Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G38521.1

Past changes in the North Atlantic storm track driven by insolation and sea ice forcing

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ABSTRACT

Changes in the strength and location of winter storms may cause significant societal and economic impacts under future climate change, but projections of future changes in Northern Hemisphere storm tracks are highly uncertain and drivers of long term changes are poorly understood. Here we develop a Late Holocene storminess reconstruction from northwest Spain and combine this with an equivalent record from the Outer Hebrides, Scotland, to measure changes in the dominant latitudinal position of the storm track. The north-south index shows storm tracks moved from a southerly position to higher latitudes over the past 4000 years likely driven by a change from meridional to zonal atmospheric circulation, associated with a negative to positive North Atlantic Oscillation (NAO) shift. We suggest that gradual polar cooling (caused by decreasing solar insolation receipt in summer and amplified by sea-ice feedbacks) and mid-latitude

warming (caused by increasing winter insolation) drove a steepening of the winter latitudinal temperature gradient through the Late Holocene, resulting in the observed change to a more northerly winter storm track. Our findings provide palaeoclimate support for observational and modeling studies that link changes in the latitudinal temperature gradient and sea-ice extent to the strength and shape of the circumpolar vortex. Together, this evidence now suggests that North Atlantic winter storm tracks may shift southward under future warming as sea ice extent decreases and the mid-high latitude temperature gradient decreases, with storms increasingly affecting southern Europe.

INTRODUCTION

Future climate change scenarios project with low certainty that there will be a northwards North Atlantic storm track shift (Collins et al., 2013), which would increase winter storminess in northern Europe. In contrast, it has recently been suggested that Arctic amplification of warming resulting from reduced sea-ice extent could have the opposite effect, causing a reduced latitudinal temperature gradient leading to a weakened circumpolar vortex, more meridional circulation patterns and persistent weather extremes in the mid-latitudes (Kim et al., 2014; Francis and Vavrus, 2012; Yang and Christensen, 2012). This is an important possibility to consider, as greater than expected economic and societal costs may be incurred if storm tracks shift southwards across mainland Europe. Improving understanding of the drivers of changes in storminess is critical to reducing uncertainty over the direction and scale of the impact of future climate change. Palaeoclimate records can be used to test different hypotheses on relationships between circulation responses and forcing mechanisms such as sea-ice variability.

Previous research suggests a number of key natural forcings on atmospheric circulation and storm track changes. Modeling shows that orbital changes through the Holocene would have caused a progressively steep temperature gradient and a northwards storm track shift (Brayshaw et al., 2010), and some palaeoclimate reconstructions have attributed trends in storminess to orbital forcing (Bakke et al., 2008; Orme et al., 2016). However, over shorter annual to centennial timescales low solar activity, particularly reductions in ultraviolet radiation, has been associated with weakened stratospheric westerly winds that induce negative NAO anomalies and a southward storm track shift (Ineson et al., 2011; Martin-Puertas et al., 2012). Oceanic forcing has also been suggested as a key driver, whereby greater southward penetration of polar water in the Atlantic may have enhanced the temperature gradient, increasing storm intensity across Europe (e.g. Sabatier et al., 2012). Evidence also suggests that reduced sea-ice can cause a weakening of the circumpolar vortex and a negative NAO pattern in winter (Kim et al., 2014; Alexander et al., 2004), which would favor a southward storm track shift.

Here we develop a storm track index spanning the Late Holocene and use this as the basis to test the dominant drivers of change over this period. We use records of particulate influx in peat deposits to develop storminess reconstructions from two locations at opposite ends of the storm track gradient, reflected in their relationship with the NAO dipole; storminess is greater in Spain when the NAO is negative and enhanced in Scotland when the NAO is positive (see supplementary information 1). Thus, we can use the difference between these locations as an index of long term changes in the dominant storm tracks.

METHODS

Pedrido Bog is an ombrotrophic peat bog in northwest Spain (Fig. 1; 43.4503 N, 7.5292 W; 770 m altitude; see supplementary information 1). A 2.5 m long core was sampled using a Russian corer in 2003. Eight samples were ^{210}Pb dated and thirty samples were AMS radiocarbon dated (see supplementary information 2), and sample ages were estimated using Bayesian analysis in OxCal version 4.2.3 (Ramsey, 2009).

In ombrotrophic peat bogs mineral material can only be received from the atmosphere, therefore measurements of sand content through a peat core can be used as a storminess proxy. The storminess reconstruction was developed from the Ignition Residue and weight of sand sized sediment (120–180 μm and >180 μm) in 5 cm^3 of wet material at 1 cm increments following the methods in Orme et al. (2016).

