, 0.766)	0.359 (0.277, 0.523)	0.286 (0.228, 0.397)
$d\text{-excess}$	0.266 (0.212, 0.371)	0.272 (0.214, 0.397)	0.343 (0.282, 0.445)	0.246 (0.210, 0.304)	0.340 (0.265, 0.489)	0.290 (0.245, 0.363)	0.351 (0.295, 0.441)
rBC	0.309 (0.251, 0.415)	0.408 (0.292, 0.682)	0.312 (0.253, 0.416)	0.269 (0.222, 0.346)	0.267 (0.226, 0.331)	0.204 (0.179, 0.242)	0.183 (0.160, 0.217)
rBC _{diam}	0.592 (0.432, 0.860)	0.571 (0.396, 0.872)	0.447 (0.338, 0.661)	0.325 (0.265, 0.420)	0.598 (0.439, 0.859)	0.622 (0.464, 0.891)	0.423 (0.329, 0.603)
ssNa	0.667 (0.480, 0.936)	0.707 (0.484, 0.958)	0.402 (0.307, 0.590)	0.430 (0.334, 0.595)	0.531 (0.400, 0.769)	0.427 (0.327, 0.614)	0.337 (0.279, 0.432)
Cl	0.339 (0.259, 0.502)	0.492 (0.328, 0.840)	0.257 (0.207, 0.346)	0.269 (0.220, 0.351)	0.339 (0.262, 0.493)	0.252 (0.205, 0.333)	0.234 (0.196, 0.295)
nssCa	0.202 (0.162, 0.287)	0.182 (0.139, 0.291)	0.131 (0.108, 0.177)	0.151 (0.127, 0.192)	0.173 (0.143, 0.220)	0.131 (0.113, 0.161)	0.124 (0.108, 0.149)
Insol. particle	0.252 (0.213, 0.313)	0.249 (0.206, 0.325)	0.195 (0.173, 0.226)	0.181 (0.162, 0.205)	0.216 (0.192, 0.250)	0.190 (0.171, 0.213)	0.176 (0.161, 0.196)
Ce	0.186 (0.159, 0.229)	0.150 (0.125, 0.190)	0.120 (0.106, 0.143)	0.156 (0.139, 0.180)	0.167 (0.145, 0.200)	0.217 (0.191, 0.260)	0.234 (0.194, 0.295)

Table S6. Same as Table S2, but for posterior estimates of the slope (unit: kyr⁻¹) in the interstadial period after the transition (i.e., s_{GI} in Eq. 2)

	D-O #5.2	D-O #6	D-O #7	D-O #8	D-O #10	D-O #11	D-O #12
$\delta^{18}O$	0.092 (-0.410, 0.854)	0.233 (-0.256, 1.190)	0.177 (-0.273, 0.752)	0.125 (-0.438, 0.788)	0.178 (-0.219, 0.663)	0.077 (-0.334, 0.531)	0.341 (-0.060, 0.732)
d -excess	-0.542 (-1.066, -0.044)	-0.073 (-0.545, 0.408)	-0.069 (-0.377, 0.214)	-0.377 (-0.758, 0.018)	-0.283 (-0.670, 0.088)	-0.210 (-0.520, 0.086)	-0.203 (-0.448, 0.048)
rBC	-0.154 (-0.655, 0.309)	0.227 (-0.273, 0.744)	-0.103 (-0.448, 0.239)	-0.114 (-0.554, 0.289)	-0.413 (-0.693, -0.148)	-0.103 (-0.383, 0.170)	-0.522 (-0.775, -0.271)
rBC _{diam}	-0.285 (-0.850, 0.128)	-0.064 (-0.614, 0.377)	0.211 (-0.226, 0.611)	-0.127 (-0.607, 0.328)	-0.083 (-0.482, 0.256)	0.054 (-0.304, 0.371)	0.289 (-0.101, 0.661)
ssNa	0.137 (-0.420, 0.669)	0.001 (-0.515, 0.380)	0.013 (-0.432, 0.409)	-0.067 (-0.534, 0.362)	-0.057 (-0.444, 0.289)	-0.088 (-0.536, 0.336)	0.071 (-0.220, 0.355)
Cl	-0.052 (-0.616, 0.436)	0.065 (-0.517, 0.565)	-0.081 (-0.502, 0.324)	-0.177 (-0.652, 0.271)	-0.367 (-0.832, 0.096)	-0.141 (-0.586, 0.268)	0.187 (-0.100, 0.465)
nssCa	-0.001 (-0.564, 0.532)	-0.117 (-0.684, 0.390)	-0.062 (-0.390, 0.249)	-0.013 (-0.364, 0.357)	-0.345 (-0.663, -0.031)	-0.043 (-0.343, 0.248)	0.107 (-0.113, 0.321)
Insol. particle	0.241 (-0.145, 0.589)	0.343 (0.046, 0.633)	0.144 (-0.078, 0.352)	0.145 (-0.096, 0.367)	-0.322 (-0.503, -0.138)	0.002 (-0.198, 0.193)	0.062 (-0.080, 0.209)
Ce	0.030 (-0.356, 0.415)	-0.058 (-0.385, 0.256)	0.036 (-0.197, 0.267)	0.070 (-0.198, 0.318)	-0.081 (-0.318, 0.158)	0.098 (-0.200, 0.392)	0.171 (-0.088, 0.418)

