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Recent observed changes in severe storms over the United Kingdom and Iceland

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[1] Severe storms defined as 3-hourly pressure changes exceeding an extreme magnitude, were carefully manually quality-controlled and analyzed at stations in the UK and Iceland which had at least 45 years of digitized data. Iceland showed significant distribution differences between the periods before and after 1980 with a tendency towards less extreme severe events in latter decades. In contrast, the UK regions have tended towards larger magnitude events in recent decades, particularly in the more southerly regions. There has been a significant increase in the number of severe storms over the UK as a whole since the 1950s, however, this may not be unusual in longer-term variability. For both the UK and Iceland in winter these changes in severe storms appear to be related to changes in the North Atlantic Oscillation (NAO) but UK changes during October to December do not appear to be related to changes in the NAO. **Citation:** Alexander, L. V., S. F. B. Tett, and T. Jonsson (2005), Recent observed changes in severe storms over the United Kingdom and Iceland, *Geophys. Res. Lett.*, *32*, L13704, doi:10.1029/2005GL022371.

1. Introduction

[2] Small-scale severe weather phenomena such as severe storms are notoriously difficult to detect given their rarity and small spatial scale [*Intergovernmental Panel on Climage Change* (*IPCC*), 2001]. In fact, IPCC goes further in suggesting (e.g., page 33) that there is no compelling evidence in any of the regions studied to suggest long-term change. Although, over the UK, "gale" indicators such as Jenkinson [*Jenkinson and Collison*, 1977], suggest there has been an increase in storminess in recent years, these indices are only able to resolve storms on daily timescales and are therefore less suited to detect small-scale fast moving events such as the storms of October 1987 and January 1990 which cost the UK insurance industry \$2.6 billion and \$3.9 billion, respectively [*Association of British Insurers*, 2003]. Given their devastating effects, we chose to analyse stations in the UK and Iceland with long-term 3-hourly pressure records in order to better resolve these severe storm events. Pressure changes are also likely to be a more robust measure of trend and variability than wind speed, for example, which is more sensitive to the site moves and instrumentation changes that can cause inhomogeneities [*WASA Group*, 1998]. An absolute mean sea-level pressure (MSLP) change over 3 hours of 10 hPa, chosen from forecasting classifications for severe gales, was set as the threshold to define a "severe storm event" at an individual station. In this paper we present our quality control procedure for each event and our analysis of the distribution of these over the past 50 years along with a comparison of our results with other storms indicators.

2. Data Availability and Quality Control

[3] Twenty-one stations in the UK and seven stations in Iceland had at least 45 years of 3-hourly MSLP data available for this study (Figure 1 and Table 1). After 1957 most stations had 3-hourly digitized records. The stations are reasonably well spatially distributed (Figure 1) although there are mostly coastal stations in Iceland, while northern England and southern Scotland have no stations. Data were extracted from the first available digitized record at each station to the end of 2003 (Table 1).

[4] For UK data, each severe storm event defined was hand-checked against Daily Weather Records (DWR), which contain pressure charts for each six-hour period and synoptic messages for a selection of stations. Most stations used in this study were contained in the DWR's so exact values could be obtained by decoding synoptic messages. The remaining stations were compared with substitute neighboring stations. Although Iceland has around two to three times as many severe storms as the UK, the quality control procedure was similar i.e. original station journals were checked in the same way for internal and external consistency. In all over 500 errors were detected, mostly related to transcription errors prior to 1980, about the time automatic digitization was introduced. Any missing data were also checked against original records to ensure no storm events had been missed.

[5] Analysis of the data for each station before and after quality control (QC) showed some significant differences in the time series of severe storm events. For example, Aldergrove in Northern Ireland, prior to QC, had no trend in the number of annual events since 1949 but after QC it had a significant (5% level) increase (not shown). The sensitivity of the analysis highlights the importance and need for this type of "hands-on" quality control.

3. Distribution Changes and Trend Analysis

[6] Although the storm events defined here are likely to cause the most damage and have the biggest societal impact, they only account for <0.1% of the whole distribu-

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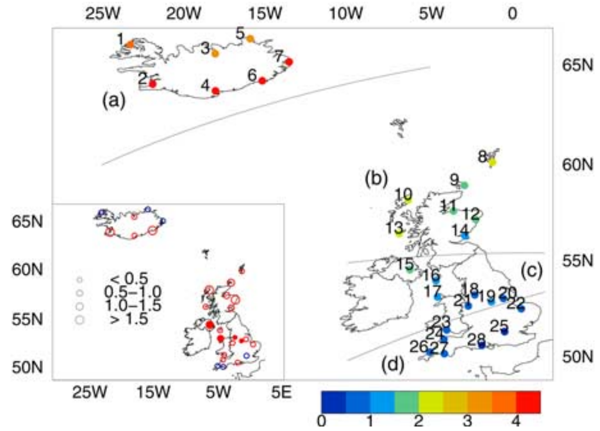