A North-South index of storm track position was calculated by contrasting between sand content from the Pedrido Bog reconstruction and similar reconstructions from the Outer Hebrides (Orme et al., 2016; see Supplementary Information 1). The two Hebrides reconstructions (ignition residue measurements) and the Pedrido reconstruction (120–180 μm sand fraction) were selected as these proxies best represented the sand content in each core. These were standardised and each smoothed and downsampled to the same 20 year resolution. The Outer Hebrides results were then averaged together to maximise the regional signal, and the normalized Pedrido reconstruction was subtracted from the combined Hebrides reconstruction.

LATE HOLOCENE STORMINESS IN NORTHWEST SPAIN

Sediment influx in the Spanish site was significantly greater in the early part of the record between c. 4000 and 1800 cal yr B.P. than during the past 1800 years (Fig. 2).

There are also a series of peaks in sediment content between 3900 and 1800 cal yr B.P. (c.3800, 3550, 3300, 2850, 2400, 1950 and 250 cal yr B.P.) suggesting shorter phases of intense storminess were overlain on the multi-millennial trend of higher to lower storminess. Greater dust influx during storms could result from human disturbance of soil in the vicinity of the bog. Deforestation occurred throughout much of the Late Holocene in northwest Spain, but in general forest cover is greater before than after 2000 cal yrs BP (e.g. Mighall et al., 2006). We thus favor a climatic interpretation as the record compares well with regional climate reconstructions from marine cores, which are likely to be less influenced by anthropogenic changes. For example, there was a strong hydrodynamic regime (caused by prevalent winter storms) at 4800–2200 cal yr B.P. (Martins et al., 2007), high terrestrial input (caused by high precipitation) at 4200–2100 cal yr B.P. (Pena et al., 2010) and humid conditions at 3500-1800 cal yr B.P. (Mojtahid et al., 2013), supporting the interpretation of the Pedrido reconstruction as a record of regional storminess variability.

NORTH-SOUTH STORM TRACK INDEX

The north-south storm track index (Fig. 2), suggests that there was a more southerly storm track earlier in the Late Holocene from c. 4000 cal yr B.P., with a transition to a northerly storm track occurring over the period 3000–800 cal yr B.P..

The long term trend of a northward movement of the storm track over the Late Holocene is associated with a series of other indicators of ocean circulation and terrestrial climate, including increased wind-driven Atlantic Water inflow to the Nordic Sea (Giraudeau et al., 2010; Fig. 3A), gradually increasing storminess in northern Europe (Andresen et al., 2005) and increasing winter precipitation, reflected in records of glacial extent in Norway (Bakke et al., 2008). A negative-to-positive NAO transition at 2000 cal yr B.P. (Olsen et al., 2012; Fig. 3B), supports the contention that there is a consistent relationship between storminess and the NAO over millennial timescales, although the lower magnitude centennial scale patterns of NAO variability are debated (Ortega et al., 2015). The long-term movement of the storm track may reflect a change from meridional to zonal circulation of the circumpolar vortex (Bakke et al., 2008), as more meridional circulation of the atmosphere between 3100 and 2400 cal yr B.P. has also been suggested as a driver of high sea-salt and dust influx in Greenland (O'Brien et al., 1995) and warmer and less stable conditions in the Norwegian Sea (Moros et al., 2004). Previous suggestions that a cooler North Atlantic and drier continental Eurasia indicate a more negative NAO shift over the Late Holocene (Müller et al., 2012) are equally well-explained by this circulation change.

The centennial scale cold events that have punctuated the Holocene are not so clearly shown by the N-S storm track index, despite evidence of more intense storms in Europe during some of these shorter periods such as the Little Ice Age (e.g. Sabatier et al., 2012). Differences in proxy sensitivity may explain this, as reconstructions based on lagoonal sediments record the occurrence of infrequent, highly intense storms when barriers are overtopped, whereas sand deposition to bogs occurs during a wider range of conditions. Furthermore, lagoonal sediments are affected by long-term sea-level rise, such that millennial scale trends in storminess are more difficult to establish (Sabatier et al., 2012).

