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# Fluctuations in autumn–winter severe storms over the British Isles: 1920 to present

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**ABSTRACT:** An examination of extreme storms across the British Isles over the last 85 years during the boreal autumn [October, November, December (OND)] and winter [January, February, March (JFM)] shows that large-scale natural climate variability plays an important role in modulating the intensity and frequency of these events.

Severe storms across the British Isles were most prominent in the 1920s and 1990s in OND, and in the 1920s, 1980s and 1990s in JFM. There is a significant correlation between JFM severe storminess across the British Isles and both the Gibraltar–South-West (SW) Iceland and Azores–Iceland indices of the North Atlantic Oscillation (NAO), but this relationship fluctuates over the 85 years of data. Strongest NAO relationships occur during 1970–1990 and 1940–1960, with a weaker correlation in the 1920s–1940s, and effectively no correlation in 1950–1970. There is no significant relationship between the Gibraltar–SW Iceland NAO and severe storms in OND, but a significant correlation exists with the Azores–Iceland NAO and there is a clear link to a pattern in mean sea level pressure (MSLP) extending from the tropical Atlantic to higher latitudes of the North Atlantic. El Niño Southern Oscillation (ENSO) influences from the Pacific Ocean also appear to play a role in modulating OND severe storms over the British Isles. Importantly, severe storms in OND and JFM seasons respond to different physical mechanisms.

Future work is needed to extend this study back into the late 19th century in order to evaluate fully any changes in severe storms across the British Isles using a longer instrumental record. This may be best achieved through long historical surface-observations-only global reanalyses, which can reconstruct tropospheric weather variables using longer instrumental records of daily to sub-daily MSLP. Copyright © Royal Meteorological Society and Crown Copyright, 2008

KEY WORDS historical severe storminess; climatic variability; pressure tendencies

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## 1. Introduction

One area of growing concern in climate science is the impact that global warming could have through modulations of the nature and characteristics of naturally occurring extreme events, such as severe mid-latitude storms. However, both observational and modelling studies of historical and future storminess patterns and scenarios are divided on the role that global warming has played, or could play, in changing patterns of mid-latitude storms (Bijl *et al.*, 1999; Alexandersson *et al.*, 2000; IPCC, 2001, 2007; Dawson *et al.*, 2002; Barrington and Von Storch, 2004; de Kraker, 2005).

The majority of studies of historical European storminess are based on anecdotal evidence and historical documentary observations up to the 18th century, and on instrumental measurements, such as wind gust characteristics, daily pressure tendencies and geostrophic wind deduced from triangles of pressure stations. The papers of

Lamb (1991); Lamb and Frydendahl (1991); Alexandersson *et al.* (1998, 2000); Sweeney (2000); Hickey (2003); Smits *et al.* (2005); Jonsson and Hanna (2007) and Hanna *et al.* (2008); Matulla *et al.* (2008) are prime examples of these various types of studies. These approaches have provided various measures of storminess down to daily timescales, but to resolve smaller timescale severe storms requires sub-daily observations.

In this paper, extreme mean sea level pressure (MSLP) changes over the British Isles during boreal autumn [October, November, December (OND)] and winter [January, February, March (JFM)] have been analysed since 1920 using newly digitized 3-hourly station data. Intense storm events occurring on sub-daily timescales are likely to have significant impact on a densely populated region such as the British Isles. This work builds on the study by Alexander *et al.* (2005) that analysed similar data since the late 1950s, and was undertaken as part of an extension of the examination of variability and trends in severe storms over the last 85 years.

## 2. Data and methods

Following the work of Alexander *et al.* (2005), 3-hourly pressure data for the British Isles were digitized in order

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† The contribution of R. Allan was written in the course of his employment at the Met Office, UK and is published with the permission of the Controller of HMSO and the Queen's Printer for Scotland.

to extend the severe storms record back before 1957. The major source of these data, the UK Daily Weather Reports (DWRs), contain sub-daily data from a wide range of UK and Irish locations from 1920 (Figure 1). Until the early 1940s, meteorological data in the DWRs reveal that many inland stations across the British Isles did not make 2100 and 0000 GMT observations, and only coastal station data, often from lighthouses, provided full 3-hourly MSLP coverage (Figure 2). Specific details of other data problems encountered in this study are given in Appendix 1, and the potential to extend the 3-hourly data further back in time is detailed in Appendix 2.

Figure 1 shows the stations used in this study. The red squares denote locations with data just for 1957–2003, which were used both in Alexander *et al.* (2005) and in this study. Blue squares are additional stations digitized by this study covering only the period 1920–1960. Black crosses are station locations with data that extend from 1920 to 2004.

This paper used the same classification for severe gales in the United Kingdom as in Alexander *et al.* (2005). A severe storm event was registered if an MSLP change of  $\pm 10$  hPa occurred between the 3-hourly observations at an individual station. Based on the distribution, number and spatial structure of severe storm

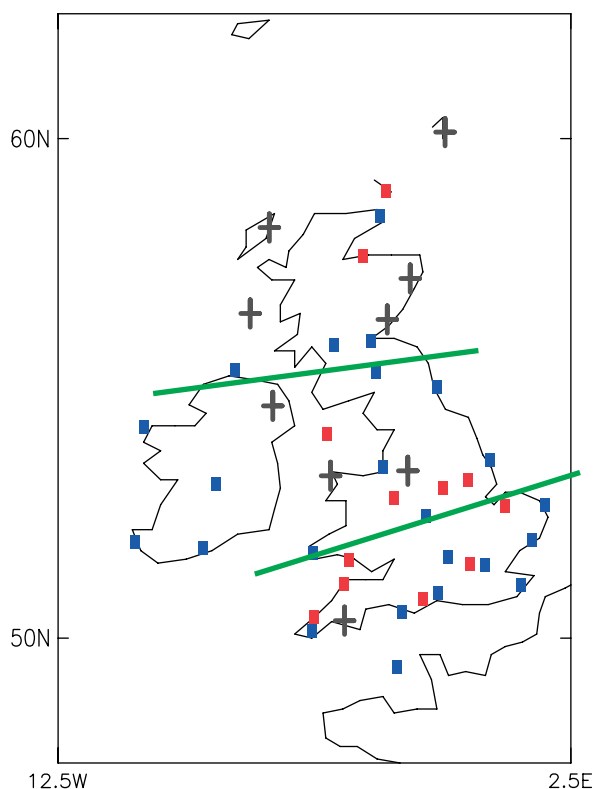


Figure 1. UK and Irish stations with 3-hourly MSLP data used in this paper. Red squares: stations for which data for just 1957–2003 were used in both Alexander *et al.* (2005) and in this study. Blue squares: earlier stations available to this study covering the period 1920–1960. Black crosses: stations for which data for 1957–2003 were used by Alexander *et al.* (2005) and for 1920–2004 in this study. Green lines denote the break-up into northern, central and southern regions of the British Isles.

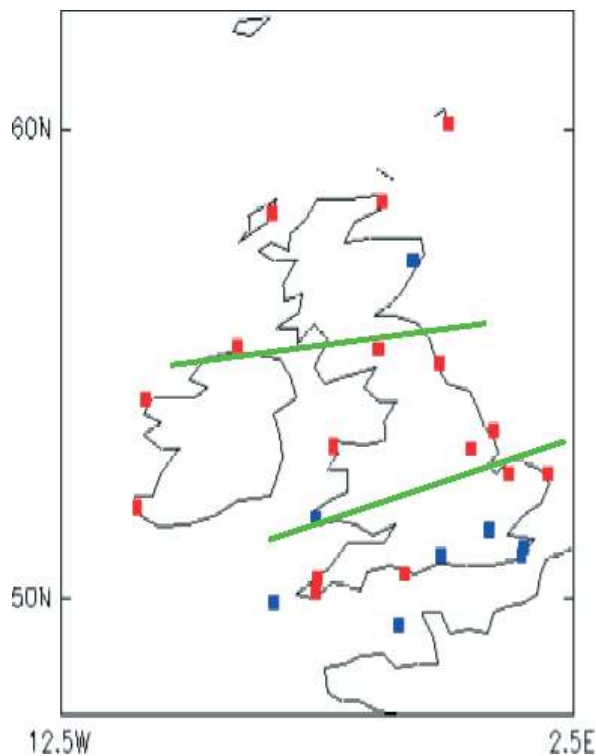


Figure 2. UK and Irish stations with full 3-hourly MSLP data from 1920. Red squares: stations having fully digitized 3-hourly MSLP from 1920 used in this study. Blue squares: stations which have all 3-hourly MSLP from 1920 but which we did not use because they have not been completely digitized. Green lines denote the break-up into northern, central and southern regions of the British Isles.

events, Alexander *et al.* (2005) split the United Kingdom into the three regions shown in Figure 1 (northern, central and southern). This procedure was followed here and extended to include Ireland. Thus, a severe storm passing the MSLP change criteria in one region of the British Isles was defined as one third of a storm. As with the Alexander *et al.* (2005) study, there had to be at least two stations in a region registering at least a  $\pm 10$  hPa pressure change in 3 h to qualify as a severe storm. Individual storm events were again registered if events were separated by a period of at least 12 h, as in Alexander *et al.* (2005).