Figure 1. The annual average number of severe storms at stations used in the analysis. Station names and start dates are given in Table 1. Lines separate the regions used in the analysis: (a) Iceland, (b) Northern UK, (c) Central UK, and (d) Southern UK. The inset shows the linear trends (red positive; blue negative) in the number of severe storms over the period of record and filled circles indicate where trends are significant [*Wang and Swail*, 2001].

tion of 3-hourly pressure changes. The annual average number of severe storms at each station varies from less than one in southern Britain to around four in Iceland (Figure 1), making it extremely difficult to perform robust and meaningful statistical analysis. Thus we used several methods to analyse changes. Probability density functions (PDF) and timeseries of 3-hourly pressure changes greater than 10 hPa were analysed. The winter-half year (Oct–Mar) is chosen for analysis since, by our definition, most severe storm events (> 95%) occur during this time.

[7] Unless otherwise indicated, trends and significance are calculated using the method of *Wang and Swail* [2001]. This method is appropriate as it was previously used to analyse relatively short timeseries of significant wave height extremes and takes account of the effect of autocorrelation. A detailed description of the method is given by *Wang and Swail* [2001]. Significance is tested at the 5% level throughout.

[8] Four stations located in the central part of the UK (Figure 1) show a significant trend in the number of annual severe storm events. All other stations have non-significant trends although, interestingly, the most northerly stations in Iceland and the most southerly stations in the UK have decreasing trends. For each station we also looked at PDF's of the 3-hourly pressure changes greater than 10 hPa from two periods of approximately the same length based on the start date at station. Although there were no significant changes between the two time periods at any station, patterns did emerge across different regions. Icelandic stations on the whole showed that the upper tail of the distribution became less extended in the second period compared with the first period i.e. there were fewer "very severe" (greater than a 3-hourly 14 hPa change) storm events in the latter period. In Scotland there was a mixed pattern, with some stations showing the same shift as Icelandic stations while others had more very severe events in the latter period. Nearly all stations in the rest of the UK showed that the distributions of the latter time period shifted to the right when compared with the earlier period.

[9] From the distribution of severe storms, the average number of events at each station and the spatial structure of all the stations, we split the UK up into three regions (north, central, and south), each containing seven stations (see Figure 1). This makes the analyses more comparable with the seven Icelandic stations. So that the same event does not get counted more than once in each region, a "regional" severe storm was defined if at least two of the seven stations in a region detected the same event (events had to be separated by at least 12 hours). Although this excludes single events at some of the more isolated stations it gives a better indication of the number of more widespread events. Table 2 indicates how many severe storms occurred in each region for the two multi-decadal periods during the winter-half year. Except for the most southerly region, there are more "regional" severe storms between October and March in every region in the most recent decades, although these have increased very little in Iceland while events in northern UK have almost doubled. With a 135% increase, the central UK region has experienced the largest change.

[10] For each region we compare the PDFs from two multi-decadal time periods, the start date of the first period chosen between 1957 and 1959 depending when all stations in that region had started reporting (see Table 1). In Iceland (Figure 2a) there appears to be a reduction in the number of very severe events in the most recent decades. In Scotland (Figure 2b) the pattern is more mixed with no clear change from one period to the next. The distributions for the central (Figure 2c) and particularly the southern (Figure 2d) UK regions show a marked shift towards very severe events in the most recent decades. However, an analysis of the raw

Table 1. Stations Used in the Analysis as Shown in Figure 1[a]

Station Name	Start Year	Average, hPa
Galtarviti-Bolungarvik	1949	12.38
Reykjavik	1949	12.17
Akureyri	1949	11.89
Kirkjubaejarklaustur	1953	12.05
Raufarhofn	1952	12.18
Akurnes-Hornafjordur	1949	12.25
Dalatangi	1949	12.22
Lerwick	1957	11.64
Kirkwall	1957	11.82
Stornoway	1957	11.88
Kinloss	1959	11.92
Dyce	1957	11.80
Tiree	1957	11.96
Leuchars	1957	11.84
Aldergrove	1949	11.84
Ronaldsway	1957	11.63
Valley	1957	11.86
Ringway	1949	11.72
Nottingham	1957	11.53
Waddington	1950	11.53
Shawbury	1957	11.36
Marham	1957	11.64
Mumbleshead	1958	11.96
Chivenor	1957	12.04
Heathrow	1949	11.18
St. Mawgan	1957	11.30
Plymouth	1949	11.42
Hurn	1957	11.66

[a]The start date of each station record is also given along with the average 3-hour pressure change of each severe storm event.