STORM TRACK FORCINGS

The primary driver of the long-term millennial change in storminess and changes in the winter latitudinal temperature gradient is a shift in orbitally-driven solar insolation (Fig. 4). In mid-latitudes (45–60°N) the winter insolation receipt has increased since 4000 cal yr B.P., with December insolation at 60°N increased by around 3 W m^{-2} (Berger and Loutre, 1991; Fig. 3G), although this would have been partially offset by the short-term reductions associated with a grand solar minima of ~1 W m^{-2} during some short periods of several decades to centuries (Fig. 3E; Steinhilber et al., 2012; Martin-Puertas et al., 2012). The mid-latitudes therefore would have warmed in winter over the last 4000 years.

In contrast to warming winters at mid-latitudes, orbital changes drove a decrease in summer insolation of around 17 W m^{-2} at 90°N since 4000 cal yr B.P. that would have had an especially strong influence, as in the polar regions summer insolation is a much greater proportion of the total insolation receipt (Berger and Loutre, 1991; Fig. 3F). This, plus the effect of decreasing solar activity (Steinhilber et al., 2012; Fig. 3E), is likely to have caused the decrease in Arctic temperatures through the Late Holocene, as shown by ice-core and marine archives (Alley, 2004; Kim et al., 2004). Summer cooling also caused more extensive sea-ice formation, especially after c.2000 cal yr B.P. (Müller et al., 2012; Vare et al., 2009; Fig. 3D). Sea-ice provides a mechanism through which the summer insolation receipt would also have influenced winter temperatures, as low (high) sea-ice extent and formation enhances (reduces) the heat flux from the ocean to the atmosphere, particularly in winter (Alexander et al., 2004). Therefore, before c.2000 cal yr B.P., higher insolation receipt in Arctic summers would have caused low sea-ice extent and winter warming, and decreasing summer insolation after 2000 cal yr B.P. enhanced sea-ice extent resulting in gradual winter cooling of the atmosphere (Fig. 4).

The findings support the hypothesis that a combination of decreasing Arctic summer insolation receipt (with ensuing sea ice feedbacks leading to winter cooling) and orbitally driven mid-latitude winter warming, caused a gradual steepening of the latitudinal temperature gradient between the mid to high latitudes during the Late Holocene. This would have strengthened the polar vortex and driven a change from meridional to more zonal circulation and a northwards shift in the storm track observed in the North-South Index (Fig. 4). This proposed millennial scale trend and dynamic explanation does not exclude the possibility of decadal-centennial changes driven by solar variability (e.g. Martin-Puertas et al., 2012), which were superimposed on this long term shift.

FUTURE CIRCULATION CHANGES

Our results thus provide palaeoclimate evidence that supports predictions that future Arctic amplification of warming and sea-ice reductions have the potential to reduce the latitudinal temperature gradient (with greater warming in the poles than the mid-latitudes), resulting in meridional circulation and higher winter storminess in southern Europe (Francis and Vavrus, 2012; Kim et al., 2014), rather than a northward storm track shift (Collins et al., 2013). Models have also suggested that sea ice reductions lead to negative NAO circulation patterns and colder winters in Europe (Yang and Christensen, 2012) supporting the link between the hypothesized storminess trend and the NAO.

However, the response of the storm track to global warming is likely to be modified by a range of factors. In the Atlantic region, ocean circulation is a major driver of uncertainties in model projections (Woollings et al., 2012). Model simulations demonstrate that weakening of Atlantic ocean circulation causes cooling to the south of Greenland and a steeper temperature gradient south of the British Isles, which acts to shift the storm track further south (Woollings et al., 2012). Furthermore, models that incorporate the stratosphere have shown that increased strength of the Brewer-Dobson circulation leads to a southward shifted polar night jet, greater eddy growth in the mid-latitudes and enhanced storminess in western and central Europe (Scaife et al., 2012). Factors such as these may therefore further strengthen the trend towards greater storminess in Southern Europe.

If correct, the findings presented here have important implications for assessments of future climate impacts and necessary adaptation measures in Europe, raising the risk of greater-than-expected environmental, societal and economic damage in different regions to those currently thought to be most at risk.

ACKNOWLEDGMENTS

L.C.O. was funded by the University of Exeter and a British Geological Survey University Funding Initiative (BUFI) Studentship. We are grateful to the ACCROTELM Project, supported by the European Commission Contract No. EVK2-CT-2002–00166, for contributing the dated Pedrido Bog core.

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FIGURE CAPTIONS

Figure 1. Map illustrating the location of Pedrido Bog in northwest Spain and storm reconstruction sites from the Outer Hebrides, Scotland (Orme et al., 2016) used to develop the North-South storm track index. *Inset*: Pedrido Bog location in the Galicia.

