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North Atlantic storminess and Atlantic Meridional Overturning Circulation during the last Millennium: Reconciling contradictory proxy records of NAO variability

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ABSTRACT

Within the last Millennium, the transition between the Medieval Climate Anomaly (MCA; ca. 1000–1300 CE) and the Little Ice Age (LIA; ca. 1400–1800 CE) has been recorded in a global array of climatic and oceanographic proxies. In this study, we review proxy evidence for two alternative hypotheses for the effects of this shift in the North Atlantic region. One hypothesis postulates that the MCA/LIA transition included a weakening of the Atlantic Meridional Overturning Circulation (AMOC) and a transition to more negative North Atlantic Oscillation (NAO) conditions, resulting in a strong cooling of the North Atlantic region. The alternative hypothesis proposes a MCA/LIA shift to an increased number of storms over the North Atlantic linked to increased mid-latitude cyclogenesis and hence a pervasive positive NAO state. The two sets of proxy records and thus of the two competing hypotheses are then reconciled based on available results from climate model simulations of the last Millennium. While an increase in storm frequency implicates positive NAO, increased intensity would be consistent with negative NAO during the LIA. Such an increase in cyclone intensity could have resulted from the steepening of the meridional temperature gradient as the poles cooled more strongly than the Tropics from the MCA into the LIA.

1. Introduction

An increasing number of high-resolution proxy records covering the last Millennium has become available in recent years (for an overview see Jones et al., 2009) providing an increasingly powerful reference frame for assessing current and future climate conditions. Synoptic-scale processes driving observed variations in these paleoclimate data have been simulated and interpreted using coupled climate models (e.g. Raible et al., 2007; Seager et al., 2008). Moreover, model simulations have proved to be useful in separating externally forced climate signals (Yoshimori et al., 2005), including volcanism (Fischer et al., 2007; Emile-Geay et al., 2008) and solar variability (Shindell et al., 2001), from internal climate variability, which is largely driven by ocean–atmosphere interactions (Wunsch, 1999; Raible et al., 2005; Seager et al., 2008; Gonzalez-Rouco et al., 2011).

Within the last Millennium, the transition between the Medieval Climate Anomaly (MCA; ca. 1000–1300 CE; Lamb, 1965) and the Little Ice Age (LIA; ca. 1400–1800 CE) has been recorded in a global array of climatic and oceanographic proxies, but the climate parameters involved in the transition, as well as the direction of the transition (positive to negative anomalies or vice versa), differ strongly between regions, proxies (Vinther et al., 2010; Diaz et al., 2011), and seasons (Goosse et al., 2012). The timing of the transition period is also subject to considerable incoherency, related partly to current limitations of proxy records, including location, linearity, and seasonality of the proxy response, and dating uncertainties (Trouet and Baker, 2009).

Graham et al. (2007), Seager et al. (2007), Herweijer et al. (2007), and Burgman et al. (2010) have compiled a global data set of proxies recording MCA/LIA hydroclimate and have postulated shifts in tropical Pacific SST patterns as the most likely drivers of the MCA/LIA transition. Modern analogs to spatial patterns of Medieval hydroclimate (Seager et al., 2007) suggest a La Niña-like state of the Medieval tropical Pacific Ocean, possibly in response to external radiative forcing (Emile-Geay et al., 2008). This led to the hypothesis that high solar irradiance and weak volcanism during the MCA (Crowley, 2000; Gao et al., 2008; Steinhilber et al., 2009) induced an east–west sea-surface temperature (SST) gradient along the tropical Pacific Ocean through the so-called thermostat mechanism (Clement et al., 1996; Mann et al., 2005). Within this mechanism, differences in thermocline depth between the western (deep) and eastern (shallow) tropical Pacific result in differing surface temperature responses to increased irradiance. In the western Pacific, surface heating results in surface temperature increases, whereas in the eastern Pacific it is offset by vertical advection and the surface temperature response is much

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smaller. The resulting increased zonal SST gradient enhances trade winds and leads to further anomalous upwelling and a La Niña-like state in the eastern tropical Pacific.

The purported La Niña-like state of the Medieval Pacific Ocean is hypothesized to affect the North Atlantic region in two potentially linked ways: (1) by strengthening the Atlantic Meridional Overturning Circulation (AMOC) (Seager et al., 2007) and (2) by inducing a positive North Atlantic Oscillation (NAO) anomaly through tropospheric dynamics (Pozo-Vazquez et al., 2001).

