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# AN ANALYSIS OF ICELANDIC CLIMATE SINCE THE NINETEENTH CENTURY

EDWARD HANNA,<sup>a</sup>\* TRAUSTI JÓNSSON<sup>b</sup> and JASON E. BOX<sup>c</sup>

<sup>a</sup> Department of Geography, University of Sheffield, Sheffield, UK <sup>b</sup> Icelandic Meteorological Office, Reykjavik, Iceland <sup>c</sup> Byrd Polar Research Center, The Ohio State University, Columbus, OH, USA

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#### ABSTRACT

New, long monthly series of Icelandic air pressure, temperature, precipitation and sunshine data are presented and analysed to determine possible evidence of recent climatic changes in Iceland. Climatic series are compared with the North Atlantic oscillation (NAO) indices; Icelandic temperature and precipitation are moderately but significantly correlated with the NAO. An updated south-north Iceland temperature index is discussed in relation to 20th century reductions in seaice coverage. Net warming over Iceland occurred over all long-term records from the mid19th century to the present, consistent with observed global warming trends, but superimposed on this was a marked cooling between the 1940s and early 1980s; Icelandic warming resumed around 1985. The mid-late 20th century cooling is in agreement with observed cooling in southern Greenland, suggesting that large-scale changes in atmospheric circulation were probably responsible. The 1930s was the warmest decade of the 20th century in Iceland, in contrast to the Northern Hemisphere land average. There was a distinct 20th century dipole in temperatures between Iceland and northwestern Europe, with 1941 serving as an extreme year, i.e. cold Europe and warm Iceland and Greenland. There are also signs of a precipitation increase since the late 19th century, although this is significant for only one out of three stations. Moreover, precipitation rates exhibit a positive correlation with temperature. There were no statistically significant overall long-term changes in pressure or sunshine duration. However, there are statistically significant negative correlations of precipitation with the sunshine data. There is evidence of possible solar forcing of Icelandic temperature and pressure. Results from the analysis aid our understanding of recent and ongoing changes in Icelandic and North Atlantic climate. The results should help us interpret these changes in the context of larger scale atmospheric/subpolar variability and future climate-change predictions. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: Iceland; climatic change; global warming; temperature; precipitation; North Atlantic oscillation; homogenization

# 1. INTRODUCTION

Iceland, located in a climatically critical part of the North Atlantic, is an island where earth, air, fire and ice literally meet, and its environs are a key region of ocean-atmosphere interaction, atmospheric dynamics and cyclogenesis (Wang and Rogers, 2001) (Figure 1). As such, Icelandic climate is sensitive to changes in storm tracks and positions. Moreover the northwest coast of Iceland lies only  $\sim$ 400 km from Greenland, so Iceland can be climatically influenced by this huge land/ice mass nearby, although it is more often affected by relatively mild Atlantic Ocean currents. Sea ice in the Greenland Sea sometimes extends south to the north Icelandic coast in winter, lowering regional temperatures (Bergpórsson, 1969; Ogilvie *et al.*, 2000). Iceland has large, temperate glaciers, which are more sensitive to temperature changes than frozen-bed glaciers (Björnsson, 1996). Here, we report some of the significant available Icelandic instrumental climate records

<sup>\*</sup>Correspondence to: Edward Hanna, Department of Geography, University of Sheffield, Winter Street, Sheffield S10 2TN, UK; e-mail: e.hanna@sheffield.ac.uk



Figure 1. Map of Icelandic and other meteorological stations used in the analysis; includes sea-level pressure hPa 2002 annual mean from the National Centers for Environmental Prediction Operational Dataset (source: http://www.cdc.noaa.gov/HistData/), showing prevailing cyclonic conditions over and around Iceland

for the first time in an English-language journal, and we also analyse and discuss the data in the context of recent (sub-) Arctic/global climatic change.

#### 2. PRESSURE

An updated form of the southwest Iceland pressure series (Jones *et al.*, 1997) is presented. The monthly series combines data from Reykjavik and nearby Stykkishólmur (Figure 1) and spans 1820–2002. Annual means are shown in Figure 2. As might be expected with the vigorous North Atlantic circulation, there is a distinct seasonal cycle in atmospheric pressure in Iceland, with winter minima: the month with the lowest mean pressure was January at 998.7 hPa; the highest was May at 1013.2 hPa. There are coherent semi-decadal oscillations in pressure, as indicated by running means (Figure 3). Similarly, the variance changes with time on a semi-decadal basis (Figure 3). Spectral analysis shows no single dominant peak, but the 12 year peak is suggestive of solar activity, which is known to have an 11 year period, and is suggested in an 11.6 year period found in the GRIP ice core in Greenland (Johnsen *et al.*, 1997) (Figure 4). Perhaps surprisingly, despite the long period, there were no significant overall trends for either the annual averages or any of the months. However, in recent decades, the winter low-pressure season has lasted longer and ended later, and this was linked with a positive tendency in the North Atlantic oscillation (NAO) from the 1960s to 2000 (Jónsson and Miles, 2001).

