Interglacial intensity in the North Atlantic over the last 800,000 years: investigating the complexity of the mid-Brunhes Event (MBE).

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Abstract

The mid-Brunhes Event (MBE) represents a step-like shift in the intensity of interglacial warmth that occurs between MIS 13 and MIS 11, with interglacials MIS 19-13 being significantly cooler than interglacials MIS 11-1. A transect of palaeoclimatic records in the North Atlantic from 40°N through to the Nordic Seas indicates that there are strong differences in the expression of the MBE at different latitudes in this region. Between 40 and 56°N sea surface temperature and air temperature records suggest that all interglacials of the past 800,000 years were characterised by similar levels of warmth, therefore, there is no evidence for a MBE in these latitudes of the North Atlantic. North of 56°N there is increasing evidence for cooler climates during interglacials MIS 19-13 relative to MIS 11-1. This review suggests that the North Atlantic was anomalous in comparison to the other records of interglacial climate diversity which suggest that the MBE was a global event. Furthermore, the strong spatial difference in temperature conditions during interglacials MIS 19-13 in the North Atlantic means that this region would have been characterised by strong temperature gradients during interglacial episodes of this time interval.

Introduction

The mid-Brunhes Event (MBE) is the most pronounced climatic shift of the past 800,000 years (Jansen et al., 1986; Candy et al., 2010). It represents a step-like change in the intensity of interglacial warmth that occurs between MIS13-11 (EPICA, 2004). This shift is important to our understanding of global warming in the geological past as it shows that interglacials of very different thermal regimes can be generated by similar patterns of insolation. Lang and Wolff (2010) have argued that this is a global event, whereas Meckler et al. (2012) have argued that it is not expressed in low-latitude regions. Climate modelling by Yin and Berger (2012) suggest that the MBE is most strongly expressed in the high-latitudes, is absent in the low-latitudes and has variable expression in the mid-latitudes. Validating these different ideas is problematic because of the paucity of climate records that have a high-enough resolution and long enough duration to investigate interglacial climate diversity over the past 800,000 years (Lang and Wolff, 2010). It is only in the north Atlantic that a sufficient density of appropriate records exists to investigate how long-term patterns of interglacial warmth vary between different latitudes (e.g. McManus et al., 1999; Lawrence et al., 2009). This study investigates the expression of the MBE in the North Atlantic along a transect of sites from 40^{o}N-62^{o}N.

Methodology

Lang and Wolff's (2010) review of interglacial climates of the past 800,000 years concluded that "*strong interglacials are confined to the last 450 ka, and that this is a globally robust pattern*". This is the clearest definition of the MBE yet published. As such the intensity/strength of the MBE can be calculated, for any given palaeoclimatic record, by subtracting the mean, maximum interglacial intensity of pre-MBE interglacials from the mean, maximum interglacial intensity of post-MBE interglacials:

$$\text{MBE intensity} = \text{MTMAX}_{\text{postMBE}} - \text{MTMAX}_{\text{preMBE}}$$

Where:

$\text{MTMAX}_{\text{postMBE}} = (\text{MIS1}_{\text{TMAX}} + \text{MIS5e}_{\text{TMAX}} + \text{MIS7}_{\text{TMAX}} + \text{MIS9}_{\text{TMAX}} + \text{MIS11}_{\text{TMAX}})/5$

$\text{MTMAX}_{\text{preMBE}} = (\text{MIS13}_{\text{TMAX}} + \text{MIS15}_{\text{TMAX}} + \text{MIS17}_{\text{TMAX}} + \text{MIS19}_{\text{TMAX}})/4$

$\text{MIS}n_{\text{TMAX}}$ = the maximum temperature value recorded in the time interval of MIS*n*.

In any record where the MBE is present the MBE intensity will always be >0. In the EPICA deuterium based air temperature anomaly record and the ODP 1090 sea surface temperature record from the southern ocean (Figure 1 and Table 1), MBE intensity = 4.47 and 3.16 respectively. This means that, on average, pre-MBE interglacials in Antarctica were 4.47^{o}C cooler than post-MBE interglacials, whilst in the ODP 1090 record of the southern ocean pre-MBE interglacials were, on average, 3.16^{o}C cooler than post-MBE interglacials. This approach does not consider interglacial duration or the relative timing of the interglacial within a warm stage, it simply identifies the maximum temperature value within the chronological boundaries of each warm stage and uses these values in the calculation. This is considered the most appropriate approach as the MBE is primarily defined by shifts in maximum interglacial intensity not by duration of relative warmth.

