Solar forcing of North Atlantic surface temperature and salinity over the last millennium

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During the last millennium, climate in the North Atlantic region has been characterised by variations, which, despite their small magnitude, had important societal impacts[1]. The most favoured explanations for this variability invoke external forcing related to variable solar activity and explosive volcanism, with changes amplified by ocean and atmosphere feedbacks, mainly involving the Atlantic Meridional Overturning Circulation and the North Atlantic Oscillation[2]. However, the scarcity of highly resolved archives has hampered our understanding of the role that ocean-atmosphere interactions played in these climate oscillations. Here, results from a sub-decadally resolved marine sediment core show multidecadal to centennial-scale abrupt changes in the properties of the upper limb of the Atlantic Meridional Overturning Circulation between 818-1780 years AD. These fluctuations present a strong correlation with solar irradiance variability. Model simulations support this finding and reveal that these hydrographic changes likely resulted from variability in the strength of the Subpolar Gyre driven by the frequency and persistence of atmospheric blocking events in the eastern North Atlantic as a response to solar irradiance variability. This coupled ocean-atmosphere response to solar irradiance minima may have contributed towards the consecutive cold winters documented in Europe during the Little Ice Age (1450-1850 years AD).

The import of salt to higher latitudes by the North Atlantic Current (NAC) is essential for maintaining the high density of surface waters in the Nordic and Labrador Seas[3,4], a pre-requisite for deep water formation. Deepwater formation is critical for the Atlantic Meridional Overturning Circulation (AMOC) and therefore of great importance to the climate system. Additionally, the heat released from the NAC, aided by the westerly winds, contributes to ameliorating the climate of Europe[5]. Because of its large heat capacity, the ocean is expected to be amongst the most predictable components of the climate system at multidecadal time-scales. It is therefore of paramount importance to study past variability in the properties of the NAC beyond the instrumental record to better constrain natural ocean variability and its potential impacts on regional and global future climate.

To investigate multidecadal hydrographic variability of the NAC during the last millennium, we use marine sediment core RAPiD-17-5P (61° 28.90'N, 19° 32.16'W, 2303 m water depth; Fig. 1) recovered from the Iceland Basin. The upper 600 m of the water column at the core-site are dominated by the northward flowing NAC[3]. Temperature and salinity reconstructions were produced by analysing paired Mg/Ca-$\delta^{18}O$ signals in the shells of the planktonic foraminifera *Globorotalia inflata* (Supplementary Methods). The concentration of Mg in calcite foraminiferal tests is an established proxy for temperature[6], which combined with the $\delta^{18}O$ composition of the same calcite, allows the isolation of the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) and the estimation of salinity. *G. inflata* lives close to the base of the seasonal thermocline[7] and, due to the limited seasonal variation at this depth, it principally records mean annual temperatures[8]. The chronology for RAPiD-17-5P was obtained using 12 AMS radiocarbon dates, which yielded a linear sedimentation rate of 0.16 cm/year, providing an integrated sample resolution of ~6 years between 818-1780 years AD (Supplementary Methods).

Our results reveal abrupt multidecadal to centennial shifts in the temperature and salinity of the NAC waters of ~3.5 ±1.1°C and ~1.2±0.8 psu during the last millennium (Figure 2b,c). The magnitude of the hydrographic variability is substantial and comparable to that recorded in a lower resolution record spanning the present interglacial from a nearby site[9] which highlights the similarities in the ocean variability on a diverse range of time-scales. The timing of the hydrographic shifts show a strong correlation with Total Solar Irradiance (TSI) variability[10] (Figure 2d). Periods of solar minima (maxima) generally correspond to cold and fresh (warm and salty) conditions in the NAC (Figure 2). A Pearson's correlation coefficient of 0.51 (n=77) with 95% confidence interval [0.31; 0.67] was estimated when correlating temperature and TSI records, following Gaussian-interpolation to a common time-step of ~12-years (the minimum resolution of the temperature record) (Figure S3).

Wavelet transform analysis of the temperature record shows a clear 200-year cycle with enhanced power between 1200-1650 years AD (Figure S5). In addition, cross-spectral analysis shows that temperature and TSI are coherent above the 90% confidence level in the frequency range 177-227 years (Figure S4). This variance is similar to deVries solar activity cycles (~210 years) and supports the correlation found between the NAC temperature and TSI records over the last millennium.

