Solar forcing of North Atlantic climate over the last millennium

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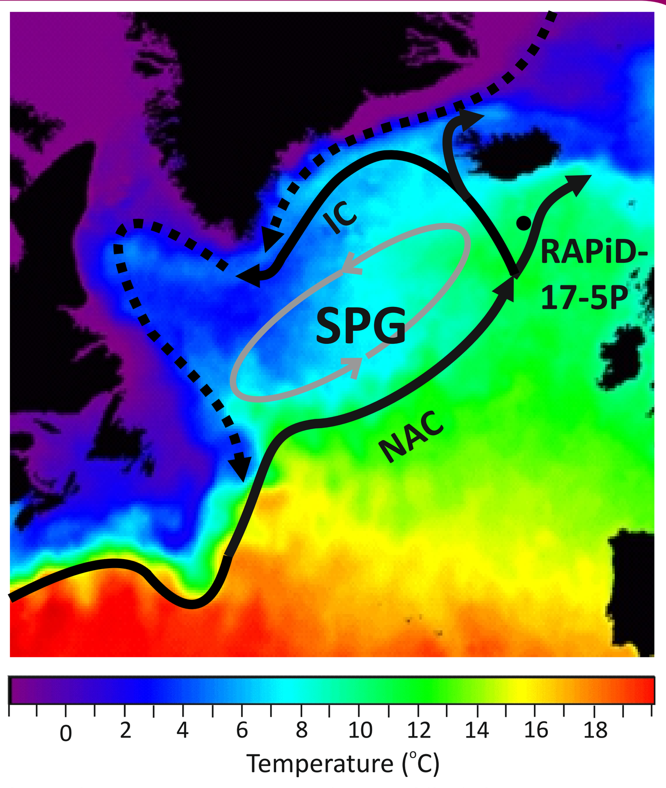
1. Introduction

In today's North Atlantic, warm salty waters flow northwards as part of the North Atlantic Current (NAC) and eventually sink to form deep south-flowing currents.The salt transport by the NAC is a pre-requisite for deepwater formation, a process that is critical for the Atlantic Meridional Overturning Circulation (AMOC) and hence the climate system. Additionally, the release of heat aided by the westerly winds from the NAC contributes to ameliorating the climate of Europe.

Over the last 1000 years, North Atlantic climate has experienced multidecadal oscillations, which, despite their small magnitude, had important societal and economic impacts. Ocean and atmospheric systems, namely the AMOC and the North Atlantic Oscillation are thought to have played an important role in these oscillations through the amplification of external forcings (volcanic activity and solar variability)[1,2]. At multidecadal timescales the ocean is expected to be amongst the most predictable components of the climate system[3] and it is therefore of paramount importance to study past variability in the properties of the NAC beyond the instrumental record in order to better understand the natural variability of the ocean and its potential impacts on regional and global future climate.

