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North Atlantic summer storm tracks over Europe dominated by internal variability over the past millennium

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Certain large, sustained anomalies in European temperatures in the last millennium do not match estimations of external climate forcing, and are likely the result of internal variation[1]. Should such anomalies occur in the future, they could be large enough to significantly modulate European temperatures away from the expected response to greenhouse forcing[2-3]. Here, past millennium temperature observations, simulations and reconstructions reveal that, continental multidecadal-mean summer temperature has varied within a span of 1K, largely controlled by external forcing. By contrastsimulation-estimated subcontinental deviations from the mean, described by the temperature contrast between northern and southern Europe (the meridional temperature gradient), vary within a span of 2K and are largely driven by internal climatic processes. These processes comprise internally generated redistributions of precipitation and cloud cover linked to oscillations in the position of the summer storm track. In contrast to recent 20th century[4] wintertime trends, regional past-millennium variations of the summer storm-track show a weak response to external forcing and dominance of stochastic internal variability. The future response of European summer temperatures to anthropogenic greenhouse forcing is likely to be spatially modulated by stochastic internal processes which have caused multiple periods of cool, wet summers[5-6] in northern Europe over the last millennium.

Climate variability has two, entangled sources. One source comes from external climate forcing factors, such as greenhouse gases, solar irradiance and volcanic eruptions. The response to changes in these forcing factors (the equilibrium climate sensitivity) reveals the magnitude and severity of long-term future warming caused by anthropogenic greenhouse gas emissions. The other source, internal climate variability, does not require changes in external forcing and may cause large amplitude deviations around the externally driven component[1]. Whilst external forcing has the capacity to influence internal variability[7], the degree of independence of the two components is a significant unknown. The contributions of internal variability in climate can be larger at continental scales[8], and the temporal and spatial structures more complex, in comparison to global scales. Thus subcontinental variability may be capable of locally masking the continental scale forced response in coming decades. Whilst the response of continentally averaged temperatures to external forcing in the Late Holocene has been scrutinized[9], the spatial structure, and dynamics, associated with deviations from the forced continental mean, remains unquantified. Here we focus on multidecadal summer temperature variability in Europe over the past millennium and its connections to the variability of storm tracks. In this region marked recent multidecadal variations in the position of the storm tracks have been detected in the observational record[5], suggesting a link to internal regional climate variability.

Proxy and model-derived records.

Analysis is facilitated by the global climate simulations of the fifth Climate Model Intercomparison Project (CMIP5), which allow for a dynamical interpretation of temperature variability, and by multiple high-resolution proxy records sensitive to summer temperature, which offer palaeoproxy evidence. The proxy-based summer temperature reconstructions represent a north-south transect in Western Europe[10-13] (see Online Methods). The climate models were driven by estimations of the main past external climate forcings, which vary among simulations depending on the different estimates used[14] (see Online Methods). We analyse simulations with the Earth System Model MPI-ESM-P, and outputs from another high-resolution model, CCSM4 (see Online Methods).

Proxy-based, gridded, past millennium climate reconstructions encompassing the European continent have previously been generated assuming that spatial temperature covariance across the region behaved, in the past, as in the observational period[15-16]. This strategy bears the risk of artificially identifying the same patterns of variability as presently observed, and overlooking periodically occurring modes of internal climate variability that do not have spatio-temporally uniform expression. . Here we construct independent regional summer temperature composites for four areas under the geographical descriptors Arctic, Central, Pyrenean and Alpine Europe, and choose not to calibrate them to modes of variability expressed in the 20th century. The proxy data set was provided by the EU 6th Framework Millennium project (Table SI1). Proxy data are dominated by highly-replicated time series of tree ring width and density variability. The Alpine series contains tree ring, and lake sediment derived data[10].

