Warming of surface waters in the mid-latitude North Atlantic during Heinrich events

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[1] During the six Heinrich events of the last 70 kyr, episodic calving from the circum-Atlantic ice sheets released large numbers of icebergs into the North Atlantic. These icebergs and associated meltwater flux are hypothesized to have led to a shutdown of Atlantic Meridional Overturning Circulation and severe cooling in large parts of the Northern Hemisphere. However, due to the limited availability of high-resolution records, the magnitude of sea surface temperature (SST) changes related to the impact of Heinrich events on the midlatitude North Atlantic is poorly constrained. Here we present a record of $U^{K}_{37}\prime$-based SSTs derived from sediments of Integrated Ocean Drilling Project Site U1313, located at the southern end of the ice-rafted debris (IRD) belt in the midlatitude North Atlantic (41°N). We demonstrate that all six Heinrich events are associated with a rapid warming of surface waters by 2–4°C in a few thousand years. The presence of IRD leaves no doubt about the simultaneous timing and correlation between rapid surface water warming and Heinrich events. We argue that this warming in the midlatitude North Atlantic is related to a northward expansion of the subtropical gyre during Heinrich events. As a wide range of studies demonstrated that in the central IRD belt Heinrich events are associated with low SSTs, these results thus identify an antiphased (seesaw) pattern in SSTs during Heinrich events between the midlatitude (warm) and northern North Atlantic (cold). This highlights the complex response of surface water characteristics in the North Atlantic to Heinrich events that is poorly reproduced by freshwater hosing experiments and challenges the widely accepted view that, within the IRD belt of the North Atlantic, Heinrich events coincide with periods of low SSTs.

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1. Introduction

[2] Sediment cores recovered from the North Atlantic, roughly between 40 and 55°N, demonstrated that between 70 and 14 kyr ago six layers rich in ice-rafted debris (IRD) were deposited during so-called Heinrich events [e.g., *Heinrich*, 1988; *Bond et al*., 1992; *Broecker et al*., 1992; *Hemming*, 2004]. Besides the high abundance of IRD, these layers are also characterized by the low abundance of foraminifera and dominance of the polar planktonic foraminifera *N. pachyderma (s.)* [e.g., *Heinrich*, 1988; *Bond et al*., 1992, 1993]. Based on the provenance and distribution pattern of the IRD, which indicate a dominant source in the Hudson area in northern Canada, Heinrich events are related to major surges of the Laurentide ice sheet that covered large parts of North America during the glacials of the Pleistocene [e.g., *Broecker et al*., 1992; *Hemming*, 2004]. Far field sea-level estimates suggest a rise of up to 15 m during Heinrich events due to massive ice surges from the Laurentide ice sheet [*Yokoyama et al*., 2001; *Chappell*, 2002]. The Heinrich events thus form one of the most dramatic examples of millennial-scale climate variability and have been a major research focus for the paleoceanographic community over the past two decades.

[3] Based on the high abundance of the polar planktonic foraminifera *N. pachyderma (s.)* in Heinrich layers, the general consensus is that the North Atlantic cooled during Heinrich events as polar waters invaded the North Atlantic [e.g., *Heinrich*, 1988; *Bond et al*., 1992]. The observation that the pattern of *N. pachyderma (s.)* abundance in the North Atlantic is tightly linked to minima in Greenland air temperature, all six Heinrich events occurred within the longest and coldest Greenland stadials (Heinrich stadials) at the end of so-called Bond cycles, suggests cooling over large regions of the Northern Hemisphere during Heinrich events [*Bond et al*., 1993]. In addition, several records from within the IRD belt, the Iberian and Portuguese margin, and all the way into the Mediterranean demonstrated that Heinrich events coincide with low SSTs (see Figure 1). However, modeling studies suggest a complex pattern of

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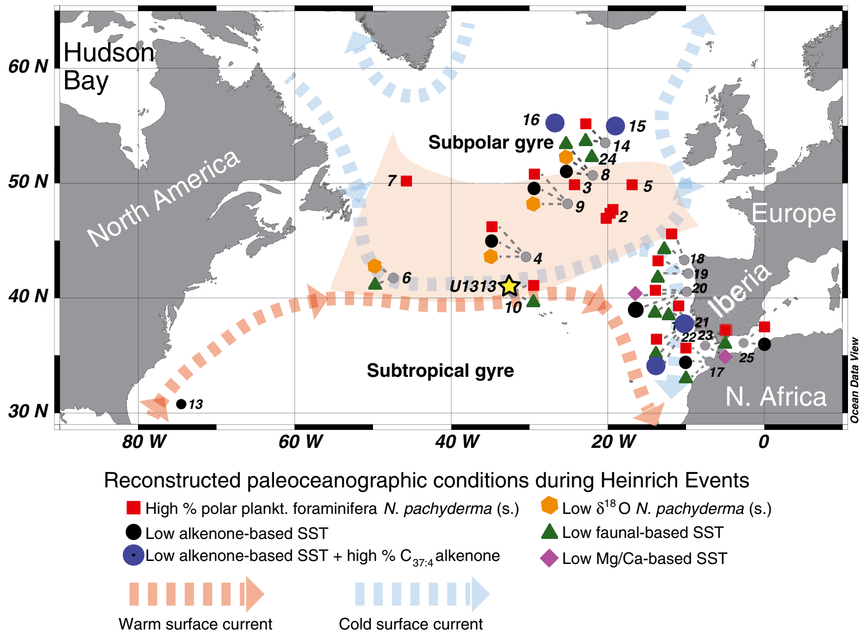

