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Key Points:
- SST midlatitude North Atlantic depict abrupt warming events during MIS 12
- Pattern similar compared to D/O events seen in (synthetic) Greenland record
- Direct impact of D/O events in the midlatitude North Atlantic during MIS 12

Correspondence to:
B. D. A. Naafs,
david.naafs@bristol.ac.uk

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Dansgaard-Oeschger forcing of sea surface temperature variability in the midlatitude North Atlantic between 500 and 400 ka (MIS 12)

B. D. A. Naafs[1], J. Hefter[2], and R. Stein[2]

[1]Organic Geochemistry Unit, School of Chemistry and Cabot Institute, University of Bristol, Bristol, UK, [2]Alfred Wegener Institute for Polar and Marine Research, Department of Marine Geology and Paleontology, Bremerhaven, Germany

Abstract Using a high-resolution record of alkenone-based sea surface temperatures (SSTs) from the midlatitude North Atlantic covering the period between 500 and 400 ka here we show that during Marine Isotope Stage (MIS) 12, SSTs in this region were characterized by numerous abrupt jumps in the order of 3–6°C, spaced every 3–4 ka. We argue that these abrupt warming events in the midlatitude North Atlantic reflect Dansgaard-Oeschger (D/O) events, which are corroborated by the correlation to the synthetic record of Greenland climate for this time period. These results demonstrate that during MIS 12 the direct influence of high-latitude climate was far larger than during the last glacial and reached all the way into the midlatitude North Atlantic. In addition the consistent temporal lag between surface water cooling and appearance of ice-rafted debris demonstrates that icebergs were not the cause for cooling in the North Atlantic at this time. We hypothesize that the extreme impact of D/O events during MIS 12 as recorded in our record must have had an imprint on global climate and will therefore be important to evaluate future high-resolution climate records or model efforts that cover this time period.

1. Introduction

The last glacial was characterized by several types of abrupt/millennial-scale climate variability as recorded in marine, terrestrial, and ice core records from the Northern Hemisphere [*Dansgaard et al.*, 1982; *Heinrich*, 1988; *Bond et al.*, 1993; *Dansgaard et al.*, 1993; *Taylor et al.*, 1993; *Bond and Lotti*, 1995; *Wang et al.*, 2001; *North Greenland Ice Core Project* (*NGRIP*) *members*, 2004]. Well-dated and high-resolution Greenland ice core records, in particular, demonstrate that during the last glacial large and rapid shifts in air temperature, up to 15°C [*Huber et al.*, 2006] in a few decades [*Stuiver and Grootes*, 2000], took place over Greenland on a regular basis. Twenty-five rapid alternations between cold (stadial) and warm (interstadial) conditions in Greenland air temperature are known as Dansgaard-Oeschger (D/O) events. Although the ultimate mechanisms leading to D/O Events is not completely understood, it is assumed that they are related to variations in the Atlantic Meridional Overturning Circulation (AMOC) [e.g., *Bond et al.*, 1999]. It is likely that through feedbacks mechanisms associated to these AMOC variations, D/O events had an impact on climate around the globe [*Voelker*, 2002].

The Greenland ice core records do not extend beyond 120 ka [*NGRIP members*, 2004], and records of comparable resolution that reach beyond the last interglacial cycle are scarce. *Barker et al.* [2011] for the first time provided insights into high-frequency Greenland climate beyond the last interglacial. Using the Antarctic ice core record and assumption that Greenland temperature anomalies (D/O events) are in antiphase with the rate of change of Antarctic temperatures (the thermal seesaw model), they generated a synthetic record of Greenland climate for the last 800 ka. However, this is a synthetic record and assumes that the seesaw operated in a similar fashion during older glacials, something that is not (well) constrained by data. As a result the occurrence and global influence of millennial-scale variations in climate further back in time is not well constrained. Here we therefore use high-resolution records from the midlatitude North Atlantic to examine the presence of abrupt millennial-scale climate variability for the period between 500 and 400 ka (MIS 13-11), far beyond the extent of the Greenland ice cores. This specific time period was selected because (1) in the long-term SST record from U1313, MIS 12 stands out as the glacial with the lowest SSTs of the last 3.5 Ma [*Naafs et al.*, 2013], and (2) other climatic records from around the world show that MIS

