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The seasonal characteristics of English Channel storminess have changed since the 19th Century

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Information from a variety of sources has suggested that increased storminess was experienced across the British Isles in the late eighteenth/early nineteenth century. However, it is not clear how stormy that period was relative to current conditions. Using newly recovered barometric pressure data that extend back to 1748 we have constructed a measure of geostrophic wind speed for the English Channel region using a pressure-triangle approach. We show that the 1790–1820s was a period of increased storminess across the region. This storminess extended throughout the year, which is different to comparable increases observed since the 1990s, which were confined to the winter season. While a strengthened North Atlantic jet stream is implicated in both periods, in the earlier period it is likely that the storm track shifted slightly to a more southerly location. We discuss the potential forcing mechanisms responsible for the changes in storminess over this multi-century timeframe.

Over the last decade two particularly stormy autumn-winter seasons have been experienced across northwest Europe. In 2021/2022 a sequence of deep low-pressure systems moved across the southern UK, northern France and the Low Countries bringing considerable wind-damage, disruption to transport networks and coastal storm surges¹. The winter of 2013/2014 was also stormy and previous analyses have suggested that those conditions were unprecedented in the last 150 years². Furthermore, there are indications that an elevated rate of storminess has been experienced across the region since the 1990s³. However, considerable uncertainty exists in our understanding of long-term changes in storm intensity and frequency, and it is not currently known if these events are indicative of a trend towards increased storminess⁴. While information from reanalysis datasets⁵ and historic climate model simulations broadly agree about the existence of an increasing trend over the last 50–60 years, particularly north of 55°N, the detection of a significant trend in observed data over the last >100 years has not been conclusively demonstrated⁶.

The principal difficulty in answering questions about long-term trends in storminess is that any potential trend is small relative to the high rate of inter-annual variability and for this reason the development of long, homogeneous series is vital. Series that extend back to the eighteenth century are particularly valuable as there is an indication from early instrumental, documentary sources and proxy series that higher rates of storminess were

experienced during the early 1800s⁷. However, a lack of long-term, homogeneous data has so far precluded conclusions being drawn about the relative strength of storminess at that time compared to modern conditions and hence the potential forcing mechanisms responsible for these variations.

Wind speed observations provide the most direct measure of storminess but these data series tend to be relatively short, and are vulnerable to site/exposure effects. Sub-daily sea-level pressure (SLP) observations provide a more reliable long-term indicator and storm series stretching back over 200 years have been constructed for certain sites across northwest Europe by analysing extremes in SLP values^{8,9}. Despite the utility of such measures, the calculation of geostrophic wind (geowind) speed using SLP data from three suitably situated stations is potentially more useful for analysing long-term trends in storminess as it provides a measure of average of wind conditions across the triangle that is a reliable proxy for the true wind speed¹⁰. The geowind triangle technique has to date been widely used but only using data back at most to the 1870s across northwest Europe¹¹.

The English Channel region is a key position for monitoring the state of the mid-latitude storm track^{12–14} and using SLP data from London (GB), Paris (FR) and De Bilt (NL)^{15,16} we have constructed a geowind triangle back to 1748 (L-P-D). The positions of the three sites are shown in Fig. 1 relative to synoptic charts (using data from the ERA5 reanalysis^{17,18}) for the two

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Fig. 1 | Sea-level pressure patterns for two significant storms over the period 1979–2020. a) 25th January 1990 and (b) 14th November 1993 both at 1200UTC. The data are taken from the ERA5 reanalysis. The three nodes of the L-P-D triangle are shown in red.