In the North Atlantic there are a number of temperature records between 40^{o}N and 57^{o}N (Figure 2 and 3). The majority of these are SST records, generated from a range of proxy data; foraminifera assemblage transfer functions (DSDP 607 (Ruddiman et al., 1989), M23414 (Kandiano and Bauch, 2003) and ODP 552 (Ruddiman et al., 1986)), U^{K}_{37} alkenone data (ODP 982 and 983 (McClymont et al., 2008; Lawrence et al., 2009)) and oxygen isotopic data (ODP 980 (McManus et al., 1999)). Air temperature records are obtainable from palaeoecological assemblages preserved in the British terrestrial record (Coope, 2010; Candy et al., 2010; 2011). Two of these records (ODP 980 and M23414) only span the last 500,000yrs (MIS1-MIS13). Although this means it is difficult to reliably calculate MBE intensity values they still provide important information on the presence/absence of the MBE. If, in such records, the peak intensity of MIS13 is as warm or warmer than MIS 1-11 it shows that "*strong interglacials*" are not "*constrained to the last 450ka*" and, therefore, implies that the MBE is absent from that record.

North of 58^{o}N, there are no continuous temperature records. However, the general temperature characteristics of interglacials can be inferred from multiple sites (Figure 2 and 3) through a number of indicators including foraminifera assemblages, particularly the abundance of *Neogloboquadrina pachyderma* (sin.) (Wright and Flower, 2002), and the abundance of an alkenone associated with the presence polar water masses (%$C_{37:4}$; McClymont et al., 2008). Further north in the Norwegian/Greenland Sea the nature of the marine records (heavily influenced by IRD) makes it more difficult to make clear conclusions about long term interglacial diversity, although basic conclusions can be made using ice-rafted detritus (IRD) concentrations, carbonate content and characteristics of biogenic materials, such as percentage of sub-polar foraminifera (see Henrich and Baumann, 1994; Helmke et al., 2003; Bauch, 2013).

The MBE in the North Atlantic 40 to 56^{o}N

The key SST records of the mid-latitude North Atlantic (40^{o}-56^{o}N) are shown in Figure 3. In all of these records there is no difference in mean interglacial temperature maxima between MIS11-1 and MIS19-13 (Table 1). In most cases the difference in mean interglacial temperature maxima is minimal, in all cases $<\pm 0.5^{o}$C difference, and within 1 standard deviation of each other (Table 1). As most of the proxy techniques that are used to reconstruct temperatures have uncertainties in the order of +/- 1.0^{o}C the differences in pre- and post-MBE warmth are all within the uncertainties of the associated techniques. In the SST records from the North Atlantic between 40-56^{o}N there is, therefore, no statistical difference between the magnitude of interglacial temperature maxima during MIS19-13 and MIS11-1. Palaeotemperature reconstructions from the British record are based on a range of proxies so a simple calculation of MBE intensity is not possible. However, even, the coolest of the MIS19-13 temperature reconstructions, West Runton, indicate climates at least as warm as the present day, whilst deposits at Sidestrand and Pakefield indicate climates as warm as the Eemian, the warmest interglacial of the past 500,000 years (Candy et al., 2010).

The MBE in the North Atlantic >56^{o}N

The key SST record in this region is ODP 982 where a U^{K}_{37} alkenone-based temperature record has been constructed for the past 4 million years (Lawrence et al., 2009). In ODP 982 the interglacials MIS19-13 are clearly cooler than MIS11-1 (Table 1). No other quantified temperature records that continuously span the past 800,000 years exist for the North Atlantic in latitudes higher than 56^{o}N. Although an alkenone SST record does exist for ODP 983 (60^{o}N; McClymont et al., 2008) the focus of the study was the Mid-Pleistocene Transition and, consequently, the SST record finishes at 500,000 yrs. Wright and Flower (2002) have suggested that interglacials MIS 19 to 13, in ODP 984 (61^{o}N) are routinely cooler than interglacials of the past 500,000 years. This is based on percentage concentrations of *N. pachyderma* (s). In records of MIS 5 from the nearby core EW9302-8JPC *N. pachyderma* (s) concentrations drop to 0% (Oppo et al., 2001), whilst during MIS 19-13 they are routinely between 25-50%. Higher concentrations of *N. pachyderma* (s) during MIS 19-13 thus suggest that these interglacials were all significantly cooler than those of the late Pleistocene. Wright and Flower (2002) proposed that during interglacials MIS 19 and 17 the polar front lay to the southeast of ODP 984 but to the northwest of ODP 980. This is supported by the $\%C_{37:4}$ alkenone concentration record at ODP 983 which indicate cold Arctic waters extending into the North Atlantic during both MIS 19 and 17 (McClymont et al., 2008).