To investigate the feedback processes linking TSI variability and the recorded abrupt ocean changes we analysed climate model simulations performed using Community Climate System Model version 4.0 (CCSM4), forced with TSI variability and volcanic aerosols for the last millennium (850-1850 years AD)[11]. The modelling results also present a strong positive correlation between temperature and salinity south of Iceland and solar irradiance (Figure 3a,b), although the hydrographic variability in the model is of smaller amplitude than in the proxy data. The highest correlations are found in the pathway of the NAC and particularly in the path of its western branch, the Irminger Current. Additional temperature and salinity proxy reconstructions of the Irminger Current, from a sediment core south of Greenland (RAPiD-35-25B - Figure 1), show broad similarities with the results from RAPiD-17-5P (Figure S6-S8), which confirm the westward propagation of the anomalies within the warm Atlantic waters via the Irminger Current found in the model (Figure 3a,b).

The similar timing of volcanic eruptions and solar minima during the last millennium (Figure 2a-b) makes the separation of their relative climatic influence difficult and has been the subject of much debate in recent literature. For instance, the injection of aerosols into the stratosphere by volcanic activity may have additionally contributed towards the cold fresh events recorded south of Iceland (Figure 2a-c)[e.g. 12]. In this study, decomposition of the relative contribution of the solar and volcanic forcing to the ocean changes was explored by performing a series of sensitivity tests in CCSM4. In these experiments we find that changes in volcanic forcing yield a qualitatively different dynamic response of the atmosphere-ocean system in our region of study compared to solar forcing which consistently explain the key changes described in the transient simulation (Figure S11-S13). We therefore conclude that solar irradiance was the dominant forcing on the centennial-scale ocean changes.

The NAC and its north-western branch, the Irminger Current, constitute the main boundary currents of the Subpolar Gyre (SPG) (Figure 1). Changes in the strength of the SPG therefore influence the properties, structure and volume transport of the surface circulation in the North Atlantic[13]. Previous modelling and palaeodata studies have interpreted changes in the hydrographic properties of the NAC, and particularly salinity south of Iceland, to be controlled by frontal mixing resulting from changes in the spatial extent of the SPG as a response to changes in its strength[9,13]. For example, during a weak and contracted SPG circulation a displacement of the Subpolar Front to the west would increase the contribution of subtropical versus subpolar waters to the NAC, making it warm and salty. In this study, however, volume transport analysis of the SPG in CCSM4 over the last millennium indicate that warmer and saltier conditions found south of Iceland and in the pathway of the Irminger Current correspond to periods of stronger SPG circulation (Figure 3c). This is in agreement with recent observations that show advection may play a dominant role in determining the properties of water masses along the Irminger Current[14] (Supplementary Discussion). An increase in the heat and particularly salt transport by the IC into the Labrador Sea may have additionally promoted deep convection in this region[4], potentially impacting the AMOC.

Since ocean gyres are largely driven by wind-stress forcing, changes in the SPG strength and NAC properties found in the proxy and model results are likely linked to shifts in atmospheric circulation. The North Atlantic Oscillation (NAO) is the dominant mode of atmospheric variability in the North Atlantic[15]. During a positive NAO state the increase in the strength of the westerlies promotes surface heat loss and ultimately leads to deeper convection in the Labrador Sea, baroclinically driving a stronger SPG. However, an emergent view derived from both model and observational data is that small-scale atmospheric patterns in the Northeast Atlantic, such as atmospheric blocking events as part of the East Atlantic Pattern or polar mesoscale storms, may contribute considerably to driving North Atlantic surface circulation[16–18].

Atmospheric blocking events are mid-latitude weather systems where a quasi-stationary high pressure system located in the Northeast Atlantic modifies the flow of the westerly winds by blocking or diverting their pathway. Blocking events derive from instabilities of the jet stream and predominantly develop in winter, typically in association with a negative NAO[19]. The impacts of the frequency and magnitude of these small-scale atmospheric systems are not restricted to the ocean[16–18] but also have important effects on European temperatures, as they block the meridional transport of warm maritime winds (which are replaced by the cold north-easterlies). For example, Atlantic blocking events are thought to have been responsible for several recent cold European winters (i.e. 1963, 2009, 2010 and 2013).