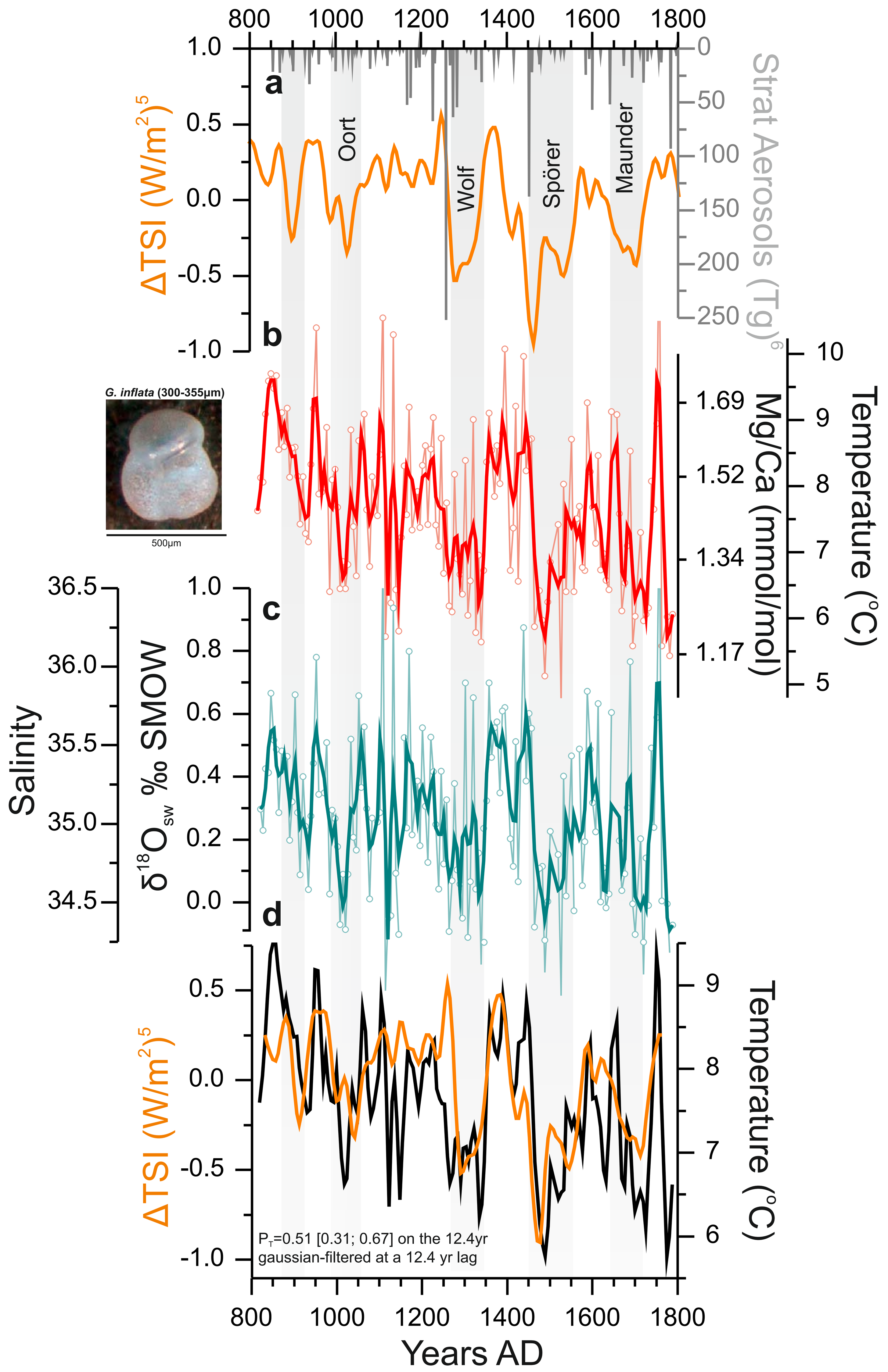
2. Materials and Methods

- Sediment core RAPiD-17-5P is located South of Iceland. The upper 600 m of the water column at the site are dominated by the northward flowing NAC[4].
- Chronology is based on 12 AMS ^{14}C dates. Calibrated dates are linearly distributed with a correlation of R^2= 0.999 over the top 7.5m, providing a resolution of 6.2 years/sample.
- Temperature and salinity reconstructions were produced by measuring paired Mg/Ca and $\delta^{18}O$ in the near-thermocline dweller planktonic foraminifera *Globorotalia inflata*.



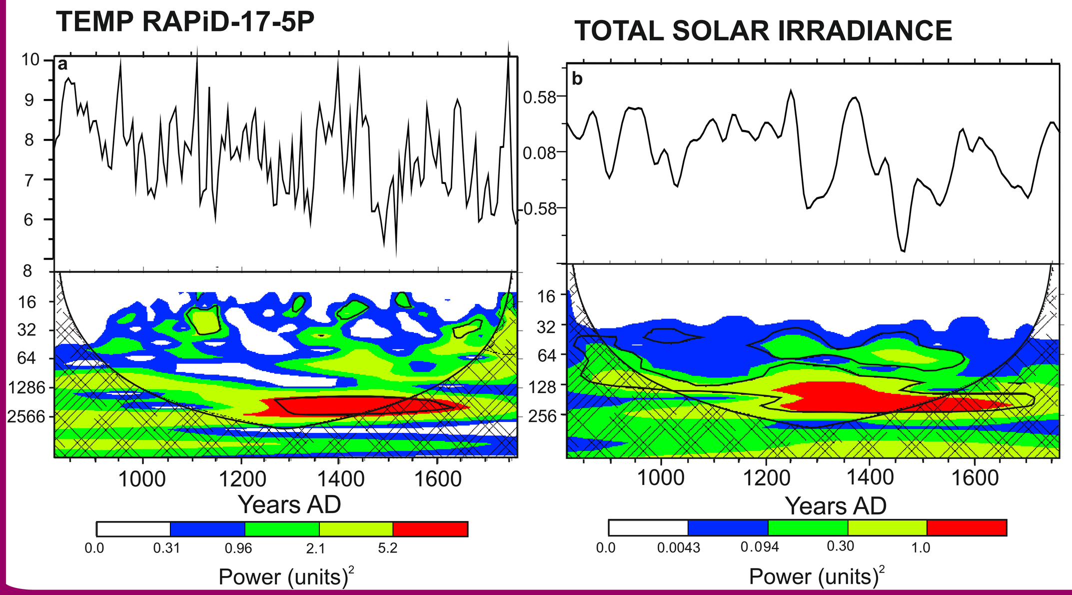
Sea surface temperature Jan 2008 (UK,Met Office). Solid arrows indicate warm and salty and the dashed lines indicate cold polar ocean currents.