Seager et al. (2007) describe the La Niña–strong AMOC connection in the following way: Southern Hemisphere westerlies are shifted southward during La Niña phases (L'Heureux and Thompson, 2006); this increases the exchange of salty water between the Indian Ocean and the South Atlantic Ocean, which in turn leads to a stronger Southern Ocean upwelling, and thus an enhanced AMOC.

The link between La Niña-like conditions in the Pacific Ocean and positive NAO anomalies in the North Atlantic region has been debated (Fraedrich, 1994), but is documented for the instrumental data period (Pozo-Vazquez et al., 2001; Bronnimann et al., 2004) and over the past 300 years (Bronnimann et al., 2007). Bronnimann (2007) suggests three possible mechanisms for ENSO influence on the North Atlantic region: (1) through downstream propagation of the ENSO signal in the North Pacific (Moron and Gouirand, 2003), (2) through changes in the Atlantic Hadley circulation in the tropical Atlantic (Ruiz-Barradas et al., 2003), or (3) through a downward propagation of ENSO-induced stratospheric anomalies (Randel, 2004). Different mechanism chains could potentially modulate ENSO influence in different seasons (Moron and Plaut, 2003).

Trouet et al. (2009) and Mann et al. (2009) used a combination of high-resolution proxy records and model simulations to evince a prevailing positive NAO mode during Medieval times and a shift to negative NAO conditions in the following centuries. Trouet et al. (2009) further hypothesized that a persistent Medieval positive NAO phase may have enhanced the AMOC (Delworth and Greatbatch, 2000) which, given a possible connection of the AMOC and North Atlantic SST fluctuations with ENSO-type variability (Timmermann et al., 2007; Oglesby et al., 2012), may in turn have reinforced La Niña-like conditions in the tropical Pacific and thus may have provided a positive feedback mechanism resulting in a prolonged phase-locked ocean–atmosphere system. According to this hypothesis, a shift in the climatic system occurred around 1300–1450 that included a weakening of the AMOC (Palastanga et al., 2011), a decreased east–west SST gradient in the tropical Pacific, and a transition to more negative NAO conditions, resulting in a strong cooling of the North Atlantic region (Miller et al., 2010) and adjacent regions during the LIA. Decreasing solar activity and stronger volcanic activity are considered possible drivers of such climatic shifts (Trouet and Baker, 2009; Gonzalez-Rouco et al., 2011), but internal variability of the atmosphere–ocean system (Wunsch, 1999; Raible et al., 2005) is a plausible alternative hypothesis. It is worth noting in this context that on interannual scales, volcanic eruptions are followed by positive winter NAO phases (Fischer et al., 2007). Assuming that only volcanic forcing is the dominant factor, the shift from a period with rather reduced volcanic activity during the MCA to a period with enhanced volcanic activity during the LIA might thus be associated with a transition from negative to positive phases of the NAO, rather than vice versa.

However, a proxy-based body of evidence also exists that contradicts this hypothesis. The most prominent of these proxies is a high-resolution marine-source sea salt sodium (ssNa) record from the GISP2 ice core in central Greenland (Meeker and Mayewski, 2002). Even though this record is not derived from the north eastern sector of the Greenland ice sheet, where accumulation records are most strongly related to number of storms (Hutterli et al., 2005), it is assumed to be a proxy for storms over the adjacent ocean through the advection of salt spray and shows low values during the MCA and a marked transition at 1400 CE to higher levels during the LIA. Dawson et al. (2003) and Dawson et al. (2007) use this record to develop the hypothesis that the LIA was characterized by enhanced storminess (defined as increased number of storms) over the northern North Atlantic (including Greenland) linked to westerly cyclogenesis and hence a pervasive strengthened NAO state, contrasting with the Trouet et al. (2009) hypothesis and the Mann et al. (2009)modeling results. In section two of our paper, we review proxy records that indicate increased North Atlantic storminess during the LIA and thus corroborate the Dawson et al. (2007) hypothesis.

Given the fact of two contradicting hypotheses settled on proxy evidence, the purpose of this study is to review the two hypotheses in great detail in the following sections. In a third and final section, we expand upon existing model-based studies (e.g., Raible et al., 2007) to provide a possible reconciliation of the two hypotheses.