Figure 1. Overview of studies from the North Atlantic that reported variations in surface water conditions during Heinrich events. When multiple proxies are reported for the same sediment core, the core location is indicated with a gray dot, and the proxies linked by gray dotted lines to the core location. A high percentage of the polar planktonic foraminifera *N. Pachyderma (s.)* indicates the influence of polar waters and hence low SSTs. A high relative abundance of the tetraunsaturated alkenones is indicative for freshwater input and influence of polar waters. Low δ^{18}O values in the polar planktonic foraminifera *N. Pachyderma (s.)* also indicate a freshwater input. Orange area indicates the location of the IRD belt [*Ruddiman*, 1977]. Interrupted red and blue lines represent the approximate location of warm and cold surface currents during the last glacial. Core locations: (1) SU8118 [*Bard et al.*, 2000], (2) area Dreizack Seamount [*Heinrich*, 1988], (3) DSDP 609 [*Bond et al.*, 1992, 1993; *Broecker et al.*, 1992], (4) SU9008 [*Grousset et al.*, 1993; *Cortijo et al.*, 1997; *Villanueva et al.*, 1998], (5) VM23-81 [*Bond et al.*, 1993], (6) CH69-K09 [*Labeyrie et al.*, 1999], (7) HU91-045-094P [*Hillaire-Marcel et al.*, 1994], (8) BOFS-5K [*Maslin et al.*, 1995; *Rosell-Melé et al.*, 1997], (9) T88-9P [*Madureira et al.*, 1997], (10) SU90-03 [*Chapman et al.*, 2000], (11) ODP 658C (not shown) [*Zhao et al.*, 1995], (12) 31K (not shown) [*Zhao et al.*, 1995], (13) ODP 1060 [*López-Martínez et al.*, 2006], (14) M23414 [*Kandiano et al.*, 2004], (15) M23415 [*Rosell-Melé et al.*, 2002], (16) M17049 [*Rosell-Melé et al.*, 2002], (17) MD04-2805 [*Penaud et al.*, 2010] Cores 18 to 23 are from the Iberian and Portuguese Margin—see overview in *Patton et al.* [2011] and *Voelker and de Abrue* [2011], (18) SU92-03, (19) MD99-2331, (20) MD95-2040, (21) MD95-2041, (22) MD01-2444, (23) MD99-2339, (24) BOFS-8K [*Maslin et al.*, 1995], (25) MD95-2043 [*Cacho et al.*, 1999]. This study uses samples from IODP Site U1313 (indicated with a star).

SSTs may appear in response to changes in the strength of the subtropical and subpolar gyres during Heinrich events, especially in the midlatitude North Atlantic [e.g., *Manabe and Stouffer*, 1999; *Renold et al.*, 2010]. Moreover, records from the Iberian and Portuguese margin, such as the widely cited alkenone-based SST record from core SU-8118 [*Bard et al.*, 2000], depict variations in the amount of cold surface waters transported by the eastern boundary current and are not representative for the midlatitude North Atlantic [*Chapman et al.*, 2000; *Stouffer et al.*, 2006; *Stocker et al.*, 2007; *Renold et al.*, 2010].

[4] The response of SSTs in the midlatitude North Atlantic to Heinrich events is thus poorly constrained. The extent of the climatic impact of Heinrich events on North Atlantic surface water characteristics (surface water freshening and cooling) controls the response of the Atlantic Meridional Overturning Circulation (AMOC) [e.g., *Stouffer et al.*, 2006; *Oka et al.*, 2012], which is thought to be the crucial feedback mechanism that influences global climate [e.g., *Sigman et al.*, 2007]. *Carlson et al.* [2008] provided evidence for the buildup of warm and salty surface waters in the subtropical North Atlantic during Heinrich events, which allowed for an early AMOC resumption. However, whether this buildup was restricted to the subtropical North Atlantic or reached into the midlatitude North Atlantic is not known. Furthermore, a recent compilation of 11 freshwater hosing experiments demonstrated that the response of SSTs in the midlatitude North Atlantic to a freshwater input is heavily model dependent [*Kageyama et al.*, 2012]. In addition, this modeling study showed that variations in temperature of the North Atlantic (40–60°N) had a dominant control on precipitation changes over Europe. Thus SSTs in the midlatitude North Atlantic are an important climatic factor, and it is therefore crucial to accurately determine the latitudinal extent of sea surface cooling in the North Atlantic during Heinrich events. Here we report a new high-resolution alkenone-based SST record

from IODP Site U1313 covering the last 70 kyr and examine the response of surface waters in the midlatitude North Atlantic to the six Heinrich events.

2. Regional Settings

[5] Integrated Ocean Drilling Project (IODP) Expedition 306 Site U1313 (latitude 41°00′N, longitude 32°57′W) is a redrill of Deep Sea Drilling Project (DSDP) Expedition 94 Site 607 and is located at the southern boundary of the IRD belt [*Ruddiman*, 1977]. At present, Site U1313 is located at the northern margin of the subtropical gyre and is predominantly influenced by the warm and oligotrophic surface waters of the North Atlantic Current. The present-day mean annual SST at Site U1313 is 18.3°C [*Locarnini et al.*, 2006]. During glacials, however, the surface water circulation in the North Atlantic was significantly different as the Arctic front (AF) was located further south, leading to lower SSTs and a steep SST gradient in the midlatitude North Atlantic [*Pflaumann et al.*, 2003]. Previous work already demonstrated that within the upper meters of Site U1313 several IRD-rich layers can be found that correlate to the Heinrich events [*Naafs et al.*, 2011].

3. Chronology

[6] The timing of the Heinrich events in the North Atlantic has accurately been determined by radiocarbon dating (H2 and H1) and correlation to the superior-dated Greenland ice core records [e.g., *Bond et al.*, 1992, 1993; *Hemming*, 2004] and, within dating limitations, is synchronous across the IRD belt. The occurrence of the Heinrich events can thus be used as stratigraphic correlation tool within the IRD belt of the North Atlantic [e.g., *Heinrich*, 1988; *Grousset et al.*, 1993; *Hemming*, 2004]. For this study, the X-ray diffraction (XRD) record from IODP Site U1313 was correlated to the well-dated X-ray fluorescence (XRF) record from IODP Site U1308 [*Hodell et al.*, 2008] to generate a high-resolution age model for IODP Site U1313. IODP Site U1308 is a redrill of DSDP Site 609, which forms one of the benchmark sites for studies of Heinrich events [e.g., *Bond et al.*, 1992; *Broecker et al.*, 1992; *Bond and Lotti*, 1995; *Hemming*, 2004] and was crucial for the recognition of the correlation between IRD events and cooling episodes in the North Atlantic and cooling events over the Greenland ice sheet during the last glacial [*Bond et al.*, 1993; *Bond and Lotti*, 1995]. The age model for Site U1308 is based on the correlation of benthic foraminiferal $\delta^{18}O$ to the LR04 reference stack, augmented by radiocarbon dates, transferred from DSDP Site 609 for the upper 35 kyr, and the correlation of benthic foraminiferal $\delta^{18}O$ between Site U1308 and MD95-2042 from 60 to 35 ka (for more details, see *Hodell et al.* [2008]).