The MBE in the Nordic Seas

The pattern of interglacial warmth in the Nordic Seas is more difficult to characterise. A number of authors have argued that a major shift to warmer interglacials occurs from MIS15 onwards (Henrich and Baumann, 1994). This suggestion is based on percentage carbonate content, however, this parameter is not simply a proxy for temperature as high concentrations of *N. pachyderma* (s) can generate high percentage carbonate values even during relatively cool episodes. There is, however, a general suggestion from across the Norwegian and Greenland seas that there is a cooler “aspect” to interglacials MIS19-13 (Jansen et al., 1988; Fronval and Jansen, 1994; Henrich and Baumann, 1994; Helmke et al., 2003). In MD992277, for example, MIS19, 17 and 13 appear to be characterised by relatively subdued warmth (Helmke et al., 2003). Although MIS15 appears to be significantly warmer than the other pre-MBE interglacials it is not comparable in magnitude to MIS11, for example, and also appears to be of relatively short duration; ca 5,000 years relative to the 10,000 years of MIS11 (Helmke et al., 2003). This pattern of cool interglacials before MIS11 is supported by other records from this region (Jansen et al., 1988; Fronval and Jansen, 1994; Henrich and Baumann, 1994).

Discussion

There is no evidence for a mid-Brunhes Event in the mid-latitude North Atlantic, south of 56^{o}N (Figure 2). Although these palaeotemperature records have been generated using a range of techniques, the validity of the reconstructions is strengthened by that fact that sites on the same approximate line of latitude produce a consistent picture. For example, in ODP 552, 980, M23414 and the British terrestrial sequence MIS13 is at least as warm as the Holocene (Ruddiman et al., 1989; McManus et al., 1999; Flower and Wright, 2002; Candy et al., 2010). North of 56^{o}N there is evidence for cooler temperatures during MIS19-13 (e.g. Lawrence et al., 2009). Although difficult to quantify this pattern is considered robust because it can be seen in alkenone, faunal and lithological proxies. This pattern appears to be true of the Nordic Seas although the nature of the proxy records makes it difficult to be precise about the nature of the thermal regime of interglacials MIS19-13 other than to say that they are ‘cool’ (Helmke et al., 2003). The mid-latitude North Atlantic is, therefore, anomalous in the light of most reviews of interglacial diversity in that “strong interglacials” (cf Lang and Wolff, 2010) occur prior to 450ka ago. Evidence for the MBE in the higher latitudes of this region is, however, consistent with the work of Yin and Berger (2012).

In the North Atlantic interglacials, MIS19-13 appear to be characterised by a southward expansion of cold polar-water into the North Atlantic relative to MIS11-1 (Wright and Flower, 2002; McClymont et al., 2008). Wright and Flower (2002) have postulated that during some interglacials of the early Middle Pleistocene the Polar Front was situated south of 61^{o}N but north of 56^{o}N. Here, we show that evidence from a range of sites supports this interpretation, but also that the expression of the MBE in the north Atlantic region is a function of the shift, equatorwards, of the polar front. In this respect the interglacial history of the North Atlantic is consistent with that of the Southern Ocean, where cooler interglacial temperatures during MIS19-13 are suggested to correspond with a more northerly position of the polar front relative to its position during MIS11-1 (Kujipers, 1989; Martinez-Garcia et al., 2009).