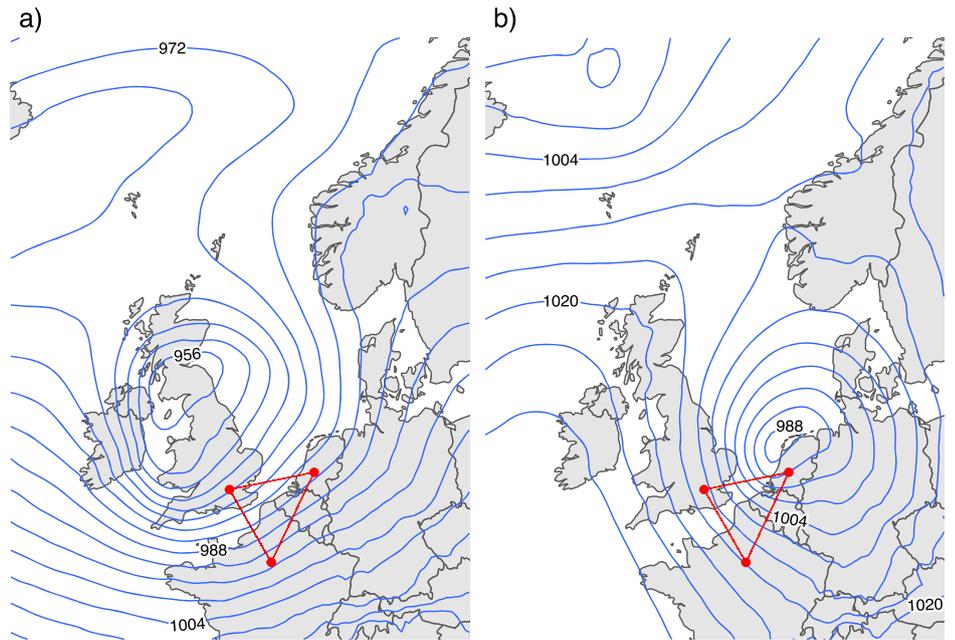
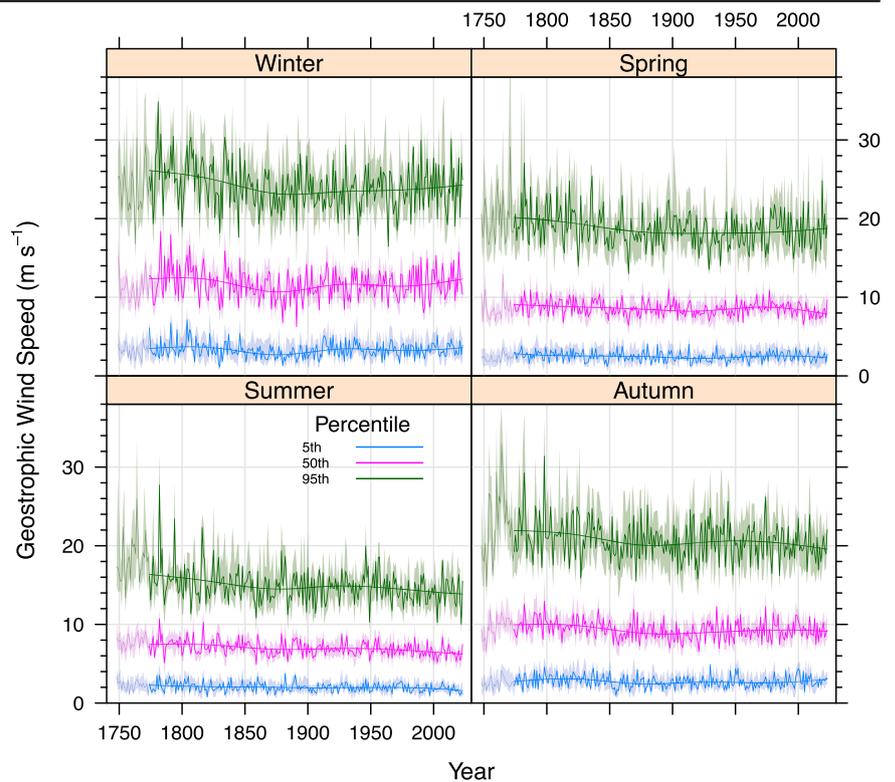


Fig. 2 | Seasonal percentiles of the geostrophic wind series. The shading indicates the 5–95% uncertainty range of the percentiles. Cubic smoothing splines with five degrees of freedom are included to highlight the low-frequency variability. The data prior to 1774 are considered less reliable and are therefore presented in a lighter shade.



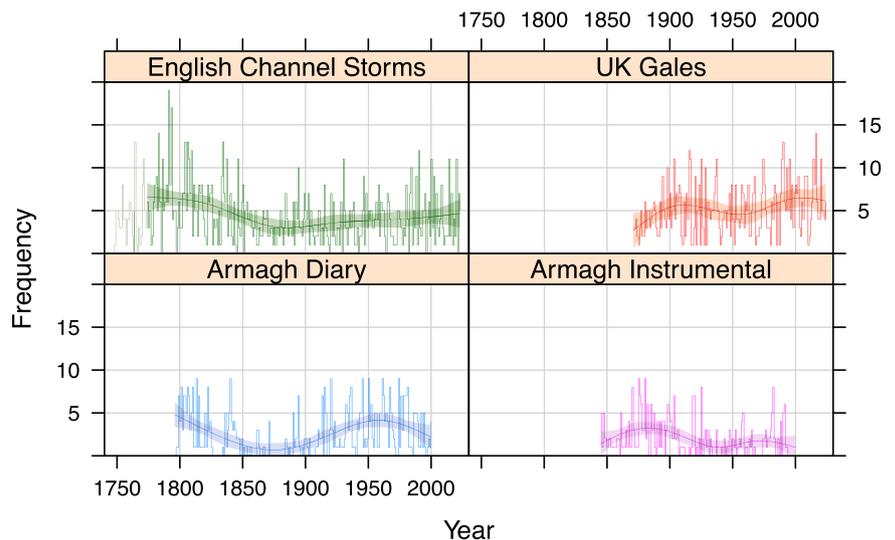
strongest geowind values in the series over the period 1979–2020. The event on the 25th January 1990 (Fig. 1a) is known as the Burns’ day storm. It developed over the 23–25th January and brought exceptionally strong westerly winds to the region. A very strong south-westerly geowind value of 44 m s^{-1} is quantified in the L-P-D triangle at noon for that event. The storm depicted in Fig. 1b. moved rapidly across Wales and England on 13th November 1993 and brought gale-force winds across southern/eastern counties of England on the following day¹⁹. The geowind value during the storm was of comparable strength the Burns’ Day storm but in this case the wind was from a north-westerly direction.

