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Reconstructions of surface ocean conditions from the northeast Atlantic and Nordic seas during the last millennium

Laura K Cunningham,[1] William EN Austin,[1] Karen Luise Knudsen,[2] Jón Eiríksson,[3,4] James D Scourse,[5] Alan D Wanamaker Jr,[6] Paul G Butler,[5] Alix G Cage,[1,7] Thomas Richter,[8] Katrine Husum,[9] Morten Hald,[9] Carin Andersson,[10] Eduardo Zorita,[11] Hans W Linderholm,[12] Björn E Gunnarson,[13,14] Marie-Alexandrine Sicre,[15] Hans Petter Sejrup,[16] Hui Jiang[17] and Rob JS Wilson[1]

Abstract
We undertake the first comprehensive effort to integrate North Atlantic marine climate records for the last millennium, highlighting some key components common within this system at a range of temporal and spatial scales. In such an approach, careful consideration needs to be given to the complexities inherent to the marine system. Composites therefore need to be hydrographically constrained and sensitive to both surface water mass variability and three-dimensional ocean dynamics. This study focuses on the northeast (NE) North Atlantic Ocean, particularly sites influenced by the North Atlantic Current. A composite plus regression approach is used to create an inter-regional NE North Atlantic reconstruction of sea surface temperature (SST) for the last 1000 years. We highlight the loss of spatial information associated with large-scale composite reconstructions of the marine environment. Regional reconstructions of SSTs off the Norwegian and Icelandic margins are presented, along with a larger-scale reconstruction spanning the NE North Atlantic. The latter indicates that the 'Medieval Climate Anomaly' warming was most pronounced before AD 1200, with a long-term cooling trend apparent after AD 1250. This trend persisted until the early 20th century, while in recent decades temperatures have been similar to those inferred for the 'Medieval Climate Anomaly'. The reconstructions are consistent with other independent records of sea-surface and surface air temperatures from the region, indicating that they are adequately capturing the climate dynamics of the last millennium. Consequently, this method could potentially be used to develop large-scale reconstructions of SSTs for other hydrographically constrained regions.

Keywords
'Little Ice Age', 'Medieval Climate Anomaly', North Atlantic Current, regional proxy-based reconstructions, sea surface temperature

Introduction

Changes in the dynamics of the North Atlantic Ocean have played a crucial role in the climatic evolution of the Northern Hemisphere over the last 1000 years (Denton and Broecker, 2008; Trouet et al., 2009, 2012; Wanamaker et al., 2012). Recent observations, proxy data and model simulations consistently demonstrate that variability in heat and moisture transport via the northerly flowing North Atlantic Current significantly influences North Atlantic climate, over both instrumental and geological timescales (Holliday, 2003; Rahmstorf, 2002; Sutton and Dong, 2012). Despite widespread recognition that centennial- and millennial-scale variability of the subpolar North Atlantic and Nordic Seas is a characteristic of Holocene climate reconstructions, the underlying drivers remain poorly understood. In particular, the mechanisms responsible for the 'Medieval Climate Anomaly' and the subsequent transition into the 'Little Ice Age' have yet to be fully elucidated (Graham et al., 2011; Wanamaker et al., 2012). Furthermore, the marine evidence for climate change spanning the last millennium is extremely limited when compared with terrestrial records available from the Northern Hemisphere. The scarcity of marine proxy data at sufficiently high temporal resolution restricts our understanding of the relative roles of internal variability and external forcing in influencing global climate (Ljungqvist et al., 2012). This deficiency was highlighted by the Intergovernmental Panel on Climate Change (AR4) '*there*

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are important limitations due to a lack of … ocean records' and '*this assessment would be improved with extensive networks of proxy data that run right up to the present day*' (Jansen et al., 2007). The number of high-resolution records of past climates derived from marine archives across the North Atlantic has, however, increased in recent years (Jones et al., 2009) and forms the basis of this study.

Regional reconstructions are more meaningful than local records with regards to understanding the role of external forcing on large-scale climatic changes, partly because local variations tend to be averaged out (Jansen et al., 2007). Within the terrestrial realm, a variety of statistical methods have been used to develop regional, hemispherical and global reconstructions of temperature (e.g. Christiansen and Ljungqvist, 2011; D'Arrigo et al., 2006; Kaufman et al., 2009; Ljungqvist et al., 2012; Mann et al., 1999, 2008, 2009; Moberg et al., 2005). Typically, such reconstructions have excluded marine records, most frequently because of concerns over the dating resolution (Kaufman et al., 2009). Similarly, there are no large-scale reconstructions of the last millennium based solely on marine records despite the long tradition of building global marine chronologies (e.g. Pisias et al., 1984). However, the recent increase in high-resolution records from the marine realm means that it is now possible to attempt such an undertaking in order to assess multidecadal climatic variability in the North Atlantic over the last millennium.

The integration of marine records across large areas of ocean however, requires careful consideration of spatial complexities inherent to the marine system. The slow mixing time of the ocean and the existence of distinct pervasive water masses generates greater regional heterogeneity than is seen in atmospheric dynamics. A composite record combining, for example, sea surface temperature (SST) records from offshore NW Africa and the Norwegian margin would be meaningless since vigorous Atlantic Meridional Overturning Circulation results in lowered SSTs off Africa and higher SSTs off Norway (Trouet et al., 2012). Composites therefore need to be hydrographically constrained and sensitive to both surface water mass variability and three-dimensional ocean dynamics. A recent review by Trouet et al. (2012) indicated a coherent pattern in proxy records situated on the main axis, or a significant side branch, of the North Atlantic Current between the Florida Straits and the Fram Strait (situated to the east of north Greenland), thereby suggesting a hydrographically consistent signal along these pathways. This hydrographical constraint has been used to define the focus area within this study, namely the NE North Atlantic Ocean, which is defined herein as the North Atlantic Ocean to the east of the mid-Atlantic Ridge and including the North Icelandic shelf, Nordic Seas and the Norwegian Margin.

This study undertakes the first comprehensive effort to integrate the North Atlantic marine climate records of the last millennium that are now available in order to identify any key components common within this system at a range of temporal and spatial scales. The aims of this study are to assess the validity and feasibility of creating integrated climatic reconstructions for the North Atlantic Ocean via statistical compositing, to explore some of the issues associated with creating such regional composites within the marine environment and to make inferences of internal and external forcing for the last millennium in the NE sector of the North Atlantic Ocean.

Palaeotemperature records

Selection of proxy records

Using the ISI Web of Knowledge Service and more general web search engines (e.g. Google Scholar) a literature search was undertaken to identify relevant records for inclusion in this study. Search terms variously included locations (e.g. Iceland, North Atlantic), timescales of interest (e.g. decadal, 'Medieval Warm Period', last millennium) and climate-related phrases (e.g. temperature, surface temperature, palaeoclimate). The identified literature was reviewed, focusing on marine palaeo-records that had previously been related to either ocean or air temperatures. The initial selection criteria was that records covered a large proportion of the last millennium, with at least one sample every 50 years, and a sample resolution of better than 20 years during the calibration period (1875–1975). This process identified 13 records from Norway, northern Iceland, Scotland and the Rockall Trough (Figure 1) which were varyingly related to SSTs, Atlantic Water temperatures or bottom water temperatures (Table 1).