The southward expansion of polar waters during MIS19-13 means that the climatic setting that existed in the North Atlantic during these intervals would have been very different to that which occurred during MIS11-1. In particular the climate of the North Atlantic during interglacials MIS19-13 would have been characterised by stronger latitudinal temperature gradients. If, during MIS19-13, sea surface and air temperatures in the region 40-56^{o}N are as warm as MIS11-1 but the regions 57^{o}N and higher are significantly cooler then much steeper temperature gradients than are experienced at the present day would have existed across the North Atlantic (Figure 4).

The MBE is routinely defined in terms of long-term shifts in the magnitude of interglacial warmth and in this respect there is no evidence for an MBE in, for example, the British Isles. However, the southward intrusion of arctic waters during MIS19-13 may have had impacts on atmospheric circulation, seasonality (of both temperature and rainfall) and annual precipitation. Consequently, although there is no evidence for the MBE in the North Atlantic (40-56^{o}N), this does mean that the climates of MIS19-13 were directly analogous to those of

MIS11-5. The climate of MIS19-13 in the North Atlantic region may have been significantly different because of this unusual synoptic setting. As MIS19-13 record the first arrival of early humans into northern Europe and persistently high levels, for warm isotopic stages, of northern hemisphere ice volume the unusual synoptic settings of these interglacial has implications, not just for the diversity of interglacial climates, but also for understanding the context of both early human evolution and long-term ice-sheet dynamics.

Captions

Table 1 – Quantification of the strength of the MBE, see text for methodology, as represented in multiple long temperature time series (s = summer SST, w = winter SST). Temperatures in these records are generated by a number of techniques making the direct comparison of the absolute temperature of an individual interglacial between different records problematic. However, the construction of a temperature difference effectively normalises the record allowing direct comparison of the strength of the MBE to be calculated. EPICA Dome C (EPICA, 2004; Jouzel et al., 2007) is based on comparing deuterium based temperature anomalies. ODP 1090 is in the Southern Ocean and is based on U^{K}_{37} quantification of sea surface temperatures (Bequey and Gersonde, 2002; Martinez-Garcia et al., 2009) . Sea surface temperatures in DSDP 607 and ODP 552 are based on foraminifera assemblages (Ruddiman et al., 1986;1989). The ODP 980 record only records the past 500,000 years and, therefore, contains a detailed record of MIS 13 but none of the other early Middle Pleistocene interglacials. The temperature difference calculated for this core is, therefore, not comparable with the others, however, it does suggest contain a peak in MIS 13 that is comparable to those of MIS 11 to 1. ODP 980 temperatures are based oxygen isotopic differences between planktonic and benthic foraminifera (McManus et al., 1999). A similar situation is found in

MD23414 (53°N, 20°W) where a SST record of the past 500,000 years records MIS 13 SST as warm as MIS 1, 7 and 9 and *N. Pachyderma* (s) concentrations of 0 (Kandiano and Bauch, 2003). Wright and Flower (2002) have calculated SST values for the early Middle Pleistocene section of ODP 980 using foraminifera-based transfer functions. Although the calculated temperatures cannot be directly compared with the SST estimates of McManus et al. (1999) they do indicate that MIS 19 to 13 in ODP 980 were at least as warm as modern day and MIS 5e values. The temperature record of ODP 982 is generated from U^{K}_{37} prime (Lawrence et al., 2009). Although the resolution of the ODP 982 is greatly reduced during MIS19 to13 the reduction in resolution is progressive and, if the lower temperatures were due to the main interglacial peaks being missed, it would be anticipated that interglacial peaks would also gradually decrease. This is not the case and there is a clear step change in interglacial intensity between MIS 13 and 11. Furthermore the pattern seen in ODP 982 is supported by other records in the region (e.g. ODP 984). ODP 984 records % *N. Pachyderma* (s) with higher percentages indicating colder waters (Wright and Flower, 2002). In this region MIS 5 is characterised by *N. Pachyderma* (s) of 0% (Oppo et al., 2001), whereas ODP 984 records values between 70 and 30% during MIS 19 to 13, indicating much cooler conditions. Standard deviations for maximum interglacial temperatures of MIS 19 to 13 and 11 to 1 are shown. Significantly the mean interglacial temperature maxima of MIS 19 to 13 and MIS 11 to 1 do not overlap even when standard deviations are included for EPICA Dome C, ODP 1090 and ODP 982. Mean interglacial temperature maxima of MIS 19 to 13 and MIS 11 to 1 do overlap at DSDFP 607, ODP 980 and ODP 552. Statistically, therefore, there is no significant difference between interglacial intensity across the MBE for those North Atlantic sites between 41 and 56°N but a significant difference in interglacial intensity in EPICA Dome C, ODP 1090 and ODP 982. Due to the limited number of interglacials in the pre- and post-MBE intervals no more detailed statistical analysis was possible.