Table S7 Same as Table S2, but for posterior estimates of the slope (unit: kyr⁻¹) in the stadial period before the transition (i.e., s_{GS} in Eq. 2)

	D-O #5.2	D-O #6	D-O #7	D-O #8	D-O #10	D-O #11	D-O #12
$\delta^{18}O$	-0.069 (-0.610, 0.487)	0.034 (-0.466, 0.666)	-0.114 (-0.688, 0.458)	0.011 (-0.447, 0.539)	-0.008 (-0.527, 0.536)	-0.131 (-0.565, 0.345)	0.113 (-0.367, 0.625)
d -excess	-0.179 (-0.658, 0.260)	-0.218 (-0.750, 0.288)	0.036 (-0.412, 0.464)	-0.400 (-0.716, -0.082)	-0.585 (-1.216, 0.005)	0.249 (-0.106, 0.575)	-0.119 (-0.528, 0.272)
rBC	0.231 (-0.217, 0.622)	-0.149 (-0.769, 0.386)	0.106 (-0.334, 0.532)	-0.166 (-0.528, 0.182)	0.524 (0.163, 0.881)	0.094 (-0.169, 0.341)	-0.109 (-0.463, 0.237)
rBC _{diam}	0.044 (-0.332, 0.401)	-0.027 (-0.529, 0.387)	-0.337 (-0.923, 0.177)	0.015 (-0.338, 0.320)	-0.143 (-0.585, 0.240)	0.021 (-0.372, 0.367)	-0.078 (-0.543, 0.332)
ssNa	-0.036 (-0.519, 0.366)	-0.029 (-0.497, 0.332)	0.084 (-0.402, 0.558)	0.066 (-0.267, 0.378)	-0.058 (-0.531, 0.381)	0.067 (-0.327, 0.443)	-0.426 (-0.828, -0.044)
Cl	-0.053 (-0.506, 0.386)	-0.065 (-0.726, 0.490)	-0.072 (-0.543, 0.404)	0.182 (-0.160, 0.495)	0.139 (-0.395, 0.661)	0.081 (-0.311, 0.478)	-0.447 (-0.863, -0.059)
nssCa	0.064 (-0.421, 0.503)	0.278 (-0.345, 0.836)	0.111 (-0.308, 0.517)	0.137 (-0.164, 0.418)	0.356 (-0.097, 0.782)	0.007 (-0.274, 0.280)	-0.147 (-0.460, 0.152)
Insol. particle	0.139 (-0.169, 0.423)	0.228 (-0.216, 0.624)	0.116 (-0.148, 0.372)	-0.052 (-0.238, 0.128)	0.477 (0.212, 0.738)	0.034 (-0.160, 0.219)	-0.013 (-0.225, 0.195)

