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 over the past 4000 years. 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 storm track. Our findings provide palaeoclimate support for short-term observational and modelling studies linking changes in the latitudinal temperature gradient and sea-ice extent to the strength and shape of the circumpolar vortex. Together, the evidence now suggests that North Atlantic storm tracks will shift southward under future warming as sea ice extent decreases, 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 reduce the impact of severe storms in southern Europe and 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 weakening of the circumpolar vortex, meridional circulation patterns and persistent weather extremes in the mid-latitudes (Kim et al., 2014; Francis and Vavrus, 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 in Europe and elsewhere 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. Modelling 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). Low solar activity has been associated with negative NAO anomalies and a southward storm track shift (Ineson et al., 2011). Oceanic forcing has also been suggested as a key driver, where greater southward penetration of polar water in the Atlantic may have enhanced the temperature gradient, increasing storm intensity across Europe (Sorrel et al., 2012; Orme et al., 2015; Sabatier et al., 2011). 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; Deser et al., 2010), which would favour a southward storm track shift. Sea-ice may also amplify other forcings. For example, if low solar activity caused increased sea-ice, this would drive a southward shift in the region of deep-water formation in the Arctic, resulting in further cooling and sea-ice formation (Renssen et al., 2006).

Here we develop a novel approach to reconstructing storm track strength and position over 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 (Andrade et al., 2008). 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 situated in the Xistral Mountains of northwest Spain (Figure 1; 43.4503 N, 7.5292 W; 770 m altitude). A 2.5 m long core was sampled using a Russian corer in 2003 as part of the ACCROTELM Project.

Eight samples were ^{210}Pb dated and thirty samples were AMS radiocarbon dated following the methods outlined in Stefanini (2008). The age-depth model was created using Bayesian analysis by OxCal version 4.2.3, which used the IntCal13 calibration curve (Ramsey, 2009; Reimer et al., 2013). The median of the 2-sigma age range was used to estimate the age for individual samples down the core.

In ombrotrophic peat bogs such as Pedrido Bog mineral material can only be received from the atmosphere, so therefore measurements of sand content through a peat core can be used as a storminess proxy (Björck and Clemmensen, 2004). The storminess reconstruction was developed by establishing 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 a two-site reconstruction from the Outer Hebrides (Orme et al., 2016). 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 and the normalised Pedrido reconstruction subtracted from the combined Hebrides reconstruction.

LATE HOLOCENE STORMINESS IN NORTHWEST SPAIN

Sediment influx in the Spanish site (Pedrido Bog) was significantly greater in the early part of the record between c. 4000 and 1800 cal yr BP than during the last 1800 years (Figure 2). There are also a series of peaks in sediment content between 3900 and 1800 cal yrs BP (c.3800, 3550, 3300, 2850, 2400 and 1950 cal yrs BP) each spanning 150 - 400 years, suggesting shorter phases of more intense storminess were overlain on the multi-millennial trend of higher to lower storminess. The reduced sediment content between 1800 and 500 cal yrs BP suggests that lower storminess prevailed until around the start of the Little Ice Age. Although previous research has suggested that dust influx can result from human disturbance (e.g. Martínez-Cortizas et al., 2005), comparison with regional climate reconstructions from marine cores supports the interpretation that the sand influx was driven by the frequency and/or intensity of extratropical cyclones (Orme et al., 2015). There was a strong hydrodynamic regime (caused by prevalent winter storms) at 4800-2200 cal yrs BP (Martins et al., 2007), high terrestrial input (caused by high precipitation) at 4200-2100 cal yrs BP (Pena et al., 2010) and humid conditions between 3500-1800 cal yrs BP (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 (Figure 2), shows low (high) values when the reconstructed storm track was in a southerly (northerly) position. The index suggests that there was a more southerly storm track earlier in the late Holocene from c. 4000 cal yrs BP, with a transition to a northerly storm track occurring through the period and especially from around 3000 to 800 cal yrs BP.