### 3. TEMPERATURE

The Reykjavik continuous temperature record begins in 1871, with another continuous series from 1822 to 1854 (Jónsson and Gardarsson, 2001). Stykkishólmur has the longest running and most uniform temperature record in Iceland. Continuous observations at Stykkishólmur date to 1845. The early Reykjavík data have been used to reconstruct the Stykkishólmur series back to 1823 (Jónsson, 1989). Other long-term records are presented for Vestmannaeyjar on the south coast, Grímsey (a small island off the north coast) and Teigarhorn, in the eastern fjords (Table I, Figure 1). Eythorsson (1949) and Jónsson and Gardarsson (2001) include detailed discussions of early Icelandic temperature records. Annual averages of these series were compared over the

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Figure 2. Southwest Iceland pressure annual series, 1823-2002, with the 10 year running mean



Figure 3. The 14 year running mean and variance of southwest Iceland pressure (faint dashed line) and Stykkishólmur temperature (solid grey line)

post-1870 period to validate their homogeneity. The results indicate high correlations ( $r \sim 0.9$ ; Figure 5). Data homogenization is partly based on the original approach by Sigfúsdóttir (1969), in which emphasis is on the consistency of the averaging method throughout the series, as well as on comparison with data from neighbouring stations, allowing adjustments to be made to the primary series. Data from Akureyri (an important town in the north of Iceland) might be of significance but have not yet been fully homogenized, and so have been excluded from this analysis. Temperature variance in the pre-1900 part of the Stykkishólmur record is much greater than the 20th century period, consistent with a more irregular sea-ice influence noted by Ogilvie and Jónsson (2001) (Figure 3).



Figure 4. Power spectrum of 180 years of southwest Iceland pressure data (1823-2002)

WMO ID	Site name	Latitude N	Longitude W	Elevation (m)	Earliest year <sup>a</sup>	Latest year
04005	Bolungarvik <sup>b</sup>	66°10′	23°15′	5	1898 T	2002
04013	Stykkisholmur	65°05′	22°44′	21	1823 T	2002
	•				1857 P	
04030	Reykjavik	64°08′	21°54′	52	1871 T	2002
04048	Vestmannaeyjar	63°24′	20°17'	118	1878 T	2002
					1881 P	
04065	Grímsey	66°32′	18°01′	16	1874 T	2002
04072	Fagurholsmyri	63°53′	16°39′	46	1898 T	2002
04092	Teigarhorn	64°41′	14°21′	21	1873 T, P	2002

Table I. Summary of Icelandic meteorological data used in this study

<sup>a</sup> T: temperature; *P*: precipitation.

<sup>b</sup> The Bolungarvik temperature series is actually a composite one; there are four stations in the area, including Ísafjöour, Holt and Galtarviti, that are involved in the reconstruction.

Table II lists long-term means and standard deviations (SDs) for 1878-2002 for selected stations. At most stations, the mean January temperatures are around or slightly below freezing and the mean July temperatures are around 8-10 °C. Unsurprisingly, the mildest station is Vestmannaeyjar and the coldest Grímsey. However, Reykjavik has the warmest temperatures in summer. Interannual variability in temperature is at least twice as great in winter as in summer, given the more variable and vigorous winter atmospheric circulation around Iceland (Serreze *et al.*, 1997).

Trend statistics for various time periods, including 'standard normal' periods, are given in Table III. Trends were calculated from least-squares linear regression, the slope coefficient of which was multiplied by the number of years in a record to get the underlying trend-line change over the period. The statistical significance of trend slopes was measured as 1 - p after Box (2002). Trends were calculated for a given period if at least 85% of data were present. Results from locations in Europe, the North Atlantic, and Greenland are included to indicate regional variations. These are based on the latest homogenized temperature data from Box (2002) for Tasiilaq/Ammassalik and Nuuk/Godthåb in Greenland, NARP2000 for Torshavn and Copenhagen (Jørgensen 2001), and Tuomenvirta *et al.* (2001) for Oslo and Stockholm.



Figure 5. Annual mean temperature at Reykjavík, Stykkishólmur and Teigarhorn, 1873–2002, with their 10 year running means. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

Over the long term, 1871–2001, most Icelandic station records (except Grímsey in summer) indicate statistically significant warming in all seasons. The length of the seasons (the conventional 3 months each season here) is different from the Icelandic custom, so the ranking of warm and cold seasons does not conform to the publications of the Icelandic Meteorological Office. The main reason is that it is considered preposterous to include March as a spring month in Iceland, as it is quite often the coldest month of the year. Therefore, it is always considered a part of the winter (December to March). The Icelandic spring is only 2 months long (April and May), as is the autumn (October and November). The long summer is defined as June to September. Vestmannaeyjar warmed the most, by 1.61 °C or by more than twice the SD over 1871–2001. Summer trends are of interest for glacier mass-balance forcing, and the trends in other seasons are also of interest for permafrost and active-layer transformations. The warming was non-uniform in time, occurring in three distinct phases, approximately from 1880 to 1900, from 1925 to 1940, and from 1983 to 2001. Warming was most rapid in 1919–33, reaching the maximum temperatures over the entire record in 1939 and 1941. The northwestern European records surveyed do not indicate any significant trends over the 1901–30 standard period, whereas Icelandic trends are highly significant (Table III), somewhat indicating a decoupling between the Icelandic and northwestern European climates. This may at least be partly due to a reduced sea-ice cover around Iceland and consequent sea-ice forcing (see Section 6), as sea ice is responsible for many key climatic feedbacks — many of them positive (e.g. see Hanna (1996)). Moreover, the most significant Icelandic trends during 1901-30 are for winter and spring, when sea-ice incidence in the area decreased markedly.

