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Historical storminess and climate 'see-saws' in the North Atlantic region

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Abstract

The existence of a well-defined climate 'see-saw' across the North Atlantic region and surrounding areas has been known for over 200 years. The occurrence of severe winters in western Greenland frequently coincides with mild winters in northern Europe. Conversely, mild winters in western Greenland are frequently associated with cold winters across northern Europe. Whereas this 'see-saw' is normally discussed in terms of air temperature and pressure differences, here we explore how the climate 'see-saw' is reflected in records of historic storminess from Scotland, NW Ireland and Iceland. It is concluded that the stormiest winters in these regions during the last ca. 150 years have occurred when western Greenland temperatures have been significantly below average. In contrast, winters of reduced storminess have coincided with winters when air temperatures have been significantly above average in western Greenland. This reconstruction of winter storminess implies a relationship between chronologies of coastal erosion and the history of North Atlantic climate 'see-saw' dynamics with sustained winter storminess, and hence increased coastal erosion, taking place when the Icelandic low pressure cell is strongly anchored within the circulation of the northern hemisphere. Considered over the last ca. 2000 years, it would appear that winter storminess and climate-driven coastal erosion was at a minimum during the Medieval Warm Period. By contrast, the time interval from ca. AD 1420 until present has been associated with sustained winter storminess across the North Atlantic that has resulted in accelerated coastal erosion and sand drift.

Keywords: historical storminess; North Atlantic climate; air temperature; climate change

1. Introduction

It is generally believed that climate change in the North Atlantic region during recent decades has resulted in an increase in winter storminess (Günther et al., 1998). The implication for coastal scientists is that many soft coastlines bordering the North Atlantic are likely to be subject to accelerated erosion in the future. Despite such predictions, we know relatively little about past patterns of winter storminess. Is it the case, for example, that the last ca. 30 years represents the stormiest interval of the last century? Or is it the case that winter storminess was at its most severe during the 19th century rather than during recent decades? To some extent, the dating

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of late Holocene coastal sediment sequences has provided information that has helped establish local chronologies of coastal change. However, such patterns of change are complicated by the existence of a climate 'see-saw' between western Greenland and northern Europe that has been known for over 200 years (e.g. Crantz, 1765; Dawson et al., 2003). For example, Van Loon and Rogers (1978) quote the missionary Hans Egede Saabye who described in a diary kept during the years 1770–78 that "...In Greenland all winters are severe, yet they are not alike. The Danes have noticed that when the winter in Denmark was severe, as we perceive it, the winter in Greenland in its manner was mild, and conversely". Similarly, it has been observed that mild winters in western Greenland frequently correspond with reduced winter temperatures in northern Europe (Barlow et al., 1997; Hurrell and van Loon, 1997). In a classic paper, Van Loon and Rogers (1978) investigated the climate 'see-saw' in more detail and listed particular years that had been described by missionaries as either exceptionally mild or severe (Table 1). The 'see-saw' in winter air temperatures is linked to interannual variability of the Icelandic low atmosphere pressure cell reflected in the North Atlantic Oscillation (NAO) index (an index based on an analysis of a time series of monthly air pressure differences between Iceland, the Azores and Lisbon) (Hurrell, 1995; Barlow et al., 1997). Thus severe winters in northern Europe occur when westerly winds in the North Atlantic region are weak, there is a blocking ridge of high pressure across the eastern Atlantic and air temperatures are higher than average across western Greenland (Greenland Above (GA) winters). During such periods, northerly flow of air along the east side of the ridge advects cold, polar air from the Arctic across Europe (Van Loon and Rogers, 1978; Lamb, 1991; Barlow et al., 1997; Rogers, 1997). By contrast, when a cold northerly airstream on the eastern flank of the winter Canadian anticyclone moves over western Greenland (Greenland Below (GB) winters), there is marked increase in cyclone frequency across the northern North Atlantic. This is accompanied by the frequent occurrence of SW winds and an increase in winter air temperatures (Fig. 1). In general terms, GB winters are characterised by a strongly positive NAO index while GA winters are often associated with a negative NAO index (Jones et al., 1997).

In a detailed study, Van Loon and Rogers (1978) represented the 'see-saw' using the air temperature records for Jakobshavn, western Greenland and Oslo (Fig. 2). The air temperature analysis of these authors identified particular winters (using December–February data) according to whether or not the average winter temperature departure from the mean value was equal to or larger than 4 °C, the latter value chosen in order to identify winters when the temperature anomalies were sufficiently above or below the long-term mean. Van Loon and Rogers (1978) identified two key and two supplementary states of the 'see-saw': (1) Greenland below-normal winter temperatures (GB) corresponded to winters when Oslo also had above-normal mean temperatures during the winter months (December–February) with the Jakobshavn–Oslo temperature anomalies at least 4 °C apart; (2) Greenland above-normal temperatures (GA) were defined as winters when Oslo also had a mean winter temperature below normal with Jakobshavn–Oslo temperature departures at least 4 °C apart; (3) winters when Jakobshavn and Oslo were both characterised by above-normal temperatures (BA); (4) both Jakobshavn and Oslo were characterised by below-normal temperatures (BB). Both BA and BB modes corre-

Table 1
Winters during the 18th century when temperatures were in opposition between Greenland and Germany (Van Loon and Rogers, 1978)

Year	Winter	
	Greenland	Germany
1709	Very mild	Extraordinarily severe
1740	Very mild	Unusually cold
1746	Mild	Cold
1756	Very harsh and severe	Very mild
1758	Hardly winter at all	Very cold
1759	Not really cold	Very cold
1764	Very cold	Very mild
1765	Very cold	Moderate
1766	Very mild	Very cold
1767	Mild	Very cold
1768	Mild	Cold
1790	Cold	Mild
1792	Very mild	Very cold
1799	Extraordinarily mild	Unusually cold
1800	Extraordinarily mild	Unusually cold