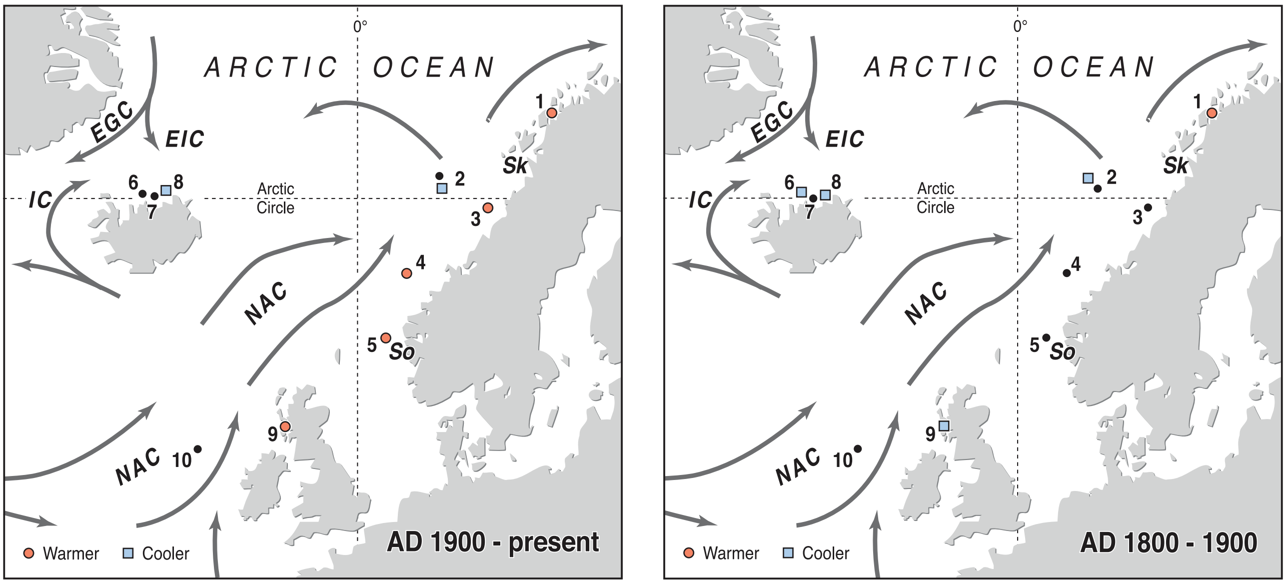
To ensure that any resulting reconstructions were dynamically meaningful, we focused only on proxy records that were consistent with local SSTs during the instrumental period (1870 onwards). One confounding factor in comparisons of SST records from multiple proxies is the actual definition of 'SST'. For example, the planktonic foraminifera *N. pachyderma* (dex.) primarily reflect temperatures at 50 m water depth; *N. pachyderma* (sin.) are thought to reflect water temperatures at 100 m water depth (Nyland et al., 2006); diatom and alkenone records will typically reflect conditions within the upper photic zone (Andersson et al., 2010). Thus reconstructions derived from these different proxies will actually reflect the temperature of water at these various depths within a thermocline gradient, yet all are typically referred to as SST reconstructions (a nomenclature also applied in this paper).

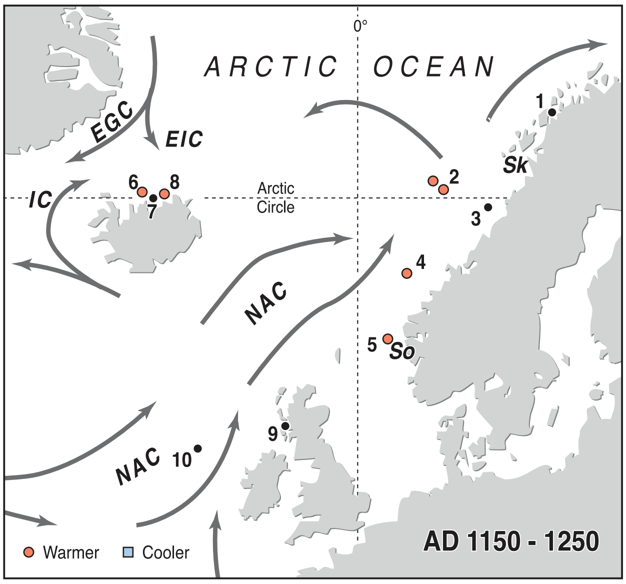
A validating process was therefore used to select only proxy records that were empirically consistent with local SST measurements. This approach consisted of correlating each record with the relevant 1° grid cell from the Hadley Centre Sea Surface Temperature data set (HadISST1; Rayner et al., 2003) from which the proxy series originated. A broad 'summer' target season of May to October was used as this encompassed the majority of 'seasons' represented by the various biological proxies. To enable this process, the proxy records were linearly interpolated between sample data points to form an annual time series, and both the proxy records and HadISST1 data subsequently smoothed using a 25 yr low-pass Gaussian filter. Proxy series were considered for further analyses if they correlated with the local HadISST1 at 0.25 or higher. Although this correlation value is rather low and did not include any significance adjustment related to series autocorrelation, this process was used simply to ensure that the original published interpretation of these records was empirically consistent with local instrumental SST temperature data.

Of the 13 proxy records identified, ten met the above criteria (Table 1; Figure 1). Six of these records were from the Norwegian Margin, three from the North Icelandic Shelf and one from the Scottish Margin. The average sample resolution of these records was typically less than 10 years. Several records were derived from benthic foraminifera, however, they originate from either fjordic sites that have a good exchange with coastal waters or locations where the bottom waters are strongly influenced by the North Atlantic Current and thus reflect regional SSTs. More detailed information regarding the proxy records identified and the reasons for their inclusion or exclusion within this study can be found in the supplementary material (available online).

Temporal coherence (1870–2008)

The screened proxy records were derived from three distinct geographical regions. All three regions are influenced by the North Atlantic Current (Figure 1; see supplementary material, available online, for more details) although this influence may be variable over time. Gridded SST data (HadISST1; Rayner et al., 2003) covering the period from 1870 to 2008 were therefore used to assess





Site No.	Site Name	Primary Reference
1.	Malangen Fjord	Hald et al., 2011
2.	Vøring Plateau	Andersson et al., 2003
3.	Ranafjord	Klitgaard Kristensen et al., 2004
4.	Norwegian Margin	Sejrup et al., 2010
5.	Norwegian Channel	Eiriksson et al., 2006
6.	Iceland Site 73	Knudsen et al., 2012
7.	North Iceland Shelf	Wanamaker et al., 2008, 2012 Butler et al., 2013
8.	Iceland Site 75	Ran et al., 2011 Knudsen et al., 2012 Sicre et al., 2008
9.	Loch Sunart	Cage and Austin, 2010
10.	Feni Drift	Richter et al., 2009

Figure 1. Temporal snapshots showing the deviation (warmer: red circles; colder: blue squares) of individual proxy records from their long-term average during specific intervals of interest which loosely correlate to the last century, the 'Little Ice Age' and the 'Medieval Warm Period'. Only deviations >1 standard deviation are highlighted. The proxy locations shown are: Malangen Fjord (1), Vøring Plateau (2), Ranafjord (3), Norwegian Margin (4), Norwegian Channel (5), Icelandic Shelf Site 73 (6), North Icelandic Shelf (7), Icelandic Shelf Site 75 (8), Loch Sunart (9) and the Feni Drift (10) (colour figure available online). Major ocean currents are shown including the North Atlantic Current (NAC), the Irminger Current (IC), the East Greenland Current (EGC) and the East Icelandic Current (EIC). The location of the two coastal hydrographic stations referred to in the supplementary material (available online) are also indicated (Sk: Skrova; So: Sognesjøen).

whether the three regions reflect a coherent climate signal over time. May to October SST time series were compiled for each region (namely Norway, Iceland and the Scottish Margin) from which proxy series are available. The correlations within, and between, the gridded SST data from these three regions were assessed to confirm the coherency of the SST signal within the instrumental period. Intra-regional SST differences during the instrumental period are relatively small (Figure 2). Within each region, the grid cells closest to the individual archives are highly correlated (Figure 2), potentially reflecting interpolation of data within the HadISST1 data set. All three regions exhibit characteristics of the smoothed Northern Hemisphere records of Rayner et al. (2003), with consistently cool SSTs in the 1920s, warmer SSTs in the 1940–1950s, cooling through the 1960–1970s and subsequent warming since the 1980–1990s. Although some distinct differences are noted between the three regions, anti-phase behaviour (e.g. Giraudeau et al., 2010; Moros et al., 2012) is not apparent (Figure 2).

Comparisons of inter-regional SSTs highlight the broad similarity between the Scottish and Norwegian SST data (Figure 2), which can largely be explained by the common influence of the warm, northwards-flowing North Atlantic Current (Figure 1). In contrast, Icelandic SSTs express higher variance and show an abrupt and pronounced cooling in the 1960s, which can be attributed to the Great Salinity Anomaly of the late 1960s and early 1970s (Dickson et al., 1988). The proximity of the North Atlantic Polar Front to the study area on the North Icelandic shelf makes this a sensitive boundary region which may experience unusually large and rapid changes in SSTs (Hurdle, 1986 and references therein). These regional comparisons highlight the multidecadal coherency of the instrumental SST data across the entire NE Atlantic and Nordic Seas whilst indicating a greater variance in SSTs on the North Icelandic shelf than elsewhere (Figure 2d). Any attempt to build inter-regional composites based on marine SST data must therefore acknowledge both the spatial and temporal complexity of the surface ocean state.

Table 1. Information regarding the various proxy records identified within this study, including the correlation with the HadISST1.1 data for the relevant grid cell. All series were smoothed with a 25 yr Gaussian filter prior to comparison. Site numbers refer to Figure 1.