Results

Changing storminess over the last 250+ years

Seasonal percentiles for the L-P-D series are shown in Fig. 2. The 95th percentiles of daily geowind values indicate moderately high rates of seasonal storminess, and combine information on both the frequency and intensity of storm conditions. An important feature of these time series is the distinct multi-decadal variability, which is most pronounced during the winter season. Increased storminess was experienced during winters in the late eighteenth/early nineteenth century. A decline in storminess then occurred to the mid-nineteenth century and a weak increase is observed in

Fig. 3 | Winter storm frequency from four different time series. Time series of winter (DJF) storm frequency from the L-P-D data (English Channel Storms), 20CR over the UK (UK Gales) and two versions of the Armagh storm series: the version obtained from weather notes (diary) and from the SLP data (instrumental). As in Fig. 2, the values before 1774 in the English Channel Storm series are shaded to indicate reduced confidence in the data before that time.



the data thereafter. Notably, the winter series shows increased storminess since the 1990s, which is in accordance with other time series for the region³. The results from a Kolmogorov-Smirnov test indicates that the sample of winter values over the period 1990–2023 is not significantly different from the sample over the period 1790–1829. These results, however, are sensitive to the exact samples of data that are compared.

Despite an apparent increase in storminess over the last 150 years, the trend in the 95th percentiles of geowind over the period 1871–2023 is not statistically significant ($0.9 \text{ m s}^{-1} \text{ century}^{-1}$, with a 95% confidence interval of -0.1 – $1.8 \text{ m s}^{-1} \text{ century}^{-1}$). This is partly due to the high-rate of inter-annual variability in the higher geowind percentiles, which is consistent throughout the series, relative to the weak long-term trends. As a reflection of this, the trend in median geowind values – which have lower interannual variance – is significant over the period 1871–2023 (0.9 [0.2 – 1.6] $\text{m s}^{-1} \text{ century}^{-1}$).

Increased storminess was also experienced in the other seasons during the 1790–1820s. However, the increase in winter storminess seen in recent decades is not observed, and a long-term decline in storminess is generally observed in the results for these seasons. This is also reflected in the annual series (Fig. S3), which shows an unprecedented rate of storminess during the early period.

Several very stormy summers were experienced in the early nineteenth century, with the summer of 1816 being a particularly stormy season as befits its title as the “year without a summer”. In contrast, the summer of 2022 was the least stormy in the record as a result of the extended atmospheric-blocking conditions that were experienced. Nonetheless, the long-term negative trends in the percentiles of geowind during these seasons are generally not significant, with an exception being in the summer season where the 50th and 90th percentiles show trends of -0.34 [-0.65 to -0.06] and -0.63 [-1.17 to -0.09] $\text{m s}^{-1} \text{ century}^{-1}$ respectively over the period 1871–2023. This corresponds to previous analyses that have suggested a weakening of mid-latitude summer storm track activity has occurred in recent decades²⁰.