Figure 1 – Examples of long palaeoclimate records that show a clear expression of the MBE. 1a is the EPICA Dome C deuterium record and shows air temperature variability in Antarctica (EPICA, 2004; Jouzel et al., 2007), 1b is the SST record from ODP 1090 in the southern Ocean (Bequey and Gersonde, 2002; Martinez-Garcia et al., 2009). In Antarctica post-MBE interglacials are, on average, 4.47^{o}C warmer than pre-MBE interglacials. In the ODP 1090 record of the southern ocean post-MBE interglacials are, on average 3.16^{o}C warmer than pre-MBE interglacials.

Figure 2 – The location of key palaeoclimate records than span the MBE, discussed in the text, in the North Atlantic and Nordic Seas. and shows the location of the key records that are discussed in the text.

Figure 3 – Palaeoclimate records from the North Atlantic that are discussed in the text. DSDP 607 (Ruddiman et al., 1989; Lawrence et al., 2010), M23414 (Kandiano and Bauch, 2003), ODP 980 (McManus et al., 1999), ODP 552 (Ruddiman et al., 1986), British Palaeoecological Record (BPR, Candy et al., 2010), ODP 982 (Lawrence et al., 2009), ODP 984 (Wright and Flower, 2002).

Figure 4 – Summary of the palaeoclimate of early Middle Pleistocene interglacials (MIS 19 to 13). Areas shown in red are those that contain evidence to suggest that interglacials MIS 19 to 13 were routinely as warm as MIS 11 to 5 (e.g. areas with no evidence for an MBE). Areas shown in blue are those that contain evidence to suggest that interglacials MIS 19 to 13

were routinely cooler than MIS 11 to 5 (e.g. areas with a clear expression for an MBE). The current position of the Polar Front is shown for reference.