2. AMOC variability over the last Millennium

In their NAO index reconstruction, Trouet et al. (2009) implicate likely changes in the AMOC, hypothesizing strong AMOC during NAO positive phases (Delworth and Greatbatch, 2000) such as the MCA. It has been widely assumed that AMOC changes over the last 1000 years have played a key role in centennial-scale climate dynamics of the North Atlantic region (Denton and Broecker, 2008). The inference that changes in heat supply via AMOC have influenced North Atlantic atmospheric climate over the last Millennium is not new (cf. Lamb and Johnson, 1959; Bjerknes, 1965; Lamb, 1972; Bryson and Murray, 1977) and is supported by recent empirical observations and numerical simulations of AMOC variability over both longer-term geological (Rahmstorf, 2002) and shorter-term instrumental (Holliday, 2003) and historical (van der Schrier and Weber, 2010; Palastanga et al., 2011) timescales.

Yang and Myers (2007) published simulations from a regional eddy-permitting ocean model of the subpolar North Atlantic with buoyancy fluxes corresponding to persistent extreme states of the NAO consistent with the hypothesis that the MCA and LIA are characterized by pervasive phases of the NAO. Thereby, positive (negative) phases are associated with high (low) precipitation over and vigorous (weak) heat transports to NW Europe generated by a strong (weak) North Atlantic Current (NAC) associated with a northward (southward) shift of tracks of wintertime Atlantic depression systems. NAO negative phases over NW Europe are conversely characterized by pervasive strong blocking anticyclones mainly over the British Isles and reduced precipitation over NW Europe (Buehler et al., 2011). Over SW Europe and North Africa, more depressions develop and track into this region leading to increased precipitation during NAO negative phases.

A large number of observational studies are available from the North Atlantic region covering the last Millennium that we review here to test this “wobbly ocean conveyor” hypothesis (Denton and Broecker, 2008; Sejrup et al., 2010). Many of these records show a clear transition from the MCA into the LIA between 1300 CE and 1400 CE, and the transition out of the LIA after 1850 CE.

Influential centennial-scale Holocene-long North Atlantic sediment records that include the last 1000 years have been provided by Bianchi and McCave (1999) and Bond et al. (2001) (Fig. 1). Bianchi and McCave (1999), using the sortable silt proxy for bottom water current flow velocity (McCave and Hall, 2006), report a reduction in Iceland–Scotland Overflow Water (ISOW) flow speed across the MCA/LIA transition at Gardar Drift south of Iceland. ISOW is a precursor for North Atlantic Deep Water (NADW) mass and this reduction implies a weakening in deep convection and NADW formation consistent with a less vigorous AMOC. Similarly low-resolution data from deep-sea sediment cores west of Ireland (Bond et al., 2001) indicate an increase in ice-rafted debris (IRD) and hence iceberg transports at mid-latitude, that presumably indicate a reduction in warm surface NAC during this period. The low resolution and relatively poor dating