[7] The Si/Sr and Ca/Sr records at Site U1308 obtained using XRF scanning trace the abundance of detrital quartz and carbonate grains, respectively [*Hodell et al.*, 2008]. The four Hudson Strait Heinrich events are marked by high Ca/Sr ratios, while Heinrich events 6 and 3 have background Ca/Sr ratios but high Si/Sr ratios [*Hodell et al.*, 2008]. The Si/Sr and Ca/Sr records from Site U1308 with tight age constrains were thus used as tuning targets for respectively the quartz/calcite and dolomite/calcite records from Site U1313 obtained using XRD. The records were tuned simultaneously using the Match 2.0 software [*Lisiecki and Lisiecki*, 2002]. Figure 2 depicts the resulting correlation between the Si/Sr and Ca/Sr records from Site 1308 and quartz/calcite

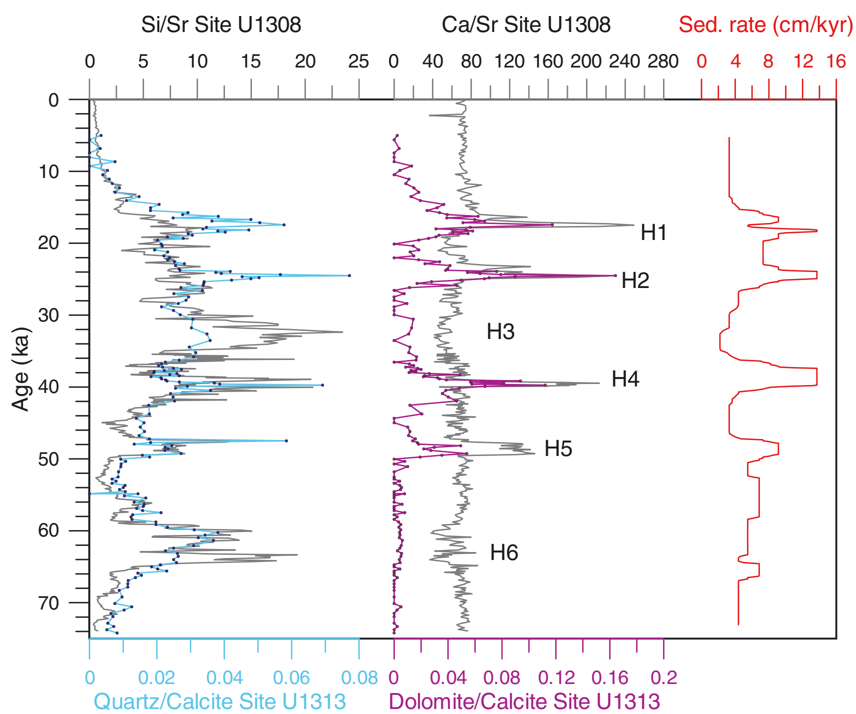

Figure 2. The chronology for Site U1313 for the upper 70 kyr that is based on the simultaneous tuning of the quartz/calcite (blue) and dolomite/calcite (purple) records to the Si/Sr and Ca/Sr records from Site U1308, which has superior age control [*Hodell et al.*, 2008]. The resulting sedimentation rates at Site U1313 are shown in red. H1–H6 indicate the six Heinrich events.

and dolomite/calcite records from Site U1313. The age model for the upper part is in broad agreement with radiocarbon dates from Site U1313 (H. Rashid et al., personal communication, 2007). Please note that the top of Hole U1313B (0 mbsf) corresponds to 0.17 m composite depth (mcd) [*Expedition 306 Scientists*, 2006], and the records thus terminate at ~5 ka. Table 1 shows the ages obtained for the six Heinrich events at IODP Site U1313, which are in agreement with the literature ages [*Hemming*, 2004].

4. Methodology and Analytical Techniques

[8] For this study, 180 samples from IODP Site U1313B (the master hole; see *Naafs et al*. [2012]) were used. The samples (10 cc) were taken at a 2 cm resolution from the upper 4 mcd, which based on our chronology (Figure 2) covers the period from 70 to 5 ka. The resulting average temporal resolution is therefore ~360 years. Samples were freeze-dried and homogenized after sampling and stored at 4°C until further processing took place. Sample aliquots were used for the organic geochemical and bulk mineralogical measurements, and the biomarker and XRD records can thus be compared directly to each other.

[9] Mean annual sea surface temperatures (0 m) were calculated using the modified alkenone unsaturation index ($U^{K'}_{37}$) [*Prahl and Wakeham*, 1987] and the global core-top calibration [*Müller et al*., 1998]. The $U^{K'}_{37}$ was determined using a LECO Pegasus III GC/TOF-MS system (for more details, see *Hefter* [2008] and *Naafs et al*. [2011]). A validated procedure was used to convert GC/TOF-MS C_{37} alkenone ratios to calibrated GC/FID values [*Hefter*, 2008]. Relative abundances of the tetraunsaturated C_{37} alkenone were calculated using *m/z* 79 peak areas, as this ionization fragment in relation to those used for the $C_{37:3}$ and $C_{37:2}$ alkenone (*m/z* 94, 58, respectively) gives results directly comparable with GC/FID data. The input of ancient organic material was monitored using the diagnostic *m/z* 253 ionization fragment for C-ring monoaromatic steroids [*Naafs et al*., 2011]. Downcore variations of the C_{28}S-monoaromatic steroid are expressed semiquantitatively by normalizing the respective peak areas to the maximum area per gram sediment detected. XRD measurements were used to determine the abundance of detrital quartz and dolomite at Site U1313 and thus the presence of Heinrich events [*Moros et al*., 2004]. XRD measurements were carried out at the AWI-Bremerhaven following the methods described in *Stein et al*. [2009] and *Naafs et al*. [2011]. The advantage of XRD over the traditional coarse fraction (>150 μm) counts as an indicator for ice-rafting events is that XRD allows us to distinguish different types of IRD and uses bulk sediments that also detect distal input of the finest IRD fraction.

[10] The carbonate content for the upper 4 mcd at Site U1313 was obtained at 1 cm resolution using a first-generation Avaatech X-ray fluorescence core scanner at the University of Bremen [*Röhl and Abrams*, 2000]. A 30 s count time, tube voltage of 20 KV, and an X-ray current of 0.87 mA were used to obtain statistically significant calcium (Ca) data. The Ca intensity counts obtained by XRF scanning were calibrated through linear correlation (r^2 = 0.98) with quantitative XRF analyses on 13 discrete samples to derive the absolute carbonate content (percent). The discrete measurements were performed with the energy-dispersive polarization X-ray fluorescence (EDPXRF) analyzer Spectro Xepos [*Wien et al*., 2005].