The analysis of Sea Level Pressure (SLP) patterns in our CCSM4 simulation reveals the presence of an anomalous high-pressure system off West Europe during periods of solar minima (Figure 4), which correspond to a weaker SPG (Figure 3c) and a colder and fresher NAC (Figure 2 and 3a,b). This finding is in line with recent studies that suggest a decrease in SPG strength with more frequent and stronger atmospheric blocking events on decadal time-scales[16,18]. The results agree with the early concept that the severe winters experienced in Europe during the Maunder Minimum were caused by periods of increased atmospheric blocking[1] and are also consistent with SLP field reconstructions which show a high pressure system over North-west Europe towards the end of the Spörer and during the Maunder Minimum[20]. Similarly, a number of studies suggest a negative NAO state during the Maunder Minimum or other periods of low TSI[21], in agreement with increased blocking arising from the weaker westerly winds.

Growing evidence for the linkage between solar variability and frequency of blocking in the Northeast Atlantic has also been provided by meteorological studies. Modern observations show strong solar modulation of the blocking frequency and positioning during the 11-year solar cycles for the last 50 years, impacting substantially on UK winter temperatures[22,23]. Periods of solar minima, such as the Maunder Minimum, have also been shown to correspond to cold temperatures in the Central England Temperature record, which is dominated by the frequency of winter blockings[24]. The regional atmospheric response to solar forcing has often been explained through variability in stratospheric temperatures as the response of ozone formation to changes in ultra violet radiation[21,22,25]. Changes in stratospheric temperatures have a top-down effect on tropospheric dynamics and hence induce variability of the jet stream[22,26]. Nonetheless, modelling studies with a simplified representation of the upper atmosphere, like CCSM4, find a similar response to solar forcing suggesting that other feedbacks such as ocean feedbacks on the atmosphere, internal climate dynamics and Pacific teleconnections may also be influential[21]. On decadal time-scales, modelling and observational studies have previously identified separate relationships between solar irradiance and Atlantic blocking events[22,23,26] and blocking events and SPG strength[16,18] individually. Our findings support a direct linkage between these three components of the Earth's climate system, which probably shaped the North Atlantic climate over the last millennium.

Climate variability on decadal timescales is largely believed to be dominated by internal processes rather than external forcing, which presents large difficulties for much-needed climate projections of the coming decades. However, the proxy evidence presented here, supported by model results, suggest that external forcing by solar variability has a considerable impact on multidecadal-centennial ocean-atmospheric dynamics, with important effects on regional climate such as European winters. In this context, predictions of a forthcoming prolonged period of low solar activity[27] imply direct climatic consequences.

Despite the hemispheric temperature changes expected from solar minima being much smaller than the warming from future CO_2 emissions, regional climate variability associated with solar-induced ocean-atmosphere feedbacks could be substantial and should be taken into consideration when projecting future climate changes.

Methods Summary

Paired $\delta^{18}O$ and Mg/Ca analyses were performed on 6-20 *Globorotalia inflata* (300-355 μm) tests. Samples were prepared using the method outlined by ref.28 and analysed using a Finnigan Element XR high-resolution inductively coupled plasma mass spectrometer (Cardiff University). Calculation of average shell weights and investigation of the co-variability of Mg/Ca record to metals such as Fe, Mn and Al shows that no secondary effects such as partial dissolution or trace metal contamination have altered the primary temperature signal in the Mg/Ca record. Mg/Ca values were converted to calcification temperatures using Mg/Ca= 0.675 exp(0.1xT) after the core-top calibration by ref.[9]. Stable isotope measurements were carried out on a Thermo Finnigan MAT 252 isotope ratio mass spectrometer coupled to a Kiel II carbonate preparation device at Cardiff University. For more details see Supplementary Methods.

Additional information

Correspondence and requests for materials should be addressed to P.M.

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Author contribution

P.M. sampled the core, processed the samples, performed the measurements, data analysis and interpretation; A.B. performed the model analysis and interpretation. I.R.H, D.J.R.T. and S.B. supervised P.M. during her PhD; I.R.H. and D.J.R.T. participated in the retrieval of the sediment core material and initiated the project; All authors contributed towards the writing of the manuscript.