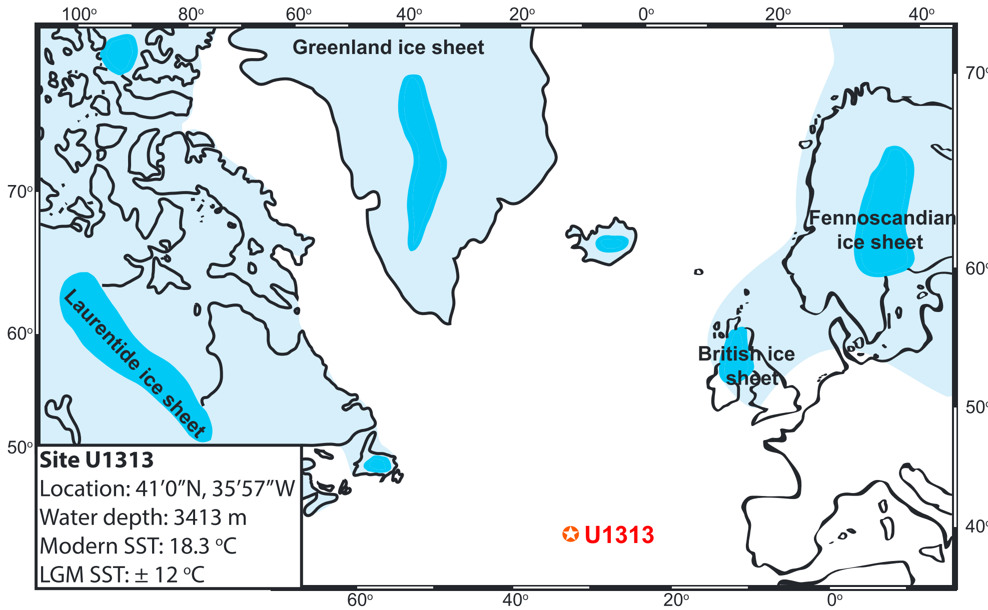

Figure 1. Location of Site U1313 within the North Atlantic. Also shown is the estimated maximum Last Glacial Maximum continental ice sheet distribution from the circum-North Atlantic.

12 was the most severe glacial of the Quaternary [*Shackleton*, 1987; *Raymo et al.*, 1990; *Rohling et al.*, 1998; *Poli et al.*, 2000; *Billups et al.*, 2006; *Bard and Rickaby*, 2009; *Lang and Wolff*, 2011; *Rohling et al.*, 2014].

2. Material and Methods

We used samples from Integrated Ocean Drilling Project (IODP) Site U1313 (Figure 1). During interglacials like the present, the midlatitude North Atlantic is influenced by the North Atlantic current (NAC) that transports warm surface waters into the higher latitudes and Site U1313 is located at the boundary between the NAC and the subtropical gyre. However, during glacials the southward migration of the Arctic Front led to much lower SSTs as the region came under the influence of the subpolar gyre and a steep SST gradient developed in the midlatitude North Atlantic [*Calvo et al.*, 2001; *Pflaumann et al.*, 2003]. Superimposed on this glacial/interglacial variability in SSTs is suborbital-scale variability, the largest of which appears to be associated with Heinrich(-like) Events [*Stein et al.*, 2009; *Naafs et al.*, 2011, 2013]. As a result, SST records from the midlatitude North Atlantic are highly sensitive recorders of climate variability.

We focus on previously published high-resolution alkenone-based SST and quartz/calcite (a proxy for ice-rafting debris (IRD) events) records from Site U1313 that cover the period between 500 and 400 ka on a temporal resolution of 370 years [*Stein et al.*, 2009; *Naafs et al.*, 2011]. We used the original age model as constructed by *Naafs et al.* [2011], which for this period is based on the simultaneous tuning of benthic foraminiferal δ^{18}O of the secondary splice from U1313 [*Voelker et al.*, 2010] to the LR04 stack [*Lisiecki and Raymo*, 2005] and lightness of the primary splice of U1313 to the carbonate content of DSDP Site 607 [*Ruddiman et al.*, 1987], which is part of the LR04 stack. At U1313 the primary and secondary splice are correlated based on physical properties (mainly lightness), and the correlation was recently updated, see *Naafs et al.* [2012]. Both the SSTs and IRD record were obtained from the same sample set, taken from the primary splice of U1313. The alkenone-based SSTs were derived using the $U^{K'}_{37}$ index and global core top calibration [*Prahl and Wakeham*, 1987; *Müller et al.*, 1998].

