Spatio-Temporal Distribution of Historical Extreme Winter Temperatures in England and Scotland – A Non-Stationary Extreme Value Analysis

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Abstract

Cold temperature extremes can have a detrimental effect on human health, public services and the economy of a country. From a public health services perspective, it is important to quantify the frequency of occurrence of extreme cold events and how this frequency changes over time in order to develop cost-effective anticipatory plans to reduce the potential impact of cold extremes on the exposed vulnerable population. Using non-stationary extreme-value analysis, the geographical and temporal distribution of cold temperature extremes over the last 160 years in several locations in England and Scotland was investigated. The temperature data were obtained from weather stations. It is then shown that the 5, 10, 50 and 100 year return levels of minimum winter temperature have increased throughout the 20th century. It was also shown that the probability of experiencing extreme cold temperatures has become very low in most locations particularly in years with a positive phase of the North Atlantic Oscillation (NAO) index. Finally, an estimate of the approximate financial risk to the UK economy of consecutive days of extreme cold temperatures is presented.

Keywords: *extreme cold temperature phenomena, health impacts of extreme cold temperatures and thresholds*

1. Introduction

Extreme weather events are, by definition, those that have low probability of occurrence but can have a high (or very high) impact on the ecosystem and biodiversity, agriculture, economy and public health (IPCC, 2012). There is strong evidence that extreme weather events such as heatwaves, droughts and intense precipitation periods, are becoming more frequent and intense worldwide (Easterling et al., 2000, Coumou and Rahmstorf, 2012) and are impacting ecosystem and human health (Field et al 2012). A rapid pace of development worldwide in the 20^{th} century leading to high amounts of greenhouse gases in the atmosphere, is a major contributing factor to an increased global mean temperature and it has been widely reported that the earth has been getting progressively warmer since the mid-20^{th} century (IPCC, 2014). Evidence indicates that this warming has been associated with an increased frequency of extreme climatic events (Rahmstorf and Coumou, 2011, Field et al, 2012). Despite this warming however there is evidence that extreme cold period will persist in the 21^{st} century (Guirguis et al 2011, Kodra et al 2011).

The extremes of temperature (hot and cold) can have detrimental acute as well as chronic impacts on public health and on many aspects of public services if the exposed vulnerable population and infrastructure are not protected. In particular, temperature extremes can have adverse effects on health (Huber et al 2017). To protect the exposed vulnerable population against temperature extremes, a country is required to invest in interventions to mitigate their impacts. Examples of such interventions in healthcare services could include developing temperature-triggered warning systems, anticipatory public services plans and responses (Kirch et. al., 2005).

With increasing demands on often over-stretched and limited public resources, it is imperative that these interventions are cost-effective in the long-term (Chalabi et al., 2016). Cost-effectiveness of the interventions would depend to a certain extent on the frequency and duration of extreme temperature episodes (Chalabi et al., 2016). There could be opportunity costs associated with the interventions if the extreme episodes are infrequent and far between, because the public funds could be invested elsewhere. It is important therefore to quantify the distribution of the extreme temperature episodes temporally and geographically.

The main purpose of this paper is to study changes in the frequency, return levels and return periods of extreme cold winter temperatures in England and Scotland over the last 160 years. It is known that the temperatures between the North of the United Kingdom and the South can vary greatly during different seasons. The North often experiences cold winters and generally cooler summers whereas the South tends to experience warmer winters and summers, in comparison. However a large body of research has recently pointed to an increased frequency of milder winters in UK as well as decrease in the number of very cold winter nights in the North (Vogelsang and Franses, 2005, Stainforth et al., 2013).

This paper begins by modelling the distribution of the extreme cold winter temperatures by analysing temperature readings in 12 weather stations across England and Scotland using: (i) a non- stationary block maxima method and (ii) a non- stationary peak over threshold method (Coles et al., 2001). Although both methods are related they provide complimentary information. The first method focuses on the annual cold extremes whereas the second method focuses on the daily cold extremes below a threshold and the day-to-day dependence of cold temperatures. Using the fitted models, we proceed to highlight the changes in the 5, 10, 50 and

100 year return levels of extreme cold temperature events as well as the probability of experiencing an extreme cold temperature event (characterised by the 85^{th}, 90^{th} and 95^{th} centile of the temperatures in each station) in any given year, and through time. These extreme temperature centiles differ from station to station where 95^{th} centile temperatures for stations in the north would be much lower than for stations in the south. Finally, an approximate financial risk to the UK economy of experiencing consecutive days of extreme cold temperatures is estimated.

2. Data and Exploratory Analysis

We used data from the UK's Met Office Integrated Data Archive System (MIDAS) (Met Office, 2006) which stores land surface and marine surface observations data from the Met Office station network and other worldwide stations. Data are available from 1853 and provide daily and hourly measurements of variables such as wind speed and direction, air and soil temperatures, rain fall measurements and other meteorological variables.

The observations of daily minimum temperatures were extracted for various locations of the MIDAS weather stations from December 1853 to February 2015. Although the accuracy of temperature measurements improved over time we did not take into account errors in temperature readings in our analysis and assumed that all the temperature readings were consistently accurate over time. For this analysis, only the three winter months of December, January and February (when the lowest temperatures are normally expected to occur) were extracted for each year. Winter of 1991-92, for example, comprised of December 1991 and January and February 1992. The temperatures of all the winter months were joined to form a long time series for each weather station.

Monthly values of the North Atlantic Oscillation (NAO) index from year 1825 to present were obtained from the Climatic Research Unit at the University of East Anglia (Hurrell, 1995, Jones et al., 1997, Climatic Research Unit (https://crudata.uea.ac.uk/cru/data/nao/). The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from Central North America to Europe. There is very strong evidence that the NAO index influences winter temperatures in the UK (Scaife et al., 2008 George et al., 2004, Woodworth et al., 2007, Osborn, 2011). A positive NAO index results in warm and wet winters in Europe and the negative index brings cold air towards Europe. Due to this, the NAO index was selected as an explanatory variable in the study of the distribution of winter temperature extremes in England and Scotland. We wished to separate the temporal variation of the historical winter extremes from the influence of the NAO acknowledging though that this approach cannot be used to investigate future temperature cold extremes because the NAO is not predictable.

Table 1 lists the names and the dates from which complete data is available for each of the weather stations. All of the 12 selected stations had at least 50 years of complete temperature data. For the purpose of our analysis, stations in Northern Ireland and Wales were excluded from this study due to large amounts of missing data in their temperature series records.

All further analysis present the results of two (Durham and Balmoral) of the 12 stations in the main body of this paper. All analyses' results of the remaining ten stations are provided in the Supplementary Material.

Table 1: MIDAS station details used in the analysis. The regional location, starting date and duration of each weather time series are given.

Station Name	**Location**	**Data start date**	**Length of series**

Oxford	South East	01/12/1853	162 years
Durham	North East	01/12/1880	135 years
Stornoway Airport	Scotland	01/12/1883	132 years
Rothampsted	East	01/12/1916	99 years
Balmoral	Scotland	01/12/1918	97 years
Leuchars	Scotland	01/12/1921	94 years
Wick Airport	Scotland	01/12/1930	85 years
Plymouth	South West	01/12/1930	85 years
Craibstone	Scotland	01/12/1931	84 years
Hastings	South East	01/12/1947	68 years
Eskdalemuir	Scotland	01/12/1954	61 years
Bude	South West	01/12/1959	56 years

Figures 1 and 2 show respectively the observed time series of the annual minimum winter temperature (AMWT) and the relationship between the AMWT and NAO for two of the stations in the study, Durham and Balmoral. The plots show the raw data (as dots) and a locally fitted polynomial regression line. Figures containing these data for each of the remaining 10 stations are given as part of the supplementary material (Figures 1A and 2A).

Durham exhibits a positive trend and Balmoral exhibits a convex quadratic trend in AMWT through time. Both stations were found to have a positive correlation between the NAO index and the AMWT, that is, higher the NAO index the higher the AMWT. In general the pattern of AMWT with time is inconsistent across locations unlike the pattern of AMWT with NAO which shows more consistent behaviour.

Additionally, as shown in Figure 1A in the supplementary material, of the six Scottish stations, four exhibit a non-linear trend in AMWT through time. Balmoral, Leuchars, Stornoway and Wick Airport all experienced a drop in AMWT between 1950 and 1970. On the other hand, Oxford, Hastings and Plymouth in the South of England and Durham in the North, exhibit a positive linear relationship between time and AMWT. Additionally, as Figure 2A in the supplementary material shows, all stations were found to have a positive correlation between the NAO index and the AMWT. The higher the NAO index the higher the AMWT. AMWT in Bude, Craibstone and Rothampsted were found to have significant association with the NAO than with time.

Figure 1: Observed time series of annual minimum winter temperature for Durham (1880-2015) and Balmoral (1918-2015).

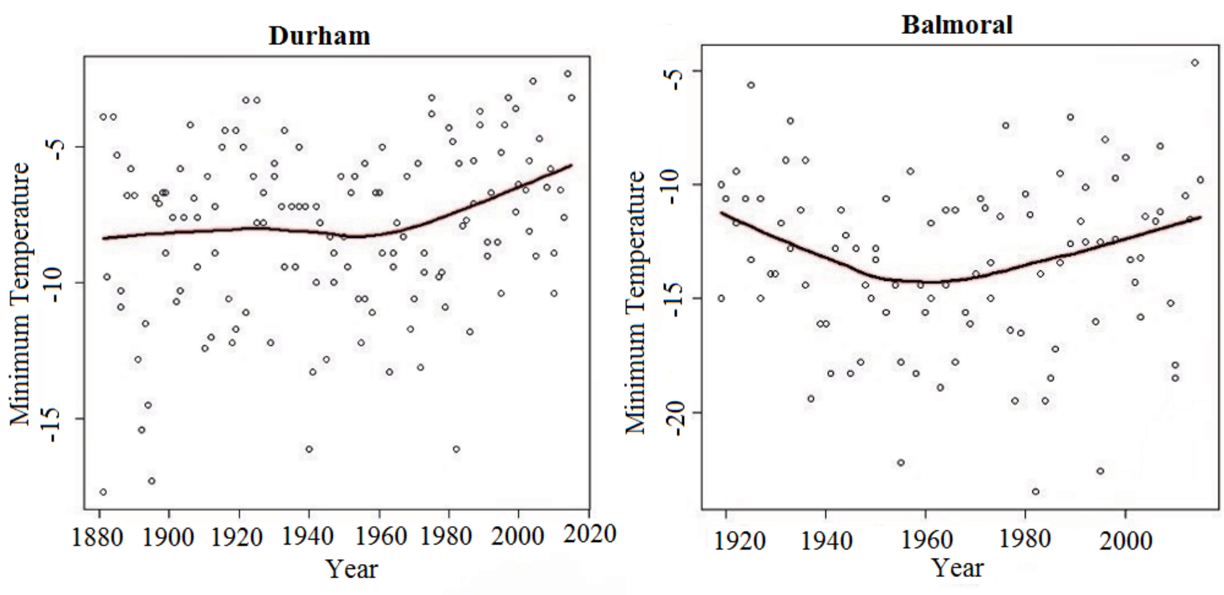
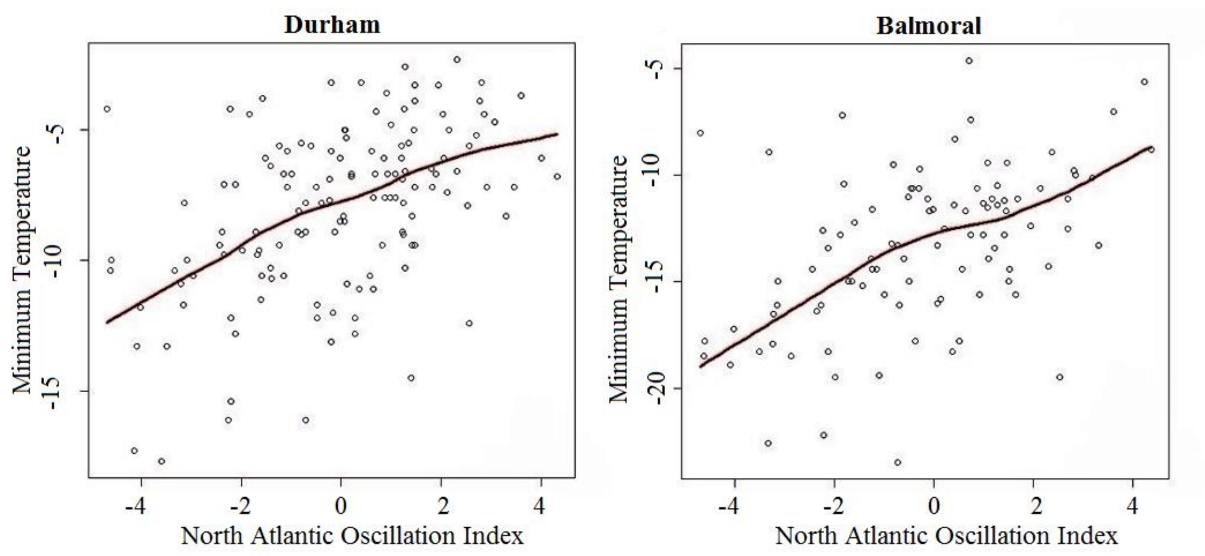


Figure 2: Observed relationship between annual minimum temperature and the NAO for Durham and Balmoral.



3. Methods

3.1 Generalised Extreme Value Distribution

From a climate physics perspective it could be argued that it would be more appropriate to estimate the Generalised Extreme Value (GEV) parameters using the Global Mean Temperature (GMT) as the dependent variable instead of time. However GMT is correlated positively with historical time and so as a first order approximation the GEV parameters were regressed against time, because it was simpler to conduct.

First the annual minimum temperatures were analysed. Although we are examining temperature minima in this section, we refer to the temperature maxima in the description of the methods and the equations, by taking the negative value of the minimum temperatures. This makes the equations easier to follow without compromising the analysis on the following grounds. If a temperature time series of length n is represented by the points $\{x_1, x_2, \dots x_n\}$ then its maximum over the period is defined by $y_{max} = max[x_1, x_2, \dots x_n]$ and its minimum by $y_{min} = max[-x_1, -x_2, \dots -x_n]$.In other words the maximum operator can be used in both definitions but in the case of the minimum, the sign of the temperatures are inverted. The correct temperature values (i.e. cold temperatures with their correct sign) are however presented in the numerical results, tables and figures.