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Figure 1

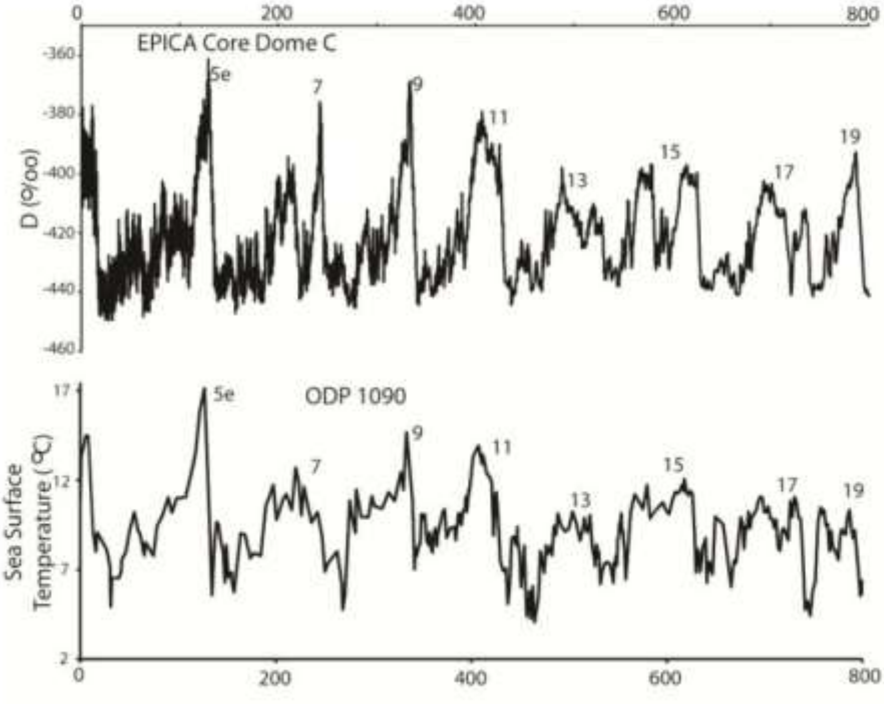


Figure 2

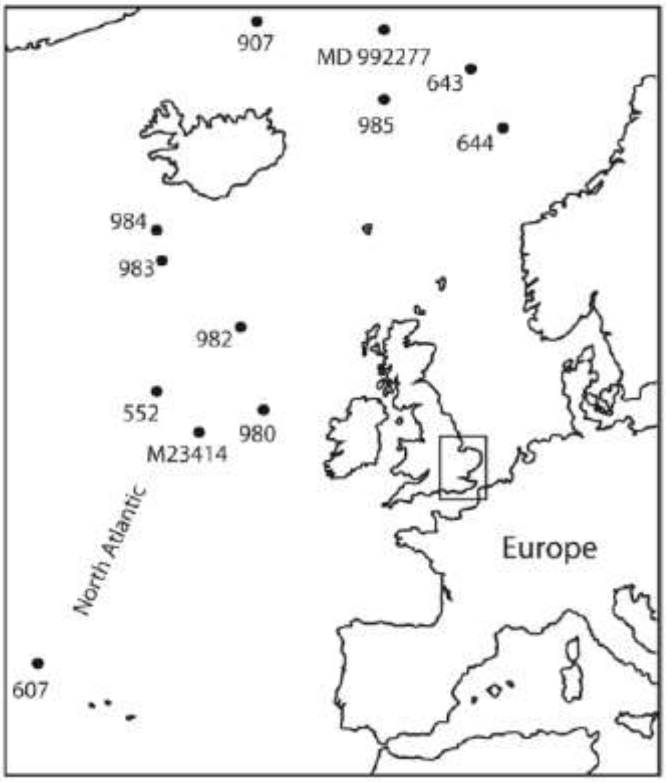
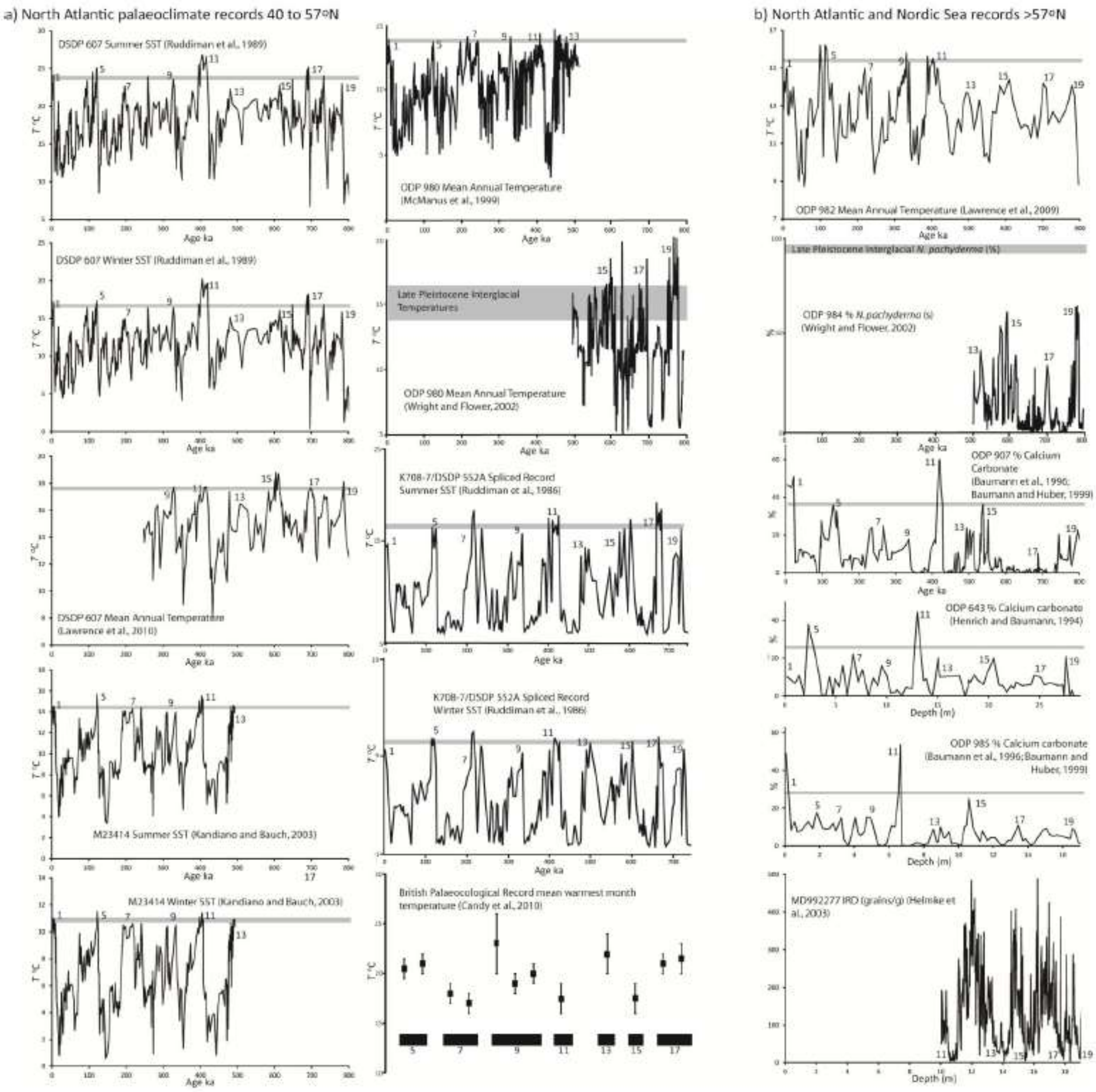