3. Results

The high-resolution alkenone-based SST record demonstrates that superimposed on the glacial cooling trend and subsequent deglaciation, between 500 and 400 ka, surface waters at Site U1313 experienced 14 cold periods (stadials), each followed by abrupt warming events leading into warm (interstadial) conditions (Figure 3b). During these rapid warming events, which based on our model are spaced every 3–4 ka, SSTs

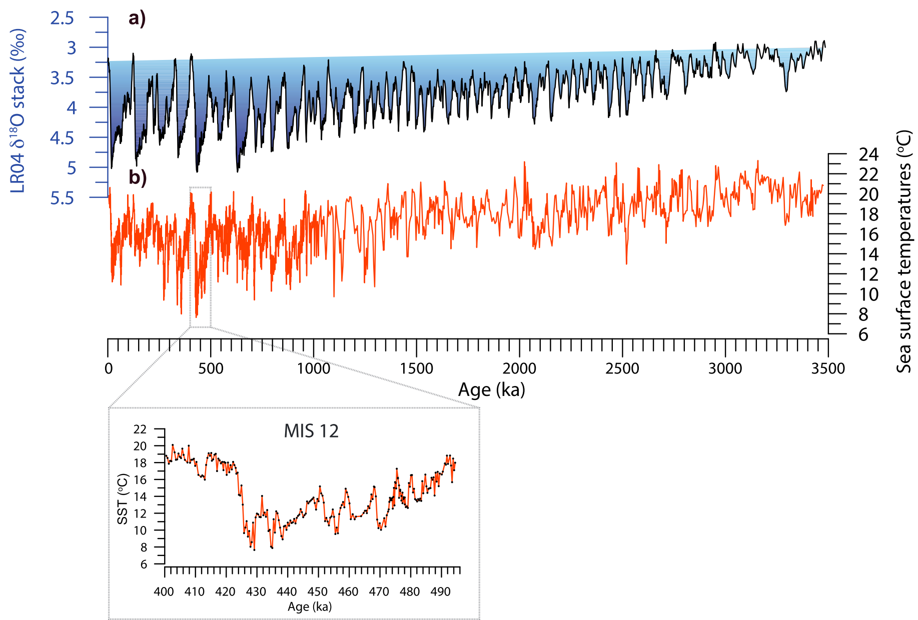

Figure 2. Long-term alkenone-based SSTs at Site U1313 over the last 3.5 Ma [*Naafs et al.*, 2013, and references therein] together with LR04 benthic oxygen isotope stack [*Lisiecki and Raymo*, 2005].

increased around 3–6°C, more than half of the deglacial warming across termination V. The latter part of interglacial MIS 13 has one of such stadial/interstadial oscillations (13.1) and glacial MIS 12 has 13 (12.1–12.14). The quartz/calcite record (Figure 3c) shows that ice-rafting debris (IRD), and thus icebergs, reached the study site roughly between 480 and 420 ka when benthic foraminiferal δ^{18}O crossed the threshold of 4.14‰ [*McManus et al.*, 1999] (Figure 3a). The highest amount of IRD was deposited between 464–446 and 440–424 ka. The latter period coincides with two North Atlantic Hudson Strait Heinrich(-like) events [*Stein et al.*, 2009; *Naafs et al.*, 2013].

4. Discussion

4.1. Nature Millennial-Scale Climate Variability

Each of the stadial/interstadial oscillations identified in the SST record from Site U1313 between 500 and 400 ka starts with an abrupt warming, followed by a period of more gradual cooling. This pattern is similar to that of the D/O events documented in Greenland ice core records [*Ganopolski and Rahmstorf*, 2001]. In addition, our SST record bears striking resemblance to the recently generated synthetic record of high-frequency Greenland climate variability (GL_t_syn_hi) [*Barker et al.*, 2011]. In the synthetic record of Greenland climate a total of 13 D/O events were identified during MIS 12 [*Barker et al.*, 2011] (Figures 3e and 3f), although the presence of one additional D/O event was recently suggested [*Lambert et al.*, 2012], indicated by a grey triangle in Figure 3. In order to better compare the synthetic record of high-frequency Greenland climate variability (GL_t_syn_hi) with SSTs at Site U1313, a similar high-frequency variability record of the SSTs at Site U1313 ($U1313_{SST}$_hi) was constructed. For this purpose, the orbital variability in the SST record was removed by subtracting the 7 ka smoothed record, the same approach as that used to generate the synthetic record of Greenland climate [*Barker et al.*, 2011] (Figure 3d). The results are almost identical when a Gaussian filter (centered at 0.3 ± 0.15 ka^{-1}) is applied to the SST data.