Ce	0.106 (-0.206, 0.399)	0.308 (-0.164, 0.682)	-0.278 (-0.569, 0.003)	0.055 (-0.143, 0.243)	0.228 (-0.109, 0.558)	-0.071 (-0.353, 0.212)	0.650 (0.265, 0.979)
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Table S8. Median, 5th, and 95th percentiles of the posterior onset time differences between proxy pairs in D-O# 5.2 (unit: years). Positive values indicate that the row proxy leads the column proxy. If the percentile interval does not include zero, this suggests that the timing difference is distinguishable from zero based on the 90% posterior credible interval.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	8 (-70, 134)	23 (-59, 153)	18 (-83, 153)	35 (-67, 166)	27 (-60, 155)	25 (-55, 150)	37 (-35, 164)	31 (-40, 155)
<i>d</i> -excess	-	-	14 (-43, 70)	6 (-76, 76)	26 (-57, 92)	17 (-47, 77)	17 (-41, 71)	27 (-15, 76)	22 (-19, 71)
rBC	-	-	-	-8 (-89, 64)	11 (-74, 80)	2 (-61, 66)	2 (-57, 60)	12 (-32, 66)	8 (-35, 62)
rBC _{diam}	-	-	-	-	18 (-76, 109)	10 (-68, 97)	9 (-62, 91)	20 (-42, 100)	15 (-45, 92)
ssNa	-	-	-	-	-	-8 (-81, 80)	-9 (-78, 75)	2 (-55, 81)	-4 (-59, 76)
Cl	-	-	-	-	-	-	-0 (-63, 61)	11 (-40, 67)	6 (-44, 63)
nssCa	-	-	-	-	-	-	-	10 (-33, 64)	4 (-35, 57)
insol. particle	-	-	-	-	-	-	-	-	-6 (-40, 34)
Ce	-	-	-	-	-	-	-	-	-

Table S9. Same as Table S8 but for D-O #6.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	11 (-59, 156)	-42 (-128, 109)	2 (-102, 153)	-11 (-144, 168)	-29 (-143, 124)	-9 (-104, 139)	-21 (-105, 127)	-6 (-89, 136)
<i>d</i> -excess	-	-	-56 (-110, 4)	-7 (-91, 46)	-27 (-134, 99)	-43 (-134, 30)	-18 (-91, 30)	-34 (-86, 17)	-13 (-70, 30)
rBC	-	-	-	46 (-50, 116)	30 (-89, 157)	12 (-88, 96)	35 (-49, 102)	22 (-47, 88)	41 (-30, 102)
rBC _{diam}	-	-	-	-	-15 (-134, 124)	-34 (-139, 72)	-13 (-97, 80)	-25 (-95, 69)	-7 (-78, 83)
ssNa	-	-	-	-	-	-19 (-164, 108)	3 (-127, 124)	-7 (-136, 111)	8 (-120, 123)
Cl	-	-	-	-	-	-	22 (-71, 122)	10 (-75, 106)	28 (-56, 123)
nssCa	-	-	-	-	-	-	-	-15 (-80, 68)	3 (-65, 82)
insol. particle	-	-	-	-	-	-	-	-	18 (-51, 77)
Ce	-	-	-	-	-	-	-	-	-

Table S10. Same as Table S8 but for D-O #7.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	-1 (-75, 89)	14 (-53, 104)	-4 (-78, 92)	12 (-64, 105)	17 (-52, 106)	14 (-47, 101)	16 (-45, 103)	11 (-48, 96)
<i>d</i> -excess	-	-	15 (-35, 64)	-3 (-62, 57)	15 (-49, 73)	20 (-35, 71)	16 (-30, 62)	17 (-26, 62)	13 (-29, 58)
rBC	-	-	-	-19 (-69, 34)	-0 (-58, 49)	4 (-41, 47)	0 (-33, 40)	1 (-29, 37)	-4 (-31, 31)
rBC _{diam}	-	-	-	-	17 (-50, 79)	22 (-35, 75)	19 (-32, 69)	20 (-28, 68)	15 (-31, 63)
ssNa	-	-	-	-	-	5 (-50, 61)	0 (-44, 57)	2 (-41, 58)	-3 (-43, 52)
Cl	-	-	-	-	-	-	-4 (-41, 41)	-3 (-36, 40)	-8 (-39, 33)
nssCa	-	-	-	-	-	-	-	1 (-28, 31)	-4 (-30, 24)
insol. particle	-	-	-	-	-	-	-	-	-5 (-28, 19)
Ce	-	-	-	-	-	-	-	-	-

Table S11. Same as Table S8 but for D-O #8.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	4 (-40, 75)	-18 (-75, 55)	5 (-54, 80)	13 (-40, 87)	10 (-44, 84)	13 (-35, 83)	8 (-35, 78)	13 (-28, 82)
<i>d</i> -excess	-	-	-22 (-68, 16)	0 (-49, 37)	9 (-34, 43)	7 (-37, 37)	10 (-27, 34)	5 (-25, 29)	9 (-18, 32)
rBC	-	-	-	22 (-32, 73)	31 (-17, 80)	28 (-19, 75)	31 (-11, 75)	26 (-9, 69)	31 (-4, 74)
rBC _{diam}	-	-	-	-	8 (-39, 60)	7 (-42, 56)	8 (-32, 56)	3 (-32, 51)	8 (-25, 56)
ssNa	-	-	-	-	-	-2 (-49, 40)	-0 (-40, 39)	-6 (-36, 34)	-1 (-31, 38)
Cl	-	-	-	-	-	-	1 (-34, 44)	-4 (-31, 38)	1 (-24, 43)
nssCa	-	-	-	-	-	-	-	-6 (-29, 29)	-1 (-21, 32)
insol. particle	-	-	-	-	-	-	-	-	5 (-15, 27)
Ce	-	-	-	-	-	-	-	-	-