Figure 3



a) North Atlantic palaeoclimate records 40 to 57°N
b) North Atlantic and Nordic Sea records >57°N
DSDP 607 Summer SST (Ruddiman et al., 1989)
ODP 980 Mean Annual Temperature (McManus et al., 1999)
ODP 982 Mean Annual Temperature (Lawrence et al., 2009)
DSDP 607 Winter SST (Ruddiman et al., 1989)
Late Pleistocene Interglacial Temperatures
ODP 980 Mean Annual Temperature (Wright and Flower, 2002)
Late Pleistocene interglacial N. pachyderma (%)
ODP 984 % N. pachyderma (s) (Wright and Flower, 2002)
K708-7/DSDP 552A Spliced Record Summer SST (Ruddiman et al., 1986)
ODP 907 % Calcium Carbonate (Baumann et al., 1996; Baumann and Huber, 1999)
DSDP 607 Mean Annual Temperature (Lawrence et al., 2010)
ODP 643 % Calcium carbonate (Henrich and Baumann, 1994)
K708-7/DSDP 552A Spliced Record Winter SST (Ruddiman et al., 1986)
M23414 Summer SST (Kandiano and Bauch, 2003)
ODP 985 % Calcium carbonate (Baumann et al., 1996; Baumann and Huber, 1999)
M23414 Winter SST (Kandiano and Bauch, 2003)
British Palaeoecological Record mean warmest month temperature (Candy et al., 2010)
MD992277 IRD (grains/g) (Helmke et al., 2003)
Age ka
Depth (m)