Table 2. The Number of "Regional" Severe Storms (n_1 & n_2) and the Average Absolute 3-Hour Pressure Difference of Those Events (d_1 & d_2) Between October and March for 1959–1982 and 1983–2003, Respectively[a]

	n_1	d_1	n_2	d_2	p
South UK	20	11.42	19	12.02	0.92
Central UK	20	11.61	47	11.89	0.64
North UK	33	11.88	63	11.97	0.91
Iceland	107	12.43	111	12.15	0.97

[a]The probability, p, that the results from the 2 time periods are statistically different is calculated using a Kolmogorov-Smirnoff test.

data shows the distribution differences are only significant in Iceland (see Table 2). This is consistent with the values in Table 2, which show a decrease in the average "intensity" of each severe event in Iceland with the largest increase in "intensity" over southern Britain.

[11] We define a severe storm over the UK as the average of the "regional" severe events. Figure 3 shows there is a significant increase in the number of severe storms in the UK in both seasons (trends of 0.53 (autumn) and 0.87 (winter) since 1959) although other studies [e.g., *Alexandersson et al.*, 2000; *Bärring and von Storch*, 2004] have shown this may not be unusual in the longer term. A binomial filter through the data shows decadal variations, a common feature between the regions in Jan–Mar being the downturn in the frequency of extreme storms since the early 1990s. Decadally filtered values for each region (not shown) also show that autumn has a much more variable pattern than winter.

4. Comparison With Other Climate Indicators

[12] To our knowledge there is no other such high-frequency, long-running storm indicator. We compare the severe storms defined here with two storm indicators with lower temporal resolution. First Jenkinson "gales" indices, which use daily MSLP data from a 5° latitude by 10° longitude gridbox over the UK to calculate the geostrophic wind flow and vorticity each day [*Jenkinson and Collison*, 1977] were calculated [see *Jones et al.*, 1999]. The number of gales in the winter-half year between 1959 and 2003 defined using Jenkinson indices show a significant upward trend. However, the Jenkinson index is likely to be inhomogeneous since different raw data have been used to calculate it over time and also its temporal scale means it is generally unable to resolve more devastating events. For example, the damaging storm on the 16 October 1987, which the Jenkinson index fails to detect, is captured at 11 of the 14 southern and central UK stations. Although we also see a significant increase in our severe storm index since 1959 (Figures 3b and 3d), this does not seem to be related to the Jenkinson index on a year to year basis; the correlation between the unsmoothed series is <0.01. The Jenkinson index detects much less than 10% of the severe storms described here and usually only when the storm occurs over a more prolonged period. However, on decadal timescales there is a much higher correlation between the two storms indicators.

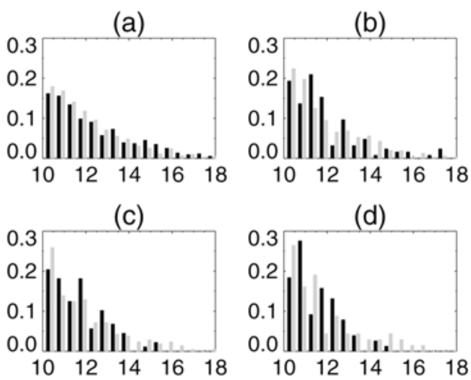

Figure 2. Probability distribution functions of absolute 3-hourly pressure changes above 10 hPa for (a) Iceland, (b) northern UK, (c) central UK, and (d) southern UK. The x-axis denotes the magnitude of 3-hourly pressure changes. Black bars indicate the period (a) and (c) 1957–1980, (b) 1959–1982, and (d) 1958–1981. Grey bars represent the period after this to 2003.