The classical approach to perform an extreme value analysis is to fit the annual maxima values using the Generalized Extreme Value (GEV) cumulative distribution function, given by Equation (1) below and is defined on the set $\left\{T: 1 + \xi\left(\frac{T-\mu}{\sigma}\right) > 0\right\}$ and where T is the annual maximum temperature, parameters $\mu, \xi\ and\ \sigma$ denote respectively the mean, shape and scale of the distribution and $\mu, \xi\ \in\ \mathbb{R}$ (set of real numbers) and $\sigma \in \mathbb{R}_+$ (set of strictly positive real numbers).

$$G(T) = \exp\left\{-\left[1 + \xi\left(\frac{T-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\} \tag{1}$$

When ξ ≈ 0 the GEV distribution corresponds to the Gumbel family, conversely for ξ > 0 the Fréchet form is adopted and for ξ < 0 the Weibull form is adopted. The underlying assumption in the derivation of GEV is that the extreme values are independent and identically distributed, which is violated in the presence of a temporal trend. Since the exploratory analysis shows that the AMWT in all stations is non-stationary in time and also depends on the NAO index, a non-stationary GEV model is fitted to each station by making the parameters a function of time and NAO index. μ and σ are expressed as polynomial functions of time (t) and NAO index (z) as follows:

$$\hat{\mu} = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + b_1 z + b_2 z^2$$

$$\hat{\sigma} = c_0 + c_1 t + c_2 t^2 + d_1 z$$

$$\hat{\xi} = f_0$$

The parameters $\{a_0, a_1, a_2, a_3, b_1, b_2, c_0, c_1, c_2, d_1, f_0\}$ of the above distribution are estimated using maximum likelihood and probability weighted moments as defined in (Coles et al.,2001). The best model for each station was selected using likelihood ratio tests for nested non-stationary models (as described in Coles et al., 2001, Ch. 6)

3.2 Peak Over Threshold Analysis

The winter *daily extreme* cold temperatures were analysed using the Peak Over Threshold (POT) method which models all data that lie below a selected threshold. Naturally there is a relationship between the POT and block maximum method as both methods are modelling extremes. However, the POT method allows more efficient use of data by considering all values that lie above a high threshold rather than just the block maximum has been widely used to model extreme environmental events (Bommier 2014).

Again, as in the previous section, in describing the POT method we refer to the temperatures above a threshold (by taking the negative of the minimum temperatures) although in reality we are modelling cold temperatures below a threshold.

The peak over threshold or the POT method allows more efficient use of data by considering all values that lie above a high threshold rather than just the maxima of blocks. Details of the POT method are described elsewhere e.g. Coles et al (2001). A brief summary is provided below.

In order to simplify the mathematical notation, we redefine some of the mathematical symbols used in the description of the GEV method whilst ensuring that the two sections are self-consistent. Denote the daily temperature by T and its probability distribution function by F. There are two features to consider in the POT method: the number of exceedances in a given block (e.g. one year or one season) and the threshold excesses $\omega = T - u$, where u is the threshold. The POT method assumes that the number of exceedances, N, in a given block follows a poisson distribution as $N \sim Poisson(\lambda)$ and the threshold excesses follow a Generalised Pareto Distribution (GPD).

Given a high threshold u, the distribution function of $\omega = T - u$ i.e. the exceedance over the threshold conditional on $T > u$ is given by

$$F_u(\omega) = \mathrm{P}(\omega \leq v | T > u)$$

$$F_u(\omega) = \mathrm{P}(T - u \le v | T > u)\,, v \ge 0$$

$$F_u(\omega) = \frac{F(u+v) - F(u)}{1 - F(u)} \sim H_{\xi,\tilde{\sigma}}(\omega) \tag{2}$$

where P denotes probability and $H_{\xi,\tilde{\sigma}}(\omega)$is the GPD distribution. $H_{\xi,\tilde{\sigma}}(\omega)$ is given by:

$$H_{\xi,\tilde{\sigma}}(\omega) = 1 - \left(1 + \frac{\xi\omega}{\tilde{\sigma}}\right)^{-\frac{1}{\xi}}, if\ \xi \ne 0\ or\ H_{\xi,\tilde{\sigma}}(\omega) = 1 - \exp\left(-\frac{\omega}{\tilde{\sigma}}\right) if\ \xi = 0 \tag{3}$$

$$where\ \omega \ge 0\ if\ \xi \ge 0; 0 \le \omega \le -\frac{\tilde{\sigma}}{\xi}\ if\ \xi < 0;\ \tilde{\sigma} = \sigma + \xi(u - \mu)$$

The $\xi\ and\ \mu$ are exactly equal to the parameters of the corresponding GEV but the scale parameter of the GPD is a function of the location, scale and shape parameters of the corresponding GEV. As in the GEV distribution, $\xi < 0$, implies that the distribution of excesses has an upper bound (Weibull distribution), $\xi > 0$ implies unbounded upper tail (Frechet distribution) and $\xi = 0$ (Gumbel distribution) is also unbounded. Once again, as with the GEV analysis, the μ and σ are expressed as polynomial functions of time (t) and NAO index (z) for every station. The details of how the thresholds for each station were selected are given in section 4.3.

3.3 Return levels and cluster analysis

Of particular relevance to extreme events is the estimated return period.

The return period is given by:

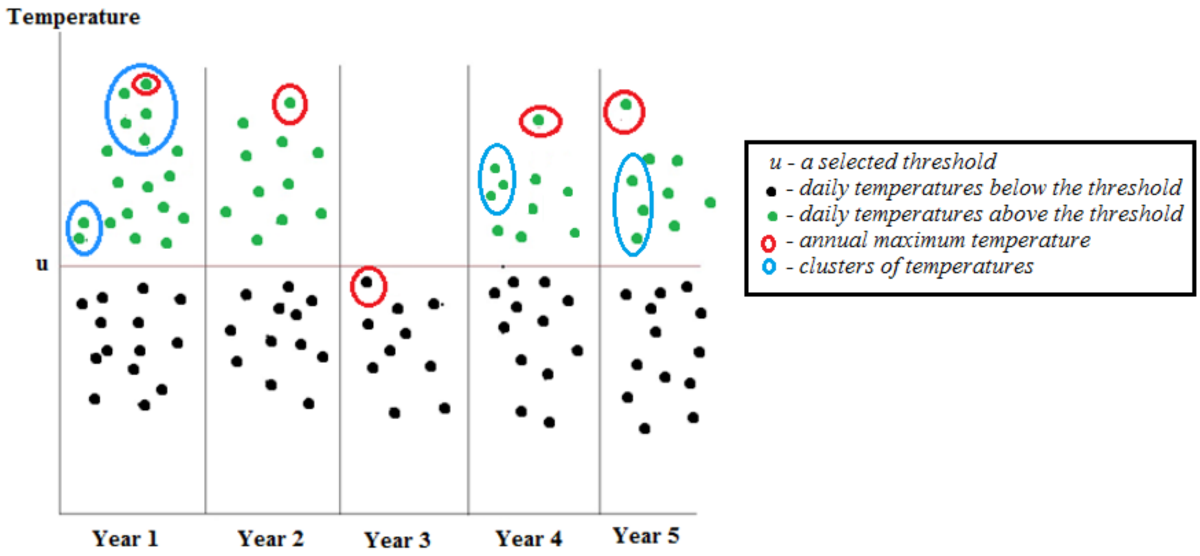
$$q_p(t,z) = \begin{cases} \mu(t,z) - \frac{\sigma(t,z)}{\xi(t,z)}\left[1 - \{-\log(1-p)\}^{-\xi(t,z)}\right], for\ \xi(t,z) \ne 0 \\ \mu(t,z) - \sigma \log\{-log(1-p)\}\,, for\ \xi(t,z) = 0 \end{cases} \tag{4}$$

In Equation (4) the parameters $\{\mu(t,z), \xi(t,z), \sigma(t,z)\}$ represent the mean, shape and scale parameters for a non-stationary GEV distribution. For ease of explaining Equation (4), it is assumed that the time series data are annual but the concept is equally valid for any unit time (daily, weekly and monthly). The return periods, however, are calculated only for the annual cold extremes. There are various ways of interpreting Equation (4). $q_p(t,z)$ is defined as the return level or the value that is expected to be exceeded every $\frac{1}{p}$ years. $q_p(t,z)$ is also known as the return level associated with the return period $\frac{1}{p}$, or $q_p(t,z)$ is exceeded annually with probability p.

The schematic in Figure 3 demonstrates the link between the GEV for annual maxima and the GPD for threshold exceedances. The schematic is divided in to 5 quadrants. Each quadrant represents one year (consecutive years 1 to 5). The horizontal line labelled "u" is a selected threshold and the green points are the daily temperatures that lie above this threshold. The black dots are the daily values below the threshold. The red circled dot is the *annual maximum*. Since temperatures tend to exhibit temporal dependence, the blue ellipsoids represent clusters of daily temperatures which are above the threshold that are separated by r days. If $r = 1$, then two temperatures are considered to be part of the same cluster if they occur consecutively. Otherwise they form another independent cluster.

The GEV distribution for the block maxima analyses and fits a distribution to the red markers and the GP distribution for the daily threshold exceedances analyses only the maxima of independent clusters that lie over the threshold. The annual maxima then becomes the maxima of a cluster if it lies over the threshold. For example, in the schematic in Figure 3, in year 3 the annual maximum is below the threshold and hence ignored in the POT analysis. Figure 3 also shows that the POT method better utilises the available data compared to the block maxima method.

Figure 3: Schematic diagram demonstrating the block maxima and POT methods.



All analyses have been conducted in R using the extRemes 2.0 package (Gilleland and Katz, 2011).

3.4 Financial Risk to the UK Economy

The following method gives an approximate measure of the financial risk to the UK economy of clusters of extreme cold days. This cost is given by the product of three terms: the probability of occurrence of a cluster of n successive cold days, the number of days in the cluster (n), and the mean financial cost to the UK economy per day of extreme cold.

The probability of occurrence of a cluster of extreme cold days are calculated as follows. For every weather station, using all the data that are below the corresponding cold threshold for that station, we identified clusters where temperatures were below the cold threshold for one, two, three and up to ten consecutive days. For example, it was seen that in 1927 in Balmoral, temperatures dipped below the selected threshold for 4 days continuously from the 16th of December till the 19th of December. This constituted a 4 day long cluster. In this manner, for each station, the probability of experiencing one to ten consecutive day long clusters of low temperatures $(p(x), x \in 1, \ldots, 10)$, was calculated, where the numerator is taken to be the number of each x day long clusters over the whole time period and the denominator is the total number of clusters over the whole time period as described in Table 1. The details of how the thresholds for each station were selected are given in section 4.3.

The Centre for Economics and Business Research estimated the economic cost of extreme weather in the UK (CEBR, 2015). They calculated that each additional day of "air frost" costs the UK economy £103 m. As a rough approximation it is assumed that this cost estimate corresponds also to the burden of cold extremes analysed in this study. This provides an underestimate because air frost is higher than the cold extreme temperatures used in this study. This is however the only economic study we found on the economic daily burden of cold weather. Based on this CEBR figure, and the estimated probabilities of cluster of successive extreme cold days, the approximate financial risk to the UK economy was calculated as $c \times p_c \times 103$ m, where p_c is the average probability of having c successive extreme cold days. To get a perspective of the health impact (mortality and morbidity) of cold weather, the percentage change in mortality risk per 1°C decrease in temperature below 5°C is 3.84% and the percentage change in hospital admissions risk for patients with chronic obstructive pulmonary disease per 1°C decrease in temperature below 8°C is 8.40% (Chalabi et al 2016). Both risk figures are unadjusted for influenza.

4. Results

4.1 GEV Analysis

The results of the GEV analysis for two stations, Durham and Balmoral, are shown in Table 2. The results for the remaining ten stations are shown in Table 6 in the Supplementary Material. The first row of the table gives the GEV parameters, the second row shows the variables used in the fitted model and the subsequent rows give the mean estimates (and their standard errors in brackets) of the variables. "NS" indicates the variables that were not used in the full model, or were found to be insignificant. As explained earlier, models for each station were fitted to the negative of the minimum temperatures (ie the annual block maxima) and so the regression coefficients correspond to this data. It is shown that in the case of Durham the mean parameter of the GEV distribution is linear with time and NAO, whereas in the case of Balmoral the mean parameter is quadratic with time but also linear with NAO. In both cases, the shape parameters of the respective GEV distributions are linear with NAO and do not show variation with time. Table 6 in the supplementary material shows the results for the remaining 10 stations. It was found that in the case of Balmoral, Leuchars, Stornoway and Wick Airport, the location parameter is non-linear with respect to time whereas in the case of Eskdalemuir, Oxford, Hastings, Plymouth and Durham, it is linear with time. In all cases, the shape parameter was consistently negative indicating a Weibull type distribution with a finite upper bound.

Table 2: Fitted non stationary GEV models for each station*.

	$\hat{\mu}$						$\hat{\sigma}$				$\hat{\xi}$
	$Intercept$	$Year$	$Year^2$	$Year^3$	NAO	NAO^2	$Intercept$	$Year$	$Year^2$	NAO	
Durham	7.988 (0.450)	−0.016 (0.005)	NS	NS	−0.659 (0.117)	NS	2.420 (0.165)	NS	NS	−0.177 (0.076)	−0.158 (0.060)
Balmoral	9.897 (0.615)	0.135 (0.011)	−0.001 (0.000)	NS	−0.685 (0.144)	NS	2.935 (0.221)	NS	NS	−0.202 (0.088)	−0.207 (0.053)

**Notes: The first row is the set GEV parameters and the second row are the polynomial regression coefficients in time and NAO. Shown below are the mean estimates of the coefficients (specified to three points after the decimal) and in brackets are the associated standard errors. NS means that the covariate was found to be insignificant.*

These regression coefficients were estimated by fitting the GEV models to the negative of the minimum temperatures (ie the annual block maxima)

Based on the above fitted models, the 5, 10, 50 and 100 year return levels of the AMWT were estimated. In the case of Eskdalemuir, Durham, Oxford, Hastings and Plymouth, each of the above period return levels of the AMWT were shown to linearly increase with time for different phases of the NAO. This was most notable in Plymouth where the 10 year return levels during the positive phases of the NAO were estimated to have increased between mid-20th century and the winter of 2014-15 from -4.5 °C to -2.9 °C. In the case of the Scottish weather stations of Balmoral, Leuchars, Stornoway and Wick, it was found that the above period return levels of the AMWT decreased from the start of the 20th century and kept falling approximately through the 1970s, after which the AMWT return levels started increasing. Stornoway and Wick Airport both exhibited high levels of increase in AMWT return levels. The 5, 10, 50 and 100 year return levels in Stornoway increased from -10°C to -6°C, -12°C to -8°C, -16°C to -11°C and -17°C to -13°C respectively, for all phases of the NAO index. Similar results were found for Wick Airport. This is shown graphically in Figure 4 for Durham and Balmoral (and in figure 4A for the remaining 10 stations, along with the full tabular results in Table 7, in the supplementary material). Note the contrasting patterns of the return levels for Durham and Balmoral. For Durham, the return level increases linearly with time for different phases of the NAO whereas for Balmoral the return level is convex and quadratic.