	Iceland					Norway						Rockall Trough	Scotland
Site name (number)	North Iceland Shelf, core site MD99-2275 (8)	North Iceland Shelf, core site MD99-2275 (8)	North Iceland Shelf, core site MD99-2275 (8)	North Iceland Shelf, core site MD99-2273 (6)	North Iceland Shelf (7)	Norwegian Channel (5)	Norwegian Margin (4)	Ranafjord (3)	Vøring Plateau (2)	Vøring Plateau (2)	Malangen Fjord (1)	Feni Drift (10)	Loch Sunart (9)
Proxy	Diatoms	Alkenones	$\delta^{18}O$ of benthic foraminifera	$\delta^{18}O$ of benthic foraminifera	*Arctica islandica* shell growth increments	δ^{18} O of benthic foraminifera	δ^{18} O of planktonic foraminifera	δ^{18} O of benthic foraminifera	$\delta^{18}O$ of planktonic foraminifera	Planktonic foraminifera	δ^{18} O of benthic foraminifera	Mg/Ca ratio of planktonic foraminifera	$\delta^{18}O$ of benthic foraminifera
Primary reference	Ran et al. (2011)	Sicre et al. (2008a, b, 2011)	Knudsen et al. (2012)	Knudsen et al. (2012)	Wanamaker et al. (2008, 2012); Butler et al. (2013)	Eiríksson et al. (2006)	Sejrup et al. (2010)	Kristensen et al. (2004)	Andersson et al. (2003)	Andersson et al. (2003)	Hald et al. (2011)	Richter et al. (2009)	Cage and Austin (2010)
Geographical location	66°33.10′N; 17°41.99′W	66°33.10′N; 17°41.99′W	66°33.10′N; 17°41.99′W	66° 45.78′N, 18° 45.02′W	66° 31.59′N, 18° 11.74′W	60°52′N, 03°44′N	63°45′N, 05°15′E	66°09.2′N, 12°39.4′N	66°97′N, 7°64′E	66°97′N, 7°64′E	69°29′N, 18°22′E	55° 39′N, 13° 59′W	56°40′N, 5°52′W
Water depth (m)	440	440	440	665	81–83	345	851	307	1048	1048	218	2543	56
Depth at which organism lived (m)	0–100	0–100	440	665	81–83	345	~ 50	307	~ 50	0–300	218	0–100	56
Climatic parameter	Summer SST	Summer SST	BWT	BWT	April–June SST	Summer SST	Late summer near SST	Atlantic water temp	Summer SST	Summer SST	BWT & Atlantic water	April–July SST	BWT
Original method of determining temperature*	Spatial calibration model (Jiang et al., 2005)	Alkenone unsaturation index (Prahl et al., 1988)	Palaeo-temperature equation (Shackleton, 1974)	Palaeo-Temperature equation (Shackleton, 1974)	Temporal Calibration (Butler et al,. 2013)	N/A	N/A	N/A	N/A	Spatial calibration model	Palaeo-temperature equation (Shackleton, 1974)	Species specific calibration (Anand et al., 2003)	O'Neil et al. (1969) palaeo-temperature equation and regional salinity: $\delta^{18}O$ mixing line (Austin and Inall, 2002)
May–October SST correlation*	0.5	0.39	0.14	0.15	0.46	−0.28*	−0.55*	−0.87*	−0.84*	0.63	0.68	−0.08	0.45
Chronological methodology	Tephro-chronology & ^{210}Pb	Tephro-chronology & ^{210}Pb	Tephro-chronology & ^{210}Pb	Tephro-chronology & ^{210}Pb	Cross-dating	^{210}Pb ^{137}Cs & AMS ^{14}C	^{210}Pb, ^{137}Cs, AMS ^{14}C & tephro chronology	^{210}Pb, ^{137}Cs & AMS ^{14}C	^{210}Pb & AMS ^{14}C	^{210}Pb& AMS ^{14}C	^{210}Pb dating AMS ^{14}C	^{210}Pb & AMS ^{14}C	^{210}Pb & AMS ^{14}C
Maximum chronological error	± 16.3	± 16.8	± 16.8	± 16.6	± 5	± 70	± 20	± 140	± 60	± 60	± 140	± 50	± 54
Maximum sample interval during the last 1000 years	17	6	15	28	1	22.5	21.3	23.8	33.9	18.2	9.62	37	14.3
Maximum sample resolution since 1875	10	5	10	13	1	11.9	7.9	11.6	11.4	11.4	5	13.7	3.3
Average sampling resolution	7.1	3	3.3	2.8	1	10.1	7.6	12.8	9.1	8.4	3.5	22.8	3.6

*Oxygen isotopes should show a negative correlation to SSTs (Bemis et al., 1998; Kim and O'Neil, 1997; Zeebe, 1999); these data series were therefore multiplied by −1 prior to compositing.

Table 2. Information regarding the nests incorporated within the composite reconstruction including the span of each nest, the proxy records included (indicated by *) and the r^2 values reflect regression coefficient with the target SST data (HadISST1; 25 year low pass Gaussian smoothing). The numbers in brackets indicate the sampling locations shown in Figure 1.

	Nest 1 AD 1253–1974 r^2 = 0.41	Nest 2 AD 1185–1253 r^2 = 0.34	Nest 3 AD 1000–1184 r^2= 0.31
Malangen Fjord (1)	*	*	*
Vøring Plateau (2) foraminiferal assemblage	*	*	*
Vøring Plateau (2) $\delta^{18}O$	*	*	*
Ranafjord (3)	*		
Norwegian Margin (4)	*	*	*
Norwegian Channel (5)	*	*	*
Icelandic Shelf Site 75 (8) alkenones	*	*	*
North Icelandic Shelf (7)	*	*	
Icelandic Shelf Site 75 (8) diatoms	*	*	*
Loch Sunart (9)	*	*	*

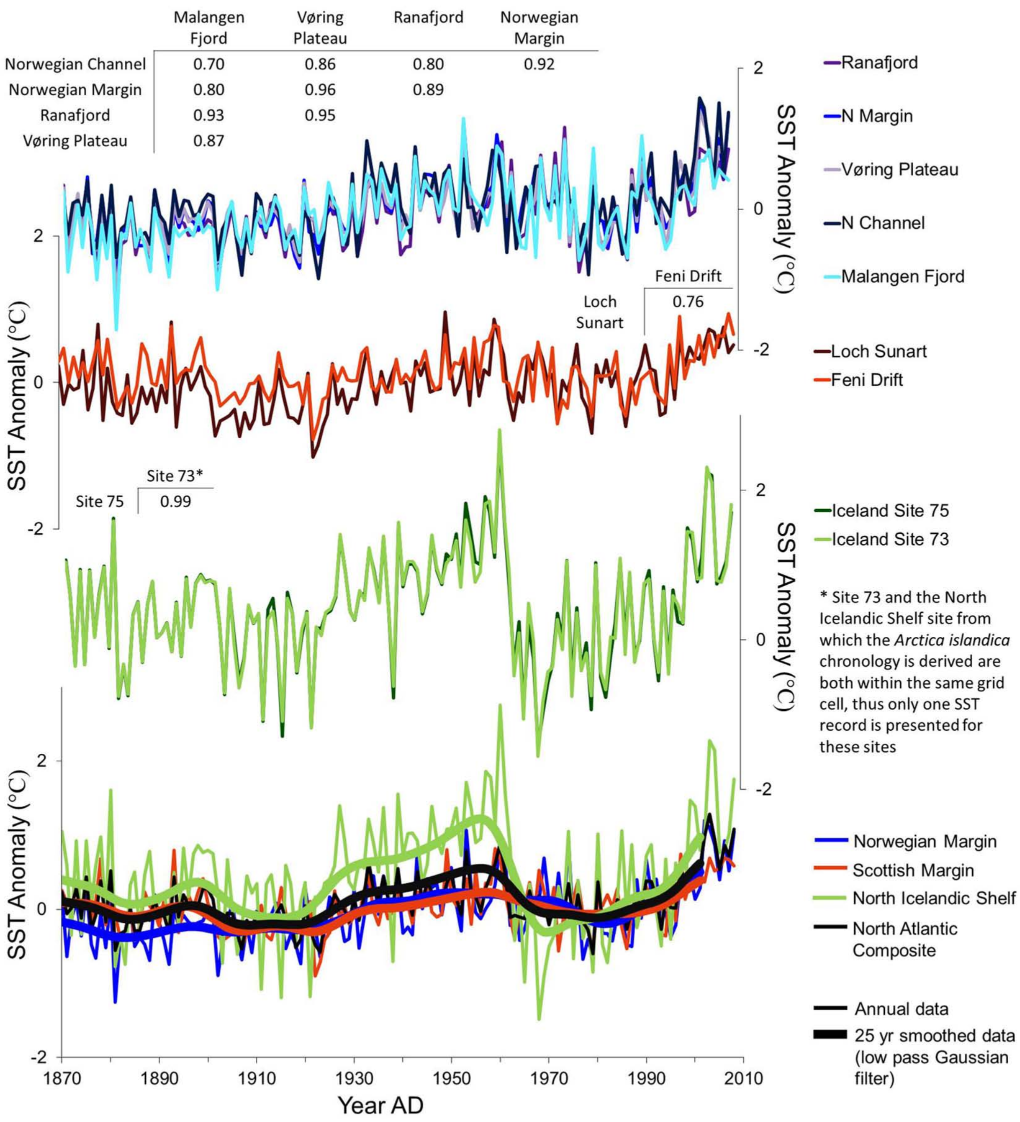


Figure 2. Comparison of HadISST1data for the grid point closest to each proxy record, both within each region and between the different regions of interest (see text for details).