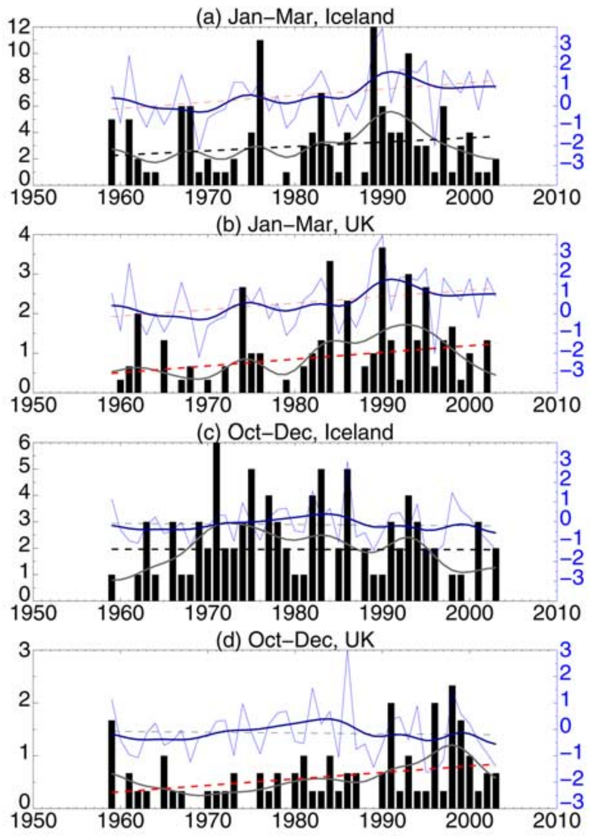

Figure 3. Time series of seasonal severe storms (black bars) for the regions and seasons indicated along with the seasonal NAO index (blue). The left hand y-axis represents the number of events occurring over the two regions. The right hand y-axis denotes the NAO index in standardized units. The smoothed lines represent the decadally averaged values calculated using a 21-term binomial filter for the NAO index (dark blue) and the number of severe storms (dark grey). The dashed line is a least-squares fit to the data. Red signifies the trend is significant [*Wang and Swail*, 2001].

[13] Next, seasonal NAO indices [*Jones et al.*, 1997] were compared with the number of severe storms over Iceland and the UK during Jan–Mar (Figures 3a and 3b) and Oct–Dec (Figures 3c and 3d). There is a significant increase in the NAO index in Jan–Mar since 1959, confirming previous results [e.g., *Jones et al.*, 1997; *Rodwell and Folland*, 2002] and the downturn in the NAO since the early 1990s corresponds to a similar decrease in the number of severe storms during this time in both countries (Figures 3a and 3b). There is some evidence to suggest the storminess in recent decades has abated [*Alexandersson et al.*, 2000]. Decadally filtered values in Jan–Mar are highly correlated with the number of storms over each region; r = 0.8 and 0.82 for Iceland and the UK respectively. However, the correlations are smaller in autumn (0.55 for Iceland) and there is a negative correlation (−0.21) between the NAO and the number of severe storms over the UK, perhaps indicating a shift of the large scale circulation pattern. Some previous studies [e.g., *Peterson et al.*, 2003] do provide evidence for an eastward shift of the NAO over the past 50 years.

5. Conclusions

[14] In this analysis we have defined and analyzed the most severe storms over the UK and Iceland and shown that their distribution over this region of the North Atlantic is likely to have changed over the past 50 years. Although there has been an increase in the number of severe storms between October and March in each year in most regions, there has been a shift towards fewer very severe events over Iceland. Northern UK shows a mixed pattern of change. There are many more regional severe events in recent decades but no significant distribution change between the two periods studied and no significant increase in severe storms. The central and southern UK regions show a tendency towards more "very severe" storms in latter decades with the number of severe events in central UK having more than doubled. Although southern UK shows little change in the number of severe events, there is evidence for their intensification in the most recent decades.

[15] Overall, the UK has seen a significant increase in the number of severe storm events over the past 50 years which in general are related to the long-term fluctuations of the NAO. An exception to this is the non-significant relationship between the NAO and severe storms over the UK in October to December, the reason for which is not clear.

[16] The difference between the distributions of severe storms between Iceland and the UK may imply a possible shift in the North Atlantic storm track, with significant implications given that the majority of people (more than 30 million) in our region of study live in southern Britain. The mechanisms for these changes have not been investigated as we do not yet have access to the very high temporal and spatial resolution climate model that would be required for such a study.

[17] With our relatively short record we cannot say with certainty that these events are unusual over longer time periods. Indeed *Bärring and von Storch* [2004] showed it was unlikely that "storminess" has significantly changed over the past 200 years in northern Europe although further investigation would be required to determine why the very intense small scale storms analysed here are not always highly correlated with other storm indicators.

[18] However, this method is limited by its lack of digitized data prior to 1950 although paper archives exist which would allow us to perform such analyses over the last 100 years.

[19] **Acknowledgments.** This work was funded by the UK Dept. of the Environment, Food, and Rural Affairs (Contract PECD/7/12/37). Thanks to David Parker, Chris Folland, Adam Scaife and Tara Ansell for their help.

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