Table 1. Depth and Age of the Heinrich Events at IODP Site U1313 Compared to the Ages of Heinrich Events at Site U1308 and the Literature Ages of Heinrich Events

	Depth at Site U1313 (mcd)	Age at Site U1313 (kyr)	Age at Site U1308 (kyr)	Literature Age
H1	0.71	~17.4	~17.5	16.8
H2	1.33	~24.5	~24.6	24
H3	1.73	~32	~32	~31
H4	2.25	~39	~39	38
H5	2.73	~49	~49	45
H6	3.47	~60	~60	~60

Ages of Heinrich events at Site U1308 are from *Hodell et al*. [2008] and literature ages of Heinrich events are from *Hemming* [2004].

5. Results

[11] At Site U1313, Heinrich events 6–1 can be identified based on their high abundance of quartz and dolomite as well as ancient organic matter (Figures 2 and 3), which coincide with intervals of increased magnetic susceptibility [*Expedition 306 Scientists*, 2006]. Dolomite/calcite and ancient organic matter are at background values in Heinrich layers 6 and 3, but quartz/calcite is elevated in these layers. The $U^{K'}_{37}$-based temperature record from Site U1313 reveals large variation in surface water temperatures during the last 70 kyr (Figure 3). From 65 to 55 ka, SSTs increase across the MIS 4/3 boundary. This is followed by a general cooling trend from 55 to 20 ka that cumulated in the Last Glacial Maximum (LGM) with SST as low as 11.2°C. Superimposed on this general cooling trend are several short periods (each a few thousand years long) during which SSTs rapidly increased by 2 to 4 °C. These rapid warming events all coincide with increased input of IRD during the Heinrich events (Figure 3). The warming seems to occur in the later phase of each Heinrich event. The most drastic warming occurred during Heinrich event 1 as SSTs rapidly increased to 18°C. Following Heinrich event 1, SSTs decreased again slightly to 16.4°C at 15 ka, only to reach full interglacial temperatures of 20°C around 10.5 ka. The early Holocene is characterized by SSTs varying around a value of 19°C.

6. Discussion

6.1. Heinrich Events

[12] The records of dolomite/calcite and quartz/calcite at Site U1313 track the increased input of IRD during the Heinrich events. The presence of IRD allows for precise determination of the relative timing of changes in surface water characteristics and relationship to Heinrich events, a crucial advantage over studies from outside the IRD belt. Dolomite is widely used as proxy for IRD originating from the Hudson area and thus icebergs from the Laurentide ice sheet [*Andrews and Tedesco*, 1992; *Bond et al*., 1992]. The absence of dolomite and ancient organic matter, an additional proxy for ice-rafting events and traced by the high abundance of C_{28}(S) monoaromatic steroid, at Site U1313 during H6 and H3 confirm results from a lower-resolution study [*Naafs et al*., 2011]. These results indicate the absence of IRD originating from the Hudson area reaching the study site during H6 and H3. This finding is normal, as at a number

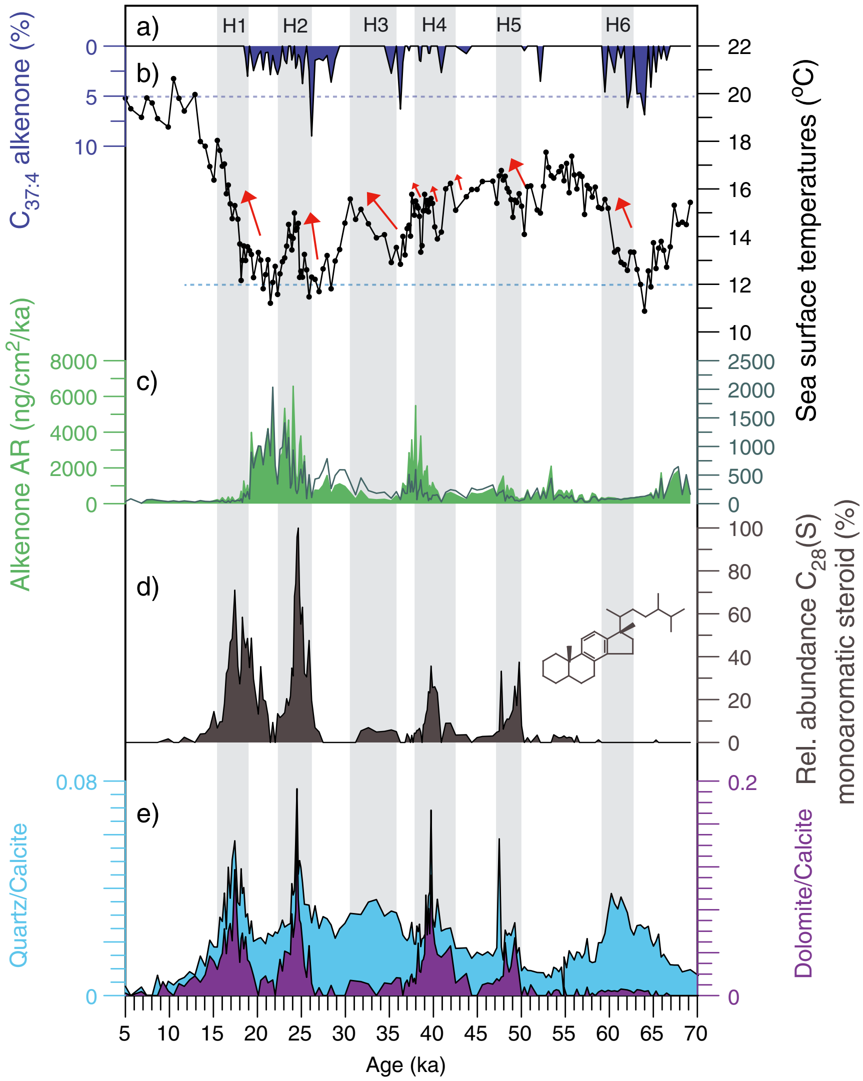

Figure 3. (a) The relative abundance of the $C_{37:4}$ alkenone; (b) $U^{K}_{37}\prime$-based SST record from Site U1313 for the period between 70 and 5 ka; (c) alkenone accumulation rates (light green filling) and concentrations in nanograms per gram (dark green line); (d) relative abundance of the C_{28}(S) monoaromatic steroid, indicative for the input of ancient organic matter during IRD events; and (e) the record of quartz/calcite (blue) and dolomite/calcite (purple) that track the occurrence of Heinrich events 6 to 1. The dotted blue lines in Figures 3a and 3b indicate the presumed threshold of 5% for $C_{37:4}$ abundances, beyond which the $U^{K}_{37}\prime$ -SST relationship breaks down [*Rosell-Melé*, 1998], and the average LGM SST (12°C) at Site U1313. Gray bars highlight Heinrich events.