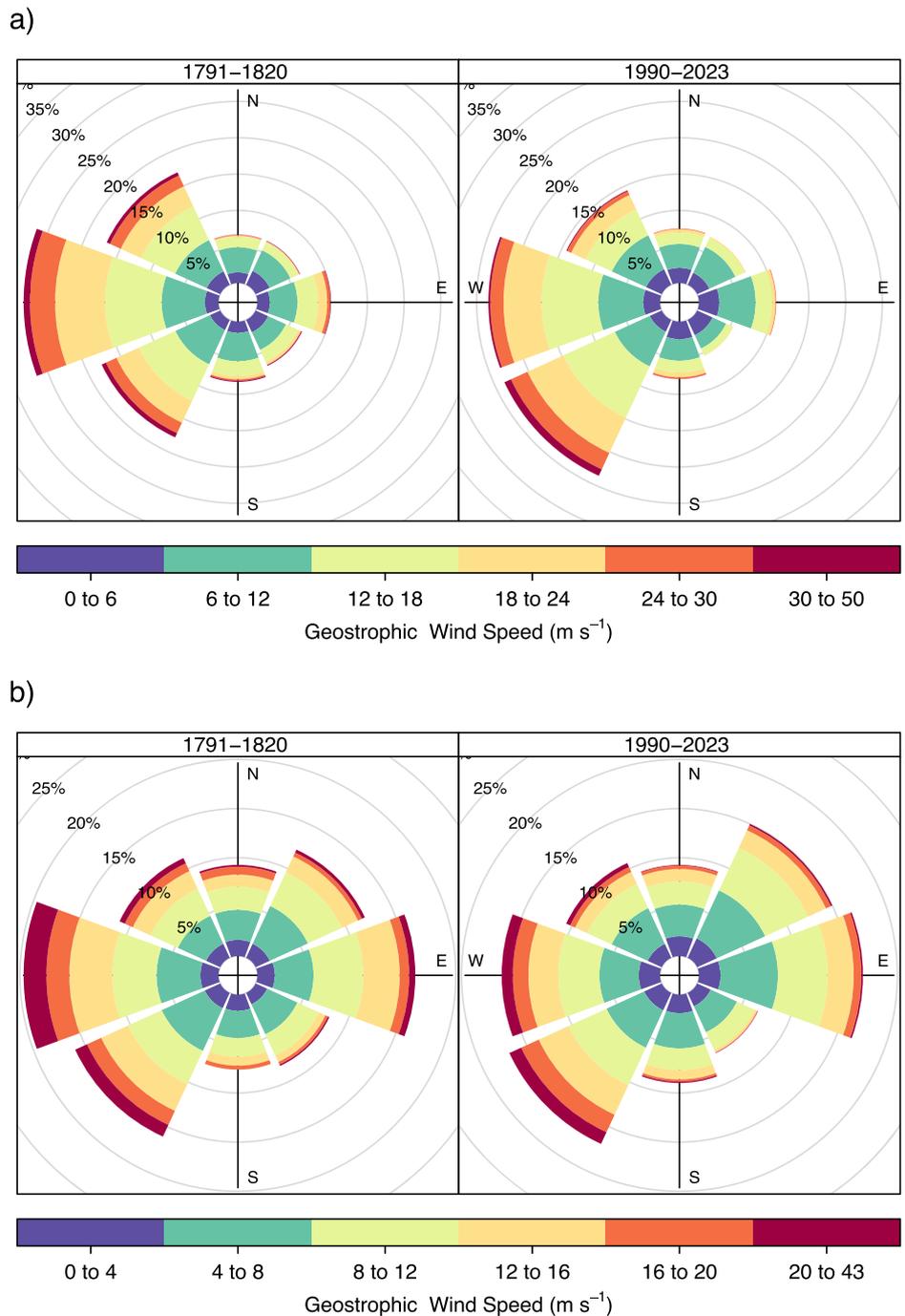
Prior to 1774 there is an indication that winter storminess was reduced. In contrast, during the summer season higher rates of storminess are indicated during that period. However, we have less confidence in the results before 1774 because there is evidence that the barometer used in the London series was liable to stick (see Supplementary Info. Discussion S1.2). This is likely to have a disproportionate effect on the results for the summer season when pressure gradients are generally lower. However, errors in the SLP data from any cause would lead to increases in the geowind values (see Supplementary Info. Discussion S1.1) and hence the multi-decadal

variability in the winter season prior to the 1850s—with a reduction in storminess before the 1770s—appears credible, especially when evaluated against other independent sources of information.

The results during the period 1790–1820 correspond to information from proxy sources, documentary sources such as weather diaries and early SLP series that have suggested that increases in storminess were experienced across western Europe at the time⁷. The gale frequency index²¹ from the Armagh Observatory in Northern Ireland provides an independent comparison for the L-P-D geowind series. The Armagh series was constructed by extracting references to storm events from the weather diary of the observatory, and the data during the winter show a similar pattern to that observed in the L-P-D geowind data of a higher frequency of storms in the 1800–1820s followed by lower values in the later nineteenth century (Fig. 3). The UK Gales series calculated from the twentieth-century reanalysis dataset (20CR)²² is also included in the comparison of winter storm frequencies, and as with the geowind series those data show an increase in storm frequency since the 1990s. A notable feature of the storm-frequency results is the exceptionally stormy winter seasons that occurred in the late eighteenth/early nineteenth century. The winters 1790/91 and 1792/93 were particularly stormy in the geowind series and this is corroborated by documentary information²³. In general though the long-term, multi-decadal pattern in the geowind frequency time series is similar to that observed in the geowind percentiles (Fig. 2).

