

# **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<sup>1</sup>. 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<sup>2</sup>. 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).**

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

42  
43 To investigate multidecadal hydrographic variability of the NAC during the last millennium,  
44 we use marine sediment core RAPID-17-5P (61° 28.90'N, 19° 32.16'W, 2303 m water depth;  
45 Fig. 1) recovered from the Iceland Basin. The upper 600 m of the water column at the  
46 core-site are dominated by the northward flowing NAC<sup>3</sup>. Temperature and salinity  
47 reconstructions were produced by analysing paired Mg/Ca- $\delta^{18}\text{O}$  signals in the shells of the  
48 planktonic foraminifera *Globorotalia inflata* (Supplementary Methods). The concentration of  
49 Mg in calcite foraminiferal tests is an established proxy for temperature<sup>6</sup>, which combined  
50 with the  $\delta^{18}\text{O}$  composition of the same calcite, allows the isolation of the  $\delta^{18}\text{O}$  of seawater  
51 ( $\delta^{18}\text{O}_{\text{sw}}$ ) and the estimation of salinity. *G. inflata* lives close to the base of the seasonal  
52 thermocline<sup>7</sup> and, due to the limited seasonal variation at this depth, it principally records  
53 mean annual temperatures<sup>8</sup>. The chronology for RAPID-17-5P was obtained using 12 AMS  
54 radiocarbon dates, which yielded a linear sedimentation rate of 0.16 cm/year, providing an  
55 integrated sample resolution of ~6 years between 818-1780 years AD (Supplementary  
56 Methods).

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

68

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

75

76 To investigate the feedback processes linking TSI variability and the recorded abrupt ocean  
77 changes we analysed climate model simulations performed using Community Climate  
78 System Model version 4.0 (CCSM4), forced with TSI variability and volcanic aerosols for  
79 the last millennium (850-1850 years AD)<sup>11</sup>. The modelling results also present a strong  
80 positive correlation between temperature and salinity south of Iceland and solar irradiance  
81 (Figure 3a,b), although the hydrographic variability in the model is of smaller amplitude than

82 in the proxy data. The highest correlations are found in the pathway of the NAC and  
83 particularly in the path of its western branch, the Irminger Current. Additional temperature  
84 and salinity proxy reconstructions of the Irminger Current, from a sediment core south of  
85 Greenland (RAPiD-35-25B - Figure 1), show broad similarities with the results from RAPiD-  
86 17-5P (Figure S6-S8), which confirm the westward propagation of the anomalies within the  
87 warm Atlantic waters via the Irminger Current found in the model (Figure 3a,b).

88

89 The similar timing of volcanic eruptions and solar minima during the last millennium (Figure  
90 2a-b) makes the separation of their relative climatic influence difficult and has been the  
91 subject of much debate in recent literature. For instance, the injection of aerosols into the  
92 stratosphere by volcanic activity may have additionally contributed towards the cold fresh  
93 events recorded south of Iceland (Figure 2a-c)<sup>e.g. 12</sup>. In this study, decomposition of the  
94 relative contribution of the solar and volcanic forcing to the ocean changes was explored by  
95 performing a series of sensitivity tests in CCSM4. In these experiments we find that changes  
96 in volcanic forcing yield a qualitatively different dynamic response of the atmosphere-ocean  
97 system in our region of study compared to solar forcing which consistently explain the key  
98 changes described in the transient simulation (Figure S11-S13). We therefore conclude that  
99 solar irradiance was the dominant forcing on the centennial-scale ocean changes.

100

101 The NAC and its north-western branch, the Irminger Current, constitute the main boundary  
102 currents of the Subpolar Gyre (SPG) (Figure 1). Changes in the strength of the SPG therefore  
103 influence the properties, structure and volume transport of the surface circulation in the North  
104 Atlantic<sup>13</sup>. Previous modelling and palaeodata studies have interpreted changes in the  
105 hydrographic properties of the NAC, and particularly salinity south of Iceland, to be  
106 controlled by frontal mixing resulting from changes in the spatial extent of the SPG as a

107 response to changes in its strength<sup>9,13</sup>. For example, during a weak and contracted SPG  
108 circulation a displacement of the Subpolar Front to the west would increase the contribution  
109 of subtropical versus subpolar waters to the NAC, making it warm and salty. In this study,  
110 however, volume transport analysis of the SPG in CCSM4 over the last millennium indicate  
111 that warmer and saltier conditions found south of Iceland and in the pathway of the Irminger  
112 Current correspond to periods of stronger SPG circulation (Figure 3c). This is in agreement  
113 with recent observations that show advection may play a dominant role in determining the  
114 properties of water masses along the Irminger Current<sup>14</sup> (Supplementary Discussion). An  
115 increase in the heat and particularly salt transport by the IC into the Labrador Sea may have  
116 additionally promoted deep convection in this region<sup>4</sup>, potentially impacting the AMOC.