The magnitude of subcontinental summer temperature variability in the simulations can be quantified by the total variance left unexplained by the mean continental temperature history. In the MPI-ESM simulation (AD 850-2005), continental mean temperature variability explains half of the total summer temperature variance in the European sector after 21-year low-pass filtering, and is significantly correlated (r=0.55, p=0.001, see Online Methods for estimation of p-values) with external climate forcing including greenhouse gases, solar variability and volcanic eruptions[17] (see Online Methods for the estimation of total external forcing). Moreover, the continental average of summer temperature also presents the 'classic' climate evolution of the last millennium, with a Medieval Climate Anomaly (MCA) in initial centuries, leading into the Little Ice Age (LIA) around AD 1700 followed by a post-industrialisation warming phase (Figure 1A). Similar results are obtained with the CCSM4 simulation (Figure S1) although there are some differences in the regional details and gradient strengths, which may be linked to the differing model physics, or differences in the contributions of internal variability. Mean continental summer temperatures simulated by both models are significantly correlated (r=0.54, p=0.0005). Despite the differences in the forcings considered[18], multidecadal continental mean summer temperature in both simulations appears to be dominated by external forcing, on the basis of both the correlation with external forcing and the widely-verified temporal evolution (e.g MCA/LIA).

Observed, modelled and proxy meridional temperature anomalies.

The potential internally-forced variability is better exposed by subtracting the continental multidecadal-mean summer temperature from the simulated grid-cell temperatures. The time series of external forcing explains ~4% of these temperature residuals. The grid-cell residuals from the continental mean are better described by the European Meridional Temperature Gradient (MTG) (defined as the slope of the regression of zonal mean temperature against latitude, see Online Methods), than by the zonal temperature gradient (defined as the slope of the regression of the meridional-mean temperature against longitude). The European meridional temperature gradient explains ~35% of the variability of the temperature residuals, the zonal gradient only ~10%. Similar results are derived from the simulation with the model CCSM4 (40% and 8% respectively), thelow correlations with the zonal temperature gradient thus ruling out a major role of external forcing in driving the temperature pattern.

A Principal Component Analysis of the temperature deviations from the continental-mean in the simulations confirms these results, with the leading pattern exhibiting a meridional sea-saw in both models, and explaining 37% (2-model average) of the variability (Figure S2). In contrast to the behaviour of the continental-mean temperature, the pairwise correlation between the mean meridional gradient in the simulations is low ($r=0.05$, $p>0.45$). We thus focus on broad-scale, internally driven, climatic mechanisms that might better explain the decadal variations in the European summer MTG.

The spatial correlation map of time series of the mean simulated MTG with summer precipitation in each model grid-cell reveals a physically consistent spatial structure (Figure 1D). Regions with temperatures lower than the long term mean tend to receive more precipitation (and thus less short-wave surface radiation) in the summertime, and vice-versa. A similar correlation analysis with baroclinic synoptic activity, defined here as the 2-6 day band-pass filtered variability of the sea-level-pressure[19] in each model grid-cell, also indicates that regions experiencing lower than average temperatures and higher than average precipitation are linked to higher than average synoptic activity (more storms than usual enter the region, Figure 1C and 1D). We will later relate this statistical relationship to decadal north-south oscillations of the summer storm-tracks in the European region[20].

The observed meridional temperature gradient

The European MTG has a similar relationship with observed, gridded precipitation and synoptic activity from meteorological reanalysis (AD 1948-1998, Figure 2A and 2B). The observed MTG record is weakly (but significantly) correlated with the continental scale temperature mean ($r=-0.26$, $p=0.001$, Figure 2D). Their multidecadal behaviour is also profoundly different, most conspicuously at the end of the 20th century when continental mean temperature shows a warming trend beginning ~AD 1960, at which time the evolution of the MTG is essentially flat. Over the record length the extremes in the continental-mean and the MTG do not generally coincide, clearly evident during the AD 2003 European heat wave[21], and the extreme temperature gradient in AD 2012 (Figure 2D).

