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The anatomy of past abrupt warmings recorded in Greenland ice

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Data availability and temporal resolution make it challenging to unravel the anatomy (duration and temporal phasing) of the Last Glacial abrupt climate changes. Here, we address these limitations by investigating the anatomy of abrupt changes using sub-decadal-scale records from Greenland ice cores. We highlight the absence of a systematic pattern in the anatomy of abrupt changes as recorded in different ice parameters. This diversity in the sequence of changes seen in ice-core data is also observed in climate parameters derived from numerical simulations which exhibit self-sustained abrupt variability arising from internal atmosphere-ice-ocean interactions. Our analysis of two ice cores shows that the diversity of abrupt warming transitions represents variability inherent to the climate system and not archive-specific noise. Our results hint that during these abrupt events, it may not be possible to infer statistically-robust leads and lags between the different components of the climate system because of their tight coupling.
Paleoclimatic records of the Last Glacial reveal a series of abrupt warming events occurring in the North Atlantic region, known as Dansgaard-Oeschger (D-O) events, with counterparts in lower latitudes and Antarctic climate archives. Oxygen isotope ($\delta^{18}O$) profiles from Greenland ice cores provide master records of this climate variability, illustrating fluctuations between Greenland Stadial (GS) phases with full glacial conditions and milder Greenland Interstadial (GI) phases (Fig. 1). The D-O climate variability is commonly linked to changes in the intensity of the Atlantic meridional overturning circulation (AMOC), resulting in heat transport changes from the low to the northern high latitudes. However, no consensus exists yet to explain what triggers the abrupt warmings, characterized by Greenland surface temperature increases of 5–16 °C within a few decades to centuries. Among the proposed paradigms, mechanisms involving changes in Nordic Seas sea-ice cover, atmospheric circulation, or the collapse of ice shelves have been investigated. Recent studies suggest that abrupt climate variability can result entirely from unforced or noise-induced oscillations of the coupled atmosphere-ice-ocean system that alter poleward energy transport (ref. 13 and 14 for reviews).

The mechanisms proposed to explain D-O event dynamics can be confronted with annual-to-decadal-scale observations of climatic changes across the globe over the GS–GI transitions. Indeed, such data sets provide a basis to map out the sequence of events, infer possible causal relations and evaluate hypothetical mechanisms of changes between different regions without relative dating uncertainties between paleoclimate records from different archives. Records of annual or close-to-annual resolution from Greenland ice cores overcome this challenge since they contain tracers recording conditions in different parts of the Earth System with each year’s precipitation, all in one archive. The $\delta^{18}O$ value of Greenland ice is mainly affected by local surface temperature changes, past changes in precipitation seasonality, the temperature at the moisture source regions, and elevation changes. Hence, although $\delta^{18}O$ is not a direct temperature proxy, it can be used as a qualitative tracer of local Greenland surface temperature changes. The second-order parameter d-excess ($d$-excess = $\delta D - 8 \cdot 18O$) is commonly interpreted as a record of past changes in evaporation conditions or shifts in mid-latitude moisture sources, whereas Ca$^{2+}$ concentrations ([Ca$^{2+}$]) in Greenland ice cores reflect both source strength and transport conditions from terrestrial sources, which are mainly the mid-latitude Asian deserts. Finally, changes in Na$^{+}$ concentrations ([Na$^{+}$]) can be interpreted as qualitative indicators of the sea-ice cover extent in the North Atlantic at the stadial-interstadial scale, whereas relative site accumulation rate changes can be estimated from the annual-layer thickness (denoted λ) (denoted λ) (denoted λ). Hence, ice-core multi-tracer studies are well suited to evaluate the precise phasing and duration of changes between different regions without relative dating uncertainty as all records come from the same core.