Figure 2. Records used in the development of the North-South storm track Index (from left): a) Age estimates from Pedrido Bog (Spain) and age-depth model (shaded) (supplementary information). b) Sediment content for Pedrido (Spain) shown as weight of sand fractions (120–180 μm, gray line and >180 μm, black line). c) Standardised 120–180 μm fraction measurements from plot b (gray line) and smoothed results (black line). d) Standardised sediment influx measurements from two sites in the Outer Hebrides (Orme et al., 2016), with the combined reconstruction (black, continuous line). e) North-South Index of storm track position, derived from the difference between the smoothed and combined records in c) and d) respectively.

Figure 3. Comparison between the north-south storm track reconstruction (C), reconstructions of the NAO (B) (Olsen et al., 2012) and wind-driven Atlantic Water Inflow (A) (Giraudeau et al., 2010), with key forcings illustrated by changes in sea ice

DOI:10.1130/G38521.1

abundance from the Fram Strait (D) (Müller et al., 2012), Total Solar Irradiance reconstruction (E) (Steinhilber et al., 2012), June Insolation at 90°N (F) and December Insolation at 60°N (G) (Berger and Loutre, 1991). The latter is shown to represent the increasing winter temperature gradient between 60°N and 90°N.

Figure 4. Schematic summary of the relationship between insolation receipt, latitudinal temperature gradients, sea ice extent and the influence of these changes of the polar vortex circulation and storm tracks. The top panel shows the patterns dominant between 4000 and 2000 cal yr B.P., and the lower panel shows the patterns dominant from 2000 cal yr B.P. to present. These represent the idealized circulation patterns and longterm trends, rather than centennial variability in circulation.

[1]GSA Data Repository item 2016xxx, xxxxxxxx, is available online at http://www.geosociety.org/pubs/ft2016.htm or on request from editing@geosociety.org.

Figures

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Journal: GEOL: Geology
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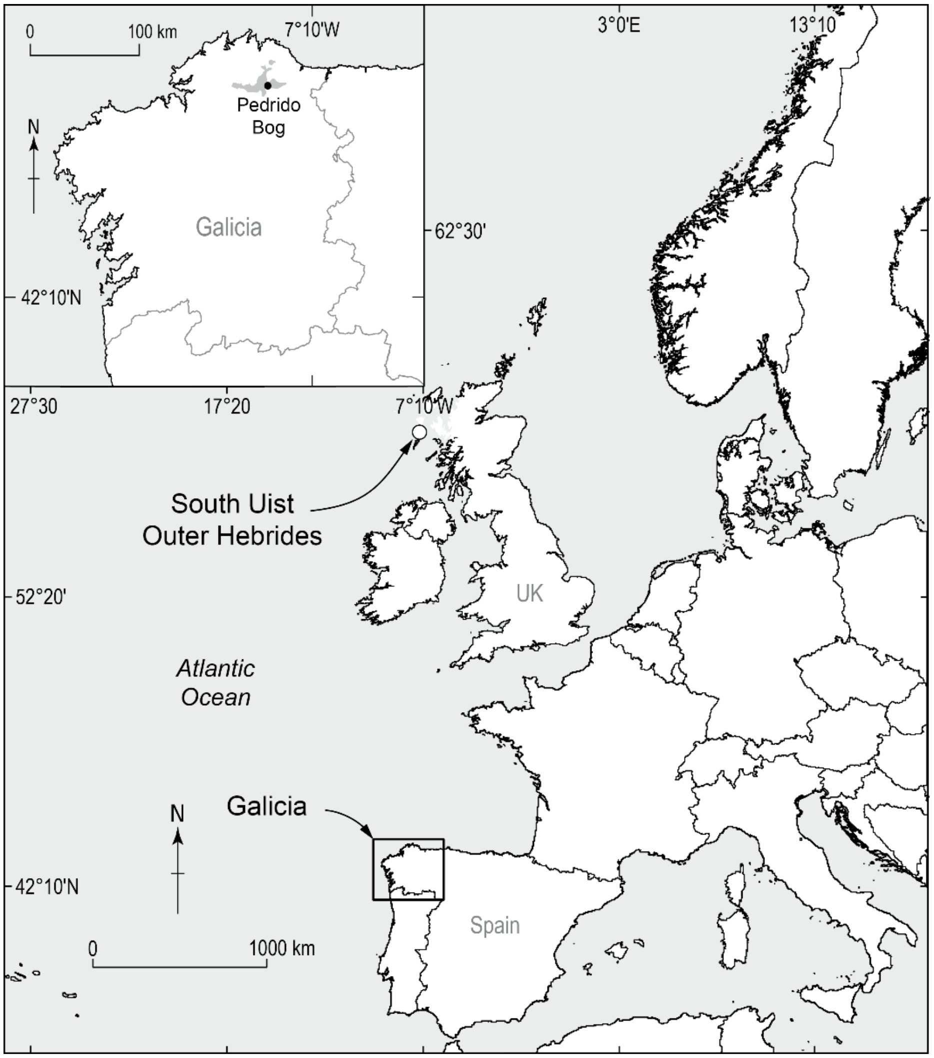