The fitted GEV models were also used to estimate the probabilities of extreme temperatures, as given by the 85th, 90th and 95th centile of the winter temperature of each of the weather stations, in any given year for extreme positive, average and negative phase of the NAO index. As with the return levels, in the case of Eskdalemuir, Durham, Oxford, Hastings and Plymouth the probability of experiencing an extreme AMWT linearly decreased with time for different phases of the NAO. In the case of the Scottish weather stations of Balmoral, Leuchars, Stornoway and Wick, the probability of extreme temperatures increased till approximately 1975 after which it drops. The probability of experiencing a temperature corresponding to the 95th centile at most weather stations dropped to zero by the winter of 2014-15. Additionally, in most stations, the drop in the return probability of extreme temperatures through time exceeds 50%. The results are shown graphically in Figure 5 for Durham and Balmoral (and in Figure 5A for the remaining 10 stations, along with the full tabular results in Table 8, in the supplementary material). Because of the relationship between return levels and probabilities of extremes, Figure 5 mirrors the findings of Figure 4: for Durham the probabilities of extreme cold winter decrease linearly with time over all NAO phases and whereas for Balmoral the counterpart probabilities of extreme cold winters are concave and quadratic.

Figure 4: The 5 (blue), 10 (red), 50 (purple) and 100 (green) year return levels of minimum winter temperature variation with time for different phases of the NAO (shown for Durham and Balmoral).

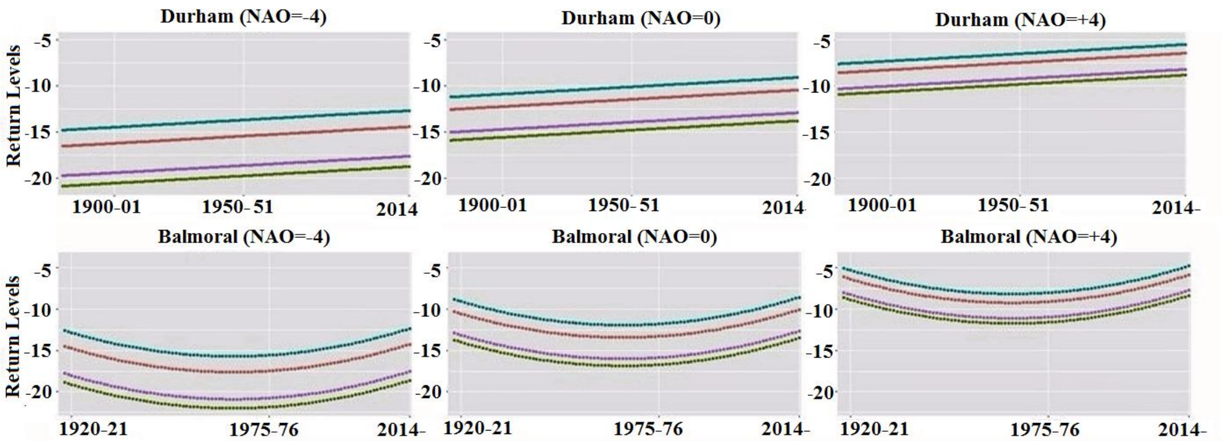
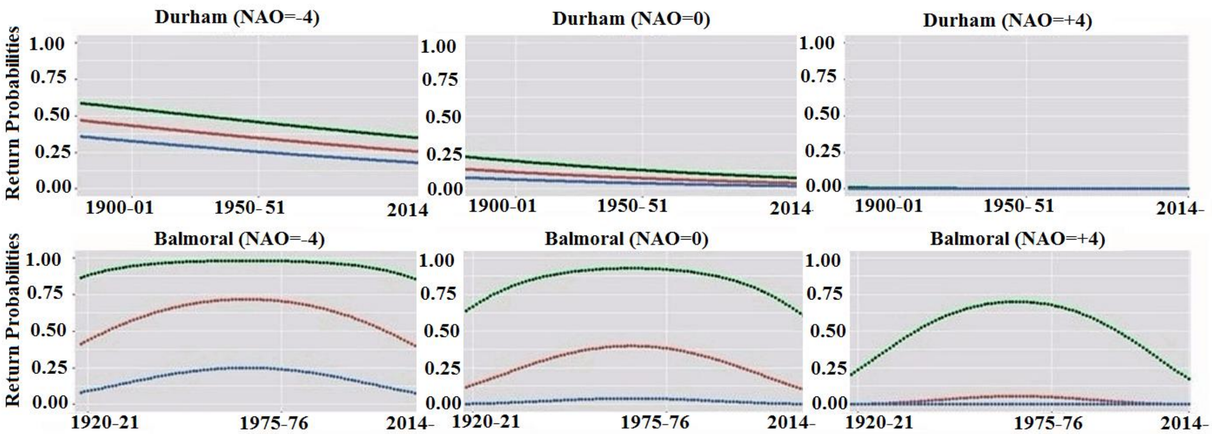


Figure 5: Probability of experiencing an extreme minimum winter temperature (defined by the 85th(green), 90th (red) and 95th (blue) centile) for different phases of the NAO (shown for Durham and Balmoral).



Durham (NAO=-4)
Durham (NAO=0)
Durham (NAO=+4)
Balmoral (NAO=-4)
Balmoral (NAO=0)
Balmoral (NAO=+4)
Return Probabilities
1.00
0.75
0.50
0.25
0.00
1900-01
1950-51
2014
1920-21
1975-76
2014-

4.2 Peak over threshold analysis

Following the analysis on the annual minimum winter temperature, threshold models were then fitted to the daily temperatures of each of the stations to examine the distribution of threshold exceedances. For each station, the thresholds were determined a priori as the 95th centile of the *minimum* temperatures in each station. Data (taken to be the negative of minimum temperatures) above the selected threshold were de-clustered and each independent cluster maxima were taken to be independent observations. Two exceedances were assumed to be independent if they were separated by at least r days, where r takes a different value for each weather station to ensure complete independence. The run length, r, is estimated in the extRemes package as the best value beyond which two extreme temperatures can be considered independent. Every weather station was estimated to have a different threshold and the selected run length, as shown in Table 3 for Durham and Balmoral (and in Table 9 in the supplementary material, for the remainder of the stations). As explained earlier, models for each station were fitted to the negative of the minimum temperatures (ie the annual block maxima) and so the regression coefficients correspond to this data. Table 3 shows that for Durham the mean of the GEV distribution decreases linearly with time and shows no association with NAO whereas for Balmoral the mean of the GEV distribution is convex and quadratic with respect to time and decreases linearly with NAO. The shape parameter of the GEV distribution for Durham shows no association with either time or NAO where in contrast the counterpart parameter for Balmoral shows positive linear association with time and negative linear association with NAO.

Table 3: Fitted threshold models for each run length for Durham and Balmoral*.

	$\hat{\mu}$						$\hat{\sigma}$				$\hat{\xi}$
	$Intercept$	$Year$	$Year^2$	$Year^3$	NAO	NAO^2	$Intercept$	$Year$	$Year^2$	NAO	
Durham $r = 3$, $u = 4$	7.409 (0.358)	-0.005 (0.004)	NS	NS	NS	NS	2.699 (0.121)	NS	NS	-	-0.118 (0.049)

Balmoral $r=5$, $u=8$	10.647 (0.470)	0.105 (0.010)	−0.001 (0.000)	NS	−0.970 (0.133)	NS	2.492 (0.334)	0.019 (0.007)	NS	−0.242 (0.084)	−0.312 (0.047)

***Notes:** The first row is the set POT parameters and the second row is the polynomial regression coefficients in time and NAO. The table shows the mean estimates of the coefficients (specified to three points after the decimal) and those in brackets are the associated standard errors. NS means that the covariate was found to be insignificant. These regression coefficients were estimated by fitting the POT models to the negative of the minimum daily temperatures that lie above the selected threshold.*

The fitted threshold models were broadly similar to the fitted GEV models for the AMWT in terms of the location parameter with some changes to the scale parameter. As with the GEV models, the best model was selected using likelihood ratio tests for nested models (as described in (Coles et al., 2001, Ch. 6)) Once again, the shape parameter was consistently negative indicating a Weibull type distribution with a finite upper bound. Based on the models fitted in able 3, the 5, 10, 50 and 100 year return levels of cluster cold extremes, below the estimated thresholds for different phases of the NAO, were estimated.

Based on the models shown in Table 3, the 5, 10, 50 and 100 year return levels were estimated. As noted in the GEV analysis, in the case of Eskdalemuir, Durham, Oxford and Plymouth, each of the above period return levels of the winter temperatures falling below a low threshold, was shown to linearly increase with time for different phases of the NAO. This was most notable in Eskdalemuir where the 50 year return level during the positive phases of the NAO were estimated to have increased significantly from -12°C to -6.1°C ,between mid 20th century and the winter of 2014-15. In the Scottish stations of Balmoral, Leuchars and Wick, it was found that the 5, 10, 50 and 100 year return levels of the winter temperatures below the threshold decreased from the start of the 20th century and kept falling approximately through the 1970s, after which the minimum winter temperature return levels start increasing. Stornoway exhibited high levels of increase in the 5, 10, 50 and 100 year return levels which increased from -11.6°C to -7.5°C, -13°C to -9°C, -15°C to -11°C and -16.3°C to-12.2°C respectively, for all phases of the NAO index. The full results are provided in the supplementary material in Tables 10 and 11.

4.3 Financial Risk to the UK Economy

Table 4 below shows the probability of 1-10 consecutive days of winter temperatures that lie below the threshold selected for each station (as calculated in section 4.2 above and shown in Table 3). The probability of experiencing 5 consecutive days of temperatures below -4^{o}C in Rothampsted was 0.04, much higher than in the Scottish stations, over the whole time period as given in Table 1. The cost of 5 consecutive days of temperatures below a low threshold on average is £13.2 million.

Table 4: Probability of experiencing 1-10 day long clusters of consecutive threshold exceedances

	Cluster size										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**>10**
Balmoral	0.446	0.300	0.134	0.058	0.025	0.013	0.010	0.010	0.003	0.000	0.003
Craibstone	0.438	0.308	0.127	0.056	0.028	0.017	0.014	0.003	0.006	0.000	0.003
Leuchars	0.617	0.218	0.085	0.034	0.019	0.013	0.008	0.002	0.000	0.002	0.002
Eskdalemuir	0.640	0.221	0.068	0.042	0.019	0.006	0.003	0.000	0.000	0.000	0.000
Stornoway	0.570	0.249	0.088	0.046	0.024	0.007	0.005	0.009	0.000	0.002	0.000
Wick	0.645	0.206	0.070	0.047	0.015	0.006	0.012	0.000	0.000	0.000	0.000
Durham	0.521	0.236	0.107	0.060	0.031	0.017	0.019	0.002	0.000	0.006	0.002
Rothampsted	0.494	0.252	0.085	0.058	0.042	0.027	0.009	0.012	0.009	0.003	0.009
Oxford	0.459	0.249	0.137	0.062	0.029	0.017	0.015	0.010	0.004	0.004	0.014
Hastings	0.478	0.208	0.111	0.075	0.031	0.022	0.013	0.018	0.013	0.009	0.022
Plymouth	0.657	0.190	0.080	0.033	0.013	0.007	0.003	0.007	0.000	0.003	0.007
Bude	0.537	0.245	0.092	0.048	0.031	0.017	0.009	0.004	0.009	0.004	0.004

The above table shows that the probability of cold clusters of size greater than 3 days is less than 10% and that of cold clusters of size greater than 5 days is less than 5%. The probabilities for cluster sizes beyond 5 days are negligible.

Table 5 averages the probabilities given in Table 4 across all stations and calculates the expected financial risk to the UK economy. As a rough approximation, it is assumed that these average probabilities apply to the whole UK.

Table 5. Average probabilities over all stations of experiencing 1-10 day clusters of consecutive threshold exceedances and the associated expected costs to the economy

	Cluster size	1	2	3	4	5	6	7	8	9	10	>10
All Stations	**Average Probability**	0.54	0.24	0.10	0.05	0.03	0.01	0.01	0.01	0.00	0.00	0.01
	Expected Cost to the Economy (in millions)	£55.81	£49.47	£30.49	£21.25	£13.18	£8.70	£7.21	£5.29	£3.40	£2.83	£6.23

It is shown that the expected financial risk decreases with the cluster size. This is because the probability of the occurrence of very long clusters is low.

5. Discussion and conclusion

This study has used statistically-based models to quantify the frequency and duration of cold weather extremes in several cities in the UK. The results of two of the stations (Balmoral and Durham) were presented in the main body of the paper and those of the remaining stations were presented in the supplementary material. Physics-based methods (Altmann and Kantz, 2005) could have equally been used instead to analyse the extreme cold events of the temperature time series records. It is difficult however to handle non-stationarity with these methods. Our models were based on non-stationary extreme value analysis. The non-stationarity is defined in terms of time and NAO. Using these models the 5, 10, 50 and 100 year return levels were determined at the different locations as well as the probabilities of experiencing extreme cold temperatures. In particular, the probabilities of experiencing 1 - 10 day long duration clusters of consecutive extreme cold days were presented. Using data from a very recent study on the economic impacts of extreme weather on the UK economy, a very approximate financial risk to the UK economy of a cluster of extreme cold spells of different durations was calculated . Although our analysis which is based on historical temperature data showed that the frequency of cold extremes have decreased and is expected to continue to do so in the future, periods of extreme cold winter can still occur with global warming (Räisänen and Ylhäisi, 2011).

In this study we have analysed cold extremes, the same method, however, is also applicable to hot extremes. The weather stations selected for the study are not representative of the whole UK, however they are reasonably spread within the south and north of the UK. It is difficult to extrapolate the findings of this study (which were based on analysing historical data) into the future because of the changing climate. Nevertheless our findings are still relevant for future assessments. They can be used to analyse the impact of extreme weather events in computer simulation experiments in order to evaluate the cost-effectiveness of protective measures for such events. This is important for the insurance industry (Smolka, 2006).

One of the key results of this study is the calculation of the probabilities of successive cold extremes. This is important for several reasons. The economic impact of successive cold weather extremes is not necessarily additive. It is very likely to be super-additive. This means that the impact of say three successive days of extreme cold weather is more than the sum of the impacts of the three extremely cold days treated as if there are independent and far between. In our burden calculations, additive impacts are assumed which imply that the calculated economic burdens represent a low (optimistic) bound.