Table S12. Same as Table S8 but for D-O #10.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	-9 (-73, 64)	25 (-33, 94)	27 (-53, 107)	18 (-50, 94)	21 (-49, 97)	15 (-46, 85)	26 (-28, 95)	8 (-49, 77)
<i>d</i> -excess	-	-	34 (-4, 81)	37 (-30, 97)	28 (-28, 82)	32 (-24, 85)	25 (-16, 73)	34 (1, 80)	16 (-18, 62)
rBC	-	-	-	2 (-61, 54)	-7 (-58, 38)	-3 (-57, 41)	-11 (-47, 26)	-1 (-28, 32)	-18 (-49, 16)
rBC _{diam}	-	-	-	-	-9 (-73, 63)	-6 (-70, 63)	-12 (-65, 54)	-2 (-49, 59)	-20 (-69, 42)
ssNa	-	-	-	-	-	5 (-58, 62)	-3 (-50, 49)	6 (-33, 55)	-11 (-54, 39)
Cl	-	-	-	-	-	-	-6 (-52, 49)	3 (-36, 55)	-15 (-55, 39)
nssCa	-	-	-	-	-	-	-	10 (-21, 45)	-8 (-42, 28)
insol. particle	-	-	-	-	-	-	-	-	-18 (-46, 9)
Ce	-	-	-	-	-	-	-	-	-

Table S13. Same as Table S8 but for D-O #11.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	16 (-31, 78)	16 (-22, 77)	-13 (-90, 57)	13 (-45, 82)	18 (-28, 81)	24 (-14, 84)	15 (-20, 75)	11 (-29, 73)
<i>d</i> -excess	-	-	0 (-29, 36)	-30 (-103, 25)	-1 (-54, 46)	3 (-37, 44)	9 (-20, 46)	0 (-25, 37)	-4 (-36, 34)
rBC	-	-	-	-31 (-102, 18)	-2 (-52, 37)	3 (-34, 34)	8 (-16, 34)	0 (-21, 24)	-5 (-32, 23)
rBC _{diam}	-	-	-	-	28 (-36, 106)	33 (-23, 106)	40 (-9, 111)	30 (-16, 100)	25 (-25, 97)
ssNa	-	-	-	-	-	4 (-45, 58)	11 (-27, 62)	2 (-33, 52)	-3 (-43, 48)
Cl	-	-	-	-	-	-	6 (-25, 42)	-3 (-30, 33)	-8 (-41, 31)
nssCa	-	-	-	-	-	-	-	-9 (-29, 16)	-13 (-40, 15)
insol. particle	-	-	-	-	-	-	-	-	-4 (-31, 19)
Ce	-	-	-	-	-	-	-	-	-

Table S14. Same as Table S8 but for D-O #12.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	-6 (-40, 29)	4 (-24, 37)	9 (-37, 52)	0 (-31, 36)	-5 (-40, 31)	4 (-23, 36)	4 (-21, 37)	-8 (-51, 31)
<i>d</i> -excess	-	-	10 (-11, 38)	15 (-27, 53)	7 (-21, 37)	1 (-30, 32)	10 (-11, 37)	10 (-8, 37)	-2 (-44, 32)
rBC	-	-	-	5 (-35, 38)	-3 (-29, 20)	-9 (-38, 13)	-0 (-18, 18)	-0 (-14, 17)	-12 (-50, 15)
rBC _{diam}	-	-	-	-	-8 (-45, 34)	-15 (-52, 28)	-5 (-39, 35)	-5 (-35, 37)	-17 (-65, 29)
ssNa	-	-	-	-	-	-6 (-38, 22)	3 (-19, 28)	3 (-16, 27)	-8 (-49, 23)
Cl	-	-	-	-	-	-	9 (-14, 37)	9 (-11, 36)	-3 (-44, 33)
nssCa	-	-	-	-	-	-	-	0 (-13, 17)	-11 (-51, 15)
insol. particle	-	-	-	-	-	-	-	-	-12 (-50, 13)
Ce	-	-	-	-	-	-	-	-	-

Table S15. Same as Table S8 but for the median across all the events.