This approach was initially applied to characterize the sequence of events at the onsets of the Holocene, GI-1e (Bølling), and GI-8c, for each of those transitions, a lead of a few years in changes in terrestrial aerosol concentrations, accumulation rate, and mid-latitude moisture sources relative to the changes in marine aerosols and the isotopic temperature was found. Such results suggest that the Greenland surface warming was preceded by changes in the conditions at the dust sources or changes to the transport to Greenland (e.g., rainfall-driven changes in aerosol washout). In parallel, the phasing between the high- and lower-latitude climate responses was investigated using ice-core

![Fig. 1 Abrupt climate variability recorded in Greenland water isotopic records.](https://example.com/fig1)

Fig. 1 Abrupt climate variability recorded in Greenland water isotopic records. a NGRIP $\delta^{18}O$ record. Studied abrupt warming transitions are highlighted with red vertical bars and Greenland Interstadials (GI) are numbered. Gray boxes indicate intervals shown in (b–g), illustrating the variety of abrupt GS–GI transitions across the Last Glacial; stadials containing Heinrich events are indicated in yellow following refs. 53, 85, and Marine Isotope Stages (MIS) are indicated in gray. b–g High-resolution $\delta^{18}O$ from NGRIP (dark blue) and NEEM (light blue) and d-excess from NGRIP (red) and NEEM (orange) over 400 yr time intervals centered on the Holocene abrupt onset (b) and the abrupt transitions into GI-5.2 (c), GI-8c (d), GI-18 (e), GI-19.2 (f), and GI-20c (g).
gas-phase measurements: the $\delta^{15}$N of $N_2$ as a tracer for Greenland surface temperature changes$^{27,28}$ and the methane concentration (CH$_4$) as a proxy for tropical climate change$^{29,30}$. Although the first studies$^{29,31}$ estimated a lag of a few decades of tropical CH$_4$ emissions behind $\delta^{15}$N at the onset of the abrupt warmings, a more recent study$^{32,33}$, focusing on the Bolling transition and using 5-yr-resolution $\delta^{15}$N and CH$_4$ records, estimated that high- and low-latitude climate changes occurred essentially synchronously at that time, with Greenland surface temperature leading atmospheric CH$_4$ emissions by $4.5^{\pm0.4}$ yrs, in agreement within errors with ref. 34.

Benefiting from the new NGRIP and NEEM high-resolution ice-core data sets, recent work extended the multi-tracer approach developed by ref. 25 and 26 to all transitions back to 60 ka b2k (thousand years before 2000 C.E.) and derived an average sequence of changes characteristic of the GI onsets by combining the estimated leads and lags for all studied transitions$^{23}$. Based on the assumption that the relative timing differences between different tracers at all GI onsets are the result of the same underlying process, it was found that changes in both local precipitation and terrestrial dust aerosol concentrations led the change in sea-salt aerosol concentrations and $\delta^{18}$O of the ice by about a decade. Event-stacking-based approaches are often applied to extract the common signal from highly variable climatic records$^{33-36}$. Although this is useful, it is also worth looking into the details of the sequence of changes over each event, especially considering the high diversity observed in the amplitude of the warming$^{6}$, the shape and duration of GS and GI$^{35,36}$ (Fig. 1), and the evolving climatic background state throughout the Glacial (orbital configuration, global ice volume, and atmospheric greenhouse gas concentrations). Taking this view, we observe that the results from ref. 23 illustrate a decadal-scale range in leads and lags from one event to the next when considering the onset of each individual transition. These differences can be interpreted as coming from different realizations of the same set of underlying mechanisms owing to noise processes in the archive and internal variability in the climate system, or alternatively as a suggestion that one common set of mechanisms or sequence of events may not adequately describe the processes of all rapid warming transitions.

The aim of this study is twofold. First, we investigate the anatomy of the D-O warming transitions down to 112 ka b2k using a multi-tracer approach relying on new and existing records from the Greenland NEEM (77.45°N, 51.08°W) and NGRIP (75°N, 42.3°W) ice cores. Having so many highly resolved ice-core records from two different locations over numerous D-O events provides the most comprehensive opportunity so far to assess the geographical representativeness of single ice-core records. Second, the anatomy of D-O warmings inferred from Greenland ice-core data is compared with new simulations from the coupled Community Climate System Model Version 4 (CCSM4) as the basis for discussing the processes involved in D-O warmings.