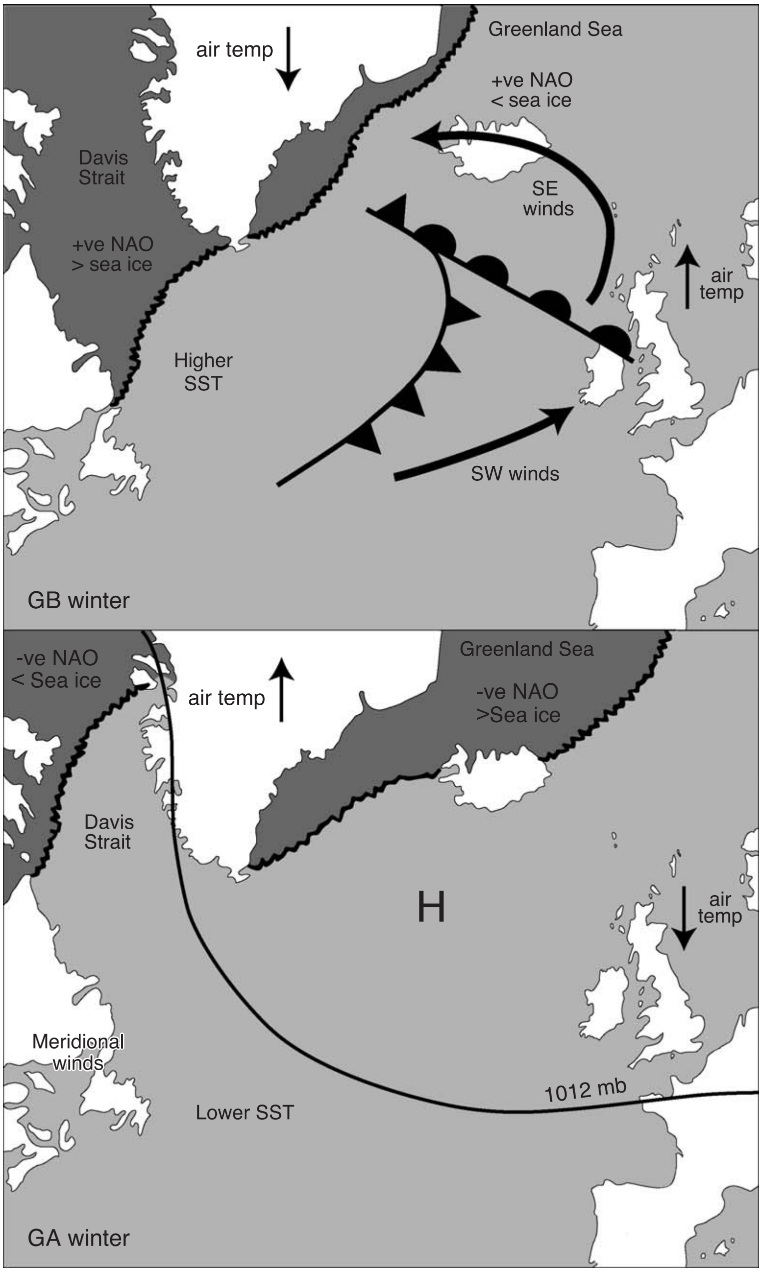

Fig. 1. Schematic illustration of North Atlantic climate 'see-saw'. Top: Key elements of GB (Greenland below/Oslo above) winter showing lower air temperatures over Greenland, increased air temperatures across Oslo, North Atlantic cyclogenesis leading to a positive NAO index as well as changes in sea surface temperature (increased) and sea ice extent. Below: Key elements of a GA (Greenland above/Oslo below) winter showing higher air temperatures over Greenland, lowered air temperatures across Oslo, the occurrence of high pressure across the North Atlantic region leading to a negative NAO index as well as changes in sea surface temperature (decreased) and sea ice extent (adapted from Greenland ice core (GISP2) analysis of Barlow, 1994).