Figure captions

Figure 1

Figure 1. Sea surface temperature map for January 2008 showing the schematic surface circulation of the North Atlantic and the core location of RAPiD-17-5P and RAPiD-35-25B (Supp. Material). Solid arrows indicate the warm salty waters from the tropics, namely the NAC and its main branches such as the Irminger Current (IC). The dashed lines indicate the cold polar south-flowing waters such as the East Greenland Current, West Greenland Current and Labrador Current which constitute the Western branch of the SPG. Location of RAPiD-17-5P (61^{o} 28.90'N, 19^{o} 32.16'W, 2303m water depth) and RAPiD-35-25B (57° 30.47'N, 48° 43.40'W, 3486 m water depth) are marked with a black circle (adapted from UK-Met office OSTIA data[29]).

Figure 2

Proxy records from RAPiD-17-5P. (a) Solar irradiance forcing reconstruction based on the cosmogenic nuclide ^{10}Be [10] (orange) and global volcanic stratospheric aerosols[30] (grey). **(b)** Temperature and **(c)** salinity/$\delta^{18}O_{sw}$ estimates derived from paired Mg/Ca and δ^{18}O measurements in *G. inflata* calcite from RAPiD-17-5P. **(d)** Three-point smoothed temperature record from RAPiD-17-5P (black) and ΔTSI[10] (orange). A 12.42 year lag has been imposed on the ΔTSI forcing as indicated from the highest Pearson Correlation (Supplementary notes, Figure S2). Shaded areas highlight the well-known periods of solar minima.

Figure 3

Modelling results from CCSM4. Pointwise correlation of TSI with **(a)** temperature and **(b)** salinity averaged between 150-204 m water depth. **(c)** Regression of TSI with the depth-integrated stream function (all time-series were filtered with a 50 year low-pass filter). Black contours show the time-average depth-integrated stream function and areas with correlations above 95% confidence threshold are dotted. Negative values indicate stronger anti-clockwise circulation. The location of RAPiD-17-5P is marked with a black circle.

Figure 4

Atmospheric changes in CCSM4. Differences in sea level pressure of weak-strong TSI composites (±1σ) in CCSM4 reveals an anomalous high pressure system during low TSI over the British Isles and the eastern North Atlantic, indicative of increased winter blocking. Time-series have been filtered with a 50 year low-pass filter (See Figure S14 for a SLP regression plot).