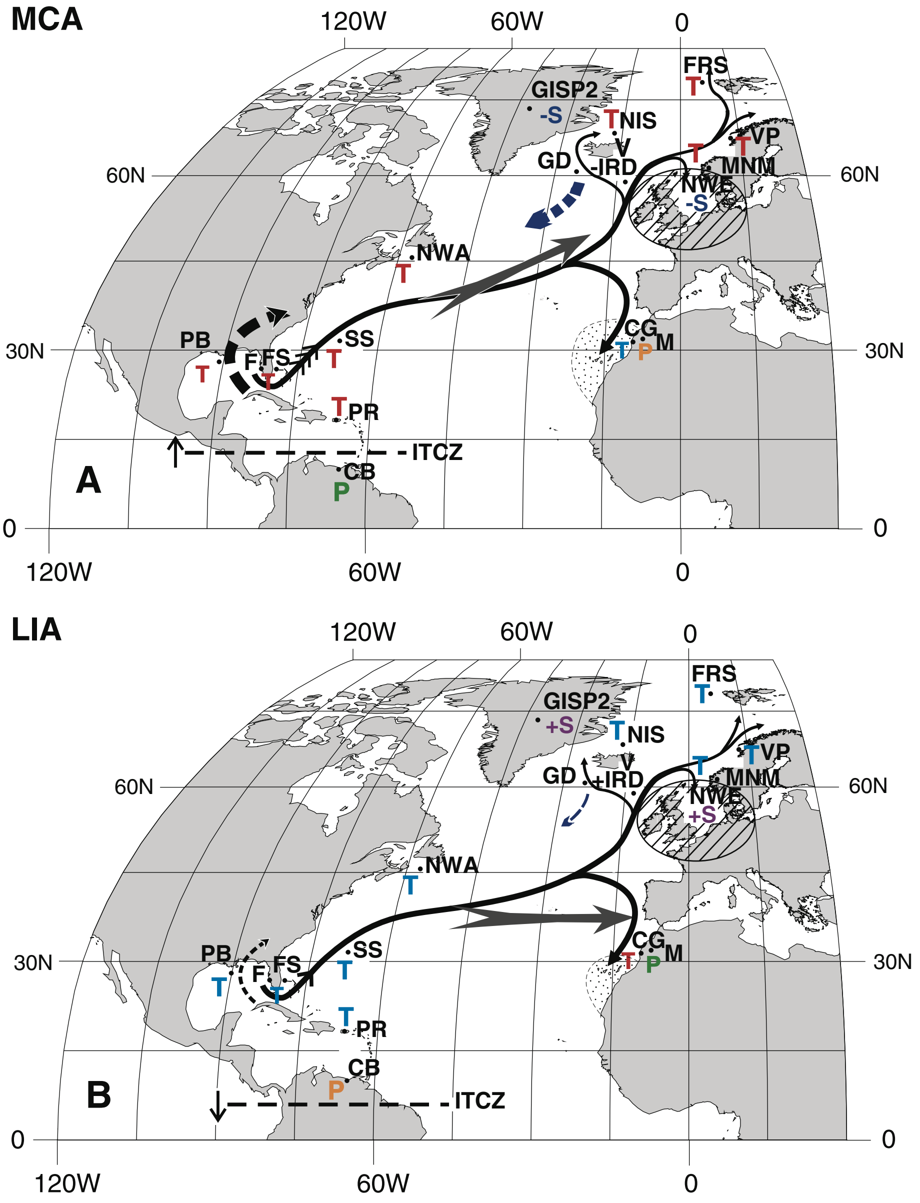

Fig. 1. North Atlantic ocean–atmosphere interactions during the Medieval Climate Anomaly (A; MCA; ca. 1000–1300 CE) and the Little Ice Age (B; LIA; ca. 1400–1800 CE). The maps indicate MCA and LIA conditions for precipitation (P; green = wet, orange = dry); mean annual sea surface temperature (T; red = warm, light blue = cool); storminess (S; violet = enhanced, dark blue = reduced) anomalies over North West Europe (NWE); amount of ice-rafted detritus (IRD); Gulf Stream/North Atlantic Current (black continuous arrow); main direction of Atlantic westerlies (gray continuous arrow); upwelling strength off North West Africa (dotted area); bottom current flow speed at Gardar Drift (GD; blue dashed arrow), and tropical hurricane frequency over the Gulf of Mexico (black dashed arrow). The number of arrows in the Florida Strait (FS) indicates Gulf Stream transport volume. CB = Cariaco Basin; PR = Puerto Rico; F = Florida; PB = Pigmy Basin; SS = Sargasso Sea; NWA = North West Atlantic; CG = Cape Ghir; M = Morocco; GISP2 = GISP2 ice core; NIS = North Icelandic Shelf; V = core V29-19; MNM = mid-Norwegian margin; VP = Vøring Plateau; FS = eastern Fram Strait; ITCZ = Intertropical Convergence Zone.

control in these studies is potentially problematic for resolving centennial-scale variability during the last 1000 years, but both the ISOW and IRD evidence have been important in developing the hypothesis of a wobbly conveyor during the last Millennium (cf. Denton and Broecker, 2008).

A series of higher resolution paleoceanographic records are available from sites located along the axis of the Gulf Stream/NAC from the Gulf of Mexico to northern Norway. Decadal-scale Mg/Ca sea surface temperature (SST) data from the Pigmy Basin in the northern Gulf of Mexico (Richey et al., 2007) register cooling of at least 2 °C below near-modern (post-1950) SSTs during phases of the LIA, following an abrupt initial cooling at ca. 1000 CE. The timing of this initial cooling is earlier than most of the MCA/LIA transition records reviewed here but consistent with some evidence for an early transition from Greenland (Vinther et al., 2010). Evidence from a depth transect of cores across the Gulf Stream in Florida Straits (Lund et al., 2006; Lynch-Stieglitz et al., 2009) indicates that the current density gradient and vertical current shear of the Gulf Stream were lower during the LIA (defined as ~1200 CE to 1850) with LIA volume transport 10% weaker than the flow measured using oceanographic instrumentation at present. A low resolution (centennial) oxygen isotope record from a sediment core in the Sargasso Sea (Keigwin, 1996) indicates SST 1 °C cooler than present (calibrated calendar age 0) during the LIA (~1600 CE), and 1 °C warmer during the MCA (~1000–1500 CE). Caribbean (Winter et al., 2000) and Florida (Druffel, 1982) corals register a 1–3 °C cooling during the LIA (1700–1815 and 1700–1725 CE respectively). These records from the western margin of the subtropical gyre are therefore consistent in indicating SSTs cooler than present during the LIA at a time when the Gulf Stream transport through the Florida Straits was reduced. Sedimentary proxy evidence (Wanner et al., 2008) and numerical simulations indicate a peak in tropical Atlantic cyclone activity during the MCA fueled by enhanced tropical SSTs (Mann et al., 2009).