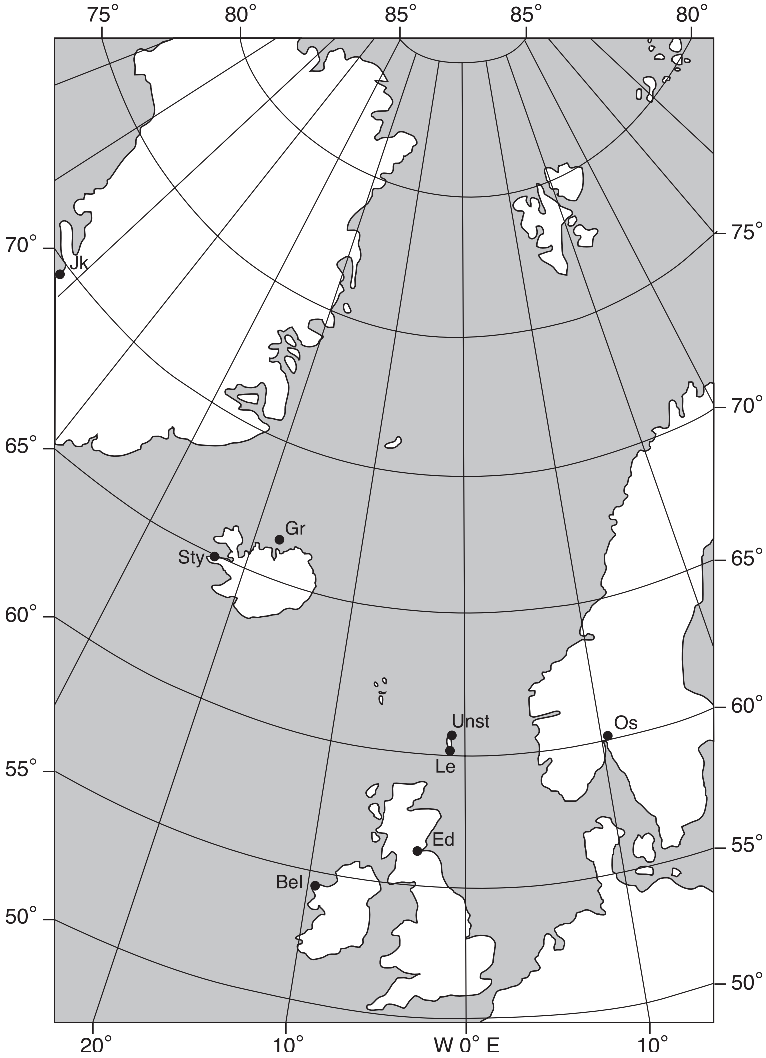

Fig. 2. Location mentioned in text. Jk: Jakobshavn, GISP2: Greenland ice core drill site, Sty: Stykkisholmur, Gr: Grimsey, Le: Lerwick, Ed: Edinburgh, Os: Oslo, Bel: Belmullet.

spond to winters when both stations have temperature departures at least 1 °C above or below their long-term monthly means. The aim of this paper is to understand how the two key elements of the ‘see-saw’, namely the GB and GA modes, are reflected in records of historic storminess for the North Atlantic region using data for Scotland, NW Ireland and Iceland. This, in turn, may contribute to our understanding of when coastlines bordering the North Atlantic may have been subject to episodes of exceptional storminess.

2. Methodology

2.1. Air temperature analysis

Van Loon and Rogers (1978) based their analysis of air temperature records using data for Jakobshavn and Oslo that cover 1840–1975. In this study, the air temperature datasets have been extended up to 1990, allowing the construction of a complete listing of GA, GB, BA and BB winters, defined by December–February air temperature parameters for the period

1840–1990 AD and compared with the corresponding NAO index values (after Jones et al., 1997) (Table 2). In respect of the UK, use has also been made of two long air temperature records for Edinburgh and Central England. The monthly air temperature record for Edinburgh extends from 1770 to the present using the analysis of Mossman (1895–1896, 1897–1898, 1902–1903) and unpublished data. The monthly air temperature record for Central England extends from 1659 to the present and comprises an updated version of Manley (1974) classic series. Analysis is made of these two air temperatures series in order to investigate whether winter temperature departures from the long-term average values show that the UK temperatures, as exemplified by the two series, belong to the northern Europe (Oslo) side of the 'see-saw'. The NAO index values (based on air pressure series) show a particularly clear relationship to GA and GB winter air temperature data. Thus, most GA winters are associated with a negative NAO index, while nearly all GB winters are associated with a positive NAO index (Table 2).

2.2. Storminess (gale day frequency) analysis

2.2.1. Scotland and Ireland

The oldest and most complete record of historic storminess in Scotland is for Edinburgh and was compiled by Mossman (1895–1896, 1897–1898,

Table 2

Updated listing of Greenland above (GA), Greenland below (GB), both above (BA) and both below (BB) winters (December–February inclusive) based on Van Loon and Rogers (1978) and new data together with corresponding NAO index (December–February inclusive) (based on Jones et al., 1997)

Greenland above	NAO	Greenland below	NAO	Both above	NAO	Both below	NAO
1985–1986	−1.00	1989–1990	+2.13	1987–1988	−0.13	1969–1970	−0.11
1984–1985	−0.53	1988–1989	+3.00	1964–1965	−1.09	1967–1968	−0.14
1981–1982	−0.22	1983–1984	+1.70	1942–1943	+1.81	1953–1954	+0.27
1979–1980	+0.32	1982–1983	+2.07	1934–1935	+1.17	1896–1897	+0.91
1978–1979	−1.97	1972–1973	+1.57	1933–1934	+0.64	1867–1868	+1.62
1976–1977	−1.90	1971–1972	+0.01	1932–1933	+0.27	1848–1849	+2.58
1974–1975	+1.96	1970–1971	−0.27	1931–1932	+0.29	1844–1845	−0.22
1968–1969	−2.20	1948–1949	+2.20	1930–1931	+0.80	1843–1844	+1.15
1962–1963	−2.22	1936–1937	+2.08	1929–1930	+1.57		
1958–1959	−0.13	1924–1925	+3.35	1926–1927	+0.91		
1947–1948	+0.49	1920–1921	+0.94	1912–1913	+2.01		
1946–1947	−1.00	1914–1915	+1.38	1872–1873	+0.46		
1941–1942	−0.30	1913–1914	+1.42	1871–1872	+0.47		
1940–1941	−0.82	1910–1911	+0.92	1850–1851	+2.23		
1939–1940	−1.09	1909–1910	+1.98	1842–1843	0.00		
1928–1929	−0.18	1908–1909	+0.94				
1927–1928	+1.14	1906–1907	+0.94				
1925–1926	+0.94	1905–1906	+1.92				
1894–1895	−1.94	1898–1899	+1.22				
1892–1893	−0.04	1897–1898	+1.74				
1880–1881	−1.57	1895–1896	+0.71				
1878–1879	−1.06	1893–1894	+2.40				
1876–1877	+1.07	1889–1890	+1.75				
1874–1875	−0.51	1886–1887	+1.35				
1870–1871	−0.71	1883–1884	+1.90				
1869–1870	−0.82	1881–1882	+3.01				
1860–1861	−0.63	1873–1874	+1.88				
1859–1860	+0.18	1865–1866	+1.78				
1846–1847	−0.81	1863–1864	+1.31				
1840–1841	−1.50	1862–1863	+2.38				
		1858–1859	+3.04				
		1857–1858	+1.75				
		1841–1842	+2.31				