In relation to the estimates of the economic daily burden as calculated in the CEBR report, on which our financial risk assessment is based, any large-scale economic model of a country is based on assumptions and hence the model's estimates are naturally subject to uncertainties. The CEBR report was the only study of its kind which investigated the economic daily burden of cold weather in England. Naturally the economic estimates are subject to uncertainties. Our aim was to provide broad and approximate estimates of the economic burden of clusters of extreme cold days of different durations. We acknowledge however that our estimates could have wide confidence/credible intervals.

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References

ALTMANN, E. G. & KANTZ, H. 2005. Recurrence time analysis, long-term correlations, and extreme events. Physical Review E, 71, 056106.

BOMMIER, E. 2014. Peaks-Over-Threshold modelling of environmental data. U.U.D.M. Project Report 2014:33, Department of Mathematics, Uppsala University.

CEBR 2015. Coping with chaos-assessing the impact of bad weather on business productivity. Centre for Economics and Business Research

CHALABI, Z., HAJAT, S., WILKINSON, P., ERENS, B., JONES, L. & MAYS, N. 2016. Evaluation of the cold weather plan for England: modelling of cost-effectiveness. Public Health 137, 13-19.

CLIMATIC RESEARCH UNIT (LINK), U. O. E. A. North Atlantic Oscillation [Online]. Available: https://crudata.uea.ac.uk/cru/data/nao/.

COLES, S., BAWA, J., TRENNER, L. & DORAZIO, P. 2001. An introduction to statistical modeling of extreme values, Springer.

COUMOU, D. & RAHMSTORF, S. 2012. A decade of weather extremes. Nature Climate Change, 2, 491-496.

EASTERLING, D. R., MEEHL, G. A., PARMESAN, C., CHANGNON, S. A., KARL, T. R. & MEARNS, L. O. 2000. Climate Extremes: Observations, Modeling, and Impacts. Science, 289, 2068-2074.

FIELD, C. B. BARROS, V., STOCKER, T.F., DAHE, Q., DOKKEN, D.J., EBI, K.L., MASTRANDREA, M.D., MACH, K.J., PLATTNER, G-K., ALLEN, S.K., TIGNOR, M. & MIDGLEY, P.M. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change, Cambridge University Press.

GEORGE, D. G., JARVINEN, M. & ARVOLA, L. 2004. The influence of the North Atlantic Oscillation on the winter characteristics of Windermere (UK) and Paajarvi (Finland). Boreal Environment Research, 9, 389-400.

GILLELAND, E. & KATZ, R. W. 2011. New software to analyze how extremes change over time. Eos, Transactions American Geophysical Union, 92, 13-14.

GUIRGUIS, K., GERSHUNOV, A., SCHWARTZ, R., BENNETT, S. 2011. Recent warm and cold daily temperature extremes in the Northern Hemisphere. Geophysical Research Letters 38: L17701.

HUBER, V., IBARRETA D, FRIELER, K. 2017. Cold- and heat-related mortality: a cautionary note on current damage functions with net benefits from climate change. Climatic Change 142, 407-418.

HURRELL, J. 1995. Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. Science 269: 676679

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA.

IPCC 2014. [Core Writing Team: R.K. Pachauri and L.A. Meyer (eds.)], Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.

JONES, P., 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.

KIRCH, W., MENNE, B., BERTOLLINI, R. (2005) Extreme weather events and public health responses. Springer, Berlin.

KODRA, E., STEINHAEUSER, K., GANGULY A.R. 2011. Persisting cold extremes under 21st century warning scenarios. Geophysical Research Letters 38: L08705

MET OFFICE 2006. UK Daily Temperature Data, Part of the Met Office Integrated Data Archive System (MIDAS). In: CENTRE, N. B. A. D. (ed.).

OSBORN, T. J. 2011. Winter 2009/2010 temperatures and a record-breaking North Atlantic Oscillation index. Weather, 66, 19-21.

RAHMSTORF, S. & COUMOU, D. 2011. Increase of extreme events in a warming world. Proceedings of the National Academy of Sciences, 108, 17905-17909.

RÄISÄNEN J, YLHÄISI J.S. 2011. Cold months in a warming climate. Geophysical Research Letters 38, L22704, doi: 10.1029/2011GL049758.

SCAIFE, A. A., ADAM, A., FOLLAND, C.K.,ALEXANDER, L.V., MOBERG, A., KNIGHT, J. R., 2008. Journal of Climate 21, 72-83.

SMOLKA, A. 2006. Natural disasters and the challenge of extreme events: risk management from an insurance perspective. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 364, 2147-2165.

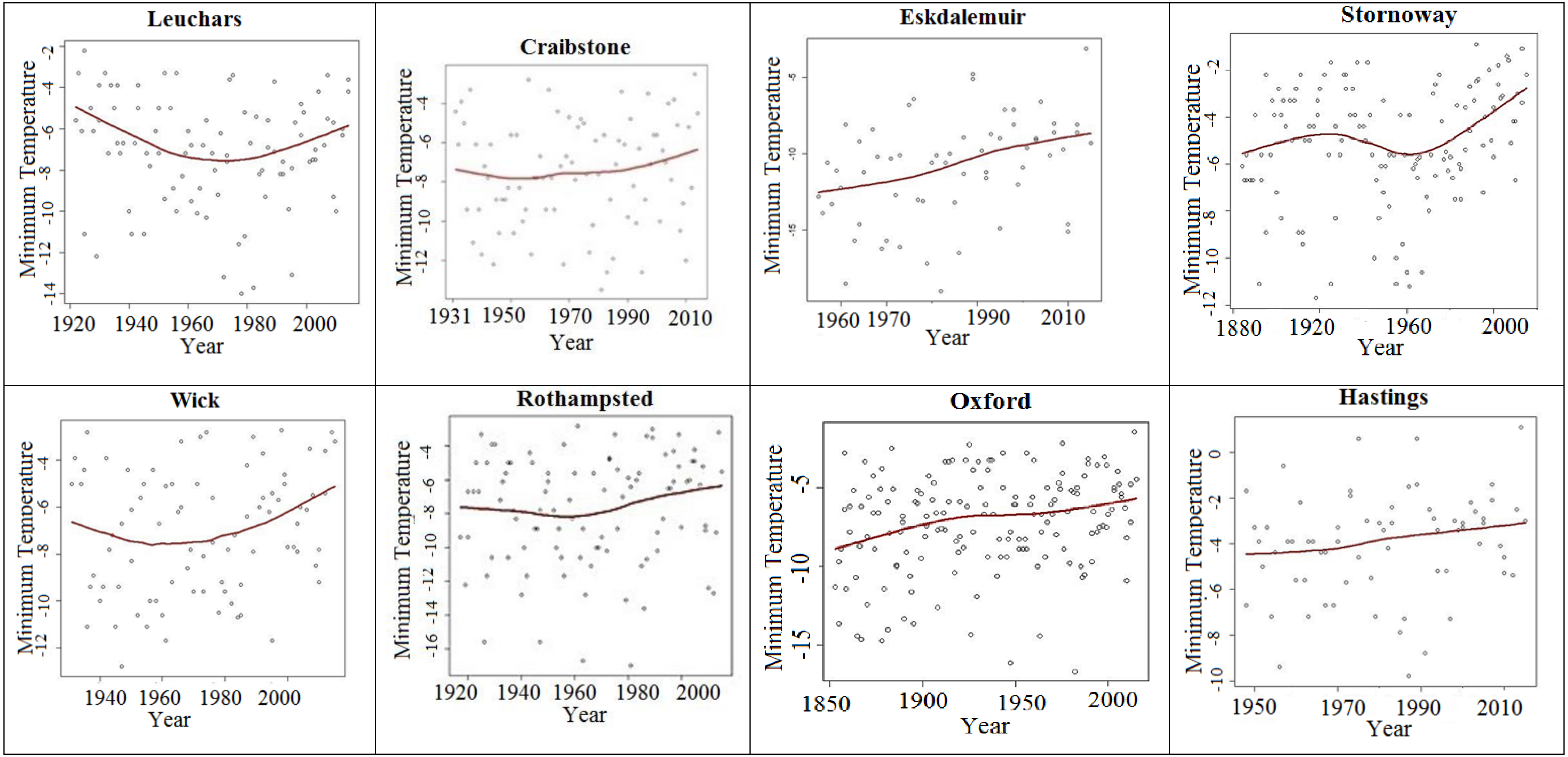
STAINFORTH, D. A., CHAPMAN, S. C. & WATKINS, N. W. 2013. Mapping climate change in European temperature distributions. Environmental Research Letters, 8, 034031.

VOGELSANG, T. J. & FRANSES, P. H. 2005. Are winters getting warmer? Environmental Modelling & Software, 20, 1449-1455.

WOODWORTH, P., FLATHER, R., WILLIAMS, J., WAKELIN, S. & JEVREJEVA, S. 2007. The dependence of UK extreme sea levels and storm surges on the North Atlantic Oscillation. Continental Shelf Research, 27, 935-946.

Supplementary Material

Figure 1A: Observed time series of annual minimum winter temperature for 10 stations (excluding Durham and Balmoral). The x-axis is the year and the y-axis is the annual minim temperature. The plots show the raw data (as dots) and a locally fitted polynomial regression line.



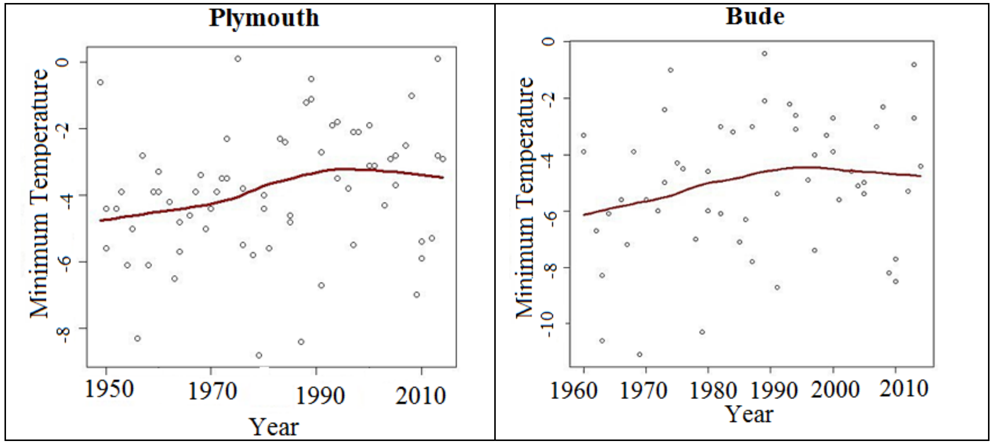
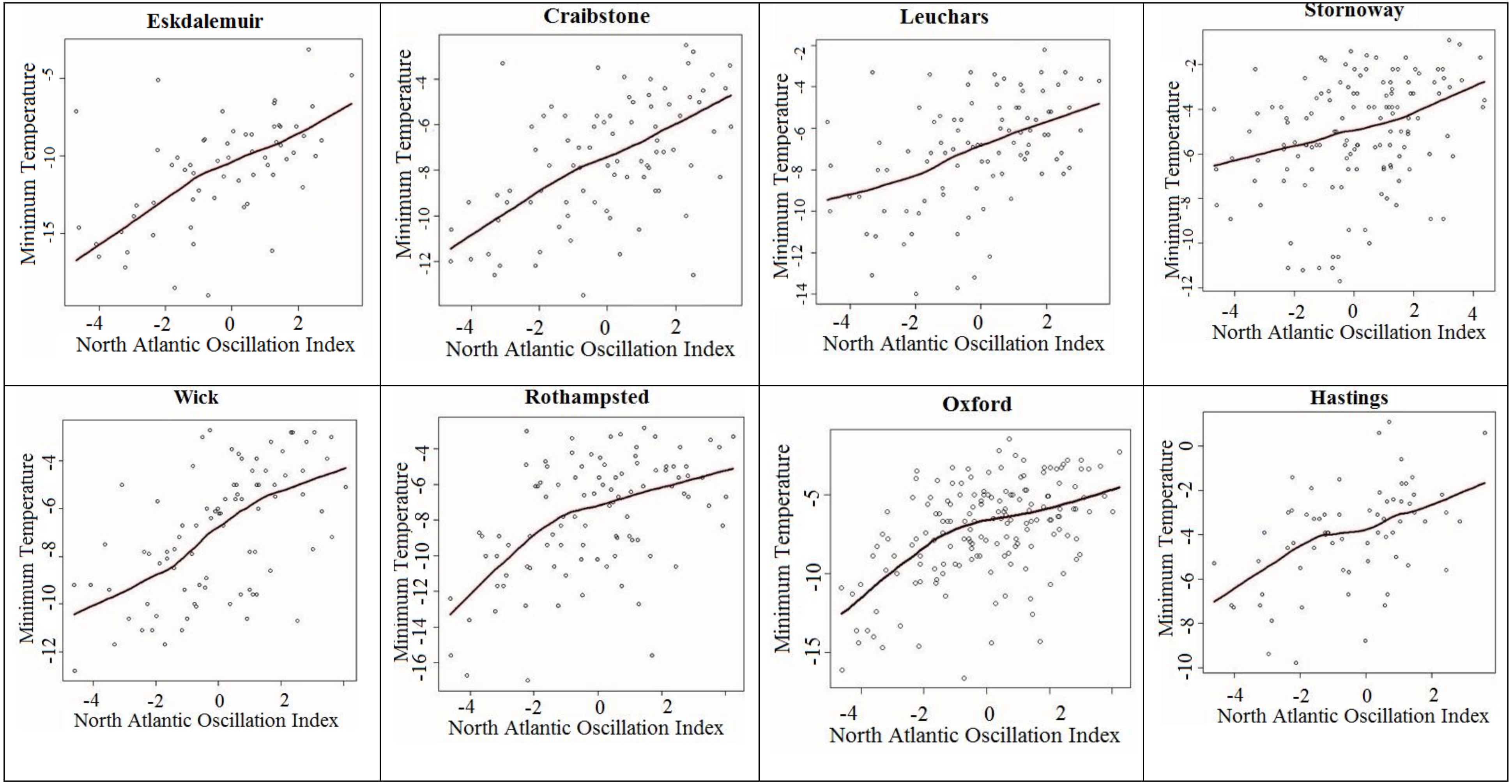

Plymouth
Minimum Temperature
0
-2
-4
-6
-8
1950
1970
1990
2010
Year
Bude
Minimum Temperature
0
-2
-4
-6
-8
-10
1960
1970
1980
1990
2000
2010
Year

Figure 2A: Observed relationship between annual minimum temperature and the NAO for 10 stations (excluding Durham and Balmoral). The x-axis is the NAO index and the y-axis is the annual minimum temperature. The plots show the raw data (as dots) and a locally fitted polynomial regression line.