Sites close to the north wall of the Gulf Stream in the northwestern Atlantic indicate cooling of the slope and shelf waters during the LIA (Keigwin et al., 2003; Marchitto and deMenocal, 2003; Sachs, 2007). High-resolution oxygen isotopic records from segments of LIA time from radiocarbon-dated annually-resolved *Arctica islandica* growth increments from the Gulf of Maine indicate reduced Gulf Stream influence during the early LIA (1320–1470 CE; Wanamaker et al., 2008b). Records from the northern North Atlantic (Norwegian margin and Arctic), including the Vøring Plateau (Andersson et al., 2003), mid-Norwegian margin (Bianchi and McCave, 1999; Kristensen et al., 2004; Burgman et al., 2010; Sejrup et al., 2010), Ranafjord (Kristensen et al., 2004), and eastern Fram Strait (Spielhagen et al., 2011) also register SST cooling across the MCA/LIA transition (~1250–1450 based on the above-mentioned records).

On the north Icelandic shelf, the North Atlantic Polar Front separates southerly flowing cold low salinity Arctic waters of the East Greenland and East Icelandic (EIC) currents from the warmer higher salinity Irminger Current (IC), an arm of the NAC, making it a particularly sensitive boundary region for identifying key climate transitions within the last Millennium. A series of sediment records employing a wide range of proxy techniques well calibrated with instrumental and historical records (cf. Ogilvie, 1984) have been published from this region, including diatoms (Jiang et al., 2002; Ran et al., 2008), planktonic and benthic foraminifera, stable oxygen and carbon isotopes, IRD (Knudsen et al., 2009; Eiríksson et al., 2010), alkenones (Sicre et al., 2008), and the sea ice biomarker proxy IP_{25} (Masse et al., 2008). The presence of multiple tephra layers of known age from Icelandic sources within the marine sequences enables excellent chronological control and assessment of ^{14}C ΔR variability (Eiríksson et al., 2010). ΔR is the regional deviation in the marine radiocarbon reservoir age from the modeled ocean surface mixed layer reservoir age. This provides a basis for reconstructing water mass changes since Atlantic water (IC) has a $\Delta R = {\sim}0$ and Arctic-derived waters (EIC) elevated values of $\Delta R = {\sim}{+}200$. These sediment-based assessments have been complemented by ΔR estimates from absolutely-dated cross-matched *A. islandica* series (Wanamaker et al., 2008a; Wanamaker, submitted for publication). Sediment and shell-based records are all consistent in indicating Atlantic waters (IC), characterized by low ΔR, high SST and low sea ice incidence, dominating both the MCA and the period since 1920 CE. In contrast Arctic waters (EIC) dominated the LIA, with elevated ΔR, low SST and high sea ice incidence.

These records from the full meridional extent of the main axis of the Gulf Stream/NAC register first order changes that are coherent in sign and timing during the last 1000 years. These changes extend from the Florida Straits to the Fram Strait and in significant side branches of the NAC (IC). An inverse SST pattern emerges away from this axis of the NAC. Cold SSTs off NW Africa (McGregor et al., 2007) relate to intensified upwelling of deep cold water during the MCA and since the LIA. This upwelling is strongly coupled to easterly wind stress (deMenocal et al., 2000). Although the SST signal is the inverse of core NAC records, this pattern is nevertheless dynamically consistent with AMOC dynamics and therefore the NAO hypothesis, since enhanced easterlies and upwelling during the MCA would link to a strengthening of the Azores high pressure cell. This intensification of easterlies and upwelling of cold deep water off NW Africa reduces precipitation and drives droughts in North Africa reflected in the drought-sensitive tree-ring record from Morocco (Esper et al., 2007). Note that this record forms the southerly pole of the NAO reconstruction presented by Trouet et al. (2009).

A marked increase in Ti, a precipitation proxy, is registered across the MCA/LIA transition just before 1400 CE in the high-resolution (~5-year) Cariaco Basin record in northernmost South America (Haug et al., 2001). This is interpreted to indicate a northerly movement of the Inter-Tropical Convergence Zone (ITCZ) during the MCA. This interpretation is supported by HadCM3 simulations, in which anomalous northwards ocean heat transports, as registered in the Florida Straits during the MCA, are linked to an enhanced cross-equatorial SST gradient, northward movement of the ITCZ, and an increase in precipitation in northernmost South America (Vellinga and Wu, 2004).