The L-P-D geowind (Fig. 2) and Armagh data²⁴ indicate that the increase in storminess during the 1790–1820s extended to the spring and autumn seasons. In the case of the geowind series, increases are also observed during the summer season, which corresponds to proxy reconstructions based on tree-ring data²⁵. As such the annual series of storminess (Figs. S3 and S4) are exceptionally high for that period, a feature that is also seen in the gale frequency index from Edinburgh²⁶. Given the unanimity of this information, it is concluded that this is likely to be a true feature of the data rather than purely an artefact of data processing (Supplementary Info Fig. S2). However, in documentary sources such as those used to construct the Armagh series, the recording of events is reliant on the assiduity of the observer²⁷. This limits the usefulness of the series for quantifying long-term change in storminess since homogeneity between different observers cannot be guaranteed. While we cannot rule out errors in the early part of the L-P-D series leading to spurious values, the geowind series provides an objective measure of storminess over the length of the series. This likely explains the discrepancy between the four datasets during the twentieth century shown in Fig. 3, and particularly between the instrument-derived and documentary-derived storm frequency record for Armagh.

Fig. 4 | Differences in wind speed and direction for two periods: 1791–1820 and 1990–2023. a) winter (December, January and February) and (b) spring (March to May).



Changing geostrophic wind direction

In addition to changes in geostrophic wind speed, the L-P-D series also allows examination of changes in geostrophic wind direction. The results (Fig. 4) indicate that recent stormy conditions occurred with wind directions that mostly occurred from a south-westerly direction; this corresponds to the findings of other analyses^{28,29}. In contrast in the period 1791–1820 the geostrophic wind direction was more variable with storms also occurring from the westerly, north-westerly and easterly directions.

Relationship of storminess to large-scale atmospheric circulation patterns

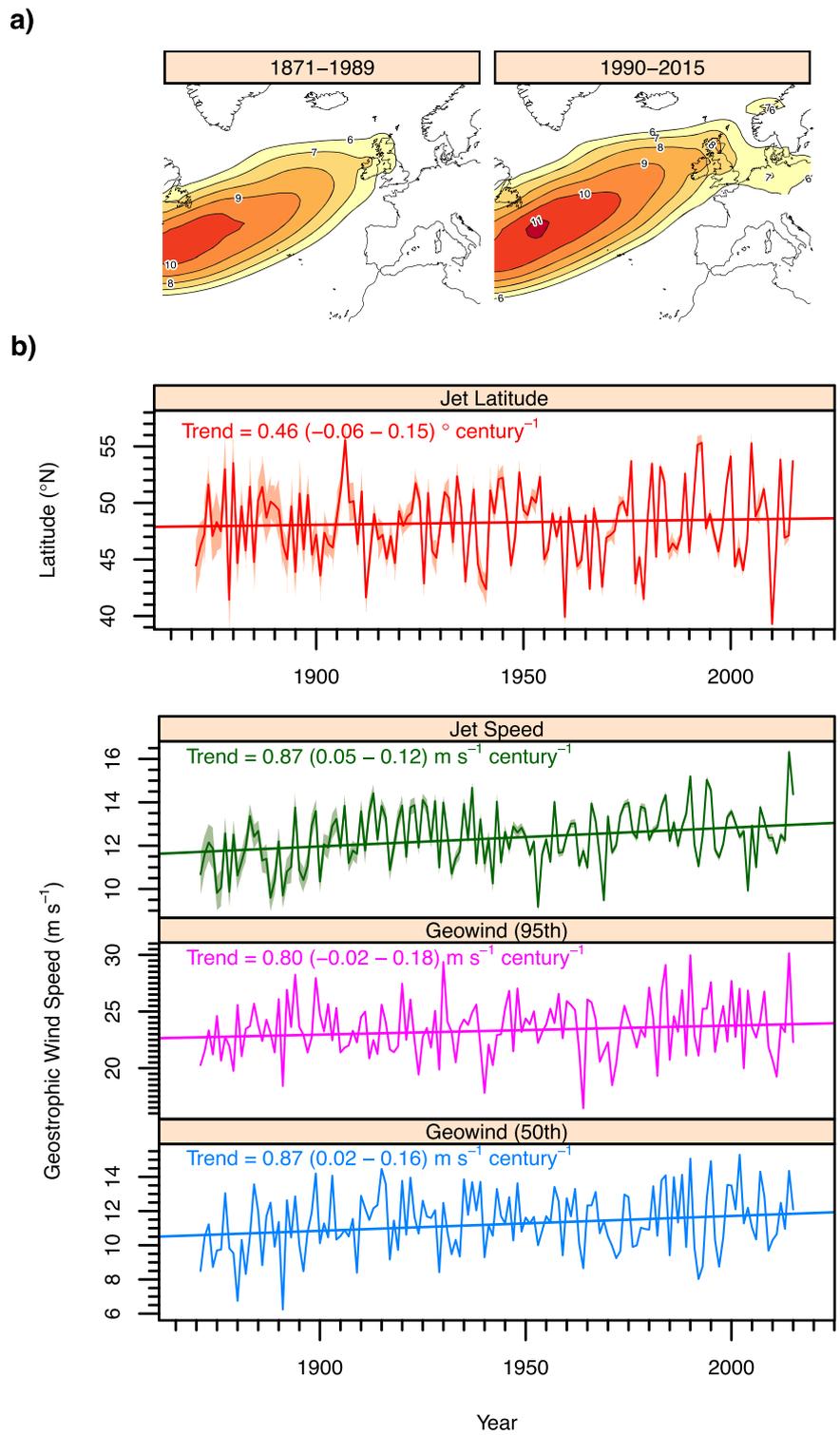
Given that the L-P-D triangle covers a relatively small region, albeit of a size that is optimal for the calculation of geostrophic wind³⁰, differences with the Armagh and UK gales series shown above would be expected for individual