of locations within the IRD belt of the North Atlantic, IRD originating from the Hudson area is absent or low in Heinrich layers 6 and 3 [e.g., *Grousset et al.*, 1993; *Gwiazda et al.*, 1996; *Hodell et al.*, 2008]. Within the eastern North Atlantic, the IRD characteristics of HL6 and HL3 indicate a larger contribution from European sources, in line with the increased abundance of quartz at Site U1313 during H6 and H3 as quartz is a proxy for IRD input from the circum-Atlantic (e.g., Greenland, Scandinavia, and/or Great Britain) [*Grousset et al.*, 2001; *Moros et al.*, 2004]. Thus Site U1313 was influenced by ice rafting during H6 and H3, although the input of IRD was lower compared to the other Heinrich events, as shown by the low sedimentation rates compared to the other Heinrich events (Figure 2), and the ice rafting most likely did not originate from the Laurentide ice sheet but from the Greenland and/or European ice sheets.

[13] Concerning the overall trend in reconstructed SSTs at U1313, the range of temperatures between 11 and 20°C during the period 70 to 5 ka fits very well with other alkenone-based SST estimates for the midlatitude North Atlantic for this time period. *Calvo et al.* [2001] published two alkenone-based SST records from Core SU90/08 (43°N) and MD95-2037 (37°N) in the North Atlantic. Site U1313 (41°N) is located directly in between these cores, and the SST record from U1313 (LGM SST ~12°C) plots right between that of the subpolar gyre (SU90/08, LGM SST ~10 °C) and the subtropical gyre (MD95-2037, LGM SST ~15.5 °C), in line with the steep SST gradient that was presented in midlatitude North Atlantic during the LGM [*Pflaumann et al.*, 2003]. The exceptions are the Heinrich events, during which SSTs at Site U1313 increase and approach those of the subtropical gyre (core MD95-2037).

6.2. Reliability of Alkenone-Based SSTs

[14] In the context of the observed increase in $U^{K}_{37}{}'$-based SSTs during Heinrich events at the study site, it is crucial to assess the reliability of $U^{K}_{37}{}'$-based SSTs in the North Atlantic. A number of potential processes are known to influence alkenone-derived temperature reconstructions in the region, in particular during the Last Glacial Maximum. In the following sections the relevant processes are therefore discussed, and based on this discussion we conclude that the $U^{K}_{37}{}'$-based SSTs are reliable and reflect genuine variations in SSTs.

6.2.1. Autochthonous Versus Allochthonous Alkenones

[15] Long-chain alkenones can be laterally advected [e.g., *Rosell-Melé et al.*, 2000; *Ohkouchi et al.*, 2002]. Large variations in alkenone production at the study site could therefore change the percentage of autochthonous (produced in the overlying surface waters) versus allochthonous alkenones (transported from elsewhere), leading to anomalous alkenone-based SSTs. To assess the influence of variations in alkenone content on the alkenone-based SSTs, we determined the concentration and accumulation rate (AR) of the diunsaturated and triunsaturated C_{37} alkenone at Site U1313 over the last 70 kyr.

[16] Overall the trends in the alkenone concentrations are very similar to those in the alkenone ARs (Figure 3). The only exception is the later part of H4, when alkenone concentrations remain low, but alkenone ARs increase. Because of the similarity, in the following section we discuss the variations in alkenone AR only. For almost every Heinrich event the alkenone AR is low (typically below 1000 ng/cm^2/kyr). Elevated alkenone ARs are limited to the periods around 40 ka and between 25 and 19 ka, including H4 and H2 (Figure 3). During H2 the increase in SSTs coincides with an increase in alkenone ARs. During the latter part of MIS 4 as well as MIS 3, alkenone ARs are often as low outside, as within Heinrich layers. Alkenone ARs during H1 are as low as during the last 15 kyr. As such, there is no correlation between alkenone ARs and an increase in alkenone-based SSTs during Heinrich events. Therefore it is unlikely that variations in the percentage of autochthonous versus allochthonous alkenones can explain the warming during Heinrich events. This is also supported by previously published results from Site U1313 that show that alkenone concentrations were similarly low during Heinrich(-like) events of previous glacials but opposite to those of the last glacial, alkenone-based SSTs were low during these ice-rafting events [*Stein et al.*, 2009].

6.2.2. $U^{K}_{37}{}'$ and Correlation to SST

[17] Another potential issue is the suggestion that the modified alkenone unsaturation index ($U^{K}_{37}{}'$) used in this study is not a reliable paleothermometer (resulting in too high SSTs) in the North Atlantic. For example, it has been suggested that in the North Atlantic when the relative abundance of tetraunsaturated C_{37} alkenone ($C_{37:4}$) is higher than 5%, $U^{K}_{37}{}'$ is not a reliable paleothermometer [*Rosell-Melé*, 1998; *Calvo et al.*, 2002). Similarly, *Bendle and Rosell-Melé* [2004] suggested that in the polar waters of the northern North Atlantic the relationship between $U^{K}_{37}{}'$ and SSTs breaks down. For the lower-temperature range (below 8°C) they suggest it might be better to use the original alkenone unsaturation index (U^{K}_{37}) [*Brassell et al.*, 1986], which includes the tetraunsaturated C_{37} alkenone ($C_{37:4}$). According to this work, the breakdown of the relationship between $U^{K}_{37}{}'$ and SST at the lower temperatures leads to a bias toward higher temperatures in marine core-top sediment samples from the polar waters on the Greenland shelf and north of Iceland. Based on these studies, if polar waters shifted south during Heinrich events to influence Site U1313, the $U^{K}_{37}{}'$-based SSTs could potentially show a bias toward high SSTs during Heinrich events.