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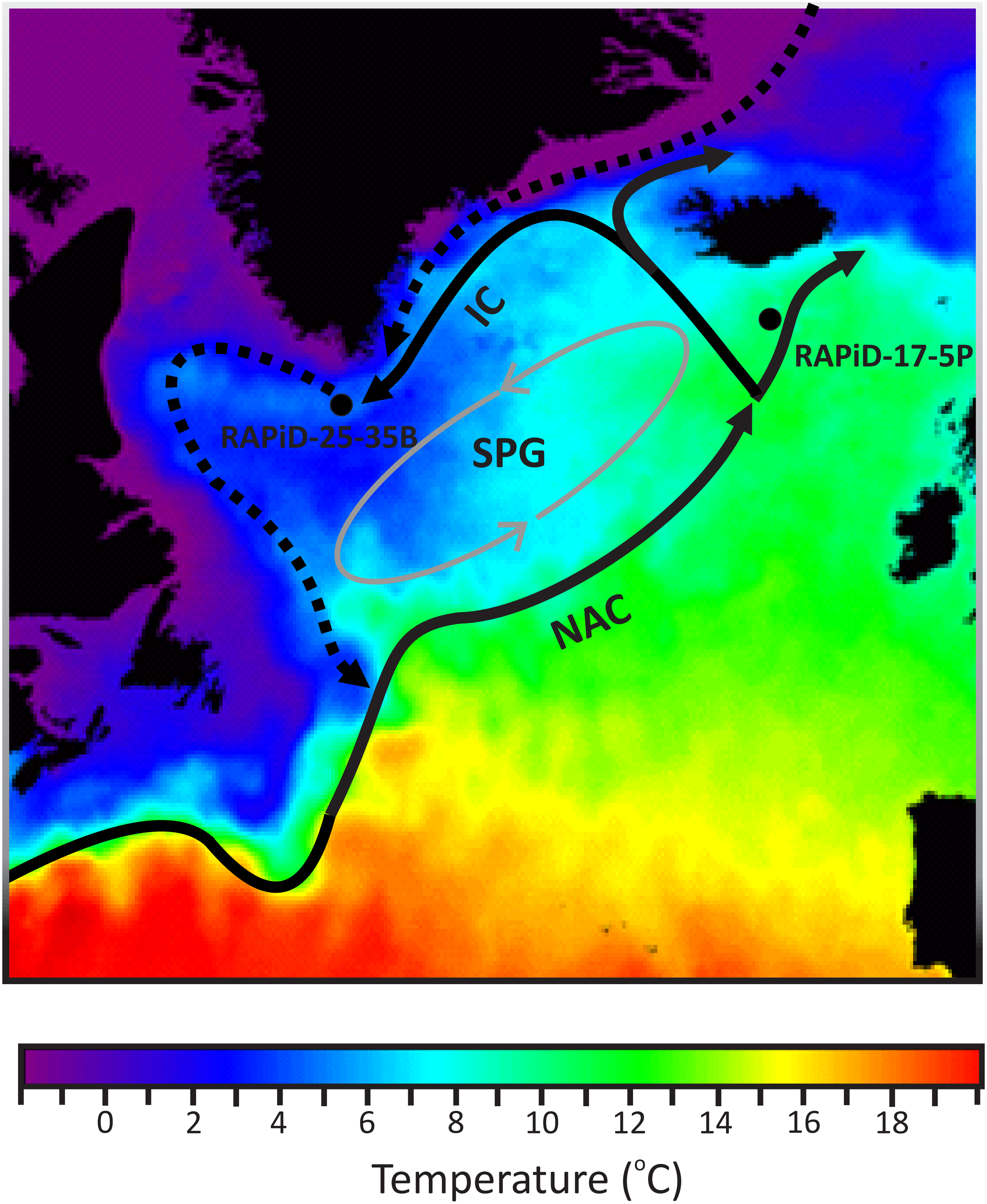
IC
RAPiD-17-5P
RAPiD-25-35B
SPG
NAC
0
2
4
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8
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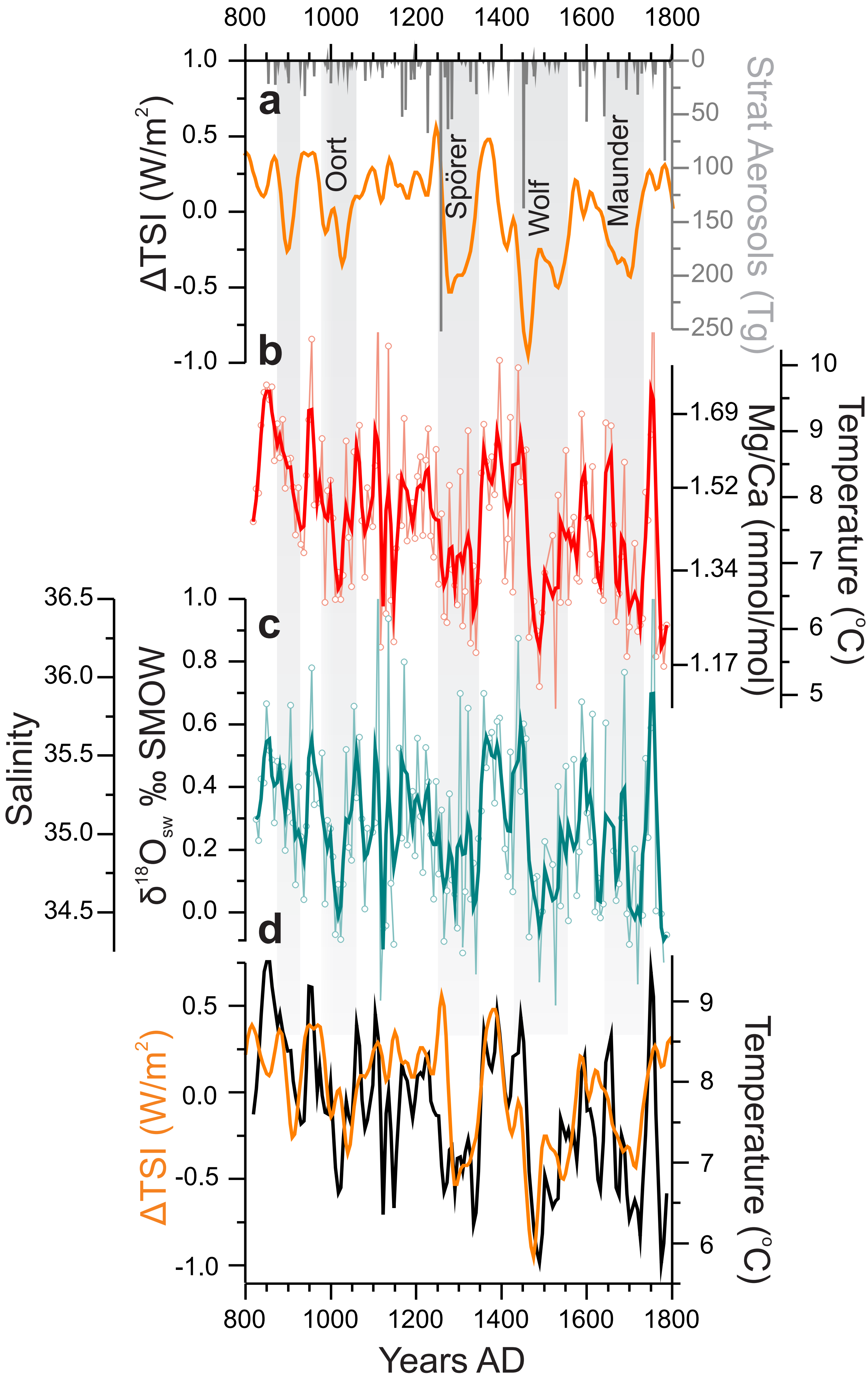
18
Temperature (°C)