Comparisons of decadal severe storm numbers from 1920 for all available stations in the British Isles and from only those with full 3-hourly data (Figures 3 and 4) suggest that a reduced station network results in a consistent reduction in severe storms numbers. For the period since 1920, a recent study by Hanna *et al.* (2008), looking at 24-h pressure tendencies at specific stations in the Northern European region back into the mid-19th century, shows that for OND and JFM seasons at UK and Irish stations (Aberdeen, Armagh, Valentia and Jersey/Guernsey) very similar decadal signals to those given in Figures 3 and 4 are evident.

Links between storminess and precipitation are particularly pertinent for the United Kingdom, given the recent severe flooding experiences and concerns about flooding due to any increases in storminess. There is pressure, not

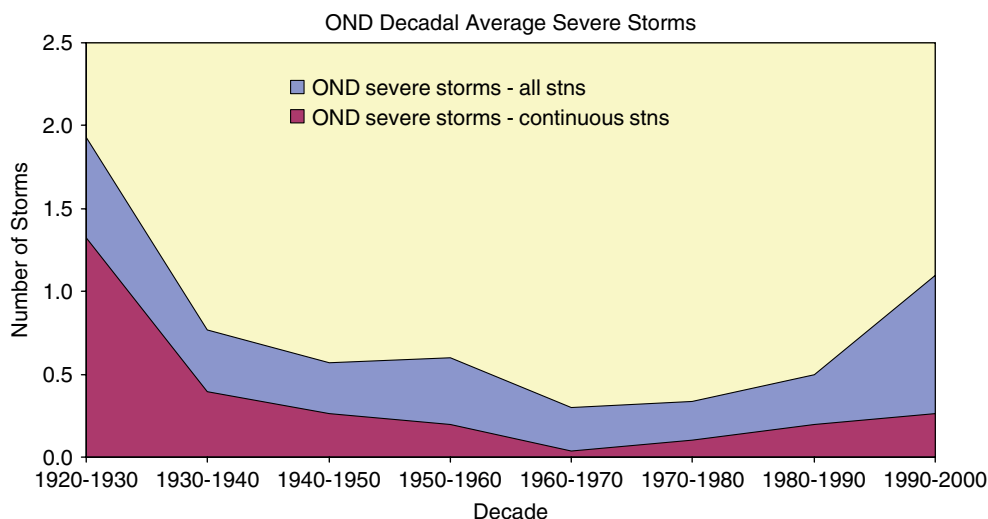


Figure 3. Comparison of OND decadal average severe storm numbers for all British Isles stations available (blue) and British Isles stations with full 3-hourly MSLP coverage. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

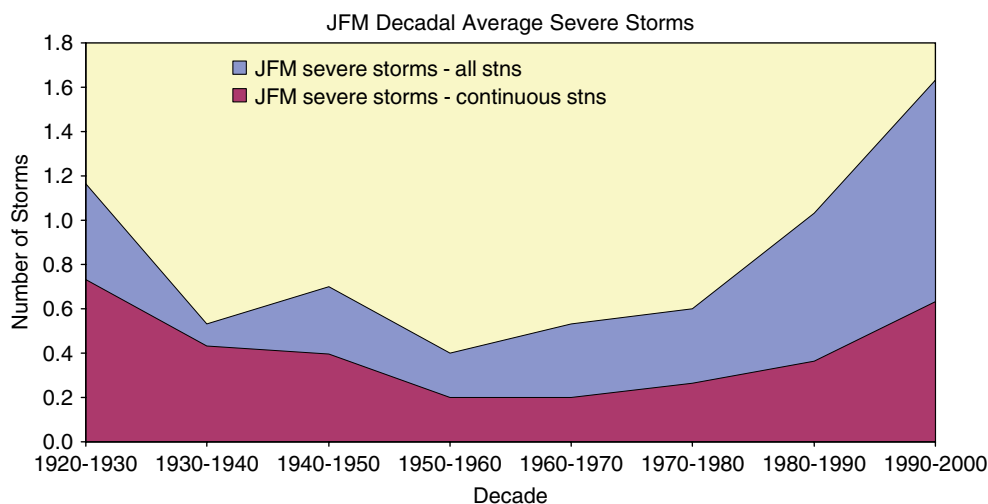


Figure 4. Comparison of JFM decadal average severe storm numbers for all British Isles stations available (blue) and British Isles stations with full 3-hourly MSLP coverage. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

just in the United Kingdom, to look at the possibilities of seasonal to decadal forecasting of storminess that include its influence on precipitation extremes. Thus, correlations and their significance are also examined between OND and JFM severe UK storminess and rainfall across the European domain. The rainfall data set used is the high spatial resolution ( $0.5^\circ$  latitude  $\times$   $0.5^\circ$  longitude) CRU TS2.1 covering the period January 1901 to December 2002 from the Climatic Research Unit (CRU) at the University of East Anglia (Mitchell and Jones, 2005).

Finally, more insight into the physical mechanisms driving OND and JFM severe storms was obtained by using the severe storms results together with the European and North Atlantic daily to MULTidecadal climATE variability (EMULATE) mean sea level pressure (EMSLP) data set (Ansell *et al.*, 2006) and a simulated annealing technique to ‘cluster’ all days within a season into sets with similar pressure patterns (Philipp *et al.*, 2007).

### 3. Results and discussion

The previous study of the recent 47-year storm dataset (Alexander *et al.*, 2005) showed an increase in the number of severe storms in the 1990s in the United Kingdom, but they concluded that it was not possible to say with any certainty that this was either indicative of climatic change or unusual unless it was seen in a longer-term context. With the addition of 40 years of data, the current analysis provides a longer database with which to assess this situation. To update the study of Alexander *et al.* (2005), we only analyse OND and JFM, so do not attempt to look at whether different break-ups of the boreal autumn and winter seasons, such as December, January, February, March (DJFM) or November, December (ND) and January, February (JF), would have an effect on our results. All correlations detailed were made using detrended data.

### 3.1. OND severe storminess

In general, pronounced inter-annual variations in OND severe storminess across the British Isles are evident in Figure 5, with most prominent activity in the 1920s and 1990s. There is evidence in the literature to support the 1920s period of a high frequency of severe storms in OND. Lamb (1991); Lamb and Frydendahl (1991); Alexandersson *et al.* (2000); Sweeney (2000); McEwen (2006); Lozano *et al.* (2004) and Hanna *et al.* (2008), all indicate that the 1920s was a period of markedly increased westerly winds and storms in autumn across the British Isles and north-west Europe. Analysis of both documentary and instrumental data for Dublin (Sweeney, 2000) shows that the 1920s was one of the windiest periods in the 20th century. This is supported by evidence for exceptional storminess along the Atlantic coast of Scotland during the late 1920s in Lozano *et al.* (2004).

Over the 85 years in this study, the number of OND severe storms shows no significant correlation ( $r = +0.17$ ) with the North Atlantic Oscillation (NAO) calculated by using the normalized Gibraltar–SW Iceland MSLP difference (Jones *et al.*, 1997) (NAO<sub>GI</sub>) (Figure 5). However, if an NAO index using the normalized Azores–Iceland MSLP difference is used (Koninklijk Nederlands Meteorologisch Instituut KNMI Explorer <http://climexp.knmi.nl/> – van Oldenborgh and Burgers 2005) (NAO<sub>AI</sub>) then the correlation with OND severe storms over the British Isles is  $r = +0.36$ , which is significant at the 99.9% level. Spatial correlations between severe UK storminess and MSLP, and differences in MSLP between the highest and lowest decile of storm frequency in JFM that are examined later in this paper (Figures 15 and 16), show that the predominate southern centre of action linked to the NAO is better represented by the Azores than Gibraltar with regard to a UK regional severe storms index. Of the other major teleconnection patterns influencing the North Atlantic-European region, the OND severe storm index over the British Isles is also significantly correlated with the East Atlantic (EA) teleconnection pattern (from when the index begins in 1950) at  $r = +0.33$  (significant at

the 99.9% level) (Barnston and Livezey, 1987). As noted on the National Oceanic and Atmospheric Administration NOAA Climate Prediction Center WWW site for the EA (<http://www.cpc.noaa.gov/data/teledoc/ea.shtml>):

‘The EA pattern is structurally similar to the NAO, and consists of a north–south dipole of anomaly centres spanning the North Atlantic from east to west. The anomaly centres of the EA pattern are displaced south-eastward to the approximate nodal lines of the NAO pattern. For this reason, the EA pattern is often interpreted as a ‘southward shifted’ NAO pattern. However, the lower-latitude centre contains a strong subtropical link in association with modulations in the subtropical ridge intensity and location. This subtropical link makes the EA pattern distinct from its NAO counterpart.’