[18] However, at Site U1313 the abundance of the $C_{37:4}$ is almost always below 5% and the $C_{37:4}$ are absent across the increase in $U^{K}_{37}{}'$-based SSTs during Heinrich events (Figure 3). The $C_{37:4}$ abundances are below the suggested 5% threshold, for which $U^{K}_{37}{}'$ is not considered a reliable paleothermometer [*Rosell-Melé*, 1998; *Calvo et al.*, 2002]. In addition, the low $C_{37:4}$ abundances argue against the influence of polar waters at Site U1313 and indicate the continuous influence of Atlantic waters [*Rosell-Melé et al.*, 1998]. Atlantic waters are characterized by low $C_{37:4}$ abundances (<5%), while values are much higher in polar waters (40–77%) and Arctic and Norwegian coastal waters (0–28%) [*Rosell-Melé et al.*, 1998; *Bendle et al.*, 2005].

[19] Moreover, $U^{K}_{37}{}'$-based temperatures at Site U1313 vary between 20 and 11°C during the last 70 kyr (Figure 3). The lowest SSTs of 10.9°C are reached at 64 ka. LGM SSTs are ~12 °C. This is well above the 8°C suggested as the threshold for the breakdown of the relationship between $U^{K}_{37}{}'$ and SST [*Bendle and Rosell-Melé*, 2004]. Even so, if during Heinrich events Site U1313 became influenced by polar waters, in which the $U^{K}_{37}{}'$ index is biased toward higher temperatures, the shift from glacial midlatitude waters outside Heinrich events (e.g., LGM SSTs at Site U1313 are ~12°C, in accordance with other studies [*Calvo et al.*, 2001]) to polar waters (today annual mean SSTs in subpolar waters are below 10°C and likely lower during the LGM) would still lead to a relative cooling of surface waters at Site U1313, as polar waters are colder than the potential warm bias of the $U^{K}_{37}{}'$.

[20] Last, if the modified alkenone unsaturation index ($U^{K}_{37}{}'$) is not a reliable paleothermometer during Heinrich events and the warm bias in polar waters causes the observed increase in SSTs, a similar temporal evolution should occur during Heinrich(-like) events of older glacials. However, data from U1313 for older glacials demonstrate that the Heinrich(-like) events (as well as regular IRD events during previous glacials) are always associated with the lowest $U^{K}_{37}{}'$-based SSTs [*Stein et al.*, 2009; *Naafs et al.*, 2011]. Based on these results, the obtained $U^{K}_{37}{}'$-based SSTs at Site U13131 are reliable and not biased toward warm temperatures due to the influence of polar waters.

6.2.3. Bioturbation

[21] Because of bioturbation, alkenones from outside Heinrich layers could be mixed into these layers, which are typically characterized by low-alkenone ARs. However, it is unlikely that bioturbation can explain the observed warming of surface waters during Heinrich events as the reconstructed SSTs are lower outside the Heinrich layers. The transfer of alkenones from outside the Heinrich layers by bioturbation would thus lead to lower SSTs and not higher, as we found. The only exception could be H1, which was followed by the Holocene during which SSTs were obviously high. However, also H1 was followed by a brief return to lower SSTs. In

addition, alkenone concentrations during the Holocene are as low as during H1 (see Figure 3), making it unlikely that bioturbation led to a significant transfer of "warm" alkenones into H1.

6.2.4. Input of Old and Reworked Alkenones

[22] *Weaver et al.* [1999] suggested that input of Cretaceous and Paleogene nannofossils can lead to too high alkenone-based SSTs that deviate from faunal-based SST estimates during ice-rafting events in the northern North Atlantic. However, the organic matter signature of Heinrich layers suggests the input of ancient organic matter with an Ordovician/Silurian age [*Rashid and Grosjean*, 2006], while the first appearance of alkenones in the sedimentary record is during the Early Cretaceous [*Brassell and Dumitrescu*, 2004]. In addition, *Rosell-Melé et al.* [2011] demonstrated that the input of reworked alkenones by IRD in the North Atlantic does not necessarily lead to higher alkenone-based SSTs in marine sediments. Finally, during older glacials, ice-rafting events at Site U1313 are always accompanied by abrupt cooling episodes [*Stein et al.*, 2009; *Naafs et al.*, 2011]. Based on

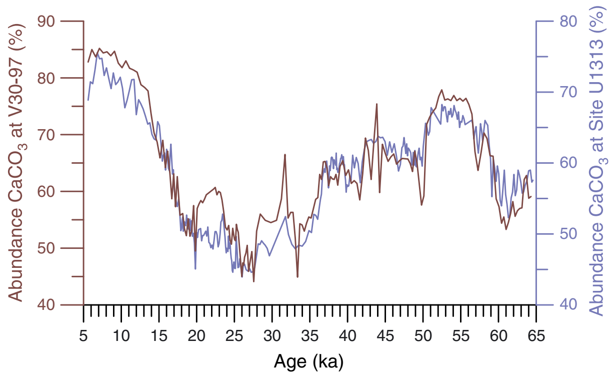

Figure 4. Tuning of carbonate record of core V30-97 (brown) to that from Site U1313 (blue) for the last 65 kyr.

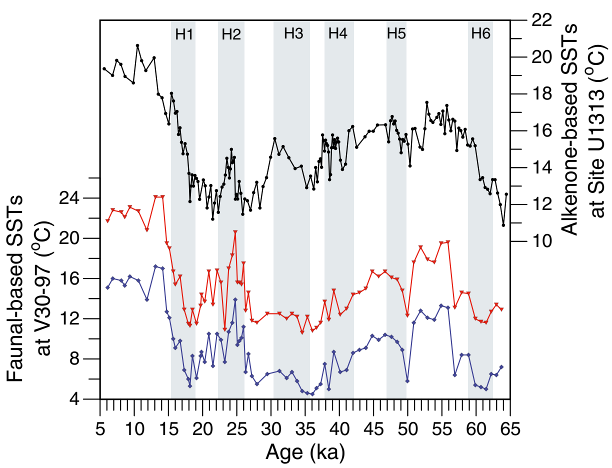

Figure 5. The alkenone-based SST record from Site U1313 (black) together with the summer (red) and winter (blue) SSTs based on census counts of planktonic foraminifera in core V30-97 [*Ruddiman et al.*, 1989], plotted on their common age model. Gray bars highlight periods of increased IRD input (Heinrich events) based on the increased abundance of quartz and dolomite (Figure 3).

these arguments, we believe that the $U^{K}_{37}{}'$-based temperatures we obtained are correct and reflect genuine variations in SSTs at Site U1313.