1902–1903) for the period 1770–1899. Mossman used a wide variety of sources to assemble data on monthly gale day frequency in his chronology for 1770–1865. For this time interval, he used a five-grade scale (0–4) in which days with an observed wind grade of 3 or higher were defined as gale days. From 1865 to 1905, systematic measurements of storminess were made using the Royal Meteorological Society definition of a gale "...where the wind speed was directly observed as being high over a time period of at least an hour and likely to reach or exceed gale strength and/or where damage to structures whether natural or artificial, was sufficient to indicate high winds of gale force or higher" (Mossman, 1895–1896, 1897–1898, 1902–1903). These observations of average wind state corresponded to six categories of which Grade 5 corresponded to a day which was 'blowing a gale' and Grade 6 corresponded to days during which there was a 'violent gale' (Mossman, 1895–1896, 1897–1898, 1902–1903). In 1905, the Beaufort classification was introduced in Scottish meteorological records with Grade 8 describing a 'fresh gale', Grade 9 a 'positively strong gale', Grade 10 a 'whole gale', Grade 11 a 'storm' and Grade 12 a 'hurricane'. During the 20th century, with the introduction of anemometers at wind recording stations, a definition of a gale day became one in which the wind speed had a sustained velocity of greater than 34 knots (17.2 m s^{-1}) sustained over a 10-min period, this broadly corresponding to the Beaufort force 8 wind speed) (Meteorological Office, 1991). In this paper, daily measurements of gale force winds (as defined above and supplementary to the Mossman data) were recovered from historic weather records held in archives at the Scottish Meteorological Office, Edinburgh, for Lerwick and Unst (Shetland Isles).

Gale frequency data using the categories described above was also compiled for Belmullet, NW Ireland for the period 1884–1998 (Fig. 2). This data was based on measurements taken three times per day and is considered to be of high reliability. Gaps in this dataset exist for the 1922–1925 and 1941–1947. It should be noted that the gale frequency measurements for 1921 are based on only 10 months of data while those for 1926, 1927, 1932 and 1933 are based on 11 months of data. The Belmullet gale frequency record for 1956–1998 is based on hourly instrumental data and is of exceptionally high reliability. Winter gale day frequency values are shown for all winter events except two (Unst/Lerwick 1897–1898 and 1898–1899) where the quality of the data is considered sufficiently poor to exclude it from further analysis. The complete gale days datasets used in this analysis are available from the authors on request.

2.2.2. Iceland

Monthly storminess data was obtained for Stykkisholmur, SE Iceland and Grimsey, N Iceland, using data from the Danish Meteorological Institute (1873–1919) and handwritten meteorological records archived at the Icelandic Meteorological Office (1845–1872; 1919–1995) (Fig. 2). The oldest records of gales for Stykkisholmur (1845–1892) are derived from the archive documents of Arni and Olaf Thorlacius who compiled painstakingly detailed records of gales (Hvassvidri), strong gales (Stormur) and violent storms (Ofsavedur). For the period 1873–1911, the 0–6 scale used in Scotland was also used in Iceland. For the time interval 1912–1949, the Beaufort scale was used, while for the period 1950–1995, the records are based on instrumental data using the standard meteorological definition of a 'gale day' (see above).

The Grimsey gale day frequency chronology commenced in 1873 and until 1949 was based on wind observations made three times per day (0800, 1400 and 2100 h). Data is missing only for the winter of 1895–1896. For the period 1949–1962, an instrumental record of wind speed based on five readings per day was used in conjunction with the standard definition of a 'gale day' in order to calculate monthly gale day frequencies while for 1963–present, the reading frequency per 24 h was increased from five to six. For all weather stations cited here, graphs of aggregate winter gale day frequency are calculated for October–March inclusive. However, for purposes of comparison with the Van Loon and Rogers (1978) climate 'see-saw' model, calculations of winter gale day frequency values are based on summations of gale day frequency for December–February.

3. Patterns of storminess change

The Edinburgh graph of winter gale day frequency for 1770–1990 exhibits 19th century storminess maxima (in excess of 40 gale days) for the winters of 1816–

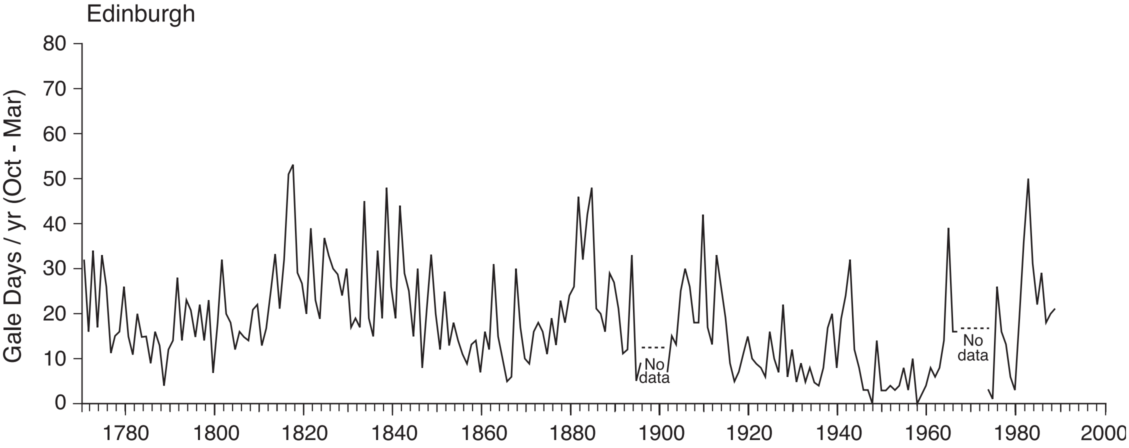

Fig. 3. Winter (October–March inclusive) gale day frequency data for Edinburgh based on Mossman and the present authors.