A correlation of the EA teleconnection with HadSLP2 MSLP (Allan and Ansell, 2006) on the KNMI Explorer WWW site (<http://climexp.knmi.nl/>) in OND from 1950 to 2004 (not shown) gives a nodal pattern of centres as described above. Thus, the OND severe storms index appears to be registering elements of the NAO<sub>AI</sub> and EA teleconnections.

The spatial pattern of correlations between OND severe storm frequency across the British Isles and OND precipitation (Mitchell and Jones, 2005) over Europe, and their statistical significance, are shown in Figure 6(a) and (b) respectively. As expected, the strongest statistically significant correlations (exceeding 99.99% level) are found over the British Isles, with values of  $r = +0.4$  to  $+0.5$  (16–25% of the rainfall variance) over SW UK and  $r = +0.5$  to  $+0.6$  (25–36% of the rainfall variance) over SW Scotland. This suggests that an ability to make predictions of OND severe storms would also provide information on rainfall variability and extremes over these parts of the United Kingdom. In fact, the area of correlations exceeding the 95% confidence level extends in a swath from SW Europe through France and the British Isles, to the Low Countries and the Baltic (Figure 6(b)). This pattern is a reflection of the mean storm track in the OND season over the European sector (Wang *et al.*, 2004, 2006).

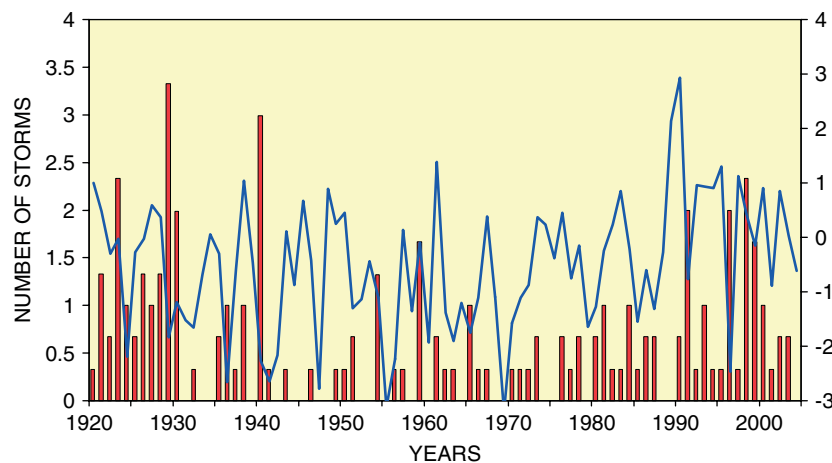


Figure 5. History of severe storm frequency over the British Isles in OND from 1920–2004. The blue trace is the normalized (relative to 1971–2000 period) NAO<sub>GI</sub> index. Correlation between the normalized Gibraltar–SW Iceland NAO<sub>GI</sub> and OND severe storms is  $r = +0.17$ .



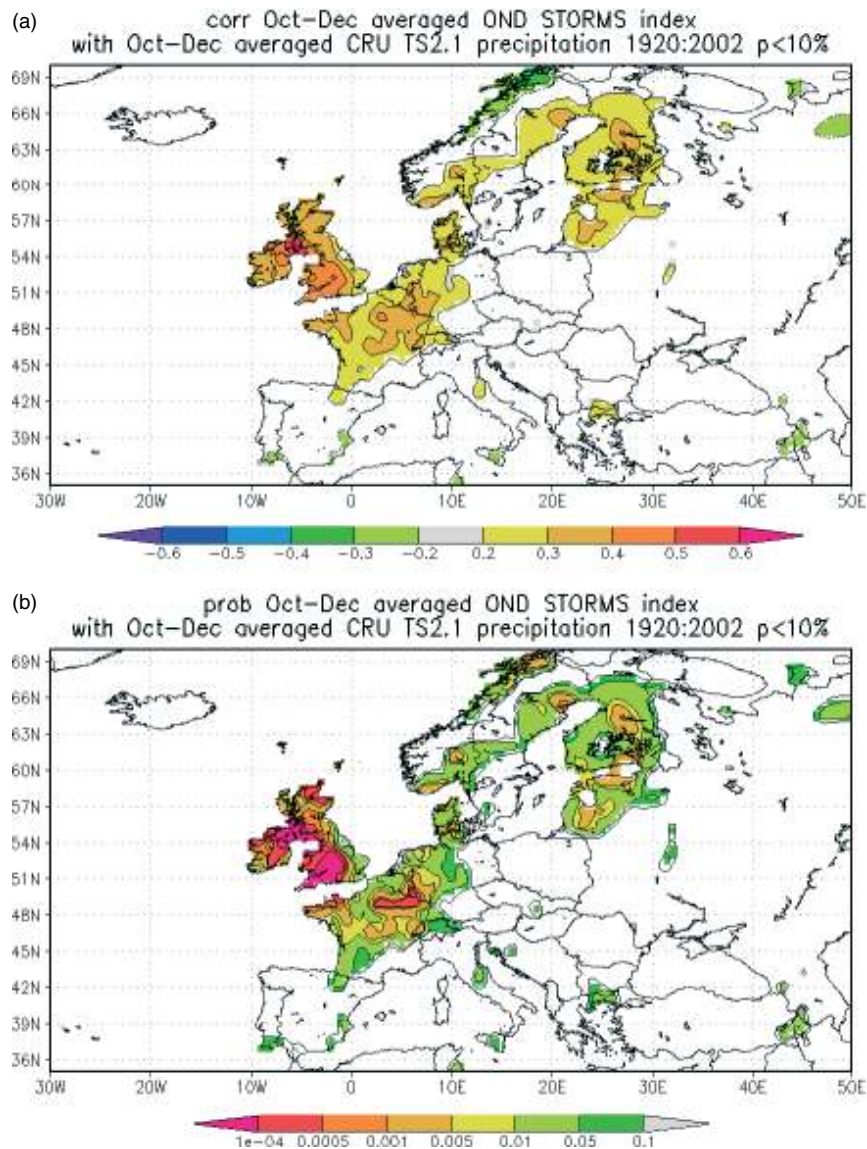


Figure 6. (a) Spatial correlations between OND severe storm frequency over the British Isles and OND CRU TS2.1 precipitation (Mitchell and Jones, 2005) over Europe. (b) Spatial distributions of levels of statistical significance of correlations.

Changes of severe storminess across the British Isles in OND are clearly seen on decadal timescales (Figure 7). The decadal plot highlights clearly the 1920s and 1990s peaks in severe storms, and a period of general reduction of major storminess events in between. Thus, extending the analysis back to 1920 emphasizes the dominance of natural climatic variability in severe storms across the British Isles in OND on inter-annual to decadal timescales.

A further breakdown of the decadal storminess into its northern, central and southern regional components across the British Isles (Figure 8) reveals that severe decadal storminess is almost always dominated by events in the northern region, which is more under the influence of the mean seasonal storm track.

### 3.2. JFM severe storminess

In JFM, severe storms across the British Isles were most frequent in the 1990s and their frequency is significantly

correlated ( $r = +0.44$ , at the 99.99% level) with the normalized  $NAO_{GI}$  index over the full 85 years of the current data set (Figure 9). A similar correlation ( $r = +0.46$ ) is found with the  $NAO_{AI}$ . In the Alexander *et al.* (2005) study, the 1959–2003 period correlation using the  $NAO_{GI}$  was slightly higher at  $r = +0.5$ . However, a 20-year running correlation analysis of the relationship between the number of severe storms over the British Isles and the normalized  $NAO_{GI}$  index over the full 1920–2004 data span (not shown) indicates that the relationship fluctuates between significant correlations of around  $r = +0.6$  (36% of the variance) for 1970–1990 and around  $r = +0.5$  (25% of the variance) for 1940–1960, and effectively no correlation in the 1950–1970 epoch. The latter correlation breakdown is coincident with more El Niño Southern Oscillation (ENSO) influence on the North Atlantic-European domain (not shown). For 1920–1940 the correlation was around  $r = +0.2$  (4% of the variance). Interestingly,