The multidecadal variations in the MTG as revealed by observational record and simulations promote investigation within the proxy record as such variability can be better characterised by the longer context available. Our north-south transect of proxy-based summer temperature reconstructions (see Online Methods) reveals a pattern of variability consistent with the picture revealed by the simulations and historical observations (Figure 1). The series begin after the Medieval Climate Anomaly and reveal a continental temperature decrease into the Little Ice Age followed by notable warming in the industrial period (Figure 1B). The proxy composite time series were smoothed in the same manner as the simulations (21-year low-pass filter), to highlight multidecadal variability, and were subsequently standardized to unit variance (with reference to AD 1264-1992). Standardization was carried out to address the different variance preservation properties of the statistical reconstruction methods used, which could have resulted in series with differing variance characteristics confounding the climate signal[9]. We note that the variance-capture properties of the proxy time series are tested and robust[10-13].

Meridional summer temperature gradient in the proxy records.

Each proxy time series can be decomposed as the sum of (1) the mean of the four regional proxy-reconstructions and (2) a residual. If all four proxy records were varying in synchrony, the variance of the residual records would be zero. Here, the sum of variance of the residuals is 35% of the original sum of variances, indicating that about one third of the variance is 'local' (linearly independent of the spatial mean) and 65% of the variance is common to all four records, and can be represented by their average.

The averaged record broadly displays the reconstructed temperature evolution of the last millennium (Figure 1B), as in the simulations, and also correlates with the same time series of external forcing[17] ($r=0.71$, $p=0.0001$), with a pre-AD 1800 correlation of $r=0.48$ ($p=0.01$), indicating that the proxies capture the forced temperature variability of the last centuries[22]. Clear minima are displayed in AD 1601 and 1817 associated with known, volcanic, forcing events (Serua and Tambora respectively) [23], although not all minima can be explained by external forcing.

In order to describe the evolution of north-south temperature differences within our proxy network (see Online Methods) we defined the meridional proxy gradient (MPG) across the proxy regions (Figure 1B). We define the MPG as the slope of the regression of the proxy indicators against latitude; it resembles the temperature slope of the gridded temperature fields (see Online Methods). The MPG explains 18% of the total proxy variance and its correlation with the total external forcing[17] in the period AD 1000-1990 (or AD 1000-1850) is small ($r<0.01$ $p=0.43$), as for the simulated MTG. To investigate the large-scale synoptic origins of this mode, we compare the MPG with the meridional temperature gradient derived from gridded temperature observations (Figure 2C). The two time series correlate strongly ($r=0.56$, $p=5x10^{-5}$) in their common period (AD 1850-1980), at both interannual and decadal time scales, demonstrating that the MPG also reflects the underlying meridional temperature gradient. The correlation patterns between the MPG and gridded summer precipitation and synoptic activity in the observational period reflect very similar structures to those derived from the observed MTG (Figures 2A, 2B and S3).

The MPG records six multidecadal extremes, three centred on AD 1310, 1730 and 1910 in which the meridional gradient swings to steeper values (indicative of strongly anomalous temperatures), and three periods around AD 1500, 1750 and 1940 in which the meridional gradient was weaker than average (Figure 1B). These extremes do not appear to be correlated to either known volcanic or solar forcing events, conspicuously so during periods of strong volcanic activity around AD 1601 and 1817. The MPG minima at AD 1500 and 1750 correspond to northern European warm anomalies, which have been noted as unforced[1]. In contrast to the winter season[22], the European summer temperature gradient exhibits large excursions and lacks a strong response to the past external forcing. The link between the MPG and the observed atmospheric circulation (Figure 2A) supports the picture from the simulation data, that the MPG is driven by atmospheric variability which modulates the location of storm centres, and cloud cover, over Western Europe.

Position of the summer storm track

The correlation pattern of the MTG (MPI-ESM-P simulation) with the summer sea-level-pressure field (SLP), and with incoming shortwave radiation at the surface, is shown in Figure 3. The SLP pattern displays a wave train of alternating positive and negative anomalies across the North Atlantic to Europe. This SLP pattern is consistent with reduced surface shortwave radiation over Northern Europe, and increased surface shortwave radiation over Southern Europe, which favours a steeper meridional temperature gradient in Western Europe. The configuration over Europe is confirmed in the corresponding correlation patterns derived from gridded instrumental data sets and from the simulation with CCSM4 (Figure S1).