3. Temperature and salinity changes - S. Iceland



- Our results show abrupt multidecadal shifts in the temperature and salinity of the NAC of ~3.5 ±1.1°C and ~1.2 ±0.8 psu. This magnitude is similar to that recorded in a lower resolution record spanning the Holocene from a nearby site[7].
- The hydrographic shifts show a strong correlation with Total Solar Irradiance (TSI) variability[5]. Periods of solar minima (maxima) generally correspond to cold and fresh (warm and salty) conditions in the NAC.

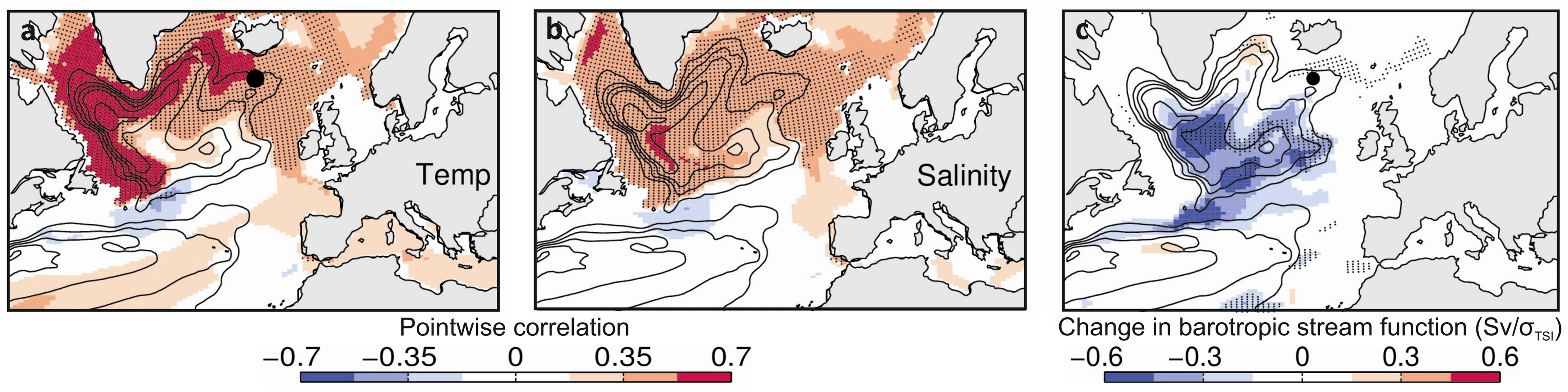
4. Time-series analysis



- A Pearson's correlation coefficient of 0.51 (n=77) with 95% confidence interval [0.31; 0.67][8] was estimated on the 12.4-year Gaussian-interpolated Temp and TSI records at a lag of 12.42 years.
- Cross-spectral analysis[9] shows that Temp and TSI are coherent above the 90%CL in the frequency range 177-227 years at a lag of 15 years. This cyclicity is similar to deVries solar activity.
- Wavelet transform analysis[10] of the temperature and TSI record shows a clear 200-year cycle with enhanced power between 1200-1650 years AD.