We use here new and existing water isotope measurements ($\delta^{18}$O, d-excess) at high resolution (5 cm) from the NGRIP ice core$^5$ (Supplementary Data 1). The temporal resolution of the measurements corresponds to 1, 3, 4, 5 yr per sample at 10, 45, 80, and 105 ka b2k, respectively. We also include in our analysis, sections from the recent NEEM high-resolution water isotope records$^{39}$ for which the 5 cm resolution corresponds to 1, 4, 7, 18 yr per sample at 10, 45, 80, and 105 ka b2k. We also present high-resolution NGRIP and NEEM [Ca$^{2+}$] and [Na$^+$] records annually interpolated and extended back to ~108 ka b2k (Methods, Supplementary Data 2). Finally, we use the NGRIP $\lambda$ record back to 60 ka b2k obtained from the GICC05 annual-layer counting based on aerosol and visual stratigraphy records (Supplementary Data 3). We restrict our $\lambda$ analyses to the last 60 ka as $\lambda$ is modeled from the stable water isotope record below this age and, therefore, is not independent of $\delta^{18}$O. The GICC05 chronology is applied to NEEM by means of interpolation between reference horizons of mainly volcanic origin$^{40}$. The NEEM annual-layer thicknesses are only available as averages between these unevenly spaced reference horizons, rendering the NEEM $\lambda$ record unsuitable for this study. The NGRIP and NEEM data sets are reported on the GICC05 chronology back to 60 ka b2k and on the flow model-extended GICC05modelext chronology below this$^{40,41}$. Age interpolation uncertainties limit the direct comparison of the absolute timing of changes between cores$^{40}$.

We use a probabilistic characterization of the transitions to infer the timing, duration, and amplitude of the local and regional changes associated with each studied D-O warming. Following refs. 23,25, we determine the relative phasing of changes in the different data sets by fitting a ramp (i.e., a linear change in the raw or logarithmically-transformed data between two stable states) to each data series within a prescribed search interval across each GS–GI transition (Supplementary Figure 1, Supplementary Table 1, Supplementary Data 4). We describe the ramp by the temporal midpoint of the ramp, the duration of the transition, the data value before the transition, and the amplitude of the change. Our probabilistic model also accounts for additive noise with autocorrelation (Methods). Note that our method is conceptually similar to ref. 23 with only minor differences in the parameter priors, whereas the uncertainty estimation is different from that employed by ref. 25, which used the RAMPFIT method$^{42}$. In the following, we only display results for transitions where the ramp-fitting technique provides an unequivocal solution, i.e., the timing and duration of the identified onset and end of the transitions do not change by more than a decade when the width of the search time window is varied (Methods, Supplementary Figure 3).

Results

To start, we describe the general characteristics of NGRIP and NEEM water isotope records. Fig. 1 displays NGRIP and NEEM high-resolution $\delta^{18}$O and d-excess records over six 400 yr time intervals around the transitions into the Holocene, GI-5.2, GI-8c, GI-18, GI-19.2, and GI-20 (Supplementary Figure 1 shows all transitions over 600 yr time intervals). Mean the $\delta^{18}$O and d-excess levels are about the same in both ice cores. Indeed, the sets of records are very similar in terms of amplitude and timing at multi-decadal-scale and show the well-known pattern comprising a cold phase, a transition, and a warm phase (characterized by less negative $\delta^{18}$O and larger d-excess values), previously identified in Greenland ice cores$^{17,20}$. Its simplest explanation is that atmospheric warming ($\delta^{18}$O) over the ice sheet takes place roughly in parallel to a moisture source shift to a cooler region (d-excess), although other factors contribute to d-excess changes. Indeed, the values of d-excess in Greenland precipitation are thought to be primarily an indicator of conditions over the subtropical North Atlantic$^{19}$, with possible small contributions from other source areas$^{43}$. Although d-excess bears a signature of vapor source characteristics (sea-surface temperature (SST) and relative humidity), it is also affected by changes in condensation temperature, the temperature difference between the source and condensation regions$^{17,44}$ and possibly different changes in seasonality at the two sites$^{45}$ and by North Atlantic sea-ice removal$^{46}$. A simple visual observation of the two records suggests that the variability is slightly smaller in NEEM compared with NGRIP. This is likely related to the stronger thinning rate in the NEEM glacial section, leading to the fact that each individual sample is the average isotopic values over a longer period at NEEM than at NGRIP. The difference is related to the influence
on flow-induced thinning of the presence of bottom melting at NGRIP\textsuperscript{3,38}, which results in NGRIP annual layers being thicker by a factor of 1.5–2 compared with NEEM during most of the Glacial\textsuperscript{38}.