Spatial patterns of the proxy records

To investigate the variability of individual reconstructions in relation to overall synoptic patterns, we determined how each record varied around the long-term mean of the common period (AD 1253–1974). Sites that varied by more than 1 standard deviation from the long-term average SST were highlighted as either warmer or cooler (Figure 1). This analysis was undertaken for three time intervals, namely: (1) AD 1900–present; (2) AD 1800–1900; and (3) AD 1150–1250 with the latter two time intervals loosely corresponding to the 'Little Ice Age' and 'Medieval Climate Anomaly', respectively. There is a great deal of debate as to the extent and timing of both the 'Little Ice Age' and 'Medieval Climate Anomaly' (Bradley and Jones, 1993; Matthews and Briffa, 2005) and the periods used within this paper were selected somewhat arbitrarily; however, the period AD 1150–1250 enables the inclusion of all but one record, thus providing a more geographically representative overview.

During the 20th century, the Scottish and coastal Norwegian locations show a strong and consistent tendency to be warmer than the long-term average temperature (Figure 1). These locations are directly influenced by the easternmost branch of the North Atlantic Current, or Norwegian Current, thus the marine evidence appears consistent with a stronger Atlantic Meridional Overturning Circulation at this time, linked to enhanced North Atlantic Current flow and northward heat transport. Away from the Norwegian coast and to the north of Iceland, temperatures have remained below the long-term mean, suggesting that the North Atlantic Current influence is not as strong at these locations during this time. This could potentially be explained by a reduced lateral extent of the North Atlantic Current because of wind forcing (Blindheim et al., 2000). Other potential explanations for these observations also include a reduced inflow of the North Atlantic Current through the western branches of the North Atlantic Current (including the Irminger Current) or from increased input of polar waters into the region via the East Icelandic Current, such as occurred during the Great Salinity Anomaly in the 1960s (Dickson et al., 1988).

Of the proxy records that show a deviation from the long-term mean between AD 1800 and 1900, all but Malangen Fjord (Site 1) indicate lower SSTs, suggesting widespread cooling of the ocean surface consistent with a reduction in Atlantic Meridional Overturning Circulation strength and hence reduced North Atlantic Current heat transport during the latter part of the 'Little Ice Age' (Figure 1). This time period represents the coolest century of the last millennium in five of the 11 records (Figure 3) thus further confirming the widespread nature of this cooling trend.

During the interval AD 1150–1250, a period which coincides with the later part of the 'Medieval Climate Anomaly', SSTs were typically higher than their long-term average (Figure 1). In contrast to the 20th century pattern (Figure 1), the coherency of the temperature signal indicates that 'Medieval Climate Anomaly' warming was more geographically widespread. The observed pattern of summer SST warming clearly indicates enhanced heat transfer via the North Atlantic Current at this time, consistent with the suggestion that the 'Medieval Climate Anomaly' was characterized by a predominantly positive winter North Atlantic Oscillation phase linked with enhanced Atlantic Meridional Overturning Circulation and heat transfer into the Nordic seas (Trouet et al., 2009, 2012; Wanamaker et al., 2012). It should be stressed that, despite this general agreement, these synoptic comparisons represent short periods of time and do not imply synchronous or pervasive changes throughout the record. Furthermore, although the recent period and 'Medieval Climate Anomaly' were both characterized by predominantly strong and positive winter North Atlantic Oscillation phases, the difference in the regional patterns of SSTs observed between these two time periods highlights the complexity of ocean dynamics within the region and could suggest different forcing mechanisms which could potentially also include direct atmospheric forcing.

Composite records

All proxies will have a component of climatically related signal and a component of noise. Combining proxy records should accentuate the common climatological signal whilst minimizing the random and proxy specific error of each series. This method may also help overcome problems resulting from poor dating control. Although combining multiple data-series can accentuate the common signal, this approach represents a compromise as gains in signal strength are offset by the loss of spatial information. Thus, as well as noise, some of the real spatial differences observed between the geographical locations will be averaged out. Such compromises between regional variability and climate signal are found in all the large-scale composites such as the Northern Hemisphere near-surface air temperature reconstructions (D'Arrigo et al., 2006; Esper et al., 2002; Ljungqvist, 2010; Ljungqvist et al., 2012) and the Arctic regional reconstruction (Kaufman et al., 2009).

In this study, a composite plus regression method (Wilson et al., 2006, 2010) was used to create regional proxy records for Iceland and Norway, as well as a single composite record for the NE North Atlantic Ocean. A composite record was not created for the Scottish margin sites as only the Loch Sunart record passed the screening criteria.

In agreement with previous studies (e.g. Bemis et al., 1998; Kim and O'Neil, 1997; Zeebe, 1999), a negative correlation was observed between foraminiferal oxygen isotope values and SSTs (Table 1 and supplementary material (available online)). The oxygen isotope series were therefore multiplied by −1 to ensure that all records had the same relative sign with respect to SST thereby facilitating compositing. Gridded May to October SST data (HadISST1; Rayner et al., 2003) were averaged over each region of interest, thus forming the target data-series. A nested approach (Wilson et al., 2010) was used whereby the first nest consisted of the mean of all the proxy data after normalisation to a common period, whilst the second nest omitted the shortest proxy series, thus extending the record further back in time (Table 2). The second shortest proxy series was then omitted before averaging to form Nest 3 which spans the last 1000 years. The quality of each mean nested series was assessed using the coefficient of determination (r^2) and the regression standard error of the estimate to quantify the decrease in confidence back in time. The resultant regression equations were used to transform the mean normalized series SST data to degrees Celsius. These three 'nests' were then spliced together forming a single composite mean record. As this method incorporates ordinary least squares regression, the resulting reconstruction will underestimate temperature variability (Christiansen et al., 2009; von Storch et al., 2004).

Creating a composite SST record from the Norwegian margin

A degree of variability is observed between the different proxy records from Norway (Figure 3a; supplementary material (available online)) which probably reflects both the spatial heterogeneity of oceanographic dynamics at the various sites as well as proxy specific uncertainties. Despite this, a strong relationship (r^2 = 0.71) is observed between the composite of these seven series and HadISST1.1 data averaged over the same region. This suggests the composite is adequately capturing climatic information over a regional scale, presumably reflecting the common