years. For example, on the 26th January 1884 an exceptionally deep depression passed over northern Ireland/Scotland. The strongest winds during that storm were experienced across northern England³¹. This is captured by the Armagh and UK gales series but only moderately high winds of 27–34 m s^{-1} are indicated in the L-P-D series. Nonetheless, a strong connection would be expected with this regional-scale index and the broader-scale atmospheric circulation of the North Atlantic at longer timescales.

Several previous analyses have attempted to relate regional storminess to large-scale modes of atmospheric circulation variability, particularly the North Atlantic Oscillation (NAO)³². The NAO provides a broad measure of the state of the atmosphere across the North Atlantic region and a much closer relationship with regional-scale storminess would be expected with the eddy-driven North Atlantic jet stream (c.f. Supplementary Information

Fig. 5 | The relationship of the winter geostrophic wind series to North Atlantic jet parameters.

a winter averages of the U850 wind speed over the pre- and post-1990 periods; (b) time series of the jet latitude/speed and the 95th and 50th percentiles in the L-P-D series for the period 1871–2015. Linear trend lines over that period are shown along with the magnitude of the trends. The values in brackets indicate the 95% uncertainty ranges of the trends. Two-sigma uncertainty ranges for the jet speed and latitude series are shaded.



Tables S8 and S9). To investigate this we have calculated winter jet speed and latitude indices from 1871 to 2015 using the 20CR dataset. The results indicate that the jet speed is significantly correlated with the winter L-P-D geowind data ($r = 0.60$ and $r = 0.41$ both at $p < 0.01$ for the median and 95th percentiles respectively), whereas the jet latitude is only weakly correlated (Supplementary Info. Table S8). An important feature of the jet speed time series is that the values show an increasing trend over the twentieth century^{33,34}. The results shown here indicate that this trend is of a comparable magnitude to the long-term trend found in the median L-P-D

geowind series. The jet latitude shows a much weaker and statistically insignificant trend (Fig. 5b) despite the appearance of a slight northward shift towards the end of series. The increased storminess across the UK in recent decades, and the tendency for these winds to be from a south-westerly direction, is associated with an extension of the jet in a north-eastward direction across the North Atlantic since the 1990s (Fig. 5a).

While uncertainty in the reanalysis datasets increases before the 1950s due to a reduction in the quantity of assimilated data, the 20CR results generally agree with the long-term changes observed in the geowind data.

However, the increased jet speeds seen in the early twentieth century, albeit lower than in recent decades, are not particularly distinct in the geowind series. It is not clear if this is a result of lower data quantity in the reanalysis or a true dynamical discrepancy between the regional storminess index and the larger-scale atmospheric circulation. Improvements to 20CR through the assimilation of newly digitised pressure data may help to explain this apparent discrepancy³⁵.