Then, we present the inferred timing of changes in ice tracers at the D-O warming onsets. Figs. 2 and 3 show the timing (onset by a factor of 1.5

Glacial\textsuperscript{38}. Then, we present the inferred timing of changes in ice tracers. The transitions in the δ\textsuperscript{18}O, d-excess, [Ca\textsuperscript{2+}], [Na\textsuperscript{+}] and annual-layer thickness λ (see legend for colors). On the top, NGRIP and NEEM δ\textsuperscript{18}O and d-excess records are represented across the Holocene onset together with the fitted ramp to illustrate how the ramp results are represented below. Transitions preceded by stadials containing Heinrich events are indicated in yellow. All timings are shown relative to the onset of the δ\textsuperscript{18}O transition (dashed vertical line). The vertical amplitude between the onset and the end of each transition is the same for all tracers, it has been set arbitrarily and does not represent the true amplitude of change for each ice-core tracer.

Fig. 2 Anatomy of Last Glacial abrupt changes inferred from an ice-core multi-tracer approach. Onset and endpoints (dots) of the studied transitions (oblique lines) towards each GI over the past 112 ka, together with associated uncertainty intervals (horizontal shaded lines) found by the ramp-fitting analysis on (a) NGRIP and (b) NEEM ice-core tracers: δ\textsuperscript{18}O, d-excess, [Ca\textsuperscript{2+}], [Na\textsuperscript{+}] and annual-layer thickness λ (see legend for colors). On the top, NGRIP and NEEM δ\textsuperscript{18}O and d-excess records are represented across the Holocene onset together with the fitted ramp to illustrate how the ramp results are represented below. Transitions preceded by stadials containing Heinrich events are indicated in yellow. All timings are shown relative to the onset of the δ\textsuperscript{18}O transition (dashed vertical line). The vertical amplitude between the onset and the end of each transition is the same for all tracers, it has been set arbitrarily and does not represent the true amplitude of change for each ice-core tracer.
patterns between the two ice cores breaks down at the bottom of the cores, i.e., in the time period earlier than GI-21.1e. We interpret this as an effect of the decreasing temporal resolution of the records through the flow-induced thinning of the ice at those depths. Because of these possible limitations, we do not consider those transitions in the following discussion.

Discussion

First, we discuss our results over the Last Deglaciation abrupt warmings, i.e., across the onsets of the Holocene and GI-1e (Bolling), and we compare them with results from refs. 23,25 (Fig. 3). The sequence of events obtained from NGRIP records is consistent with the previous studies within the uncertainty range and is also consistent with the sequence of events deduced from the NEEM data set. d-excess transition durations as estimated in the GRIP, GISP2, and Dye 3 ice cores were found to be systematically shorter than the $\delta^{18}O$ transitions and our results on both NGRIP and NEEM ice cores suggest that overall, the transitions in $\delta^{18}O$, $\lambda$, $[Ca^{2+}]$ and $[Na^+]$ last several decades while these d-excess transitions take ≤10 yr. However, considering the uncertainty intervals of the respective transition onsets, we do not identify a statistically significant sequence of changes in NGRIP characterizing both the Holocene onset and the transition into GI-1e, i.e., different phasing is possible between tracers considering the uncertainty intervals. We provide further evidence as the NEEM results confirm that within the uncertainty intervals, the data are consistent with both a synchronous change of $\delta^{18}O$ and $[Ca^{2+}]$ and a lead of $[Ca^{2+}]$ over $\delta^{18}O$. Hence, considering the uncertainty intervals estimated in our new study, the conclusions drawn from the original analysis of the Last Deglaciation abrupt warmings that suggested a beginning of the abrupt changes in the lower latitudes should be interpreted with caution.

Our observation that the onset of the two abrupt transitions occurs within a few decades of each other in the four tracers points to tight coupling and similar large-scale teleconnections between sea ice, atmospheric circulation, and isotopic temperature changes across both events. Assuming that abrupt climate change involves altered poleward energy transport by the ocean and atmosphere, it is unsurprising that the parameters vary so closely in phase. As originally proposed by ref. 47 and subsequently confirmed in a wide range of model studies, any perturbation to the northern high-latitude energy balance, whether by changes in sea-ice extent, altered heat transport by the AMOC or altered heat transport by the atmosphere, results in fast (annual- to decadal-scale) compensating changes in the other parameters.12,48,49.