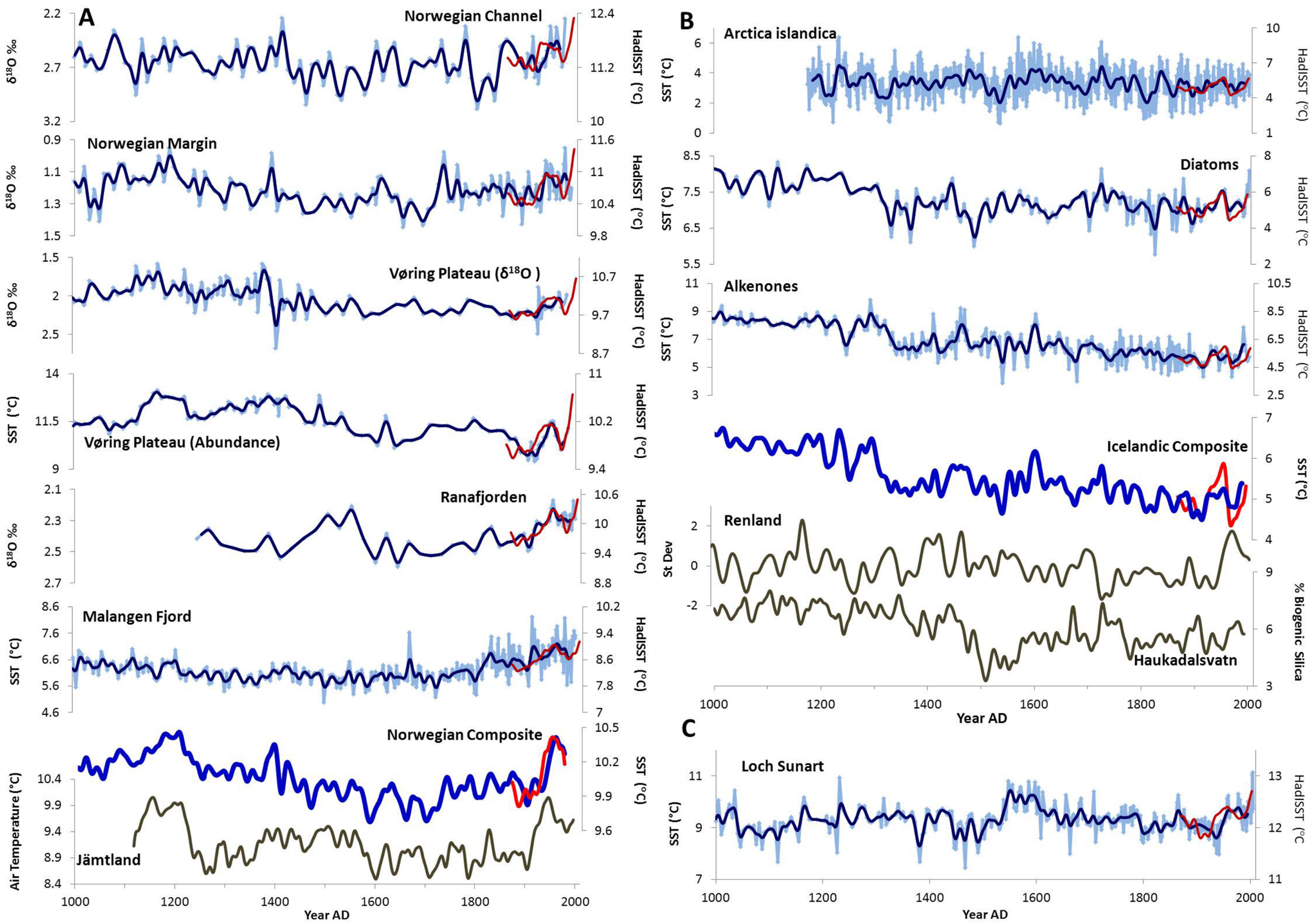


Figure 3. (a) Individual proxy records from Norway, the regional composite constructed from these six records and an April–August air temperature reconstruction from Jämtland in central Sweden (Gunnarson et al., 2011); (b) individual proxy records from Iceland and the regional composite derived from these three records are compared with a proxy record of biogenic silica from Haukadalsvatn (an Icelandic lake), which represents April–May air temperatures (Geirsdóttir et al., 2009) and a temperature reconstruction from the Renland ice core in Greenland (Kaufman et al., 2009; Vinther et al., 2009); and, (c) the Loch Sunart record from the Scottish Margin. The original proxy series (thick light line) are shown in addition to the series utilized within this paper (thick dark line) which were linearly interpolated to an annual series prior to smoothing with a 25 yr Gaussian filter. The HadISST 1.1 data for the grid cell within which the proxy record is located is also shown by (thin line). Correlations between the individual proxy records and the applicable HadISST data are shown in Table 1 (colour figure available online).

influence of the North Atlantic Current. This conclusion is further supported by a relatively strong correlation (r = 0.65; AD 1117–1974) between the Norwegian composite and the Jämtland tree-ring based April–September surface air temperature reconstruction from central Scandinavia (Figure 3a) that spans the last 900 years (Gunnarson et al., 2011). Linderholm (2001) has previously suggested a link between SSTs in the North Atlantic and air temperature records from this region.

Creating a composite SST record for the Icelandic margin

The Icelandic records (Figure 3b) are more consistent with each other than the Norwegian records, possibly reflecting the smaller geographical area covered by the proxies (Figure 1; see supplementary material (available online) for further comparisons between these three records). Given the dynamical setting, it is likely that additional Icelandic records spanning a wider geographical area would show greater variability. The relationship between a composite record consisting of these three proxies and the relevant HadISST1 data (r^2 = 0.32) (Figure 3) is stronger than those observed between the individual series and the gridded data (r^2 = 0.16–0.25), clearly demonstrating the improved signal to noise ratio that results from compositing.

The Icelandic composite record shows some similarities (r = 0.57; AD 1000–1974) with a biogenic silica record from Haukadalsvatn (an Icelandic lake) that is qualitatively interpreted as April–May air temperature (Geirsdóttir et al., 2009). One feature common to both these records is a pronounced 'Medieval Climate Anomaly', with temperatures higher than the most recent period of the reconstructions (Figure 3b). The composite record shows this warm period abruptly ending approximately AD 1300, while Geirsdóttir et al. (2009) infer a later, and more gradual cooling. In contrast, based on the $\delta^{18}O$ of planktonic and benthic foraminifera, Castañeda et al. (2004) suggest cooling of SST and bottom water temperatures commenced approximately AD 1050. Knudsen et al. (2012) found an early cooling around AD 1150–1250 based on their interpretation of transfer function results and the $\delta^{18}O$ of planktonic and benthic foraminifera. The marine composite does not show a statistically significant correlation with the adjusted $\delta^{18}O$ temperature record derived from the Renland ice core in Greenland (Kaufman et al., 2009; Vinther et al., 2009), probably reflecting the absence of a long-term cooling trend in the latter record (Figure 3b).

Creating a NE North Atlantic composite SST record

The two regional composites and the single record from Scotland all show slightly different climatic histories (Figure 3). An elevated 'Medieval Climate Anomaly' is observed within both the Icelandic and Norwegian regional composites. The Icelandic composite indicates that SSTs during the 'Medieval Climate Anomaly' were higher than the most recent period of the reconstruction (1950–1975), whereas this is not the case for the Norwegian composite. These differences highlight the spatial heterogeneity of the SST signal and regional ocean dynamics over the last millennium. While recognizing this spatial variability, we proceeded with an inter-regional composite to assess whether this would capture larger-scale processes and thus provide further insight into climatic forcing across the region. The inter-regional NE North Atlantic composite compares reasonably well with the HadISST1.1 SST data averaged over the same area (Figure 4a). The strength of the regression decreases as the number of proxy records is reduced, ranging from r^2 = 0.41 for Nest 1 to r^2 = 0.31 for Nest 3 (Figure 4).

The NE North Atlantic composite indicates that SSTs were warm during the 'Medieval Climate Anomaly', followed by a long-term decrease until around the 1940s (Figure 4a). This decreasing trend is 0.02°C per century, in good agreement with an orbitally induced decrease in summer solar insolation of 0.33 W/m^2 at 45°N during the last millennium (Hegerl et al., 2007). While an increase in SSTs is apparent within the most recent period of the record, the reconstruction only extends up to AD 1975. Direct comparison between the most recent warming (Figure 2) commonly attributed to anthropogenic greenhouse gas emissions and the 'Medieval Climate Anomaly' is therefore not possible. Similarly, splicing meteorological data onto the composite record would not be appropriate because of statistical constraints associated with the end effects of smoothing.

Spectral analysis

A multitaper method of spectral analysis (Mann and Lees, 1996) was performed to identify potential oscillatory behavior in the full NE North Atlantic composite reconstruction time series. Significant spectral peaks were identified at 102–128 years, 51–59 years, 38–43 years and 30–32 years (Figure 5a). This was consistent with the results of singular spectrum analysis (Vautard and Ghil, 1989) which identified oscillatory modes at 111 years, 55.6 years, 40 years and 31.3 years (Figure 5b). The 111 year mode shows weaker amplitude variance from the 15th to the 17th centuries, while the 55.6 year mode is generally more stable although variance is marginally weaker in the 14th and 20th centuries. Both the 40 and 31.3 year modes show weak variance prior to 1200 with the former showing weaker variance in the 18th century and the latter mode in the 17th century.

The spectral peaks identified here are consistent with other studies of ocean variability from this region, including highly resolved and more accurately dated records. Hall et al. (2010) reported an apparent periodicity of ~42 years in Mg/Ca-derived SSTs from the subpolar North Atlantic. Spectral peaks between 56–59 years and 116–117 years have also been identified in sea-ice proxies from the North Icelandic shelf, although the significance of these peaks varies between sampling location and the time frame considered (Moros et al., 2006). Wavelet analysis of a 4500 year long alkenone SST record from the North Icelandic site MD99-2275 also revealed strong oscillations in the 50–150 year band that were attributed to AMOC (Sicre et al., 2008b) and possibly reflect internal ocean variability (Delworth and Zeng, 2012). Gray et al. (2004) demonstrated significant multidecadal variability (40–80 years) in a proxy-based reconstruction of the Atlantic Multidecadal Oscillation, with the strongest peak having a frequency of 42.7 years. Similarly, Knudsen et al. (2011) reported that during the last 8000 years, variability in the North Atlantic has been dominated by a 55–70 year periodicity. This 55–70 year oscillatory pattern was not directly linked to solar activity, suggesting instead that this is related to internal ocean–atmosphere variability (Knudsen et al., 2011). Ice-core data from Greenland also indicated a 45–65 year quasi-periodicity in the Atlantic Meridional Overturning Circulation, however, a dominant 20 year mode was also observed, particularly during the LIA (Chylek et al., 2012). The intermittency of these signals further indicates internal ocean–atmosphere processes with little external forcing (Chylek et al., 2012). Modeling results also suggest that 38 and 110 year cycles in the ocean to atmosphere heat flux from the Atlantic Ocean can be attributed to natural internal variability rather than solar activity (Stocker and Mysak, 1992).