6.3. Other Evidence for Sea Surface Warming in the Midlatitude North Atlantic During Heinrich Events

[23] Additional proxy evidence for a warming of surface waters during Heinrich events in the midlatitude North Atlantic comes from Vema (V) core 30–97 (41°00'N; 32°56'W, 3371 m water depth). This core was taken in the 1970s, and the location was later drilled during DSDP Leg 94 (Site 607). V30-97 constitutes the upper 9 m (~250 ka) of DSDP Site 607 [*Ruddiman et al.*, 1987], of which U1313 again is a redrill. Crucially, for core V30-97, a record of summer and winter SSTs based on census counts of planktonic foraminifer is available [*Ruddiman and McIntyre*, 1981; *Ruddiman et al.*, 1987, 1989]. The original age model of V30-97 appears incorrect as the radiocarbon ages, obtained from bulk material, and used for the chronology are affected by the increase in total carbonate content during the deglaciation [*Chapman et al.*, 2000]. Unfortunately, no records of magnetic susceptibility or IRD counts are available for core V30-97 and after more than three decades of research, the core is depleted. Thus the position of the Heinrich layers could not be used as tie points. Also the visual inspection of the original black and white core photographs of core V30-97 did not reveal the presence of Heinrich events. In order to directly compare the faunal-based SST from V30-97 with the alkenone-based SSTs at Site U1313, the chronology of V30-97 was tuned to the chronology of Site U1313 (Figure 4). For this purpose we used the carbonate content of core V30-97 [*Ruddiman et al.*, 1987] and Site U1313 (Figure 4). Sediment cores from the North Atlantic covering the Pleistocene are characterized by large variations in carbonate content due to an increase in terrestrial sediment flux during glacials [*McManus et al.*, 1998].

[24] Although there are slight temporal offsets between the faunal- and alkenone-based SSTs records obtained from two different sediment cores, the faunal-based SSTs from V30-97 do show brief warming periods (in both the summer and winter SSTs) that coincide with the warming of surface waters during Heinrich events as seen in the alkenone-based SSTs at Site U1313 (Figure 5). This is the most clear for H5, H2, and H1. Evidence for a warming of faunal-based SSTs during Heinrich events in core V30-97 was previously suggested in a conference abstract [*Bond et al.*, 1999], but so far never published. Taken together, these results indicate that the warming in our alkenone-based record is not a proxy-specific result as the faunal-based SSTs are based on a completely independent method.

[25] The only other SST record from the southern boundary of the IRD belt comes from core SU90-03, located just south of Site U1313 at 40°30'N; 32°03'W [*Chapman et al.*, 2000]. Overall the alkenone-based SST reconstruction from Site U1313 agrees very well with the faunal-based summer and winter SST reconstructions from core SU90-03. Most importantly, the warming of surface waters during the some of the Heinrich events, at Site 90-03 identified based on the high abundance of IRD, is also found in the faunal-based SST record from this core. The warming is the most obvious during H3 and H2 when the polar planktonic foraminifera *N. pachyderma (s.)* is almost absent in core SU90-03.

However, opposite to the results from Site U1313 (and V30-97), at Site 90-03, H1 is characterized by low SSTs and an increased abundance of *N. pachyderma (s.)*. Although the abundance of *N. pachyderma (s.)* at SU90-03 during H1 is much lower compared to that of other cores in the center of the IRD belt [e.g., *Bond et al*., 1992], these results do suggest cooling of surface waters in the midlatitude North Atlantic during H1. We cannot explain the result that during H1, both the alkenone- and faunal-based SSTs at Site U1313 indicate a warming of surface waters, while the faunal-based SST record from the southern core SU90-03 indicate a cooling.

6.4. Implications of Sea Surface Warming in the Midlatitude North Atlantic During Heinrich Events

[26] The warming of surface waters as recorded at Site U1313 during each Heinrich event is novel. So far most studies showed that surface waters in the North Atlantic, and especially within the IRD belt, cooled in response to the surges of icebergs and associated meltwater fluxes (Figure 1). For the Northern Hemisphere, an increase in SSTs during a selective number of Heinrich stadials so far has only been reported for the (sub)tropical North Atlantic [e.g., *Rühlemann et al*., 1999; *Carlson et al*., 2008; *Zarriess et al*., 2011]. The overall consensus of a monotonous cooling of surface waters within the IRD belt is reinforced by most model simulations that depict widespread cooling in the North Atlantic in response to a freshwater forcing in the North Atlantic [e.g., *Stouffer et al*., 2006; *Kageyama et al*., 2010, 2012].

[27] At present, Site U1313 is located at the northern margin of the subtropical gyre and is influenced by the warm waters of the NAC. During glacials, the much lower SSTs indicate that Site U1313 became influenced by higher-latitude waters as the NAC was located to the south of U1313, in agreement with SST reconstructions of the North Atlantic during the LGM [*Ruddiman and McIntyre*, 1981; *Pflaumann et al*., 2003; *Margo Project Members*, 2009]. We argue that the warming during Heinrich events, with temperatures reaching those of core MD95-2037 that is located at 37°N in the subtropical gyre [*Calvo et al*., 2001], indicates that Site U1313 again became under the influence of the subtropical gyre. The observation that the warming started in the later phase of each Heinrich event could indicate that the expansion was not instantaneous and took time to reach the southern end of the IRD belt.

[28] An expansion of the subtropical gyre during Heinrich events is supported by freshwater hosing simulations with the Community Climate System Model (CCSM) that suggest a warming of the midlatitude North Atlantic in response to a freshwater forcing [*Stocker et al*., 2007; *Renold et al*., 2010]. According to these modeling studies, the subtropical gyre expands northward during Heinrich events because the northern boundary currents intensify, in response to an increase in wind stress, and because the subpolar gyre weakens due to a southward expansion of sea ice [*Renold et al*., 2010]. Such a weakening of the subpolar gyre is supported by the observed slowdown in AMOC during Heinrich events [*McManus et al*., 2004; *Lippold et al*., 2009] as the strength of the subpolar gyre influence the strength of the AMOC [*Hátún et al*., 2005]. In addition, proxy evidence from the western North Atlantic supports an increase in wind speed over this region during Heinrich events [*López-Martínez et al*., 2006].