Trends for the standard century 1901–2000 are presented in Table III for comparison with results from other sites over this period. There are some statistically significant positive Icelandic temperature trends over this period, mainly in summer but also annually. These are consistent with warming trends observed at northwestern European sites. The strongest period of Icelandic warming, roughly from 1919 to 1933, is characterized by largest increases of temperatures during spring, e.g.  $3.4 \,^{\circ}$ C at Reykjavik. The 1930s warming was followed by cooling between about 1940 and the early 1980s, concentrated in summer over the 1931–60 standard normal period. Over the 1984–2001 period the trends are consistently positive and statistically significant only in autumn. Thus, in some sense, Iceland did share in this recent period of warming that was observed for the Northern Hemisphere average, whereas the cooling between the 1930s and ~1980 is not so consistent with the global average (Houghton *et al.*, 2001). Some of the coldest years and seasons of the 20th century were in the late 1970s and early 1980s (especially 1979, 1983 and 1981; Table IV). There is a difference of ~3 °C between the coldest and warmest years in Reykjavik, and 6 °C between the coldest

	Ţ	able II. Icel	andic annual	and monthl	ly temperatu	re means (	standard dt	eviations in	parentheses	() for 18/8	-2002		
Site						Mean te	mperature	(°C)					
	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Stykkishólmur Reykjavik Vestmannaeyjar Grímsey Teigarhorn	3.6 (0.8) 4.3 (0.7) 4.9 (0.6) 2.3 (1.0) 3.7 (0.8)	$\begin{array}{c} -1.2 \ (2.2) \\ -0.6 \ (2.0) \\ 1.2 \ (1.6) \\ -1.3 \ (2.4) \\ -0.2 \ (2.0) \end{array}$	$\begin{array}{c} -1.3 \ (2.2) \\ -0.4 \ (1.9) \\ 1.3 \ (1.6) \\ -1.6 \ (2.2) \\ -0.1 \ (1.8) \end{array}$	$\begin{array}{c} -0.9 \ (2.3) \\ 0.3 \ (2.1) \\ 1.6 \ (1.8) \\ -1.9 \ (2.6) \\ 0.2 \ (2.3) \end{array}$	$\begin{array}{c} 1.4 \ (1.7) \\ 2.8 \ (1.5) \\ 3.3 \ (1.3) \\ -0.3 \ (1.8) \\ 1.9 \ (1.6) \end{array}$	4.9 (1.5) 6.2 (1.3) 5.9 (1.0) 2.7 (1.6) 4.4 (1.4)	8.2 (0.9) 9.2 (0.8) 8.3 (0.7) 5.8 (1.4) 7.0 (1.1)	$\begin{array}{c} 10.1 \ (0.9) \\ 10.8 \ (0.9) \\ 10.0 \ (0.7) \\ 7.7 \ (1.5) \\ 8.6 \ (1.0) \end{array}$	9.6 (1.0) 10.3 (0.9) 9.8 (0.8) 7.6 (1.4) 8.7 (1.0)	7.3 (1.3) 7.7 (1.4) 7.7 (1.1) 5.8 (1.3) 7.2 (1.1)	4.0 (1.5) 1 4.3 (1.6) 1 4.9 (1.3) 2 3.0 (1.5) ( 4.3 (1.5) 1		-0.5 (1.) -0.1 (1.) 1.5 (1.6 -0.6 (1.5 0.3 (1.8

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Site and time period	Region <sup>b</sup>	Winter	Spring	Summer	Autumn	Annual
1871-2001						
Revkiavik	I	1.5	1.0	0.5	0.9	0.98
Teigarhorn	I	1.4	1.9	1.4	1.3	1.48
Grímsev	I	1.4	0.6	-0.1	0.9	0.74
Vestmannaeviar	I	2.1	2.3	1.1	1.0	1.61
Tórshavn	NA	0.2	0.3	0.1	07	0.34
Copenhagen	FU	10	2.0	12	2.0	1 78
Oslo	FU	0.6	2.0	-0.4	0.8	0.51
Stockholm	EU	0.0	2.1	-0.4	11	1 33
1001_30	LU	0.9	2.1	1.1	1.1	1.55
Tasiilaa/Ammassalik	G	37	31	0.0	0.6	2 22
Paykiovik	U I	J.7 1.8	J.4 15	0.9	0.0	0.72
Toigarhorn	I	1.0	1.5	0.4	-0.8	0.72
Crímsov	I	1.0	1.5	1.2	-0.0	0.95
Vector	I	1.0	1.0	0.2	-0.0	1.41
Tárahaun		2.3	2.2	1.5	-0.1	1.41
Torsnavn		1.0	0.3	0.5	-0.5	0.28
Copennagen	EU	0.5	0.5	-0.4	0.7	0.35
	EU	0.5	0.2	-1.1	-0.1	-0.14
Stockholm	EU	0.0	0.6	0.1	0.1	0.18
1901–2000	G	0.5	0.0		0.5	0.10
Tasiilaq/Ammassalik	G	0.5	-0.3	-0.7	0.5	0.10
Reykjavík	I	0.4	0.4	0.0	0.1	0.22
Teigarhorn	I	0.2	0.7	0.7	0.4	0.48
Grímsey	Ι	0.5	0.1	-0.4	0.2	0.10
Vestmannaeyjar	Ι	1.1	1.1	0.6	0.7	0.87
Tórshavn	NA	0.2	0.5	0.4	0.5	0.39
Copenhagen	EU	1.3	1.6	1.1	1.5	1.36
Oslo	EU	0.0	0.8	0.1	0.8	0.44
Stockholm	EU	0.0	0.9	0.6	0.6	0.53
1931–60						
Tasiilaq/Ammassalik	G	-0.5	-0.9	-0.9	0.4	-0.47
Reykjavik	Ι	-0.8	0.1	-0.2	0.6	-0.09
Teigarhorn	Ι	0.1	0.4	-0.7	0.9	0.19
Grímsey	Ι	-0.9	0.0	-0.5	0.5	-0.22
Vestmannaeyjar	Ι	0.3	0.5	-0.9	1.0	0.24
Tórshavn	NA	-1.0	0.6	-0.2	0.6	0.01
Copenhagen	EU	-0.1	0.1	-0.4	0.4	0.03
Oslo	EU	-1.4	0.2	-0.4	0.0	-0.38
Stockholm	EU	-0.8	0.0	-0.7	0.2	-0.35
1961–90						
Tasiilaq/Ammassalik	G	0.0	-0.9	-0.8	0.7	-0.28
Reykjavik	Ι	-0.8	-1.4	-0.2	-0.3	-0.69
Teigarhorn	Ι	0.0	-0.2	0.6	-0.2	0.05
Grímsey	Ι	-0.6	-1.0	-0.1	-0.1	-0.45
Vestmannaeviar	Ι	0.1	0.5	0.8	0.2	0.41
Tórshavn	NA	0.3	-0.3	0.2	0.2	0.12
Copenhagen	EU	1.4	1.0	0.5	-0.4	0.65
Oslo	EU	2.0	1.0	0.3	-0.2	0.79
Stockholm	FU	13	11	-0.2	-0.4	0.45
	20			5.2	5.1	0.15