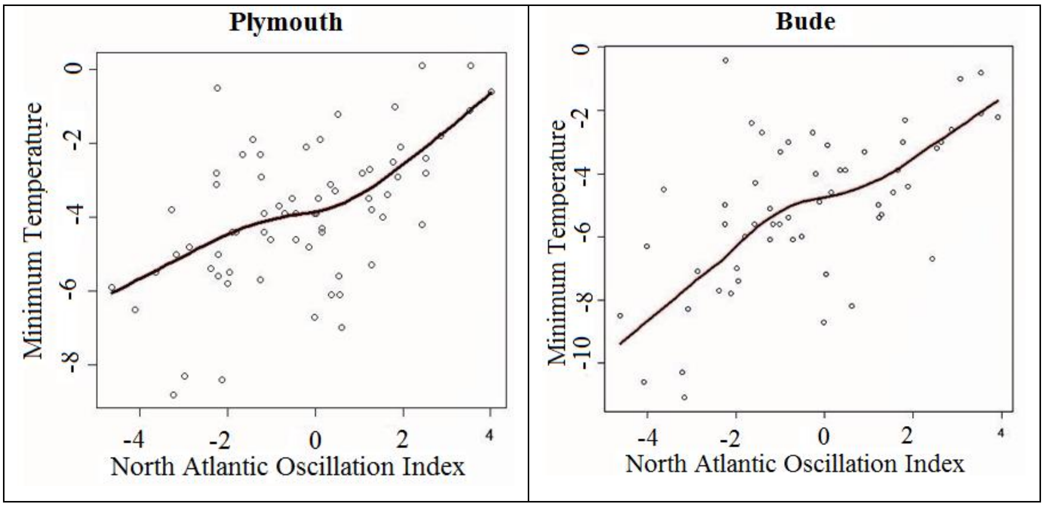
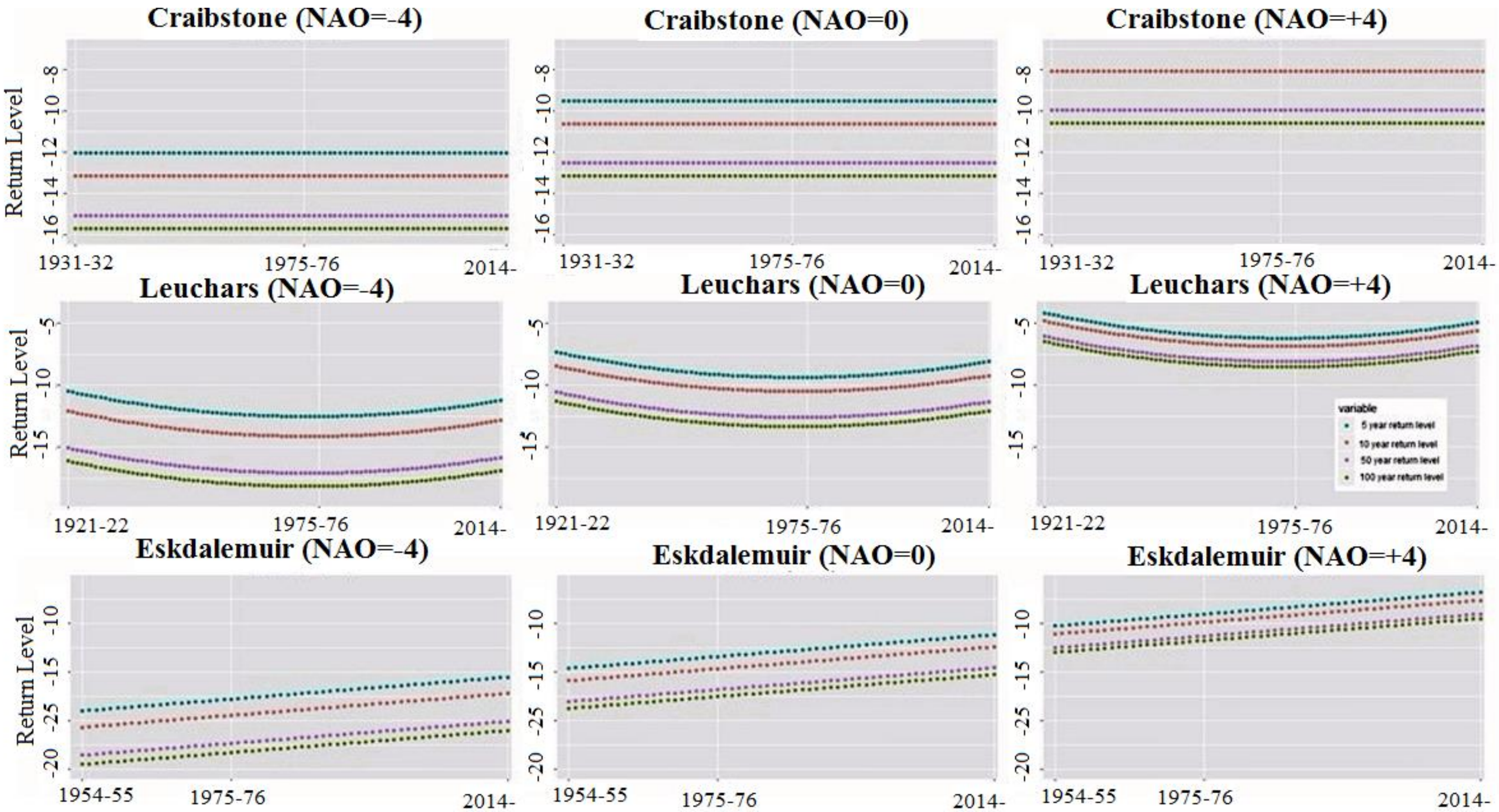
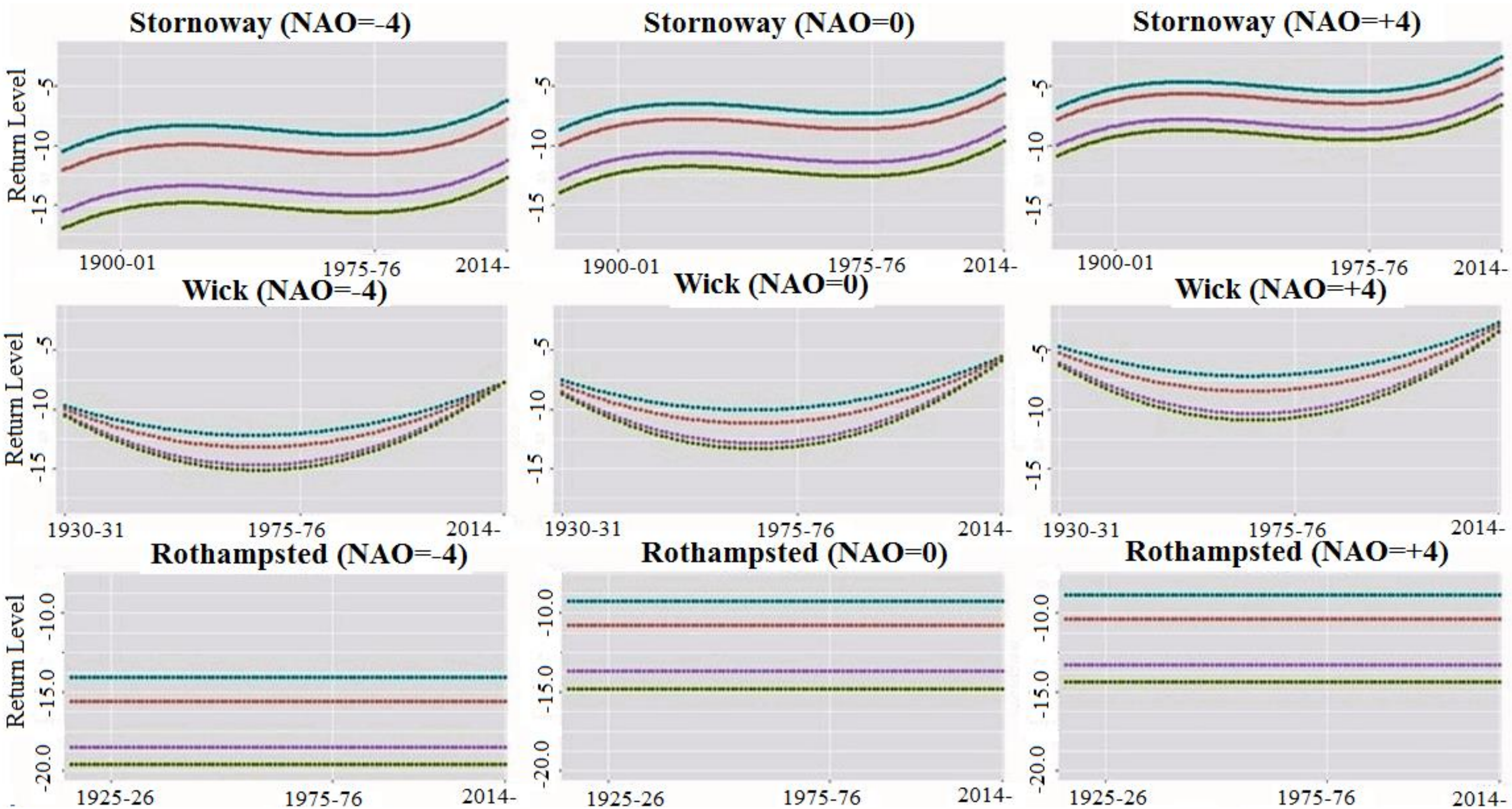


Table 6: Fitted non stationary GEV models for each station (except Durham and Balmoral). The first row is the set GEV parameters and the second row are the polynomial regression coefficients in time and NAO. Shown below are the mean estimates of the coefficients (specified to three points after the decimal) and in brackets are the associated standard errors. NS means that the covariate was found to be insignificant. These regression coefficients were estimated by fitting the GEV models to the negative of the minimum temperatures (ie the annual block maxima)

	$\hat{\mu}$						$\hat{\sigma}$				$\hat{\xi}$
	$Intercept$	$Year$	$Year^2$	$Year^3$	NAO	NAO^2	$Intercept$	$Year$	$Year^2$	NAO	
Craibstone	6.678 (0.261)	NS	NS	NS	−0.635 (0.118)	NS	2.196 (0.178)	NS	NS	NS	−0.211 (0.057)
Leuchars	4.595 (0.424)	0.080 (0.007)	0.001 (0.000)	NS	−0.510 (0.111)	NS	1.973 (0.160)	NS	NS	−0.206 (0.076)	−0.145 (0.069)
Eskdalemuir	11.486 (0.684)	−0.058 (0.019)	NS	NS	−0.820 (0.174)	NS	2.478 (0.234)	NS	NS	−0.209 (0.103)	−0.212 (0.066)
Stornoway	6.131 (0.000)	0.140 (0.000)	−0.003 (0.000)	−0.000 (0.000)	−0.305 (0.000)	NS	1.788 (0.000)	NS	NS	−0.104 (0.000)	−0.015 (0.000)
Wick Airport	6.329 (0.401)	0.029 (0.006)	−0.000 (0.000)	NS	−0.828 (0.054)	NS	0.909 (0.191)	0.097 (0.002)	−0.001 (0.000)	0.095 (0.072)	−0.336 (0.081)
Rothampsted	5.925 (0.353)	NS	NS	NS	−0.653 (0.119)	0.138 (0.049)	2.396 (0.189)	NS	NS	NS	−0.099 (0.066)
Oxford	7.459 (0.382)	−0.016 (0.004)	NS	NS	−0.722 (0.100)	NS	2.227 (0.138)	NS	NS	NS	−0.092 (0.051)
Hastings	3.684 (0.473)	−0.020 (0.117)	NS	NS	−0.595 (0.128)	NS	1.801 (0.165)	NS	NS	NS	−0.186 (0.071)
Plymouth	3.991 (0.387)	−0.024 (0.010)	NS	NS	−0.512 (0.094)	NS	1.465 (0.131)	NS	NS	NS	−0.198 (0.067)
Bude	4.143 (0.258)	NS	NS	NS	−0.603 (0.105)	NS	1.750 (0.174)	NS	NS	−0.193 (0.079)	−0.218 (0.086)

Figure 4A: The 5 (blue), 10 (red), 50 (purple) and 100 (green) year return levels of minimum winter temperature variation with time for different phases of the NAO. Each row of figures represents one weather station and for three different phases of the NAO.