	$\delta^{18}\text{O}$	<i>d</i> -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	insol. particle	Ce
$\delta^{18}\text{O}$	-	7 (-19, 39)	7 (-20, 40)	8 (-23, 44)	15 (-18, 52)	17 (-8, 48)	17 (-10, 50)	11 (-19, 46)	13 (-13, 45)
<i>d</i> -excess	-	-	-0 (-17, 17)	1 (-23, 23)	7 (-18, 33)	9 (-5, 24)	9 (-8, 26)	4 (-17, 24)	6 (-10, 21)
rBC	-	-	-	1 (-24, 24)	8 (-18, 32)	9 (-6, 25)	9 (-8, 26)	4 (-17, 25)	6 (-10, 22)
rBC _{diam}	-	-	-	-	6 (-23, 37)	8 (-12, 32)	8 (-14, 32)	3 (-22, 30)	5 (-17, 28)
ssNa	-	-	-	-	-	2 (-21, 26)	2 (-23, 27)	-3 (-31, 23)	-2 (-25, 22)
Cl	-	-	-	-	-	-	0 (-16, 14)	-5 (-25, 13)	-4 (-18, 10)
nssCa	-	-	-	-	-	-	-	-5 (-26, 15)	-4 (-19, 13)
insol. particle	-	-	-	-	-	-	-	-	1 (-17, 22)
Ce	-	-	-	-	-	-	-	-	-

Table S16. Estimated MCMC fitting bias in transition onset time from repeated calibration tests using synthetic datasets (unit: years). For each proxy, one representative D-O event was selected for calibration (Table S5). In each run, 20 synthetic datasets were randomly selected and fitted using MCMC. The fitted t_0 values were averaged and compared with the prescribed onset times to estimate the fitting bias. Positive values indicate that the fitted onset time is biased earlier than the prescribed synthetic onset, while negative values indicate the fitted onset is biased later. Detailed methods are provided in Text S2.

	$\delta^{18}\text{O}$	d -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	Insol. particle	Ce
run 1	-0.72	7.21	4.45	5.74	-7.39	3.12	1.27	1.07	0.92
run 2	3.82	5.86	0.74	6.48	-0.50	2.18	0.88	0.66	-0.44
run 3	3.47	8.60	4.25	2.87	-9.00	2.48	1.91	-0.53	-0.27
run 4	-1.83	7.19	-0.74	9.46	-4.33	2.20	-1.28	1.32	0.52
run 5	-6.28	7.40	4.26	7.37	-15.15	2.08	-0.47	-0.81	-0.55
run 6	7.56	7.43	2.55	7.46	-5.28	2.41	3.00	-2.37	0.54
run 7	-3.61	6.95	1.46	5.46	-1.93	1.76	-0.18	-0.78	-0.54
run 8	4.29	6.31	7.01	13.85	-10.56	2.01	2.57	-2.28	1.26
run 9	0.86	8.79	3.01	6.73	-2.76	2.12	0.77	0.11	0.87
run 10	0.56	8.15	5.41	5.86	-10.51	2.13	0.16	0.71	-0.96

Table S17. Calibration test of posterior onset time estimates from the MCMC ramp-fitting framework using representative synthetic datasets. Values indicate whether the prescribed synthetic onset time falls within the estimated 5th-95th percentile posterior interval in each repeated trial (1 represents within interval, 0 represents outside interval). For each proxy, one representative D-O event was selected for calibration (Table S5), and the procedure was repeated 10 times using independent random subsets of synthetic datasets to assess robustness (Text S2).

	$\delta^{18}\text{O}$	d -excess	rBC	rBC _{diam}	ssNa	Cl	nssCa	Insol. particle	Ce
run 1	1	0	1	1	1	1	1	1	1
run 2	1	0	1	1	1	1	1	1	1
run 3	1	0	1	1	1	1	1	1	1
run 4	1	0	1	1	1	1	1	1	1
run 5	1	0	1	1	1	1	1	1	1
run 6	1	0	1	1	1	1	1	1	1
run 7	1	0	1	1	1	1	1	1	1
run 8	1	0	1	1	1	1	1	1	1
run 9	1	0	1	1	1	1	1	1	1
run 10	1	0	1	1	1	1	1	1	1

Table S18. Wet scavenging efficiencies for different types of aerosols used in the simplified model in this study and reported in the literature

Wet scavenging efficiency [*]	This work	Markle et al. ⁴	Schüpbach et al. ¹² (rain/snow)
rBC	Size dependent ^{**}	N/A	N/A
ssNa/Cl	1000	1500±500	600/2000
nssCa/Ce/insol. particles	800	1400±500	1420/840 ^{***}

^{*} Units: (g aerosol/g precipitation)/(g aerosol/g air)

^{**} See Methods and Figure S13 for detailed information.