The correlation of the simulated MTG with the total radiation balance at the top of the atmosphere (including shortwave and longwave radiation, positive when directed downwards) indicates that, when the MTG is steeper (higher), below average net energy amounts are entering the atmosphere in Northern Europe and greater than average energy amounts are entering the atmosphere in Southern Europe (Figure 3C). The implied meridional transport of energy, therefore, counteracts the MTG indicating that the meridional energy transport is not the driving factor for variations in the temperature gradient.

We find that the MTG is linked to the position of the storm tracks in the MPI-ESM simulation over the period AD 850-2005. We applied a storm-tracking algorithm to identify the simulated individual storms in the North Atlantic-European sector during the summer (JJA). The algorithm[24] uses the 6-hourly sea level pressure (MSLP) minima and additionally requests threshold values for vorticity at 850 mb height, storm track length and the MSLP gradient to define the presence of a storm (see Online Methods). In order to evaluate summers more affected by northward/southward moving storms we divided the region east of 10°W into two sections, north and south of 52.5°N, and calculated the ratio of the number of northern versus southern storms in sliding 21-year windows (Figure 3D). This smoothed record correlates with the smoothed simulated MTG record ($r=0.53$, $p=5\times10^{-5}$), indicating that the meridional shifts of the storm tracks contribute to maintaining the MTG, likely through anomalies in surface shortwave radiation (Figure 3B). By altering the atmospheric radiation properties cyclones have a cooling effect over land areas in summer, and hence, more frequent (fewer) storms result in lower (higher) temperatures than normal, and thus in an enhanced (weakened) MTG. The opposite is the case for the southern regions. In contrast, the ratio of south/north storms is not correlated at decadal scales with average continental temperature ($r<0.004$, $p=0.495$), and only rather weakly with total external forcing ($r=0.18$, $p=0.2$). Thus, the position of the European-Atlantic summer storm tracks in the simulation has, on average, varied independent of external climate forcing over the last 800 years, a supportive result to scenario simulations exploring the winter North Pacific storm track[25.] These results strongly suggest that the variations in the external forcing over the past centuries have not been strong enough to distinctively affect the summer storm tracks in the North Atlantic region, and possibly elsewhere.

We have also explored to what extent the MTG is related to large-scale modes of climate variability in the atmosphere and in the North Atlantic Ocean. A candidate is the North Atlantic Meridional Overturning Circulation (AMOC), since it affects meridional advection of heat by the ocean thus impacting sea-surface-temperatures in the North Atlantic[26]. In the MPI-ESM simulation, the link between the MTG and the AMOC at decadal timescales is weak but statistically significant with an unlagged correlation of $r=-0.27$ ($p=0.01$) and lower values for time-lagged indices. The spatial pattern of correlation between the AMOC index and near surface temperature in the North-Atlantic European sector at decadal time scales confirms that a more intense AMOC tends to reduce the meridional temperature gradient, this influence describes a large-scale North Atlantic pattern consistent with the canonical structure of the AMOC. Its influence is mostly restricted to the ocean surface and it is weak over European land (Figure S4). The Summer North Atlantic Oscillation (SNAO) has been identified as a pattern of low-frequency climate variability in this region, with a distinguishable sea-level-pressure pattern[27] showing a centre of action over the North Sea and extending over Northern Europe. This pattern is clearly different from the sea-level-pressure pattern linked to the MTG in the model (Figure 3A) and in observations (Figure S3), and therefore we conclude that there is no strong link between the variability of the MTG and the SNAO. Previous studies on the variability of the winter NAO in the CMIP models also indicated that most of its decadal variability is unforced[28].