Table III. Regional temperature trends over various periods, including standard periods<sup>a</sup>

<sup>a</sup> Trends with statistical significance at or above 90% are in bold. Italic bold values indicate significance at or above 99%.

<sup>b</sup> EU: Europe; G: Greenland; I: Iceland; NA: North Atlantic.

Site/season	С	oldest 5 y	ears (colo	dest on let	ft)	Wai	mest 5 ye	ears (warr	nest on ri	ght)
Reykjavik										
Winter	1918	1936	1955	1920	1981	1946	1932	1972	1929	1987
Spring	1979	1920	1914	1924	1951	1928	1960	1929	1964	1974
Summer	1983	1921	1922	1907	1992	1934	1933	1950	1941	1939
Autumn	1917	1981	1923	1907	1926	1915	1939	1945	1941	1958
Annual	1979	1919	1907	1983	1903	1964	1933	1945	1939	1941
Grímsey										
Winter	1918	1902	1936	1969	1981	1991	1953	1929	1946	1972
Spring	1902	1968	1979	1914	1967	1928	1929	1960	1964	1974
Summer	1915	1907	1902	1903	1979	1934	1955	1953	1933	1939
Autumn	1917	1923	1919	1963	1981	1945	1960	1959	1958	1941
Annual	1902	1918	1917	1907	1979	1933	1953	1960	1939	1941
Teigarhorn										
Winter	1918	1936	1966	1902	1981	1953	1948	1946	1929	1972
Spring	1979	1919	1968	1906	1902	1960	1939	1929	1964	1974
Summer	1907	1902	1903	1922	1918	1926	1934	1984	1995	1933
Autumn	1917	1919	1969	1981	1923	1960	1961	1945	1941	1958
Annual	1979	1902	1907	1969	1968	1945	1953	1946	1960	1972
Tasiilaq/Ammassalik										
Winter	1918	1920	1971	1905	1981	1947	1926	1932	1946	1929
Spring	1990	1914	1969	1906	1983	1941	1945	1939	1923	1929
Summer	1983	1992	1970	1987	1989	1950	1933	1936	1947	1932
Autumn	1917	1923	1904	1971	1907	1945	1960	1915	1939	1941
Annual	1910	1983	1971	1907	1981	1932	1941	1928	1939	1929
Tórshavn										
Winter	1955	1979	1906	1995	1918	1953	1972	1992	1932	1934
Spring	1924	1995	1979	1917	1906	1964	1959	1991	1960	1974
Summer	1907	1902	1993	1928	1922	1947	1984	1955	1960	1933
Autumn	1919	1923	1917	1969	1973	1953	1920	1959	1958	1945
Annual	1919	1979	1917	1902	1907	1946	1933	1991	1953	1959
Copenhagen										
Winter	1940	1942	1963	1947	1941	2000	1975	1974	1989	1990
Spring	1942	1909	1917	1924	1941	1921	2000	1989	1993	1990
Summer	1902	1907	1987	1922	1928	1994	1975	1947	1992	1997
Autumn	1922	1905	1912	1902	1919	1999	1934	2000	1938	1949
Annual	1942	1902	1940	1909	1922	1934	1975	1992	1989	1990
Oslo										
Winter	1941	1985	1917	1942	1940	1974	1932	1934	1989	1990
Spring	1909	1924	1917	1958	1962	1974	1993	1943	1921	1990
Summer	1928	1907	1962	1993	1987	1914	1901	1955	1947	1997
Autumn	1952	1915	1925	1902	1905	1953	1949	1938	1961	1999
Annual	1915	1985	1902	1942	1941	1975	1949	1934	1989	1990
Stockholm										
Winter	1985	1942	1940	1941	1970	1992	1934	1974	1989	1990
Spring	1917	1942	1902	1909	1955	1993	1989	1943	1990	1921
Summer	1902	1928	1987	1907	1962	1999	1969	1947	1901	1997
Autumn	1925	1952	1973	1915	1912	1934	1938	1961	1949	1999
Annual	1942	1902	1985	1941	1915	1938	1934	1990	1975	1989

Table IV. Ranking of coldest and warmest years over the standard century (1901-2000)<sup>a</sup>

<sup>a</sup> 1941 is in bold to illustrate the occasional dipole between Iceland/Greenland and northwestern Europe.

and warmest winters and springs. The 1990s was definitely *not* the warmest decade of the 20th century in Iceland, in contrast to the Northern Hemisphere land average (Houghton *et al.*, 2001). It was cooler than the 1930s by 0.45 °C for Reykjavik, 0.41 °C for Stykkishólmur and 0.16 °C for Teigarhorn. The overall coldest years occurred before 1900.