Stornoway (NAO=-4)
Stornoway (NAO=0)
Stornoway (NAO=+4)
Return Level
-5
-10
-15
1900-01
1975-76
2014-
Wick (NAO=-4)
Wick (NAO=0)
Wick (NAO=+4)
1930-31
Rothampsted (NAO=-4)
Rothampsted (NAO=0)
Rothampsted (NAO=+4)
-10.0
-15.0
-20.0
1925-26

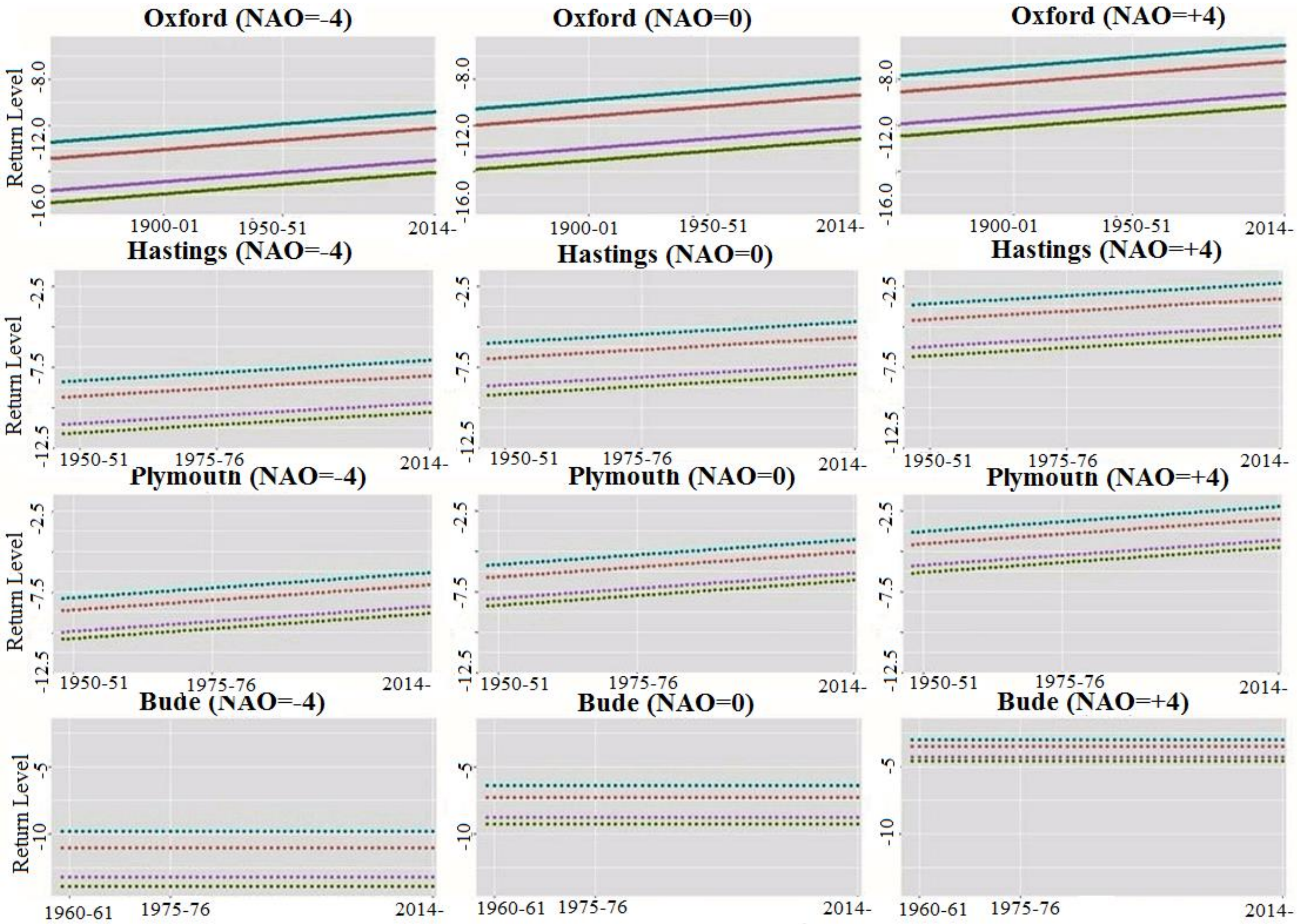
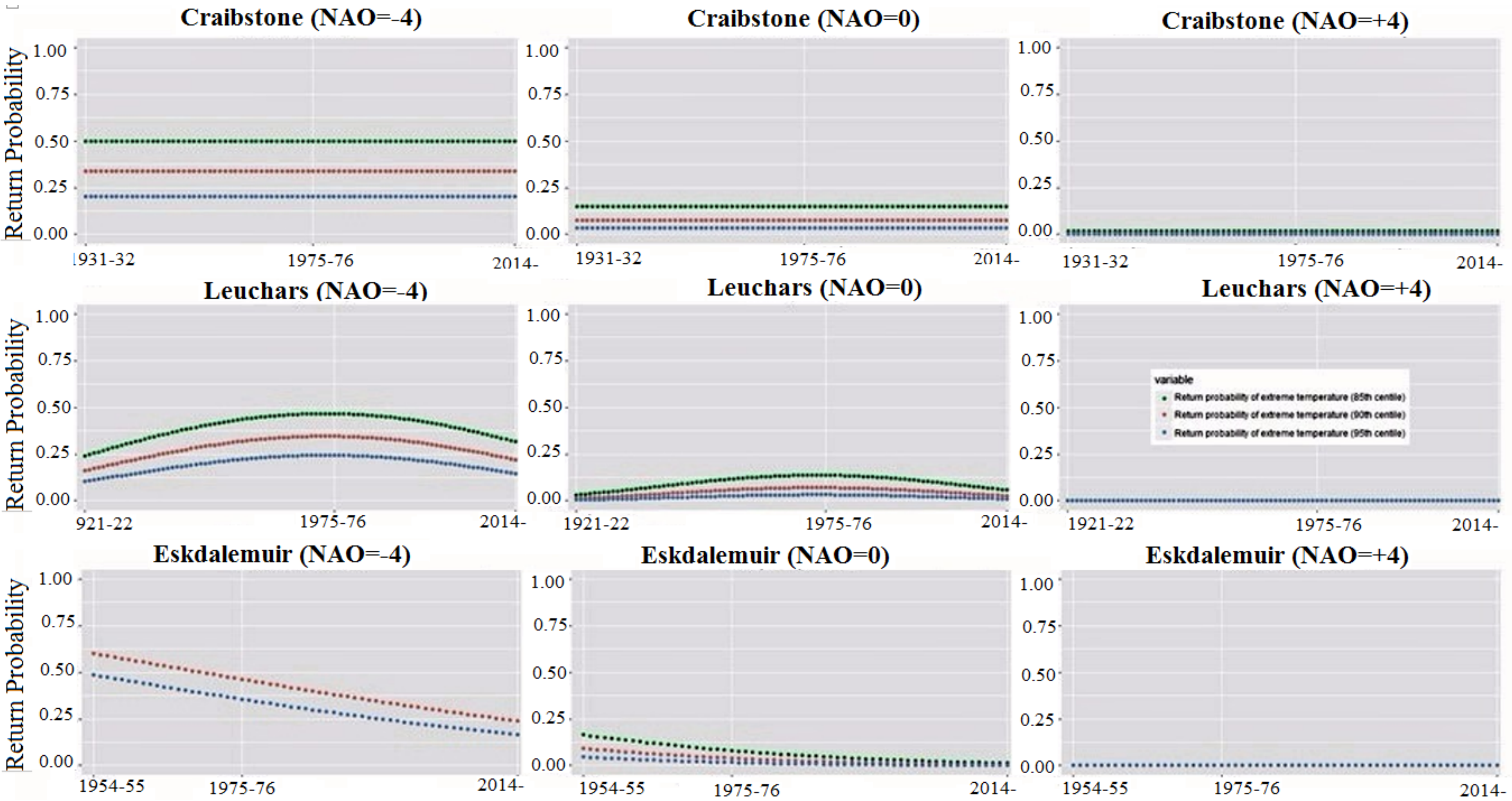
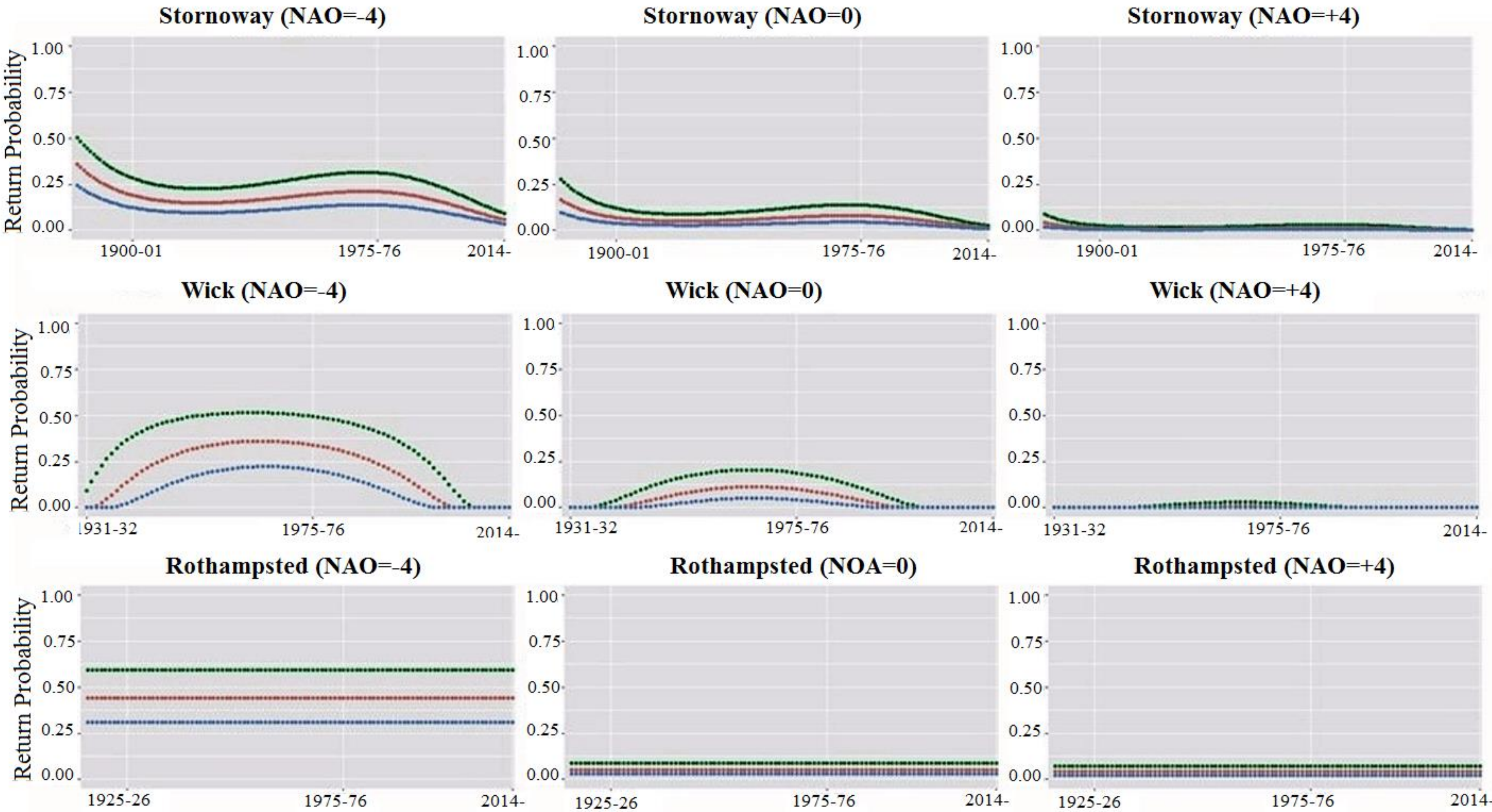

Oxford (NAO=-4)
Oxford (NAO=0)
Oxford (NAO=+4)
Return Level
-8.0
-12.0
-16.0
1900-01
1950-51
2014-
Hastings (NAO=-4)
Hastings (NAO=0)
Hastings (NAO=+4)
-2.5
-7.5
-12.5
1950-51
1975-76
Plymouth (NAO=-4)
Plymouth (NAO=0)
Plymouth (NAO=+4)
Bude (NAO=-4)
Bude (NAO=0)
Bude (NAO=+4)
-5
-10
1960-61

Figure 5A: Probability of experiencing an extreme minimum winter temperature (defined by the 85th(green), 90th (red) and 95th (blue) centile) for different phases of the NAO. Each row of figures represents one weather station and for three different phases of the NAO.





Stornoway (NAO=-4)
Stornoway (NAO=0)
Stornoway (NAO=+4)
Wick (NAO=-4)
Wick (NAO=0)
Wick (NAO=+4)
Rothampsted (NAO=-4)
Rothampsted (NOA=0)
Rothampsted (NAO=+4)
Return Probability
1.00
0.75
0.50
0.25
0.00
1900-01
1975-76
2014-
1931-32
1925-26

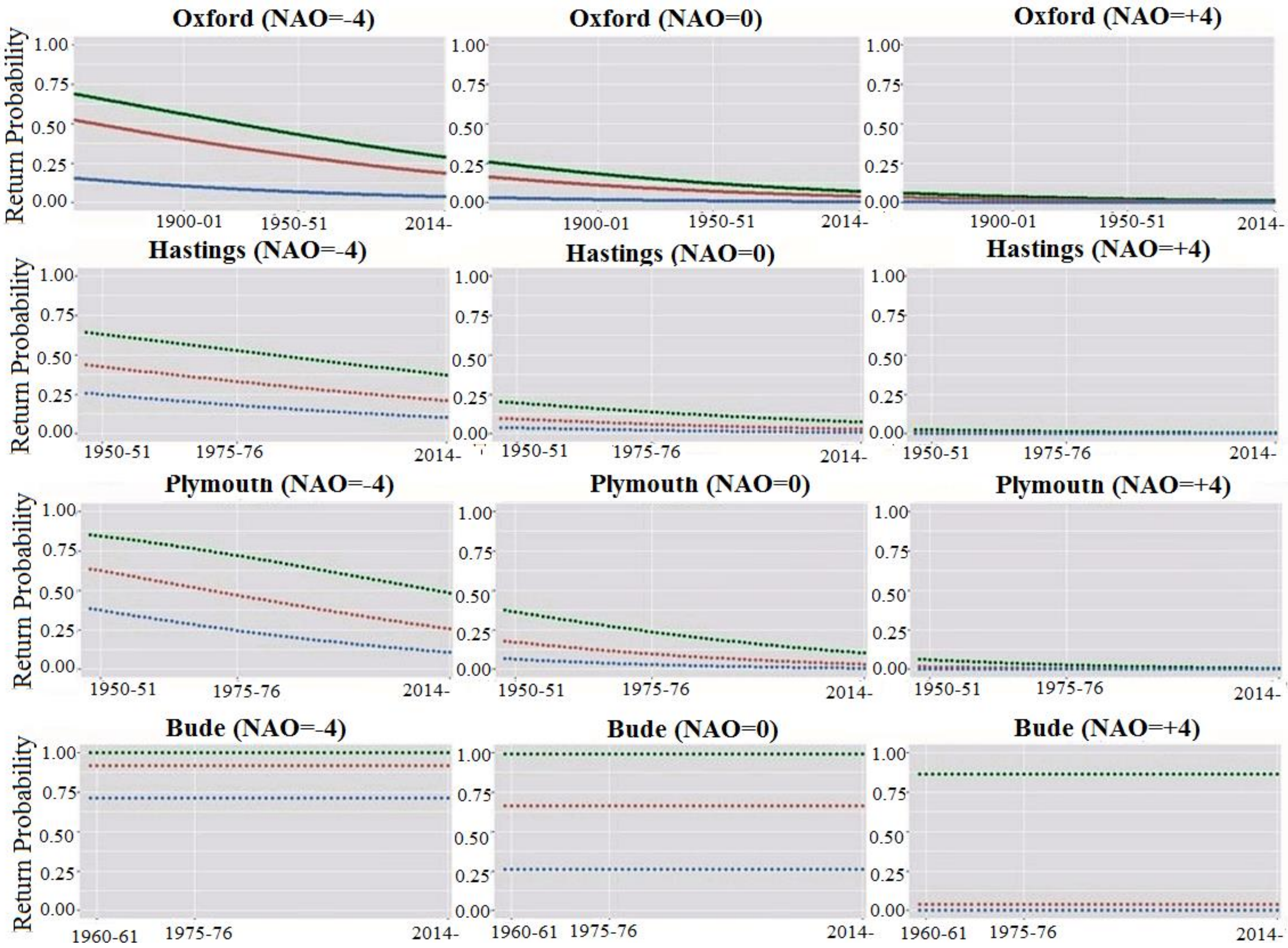

Oxford (NAO=-4)
Oxford (NAO=0)
Oxford (NAO=+4)
Hastings (NAO=-4)
Hastings (NAO=0)
Hastings (NAO=+4)
Plymouth (NAO=-4)
Plymouth (NAO=0)
Plymouth (NAO=+4)
Bude (NAO=-4)
Bude (NAO=0)
Bude (NAO=+4)
Return Probability
1.00
0.75
0.50
0.25
0.00
1900-01
1950-51
1975-76
1960-61
2014-