1817, 1817–1818, 1833–1834, 1838–1839, 1841–1842, 1883–1884 and 1884–1885 (Fig. 3). For the 20th century, winters with gale day frequencies greater than 40 only appear to have occurred during 1909–1910, 1964–1965 and 1982–1983. By contrast, intervals with gale day minima appear to have been a characteristic of the intervals ca. 1770–1810, 1850–1880 and 1920–1960 (Dawson et al., 1997).

The second longest chronology of gale day frequency is from Stykkisholmur, SE Iceland for the period 1845–present (Fig. 4). Like the Edinburgh record, this chronology spans a period of time that incorporates three different methods and scales of measuring gale day frequency. Notwithstanding these methodological problems, there is evidence from Stykkisholmur of marked temporal variations in winter gale day frequency values within individual periods of time when any specific method of gale day measurement was utilised (Fig. 4). For example, for the period up to 1912 when the 0–6 scale of mea-

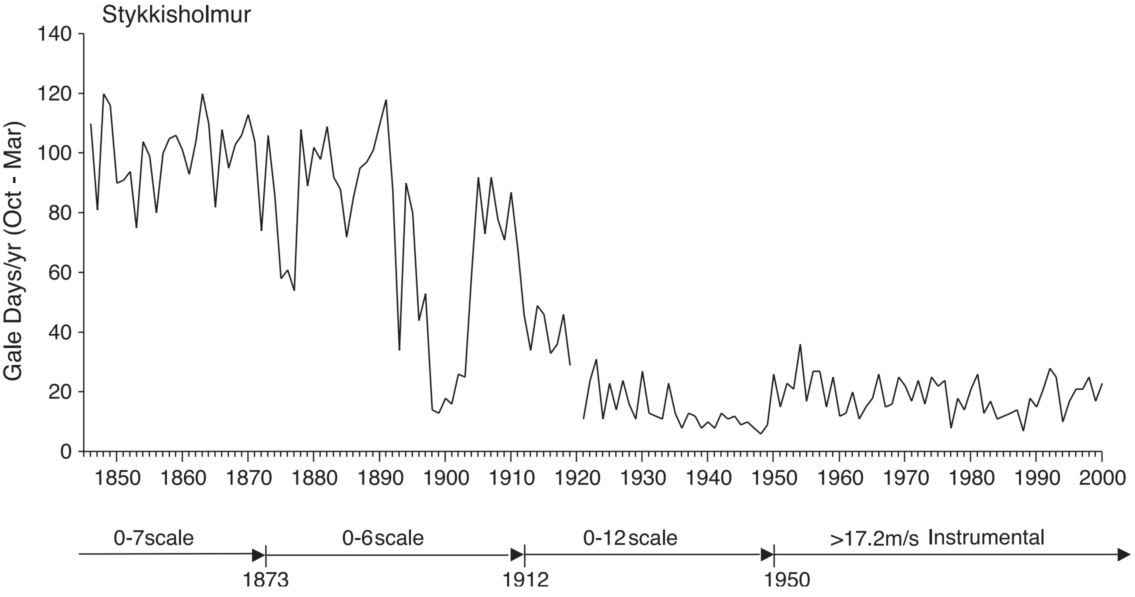

Fig. 4. Winter (October–March inclusive) gale day frequency data for Stykkisholmur, Iceland. Dates of measurement change are also indicated.

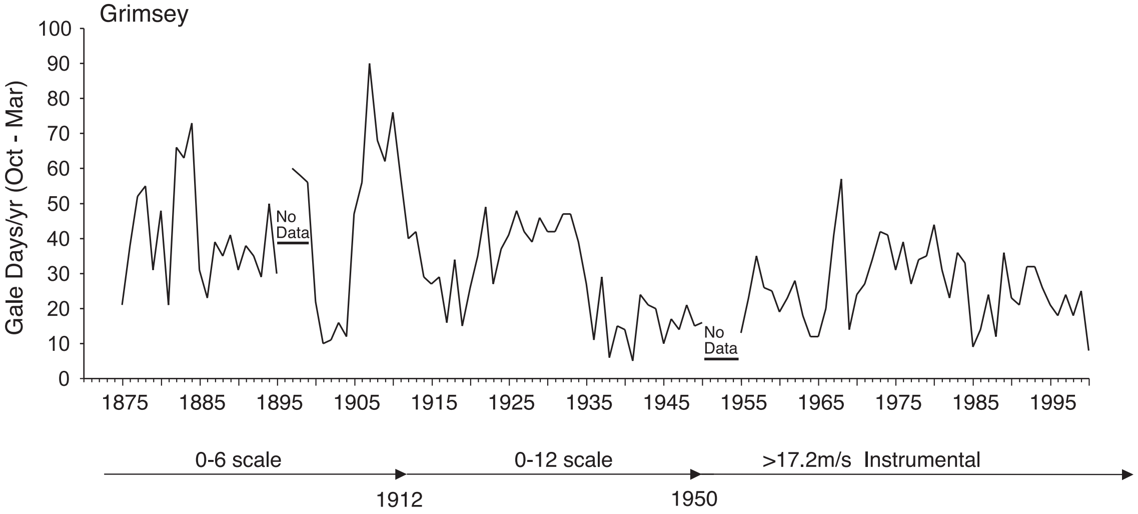

Fig. 5. Winter (October–March inclusive) gale day frequency data for Grimsey, N Iceland. Dates of measurement changes are also indicated.