In an analysis of Greenland temperature records, Box (2002) lists 1939 and 1941 among the five warmest years and 1907 and 1983 among the five coldest years for the nearest site to Iceland, Tasiilaq, southeast Greenland. This is consistent with the results from Reykjavik (Table IV). Furthermore, this is consistent with the often-cited temperature dipole between Greenland and northwestern Europe (e.g. Van Loon and Rogers, 1978). Thus, 1941 was one of the coldest years of the 20th century in northwestern Europe, e.g. Copenhagen, Oslo, Stockholm (Table IV). 1983 was the 11th warmest year in Copenhagen, 13th warmest year in Oslo, and 18th warmest in Stockholm. However, other years do not exhibit the dipole: e.g. 1979 was cold both in Iceland and northwestern Europe (coldest year at Reykjavik and Teigarhorn and 9th coldest year in Oslo). 1907 was also rather cold, but not unusually so, in northwestern Europe.

The apparent dipole in temperature and the NAO is illustrated statistically in Table V. The Icelandic cooling from the 1940s to the 1980s is in broad agreement with a general cooling between the late 1950s and the 1990s observed in western and southern Greenland (Przybylak, 2000; Box, 2002; Hanna and Cappelen, 2003) and also agrees with the P.D. Jones/Hadley Centre data shown in Serreze *et al.* (2000) of a widespread cooling (or at least muted warming) over southern Greenland, Iceland and the northwestern North Atlantic. These regions experienced a prolonged and deeper mid-20th century cooling when compared with the global warming trend (e.g. Houghton *et al.*, 2001). The contrast is attributable to variations in the intensity of the Icelandic low and is thus linked to the NAO.

There is a weak, yet statistically significant negative correlation of Icelandic temperature anomalies and the NAO index for Reykjavik in all seasons (Table V). Consistent with Box (2002) for Greenland, a slightly better correlation of Icelandic temperatures is observed for the Azores–Iceland NAO index than the Portugal–Iceland station-based NAO index, so we use Azores–Iceland here. The Reykjavik correlations are very similar in magnitude to those in Tasiilaq, Greenland. There is apparently a strong gradient in the effect of the NAO across Iceland, so that Teigarhorn in the southeast has a weak but significant positive correlation of its temperature with NAO in summer. The pattern for adjacent regions, Greenland and northwestern Europe, is also indicative of the NAO. This inverse temperature pattern is also reflected in the Fagurholsmyri minus Bolungarvík/Ísafjörour (southeast minus northwest Iceland) temperature for the 20th century (Figure 6). Copenhagen and Nuuk temperatures are the latest homogenized annual values (Cappelen, 2003). The correlation coefficient between 10-year running means of the two series is 0.58. The fact that this relation shows up so clearly even on this small distance scale is indicative of the strong gradient in climate across Iceland from the southeast to the northwest.

Table V. Azores–Iceland (Rogers, 1997) NAO index correlation with temperature anomalies over the standard century, 1901–2000<sup>a</sup>

	Winter	Spring	Summer	Autumn	Annual
Nuuk/Godthåb	-0.62	-0.61	-0.25	-0.50	-0.50
Tasiilag/Ammassalik	-0.19	-0.23	-0.04	-0.28	-0.19
Reykjavik	-0.18	-0.23	-0.17	-0.26	-0.21
Grímsey	-0.23	-0.17	-0.06	-0.22	-0.17
Teigarhorn	0.09	-0.03	0.25	-0.04	0.07
Tórshavn	0.14	0.20	0.31	0.04	0.17
Oslo	0.56	0.53	0.25	0.55	0.47
Copenhagen	0.57	0.54	0.19	0.47	0.44
Stockholm	0.57	0.58	0.40	0.57	0.53

<sup>a</sup> Correlation coefficients with statistical significance at or above 90% are in bold. Italic bold values indicate significance at or above 99%.



Figure 6. Fagurholsmyri minus Bolungarvik/Ísafjörour (southeast minus northwest Iceland) and Copenhagen minus Nuuk temperature compared, 1898–2002. Copenhagen and Nuuk temperature are from Cappelen (2003). This figure is available in colour online at http://www.interscience.wiley.com/ijoc

The pre-20th century extremes (Table VI) do not appear to exhibit as clear a dipole as has appeared in standard 20th century data (Table IV). We speculate that this missing signal may be due to changes in causal mechanisms, including much weaker anthropogenic forcing in the 19th century. The overall coldest years occurred in 1859 and 1866 in the longer (1823–2002) Stykkisholmur record. These temperature minima coincide with the latter of two temperature minima (~1850) that define the Little Ice Age, as measured by Greenland Ice Sheet borehole temperatures (Dahl-Jensen *et al.*, 1998). The earlier minimum near AD 1500 was roughly 0.2 °C warmer than the ~1850 minimum. The 1850s and 1860s were also periods of relatively few and declining sunspots and presumed low solar activity, which might perhaps partly explain this cold period (e.g. Crowley, 2000). The 11-year running means of Stykkishólmur temperature and sunspot numbers, 1828–1997, are significantly correlated (r =0.47; sunspot numbers were obtained from the National Geophysical Data Center, Boulder, CO, USA: ftp://ftp.ngdc.noaa.gov/STP/SOLAR\_DATA/SUNSPOT\_NUMBERS/MONTHLY). No obvious temperature anomalies associated with volcanic signals were found in the Icelandic temperature data. This is consistent with the pattern implied by Box (2002) and Robock (2000) for Greenland, i.e. a strong volcanic signal in Baffin Bay but curiously not over southeast Greenland or Iceland.