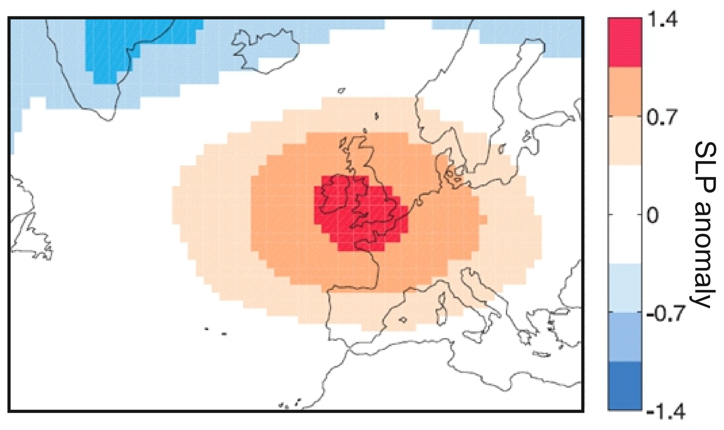
5. Model results from CCSM4

- Analysis of model simulations performed with CCSM4 (850-1850 years AD)[11], forced with TSI variability and volcanic aerosols present a strong positive correlation between temperature and salinity South of Iceland and solar irradiance.
- Highest correlations are found in the pathway of the western branch of the NAC, the Irminger Current.
- Volume transport analysis of the Subpolar Gyre (SPG) indicate that warmer and saltier conditions correspond to periods of stronger SPG circulation



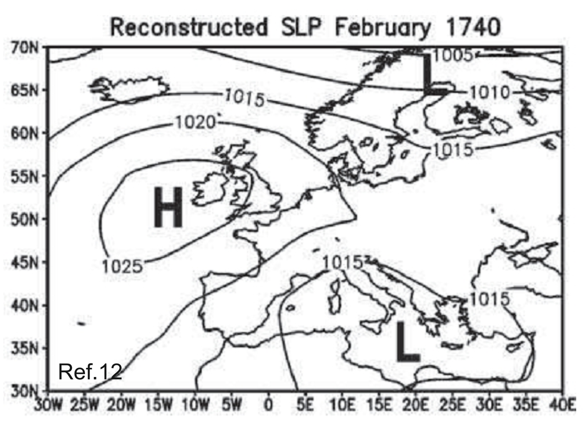
Pointwise correlation of TSI with (a) temperature and (b) salinity averaged between 150-204 m water depth and (c) the depth-integrated stream function (all time-series were filtered with a 50 year low-pass filter). Black contours show the time-average depth-integrated stream function and areas with correlations above 95% confidence threshold are dotted.

6. Atmospheric changes



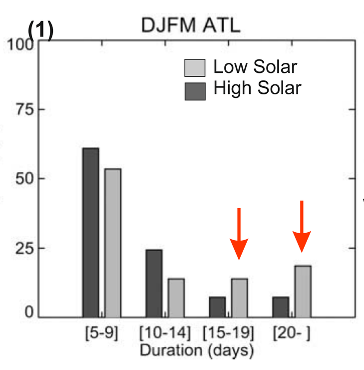
6.1 Atlantic Blockings

- Anomalous high-pressure system off West Europe during periods of solar minima in CCSM4*(left)*. This has also been documented during the Wolf and Maunder Minima[12] *(right)*.



- Blocking events are mid-latitude weather systems where a quasi stationary high pressure system located in the Northeast Atlantic modifies and diverts the eastward flow of the westerlies by blocking its pathway. These can have important consequences on the N. Atlantic ocean circulation[13,14] and European climate[15].

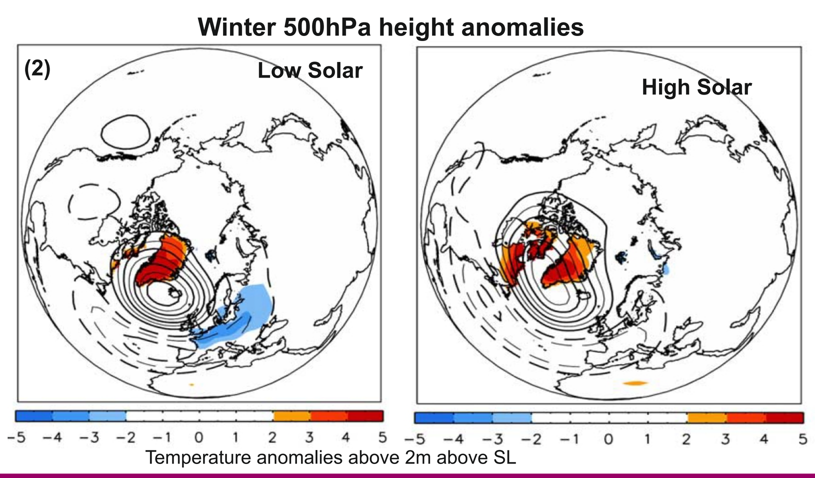
6.2 Atlantic blockings and solar variability