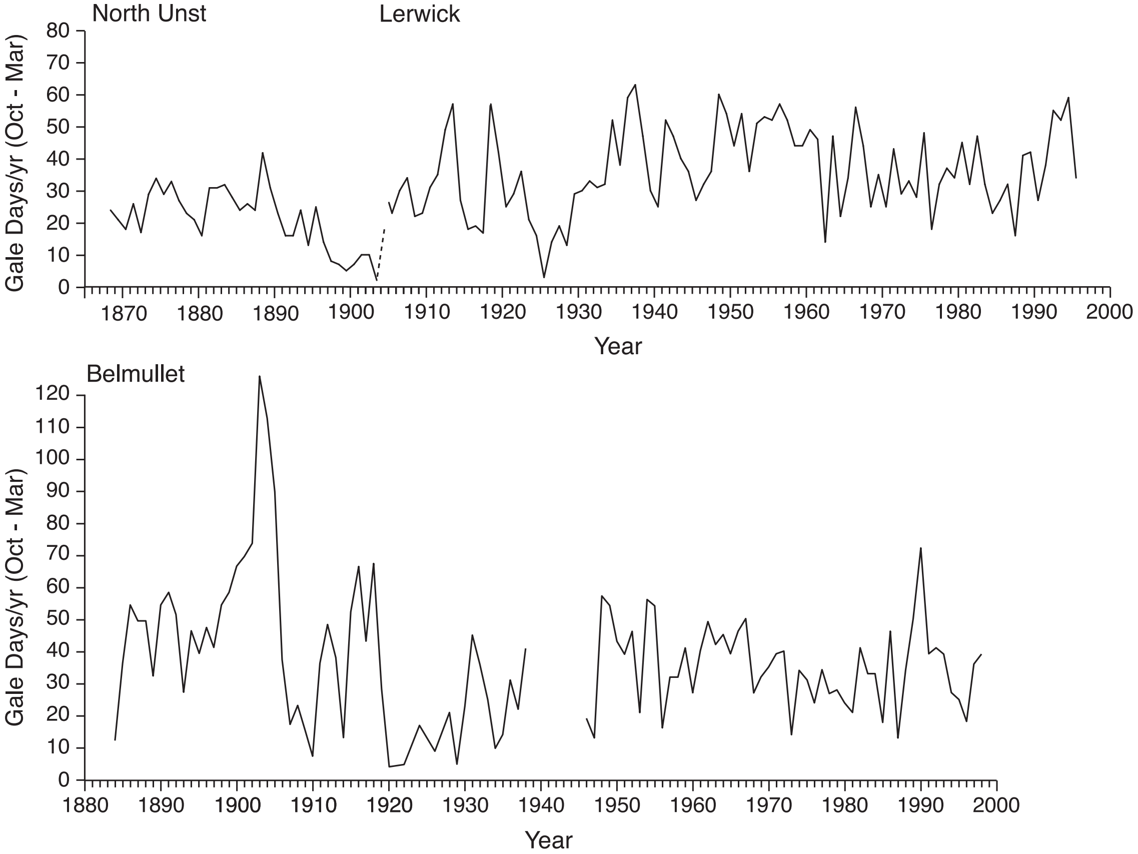

Fig. 6. Winter (October–March inclusive) gale day frequency data for Lerwick and N Unst (Shetland Isles) and Belmullet (NW Ireland).

surement was employed, there were significant changes in winter day frequency with an exceptionally pronounced gale day minimum between 1895 and 1905. Similarly, within the Beaufort measurement scale for the time interval between 1912 and 1950, significant fluctuations in gale day frequency are also evident. The gale day frequency record for Grimsey, N Iceland, also exhibits marked annual fluctuations within time intervals each characterised by different methods of measurement (Fig. 5). The Belmullet and Lerwick/Unst (Shetland Isles) storminess records are shorter, each commencing in the last decades of the 19th century and extending to the present day (Fig. 6). Each graph exhibits pronounced gale day minima and maxima. It is also clear, however, that there is sufficient regional variability in each storm record to make difficult any comparison of patterns of storminess change between individual stations.

4. Climate 'see-saws'

In order to test the Van Loon and Rogers (1978) hypothesis of GB and GA scenarios, winter gale day

Table 3
Greenland below (GB) winters for the period 1840–1990 showing winter (December–February) gale day frequencies, together with mean values for Edinburgh, Stykkisholmur, Grimsey, Belmullet and Unst/Lerwick (Shetland Isles)