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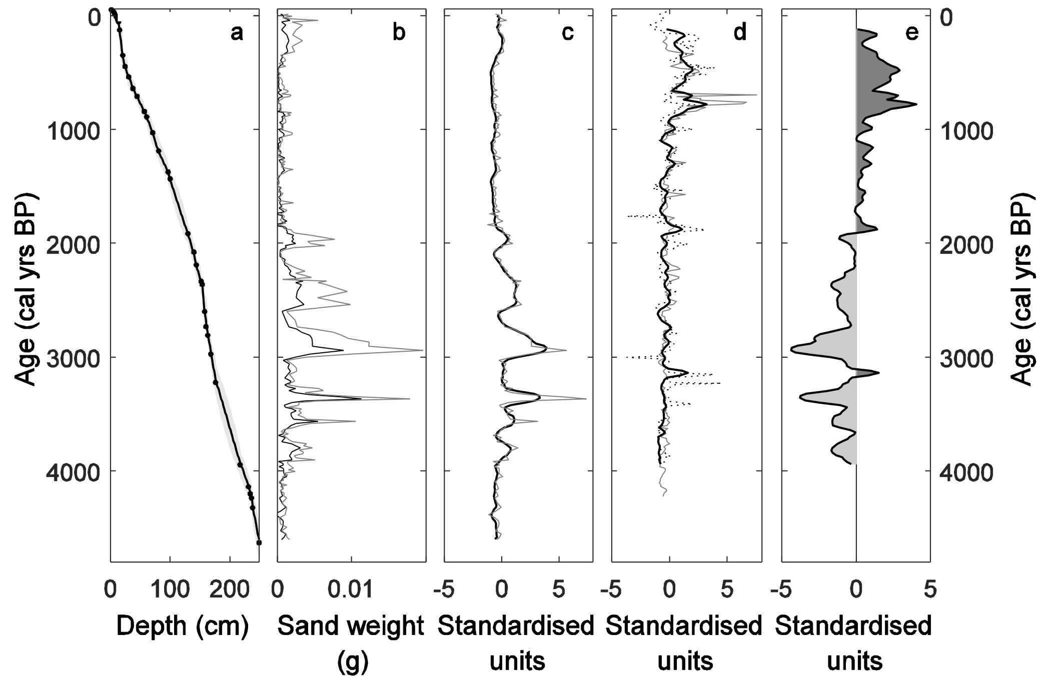

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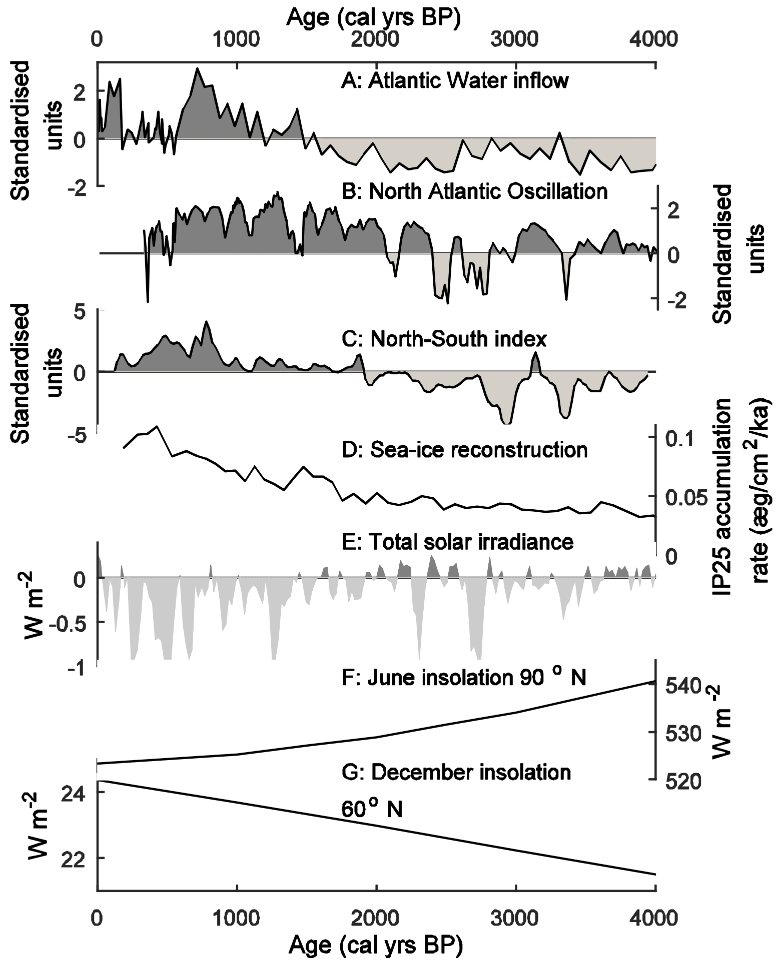