Large-scale atmospheric changes were not the same during different parts of the period. The correspondence between semi-decadal oscillations and variance in southwest Iceland pressure and Stykkishólmur temperature is not coherent across the entire time series, though it has suggestive positive and negative correlation phases (Figure 3). The 1965–71 cold period was characterized by relatively high pressure and diminished warm-air advection, and also by the Great Salinity Anomaly (GSA). The GSA was a widespread freshening of the upper few hundred metres of the northern North Atlantic, which restricted convection and enhanced surface cooling (Dickson *et al.*, 1988; Serreze *et al.*, 1992). During 1979–83 and 1989–95, pressure was low and the

Site	(	Coldest 5	years (cold	lest on left	)	Wa	armest 5 y	ears (warn	nest on rig	ht)
Reykjavik	1886	1887	1885	1892	1979	1964	1933	1945	1939	1941
Grímsey	1881	1892	1882	1902	1886	1933	1953	1960	1939	1941
Teigarhorn	1881	1892	1888	1887	1882	1945	1953	1946	1960	1972
Copenhagen	1879	1888	1881	1942	1902	1934	1975	1992	1989	1990

Table VI. Ranking of coldest and warmest years over the 1873-2001 period

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low temperatures then were associated with expansion of the main polar vortex towards Greenland (causing the cooling there). These two 'modes' of cold weather in Iceland weaken the link between temperature and the NAO in Iceland; the NAO was weak in the late 1960s but strong during the later periods. So, Iceland can experience cold temperatures at both ends of the NAO scale.

#### 4. PRECIPITATION

The Icelandic Meteorological Office has three precipitation records extending back to the late 1800s (Jónsson, 1994). Reykjavik is not one of these. Although precipitation measurements started there in 1884, a lapse of observations occurred from 1907 to 1920, which can be partly filled with information from a station nearby. The Reykjavik station has been moved repeatedly around the town, giving especially poor data homogeneity, particularly due to the 1931 site relocation from a very sheltered backyard to a relatively exposed rooftop (Jónsson, 2003). There were nearby precipitation measurements for comparative purposes during some of the relocations, but site-to-site differences are large. In the case of Vestmannaeyjar, off the southern coast, the station history is much less complicated and it has the most reliable and complete long-term precipitation record (1881–2002) Therefore, the Vestmannaeyjar record is used as the primary data set here. Its documented changes include:

- 1. a minor change in location in June 1906;
- 2. a change in the type of instrument in about 1915;
- 3. a major relocation in October 1921 (from the village to a lighthouse);
- 4. a wind shield added to the instrument in October 1957.

Sources for these changes are mainly original lists and correspondence in the archive of the Icelandic Meteorological Office, and the original correspondence for (2) cited in Brandt (1994). In addition to the above, the observers have been relatively few individuals. As there have been no attempts to correct the series, nor are there any gaps that have been artificially filled in, the Vestmannaeyjar series consists entirely of material that has been accessible in the publications of the Icelandic Meteorological Office and (prior to 1920) by the Danish Meteorological Institute (Jónsson, 2003). The two other long-running precipitation series are from Stykkishólmur (1857–2002) and Teigarhorn (1873–2002) (Figures 7 and 8, Tables I and VII).

The homogeneity of the precipitation records is, of course, questionable, but it is impossible to use 'standard' methods to correct them because the stations are so far apart. However, this does not mean that the data cannot be used, especially given the high value of such long records. The precipitation records are useful to indicate interdecadal variability and are more questionable for deriving long-term 'trends'. One may demonstrate that data homogeneity is a second-order problem if the variance is consistent between different stations through time, i.e. running variance plot, as in Box (2002). This is indeed the case: our graph looks very convincing, and the similarity of the different station profiles is at least a substantial argument for homogeneity (Figure 7).

Further support for homogeneity comes from examination of station metadata and comparison (where possible) with neighbouring stations. At Vestmannaeyjar, the major change is the gauge being moved from the village to the lighthouse. The lighthouse is much windier than the village and should, therefore, measure less precipitation. Continuous comparative measurements were made from 1965 to 1973. During this period the precipitation caught in the village was 97% of the amount at the lighthouse (Jónsson, 2003). Because the average difference was small (although individual monthly differences were much greater), and other possible error sources much larger, a bulk correction of the pre-1921 measurements was not considered. The Stykkishólmur station has been moved repeatedly, albeit within a radius of 1-2 km, so there are many possibilities for breaks, even recently. However, comparison with Reykjavik data shows a relatively constant ratio of ~0.7–0.9 (Stykkishólmur/Reykjavik precipitation).

Mean annual precipitation (1881–2002) was 1444 mm at Vestmannaeyjar, 1261 mm at Teigarhorn and 700 mm at Stykkishólmur. The heaviest precipitation usually occurs in southeasterly and southerly winds, so that Stykkishólmur, in the centre of the west of the country and north of a mountain barrier, is partly protected.



Figure 7. The 10 year running variance of precipitation at three Icelandic stations. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

Table VII.	Icelandic station precipitation means, SDs and least-squares linear regression trend-line changes,	1881 - 2002.
	Trends more than one SD are shown in bold	

Site	Annual	DJF	MAM	JJA	SON
Stykkishólmur					
Mean (mm)	699.8	218.1	138.3	122.7	220.8
SD (mm)	150.9	84.3	52.1	46.6	69.8
Trend-line change (mm)	58.0	20.2	50.0	12.2	-24.5
Vestmannaeyjar					
Mean (mm)	1443.5	419.3	312.0	279.6	433.1
SD (mm)	212.4	89.3	86.6	95.0	112.2
Trend-line change (mm)	307.9	49.8	93.1	122.4	42.8
Teigarhorn					
Mean (mm)	1260.5	381.1	249.3	246.2	383.8
SD (mm)	250.6	120.7	100.5	104.6	111.0
Trend-line change (mm)	101.0	-2.4	15.6	56.2	31.6

However, there are very large local effects due to complex topography, complicating any generalizations. Easterly winds are dry in the west but very wet in the east of Iceland. Winds directly from the west are usually dry, probably owing to the influence of Greenland, but southwesterly winds are wet in the west, south and the southeast, including Teigarhorn. So, Teigarhorn has a more favourable exposure to the wettest wind directions than Stykkishólmur but is not completely dry when there is a wet southwesterly wind. Vestmannaeyjar is exposed to many directions, so is the wettest of the three stations. Precipitation has a seasonal minimum in June (Vestmannaeyjar and Teigarhorn) or May (Stykkishólmur) and maximum in October, and this is reflected by the seasonal totals, which are lower in summer and higher in autumn and winter (Table VII).