GB/Oslo above winters	Edinburgh	Stykkisholmur	Grimsey	Belmullet	Unst/Lerwick
1841–1842	23				
1857–1858	11	68			
1858–1859	11	83			
1862–1863	24	82			
1863–1864	11	67			
1865–1866	5	84			
1873–1874	8	56			24
1881–1882	14	78	46		16
1883–1884	23	59	49		17
1886–1887	12	65	27	21	20
1889–1890	20	72	20	20	19
1893–1894	22	58	30	35	16
1895–1896	4	32	–	14	20
1897–1898	16	6	46	30	–
1898–1899	15	7	41	28	–
1905–1906	19	54	50	33	12
1906–1907	17	70	73	7	17
1908–1909	12	49	49	7	10
1909–1910	24	63	59	5	13
1910–1911	13	50	42	13	21
1913–1914	18	39	25	8	36
1914–1915	12	35	20	11	21
1920–1921	4	6	23	1	10
1924–1925	15	18	31	–	13
1936–1937	6	9	16	25	39
1948–1949	14	4	14	32	36
1970–1971	3	10	17	13	14
1971–1972	5	17	20	20	25
1972–1973	1	13	28	13	15
1982–1983	32	12	25	22	30
1983–1984	18	8	22	21	20
1988–1989	17	14	30	30	30
1989–1990	14	11	14	39	26
Mean gale days per winter	14.03	40.59	32.68	19.48	20.80

frequency values were calculated for identical time intervals (e.g. December–February aggregate values). The lists of GA and GB winters were extended beyond the period of the Van Loon and Rogers (1978) analysis to 1990 using recent meteorological data conforming to the same criteria. Winter gale day frequency values were thus calculated for GB and GA winters for Edinburgh, Stykkisholmur, Grimsey, Belmullet and Lerwick/Unst (Shetland Isles) (Tables 3 and 4).

Inspection of Tables 3 and 4show a clear difference between the two datasets with the winter gale day frequency values for all stations being much higher during GB rather than GA winters. For example, the mean winter gale day frequency value for Edinburgh for GB winters (14.03) contrasts with the lower value for GA winters (6.23). Similarly the gale day frequency values for Stykkisholmur are almost double the value in GB winters (40.59) than during GA winters (20.72). The Grimsey data for northern Iceland also exhibits a similar pattern with higher GB winter gale days frequency averages (32.68) compared with the GA winter average (14.83). In respect of Belmullet and the Shetland Isles, the contrast between higher storm frequency during GB winters and lower storm frequency during GA winters is also evident in the differences in the values between the two types of winter. Thus the values for Belmullet decrease from 19.48 (GB winter) to 9.21 during GA winters while the Lerwick/Unst data exhibits a difference between 20.80 (GB winters) and 13.27 (GA winters). Compar-

Table 4
Greenland above (GA) winters for the period 1840–1990 showing winter (December–February) gale day frequencies, together with mean values for Edinburgh, Stykkisholmur, Grimsey, Belmullet and Unst/Lerwick (Shetland Isles)

GA/Oslo below winters	Edinburgh	Stykkisholmur	Grimsey	Belmullet	Unst/Lerwick
1840–1841	9				
1846–1847	3	40			
1859–1860	1	57			
1860–1861	8	37			
1869–1870	5	59			6
1870–1871	6	58			11
1874–1875	8	33	9		15
1876–1877	12	28	30		23
1878–1879	6	41	14		6
1880–1881	9	54	8		3
1892–1893	4	13	17	6	7
1894–1895	3	35	15	21	7
1925–1926	8	7	25	–	1
1927–1928	16	9	25	6	11
1928–1929	3	7	22	2	10
1939–1940	0	5	6	7	15
1940–1941	7	7	5	–	13
1941–1942	16	8	15	–	30
1946–1947	1	5	10	–	26
1947–1948	0	3	13	–	12
1958–1959	0	18	17	–	33
1962–1963	3	7	13	11	7
1968–1969	12	12	8	10	13
1974–1975	1	15	24	26	26
1976–1977	3	3	14	0	6
1978–1979	1	8	16	5	8
1979–1980	2	9	24	10	18
1981–1982	16	9	15	11	17
1984–1985	7	9	5	3	10
1985–1986	17	5	6	11	11
Mean gale days per winter	6.03	20.72	14.83	9.21	13.27

Table 5
Winter air temperature departures from long-term average (°C) for Edinburgh and central England and winter gale day frequencies for Edinburgh, 1789–1835 (based on Mossman, 1895–1896, 1897–1898, 1902–1903)

	Edinburgh above average winter air temperatures (°C) (December–February) as departures from mean	Central England above average winter air temperatures (°C) (December–February) as departures from mean	Edinburgh gale days (after Mossman, 1895–1899)
1834–1835	+0.94	+0.98	4
1833–1834	+ *1.37*	+ *2.78*	26
1832–1833	+0.04	+0.25	10
1831–1832	+1.24	+0.35	9
1827–1828	+ *1.31*	+ *1.98*	21
1824–1825	+0.34	+0.52	22
1823–1824	+0.24	+0.85	12
1821–1822	+ *1.14*	+ *2.05*	18
1803–1804	+0.07	+0.62	6
1800–1801	+0.07	+0.48	11
1797–1798	+0.47	+0.38	15
1795–1796	+ *2.34*	+ *2.45*	10
1793–1794	+ *1.31*	+ *1.02*	12
1792–1793	+0.07	+0.15	14
1790–1791	+0.27	+0.68	16
1789–1790	+ *2.47*	+ *1.92*	11

Positive winter air temperature anomalies of greater than 1 °C are in italics.

ison of these observations with data for the late 18th and early 19th centuries can also be undertaken in respect of the meteorological analysis of Mossman for Edinburgh for the period 1789–1835 (Table 5). During this time interval, there were 16 winters during which higher than average winter air temperatures occurred both in the Edinburgh and central England temperature series. Of these, six winters were characterised by temperatures in both areas higher than 1 °C and were also associated with high winter gale frequencies (range between 10 and 26).

5. Discussion

There appears to be a clear link between GB winters and periods of increased winter storminess across the North Atlantic region. It would also appear that winters of decreased storminess generally coincide with GA winters. The analysis described here supports the arguments of Van Loon and Rogers (1978), in particular the notion that GB winters are generally characterised by increases in average air temperature across northern Europe while during GA winters there is a decrease in average air temperatures. The air temperature analysis undertaken here also points to an air temperature 'see-saw' between western Greenland and the UK in addition to the conventional 'see-saw' described by Van Loon and Rogers (1978) for Jakobshavn and Oslo.