These last Millennium North Atlantic marine records, supported by a number of numerical simulations, are therefore consistent with the hypothesis that the MCA was characterized by stronger AMOC and a pervasive positive state of the NAO, and vice versa during the LIA. The evidence from marine proxies for enhanced (reduced) AMOC states with heat and moisture supply to NW Europe during the MCA (LIA) implies enhanced (reduced) mid-latitude cyclone activity during the MCA (LIA); hence reduced storminess should characterize the LIA. This conclusion, however, notably conflicts with storminess proxies from Greenland ice core records and from northwestern European historical and sedimentary storminess proxies (detailed below).

3. North Atlantic LIA storminess

The content of marine-source ssNa aerosols (Na^+ ion) in the GISP2 ice core record, a proxy for storminess over the adjacent ocean through the advection of salt spray, is high during the LIA with a marked transition from reduced levels during the MCA at 1400 CE (Fig. 2; Meeker and Mayewski, 2002). Dawson et al. (2007) use this record to infer an “NAO dormant” phase characterized by low winter storminess prior to 1400–1420 CE, followed by a high winter storminess “NAO active” phase thereafter linked to a threshold change in atmospheric circulation. Furthermore, they link this “active” NAO state during the LIA with a vigorous AMOC inducing increased deep water formation in the North Atlantic and “streamlined” thermohaline circulation. This scenario clearly conflicts with the marine proxy evidence reviewed above.

The evidence from Greenland is nevertheless supported by a wide range of historical and proxy datasets from NW Europe for enhanced storminess during the LIA. The onset of the LIA in NW Europe is notably marked by coastal dune development across western European coastlines linked to very strong winds during storms (Clarke and Rendell, 2009; Hansom and Hall, 2009) and often inundating local settlements and therefore with supporting archival evidence (cf. Lamb, 1995; Bailey et al., 2001). A number of studies of Aeolian sand deposition records from western Denmark exist that have recorded a period of destabilization of coastal sand dunes and sand migration during the LIA and have ascribed it to a combination of increased storminess and sea-level fluctuations (Szkornik et al., 2008; Clemmensen et al., 2001; Aagaard et al., 2007). Similar records and interpretations are available for the British Isles (Hansom and Hall, 2009) and Scotland (Gilbertson et al., 1999; Wilson, 2002) but none of these are of sufficient resolution to highlight seasonality. Seasonal information on storm frequency is provided by historical naval documents. In an analysis of Royal Navy ships' log books from the English Channel and southwestern approaches covering the period between 1685 and 1750 CE, Wheeler et al. (2010) note a markedly enhanced gale frequency during one of coldest episodes of the LIA in the late seventeenth century (1685–1700 CE) towards the end of the Maunder Minimum (MM). During these cold years of the MM the gale index – the proportion of days with a gale – was markedly higher, with the warming of the 1730s marked by a reduction in gale activity (Wheeler et al., 2010). In contrast to the overall 1685–1750 CE period, when there appears to have been a dominance of more frequent severe gales in winter, the specific 1685–1700 CE experienced the most severe gales during spring and autumn (Wheeler et al., 2010) with a decrease in the summer, particularly July. This late phase of the MM is also registered by the deflation of sand into the ombrotrophic peat bogs of Store mosse and Undarmosse in southwest Sweden (De Jong et al., 2006). More evidence for increased storm severity during the MM is provided by an archive-based reconstruction (1570–1990)