Interannual variability was  $\sim 14-21\%$  of the mean values, and there is reasonable qualitative agreement between 10-year running means of the Stykkishólmur and Teigarhorn precipitation series, and less good agreement of either of these series with Vestmannaeyjar precipitation (Figure 8). The discrepancy between the Stykkishólmur and the Teigarhorn series on the one hand and the Vestmannaeyjar on the other hand is



Figure 8. Annual precipitation at Vestmannaeyjar, Stykkishólmur and Teigarhorn, 1881–2002, with their 10 year running means. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

very clear during three periods: (1) around 1980, when a dry period in Stykkishólmur and Teigarhorn is entirely absent in Vestmannaeyjar; (2) the years before 1920 are dry in Stykkishólmur and at Teigarhorn but not especially so in Vestmannaeyjar; (3) the high-precipitation era in the 1930s is 'delayed' in Vestmannaeyjar compared with the other stations. At Stykkishólmur there are many grounds for cases of homogeneity breaks. Precipitation records from Reykjavik and Eyrarbakki in the southwest are long term but broken; they mainly confirm the timing of many of the maxima and minima of the Teigarhorn and Stykkishólmur series.

There were overall positive trends at all three stations, but the increase is statistically significant only at Vestmannaeyjar, where the underlying trend line increases by 21% from 1881 to 2002. (There is a suggestion of a larger upward trend at Eyrarbakki.) Eythorsson (1949) found a concurrent increase of precipitation and temperature, 1857–1945, at Stykkishólmur. Here, Teigarhorn and Stykkishólmur temperature and precipitation, 1881–2002, are weakly but significantly positively correlated, i.e. r = 0.40 and 0.34 respectively. So, warm periods are significantly wetter on the whole, although ranking of period extremes is not the same for the two variables (Figure 9). However, at least part of the precipitation increase that we observe may be due to the introduction of wind shields in the 1950s and 1960s, and/or more of the precipitation falling as rain rather than snow (Førland and Hanssen-Bauer, 2000). The precipitation series are significantly negatively correlated with southwest Iceland pressure (Vestmannaeyjar, r = -0.22; Teigarhorn, r = -0.29; Stykkishólmur, r = -0.58), so the overall periods of lower pressure are wetter, although other factors obviously influence the amount of precipitation received.

There are relatively weak correlation coefficients of 0.45, 0.36 and 0.29 for annual precipitation at Teigarhorn, Vestmannaeyjar and Stykkishólmur respectively with the annual (Hurrell) NAO index; however, given the long records, these are statistically significant (p < 0.05). The NAO index used here was calculated by Dr Jim Hurrell (http://www.cgd.ucar.edu/~jhurrell/nao.stat.html) and is based on the difference of normalized sea level-pressure data between Ponta Delgada, Azores, and Stykkishólmur/Reykjavik, Iceland. Station data were originally obtained from the World Monthly Surface Climatology. Correlating monthly precipitation against Hurrell's monthly values of NAO gives the strongest results in February at Vestmannaeyjar and Teigarhorn (r = 0.51 and 0.51), and in March at Stykkishólmur (r = 0.31). These results suggest that the amount of precipitation is influenced by the state of the NAO, although correlations are relatively low and other factors are likely to be involved. Climatic change might be expected to change the position, intensity and frequency of storms, and hence the storm tracks, over Iceland (Serreze *et al.*, 1997), but this may only



Figure 9. Comparison of temperature and precipitation at Teigarhorn, 1873-2002, with their 10 year running means. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

partly be reflected in the precipitation data. Unfortunately, there is no similar long-term wind-speed record available from Iceland, which might shed further light on this question.

# 5. SUNSHINE AND CLOUD COVER

Cloud-cover records can serve as good indicators of possible causes of climatic change over the past decades; however, there are notable inconsistencies in cloud-cover observations/observers. There is also an observationtime bias. Monthly data regarding duration of bright sunshine in Reykjavik, 1923–2002, were readily available and considered more reliable (Figure 10). These were taken using a Campbell-Stokes sunshine recorder and show an extreme seasonal variation in mean monthly sun hours between 189.2 in May to just 9.7 in December. This range is due to the high latitude (64.1 °N; the maximum length of daylight in Reykjavik is about 21 h, but the maximum recordable sunshine per day is about 18 h (the sun is too low during the remaining 3 h to be registered). In December and January the sun is so low on the horizon (2.7° at the solstice) that it just barely registers on the recorder, even on a clear day). Evidently, there are more clear days in winter than in summer, and there is no apparent seasonal cycle of cloudiness. Mean annual sunshine was 1274 h (mean Reykjavik cloud cover 1971–2000 was 5.94 oktas). Interannual variations are relatively large, with SDs about 25–33% of the monthly totals in summer, rising almost to match the (very low) monthly totals in winter. There is no apparent secular trend in the Reykjavik sunshine record, either for the year or any month. There is no correlation between annual sunshine duration and temperature, or between sunshine and pressure. However, there are statistically significant negative correlations of Vestmannaeyjar, Teigarhorn and Stykkishólmur precipitation with the sunshine data (r = -0.50, -0.43 and -0.23 respectively).