Whereas GB winters are associated with cold northerly winds along the eastern flank of the Canadian anticyclone, GB winters are also associated with increased cyclone frequency across the North Atlantic region. It is considered that southwesterly winds associated with North Atlantic winter low pressure systems produce higher than average air temperatures across the North Atlantic region. This pattern of air circulation associated with GB winters is indicative of a positive NAO index (Fig. 1). In general terms, the most positive NAO index winters coincide with the most extreme GB winters. Conversely, GA winters appear to be associated with an expansion of winter high pressure across much of northern Europe and as a result there appears to be a coincidence of GA winters with decreased winter air temperature across the UK and a decrease in winter gale day frequencies.

The association of increased winter gale day frequency with GB winters and decreased winter gale day frequency with GA winters holds true irrespective of the type of gale day dataset used. The GB and GA differences are evident not only in the early 0–4 and 0–6 scales of gale day measurement, but they are also evident for the time intervals when both the simple Beaufort 0–12 scale of measurement and the more recent instrumental measurements of wind speeds have been used.

In their original analysis, Van Loon and Rogers (1978) maintained that in respect of long-term changes in winter air temperature and air pressure, the patterns of change were closely connected with changes in the frequency of air circulation types. We agree with this observation, and maintain that it is unlikely that the observed changes in both gale day frequency and air temperature are attributable to temporal changes in solar radiation or to the widely discussed concept of ‘global warming’. The results have implications in respect of our understanding of when, during historical times, individual stretches of coastline along the North Atlantic coastal margin have been particularly susceptible to accelerated coastal erosion. It is argued here that the reconstruction of winter storminess made here implies a relationship between the chronology of coastal erosion and the history of North Atlantic climate ‘see-saw’ dynamics. In a reconstruction of northern hemisphere tropospheric circulation using Greenland ice core chemistry data, Meeker and Mayewski (2002) identified a major reorganisation in atmospheric circulation that took place ca. AD 1420. During the preceding Medieval Warm Period, winter storminess across the North Atlantic was at a minimum. By contrast, the time interval from ca. AD 1420 until present has been associated with cells of winter Icelandic low pressure that have been strongly anchored within northern hemisphere circulation. A consequence of this profound reorganisation of tropospheric circulation has been a sustained increase in the frequency and severity of North Atlantic winter storms and a corresponding increase in coastal erosion and sand drift.

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References

Barlow, L.K., 1994. Evaluation of seasonal to decadal scale deuterium and deuterium excess signals, GISP2 ice core, Summit, Greenland, AD 1270–1985. Unpublished PhD thesis. University of Colorado, Boulder, 290 pp.

Barlow, L.K., Rogers, J.C., Serreze, M.C., Barry, R.G., 1997. Aspects of climate variability in the North Atlantic sector: Discussion and relation to the Greenland Ice Sheet Project 2 high-resolution isotopic signal. Journal of Geophysical Research 102 (C12), 26333–26344.

Crantz, D., 1765. Historie von Gronland. Barby und Leipzig. (English translation: History of Greenland, 2nd ed., 2 vols., Longman, London, 1820).

Dawson, A.G., Hickey, K.R., McKenna, J., Foster, I.D.L., 1997. 200-year record of gales frequency, Edinburgh, Scotland: possible link with high magnitude volcanic eruptions. Holocene 7 (3), 337–341.

Dawson, A.G., Elliott, L., Mayewski, P., Lockett, P., Noone, S., Hickey, K., Holt, T., Wadhams, P., Foster, I.D.L., 2003. Late-Holocene North Atlantic climate ‘seesaws’, storminess changes and Greenland ice sheet (GISP2) palaeoclimates. Holocene 13, 381–392.

Günther, H., Rosenthal, W., Stawarz, M., Carretero, J.C., Gomez, M., Lozano, I., Serano, O., Reistad, M., 1998. The wave climate of the Northeast Atlantic over the period 1955–94: the WASA wave hindcast. Global Atmosphere and Ocean System 6, 121–163.

Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperature and precipitation. Nature 269, 676–679.

Hurrell, J.W., van Loon, H., 1997. Decadal variations in climate associated with the North Atlantic Oscillation. Climate Change 36, 301–326.

Jones, P.D., Jonsson, T., Wheeler, D., 1997. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. International Journal of Climatology 17, 1433–1450.

Lamb, H.H., 1991. Historic Storms of the North Sea, British Isles and Northwest Europe. Cambridge Univ. Press, Cambridge, 204 pp.

Manley, G., 1974. Central England temperatures: monthly means 1695 to 1973. Quarterly Journal of the Royal Meteorological Society 100, 389–405.

Meeker, L.D., Mayewski, P.A., 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. Holocene 12, 257–266.

Meteorological Office, 1991. Meteorological Glossary. HMSO Publication, London. Meterological Office, 985, 335 pp.

Mossman, R.C., 1895. The meteorology of Edinburgh: Part 1. Transactions of the Royal Society of Edinburgh 38, 681–756.

Mossman, R.C., 1897. The meteorology of Edinburgh: Part 2. Transactions of the Royal Society of Edinburgh 39 (63-175), 476–483.

Mossman, R.C., 1902. The meteorology of Edinburgh: Part 3. Transactions of the Royal Society of Edinburgh 40, 469–510.

Rogers, J.C., 1997. North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe. Journal of Climate 10, 1635–1647.

Van Loon, H., Rogers, J.C., 1978. The seesaw in winter temperatures between Greenland and Northern Europe: Part I. General description. Monthly Weather Review 106, 296–310.