It should be noted, however, that only 18.2% of the total variance within the NE North Atlantic composite is explained by the four oscillatory modes identified above (111 years, 55.6 years, 40 years and 31.3 years). If these oscillations are related to internal forcing in the NE Atlantic system, this suggests that quasi-periodic internal forcing of ocean variability has had only

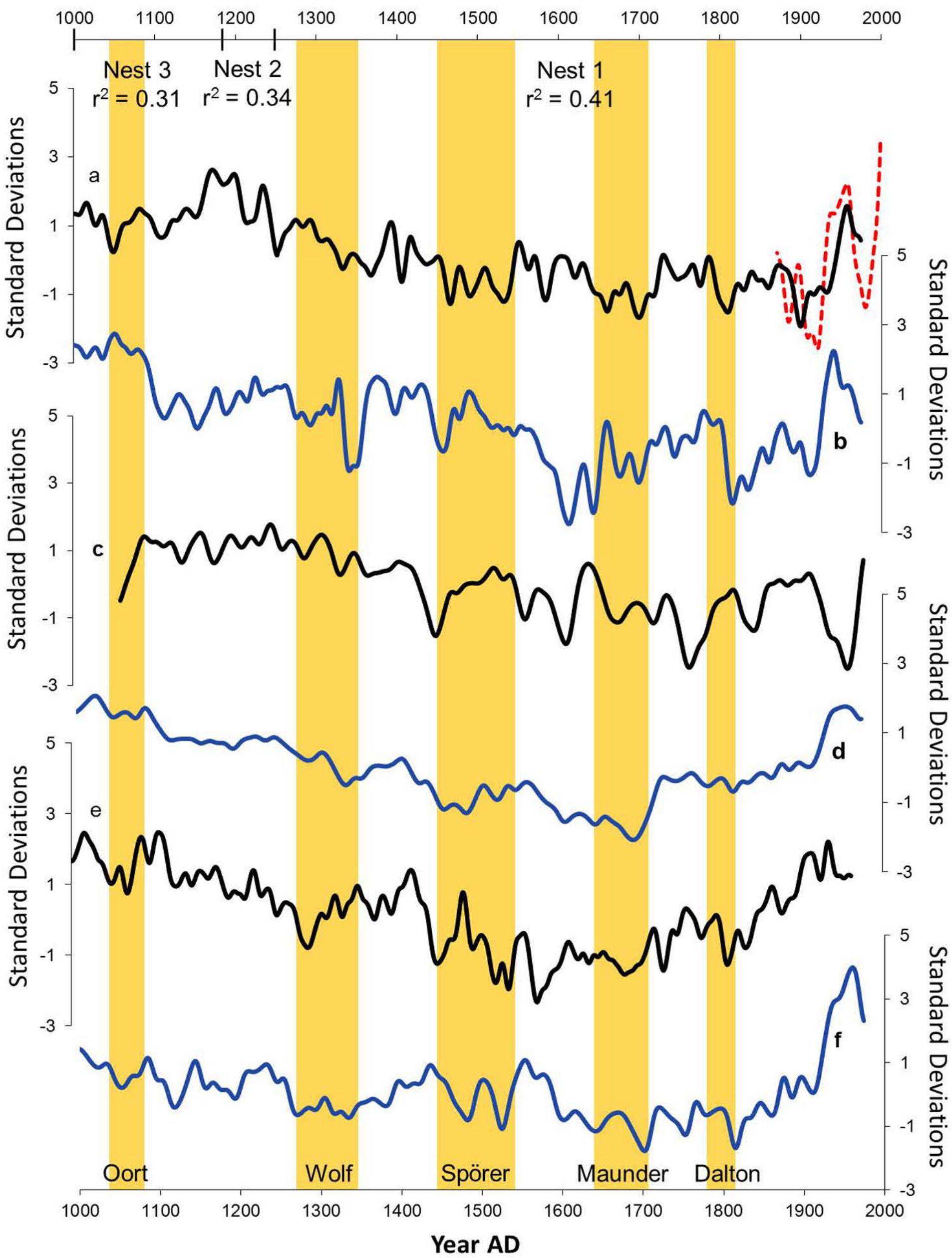


Figure 4. (a) The NE North Atlantic composite SST reconstruction (solid line) compared with the May–October HadISST data averaged over this region (dotted line) with other regional and large-scale proxy based climate reconstructions, namely: (b) the Atlantic Multidecadal Oscillation (Mann et al., 2009); (c) the North Atlantic Oscillation (Trouet et al., 2009); (d) extra-tropical Northern Hemisphere temperatures (Ljungqvist, 2010); (e) Northern Hemisphere temperatures (Moberg et al., 2005); and (f) Arctic air temperatures (Kaufman et al., 2009). Shaded columns indicate solar minima (colour figure available online).

a relatively weak influence on climatic variability during the last millennium. In fact, the majority of the overall variance (79.5%) of the marine composite is related to the secular scale (>200 years) trend (mostly a linear decrease) which is potentially associated with the orbitally forced, long-term decline in summer solar insolation from the 'Medieval Climate Anomaly' until the 20th century. This suggestion is consistent with the findings of Knudsen et al. (2011) who noted that the dominance of the 55–70 yr oscillation has weakened since 2000 BP in association with the general decline in SST. Shorter-term changes in solar irradiance may also contribute to the observed variability in SSTs, as three of the four coldest periods coincide with the Spörer, Maunder and Dalton solar minima (Figure 4).

Comparisons with other modes of climate variability

Over decadal timescales, summer SSTs within the North Atlantic Ocean are influenced by the Atlantic Multidecadal Oscillation. The Atlantic Multidecadal Oscillation is a large-scale pattern of variability in SSTs which is associated with internal climatic variability linked to Atlantic Meridional Overturning Circulation (Delworth and Mann, 2000; Knight et al., 2005). The marine composite reconstruction correlates well (r = 0.64; AD 1865–1974; 25 yr Gaussian smoothed data) with the observed Atlantic Multidecadal Oscillation index (Enfield et al., 2001) calculated from an area weighted average of the Kaplan et al. (1998) SST