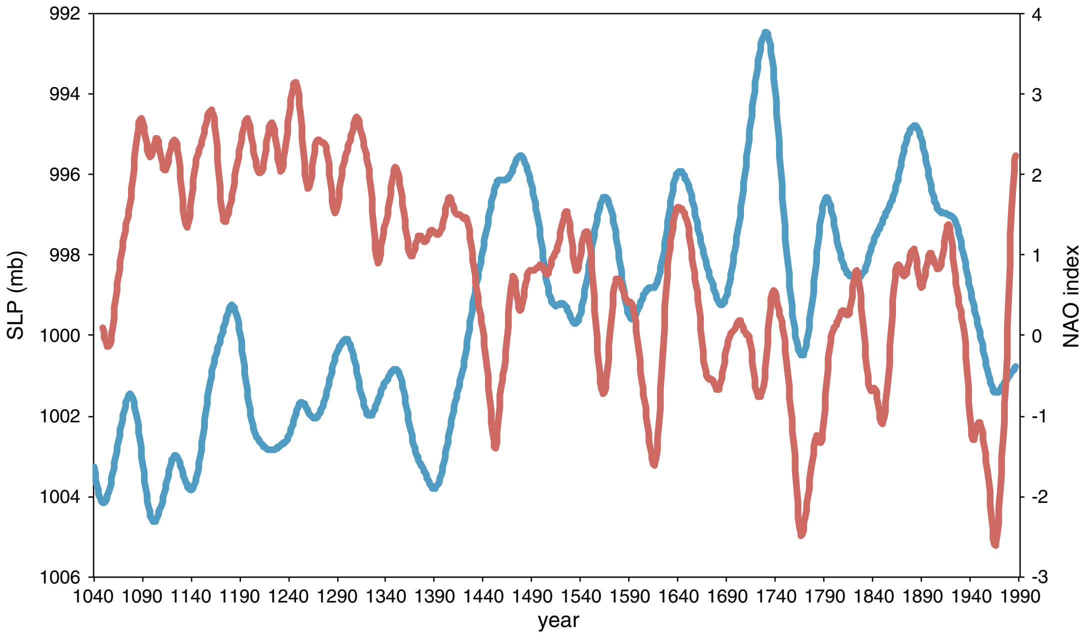

Fig. 2. Two examples of proxy series illustrating two contrasting hypotheses for the MCA/LIA transition. The GISP 2 ssNa ice core record (blue; 600–1986 CE; Meeker and Mayewski, 2002) is a proxy for Icelandic Low (IL) SLP and shows a shift from negative IL (positive NAO) to positive IL (negative NAO) around 1400. A tree-ring and speleothem-based reconstruction of the NAO (red; 1049–1995 CE; Trouet et al., 2009) shows the opposite: a shift from predominantly positive to negative NAO conditions around 1450. The IL SLP record was inverted for visual comparison and smoothed using a cubic spline.

of storminess over the Northwest Atlantic and the North Sea (Lamb and Frydendahl, 1991), which shows a sequence of severe, predominantly winter half year (October–March) storms in the period 1690–1720 CE. Lamb (1988) also observed that these intense storms of the late seventeenth century were recorded in spring and autumn and not in winter and hypothesized that the presence of blocking winter anticyclones might have inhibited storm tracks over this region. Therefore not only was the LIA as a whole marked by an increase in storm activity, but the coldest phases of the LIA, notably the MM, were characterized by an intensification of gales.

It is worth noting, however, that increased storm activity during the LIA was not restricted to northwestern Europe, but was also recorded further south along the Atlantic coast in The Netherlands (Jelgersma et al., 1995) and northern (Sorrel et al., 2009) and southwestern France (Clarke et al., 2002). These regions are located at the southern margin of North Atlantic westerly storm tracks during positive NAO phases and could thus potentially support the high winter storminess LIA scenario. However, sedimentary records of LIA coastal dune accretion have also been found further south on the French Mediterranean coast (Dezileau et al., 2011) and in the western Iberian Peninsula (Borja et al., 1999; Zazo et al., 2005; Clarke and Rendell, 2006), two regions where twentieth century sea surges are linked to negative rather than positive NAO phases (Ullmann et al., 2008; Hurrell et al., 2003). Whereas persistent NAO phases might control the relative position of dominant storm tracks in the North Atlantic region and land use changes may result in periods of Aeolian sand drift activity at a regional level (Clarke and Rendell, 2009), an alternative forcing mechanism is likely at the base of European-wide synchronicity in the sand deposition chronologies during the LIA. Relative sea-level fluctuations resulting in additional supply of sand during sea-level falls (Wilson et al., 2001) and increased storm surges during sea-level rises (Aagaard et al., 2007; Szkornik et al., 2008) have been proposed as possible mechanisms for broad-scale LIA sand mobilization.