# 6. VESTMANNAEYJAR-GRÍMSEY TEMPERATURE DIFFERENCE

Figure 11 features the temperature difference between the extreme south (Vestmannaeyjar) and the extreme north (Grímsey) of Iceland. This difference is used as an indicator of continentality of the island. In its form,



Figure 10. Reykjavik annual sunshine record, 1923-2002, with the 10 year running mean



Figure 11. Vestmannaeyjar-Grímsey (Icelandic south-north) annual mean temperature difference and Koch sea-ice index, with their 10 year running means. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

presented for March 1878–1999, this temperature index shows some qualitative agreement with the Koch index of sea ice around Iceland given by Ogilvie and Jónsson (2001); however, they did not present a direct statistical comparison. The Koch index measures residence time of sea ice near the Icelandic coast and the length of coast affected each year (Wallevik and Sigurjónsson, 1998). When ice is present along the northern coast, Iceland temporarily assumes a more continental-type climate; whereas southern coastal temperature anomalies are quite small (due to the proximity to the open ocean), temperature anomalies on the northern coast are much greater than normal, giving a large south–north temperature difference (Ogilvie and Jónsson, 2001). Such periods occurred in the late 19th century and late 1960s (Ogilvie and Jónsson, 2001). Here, we present an updated form of the temperature difference data for 1878–2000; former gaps in the March series are filled and series are now given for other months of the year. We also directly correlate temperature difference with the Koch ice index for the first time (Figure 11).

The mean annual Vestmannaeyjar–Grimsey temperature difference was 2.6 °C, with mean monthly values ranging from 1.9 °C in September to 3.7 °C in April; March, at 3.6 °C, was only marginally lower. Seasonal

Table VIII. Vestmannaeyjar–Grímsey (Icelandic south–north) temperature difference: means, standard deviations and least-squares linear regression trend-line changes for 1878–2000. Significant trends at the 0.1 level are shown in bold

	Annual	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean (°C)	2.57	2.49	2.95	3.55	3.65	3.25	2.51	2.38	2.20	1.89	1.94	1.92	2.10
SD (°C)	0.59	1.36	1.27	1.47	1.15	1.05	1.21	1.36	1.10	0.71	0.64	0.85	0.92
Trend-line change (°C)	-0.85	-0.84	-1.11	-1.75	-1.54	-1.34	-0.94	-1.25	-1.15	0.25	-0.02	-0.60	0.09

variation in this 'continentality index' reflects the late winter/early spring peak of sea ice near or around Iceland. There was a notable downward trend, of -0.9 °C, for the year as a whole, with particularly strong downward trends, of -1.3 to 1.7 °C, for the key spring months of March–May (Table VIII). This reflects an overall reduction of sea ice in Icelandic waters during the 20th century. Indeed, the Icelandic south–north annual mean temperature difference and sea-ice index for 1880–1990 are significantly correlated with r = 0.65. Greenland Sea sea-ice cover (which affects Iceland) experiences large interannual fluctuations due to frequent transient storms and their variations. However, widespread significant reductions of Arctic (including Greenland Sea) sea-ice cover have been reported for the past few decades and are linked with regional anomalies (warming) of surface temperatures (Comiso, 2002; Parkinson and Cavalieri, 2002).

# 7. CONCLUSIONS

The climatic data surveyed here suggest that Iceland experienced a warming of between  $\sim 0.7-1.6$  °C during 1871–2002, consistent with 20th century global warming trends (Houghton *et al.*, 2001). The warming was not gradual through time; rather, it was concentrated in the 1920s and 1930s and more recently from 1987 to 2002. There was a marked cooling from the 1940s to the 1980s, which is much more pronounced and prolonged than in the global temperature series. This result is perhaps no surprise, since regional amplitudes of change tend to be greater than global, but it is in line with other recent studies of climate change in this part of the (sub-) Arctic, and suggests that distinct changes in atmospheric circulation probably gave cooler conditions over Iceland. The warmest year in the 20th century Reykjavik record was 1941 and the coldest was 1979. The full 1873–2002 records indicate that the coldest years occurred before the 20th century, and 1859 and 1866 were very cold years. Warming resumed in the late 1980s and 1990s; however, as for Greenland, this was not the warmest period in Iceland.

On the whole, warmer periods seem to be wetter, and precipitation appears to have increased somewhat in line with the overall warming. However, the precipitation trends are less significant and the uncertainties are greater than with the temperature records, to some extent owing to precipitation sampling error. From changes in the south–north temperature difference, as well as in the ice index itself, sea ice around the Icelandic (north) coast seems to have become rarer over the past 120 years.

A clear correspondence of extreme temperatures in Iceland and southern Greenland exists. This includes the conclusion that the most recent decade of the 1990s does not contain the warmest annual temperatures. This is in contrast to global average temperatures. An inverse pattern of extreme temperatures is sometimes, but not always, observed for the 20th century when Icelandic temperatures are compared with northwestern European temperatures. These patterns are linked with variations in the intensity of the North Atlantic atmospheric circulation, as indicated by the NAO index. The NAO correlations are often highly suggestive, but less often statistically significant. Sampling errors and data inhomogeneities associated with station relocation are partly to blame for reduced resolution of causal mechanisms. The fact that Iceland lies near one dipole of the NAO is probably a major factor weakening correlation of its climate with the NAO. Also, the NAO index is a purely statistical measure, imperfectly representing the underlying physical mechanisms and causes. Nevertheless, the patterns of temperature, precipitation, pressure and sunshine, taken together, form a coherent picture of the regional atmospheric circulation, which is dominated by the Icelandic low.

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