Although small differences in timing (1–4 ka) exist due to uncertainties associated to the different age models, every abrupt warming event at Site U1313 during MIS 12 appears to correspond to a D/O event in the synthetic Greenland climate record (compare Figures 3d and 3e). It is important to mention that this is not a result inherent to the generation of the $U1313_{SST}$_hi as each D/O event can be identified in the unfiltered SST record (Figure 3b). Based on the similarity in pattern with D/O events of the last glacial and correlation with the synthetic record of Greenland climate, we interpret the abrupt warming events at site U1313 between 500 and 400 ka to reflect the direct imprint of D/O events during this time period.

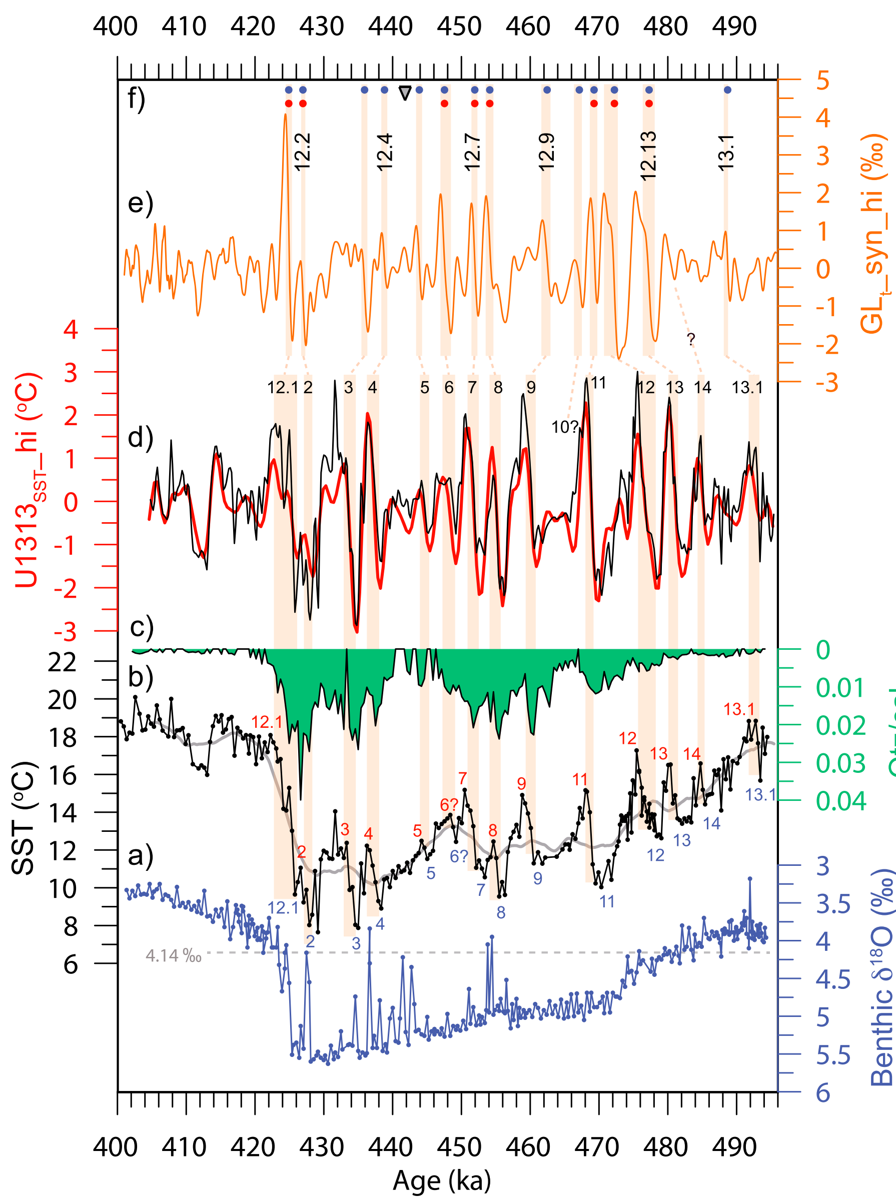

Figure 3. (a) Benthic foraminiferal $\delta^{18}O$ from the secondary splice of Site U1313 [*Voelker et al.*, 2010], (b) alkenone-based SST record from the primary splice of Site U1313 [*Stein et al.*, 2009; *Naafs et al.*, 2011] and 7 ka moving average (grey) with numbering indicating stadial (blue) and interstadial (red) conditions, (c) quartz/calcite record from the primary splice of Site U1313 [*Stein et al.*, 2009; *Naafs et al.*, 2011], (d) high-frequency variability in the alkenone-based SST record obtained by subtraction of the 7 ka smoothed record (black) and Gaussian filter (red) with numbering corresponding to rapid warming events, (e) synthetic record of high-frequency climate variability over Greenland [*Barker et al.*, 2011], and (f) the identified D/O events in the Greenland record with a fixed (red) and variable threshold to take into account the poorer resolution of the ice core record further back in time (blue) [*Barker et al.*, 2011]. The timing of the recently suggested minor extra D/O event [*Lambert et al.*, 2012] is indicated by the gray triangle. Orange bars highlight rapid warming events in the midlatitude North Atlantic (Figures 3b and 3d) and over Greenland (Figures 3e and 3f).