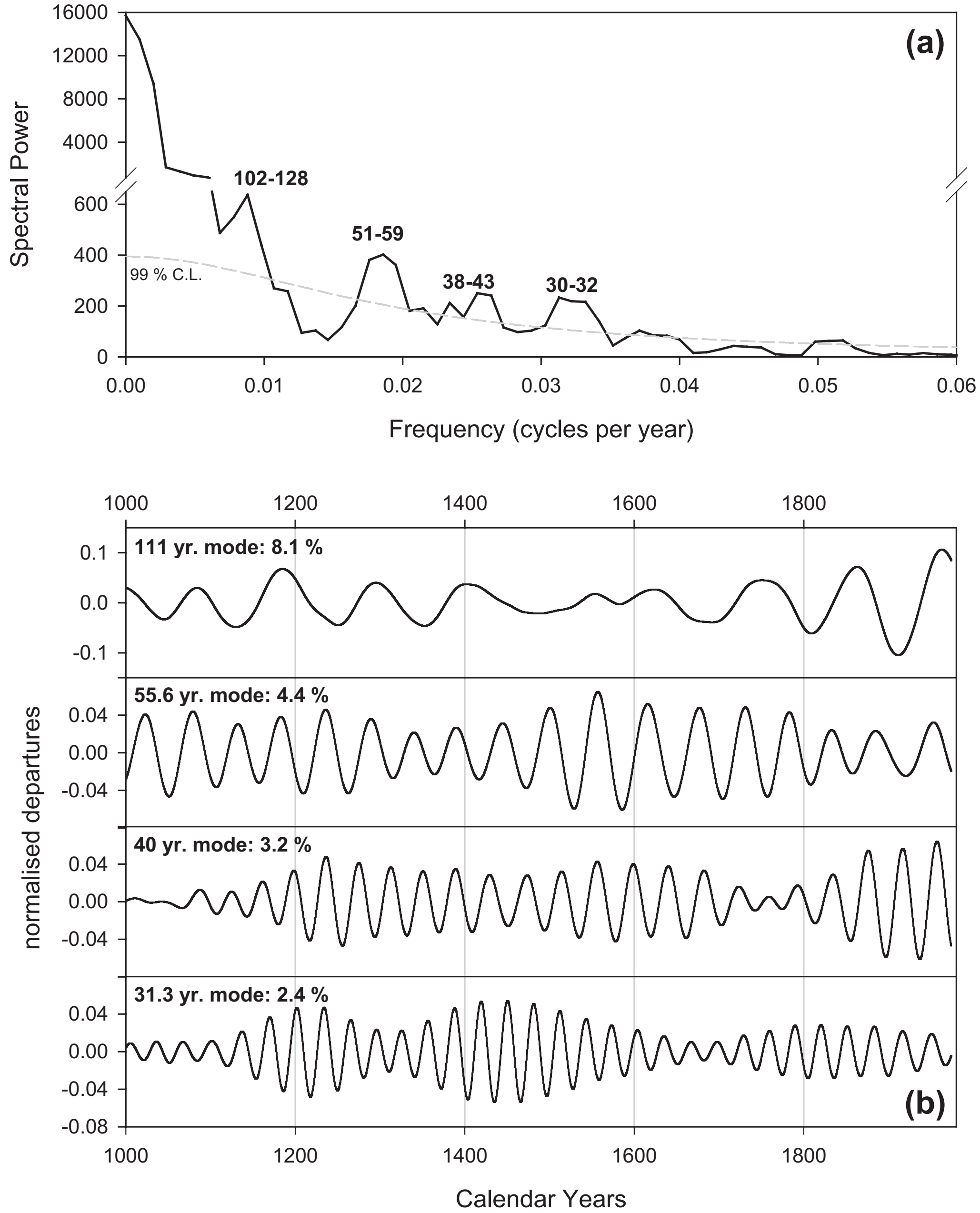


Figure 5. (a) Multitaper method spectral analysis (Mann and Lees, 1996) for the full marine composite series (1000–1974). Number of tapers = 3; dashed significance line = 99% CL. Significant spectral peaks are labeled. (b) Oscillatory modes identified through singular spectrum analysis (Vautard and Ghil, 1989). The percentage values denote the amount of variance explained by each mode.

series over the North Atlantic (0–70°N). This correlation indicates that the changes in SST observed within the composite record reflect broader regional changes. This is further supported by a significant correlation (r = 0.54; AD 1000–1974) between the marine composite record and the independent Mann et al. (2009) reconstruction of Atlantic Multidecadal Oscillation during the last millennium (Figure 4b). Furthermore, quasi-persistent ~55–70 year oscillations within proxy records from the North Atlantic region have previously been linked to the Atlantic Multidecadal Oscillation (Knudsen et al., 2011), consistent with the 55.6 yr oscillation observed within the marine composite presented here (Figure 5). A longer alkenone record from the North Icelandic Shelf also attributed strong oscillations in the 50–150 year band to dynamics within the Atlantic Meridional Overturning Circulation (Sicre et al., 2008b).

To date, most reconstructions of the Atlantic Multidecadal Oscillation predominantly incorporate dendrochronological records (e.g. Gray et al., 2004; Mann et al., 2009). The analyses presented here indicate the feasibility of creating more direct reconstructions of the Atlantic Multidecadal Oscillation based on multiple marine records. The observed correlation with the Atlantic Multidecadal Oscillation could potentially be further improved through incorporating only the higher-resolution records with more robust age–depth models. Observational and proxy data suggest that the Atlantic Multidecadal Oscillation influences climate variability across North America and Europe as well as in Eurasia (Feng and Hu, 2008; Knight et al., 2006) thus the Atlantic Multidecadal Oscillation may partially explain some of the similarities observed between the marine composite and regional air temperature reconstructions. This suggestion is speculative

however, as the underlying driver of the Atlantic Multidecadal Oscillation and potential interconnections with terrestrial climate regimes and higher frequency (~7–25 yr) atmospheric patterns (such as the North Atlantic Oscillation and Arctic Oscillation) still needs to be resolved (Gray et al., 2004).

A comparison of the NE North Atlantic composite with the North Atlantic Oscillation reconstruction (Trouet et al., 2009) shows a moderate correlation (r = 0.49; AD 1049–1974; 25 yr Gaussian smoothing; Figure 4c). The North Atlantic Oscillation has a strong spatial component (Grossman and Klotzbach, 2009; Marshall et al., 2001), thus the compositing approach applied herein could potentially obscure any relationships between the North Atlantic Oscillation and the regional records. This does not appear to be the case, however, as the regional composites for Iceland and Norway showed slightly weaker correlations with the North Atlantic Oscillation (r = 0.40 and r = 0.45, respectively, for the time period AD 1049–1974) than the NE North Atlantic composite. Differences in seasonality may contribute to the variations observed between the May to October SST record presented here and the Trouet et al. (2009) reconstruction, as the North Atlantic Oscillation is predominantly a winter phenomenon. However, the marine composite similarly correlates (r = 0.45; AD 1661–1965) with warm season sea-level pressure associated with the related Arctic Oscillation (D'Arrigo et al., 2003). This suggests that the North Atlantic Oscillation or Arctic Oscillation do not play a major role in influencing summer SSTs in this region, at least on the timescales examined in this study. This is consistent with the findings of Walter and Graf (2002) who showed that the strong correlation between SST and the North Atlantic Oscillation observed since the 1960s is not maintained over time.

Comparisons with air temperature reconstructions

Similar long-term trends are observed between the NE Atlantic composite, the Ljungqvist (2010) extra-tropical Northern Hemisphere reconstruction (Figure 4d; r = 0.69; AD 1000–1974) and the Moberg et al. (2005) Northern Hemisphere reconstruction (r = 0.58; AD 1000–1969), reflecting the link between SSTs in the NE Atlantic and large-scale climate dynamics. The maximum anomaly during the 'Medieval Climate Anomaly' occurs about 100 years later in the SST reconstruction than in the Ljungqvist and Moberg reconstructions, thereby agreeing well with reconstructions of solar activity (Bard et al., 1997; Muscheler et al., 2007). The coolest part of the 'Little Ice Age' is similarly delayed in the NE Atlantic composite occurring ~AD 1800 and again ~AD 1900 as opposed to ~AD 1700 and ~AD 1600, respectively, in the Ljungqvist (2010) and Moberg et al. (2005) reconstructions. Recent warming is considerably more abrupt in the SST record although all three reconstructions suggest that mid-20th century temperatures have returned to levels close to those last seen during the warmest parts of the 'Medieval Climate Anomaly'. The reconstruction of Arctic air temperatures (Kaufman et al., 2009; r = 0.41; AD 1000–1974; Figure 4f) also shows pronounced warming during the 20th century, however these exceed temperatures reconstructed for the 'Medieval Climate Anomaly', potentially reflecting polar amplification of recent warming (cf. Spielhagen et al., 2011). The Arctic record has a long-term cooling trend that persists throughout the last millennium (and indeed through the past two millennia). This trend reaches its coolest point in the early 19th century, comparable with the coolest point of the NE Atlantic SST composite (Figure 4a, d). Overall, these results indicate that the composite SST record adequately reflects large-scale climatic dynamics despite the potential damping of local-scale information.

Uncertainties

Reconstructions of the climate of the last millennium derived from marine sediment cores are often hampered by poorly defined uncertainties, and we feel that a discussion of these uncertainties is needed to appreciate the marine composite record detailed herein. Within the current study, several potential sources of error or uncertainty can be identified, including the methodological approach used, chronological errors, sample replication, spatial heterogeneity and calibration error.

Methodological uncertainties

All climate reconstructions rely on the assumption of a stable relationship between the proxy data and measured temperature data during a common period, called the calibration period (Christiansen and Ljungqvist, 2011). Calibration is commonly done using ordinary least squares regression or simple scaling (i.e. same mean and standard deviation; Esper et al., 2005). In this study, we calibrate using linear regression and utilise the standard error of the prediction to generate 2-sigma error ranges (Figure 6) to account for past temperature estimates outside the range of the instrumental data and subsequent increase in uncertainty for these periods.

The choice of compositing methodology can also influence the resulting large-scale mean series. To assess the uncertainty associated with this, other methodological approaches, including simple compositing with and without variance stabilization (Osborn et al., 1997) and spatially weighted averaging, were also explored. The final composite series did not significantly change between each methodological variant (Figure 6a) with the largest deviation being noted around 1550–1650 for the 'equal regional weighting' option where the single Scottish record is weighted more strongly compared with the individual records from the other regions. Overall, after calibration, the difference between the four variants is minimal (Figure 6a), and we therefore conclude that the broad secular scale features in the series are robust irrespective of the exact methodology applied.

Finally, within an individual proxy series, different methods of combining data from multiple sediment cores also represent a source of uncertainty. To investigate this, we examined the effects of different 'splicing' methods associated with the alkenone data from the North Icelandic Shelf (see supplementary material (available online) for further information). This demonstrated that variations within the individual record produced only minor alterations to the amplitude of change observed within the composite record (Figure 6b), thus again highlighting the advantage of a composite approach to emphasizing the climatic signal whilst reducing potential errors associated with individual series.