Discussion

Using the exceptionally long L-P-D geowind series we have demonstrated marked seasonal differences in the long-term changes in storminess across the English Channel over the last 250 years. For the winter season, the evidence indicates that increased rates of storm intensity and frequency were experienced during the 1790–1820s and since the 1990s, with reduced storminess occurring during the mid-to-late nineteenth century. The results during the 1790–1820s agree with evidence from a coupled ocean-atmosphere modelling exercise³⁶ that has previously indicated that the increased storminess resulted from a southern displacement of the storm track, accompanied by more variability, and an increase in the jet speed. This corresponds to an increase in atmospheric blocking across northern Europe, and is supported by storm indices developed for southern Sweden back to 1780 using SLP data, which showed a reduced incidence of storminess during the period³⁷, as well as the indication of anomalously low average atmospheric pressure across western Europe during the period^{15,38}. Increased summer storminess across central Europe in the late 1830s to early 1850s has also been previously noted⁹.

The relative contribution of solar versus volcanic forcing to these changes in the atmospheric circulation during the early nineteenth century has been debated for some time. However, recent evidence has concluded that increased volcanic activity was the dominant forcing mechanism, at least in the period after the 1820s⁹. It is not clear if this was also the case before that time. This was likely reinforced by anomalous sea-surface temperature conditions that prolonged the conditions. Hence, although internal climate variability cannot be ruled out it appears that a natural forcing mechanism can be implicated in the results seen for the early period. Two features of the results presented in this paper correspond to these previous findings. Firstly, the predominance of storms with a westerly geowind direction, in combination with increased easterly and northerly airflows, would suggest a slight southward shift in the storm track; secondly, the persistence of storminess throughout the spring/summer season indicates a significant ocean-atmosphere connection.

Previous analyses have indicated that an increase in winter storminess has occurred since the late nineteenth century, while a reduction has been observed in the summer season¹¹. While we see a significant trend in average geowind values since 1871, this is not the case for the higher wind speeds. This may reflect the relatively small region considered and the once-daily sampling of pressure values, which result in relatively high interannual variance in the geowind data compared to the weak trend over the last 150 years. However, there is a demonstrable link to increasing winter jet speeds and the north-eastwards extension of the eddy-driven jet over the last 30–40 years. The elongation of the storm track across the northeast Atlantic region since the 1990s is qualitatively similar to that indicated in climate model projections³⁹, and previous studies have connected these changes to anthropogenic forcing, either through greenhouse gas forcing⁴⁰ or aerosol effects⁴¹. However, considerable uncertainty exists in our understanding of the influence of anthropogenic forcing on the atmospheric circulation across the North Atlantic region, including the jet stream and regional-scale storminess⁴². Models tend to underestimate trends in the atmospheric pressure gradient across the North Atlantic and this hinders the attribution of the observed changes. The view presented in several papers, that would counter the argument for anthropogenic forcing, is that the apparent trend in storminess is merely the manifestation of unforced decadal-scale variability⁶; such variability is not well represented in model simulations⁴². Multi-decadal variability is an important feature of the geowind series presented in this paper. Indeed, the reduced winter storminess in the mid-

to-late nineteenth century, when most instrumental series begin, may itself be viewed as anomalous in the context of this extended record. A key feature of the data, however, is the seasonal differences in storm variability during the twentieth century, which may indicate a different response to anthropogenic aerosols compared to a volcanic aerosol forcing in the early nineteenth century. Further analysis of this long-term storm information alongside climate model simulations and reanalysis data is required in order for the key drivers of the observed changes to be identified.

Methods

Geostrophic wind speed calculations

The geostrophic wind speed and uncertainty values in the percentiles of geostrophic wind speed were calculated from the three station series using the method described by Krueger et al.⁴³. Before the standardisation of recording times by meteorological agencies in the late nineteenth century, the pressure observations at the three sites were recorded according to local time. These have been converted where necessary to UTC¹⁵. It should be noted, however, that the results rely on the assiduity of the observer in accurately recording the observation at the stated time. Discrepancies in this recording-practice, which are more likely in the earliest data, could lead to spurious errors in the geowind values. The effect of such values on the results was mitigated through the quality-control tests described below.

The number of observations per day varied depending on the period considered and differed in each of the three pressure series¹⁵. Noon values are the most consistent in the Paris series and for that reason the time series at the three sites were interpolated to provide sequences of once-per-day values at 1200UTC. In the London series prior to 1854 this involved interpolating between morning and mid-afternoon readings (generally at 8 am and 3 pm); after that time there were more observations per day, including values close to noon. Before 1774 and during the 1781–87 period only once daily values are available in the London series. The De Bilt record has consistent values three-times per day (morning, noon and afternoon) throughout the record, and from 1902 hourly values are available. To interpolate to a noon value a linear interpolator was used. This was found to give more stable results than a spline interpolator for the twice-daily observing schedule.