Next, we extend our discussion to the sequence of changes over Last Glacial abrupt warmings. Our analysis identifies a range of transition durations and no systematic pattern of leads and lags between the different tracers across the GS–GI transitions. Several possible interpretations of this observation can be proposed. First, we consider whether the transitions could appear to be different owing to depositional noise and local artefacts. Differences at
multi-annual scale between NGRIP and NEEM records slightly affect the relative timing of the onsets of the changes in the different tracers. The isotopic differences are likely linked to different seasonality, meso-scale atmosphere dynamics, and local processes affecting the two sites, whereas differences in the moisture source origin or transportation paths also could play a secondary role. However, the patterns of the transition durations in NGRIP and in NEEM are overall similar despite large event-to-event variability (Fig. 1b–g), suggesting that these varying durations represent a real climate signal and are not artefacts of local depositional noise. This visual consistency (Fig. 4 and Supplementary Figure 4) is supported by testing the null hypothesis that the transition durations in the tracers and events investigated in both cores come from the same distribution (accounting for duration uncertainties, see Methods). When applied to each event individually, the null hypothesis is only rejected for two transitions out of 24 for $\delta^{18}O$, one transition out of 13 for d-excess and two transitions out of 21 for $[\text{Ca}^{2+}]$ while it is never rejected for the studied transitions in $[\text{Na}^+]$. We also consider all the events simultaneously by testing the null hypothesis that there is no significant difference between the weighted transition durations for the two sites in each tracer. In this case, the null hypothesis is never rejected. Analyzing all transitions together and testing whether the durations correlate between the records from NGRIP and NEEM reveal significant correlation when we apply the test to (1) $\delta^{18}O$ or $[\text{Na}^+]$ records individually, (2) to the combined water isotopic tracers, (3) to the combined impurity tracers, and (4) to all tracers together (Methods, Supplementary Table 2 and Supplementary Figure 4).

Owing to the strong inter-core consistency, we argue that it is unlikely that the transitions appear different from one event to the next because of archive noise or local artefacts. Instead, we propose two alternative interpretations. The transitions could be different realizations originating from the same set of processes but expressed slightly differently between events because of

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**Fig. 4 Duration estimates of the $\delta^{18}O$, d-excess, $[\text{Ca}^{2+}]$, $[\text{Na}^+]$, and annual-layer thickness ($\lambda$) transitions into each GI.** Duration estimates inferred from (a) NGRIP data sets and (b) NEEM data sets. Transitions highlighted in yellow are preceded by a stadial containing a Heinrich event. Gray shading indicates the section at the bottom of the two cores where duration data should be interpreted with caution owing to marginal data resolution. Uncertainty intervals in the transition duration range from 2 to 262 yr with a mean of 86 yr (they are omitted here for clarity purposes but are shown in Supplementary Figure 4 and tabulated in Supplementary Data 4).
internal climate variability. Our observed timing differences between tracers at the onsets of the transitions are small, especially considering the uncertainty intervals, and internal climate variability could affect the signal propagation on regional-to-hemispheric scale and/or our ability to detect the precise onsets of transitions in different proxies. This is the underlying assumption in ref. 23 and if this assumption is fulfilled, the estimated timing differences of the individual onsets of the transitions into interstadials can be combined to reduce the influence of internal climate variability and infer the underlying archetypical sequence of events.

Alternatively, the transitions could be different from one event to the other because the mechanisms impacting abrupt changes are different. Indeed, we observe that GI-18 stands out in the two ice cores with surprisingly ~150 yr-long transitions in both δ¹⁸O and D-excess. This transition occurs under atypical climatic background conditions as Marine Isotope Stage (MIS) 4 is characterized by a local ice-sheet maximum and GI-18 follows one of the longest stadials, GS-19.1, which lasts 5300 yr. Interestingly, the low-latitude counterpart of GI-18 as recorded in the Hulu cave isotopic record is not as clear as for the other abrupt events and neither is it in Antarctica where the classic bipolar seesaw pattern cannot be identified unambiguously. In this context, we investigate first the potential role of changes in the climatic background state (Supplementary Figure 6). However, even if the anatomy of the GI-18 transition was related to the specific climatic background state, the latter cannot explain the diversity of transition durations observed across the abrupt warming transitions within MIS 3. Here, differences are observed between neighboring events just 1–2 millennia apart, i.e., on much shorter timescales than the orbital-scale changes of the climatic background. Also, we do not find a significant correlation between the transition durations in the different ice tracers and the amplitude of key parameters of the background climate state (Supplementary Figure 6). Hence, although slow-varying forcings may influence the durations of GI and GS, they seem unable to systematically explain the differences in the durations observed between successive transitions. Finally, we investigate whether there is a link between the observed phasing and duration of transitions and the presence of large ice-rafting debris events, which occurred during some of the stadials preceding the GI onsets, the so-called Heinrich Events. We find no systematic differences between the anatomy of the transitions following stadials containing Heinrich events and those without (Figs. 1–3).