Table 7: Return levels of AMWT for extreme positive, average and negative phase of the NAO index

		5 Year Return Level			10 Year Return Level			50 Year Return Level			100 Year Return Level		
Station	Year	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO
Balmoral	1920-21	-19.857 ºC	-14.075 ºC	-10.294 ºC	-19.764 ºC	-15.572 ºC	-11.380 ºC	-23.050 ºC	-18.150 ºC	-13.250 ºC	-24.136 ºC	-19.002 ºC	-13.867 ºC
	1950-51	-20.392 ºC	-16.611 ºC	-12.830 ºC	-22.299 ºC	-18.107 ºC	-13.915 ºC	-25.586 ºC	-20.686 ºC	-15.785 ºC	-26.672 ºC	-21.537 ºC	-16.403 ºC
	1975-76	-20.572 ºC	-16.791 ºC	-13.010 ºC	-22.479 ºC	-18.287 ºC	-14.095 ºC	-25.766 ºC	-20.865 ºC	-15.965 ºC	-26.851 ºC	-21.717 ºC	-16.583 ºC
	2000-01	-18.994 ºC	-15.213 ºC	-11.432 ºC	-20.901 ºC	-16.709 ºC	-12.517 ºC	-24.187 ºC	-19.287 ºC	-14.387 ºC	-25.273 ºC	-20.139 ºC	-15.004 ºC
	2014-15	-17.342 ºC	-13.561 ºC	-9.780 ºC	-19.2491 ºC	-15.057 ºC	-10.865 ºC	-22.536 ºC	-17.636 ºC	-12.735 ºC	-23.621 ºC	-18.487 ºC	-13.353 ºC
Bude	All years	-9.783 ºC	-6.382 ºC	-2.981 ºC	-11.044 ºC	-7.257 ºC	-3.470 ºC	-13.188 ºC	-8.744 ºC	-4.300 ºC	-13.888 ºC	-9.229 ºC	-4.571 ºC
Craibstone	All years	-12.043 ºC	-9.503 ºC	-6.963 ºC	-13.154 ºC	-10.614 ºC	-8.074 ºC	-15.060 ºC	-12.520 ºC	-9.980 ºC	-15.687 ºC	-13.146 ºC	-10.606 ºC
Durham	1880-81	-14.786 ºC	-11.204 ºC	-7.622 ºC	-16.533 ºC	-12.556 ºC	-8.578 ºC	-19.722 ºC	-15.022 ºC	-10.323 ºC	-20.839 ºC	-15.886 ºC	-10.934 ºC
	1900-01	-14.473 ºC	-10.891 ºC	-7.309 ºC	-16.220 ºC	-12.242 ºC	-8.264 ºC	-19.408 ºC	-14.709 ºC	-10.009 ºC	-20.525 ºC	-15.573 ºC	-10.620 ºC
	1925-26	-14.081 ºC	-10.499 ºC	-6.916 ºC	-15.828 ºC	-11.850 ºC	-7.872 ºC	-19.016 ºC	-14.316 ºC	-9.617 ºC	-20.133 ºC	-15.181 ºC	-10.228 ºC
	1950-51	-13.689 ºC	-10.107 ºC	-6.524 ºC	-15.436 ºC	-11.458 ºC	-7.480 ºC	-18.624 ºC	-13.924 ºC	-9.225 ºC	-19.741 ºC	-14.789 ºC	-9.836 ºC
	1975-76	-13.297 ºC	-9.715 ºC	-6.132 ºC	-15.044 ºC	-11.066 ºC	-7.088 ºC	-18.232 ºC	-13.532 ºC	-8.833 ºC	-19.349 ºC	-14.397 ºC	-9.444 ºC
	2000-01	-12.905 ºC	-9.323 ºC	-5.740 ºC	-14.652 ºC	-10.674 ºC	-6.696 ºC	-17.840 ºC	-13.140 ºC	-8.441 ºC	-18.957 ºC	-14.005 ºC	-9.052 ºC
	2014-15	-12.685 ºC	-9.103 ºC	-5.521 ºC	-14.432 ºC	-10.455 ºC	-6.477 ºC	-17.620 ºC	-12.921 ºC	-8.221 ºC	-18.738 ºC	-13.785 ºC	-8.833 ºC
Oxford	1853-54	-13.453 ºC	-10.564 ºC	-7.675 ºC	-14.861 ºC	-11.972 ºC	-9.083 ºC	-17.638 ºC	-14.749 ºC	-11.860 ºC	-18.691 ºC	-15.802 ºC	-12.914 ºC
	1875-76	-13.096 ºC	-10.207 ºC	-7.318 ºC	-14.504 ºC	-11.615 ºC	-8.726 ºC	-17.281 ºC	-14.392 ºC	-11.503 ºC	-18.334 ºC	-15.445 ºC	-12.557 ºC
	1900-01	-12.690 ºC	-9.801 ºC	-6.912 ºC	-14.098 ºC	-11.209 ºC	-8.320 ºC	-16.875 ºC	-13.986 ºC	-11.098 ºC	-17.929 ºC	-15.04 ºC	-12.151 ºC
	1925-26	-12.284 ºC	-9.396 ºC	-6.507 ºC	-13.692 ºC	-10.803 ºC	-7.915 ºC	-16.470 ºC	-13.581 ºC	-10.692 ºC	-17.523 ºC	-14.634 ºC	-11.745 ºC
	1950-51	-11.879 ºC	-8.990 ºC	-6.101 ºC	-13.287 ºC	-10.398 ºC	-7.509 ºC	-16.064 ºC	-13.175 ºC	-10.286 ºC	-17.117 ºC	-14.228 ºC	-11.34 ºC

		5 Year Return Level			10 Year Return Level			50 Year Return Level			100 Year Return Level		
Station	Year	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO
	1975-76	-11.473 °C	-8.584 °C	-5.695 °C	-12.881 °C	-9.992 °C	-7.103 °C	-15.658 °C	-12.769 °C	-9.880 °C	-16.711 °C	-13.823 °C	-10.934 °C
	2000-01	-11.067 °C	-8.179 °C	-5.290 °C	-12.475 °C	-9.586 °C	-6.697 °C	-15.252 °C	-12.36 4 °C	-9.475 °C	-16.306 °C	-13.417 °C	-10.528 °C
	2014-15	-10.840 °C	-7.951 °C	-5.063 °C	-12.248 °C	-9.359 °C	-6.470 °C	-15.025 °C	-12.136 °C	-9.248 °C	-16.079 °C	-13.19 °C	-10.301 °C
Rothampsted	All years	-14.082 °C	-9.265 °C	-8.859 °C	-15.577 °C	-10.760 °C	-10.353 °C	-18.501 °C	-13.684 °C	-13.278 °C	-19.601 °C	-14.784 °C	-14.378 °C
Leuchars	1925-26	10.785 °C	7.634 °C	4.483 °C	12.386 °C	8.763 °C	5.140 °C	15.351 °C	10.854 °C	6.357 °C	16.406 °C	11.598 °C	6.79 °C
	1950-51	12.119 °C	8.968 °C	5.817 °C	13.719 °C	10.096 °C	6.474 °C	16.684 °C	12.187 °C	7.691 °C	17.739 °C	12.931 °C	8.124 °C
	1975-76	12.511 °C	9.360 °C	6.209 °C	14.111 °C	10.489 °C	6.866 °C	17.076 °C	12.580 °C	8.083 °C	18.131 °C	13.324 °C	8.516 °C
	2000-01	11.962 °C	8.811 °C	5.660 °C	13.563 °C	9.940 °C	6.317 °C	16.528 °C	12.031 °C	7.534 °C	17.583 °C	12.775 °C	7.967 °C
	2014-15	11.244 °C	8.093 °C	4.942 °C	12.844 °C	9.222 °C	5.599 °C	15.809 °C	11.313 °C	6.816 °C	16.864 °C	12.057 °C	7.249 °C
Eskdalemuir	1954-55	-18.970 °C	-14.612 °C	-10.255 °C	-20.644 °C	-15.863 °C	-11.083 °C	-23.512 °C	-18.007 °C	-12.502 °C	-24.453 °C	-18.71 °C	-12.967 °C
	1975-76	-17.757 °C	-13.400 °C	-9.042 °C	-19.431 °C	-14.651 °C	-9.870 °C	-22.299 °C	-16.794 °C	-11.289 °C	-23.24 °C	-17.497 °C	-11.755 °C
	2000-01	-16.313 °C	-11.956 °C	-7.598 °C	-17.987 °C	-13.207 °C	-8.426 °C	-20.855 °C	-15.350 °C	-9.845 °C	-21.796 °C	-16.054 °C	-10.311 °C
	2014-15	-15.505 °C	-11.147 °C	-6.790 °C	-17.179 °C	-12.398 °C	-7.618 °C	-20.047 °C	-14.542 °C	-9.036 °C	-20.988 °C	-15.245 °C	-9.502 °C
Hastings	1950-51	-8.344 °C	-5.963 °C	-3.582 °C	-9.298 °C	-6.917 °C	-4.536 °C	-10.983 °C	-8.602 °C	-6.221 °C	-11.553 °C	-9.173 °C	-6.792 °C
	1975-76	-7.849 °C	-5.469 °C	-3.088 °C	-8.804 °C	-6.423 °C	-4.042 °C	-10.488 °C	-8.108 °C	-5.727 °C	-11.059 °C	-8.678 °C	-6.297 °C
	2000-01	-7.355 °C	-4.974 °C	-2.593 °C	-8.309 °C	-5.928 °C	-3.547 °C	-9.994 °C	-7.613 °C	-5.232 °C	-10.564 °C	-8.183 °C	-5.802 °C
	2014-15	-7.078 °C	-4.697 °C	-2.316 °C	-8.032 °C	-5.651 °C	-3.270 °C	-9.717 °C	-7.336 °C	-4.955 °C	-10.287 °C	-7.906 °C	-5.526 °C
Plymouth	1950-51	-7.867 °C	-5.819 °C	-3.772 °C	-8.625 °C	-6.578 °C	-4.531 °C	-9.946 °C	-7.899 °C	-5.852 °C	-10.387 °C	-8.34 °C	-6.293 °C
	1975-76	-7.261 °C	-5.214 °C	-3.167 °C	-8.02 °C	-5.973 °C	-3.925 °C	-9.341 °C	-7.294 °C	-5.246 °C	-9.782 °C	-7.735 °C	-5.687 °C
	2000-01	-6.656 °C	-4.608 °C	-2.561 °C	-7.414 °C	-5.367 °C	-3.32 °C	-8.735 °C	-6.688 °C	-4.641 °C	-9.176 °C	-7.129 °C	-5.082 °C
	2014-15	-6.317 °C	-4.269 °C	-2.222 °C	-7.075 °C	-5.028 °C	-2.981 °C	-8.396 °C	-6.349 °C	-4.302 °C	-8.837 °C	-6.79 °C	-4.743 °C

		5 Year Return Level			10 Year Return Level			50 Year Return Level			100 Year Return Level		
Station	Year	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO
Stornoway	1883-84	-10.485 °C	-8.646 °C	-6.808 °C	-12.093 °C	-9.951 °C	-7.809 °C	-15.572 °C	-12.772 °C	-9.973 °C	-17.017 °C	-13.945 °C	-10.872 °C
	1900-01	-8.866 °C	-7.028 °C	-5.189 °C	-10.475 °C	-8.332 °C	-6.19 °C	-13.953 °C	-11.154 °C	-8.354 °C	-15.398 °C	-12.326 °C	-9.254 °C
	1925-26	-8.316 °C	-6.478 °C	-4.639 °C	-9.925 °C	-7.782 °C	-5.64 °C	-13.403 °C	-10.604 °C	-7.804 °C	-14.848 °C	-11.776 °C	-8.704 °C
	1950-51	-8.82 °C	-6.982 °C	-5.144 °C	-10.429 °C	-8.287 °C	-6.144 °C	-13.907 °C	-11.108 °C	-8.309 °C	-15.352 °C	-12.28 °C	-9.208 °C
	1975-76	-9.12 °C	-7.281 °C	-5.443 °C	-10.728 °C	-8.586 °C	-6.444 °C	-14.207 °C	-11.407 °C	-8.608 °C	-15.652 °C	-12.58 °C	-9.507 °C
	2000-01	-7.955 °C	-6.117 °C	-4.279 °C	-9.564 °C	-7.422 °C	-5.28 °C	-13.043 °C	-10.243 °C	-7.444 °C	-14.488 °C	-11.415 °C	-8.343 °C
	2014-15	-6.195 °C	-4.357 °C	-2.518 °C	-7.804 °C	-5.661 °C	-3.519 °C	-11.282 °C	-8.483 °C	-5.683 °C	-12.727 °C	-9.655 °C	-6.582 °C
Wick	1930-31	-9.689 °C	-7.541 °C	-4.678 °C	-9.977 °C	-7.944 °C	-5.233 °C	-10.405 °C	-8.542 °C	-6.059 °C	-10.526 °C	-8.711 °C	-6.291 °C
	1950-51	-11.699 °C	-9.552 °C	-6.688 °C	-12.547 °C	-10.514 °C	-7.803 °C	-13.807 °C	-11.944 °C	-9.461 °C	-14.162 °C	-12.347 °C	-9.928 °C
	1975-76	-12.033 °C	-9.885 °C	-7.021 °C	-13.029 °C	-10.995 °C	-8.285 °C	-14.508 °C	-12.645 °C	-10.162 °C	-14.925 °C	-13.11 °C	-10.691 °C
	2000-01	-9.944 °C	-7.796 °C	-4.933 °C	-10.475 °C	-8.442 °C	-5.731 °C	-11.263 °C	-9.4 °C	-6.916 °C	-11.485 °C	-9.67 °C	-7.251 °C
	2014-15	-7.717 °C	-5.569 °C	-2.705 °C	-7.719 °C	-5.686 °C	-2.975 °C	-7.722 °C	-5.859 °C	-3.375 °C	-7.723 °C	-5.908 °C	-3.488 °C