Taking the three noon SLP values on a given day as p_1 , p_2 and p_3 , a plane is fitted to the data using the following three equations:

$$\begin{bmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} \quad (1)$$

where given the longitude (λ) and latitude (ϕ) at site i , and the earth's radius ($R = 6378100 \text{ m}$), $x_i = R\lambda_i \cos \phi_i$ and $y_i = R\phi_i$. The three pressure series have been constructed by joining data segments from different sites¹⁵. However, since the three series have been homogenised to the data from the final segments of the series (Heathrow airport for London, Montsouris for Paris and De Bilt) the latitude and longitude coordinates (λ_i and ϕ_i) from these sites are used throughout the respective series.

Having solved the equations for the three unknowns (a , b and c), we derive the zonal and meridional geostrophic wind components as:

$$u_g = -\frac{b}{\rho f} \quad (2)$$

$$v_g = \frac{a}{\rho f} \quad (3)$$

where ρ is the density of air (1.25 kg/m^3) and f is Coriolis parameter, which is taken as $f = \Omega \sin \phi_i$ with the earth's rotation rate ($\Omega = 2\pi/(24 * 3600)$). In the calculation of u_g and v_g the Coriolis parameter (f) is averaged across the three sites. The wind speed (w_g) and wind direction (w_d , taking the convention of the direction from which the wind is blowing) were then

calculated as:

$$w_g = \sqrt{u_g^2 + v_g^2} \quad (4)$$

$$w_d = \left(\text{atan2}(u_g, v_g) \frac{180}{\pi} \right) + 180 \quad (5)$$

The quality control (QC) codes provided with the data were used to exclude values considered to be unreliable. These values were removed prior to performing the temporal interpolation. The (interpolated) noon values were then checked in relation to the other series and for large day-to-day pressure changes as was done in the original construction of the data series by manually checking plots of the pressure series for the days surrounding large pressure changes in any of the three series.

As the percentile values in Fig. 2 are based on one geostrophic wind speed value per day there is the potential that the series misses certain fast-moving storm systems and that the series underestimate the degree of storminess in a particular season. To investigate the magnitude of this effect we calculated the geostrophic wind speed series over the period 1949–2020 using three-hourly SLP values. The results (see Supplementary Information Discussion S1.3) indicate that while discrepancies relative to the noon series exist for certain years, this does not have an appreciable effect on the long-term trends in the series. If there were more fast-moving storm systems in the earlier period then this may change the long-term trends. However, since storminess during the period 1790–1820 appears to have arisen from changes in the large-scale planetary waves^{36,44} this appears to be unlikely.

In addition, we tested the effect of the changing temporal sampling in the London series by re-creating Fig. 2 but using the London subsampled to a once daily value (at 8UTC or the nearest values within 2 h). The results (Fig. S14) show that this has the effect of changing the values for individual years but the long-term trends remain comparable to those shown in Fig. 2.

The storm frequencies shown in Fig. 3 (English Channel Storms) are calculated as the number of daily geostrophic wind speeds at noon greater than 25 m s^{-1} . Direct comparison against the storm frequency shown in the UK gales index is not possible because that series combines flow vectors and vorticity in the calculation of the geostrophic wind speed. In Fig. 3 only UK gale values classified as “severe gales” ($G > 40$) are plotted.

Jetstream calculations

The jet speed and latitude metrics were calculated following the method described by Woollings, et al.³⁴, using the 20th Century Reanalysis dataset (20CR, version 3)⁴⁵. Although the 20CR provides data back to 1806, the values prior to 1870 were not considered reliable due to a lack of pressure data with which to constrain the reanalysis (see Supplementary Information Fig. S5).

Trend calculations

Linear trends in the geowind percentile values, and in the jet speed/latitude time series, were calculated using the Theil-Sen approach and as such the trend values are not as susceptible to the presence of outliers compared to a typical least-squares linear regression trend calculation. Uncertainty ranges in the trends were calculated using the pre-whitening approach^{46,47}, which takes into account lag-1 autocorrelation in the time series. A discrepancy regarding the long-term trend in the jet latitude significance here compared to the analysis by Hallam et al.³³ (0.04°/decade and not significant vs. 0.1°/decade and significant) is likely due to use of Theil-Sen method and a stricter significance test here, along with the different time periods over which the trend is calculated (1871–2015 vs. 1871–2011), the use of a newer version of 20CR and a different jet calculation method.

Data availability

Data for the three stations can be accessed from the following Figshare Repository: <https://doi.org/10.6084/m9.figshare.24242302.v1>. Additional data can be accessed from <https://doi.org/10.6084/m9.figshare.24938640>.

Code availability

The code used in this paper can be accessed from https://github.com/rcornes/LPD_SLP.

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R.C.C. generated the data series and conducted the statistical analyses. P.D.J. conceived the research. Both authors contributed to the analysis of the results and the writing of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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