Chronological uncertainties

Uncertainties associated with the dating methods are often poorly constrained in palaeoceanographic reconstructions of the last millennium. For example, large variations (of up to 200 years) in the radiocarbon reservoir age can occur in dynamic oceanic settings, such as the North Icelandic Shelf (Eiríksson et al., 2011). Despite this, potential errors associated with chronological uncertainties are rarely incorporated into sediment age–depth models and the resulting reconstructions. Within the current study, we have relied on the published age–depths models. The influence of any age uncertainties should be partially mitigated by the 25 yr Gaussian filter used to smooth the records. A 25 yr filter is appropriate given the average sample resolution of the selected proxy records was typically better than one sample every 10 years (Table 1). This is consistent with previous

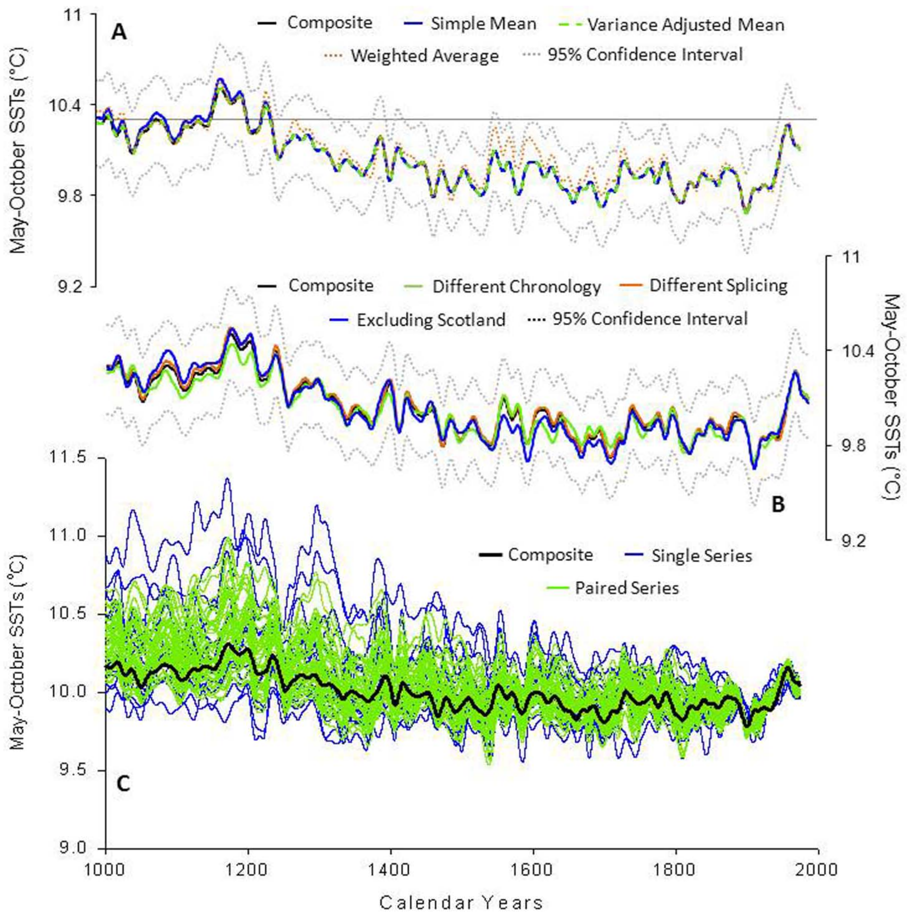


Figure 6. Comparison of the NE North Atlantic SST composite with (a) reconstructions produced using different methodologies, namely simple averaging, variance adjusted simple averaging and spatially weighted simple averaging; and (b) variants that, respectively, incorporated a different age–depth chronology for the Norwegian Margin Record, a different splicing method for the alkenone data from the North Icelandic Shelf and excluded the Scottish Margin data; (c) ensemble composite plots of all possible single (1 series from both Iceland and Norwegian shelf) and paired (2 series from both Iceland and Norwegian shelf) composite time series. Each series has been regressed to the target (May–October) SST instrumental series (1880–1974). The thin horizontal line in (a) shows the mean value of the instrumental data for the 25 year period between 1984 and 2008.

studies (e.g. Kaufman et al., 2009; Ljungqvist et al., 2012; Moberg et al., 2005) where the chronological uncertainties of individual records are not addressed other than by smoothing. However, to further investigate the influence of chronological uncertainties within this study, the effects of two alternative age-models from the Norwegian Margin record (Berstad et al., 2003; Sejrup et al., 2010) were explored using a sensitivity analysis. The initial age-model (Berstad et al., 2003) had an error of ±140 years and was based on ^{210}Pb and ^{137}Cs in combination with two radiocarbon dates. A revised age-model (Sejrup et al., 2010) included an additional seven radiocarbon dates within the last millennium (and a total of 90 dates spanning the Holocene) as well as tephrochronology, thereby reducing the reported chronological error to ±20 years.

The revised record for the Norwegian Margin (Sejrup et al., 2010) revealed that the initial chronology (Berstad et al., 2003) progressively overestimated the age of samples. Despite this, the chronological differences of using the two variants resulted in only minor changes to the final composite record with a correlation of $r = 0.98$ between the two composite variants. The changes predominantly affected the amplitude of change rather than the timing (Figure 6b). These findings are reassuring given the chronological uncertainties associated with several of the proxy records incorporated within this study and highlights the strength of a composite approach whereby uncertainties within individual records are minimized. The relatively good correlations observed between the NE North Atlantic composite record and annually resolved palaeoclimate reconstructions, including the common oscillatory modes, also suggest that chronological uncertainties have relatively little impact at timescales >25 years within this study.

Spatial heterogeneity

The compromise between spatial dynamical information (see Figure 1) and large-scale applicability is apparent in a comparison between the composite records from the individual regions and the NE North Atlantic composite (Figures 3 and 4). The Norwegian composite (which integrates six proxy records) unsurprisingly shows the most similarity to the full NE North Atlantic composite. The Icelandic composite (three proxies) shows a warmer and more sustained ‘Medieval Climate Anomaly’, and reduced recent warming, compared with the inter-regional composite. In contrast, the Scottish record shows a much cooler ‘Medieval Climate Anomaly’. Although such differences may seem critical, a sensitivity analysis (Figure 6b) indicates the Scottish record does not significantly influence the NE North Atlantic composite.

In order to assess the relatively robust nature of the long-term trends in the full composite record and to quantify the sampling distribution from the data, we undertook a subsampling exercise of all possible single and paired composite variants using records from both the Icelandic and Norwegian shelves. This results in 18 single and 45 paired composite series. This demonstrated that the basic long-term shape of the composite remains relatively stable even if the proxy data is limited to only one or two records from Iceland and Norway (Figure 6c). In almost all iterations, the 'Medieval Climate Anomaly' is clearly warmer that the 1450–1900 period and therefore appears to be a robust feature of the NE North Atlantic region. This also highlights that combining multiple records reduces the overall variance observed, as localized differences are averaged out. This is also true of terrestrial records (Jansen et al., 2007). As discussed above, this potentially results in the loss of small-scale spatial information but can also strengthen the observed larger-scale climate/proxy relationship and help identify external forcing related signals.

Replication

Another issue that pervades palaeoceanographic reconstructions based on marine records is lack of replication. There are many reasons for this, not least cost. Such lack of replication demands caution when integrating and compositing marine data. However, integration of data from widely separated non-replicated records tests the strength of any common signal and thus contributes to circumventing the replication issue. As stated above, the composite reconstruction was relatively stable even when restricted to only one or two records from each of Norway and Iceland (Figure 6c), thus reflecting the strength of the common large-scale climatic signal.

Conclusions

This paper presents the first composite SST reconstruction for the NE North Atlantic region, incorporating ten records from Norway, Iceland and Scotland. The proxy records show differences both within and between regions. Compositing these records therefore represents a compromise between the loss of localized dynamical information while strengthening the signal to noise ratio of the final regional and larger-scale temperature reconstructions. We highlight the complexity of ocean circulation within the region, accepting that some of this complexity is lost when larger-scale composites are created. Accordingly, a larger-scale NE North Atlantic composite record was also produced, which correlated well with previous reconstructions of the Atlantic Multidecadal Oscillation and Northern Hemisphere air temperature records thus confirming the applicability of this approach. The composite SST reconstruction suggests that the warm 'Medieval Climate Anomaly' was most pronounced before AD 1200, with a long-term cooling trend apparent after AD 1250, consistent both with orbital forcing and a weakening Atlantic Meridional Overturning Circulation (Lund et al., 2006; Wanamaker et al., 2012). This cooling trend persisted until the early 20th century after which temperatures rose to be similar to those inferred for the 'Medieval Climate Anomaly'. This long-term cooling trend accounts for most of the variance observed within the NE North Atlantic composite record but, embedded within this, spectral analysis also identified oscillatory modes at 110, 55.6, 40 and 31 years which possibly reflect internal ocean variability associated with the Atlantic Multidecadal Oscillation.

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