Next, we provide a model perspective on the anatomy of D-O warmings. Early simulations from a coupled global ocean–atmosphere–sea-ice model forced with different freshwater amounts in the North Atlantic have shown that multiple stable or quasi-stable states of the AMOC strength could exist and that rapid transitions between these states do not have identical climate expressions as modeled temperature and precipitation changes are not linearly related to the AMOC strength. Regional and local feedbacks, such as the sea-ice-margin shift and albedo feedbacks (owing to changes in sea-ice and snow extent), also come into play and complicate the response further, e.g., the relative importance of these controlling factors on the water isotopic records may differ from one event to the other leading to a variety of transitions recorded in these proxies. Owing to their design, those simulations only illustrate that transitions can be expressed differently when a single forcing (i.e., freshwater release into the North Atlantic), modulated by regional feedbacks, is involved. However, recent modeling studies suggest that D-O events could result from unforced climate oscillations linked to dynamics internal to the climate system such as atmosphere-ice-ocean interactions altering poleward energy transport.

For comparison with our proxy-based results, we investigate the sequence of changes and the durations of the transitions in different components of the climate system across such spontaneous D-O-like oscillations in a low-resolution version of CCSM4. We consider three simulations run under slightly different prescribed atmospheric CO₂ concentrations (185, 200, and 210 ppmv), each containing two spontaneous D-O-like transitions (Fig. 5, Supplementary Figure 7, Supplementary Table 3). Over each D-O-like transition, we extract the time series of four climatic measures from the model on the assumption that they reflect some of the same elements of the climate system as our ice-core proxy data. We look into simulated time series of (1) annual surface air temperature and (2) annual precipitation rate at the NGIP site, (3) the sea-ice extent in the Inrminger Sea, as this is the most sensitive location under interstadial-stadial changes in CCSM4 (Supplementary Figure 8), and (4) the North Atlantic Oscillation (NAO) index as a tracer for North Atlantic atmospheric circulation changes (Supplementary Figure 9, Methods). By applying our ramp-fitting-based approach to the modeled time series, we find transitions consistent with those observed in the ice-core data (Fig. 5 and Supplementary Figure 7). All modeled transitions are less than 100 yr long and can be as short as a couple of decades (the average width of the associated uncertainty intervals is 58 yr). Transitions in the simulated time series occur within a few decades of each other, with no consistent sequence within their respective uncertainty intervals. Finally, the transition in all parameters always begins before the leading parameter has reached its post-transition level. As the model climate time series do not contain archive noise, our combined model-data approach strongly supports the idea that the variability is seen in the ice tracers from one abrupt transition to the next mainly represents variability inherent to the climate system rather than noise related to how changes in the climate system are recorded in Greenland ice-core proxies. Going one step further, the model-data comparison raises the possibility that it may not be possible to resolve significant leads and lags between components of the climate system that are so tightly coupled, particularly when feedbacks between them are implicit in the nature of abrupt climate change.

The absence of a systematic pattern in the phasing or duration of transitions in different parameters, as seen in both model- and proxy-based climate parameters, could be the result of internal climate variability superimposed on a common set of mechanisms. In such a context, the ref. 23 approach of combining the estimated leads and lags for all studied transitions in order to obtain a common signal is appropriate and their resulting conclusions valid. Alternatively, there might not be a unique sequence of changes representing D-O warmings nor a unique trigger per se to these abrupt changes. These two scenarios are difficult to separate: if there are indeed multiple possible cascades of processes that can trigger a D-O event, then, the sequence may itself be sensitive to internal climate variability. The second scenario is consistent with the physics displayed in a growing number of model experiments where D-O-like oscillations can result from different processes, e.g., by forced freshwater fluxes, forced insolation change, or unforced internal oscillations. In the case of unforced internal oscillations, destabilization of the climate system could occur owing to a range of mechanisms (e.g., stochastic atmospheric variability, ocean convective instability, and their couplings with sea-ice extent) that could be different from one event to the next. Although the precise forcing and sequence of events vary between these examples, the end-result of abrupt climate change characterized by large sea-ice, atmospheric circulation, and temperature anomalies, is common to all.