a
b
c
d
Oort
Spörer
Wolf
Maunder
ΔTSI (W/m²)
Strat Aerosols (Tg)
Mg/Ca (mmol/mol)
Temperature (°C)
Salinity
δ¹⁸O‰ SMOW
ΔTSI (W/m²)
Temperature (°C)
Years AD

Figure 3.

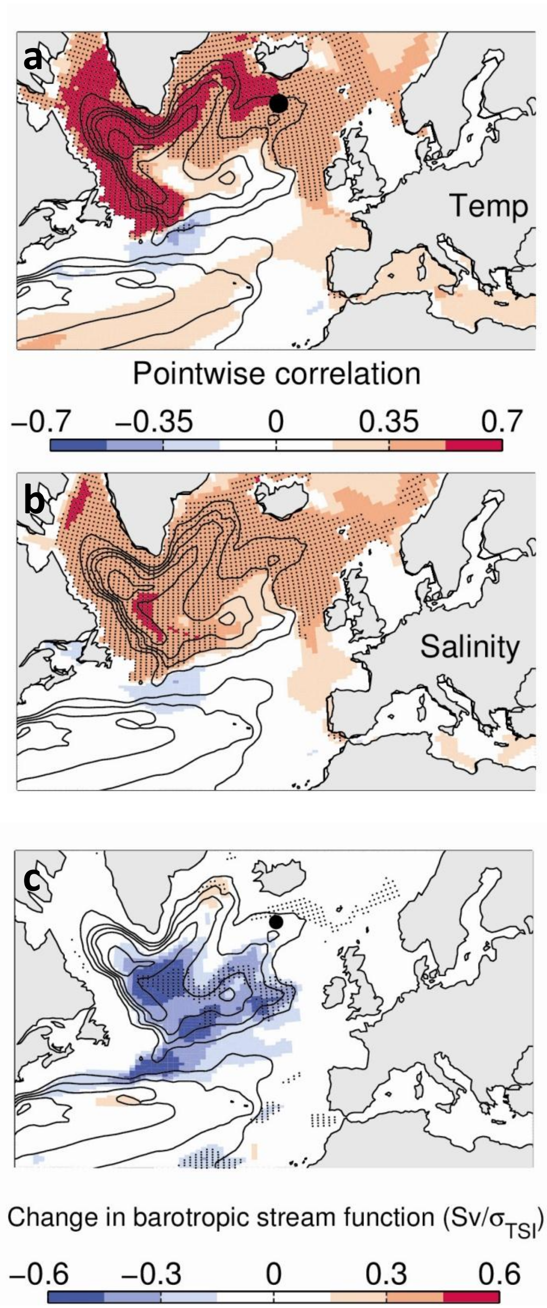

a
Temp
Pointwise correlation
−0.7 −0.35 0 0.35 0.7
b
Salinity
c
Change in barotropic stream function (Sv/σ_{TSI})
−0.6 −0.3 0 0.3 0.6

Figure 4.