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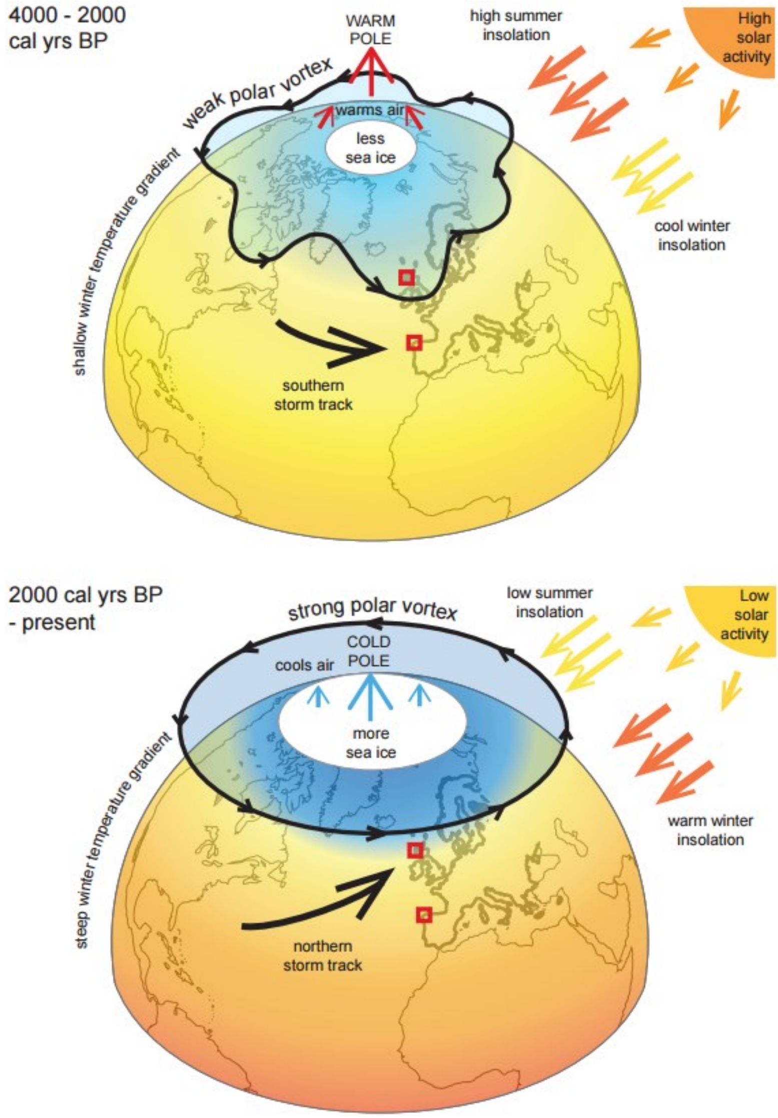
4000 - 2000
cal yrs BP
WARM
POLE
high summer
insolation
High
solar
activity
weak polar vortex
warms air
less
sea ice
shallow winter temperature gradient
cool winter
insolation
southern
storm track
2000 cal yrs BP
- present
strong polar vortex
low summer
insolation
Low
solar
activity
COLD
POLE
cools air
more
sea ice
steep winter temperature gradient
warm winter
insolation
northern
storm track