The emerging picture of the D-O warmings is one in which the components of the climate system are so tightly coupled that it
Fig. 5 Anatomy of self-sustained abrupt transitions simulated in CCSM4. Onset and endpoints (dots) of modeled abrupt transitions (oblique lines) together with associated uncertainty intervals (horizontal shaded lines) found by the ramp-fitting analysis on time series of the annual surface air temperature (blue) and the annual precipitation rate (black) both at the model grid point closest to NGRIP, the sea-ice extent in the Irminger Seas (light orange) and an NAO index defined as PCI of sea-level pressure variations in the North Atlantic region (purple; details in SOM) over the two unforced oscillations simulated in CCSM4 with atmospheric CO₂ concentrations of (a–b) 185 ppm, (c) 200 ppm, and (d) 210 ppm. The time series (numbered 1–6) are shown in Supplementary Figure 7. (a) simulated time series for each climate parameter from the first modeled abrupt change under a CO₂ concentration background of 185 ppm are represented together with the resulting identification of the onset and the end of the abrupt transition from the ramp-fitting analysis to illustrate what is represented in (b–d). All transitions are shown relative to the timing of the onset of the NGRIP surface air temperature transition (dashed vertical line). The vertical amplitude between the onset and the end of each transition is the same for all tracers, it has been set arbitrarily and does not represent the true amplitude of change for each ice-core tracer. (e) Zoom on the duration estimates of the transitions in the simulated climatic parameters. Uncertainty intervals in the transition duration range from 15 to 118 yr with a mean of 57 yr (they are omitted here for clarity purposes).