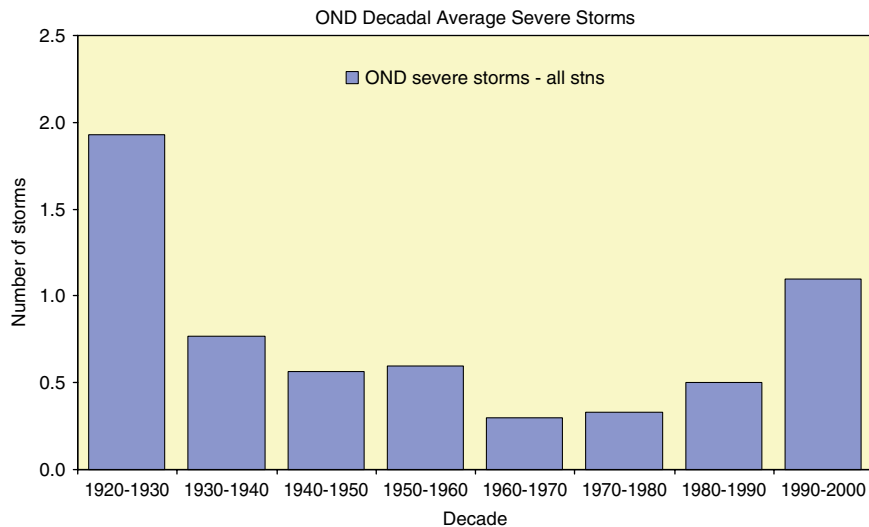


Figure 7. History of OND decadal average severe storm frequency over the British Isles from 1920. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

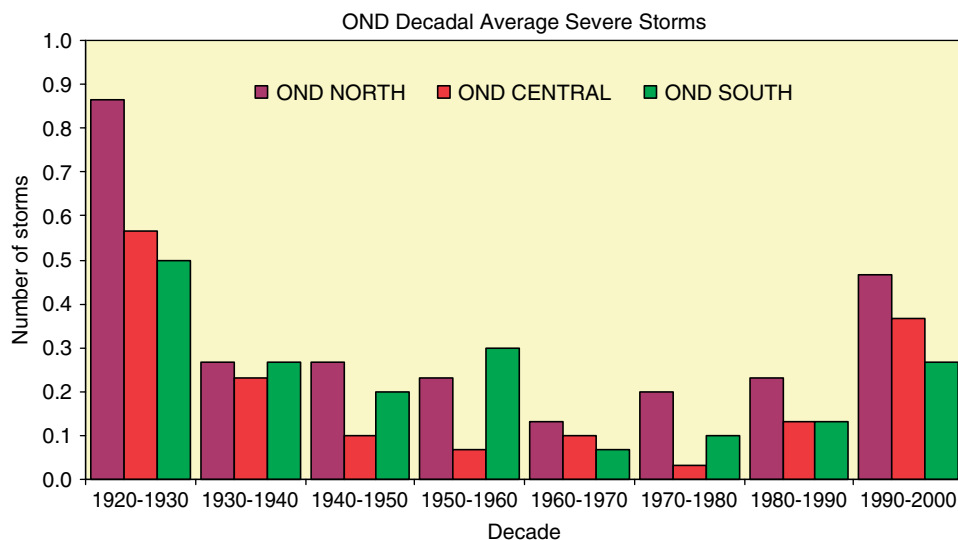


Figure 8. History of OND decadal average severe storm frequency in northern, central and southern regions of the British Isles from 1920. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

there is no significant correlation between the number of severe storms across the British Isles in OND and in JFM, whether JFM is taken in the same calendar year or the following one.

Correlations between JFM severe storm frequency over the British Isles and JFM precipitation (Mitchell and Jones, 2005) over the European region in Figure 10(a) show strongest positive (negative) values over the British Isles and SW Norway (Portugal and Spain plus Turkey and the northern margins of the Black Sea). These relationships are statistically significant above the 99.5% confidence level (Figure 10(b)), and account for up to 10 and 35% of the variance in rainfall depending on the region. As for OND, the precipitation correlations in JFM reflect the NAO dominated pattern of storm tracks (Wang *et al.*, 2004, 2006). Note that a positive storminess index is linked with drought and low cloud fraction

(not shown) across the central-eastern Mediterranean and into the Black Sea region in JFM (Figure 10(a) and (b)), but not in OND (Figure 6(a) and (b)). This difference may be due to the very marked and coherent zonal extent of NAO correlations across the whole of the North Atlantic-European sector, with the storm track at a maximum over the northern half of Europe, in JFM.

The decadal modulation of JFM severe storm frequency is closely matched with the decadal behaviour of the NAO<sub>GI</sub> (Figure 11). As in OND, the JFM decadal pattern shows dominant periods of severe storms in the 1920s and 1990s. However in JFM, the 1990s experienced the largest number of severe storms, with a secondary peak in the 1980s (Figure 9). Natural variability is again evident in JFM, and the increasing trend in severe storms reported by Alexander *et al.* (2005) since

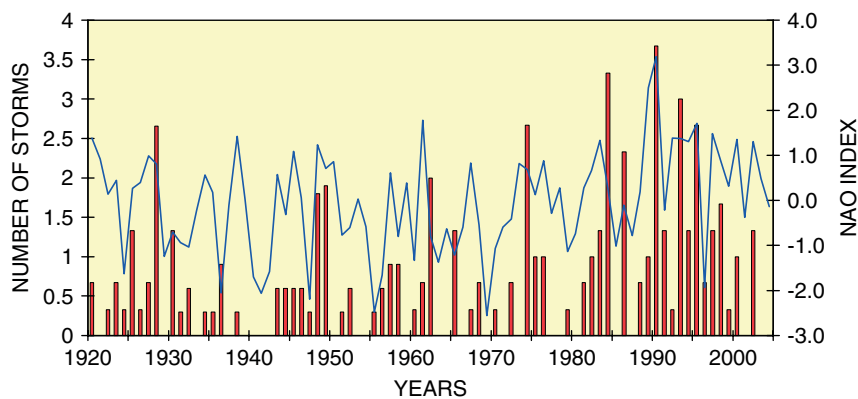


Figure 9. History of severe storm frequency over the British Isles (MSLP changes of more than  $\pm 10$  hPa in 3 h) in JFM from 1920–2004. The blue trace is the normalized (relative to 1971–2000 period)  $NAO_{GI}$  index. Correlation between the normalized Gibraltar–SW Iceland  $NAO_{GI}$  and JFM severe storms is  $r = +0.44$  (this is significant at the 99.99% level, and explains 19% of the variance).