These results for the first time demonstrate that the D/O events during MIS 12, and thus high-latitude climate, directly influenced surface water characteristics (SSTs) in the midlatitude (40°N) North Atlantic. This is surprising as during the last glacial SSTs in the midlatitude North Atlantic were decoupled from D/O events [*Bond and Lotti*, 1995] and D/O events influenced SSTs only in the northern North Atlantic [*van Kreveld et al.*, 2000]. The long-term alkenone-based SST record also demonstrates that similar millennial-scale variability in SSTs was absent at Site U1313 during other glacials [*Stein et al.*, 2009; *Naafs et al.*, 2011, 2013]. This indicates

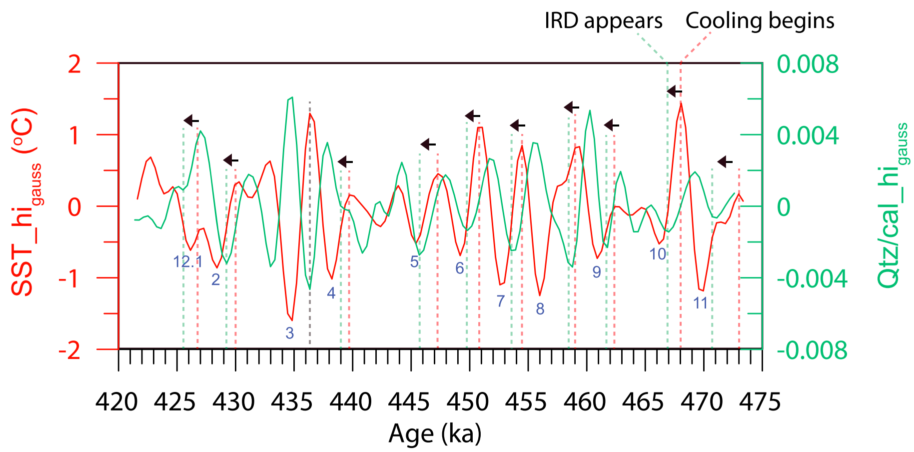

Figure 4. High-frequency alkenone-based SST record together with the high-frequency quartz/calcite record (green) from U1313, indicative for ice-rafting events (obtained using a Gaussian filter). Red-dashed lines indicate the onset of cooling at Site U1313 and green-dashed lines the onset of ice rafting events. Blue numbers indicate stadials. Besides stadial 12.3, cooling always started before the onset of ice-rafting in the midlatitude North Atlantic (U1313).

that MIS 12 marks an extreme glacial during which the direct influence of high-latitude millennial-scale climate reached into the midlatitudes, most likely through an extreme southward migration of the Arctic Front. This is supported by the long-term SST record from Site U1313 that depicts the lowest SSTs (Figure 2), and thus highest influence of polar waters, of the last 3.4 Ma during MIS 12 [*Naafs et al.*, 2012, 2013]. During the last glacial, SSTs at Site U1313 never decreased below ±12°C, while during MIS 12 they got as low as 8°C. At present, waters with annual SSTs of 8°C are found around Iceland and Norway. In addition, other climatic records from around the world show that MIS 12 was the most severe glacial of the Quaternary, characterized by large frontal shifts and the largest reduction in North Atlantic deep water influence at our study site [*Shackleton*, 1987; *Raymo et al.*, 1990; *Rohling et al.*, 1998; *Poli et al.*, 2000; *Billups et al.*, 2006; *Bard and Rickaby*, 2009; *Lang and Wolff*, 2011; *Rohling et al.*, 2014].