^{***} These wet scavenging efficiencies were used in the model with a reduced precipitation rate equal to 10% of actual precipitation to account for the reduced wet deposition of dust during the long-range transport in the free troposphere.

Reference

- 1 Slattery, J., Sime, L. C., Muschitiello, F. & Riechers, K. Estimating biases during detection of leads and lags between climate elements across Dansgaard–Oeschger events. *Clim. Past* **20**, 2431–2454 (2024). <https://doi.org/10.5194/cp-20-2431-2024>
- 2 Erhardt, T. *et al.* Decadal-scale progression of the onset of Dansgaard–Oeschger warming events. *Clim. Past* **15**, 811–825 (2019). <https://doi.org/10.5194/cp-15-811-2019>
- 3 Goodman, J. & Weare, J. Ensemble samplers with affine invariance. *Communications in Applied Mathematics and Computational Science* **5**, 65–80 (2010). <https://doi.org/10.2140/camcos.2010.5.65>
- 4 Markle, B. R., Steig, E. J., Roe, G. H., Winckler, G. & McConnell, J. R. Concomitant variability in high-latitude aerosols, water isotopes and the hydrologic cycle. *Nature Geoscience* **11**, 853–859 (2018). <https://doi.org/10.1038/s41561-018-0210-9>
- 5 Cuffey, K. M. & Clow, G. D. Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research: Oceans* **102**, 26383–26396 (1997). <https://doi.org/10.1029/96JC03981>
- 6 Masson-Delmotte, V. *et al.* Past and future polar amplification of climate change: climate model intercomparisons and ice-core constraints. *Climate Dynamics* **26**, 513–529 (2006). <https://doi.org/10.1007/s00382-005-0081-9>
- 7 Otto-Bliesner, B. L. *et al.* Last Glacial Maximum and Holocene Climate in CCSM3. *Journal of Climate* **19**, 2526–2544 (2006). <https://doi.org/10.1175/JCLI3748.1>
- 8 Dana, M. T. & Hales, J. M. Statistical aspects of the washout of polydisperse aerosols. *Atmospheric Environment (1967)* **10**, 45–50 (1976).
- 9 Croft, B. *et al.* Influences of in-cloud aerosol scavenging parameterizations on aerosol concentrations and wet deposition in ECHAM5-HAM. *Atmos. Chem. Phys.* **10**, 1511–1543 (2010). <https://doi.org/10.5194/acp-10-1511-2010>
- 10 Jacob, D. J. *Introduction to atmospheric chemistry*. (Princeton university press, 1999).
- 11 Dahl-Jensen, D. *et al.* Eemian interglacial reconstructed from a Greenland folded ice core. *Nature* **493**, 489–494 (2013). <https://doi.org/10.1038/nature11789>
- 12 Schüpbach, S. *et al.* Greenland records of aerosol source and atmospheric lifetime changes from the Eemian to the Holocene. *Nature Communications* **9**, 1476 (2018). <https://doi.org/10.1038/s41467-018-03924-3>
- 13 Rasmussen, S. O. *et al.* A first chronology for the North Greenland Eemian Ice Drilling (NEEM) ice core. *Clim. Past* **9**, 2713–2730 (2013). <https://doi.org/10.5194/cp-9-2713-2013>
- 14 Kelley, M. *et al.* GISS-E2.1: Configurations and Climatology. *Journal of Advances in Modeling Earth Systems* **12**, e2019MS002025 (2020). <https://doi.org/10.1029/2019MS002025>
- 15 Rienecker, M. M. *et al.* MERRA: NASA’s Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate* **24**, 3624–3648 (2011). <https://doi.org/10.1175/JCLI-D-11-00015.1>
- 16 Ohata, S., Moteki, N., Mori, T., Koike, M. & Kondo, Y. A key process controlling the wet removal of aerosols: new observational evidence. *Scientific Reports* **6**, 34113 (2016). <https://doi.org/10.1038/srep34113>