Figure 4

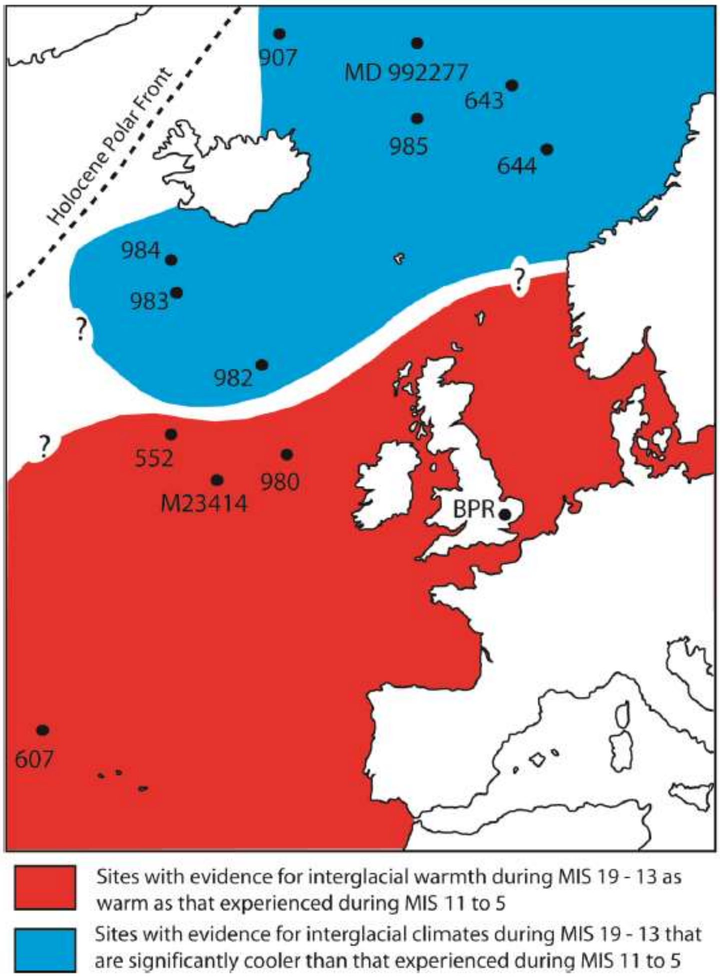

Holocene Polar Front
907
MD 992277
643
985
644
984
983
982
?
?
?
552
980
M23414
BPR
607
Sites with evidence for interglacial warmth during MIS 19 - 13 as warm as that experienced during MIS 11 to 5
Sites with evidence for interglacial climates during MIS 19 - 13 that are significantly cooler than that experienced during MIS 11 to 5

Table 1

Table 1. Quantification of the strength of the MBE, see text for methodology, as represented in multiple long temperature time series (s = summer SST, w = winter SST).

	EPICA Dome C	ODP 1090	DSDP 607	DSDP 607	DSDP 607	ODP 552	M23414	M23414	ODP 982	ODP 643A	ODP 907	ODP 985	Temp. difference between interglacial peaks at 41°N
Latitude:	−75.100000	−42.913 700	41.001 200	41.001 200	41.001 200	56.042700	53.538333	53.538 333	57.512 667	67.715 000	69.241 500	66.941 400	
Longitude:	123.350 000	8.899 700	−32.957 300	−32.957 300	−32.957 300	−23.231 300	−20.288 333	−20.288 333	−15.854 183	1.033 300	−12.698 300	−6.450 300	
Isotope stage	Deuterium SST	Alkenone SST	Foram SST (s)	Foram SST (w)	Alkenone SST	Foram SST (w)	Foram SST (s)	Foram SST (s)	Alkenone SST	$CaCO_3$ (%)	$CaCO_3$ (%)	$CaCO_3$ (%)	and 57°N
1	2.12	14.51	24.10	17.20		9.80	14.40	11.00	15.00	10.28	48.86	50.77	
5	5.46	17.14	25.10	17.40		11.00	15.70	11.50	16.20	37.93	17.59	34.82	
7	2.73	10.22	20.50	13.80		11.60	14.40	10.60	15.00	22.10	15.08	24.82	
9	3.75	14.67	23.60	16.40	17.70	9.40	14.00	10.50	15.80	15.90	15.42	17.73	1.90
11	3.15	13.93	26.60	19.50	17.70	11.10	15.40	11.40	15.60	44.34	53.53	60.03	2.10
Mean	3.44	14.09	23.98	16.86	17.70	10.58	14.78	11.00	15.52	26.11	30.10	37.63	2.18
SD	1.14	2.23	2.02	1.84	n/a	0.84	0.65	0.40	0.47	14.52	19.36	17.62	
13	−1.36	10.24	22.30	15.20	17.40	10.60	14.60	10.90	13.70	20.28	10.02	23.84	3.70
15	−0.92	12.07	22.90	16.10	18.80	10.70			14.40	20.03	25.16	36.38	4.40
17	−1.55	11.07	25.20	18.20	17.60	11.10			14.20	11.14	10.87	10.33	3.40
19	−0.54	10.35	24.00	16.80	18.10	9.90			14.10	21.02	8.63	22.71	4.00
Mean	−1.09	10.93	23.60	16.58	17.98	10.58	14.60	10.90	14.10	18.12	13.67	23.32	3.88
SD	0.39	0.73	1.11	1.10	0.54	0.43	0.00	0.00	0.25	4.67	7.72	10.64	
Temp. difference	4.53	3.16	0.38	0.28	−0.28	0.01	0.18	0.10	1.42				