117

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

128

129 Atmospheric blocking events are mid-latitude weather systems where a quasi-stationary high  
130 pressure system located in the Northeast Atlantic modifies the flow of the westerly winds by  
131 blocking or diverting their pathway. Blocking events derive from instabilities of the jet

132 stream and predominantly develop in winter, typically in association with a negative NAO<sup>19</sup>.  
133 The impacts of the frequency and magnitude of these small-scale atmospheric systems are not  
134 restricted to the ocean<sup>16-18</sup> but also have important effects on European temperatures, as they  
135 block the meridional transport of warm maritime winds (which are replaced by the cold  
136 north-easterlies). For example, Atlantic blocking events are thought to have been responsible  
137 for several recent cold European winters (i.e. 1963, 2009, 2010 and 2013).

138

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

151

152 Growing evidence for the linkage between solar variability and frequency of blocking in the  
153 Northeast Atlantic has also been provided by meteorological studies. Modern observations  
154 show strong solar modulation of the blocking frequency and positioning during the 11-year  
155 solar cycles for the last 50 years, impacting substantially on UK winter temperatures<sup>22,23</sup>.

156 Periods of solar minima, such as the Maunder Minimum, have also been shown to correspond

157 to cold temperatures in the Central England Temperature record, which is dominated by the  
158 frequency of winter blockings<sup>24</sup>. The regional atmospheric response to solar forcing has often  
159 been explained through variability in stratospheric temperatures as the response of ozone  
160 formation to changes in ultra violet radiation<sup>21,22,25</sup>. Changes in stratospheric temperatures  
161 have a top-down effect on tropospheric dynamics and hence induce variability of the jet  
162 stream<sup>22,26</sup>. Nonetheless, modelling studies with a simplified representation of the upper  
163 atmosphere, like CCSM4, find a similar response to solar forcing suggesting that other  
164 feedbacks such as ocean feedbacks on the atmosphere, internal climate dynamics and Pacific  
165 teleconnections may also be influential<sup>21</sup>. On decadal time-scales, modelling and  
166 observational studies have previously identified separate relationships between solar  
167 irradiance and Atlantic blocking events<sup>22,23,26</sup> and blocking events and SPG strength<sup>16,18</sup>  
168 individually. Our findings support a direct linkage between these three components of the  
169 Earth's climate system, which probably shaped the North Atlantic climate over the last  
170 millennium.

171  
172 Climate variability on decadal timescales is largely believed to be dominated by internal  
173 processes rather than external forcing, which presents large difficulties for much-needed  
174 climate projections of the coming decades. However, the proxy evidence presented here,  
175 supported by model results, suggest that external forcing by solar variability has a  
176 considerable impact on multidecadal-centennial ocean-atmospheric dynamics, with important  
177 effects on regional climate such as European winters. In this context, predictions of a  
178 forthcoming prolonged period of low solar activity<sup>27</sup> imply direct climatic consequences.

179  
180 Despite the hemispheric temperature changes expected from solar minima being much  
181 smaller than the warming from future CO<sub>2</sub> emissions, regional climate variability associated

182 with solar-induced ocean-atmosphere feedbacks could be substantial and should be taken into  
183 consideration when projecting future climate changes.

184

### 185 **Methods Summary**

186 Paired  $\delta^{18}\text{O}$  and Mg/Ca analyses were performed on 6-20 *Globorotalia inflata* (300-355  $\mu\text{m}$ )  
187 tests. Samples were prepared using the method outlined by ref.28 and analysed using a  
188 Finnigan Element XR high-resolution inductively coupled plasma mass spectrometer (Cardiff  
189 University). Calculation of average shell weights and investigation of the co-variability of  
190 Mg/Ca record to metals such as Fe, Mn and Al shows that no secondary effects such as  
191 partial dissolution or trace metal contamination have altered the primary temperature signal in  
192 the Mg/Ca record. Mg/Ca values were converted to calcification temperatures using  $\text{Mg/Ca} =$   
193  $0.675 \exp(0.1xT)$  after the core-top calibration by ref.<sup>9</sup>. Stable isotope measurements were  
194 carried out on a Thermo Finnigan MAT 252 isotope ratio mass spectrometer coupled to a  
195 Kiel II carbonate preparation device at Cardiff University. For more details see  
196 Supplementary Methods.

197

### 198 **Additional information**

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

200

201

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214

### 215 **Author contribution**

216 P.M. sampled the core, processed the samples, performed the measurements, data analysis  
217 and interpretation; A.B. performed the model analysis and interpretation. I.R.H, D.J.R.T. and  
218 S.B. supervised P.M. during her PhD; I.R.H. and D.J.R.T. participated in the retrieval of the  
219 sediment core material and initiated the project; All authors contributed towards the writing  
220 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° 28.90'N, 19° 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<sup>29</sup>).

#### **Figure 2**

**Proxy records from RAPiD-17-5P. (a)** Solar irradiance forcing reconstruction based on the cosmogenic nuclide  $^{10}\text{Be}$  <sup>10</sup> (orange) and global volcanic stratospheric aerosols<sup>30</sup> (grey). **(b)** Temperature and **(c)** salinity/ $\delta^{18}\text{O}_{\text{sw}}$  estimates derived from paired Mg/Ca and  $\delta^{18}\text{O}$  measurements in *G. inflata* calcite from RAPiD-17-5P. **(d)** Three-point smoothed

temperature record from RAPiD-17-5P (black) and  $\Delta\text{TSI}^{10}$  (orange). A 12.42 year lag has been imposed on the  $\Delta\text{TSI}$  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 ( $\pm 1\sigma$ ) 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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