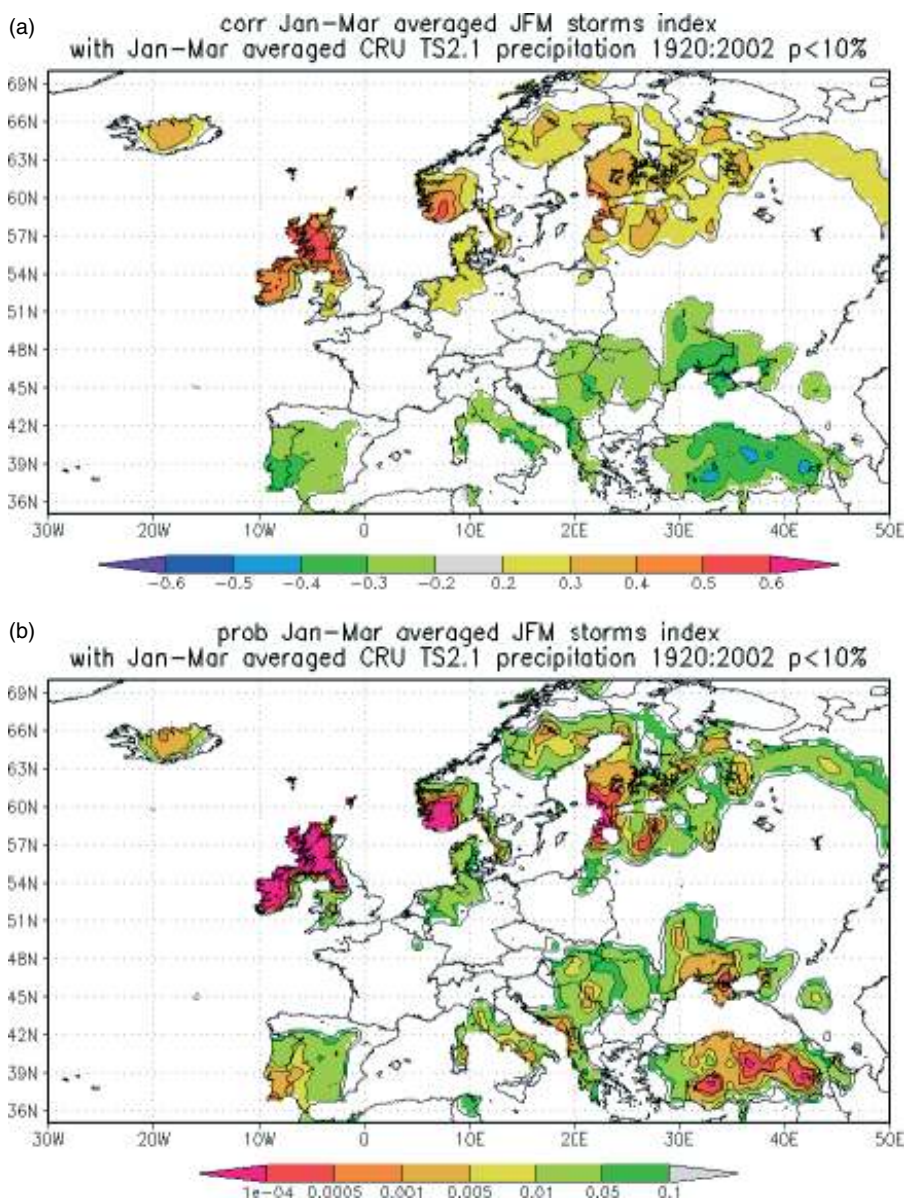


Figure 10. (a) Spatial correlations between JFM severe storm frequency over the British Isles and JFM CRU TS2.1 precipitation (Mitchell and Jones, 2005) over Europe. (b) Spatial distributions of levels of statistical significance of correlations.



the 1960s is again put into perspective by the longer record in this study.

The regional breakdown of the decadal pattern of severe storm frequency over the British Isles in JFM in Figure 12 is similar to that in OND, with the dominance of severe storms in the northern region. When taken over the full record in Figure 12, events in the central and southern regions make an overall similar contribution to the number of severe storms. However, in recent decades, the central region's contribution to the total number of severe storms has reached the highest value in the available record.

Thus, the NAO plays a very significant role in modulating JFM severe storm activity and, as observed by

Alexandersson *et al.* (2000); Jonsson and Hanna (2007) and Hanna *et al.* (2008), multi-decadal climate variability on large spatial scales plays an important role in modulating severe storms over the British Isles (and north-western Europe) during autumn and winter. The strong NAO modulation provides more of a potential basis for seasonal to decadal forecasting of severe storms over the British Isles in JFM than in OND.

3.3. Physical mechanisms underlying variability of severe storms over the British Isles: OND and JFM

Linearly detrended globally complete sea surface temperature (SST; Rayner *et al.*, 2003) and MSLP (HadSLP2; Allan and Ansell, 2006) data were used to examine the

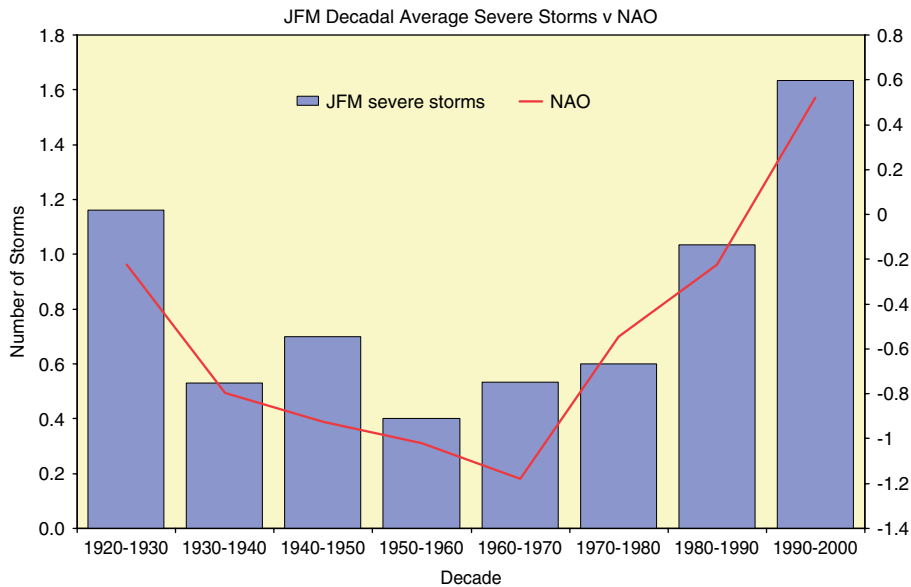


Figure 11. History of JFM decadal average severe storm frequency over the British Isles and decadal average normalized NAO<sub>GI</sub> from 1920. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

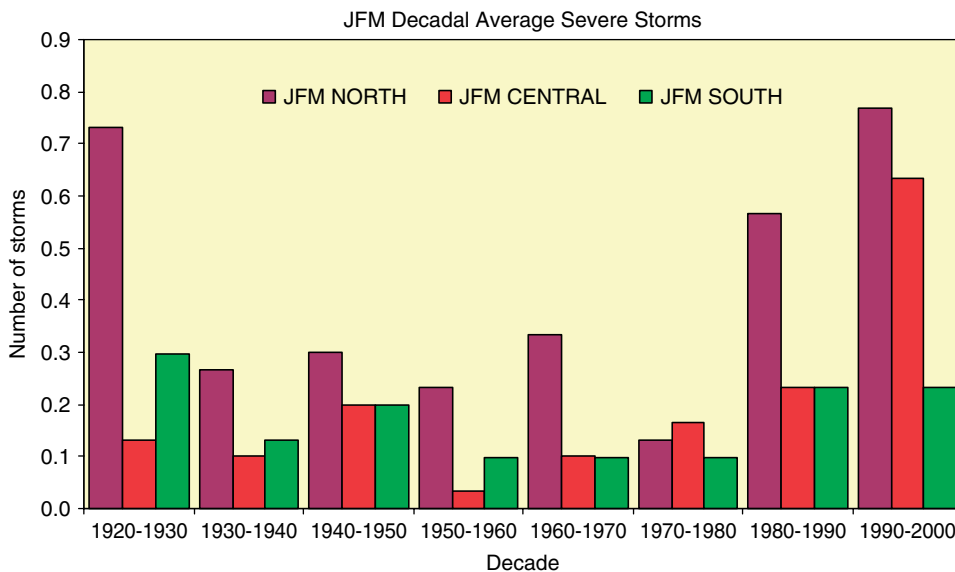


Figure 12. History of JFM decadal average severe storm frequency in northern, central and southern regions of the British Isles from 1920. This figure is available in colour online at [www.interscience.wiley.com/ijoc](http://www.interscience.wiley.com/ijoc)

physical mechanisms underlying OND and JFM severe storms.

In OND, Alexander *et al.* (2005) reported little link between the  $NAO_{GI}$  and the number of severe storms. In the extended 1920–2004 data set, an ‘NAO-like’ pattern was found to be significantly correlated with OND severe storms over the British Isles (above the 99% correlation significance level of  $r = \pm 0.3$ ) (Figure 13). This correlation pattern is indicative of a ‘Rossby-like’ wave train in MSLP (red arrow in Figure 13), and also appears in 500-hPa geopotential heights from 1948–2004 (not shown). This pattern is accompanied by a distinct mid-Atlantic SST anomaly (Figure 13). The core of an ‘El Niño-like’ signal is evident in the tropical Pacific, and is significant at the 95% level.

The climatic features driving OND severe storms over the British Isles in Figure 13 are highlighted further if the spatial patterns of MSLP and SST for years in the highest decile of storm frequency are compared with years in the lowest decile of storm frequency during 1920–2004 (Figure 14). This diagram indicates that the ‘Rossby-like’ wave train in MSLP and the SST structure in the North

Atlantic are prominent in the stormiest years in OND over the British Isles. Interestingly, the ‘El Niño-like’ signal in the tropical Pacific is strongly highlighted and may play an important role in storminess across the British Isles in this season. This Pacific structure is more like the SST pattern seen during lower frequency quasi-decadal episodes than the warm tongue extending eastwards across the equatorial Pacific from South America that characterizes more ‘classical’ El Niño events. This would fit with the finding in Meinke *et al.* (2005) linking the quasi-decadal ENSO signal to UK and European rainfall extremes in OND.