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. Increased wind-driven Atlantic Water inflow to the Nordic Sea (Giraudeau et al., 2010; Figure 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). Similarly, a negative-to-positive NAO transition at 2000 cal yrs BP (Olsen et al., 2012; Figure 3B) supports the contention that there is a consistent relationship between storminess and the NAO over millennial timescales. 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

3100-2400 cal yrs BP 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).

STORM TRACK FORCINGS

The primary driver of the long-term change in storminess and changes in the winter latitudinal temperature gradient is a shift in orbitally-driven solar insolation (see summary in Figure 4). In mid-latitudes (45-60^{o}N) the winter insolation receipt has increased since 4000 cal yrs BP, with December insolation at 60^{0}N increased by around 3 W m^{-2} (Berger and Loutre, 1991; Figure 3G), a much larger change than the short-term reductions associated with a grand solar minima of ~1 W m^{-2} (Steinhilber et al., 2012; Figure 3E). The mid-latitudes therefore would have warmed in winter through this period.

In contrast to warming winters at mid-latitudes, orbital changes drove a decrease in summer insolation of around 17 W m^{-2} since 4000 cal yrs BP that would have had an especially strong influence in the polar regions, where summer insolation is a much greater proportion of the total insolation receipt (Berger and Loutre, 1991; Figure 3F). This, plus the effect of decreasing solar activity (Steinhilber et al., 2012; Figure 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 yrs BP (Müller et al., 2012; Vare et al., 2009; Figure 3D). Sea-ice extent may have been further amplified by a positive feedback between climate cooling and sea-ice, through a southward shift of the region of deep-water formation, causing further ocean cooling and enhanced sea-ice formation (Renssen et al., 2006). 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 yrs BP, higher insolation receipt in Arctic summers would have caused low sea-ice extent and winter warming, and decreasing summer insolation after 2000 cal yrs BP enhanced sea-ice extent resulting in gradual winter cooling of the atmosphere (Figure 4).

The combination of Arctic sea-ice driven cooling in winter, and orbitally driven mid-latitude winter warming, caused a gradual steepening of the latitudinal temperature gradient between the mid to high latitudes. 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 (Figure 4).

CONCLUSIONS

The findings support the hypothesis that storm tracks shifted southwards during periods with reduced winter insolation, such as the mid-Holocene (Brayshaw et al., 2010). We show that storm tracks moved northwards during the Late Holocene and propose that it was the combined effects of Arctic summer insolation receipt and ensuing sea-ice feedbacks, as well as winter insolation at mid-latitudes, which together controlled the temperature gradient and storm track patterns in winter. The atmospheric circulation and North Atlantic storm track position may therefore be highly sensitive to relatively small changes in the latitudinal temperature gradient. 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, resulting in meridional circulation and higher winter storminess in southern Europe (Francis and Vavrus, 2012; Kim et al., 2014), rather than a northward movement as previously suggested (Collins et al., 2013). This result has important implications for assessments of future climate impacts and necessary adaptation measures in the region, raising the risk of greater-than-expected environmental, societal and economic damage in different regions to those currently thought to be most at risk.

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FIGURE CAPTIONS

Figure 1: Map illustrating the location of Pedrido Bog. *Left*: locations 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. *Right*: Pedrido Bog location in the Xistral Mountains, 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) (see supplementary information). Note error estimates are shown but smaller than symbols. b) Sediment content for Pedrido (Spain) shown as weight of sand fractions (120-180 µm, grey line and >180 µm, black line). c) Standardised

120-180 µm fraction measurements from plot b (grey line) and smoothed results (black line). d) Standardised sediment influx measurements from two sites in the Outer Hebrides (Orme et al., 2016), with standardised combined reconstruction (black, continuous line). e) North-South Index of storm track position, derived from the difference between the records in c) and d).

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 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 on the strength and circulation pattern of the polar vortex and storm tracks. The top panel shows the patterns dominant between 4000 and 2000 cal yrs BP, and the lower panel shows the patterns dominant from 2000 cal yrs BP to present.