**Methods**

**Greenland NGRIP and NEEM ice-core measurements.** The NEEM water isotope sections are part of the continuous high-resolution water isotope record covering 8–130 ky b2k. Analyses have been performed at the Niels Bohr Institute at the University of Copenhagen using IR Cavity Ring Down Spectrometry on discrete samples with a resolution of 5 cm. The combined uncertainty of the measurements (1σ) is 0.05‰ and 0.4 ‰ for δ¹⁸O and δD, respectively. In the present study, we use and show 600-yr-long sections covering 25 abrupt transitions (Supplementary Figure 1). In addition to using the existing NGRIP high-resolution δ¹⁸O profile, we also present new d-excess data from the NGRIP ice-core for 300–500-yr-long time windows centered on 12 abrupt transitions that were measured at 5 cm resolution at the Institute of Arctic and Alpine Research (INSTAAR) Stable Isotope Lab (SIL) (University of Colorado) (Supplementary Data 1). The first set of measurements were performed in 2006–2007 across the onsets of GI-3, GI-4, GI-5.2, GI-8c, GI-10, GI-11, GI-12c, GI-18, GI-19.1, GI-19.2 GI-20c, and GI-25 using automated uranium reduction system coupled to a VG SIRA II dual-inlet mass spectrometer. A second set of measurements was performed in 2016–2017 using a Picarro CRDS analyser in order to fill some data gaps remaining from the 2006–2007 data set. In addition, the full section covering GI-18 as well as 20 depth levels for each other section that were already measured back in 2006, was re-measured with the Picarro instrument in order to quantify possible offsets between the old and the newer datasets. Accuracy for new NGRIP δ¹⁸O and δD measurements using the mass spectrometry-based method is 0.07‰ and 0.5‰ for δ¹⁸O and δD, respectively, and is 0.1‰ and 1‰ for δ¹⁸O and δD, respectively, using the laser spectroscopy-based method. The water isotope records (δ¹⁸O, d-excess) have a temporal resolution of better than 1 yr at 10 ka b2k, ~3 yr at 45 ka b2k, ~4 yr at 80 ka b2k, and ~5 yr at 105 ka b2k for NGRIP and of ~1 yr at 10 ka b2k, ~4 yr at 45 ka b2k, ~7 yr at 80 ka b2k, and ~18 yr at 105 ka b2k for NEEM.
The NGRIP and NEEM high-resolution [Ca\textsuperscript{2+}] and [Na\textsuperscript{+}] records over the past 60 ka are published in ref. 38, and in our study, we present the records extended back to 621 ka by extracting data from 18 [18O] records in NGRIP and NEEM ice cores using the continuous flow analysis (CFA) system of the University of Bern allowing for an annual-to-pluri-annual temporal resolution (methodological details are presented in refs. 25,36). The effective resolution of the CFA records is between 1 and 2 cm and the relative concentration uncertainty is typically 10%. Here, we use the [Ca\textsuperscript{2+}] and [Na\textsuperscript{+}] records averaged towards a dust load (\textit{df}) from reference 38 (Supplementary Table 1). The ramp function is parametrized by the proposed noise characteristics (see ref.23). Credible parameter ranges are calculated allowing for an annual-to-pluri-annual temporal resolution (methodological details back to ~108 ka b2k (Supplementary Data 2)). They were measured on both ice cores and a 103\textsuperscript{18}O data series from continuous measurements (Supplementary Table 1). The [Ca\textsuperscript{2+}] and [Na\textsuperscript{+}] data from continuous flow analysis measurements were sampled in 1 mm resolution, but annual means were used in this analysis, whereas the more sparsely sampled isotopic data were used in their original measured resolution. No function of the shape of the distribution of the data was employed to predict noise. The distributions of impurity data are generally closer to being log-normal than normal, the more sparsely sampled isotope data were used in their original measured resolution. Further we verif...
realizations), demonstrating that despite the large scatter in durations between events and sometimes even between species, the results from the two cores show a highly coherent signal. The geomorphologic criteria and the resulting stratigraphic sequences are well preserved in the three cores, and the resulting time series are a valuable tool for investigating the variability of the North Atlantic during the last glacial period. A robust characterization of the AMOC in the NCAR CESM has been shown to require long and possibly multi-millennial-scale simulations in length.24 Therefore, the results obtained for the first set of D-O transitions (modeled events 1, 3, and 5) and the duration of the transition associated with atmospheric circulation changes in this sub-polar region of the North Atlantic. The durations of the transitions in the different modeled physical parameters seem to be slightly longer during the second transition compared with the first one (Figure 5 and Supplementary Figure 7). An explanation may lie in the length of the simulation needed to get stable statistics in a glacial climate. It is known that the AMOC may never be in a stable state and exhibit intermittency throughout an entire simulation. This is associated not only with the long timescales associated with the deep ocean to reach equilibrium but also with natural variability associated with the ocean circulation itself. A robust characterization of the AMOC in the NCAR CESM has been shown to require long and possibly multi-millennial-scale simulations in length.24 Therefore, the results obtained for the first set of D-O transitions (modeled events 1, 3, and 5) and the duration of the transition associated with atmospheric circulation changes in this sub-polar region of the North Atlantic. The durations of the transitions in the different modeled physical parameters seem to be slightly longer during the second transition compared with the first one (Figure 5 and Supplementary Figure 7). An explanation may lie in the length of the simulation needed to get stable statistics in a glacial climate. It is known that the AMOC may never be in a stable state and exhibit intermittency throughout an entire simulation. This is associated not only with the long timescales associated with the deep ocean to reach equilibrium but also with natural variability associated with the ocean circulation itself. A robust characterization of the AMOC in the NCAR CESM has been shown to require long and possibly multi-millennial-scale simulations in length.24 Therefore, the results obtained for the first set of D-O transitions (modeled events 1, 3, and 5) and the duration of the transition associated with atmospheric circulation changes in this sub-polar region of the North Atlantic. The durations of the transitions in the different modeled physical parameters seem to be slightly longer during the second transition compared with the first one (Figure 5 and Supplementary Figure 7).
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Author contributions

E.C., T.J.P., S.O.R., and J.W.C.W. designed the project. T.J.P., V.G., B.V., and B.M.V. performed the water isotopic measurements. A.G. and S.O.R. developed the ramp-fitting tool and G.V., designed, performed and analyzed the CCSM4 simulations. E.C. performed the ramp-fitting analyses on the ice-core data set, led the interpretation and discussion of the results, and wrote the manuscript with contributions from T.E., H.F., J.B.P., G.V., A. L., A.S., and S.O.R. All authors contributed to the discussion of the results and the polishing of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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