When examined spatially over the full 1920–2004 period, the severe storms index in JFM shows the expected strong relationship with the NAO pattern (large areas of correlation above  $r = \pm 0.3$ , significant at the 99% level) in MSLP, and also displays a concurrent relationship with the ‘tripolar’ SST structure over the North Atlantic (the high latitude and tropical North Atlantic negative SST parts of the SST tripole are significant at the 99% level) (Figure 15). A successive 20-year analysis of these spatial correlations (not shown)

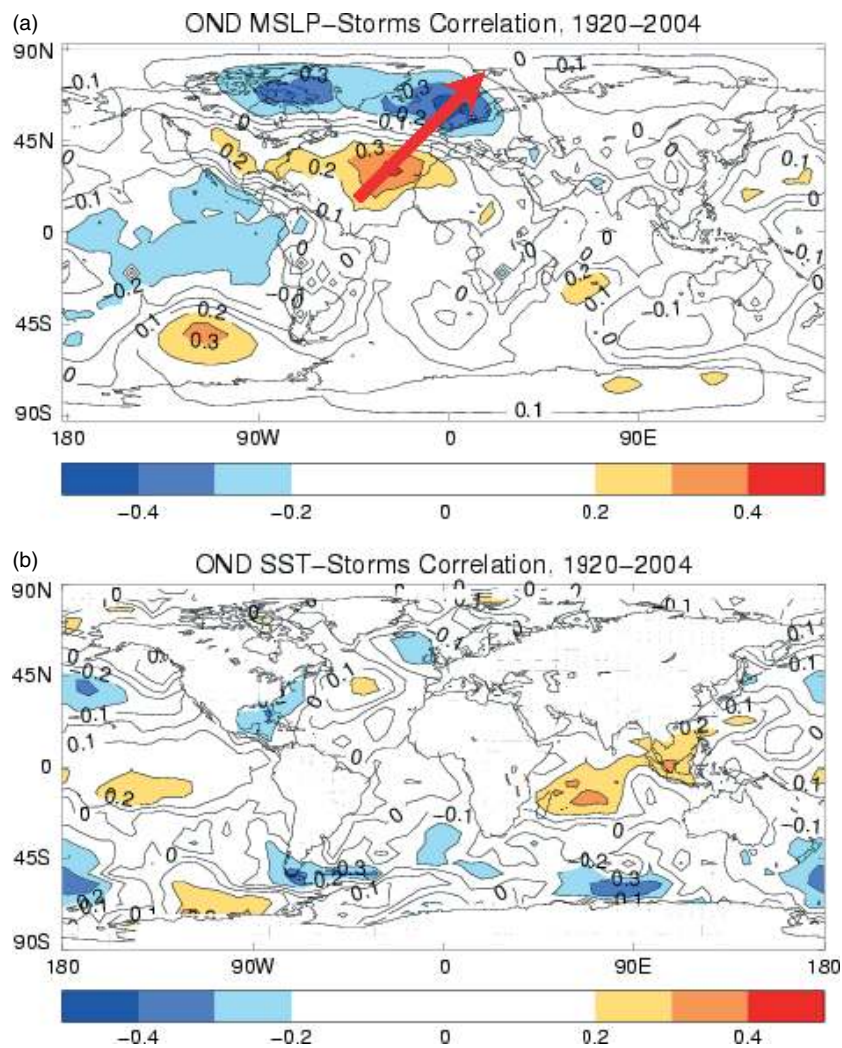


Figure 13. Correlations between OND severe storm frequency over the British Isles and HadSLP2 MSLP (a) and HadISST (b), 1920–2004. Only correlations that are significant at, or above, the 95% level are shaded.

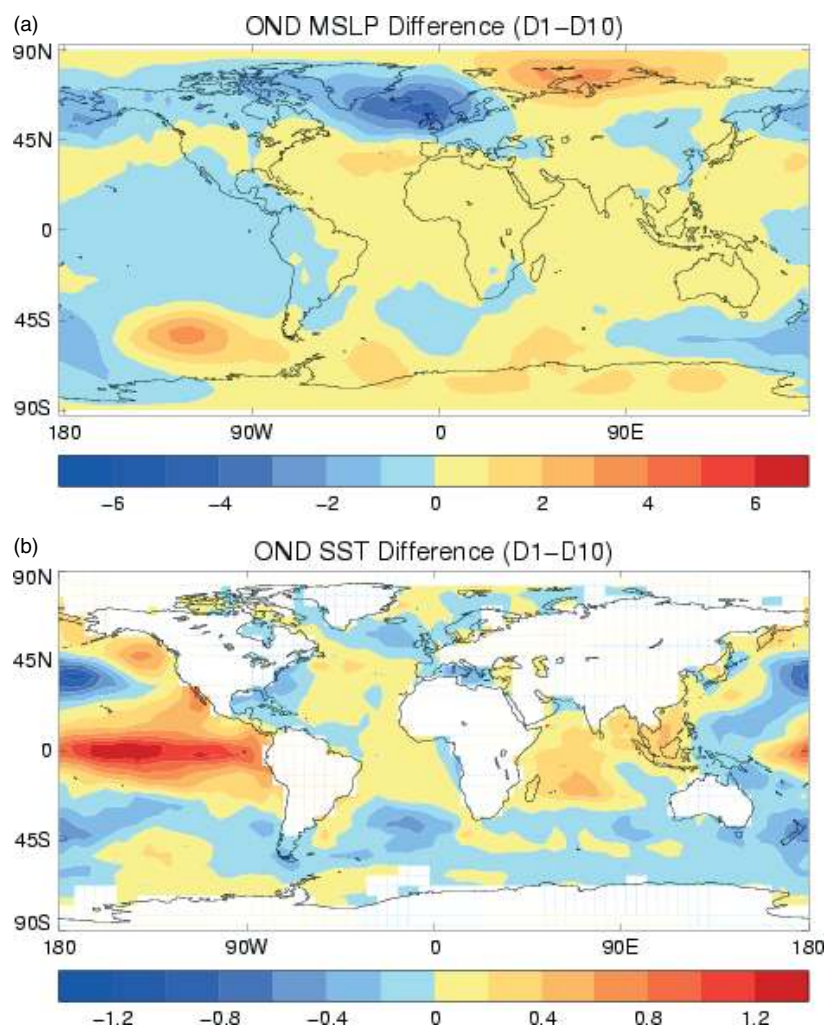


Figure 14. (a) OND MSLP (hPa) and (b) SST (°C) for years in the highest decile of storm frequency minus years in the lowest decile of storm frequency during 1920–2004 over the British Isles.

reveals an NAO MSLP and ‘tripolar’ North Atlantic SST relationship, which waxes (waned) as the British Isles extreme storms index becomes larger (smaller) in magnitude. These fluctuations are most robust in the 1970–1990 and 1940–1960 periods, with the former showing the strongest relationships.

If the spatial patterns of JFM MSLP and SST for years in the highest decile of storm frequency are compared with years in the lowest decile during 1920–2004, the link to the NAO is clearly marked (Figure 16). However, the ‘tripolar’ SST pattern over the North Atlantic area that is so prominent in Figure 15 is weaker.

Further insight into the drivers of severe storms over the British Isles since 1920 can be obtained by looking at synoptic patterns over the Western European region on days when extreme storm events occur. Philipp *et al.* (2007) categorized atmospheric circulation patterns over Europe using the homogenized daily EMSLP dataset (Ansell *et al.*, 2006) and simulated annealing to ‘cluster’ all days within a season into sets with similar pressure patterns. This method yields almost equiprobable patterns, allowing robust statistical analyses of the varying extent to which each large-scale pattern is associated with

severe storms. In this study, daily clusters were analysed from this data set for autumn (ND) and winter (JF).

Figure 17 shows the seven commonest daily large-scale circulation clusters for both seasons defined using all daily pressure patterns between 1850 and 2003. It is clear that the most usual pattern in both seasons is the NAO (cluster 1 in each case). There are similarities between the patterns in each season although their associated relative daily frequencies vary, e.g. the fourth most common cluster in autumn is similar to the sixth most common cluster in winter. A time series analysis indicated no significant trends in the relative frequency of each cluster since 1920, although an increase in cluster 2 in winter in the past two decades appears to be unusual in the context of the longer-term record since 1850 (not shown).