4.2. Correlation Stadials and IRD Events

For the last glacial, D/O events coincide with ice-rafting events in the northern North Atlantic [*Bond and Lotti*, 1995; *Bond et al.*, 1997; *van Kreveld et al.*, 2000]. To investigate the relationship between D/O events and ice-rafting events in the midlatitude North Atlantic during MIS 12, the quartz/calcite and SST records were compared. Importantly, these proxy data sets were generated on the same samples, allowing us to compare directly the phasing of rates of change between them in a manner that is independent of the age model applied. For this purpose we applied a Gaussian filter (centered at $0.3 \pm 0.15\ \text{ka}^{-1}$) to the SST and quartz/calcite records to construct a high-frequency record. Quartz/calcite is a general IRD proxy and at Site U1313 indicates the presence of IRD originating from circum-Atlantic ice sheets [*Stein et al.*, 2009; *Naafs et al.*, 2011].

For the period 475 and 420 ka when ice-rafting events influenced the study site, each stadial (low SSTs) coincides with an ice-rafting event as shown by increase in quartz/calcite (Figures 3c and 4). However, for all but one stadial (12.3) the onset of ice-rafting consistently lags the onset of cooling (1–2 ka or 4–8 cm in the depth domain) and hence the start of stadial conditions (Figure 4). Similar temporal offsets have been identified in the northern North Atlantic during the last glacial [*Bond and Lotti*, 1995; *van Kreveld et al.*, 2000] and indicate that icebergs did not cause the cooling in the North Atlantic during the D/O events of the middle Pleistocene. For the last glacial, modeling studies suggest that the offset reflects the time needed to increase subsurface ocean temperatures in the northern North Atlantic, due to a breakdown in ocean convection (AMOC), which subsequently triggered the circum-Atlantic ice sheets to surge [*Shaffer et al.*, 2004]. Such buildup of warm subsurface waters in the northern North Atlantic during stadials is supported by paleoproxy records from the North Atlantic and Nordic Seas [*Rasmussen and Thomsen*, 2004].

Following this concept, the temporal offset between the onset of stadial conditions and ice surges as observed at Site U1313 throughout MIS 12 leads us to speculate that during this time period a similar mechanism was operating, being responsible for the D/O variability observed in other records during MIS 12

[*Oppo et al.*, 1998; *Poli et al.*, 2000]. In this context it is interesting that dolomite, indicative for Hudson Strait Heinrich(-like) Events originating from the Laurentide ice sheet (LIS), is only abundant during the last three stadials of MIS 12 when SSTs were the lowest [*Stein et al.*, 2009; *Naafs et al.*, 2011, 2013]. This suggests that during the majority of MIS 12 the LIS was not sensitive to the subsurface warming that presumably triggered ice surges from the other circum-Atlantic ice sheets, analogues to the last glacial when only six stadials coincided with Heinrich Events [*Bond et al.*, 1993].

5. Conclusions

Identification of abrupt sea surface warming events in the midlatitude North Atlantic between 500 and 400 ka sheds new light onto the occurrence and extent of millennial-scale climate variability during the Quaternary. We suggest that the abrupt warming events reflect the imprint of D/O events, which influence thus extended all the way into the midlatitude North Atlantic during MIS 12. This is supported by the correlation between the SST record and synthetic record of high-frequency climate variability over Greenland. During full glacial conditions, each stadial preceding a D/O event is characterized by an ice-rafting event, reflecting surges from the circum-Atlantic ice sheets. The temporal offset between the start of stadial conditions (cooling) and onset of ice-rafting suggests that these millennial-scale ice rafting events were triggered by subsurface ocean warming due to perturbation in AMOC, in analog to the processes of the last glacial. Importantly this also demonstrates that the icebergs are not the trigger for the observed decrease in SSTs during these events. To date other high-resolution records documenting the influence of D/O events for the period between 500 and 400 are scarce, and the extent of individual ice sheets during this time period is poorly constrained. Our record provides a clear test for future high-resolution climate records and modeling efforts that cover this time period as the extreme extent of the influence of D/O events during MIS 12 must have had a clear imprint on climate around the world.

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