[29] However, the CCSM simulations incorporate modern boundary conditions such as atmospheric CO_2 and orbital parameters and do not include full glacial boundary conditions [*Stocker et al*., 2007; *Renold et al*., 2010]. The response of the North Atlantic to a freshwater flux is different in a glacial and interglacial state, especially in terms of AMOC strength [*Ganopolski and Rahmstorf*, 2001; *Kageyama et al*., 2010]. In a recent model comparison of hosing experiments using full glacial boundary conditions, a warming in the midlatitude North Atlantic is absent in most runs [*Kageyama et al*., 2012]. Actually, in almost all of these models the warming of surface waters is restricted to the Southern Hemisphere, while there is a substantial amount of evidence indicating that surface waters in parts of the (sub)tropical North Atlantic warmed during Heinrich events [e.g., *Rühlemann et al*., 1999; *Carlson et al*., 2008; *Zarriess et al*., 2011]. The only model in this comparison that shows a warming in the midlatitude North Atlantic is the same CCSM that produces the warming using modern boundary conditions. This suggests that the warming in the CCSM is generated independent of the boundary conditions, and CCSM is the only model that is consistent with the paleodata. The absence of a warming in most hosing experiments highlights that climate models are still unable to accurately reproduce regional climatic patterns and urges the modeling community to test model simulations against the wide body of paleodata available. In addition, as the extent of surface cooling in the North Atlantic influences the AMOC strength [*Oka et al*., 2012], accurate representation of SSTs in the North Atlantic in climate models, guided by the paleodata provided here, will likely reduce the large scatter in AMOC response that currently exists in various climate models [*Kageyama et al*., 2012].

[30] In the context of the CCSM model results, the increase of SSTs at Site U1313 is a local signal for the midlatitude North Atlantic. It does not indicate the presence of the fulcrum of the bipolar seesaw, which was probably located further to the south in the subtropical North Atlantic [*Zarriess et al*., 2011]. Rather, it suggests the presence of a second oceanic seesaw with a steep SST gradient across the southern end of the IRD belt (the North Atlantic seesaw). The midlatitude North Atlantic warms in response to the expansion of the subtropical gyre, while the northern North Atlantic cools in response to the massive input of icebergs and melt water during Heinrich events. These results are in agreement with both modeling results and proxy data from the northwestern subtropical Atlantic, which indicate the buildup of heat during periods of reduced AMOC (e.g., H1) in this region [*Rühlemann et al*., 1999; *Carlson et al*., 2008]. Due to the general absence of continuous SST reconstructions at the southern boundary of the IRD belt, these results are novel and highlight the complex impact of all six Heinrich events on surface water characteristics in the North Atlantic with a cooling of surface waters in the center and a warming at the southern end of the IRD belt.

[31] Previously published results from Site U1313 indicate that between 960 and 320 ka, ice-rafting events, including the HS Heinrich(-like) events, always coincided with the lowest SSTs during glacials [*Stein et al*., 2009; *Naafs et al*., 2011]. In fact, the lowest SSTs of the last 3.5 Myr at Site U1313 were reached during HS Heinrich(-like) events 12.1 and 12.2 [*Naafs et al*., 2011, 2012]. Although so far no information is available about SSTs at Site U1313 during

MIS 95 (320–70 ka), it thus appears that the warming of SSTs in the midlatitude North Atlantic during the Heinrich events of the last 70 kyr is unique for the last 1 Myr. As we argue that the warming during Heinrich events is related to an expansion of the subtropical gyre, due to the intensification of the northern boundary currents and weakening of the subpolar gyre [*Renold et al.*, 2010], the absence of similar warming during other glacials suggests that the subtropical gyre did not expand as far north during previous Heinrich(-like) events. Up-to-date evidence for a warming of SSTs outside the IRD belt is limited to the Heinrich events of the last 70 kyr.

[32] However, the response of sea surface temperatures at Site U1313 itself depends on the position of the oceanic fronts, which among others is determined by the position of the main atmospheric wind systems. For example, MIS 12 is known to be associated with large frontal shifts and is the most severe glacial of the Quaternary [e.g., *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]. Thus the subtropical gyre might have expanded during the Heinrich(-like) events of MIS 12; however, the extreme southward migration of the Arctic front did not allow warm surface waters to reach Site U1313. Also, the absence of evidence for a warming of surface waters outside the IRD belt is hampered by the problem to accurately correlate millennial-scale climate variability beyond the range of radiocarbon dating. Similarly, virtually nothing is known about the wind strength and thus whether the boundary currents intensified during Heinrich(-like) events. Well-dated additional marine records north and south of Site U1313 are needed to test whether expansions of the subtropical gyre were an integral response to freshwater fluxes into the North Atlantic during other glacials. However, in the context of the last 1 Myr, the warming observed during the most recent six Heinrich events suggests that only during the Heinrich events the extent of surface water cooling in the North Atlantic was confined to the area of the North Atlantic north of U1313 (41°N).

[33] *Oka et al.* [2012] demonstrated that the extent of cooling in the North Atlantic has a large influence on AMOC, simulating a large (and sudden) reduction in AMOC only by reducing surface temperatures in the North Atlantic. As the cooling of the North Atlantic during the Heinrich events of the last glacial period was the most confined, we speculate that the AMOC reduction was the smallest during the most recent six Heinrich events. Although millennial-scale reconstructions of AMOC variations for older glacials are not available, this scenario is supported by the observation that the strongest reduction in the influence of North Atlantic Deep Water in the deep North Atlantic occurred during MIS 12 [*Raymo et al.*, 1990; *Hodell et al.*, 2008], which coincides with the lowest SSTs of the last 3.5 Myr at Site U1313 [*Naafs et al.*, 2011, 2012].

7. Conclusions

[34] Here we reported a novel alkenone-based sea surface temperature record from the southern end of the IRD belt for the period from 70 to 5 ka that sheds new light on the response of surface water characteristics in the midlatitude North Atlantic to Heinrich events. The SST record demonstrates that during each Heinrich event surface waters in the midlatitude North Atlantic rapidly warmed by 2 to 4°C. These results are supported by faunal-based SSTs from core V30-97, which is from the same location as Site U1313. We argue that the warming of surface waters in the midlatitude North Atlantic was caused by the northward expansion of the subtropical gyre during Heinrich events. As it is well known that the northern North Atlantic cooled during Heinrich events, this opposite behavior between the midlatitude North Atlantic (warm) and northern North Atlantic (cold) suggests the presence of a second oceanic seesaw, the North Atlantic seesaw. A comparison with an array of model simulations highlights the failure of most models to reproduce regional SST patterns and urges for more data-driven model simulations. In the context of the long high-resolution temperature record from Site U1313, the response of the midlatitude North Atlantic to the six Heinrich events of the last 70 kyr was unique, indicating an abnormal northward expansion of the subtropical gyre compared to Heinrich(-like) events of previous glacials.

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