Using our definition of a severe storm over the British Isles, the cluster pattern for each event was determined and timelines of the cluster numbers during each storm event for both autumn and winter are shown in Figure 18. In autumn, the NAO (cluster 1) and a Scandinavian-low/Azores-high ‘EA-like’ pattern (cluster 4) dominate and, when combined with a third pattern with a low



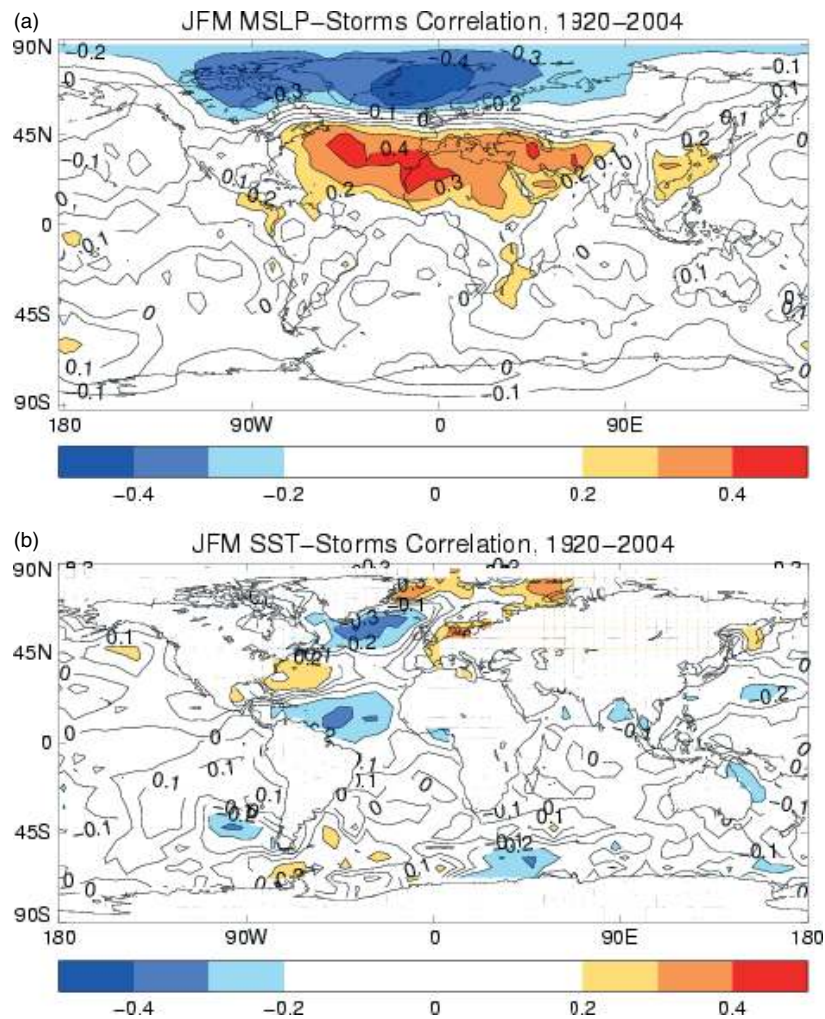


Figure 15. Correlations between JFM severe storm frequency over the British Isles and HadSLP2 (a) and HadISST (b), 1920–2004. Only correlations that are significant at, or above, the 95% level are shaded.

centred over Northern Britain (cluster 6), drive over 80% of severe storm events in the British Isles. In winter, the NAO pattern (cluster 1) is even more dominant than in autumn driving over half of the severe storm events alone. Similar to autumn, an ‘EA-like’ pattern (cluster 6) is the second most common driver of storm events in winter but unlike autumn the third most common pattern in winter has high pressure centred over western Europe (cluster 2). These three patterns together drive 90% of the storms in winter. Therefore, although there are similarities between the daily driving mechanisms in each season with three large-scale synoptic patterns driving the vast majority of severe storm events over the British Isles, there does appear to be some difference in how these patterns are manifest between the autumn and winter period. Thus during OND, tropical to mid-latitude North Atlantic and lesser Pacific ‘ENSO-like’ influences dominate, whereas NAO influences predominate in JFM.

#### 4. Conclusions

Earlier research on severe storms in the United Kingdom (Alexander *et al.*, 2005) has been extended to cover the

United Kingdom and Ireland for the period 1920–2004. This has provided a greater insight into OND and JFM storminess across the British Isles and the underlying physical mechanism.

In the OND season, the 1920s period was the most active for severe storms across the British Isles, with a secondary peak in the 1990s. This suggests that climatic variability plays an important role in modulating OND severe storms. Over the British Isles, severe storms in OND are significantly correlated with a ‘Rossby-like’ wave train in MSLP linking the tropical Atlantic to higher latitudes of the North Atlantic, together with a mid-Atlantic SST anomaly. A significant correlation was found with the Azores–Iceland NAO (NAO<sub>AI</sub>), but not with the Gibraltar–SW Iceland NAO (NAO<sub>GI</sub>). A weak overall ‘El Niño-like’ signal in the tropical Pacific Ocean is evident, but it is pronouncedly in extremely stormy years. This signal is similar to the lower frequency quasi-decadal ‘El Niño-like’ pattern linked to UK rainfall variability.

During JFM, the Alexander *et al.* (2005) finding that the 1990s experienced the most severe storm activity continues to be seen when data are extended to the



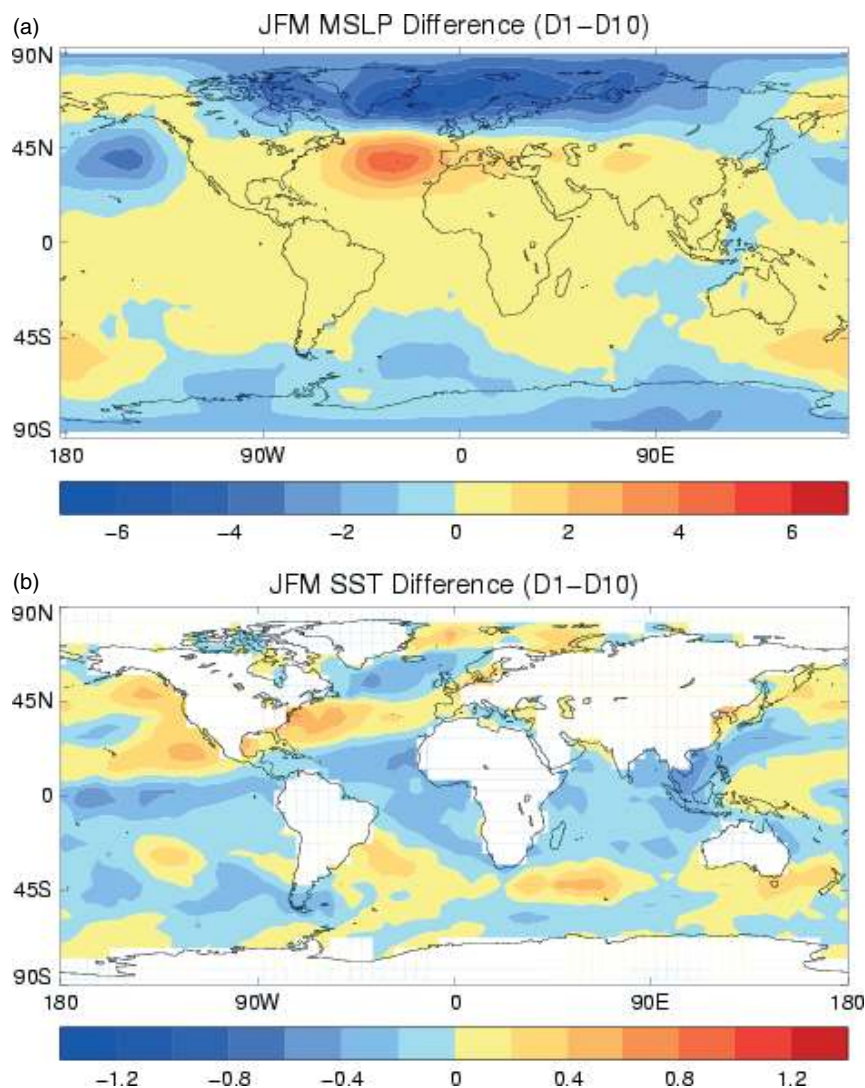


Figure 16. (a) JFM MSLP (hPa) and (b) SST ( $^{\circ}\text{C}$ ) for years in the highest decile of storm frequency minus years in the lowest decile of storm frequency during 1920–2004 over the British Isles.

1920–2004 timeframe. A simple linear trend analysis still indicates an increase in severe storm activity up to the 1990s. However, as in OND, the longer 85-year data set reveals the presence of climatic variability modulating severe storm activity across the British Isles. There is also a significant correlation between JFM severe storminess over the British Isles and the NAO. However, the NAO correlation was found to fluctuate over the 85 years of data with the strongest relationships ( $r=+0.6$ ) occurring in 1970–1990 and 1940–1960 ( $r=+0.5$ ), a weaker correlation in the 1920s–1940s ( $r=+0.2$ ) and effectively no correlation in the 1950–1970 epoch. This changing NAO relationship is highlighted further in the spatial correlations between JFM severe storms and global fields of MSLP and SST, which show the NAO pattern in MSLP and a concurrent (though less significant) ‘tripolar’ SST structure over the North Atlantic Ocean.

Several important points can be drawn from this study:

Climatic variability plays an important role in modulating autumn–winter severe storminess across the British

Isles, and it must be taken into account when attempting to resolve the influence that climatic change may have on severe storm activity.

During the JFM season in epochs when the NAO is most active and robust, some statistical ability to predict the NAO on a seasonal basis has been shown (Rodwell and Folland, 2002). Thus it may be possible to predict severe storminess activity over the British Isles with some skill using a combination of the above method and dynamical seasonal forecasting methods (Folland *et al.*, 2006; Graham *et al.*, 2006).