- Observational data shows strong solar modulation of frequency/magnitude and positioning of blocking events during 11-yr solar cycles[16].
- The Central England Temperature record (back to 1650 yrs AD) shows anomalous cold winters related to increased atmospheric blocking events during the Maunder Minima[17].

(1) More persistent N. Atlantic blocking events during solar minima (ref.16).

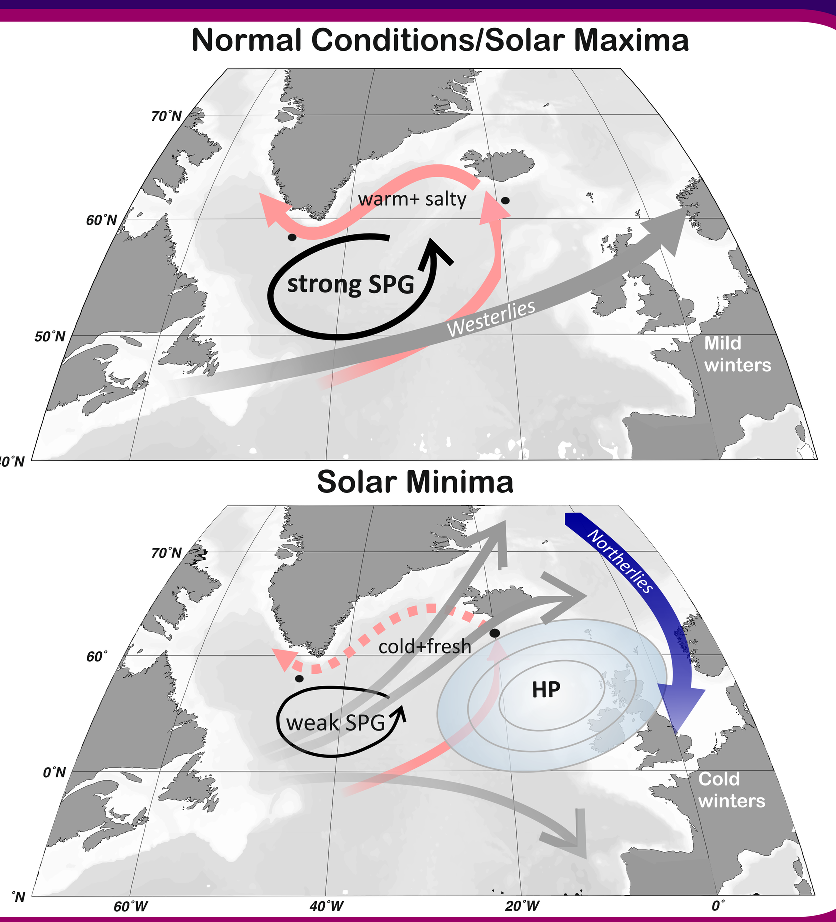
(2) High pressure systems are located further to the North East affecting the European winters during solar lows (ref.16).



- The strong regional atmospheric response to solar forcing has been explained to be caused by complex stratospheric feedbacks (involving O^3 and top-down effects), Pacific teleconnections, ocean feedback on atmospheric changes[18].

7. Conclusions

- Proxy results show abrupt multidecadal-scale changes in the properties of the upper limb of the AMOC between 830-1760 years AD with a strong correlation with solar irradiance.
- Model simulations support this finding and reveal that these hydrographic changes likely resulted from variability in the strength of the N. Atlantic SPG driven by the frequency and persistence of atmospheric blocking events in the eastern North Atlantic as a response to solar irradiance variability.
- Separate relationships between solar irradiance and Atlantic blocking events and SPG strength have been previously identified. Our findings support a direct linkage between these three components of the Earth's climate system, which may have shaped the North Atlantic climate over the last millennium.



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