We present evidence from palaeoclimate simulations, observational and proxy data revealing that variations of the summer meridional temperature gradient over Europe are largely independent of external climate forcing over the last millennium. In addition, palaeoclimate simulations, and the observational record, consistently indicate that this gradient expresses a pattern of distinct internal spatial shifts in synoptic activity linked to spatial patterns of precipitation and cloudiness anomalies. At the regional scale, these internal fluctuations, independent of external forcing, strongly modulate the mean continental temperature response, at decadal timescales. In phases when a strong MTG exists, these anomalies display a physically consistent dipolar structure, with those areas of Europe experiencing anomalously low (high) temperatures also being those which receive more (less) precipitation and cloudiness.

The two paleoclimate simulations analysed here present remarkably similar results, although both climate models are structurally quite different, strongly suggesting that the results do not depend on the climate model used. However, climate models still struggle to realistically represent the simulation of atmospheric blocking, still a deficiency in state-of-the-art models, which could indirectly affect the simulated variability of storminess in this region[29].

The behaviour of the MTG/MPG, associated with the meridional differences in cloudiness and precipitation linked to the centre of European summer storminess is revealed, by the recent palaeoclimate perspective, to be largely unforced. Whilst this could relate to the surmised small variations of past external forcing it may also indicate that the forced increase in European summer temperatures in the next few decades is likely to be significantly modulated, critically either enhancing or countering forced warming, by powerful internal changes in Europe's meridional temperature gradient.

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Author contributions:

MHG: project planning and design, data analysis, manuscript preparation. EZ: data analysis and manuscript preparation. DM: project planning and design, data analysis, manuscript preparation. MZ: data analysis, manuscript preparation. GHFY: project planning, data analysis, manuscript preparation. IR: project planning, data analysis, manuscript preparation.

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Figure captions

Figure 1. Spatio-temporal structure of simulated (MPI-ESM-P, AD 850-2005) and proxy mean continental and meridional temperature gradients (meridional gradient of European June-August (JJA) near-surface temperature). A) Continental JJA mean temperature (red) and the MTG (blue, 21-yr low-pass filtered). B) Time series (21-yr low-pass filtered) of average JJA temperature indicators (proxy continental temperature, red) and of the MPG (blue, AD 1260-1996). Anomalies at AD 1310, 1730 and 1900 are indicated. C) Spatial correlation between the MTG and near-surface temperature, D) JJA precipitation and E) synoptic activity (high pass filtered [2-to-6 days] variance of the daily sea-level-pressure). 95% significance is close to ±0.20 (See Online Methods).

Figure 2. Spatio-temporal structure of the European summer (JJA) near-surface temperature meridional gradient from observational data. A) Spatial correlation between the observed summer MTG and synoptic activity (NCEP/NCAR meteorological reanalysis), AD 1948-2012. 95% significance is close to ±0.25 [See Online Methods]. B) Spatial correlation between the observed summer MTG and JJA precipitation AD 1900-1998[30].95% significance is close to ±0.20. C) Standardized time series of the instrumental MTG (blue) and the Meridional Proxy Gradient (MPG, red). Interannual and decadal (indicated) correlations $p=5x10^{-5}$ and p=0.01 respectively. D) Time series of observed continental JJA mean temperature (red) and MTG (blue, HadCRUT4 gridded temperature), correlation (p=0.001) indicated.

Figure 3 Climate patterns linked to simulated summer (JJA) MTG (MPI-ESM-P, AD 850-2005). A) Correlation between the MTG time series and JJA sea-level-pressure over the North-Atlantic European sector. B) Spatial correlation between the MTG and downwelling short wave radiation at the surface. C) Spatial correlation between the MTG and total upwelling radiation (shortwave plus longwave, negative directed upwards) at the top of the atmosphere. 95% significance level is close to ±0.20 [See Online Methods]. D) Time series of the ratio between the number of northern to southern JJA extra-tropical cyclones, and the JJA MTG, (both 21-year low-pass filtered). The correlation ($p=5x10^{-5}$) is indicated. All series have been previously smoothed with a 21-year low-pass filter.