The results from this study suggest that natural climate variability will play an important role in future changes in storminess, and thus could overwhelm any anthropogenic signal there might be.

Extensions to the network of stations over the British Isles to facilitate severe storms analyses back into the later part of the 19th century are likely to be most effective and revealing if they are part of wider efforts to use such sub-daily MSLP in historical global surface-observations-only reanalyses (Compo *et al.*, 2006).

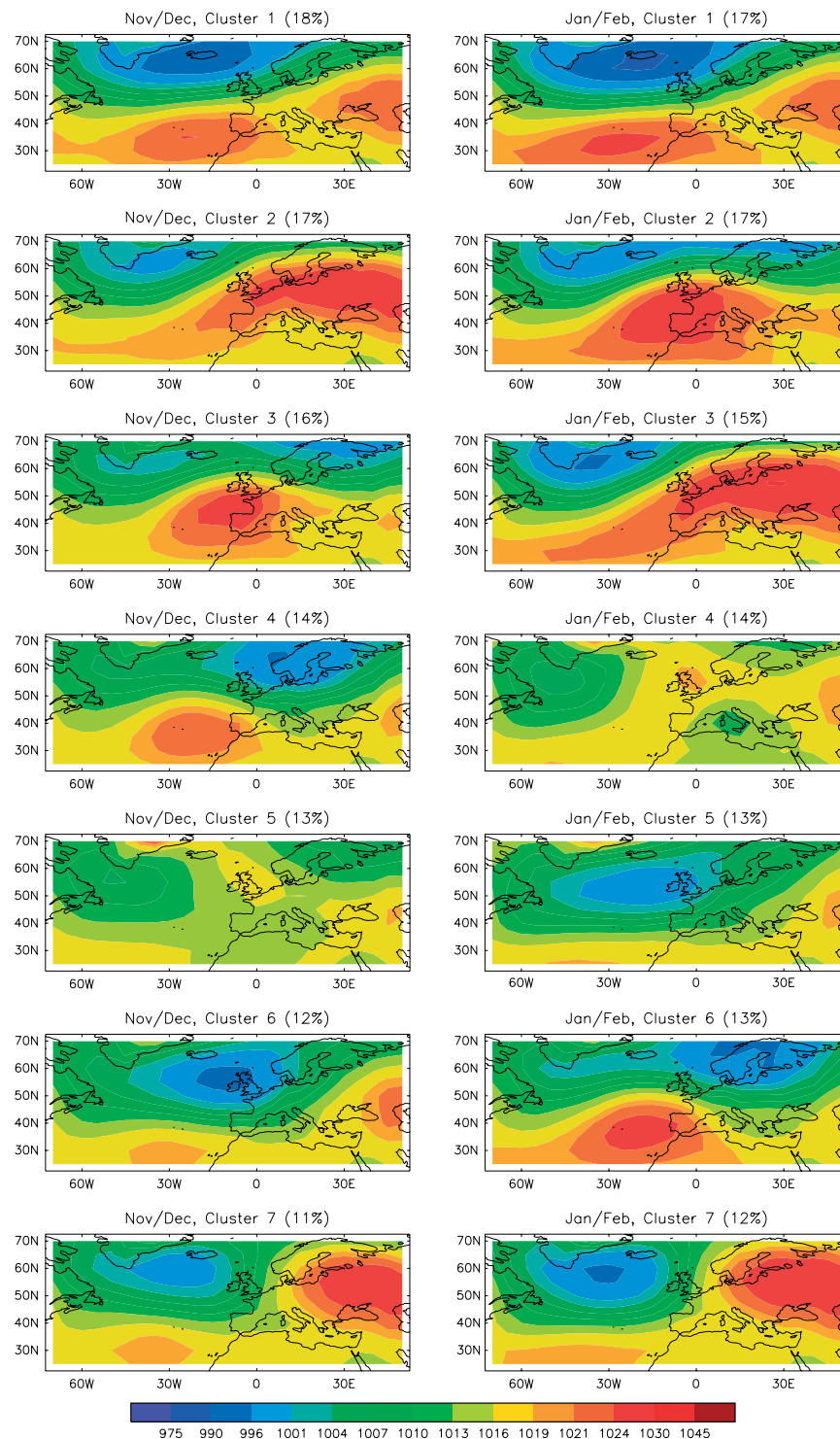


Figure 17. Simulated annealing cluster patterns calculated from 1850 to 2003 and shown as actual mean sea level pressures (hPa) for ND and JF seasons. Numbers in brackets indicate the percentage of time in the period that has been associated with each cluster. The colours from blue to red indicate low to high pressure respectively.

**Appendix 1: Data problems in the 1920–1960 digitization**

While checking the 3-hourly MSLP data digitized for this study, it was found that sections in the DWRs covering ‘Corrections and Additions’ to the published data were only bound into the original books. These observations were not keyed, because the digitization project only

had access to duplicate copies of the DWRs in the Met Office Library, which had no ‘Corrections and Additions’ sections in them. This is because removal of the original manuscripts for digitization from the Met Office Archives was not permitted. Many remote stations in the north of the United Kingdom and Ireland appear to have regularly sent in their data late, and these only appear in the ‘Corrections and Additions’ sections of the DWRs. This

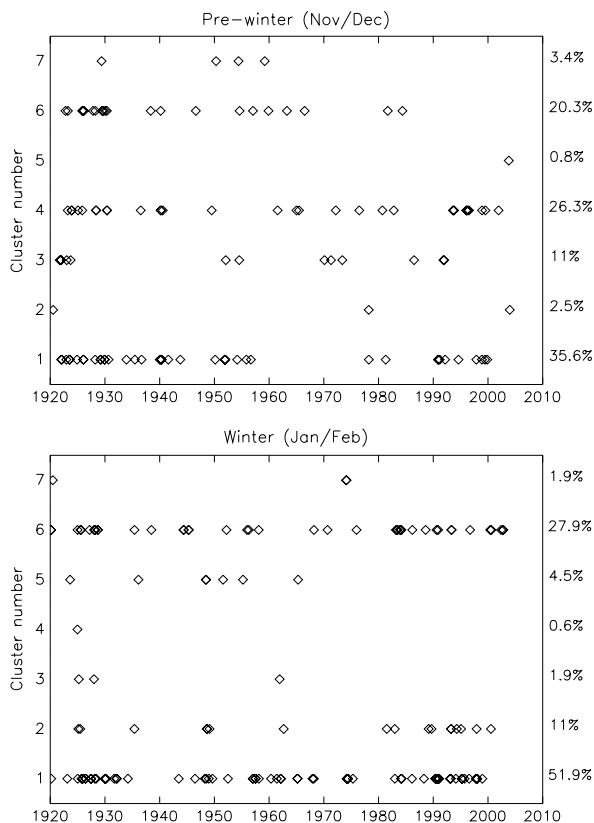


Figure 18. Timeline representing the synoptic patterns (Figure 17) calculated from EMSLP (Ansell *et al.*, 2006) associated with severe storm events in the British Isles for (a) November/December and (b) January/February. Percentages on the right-hand side represent the frequency of storms since 1920 occurring during each cluster type.

seems to have particularly affected data for 1919, so the current study used data from 1920. Future keying of data in the ‘Corrections and Additions’ sections of the DWRs would fill gaps in some northern UK and Irish station records that extend into the 1930s and 1940s. Finally, an analysis of the DWRs prior to the 1 March 1930 indicated that the published 3-hourly MSLP tendencies were only half the observed values; this was taken into account when assembling the final stations series.

## Appendix 2: Future extensions of 3-hourly observations

Sub-daily observations from 1874 were made initially at seven UK and Irish first-order observatories in the Met Office network. Sub-daily pressure data for 1874–1886 from these observatories were located in the DWRs and digitized. However, from 1887 to 1899, only pentad (5-day) data were published in the DWRs. When sub-daily data were again published in the DWRs in 1900, they were initially only from four and then three first-order observatories (only two, at Kew and Valentia, were consistently available during this period) and the DWR records ceased in 1915. These data have yet to be digitized. Subsequent investigations have located registers of 3-hourly MSLP among the ‘Climatological returns’ in the

Met Office Archives for Dungeness (1884–1979), Scilly Islands (1873–1995), Holyhead (1873–1951) and Spurn Head (1879–1964). Data in these sources have not been digitized. In addition, logbooks with potential meteorological observations for the Point Lynas lighthouse and telegraph station (1867–1964) on Anglesey are held by the Anglesey Record Office in Wales, and weather books for the Low Lighthouse, North Shields (1887–1921) are in the Tyne and Wear Archives Service in the north of the United Kingdom.

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