4. Reconciling the two hypotheses

In their inference of LIA storminess conditions, some proxy records explicitly refer to the winter season (Meeker and Mayewski, 2002; De Jong et al., 2006; Dawson et al., 2010), the season when the NAO is the dominant atmospheric circulation mode. The majority of past sand deposition and storminess records, however, apart from archival sources, do not provide seasonal differentiation. The seasonality of LIA storminess in northwestern Europe as recorded in proxy records could thus be instrumental in reconciling the two contradictory MCA/LIA NAO hypotheses described in Sections 1 and 2. Many of the northern European records described as supporting North Atlantic LIA storminess in Section 2 do not provide seasonal information, could potentially describe spring, summer, or autumn rather than winter storminess conditions, and could thus be linked to different atmospheric circulation patterns than the winter NAO. Clemmensen et al. (2009) attributed the onset of Aeolian activity events recorded in a deposit chronology from western Denmark (including an event between 1550 and 1650 CE) to frequent cyclone passage during cool and/or wet summers. For the MM in particular, historical naval logbooks from the English Channel attest to increased autumn and spring storminess, but a decrease in the occurrence of winter storms (Wheeler et al., 2010). In an ensemble modeling study comparing the behavior of the synoptic scale variability between LIA and today, Raible et al. (2007) also demonstrated a decrease of the number of storms over the northern North Atlantic and Northern Europe during the MM in all seasons and winter in particular.

In the same ensemble simulations of Raible et al. (2007), blocking situations were increased during the MM, pointing to a negative phase of the NAO. Also, the synoptic scale atmospheric variability during the MM, characterized by individually detected and tracked mid-latitude cyclones in the North Atlantic, was generally shifted southwards at the exit region of the storm track (i.e., over Europe). This is in agreement with the mean pressure change pattern between the LIA and the present that they reported to be similar to the negative phase of the NAO. More modeling studies confirm this result: Spangehl et al. (2010) compared ensemble simulations for the past 400 years generated by three different coupled GCMs and found that the MM showed a consistent negative phase of the NAO compared to today. A similar change was found in a third modeling study (Mann et al., 2009) for the difference between the LIA and the MCA. Recently, Gomez-Navarro et al. (2011) showed in regional simulations of the last Millennium that the time behavior of the NAO is to a great extent dominated by internal variability; only in periods of strong deviations of the external forcing like the MM a signal in the NAO is detectable. This is in agreement with Gonzalez-Rouco et al. (2011), who investigated a set of Millennium simulations performed with different coupled climate models. In contrast, Swingedouw et al. (2011) found in Millennium-scale simulations performed with a different climate model that the response of the NAO to solar forcing could be lagged by up to 50 years. They hypothesized that this lag is linked to a northward displacement of the convection in the tropical Pacific initiating a wave train that could reach the North Atlantic. Despite potential differences in modeled amplitude and forcing mechanisms, some modeling studies thus agree with the Trouet et al. (2009) hypothesis of a negative LIA NAO.

However, when investigating the intensity (rather than frequency) of the cyclones, Raible et al. (2007) found that the mean and extreme cyclone intensity were enhanced during the MM compared to today. In particular in areas such as northern Europe, where the number of cyclones showed a decrease during the MM, the intensity of the cyclones showed a significant increase. The reason for such a behavior was further investigated by the authors and they were able to identify that an enhanced meridional temperature gradient during the MM (due to polar amplification) was the major driver of this cyclone intensification, via increased lower tropospheric baroclinicity and a decrease in static stability. The discrepancy between cyclone intensity and cyclone frequency during the MM that emerges from this modeling exercise, both of which are often combined in proxy records of past storm activity, can possibly unify the seeming differences between proxy data sets leading to contradicting storminess and NAO hypotheses. A set of model simulations is currently available that covers the entire past Millennium (Gonzalez-Rouco et al., 2006; Ammann et al., 2007; Hofer et al., 2010; Jungclaus et al., 2010) and focuses on different aspects of the climate system, and that could further contribute to resolving the apparent disagreement between the two hypotheses.

5. Conclusion

Numerical climate modeling simulations that link persistent La Niña-like conditions in the Pacific with pervasive positive NAO in the North Atlantic linked to a strengthening of AMOC during the MCA are supported by multiple instrumental, historical archive, and proxy climate data covering the last Millennium. This pattern was reversed following the transition into the LIA. During persistent positive NAO phases enhanced westerly cyclogenesis is assumed to have increased the number of winter cyclones crossing NW Europe, hence storminess. However, this coherent dynamical and synoptic climatological model conflicts with many datasets, notably the ssNa proxy in Greenland ice cores, indicating enhanced storminess after the transition into the LIA. This apparent conflict is resolved by ensemble simulations of the coupled ocean–atmosphere general circulation model for the MM. This indicates an increase of mid-latitude blocking anticyclones and a decrease of mid-latitude cyclones during the LIA consistent with a NAO negative phase. However, the intensity of cyclones during the LIA is found to be increased. Enhanced storminess during the LIA, recorded in proxies, may therefore be a product of more intense, rather than more frequent, storms.

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