Table 8: probability of experiencing an extreme temperature (as given by the 85th, 90th and 95th quantile of temperature data) in any given year for extreme positive, average and negative phase of the NAO index

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
	Temp	***-10 ºC***	***-15 ºC***	***-20 ºC***	***-10 ºC***	***-15 ºC***	***-20 ºC***	***-10 ºC***	***-15 ºC***	***-20 ºC***
Balmoral	1920-21	0.879	0.436	0.091	0.668	0.133	0.004	0.235	0.002	0.000
	1950-51	0.974	0.687	0.227	0.910	0.361	0.033	0.647	0.042	0.000
	1975-76	0.978	0.704	0.239	0.920	0.382	0.037	0.677	0.050	0.000
	2000-01	0.934	0.549	0.141	0.796	0.218	0.011	0.404	0.010	0.000
	2014-15	0.847	0.387	0.073	0.604	0.103	0.002	0.176	0.001	0.000
	Temp	***-1 ºC***	***-4 ºC***	***-6 ºC***	***-1 ºC***	***-4 ºC***	***-6 ºC***	***-1 ºC***	***-4 ºC***	***-6 ºC***
Bude	All years	0.998	0.918	0.711	0.989	0.662	0.259	0.865	0.039	0.000
	Temp	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***
Craibstone	All years	0.499	0.337	0.205	0.149	0.076	0.033	0.020	0.006	0.001
	Temp	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***
Durham	1880-81	0.586	0.468	0.358	0.220	0.135	0.077	0.009	0.002	0.000
	1900-01	0.548	0.432	0.326	0.190	0.114	0.064	0.006	0.001	0.000
	1925-26	0.502	0.389	0.289	0.157	0.092	0.050	0.004	0.001	0.000
	1950-51	0.456	0.348	0.254	0.128	0.073	0.039	0.002	0.000	0.000
	1975-76	0.412	0.309	0.222	0.104	0.058	0.030	0.001	0.000	0.000
	2000-01	0.370	0.273	0.193	0.083	0.045	0.022	0.001	0.000	0.000

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
	2014-15	0.347	0.254	0.178	0.073	0.039	0.019	0.000	0.000	0.000
	Temp	***-10 ºC***	***-11 ºC***	***-14ºC***	***-10 ºC***	***-11 ºC***	***-14ºC***	***-10 ºC***	***-11 ºC***	***-14ºC***
Oxford	1853-54	0.686	0.522	0.154	0.257	0.163	0.032	0.061	0.034	0.005
	1875-76	0.628	0.465	0.129	0.220	0.137	0.026	0.050	0.027	0.004
	1900-01	0.561	0.403	0.105	0.182	0.111	0.020	0.039	0.021	0.003
	1925-26	0.494	0.346	0.085	0.150	0.090	0.015	0.031	0.016	0.002
	1950-51	0.431	0.294	0.068	0.123	0.072	0.012	0.024	0.013	0.001
	1975-76	0.372	0.247	0.054	0.100	0.058	0.009	0.019	0.010	0.001
	2000-01	0.317	0.206	0.043	0.080	0.046	0.007	0.014	0.007	0.001
	2014-15	0.289	0.186	0.038	0.071	0.040	0.006	0.012	0.006	0.001
	Temp	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***
Rothampsted	All years	0.592	0.442	0.311	0.089	0.053	0.030	0.072	0.042	0.024
	Temp	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***
Leuchars	1925-26	0.269	0.183	0.119	0.041	0.018	0.007	0.000	0.000	0.000
	1950-51	0.417	0.303	0.210	0.107	0.053	0.024	0.000	0.000	0.000
	1975-76	0.466	0.345	0.243	0.137	0.070	0.033	0.000	0.000	0.000
	2000-01	0.398	0.287	0.197	0.096	0.047	0.021	0.000	0.000	0.000
	2014-15	0.316	0.220	0.146	0.058	0.026	0.011	0.000	0.000	0.000
	Temp	***-15 ºC***	***-16 ºC***	***-17ºC***	***-15 ºC***	***-16 ºC***	***-17ºC***	***-15 ºC***	***-16 ºC***	***-17ºC***

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
Eskdalemuir	1954-55	0.600	0.600	0.486	0.164	0.092	0.046	0.000	0.000	0.000
	1975-76	0.463	0.463	0.355	0.080	0.039	0.017	0.000	0.000	0.000
	2000-01	0.312	0.312	0.224	0.027	0.011	0.003	0.000	0.000	0.000
	2014-15	0.240	0.240	0.165	0.013	0.004	0.001	0.000	0.000	0.000
	Temp	***-6 ºC***	***-7 ºC***	***-8ºC***	***-6 ºC***	***-7 ºC***	***-8ºC***	***-6 ºC***	***-7 ºC***	***-8ºC***
Hastings	1950-51	0.629	0.424	0.248	0.195	0.094	0.038	0.026	0.008	0.002
	1975-76	0.527	0.331	0.181	0.138	0.061	0.023	0.015	0.004	0.001
	2000-01	0.426	0.250	0.127	0.094	0.038	0.013	0.008	0.002	0.000
	2014-15	0.373	0.210	0.103	0.075	0.029	0.009	0.005	0.001	0.000
	Temp	***-5 ºC***	***-6 ºC***	***-7ºC***	***-5 ºC***	***-6 ºC***	***-7ºC***	***-5 ºC***	***-6 ºC***	***-7ºC***
Plymouth	1950-51	0.844	0.624	0.373	0.362	0.172	0.064	0.060	0.016	0.003
	1975-76	0.720	0.469	0.246	0.237	0.097	0.030	0.028	0.006	0.001
	2000-01	0.570	0.326	0.149	0.142	0.050	0.012	0.011	0.002	0.000
	2014-15	0.483	0.256	0.108	0.103	0.032	0.007	0.006	0.001	0.000
	Temp	***-8 ºC***	***-9 ºC***	***-10ºC***	***-8 ºC***	***-9 ºC***	***-10ºC***	***-8 ºC***	***-9 ºC***	***-10ºC***
Stornoway	1883-84	0.503	0.358	0.244	0.276	0.167	0.097	0.087	0.042	0.020
	1900-01	0.283	0.189	0.123	0.120	0.069	0.039	0.026	0.012	0.006
	1925-26	0.228	0.150	0.097	0.089	0.051	0.028	0.017	0.008	0.004
	1950-51	0.278	0.186	0.121	0.117	0.067	0.038	0.025	0.012	0.005

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
	1975-76	0.312	0.210	0.138	0.137	0.080	0.045	0.032	0.015	0.007
	2000-01	0.196	0.128	0.082	0.073	0.041	0.023	0.013	0.006	0.003
	2014-15	0.092	0.058	0.037	0.027	0.015	0.008	0.003	0.001	0.001
	Temp	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***
Wick	1930-31	0.094	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1950-51	0.488	0.308	0.160	0.149	0.064	0.018	0.009	0.001	0.000
	1975-76	0.494	0.339	0.204	0.188	0.100	0.042	0.024	0.006	0.000
	2000-01	0.188	0.038	0.001	0.003	0.000	0.000	0.000	0.000	0.000
	2014-15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 9: Fitted threshold models for each run length for all stations except (Durham and Balmoral). The first row is the set POT parameters and the second row is the polynomial regression coefficients in time and NAO. The table shows the mean estimates of the coefficients (specified to three points after the decimal) and those in brackets are the associated standard errors. NS means that the covariate was found to be insignificant. These regression coefficients were estimated by fitting the POT models to the negative of the minimum daily temperatures that lie above the selected threshold.

	$\hat{\mu}$						$\hat{\sigma}$				$\hat{\xi}$
	$Intercept$	$Year$	$Year^2$	$Year^3$	NAO	NAO^2	$Intercept$	$Year$	$Year^2$	NAO	
Craibstone $r = 3$, $u = 3$	6.476 (0.242)	NS	NS	NS	−0.701 (0.112)	NS	2.471 (0.118)	NS	NS	−0.133 (0.074)	−0.212 (0.049)
Leuchars $r = 4$, $u = 3$	5.038 (0.289)	0.053 (0.005)	−0.000 (0.000)	NS	−0.736 (0.081)	NS	2.042 (0.094)	NS	NS	−0.261 (0.045)	−0.170 (0.044)
Eskdalemuir $r = 7$, $u = 6$	10.720 (0.000)	−0.030 (0.000)	NS	NS	−0.956 (0.000)	NS	3.757 (0.000)	−0.029 (0.000)	NS	−0.397 (0.000)	−0.273 (0.000)
Stornoway $r = 6$, $u = 2$	5.984 (0.000)	−0.107 (0.000)	0.002 (0.000)	−0.000 (0.000)	−0.554 (0.000)	NS	2.179 (0.000)	NS	NS	−0.118 (0.000)	−0.186 (0.000)
Wick Airport $r = 3$, $u = 3$	4.899 (0.425)	0.095 (0.008)	−0.001 (0.000)	NS	−0.633 (0.097)	NS	2.310 (0.102)	NS	NS	−0.056 (0.067)	−0.335 (0.057)
Rothampsted $r = 6$, $u = 4$	6.518 (0.293)	NS	NS	NS	−0.765 (0.123)	0.015 (0.043)	2.735 (0.167)	NS	NS	−0.278 (0.082)	−0.127 (0.057)
Oxford $r = 6$, $u = 4$	7.118 (0.340)	−0.012 (0.003)	NS	NS	−0.805 (0.093)	NS	2.585 (0.131)	NS	NS	−0.240 (0.062)	−0.142 (0.044)
Hastings $r = 5$, $u = 1.5$	3.096 (0.379)	0.002 (0.008)	NS	NS	−0.550 (0.099)	NS	1.902 (0.143)	NS	NS	−0.277 (0.068)	−0.218 (0.076)
Plymouth $r = 5$, $u = 1$	3.542 (0.291)	−0.011 (0.007)	NS	NS	−0.512 (0.073)	NS	1.620 (0.087)	NS	NS	−0.182 (0.040)	−0.276 (0.050)
Bude $r = 4$, $u = 2$	4.429 (0.228)	NS	NS	NS	−0.676 (0.094)	NS	1.848 (0.110)	NS	NS	−0.158 (0.054)	−0.294 (0.063)

Table 10: Return levels of winter temperatures lying below a low thresholds for extreme positive, average and negative phase of the NAO index

		5 Year Return Level			**10 Year Return Level**			**50 Year Return Level**			**100 Year Return Level**		
Station	Year	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO
Balmoral	1920-21	-19.046 °C	-14.006 °C	-8.965 °C	-20.52 °C	-15.074 °C	-9.628 °C	-22.77 °C	-16.705 °C	-10.639 °C	-23.423 °C	-17.178 °C	-10.933 °C
	1950-51	-21.72 °C	-16.68 °C	-11.639 °C	-23.437 °C	-17.991 °C	-12.545 °C	-26.057 °C	-19.991 °C	-13.926 °C	-26.818 °C	-20.572 °C	-14.327 °C
	1975-76	-22.474 °C	-17.434 °C	-12.393 °C	-24.393 °C	-18.947 °C	-13.501 °C	-27.321 °C	-21.256 °C	-15.19 °C	-28.172 °C	-21.926 °C	-15.681 °C
	2000-01	-21.888 °C	-16.847 °C	-11.807 °C	-24.008 °C	-18.562 °C	-13.116 °C	-27.245 °C	-21.179 °C	-15.114 °C	-28.185 °C	-21.94 °C	-15.694 °C
	2014-15	-20.973 °C	-15.933 °C	-10.893 °C	-23.207 °C	-17.761 °C	-12.315 °C	-26.617 °C	-20.551 °C	-14.486 °C	-27.607 °C	-21.361 °C	-15.116 °C
Bude	All years	-10.233 °C	-6.746 °C	-3.26 °C	-11.232 °C	-7.521 °C	-3.81 °C	-12.714 °C	-8.67 °C	-4.627 °C	-13.131 °C	-8.994 °C	-4.857 °C
Craibstone	All years	-13.136 °C	-9.65 °C	-6.164 °C	-14.652 °C	-10.898 °C	-7.143 °C	-17.249 °C	-13.034 °C	-8.82 °C	-18.101 °C	-13.736 °C	-9.37 °C
Durham	1880-81	-11.116 °C	-11.116 °C	-11.116 °C	-12.742 °C	-12.742 °C	-12.742 °C	-15.852 °C	-15.852 °C	-15.852 °C	-16.996 °C	-16.996 °C	-16.996 °C
	1900-01	-11.008 °C	-11.008 °C	-11.008 °C	-12.634 °C	-12.634 °C	-12.634 °C	-15.744 °C	-15.744 °C	-15.744 °C	-16.888 °C	-16.888 °C	-16.888 °C
	1925-26	-10.874 °C	-10.874 °C	-10.874 °C	-12.499 °C	-12.499 °C	-12.499 °C	-15.61 °C	-15.61 °C	-15.61 °C	-16.754 °C	-16.754 °C	-16.754 °C
	1950-51	-10.739 °C	-10.739 °C	-10.739 °C	-12.365 °C	-12.365 °C	-12.365 °C	-15.475 °C	-15.475 °C	-15.475 °C	-16.619 °C	-16.619 °C	-16.619 °C
	1975-76	-10.605 °C	-10.605 °C	-10.605 °C	-12.23 °C	-12.23 °C	-12.23 °C	-15.341 °C	-15.341 °C	-15.341 °C	-16.485 °C	-16.485 °C	-16.485 °C
	2000-01	-10.47 °C	-10.47 °C	-10.47 °C	-12.096 °C	-12.096 °C	-12.096 °C	-15.206 °C	-15.206 °C	-15.206 °C	-16.35 °C	-16.35 °C	-16.35 °C
	2014-15	-10.395 °C	-10.395 °C	-10.395 °C	-12.021 °C	-12.021 °C	-12.021 °C	-15.131 °C	-15.131 °C	-15.131 °C	-16.275 °C	-16.275 °C	-16.275 °C
Oxford	1853-54	-15.12 °C	-10.601 °C	-6.082 °C	-17.162 °C	-12.089 °C	-7.017 °C	-20.96 °C	-14.859 °C	-8.758 °C	-22.317 °C	-15.848 °C	-9.38 °C
	1875-76	-14.86 °C	-10.341 °C	-5.822 °C	-16.902 °C	-11.83 °C	-6.758 °C	-20.7 °C	-14.599 °C	-8.498 °C	-22.058 °C	-15.589 °C	-9.12 °C
	1900-01	-14.566 °C	-10.047 °C	-5.528 °C	-16.608 °C	-11.535 °C	-6.463 °C	-20.406 °C	-14.305 °C	-8.204 °C	-21.763 °C	-15.294 °C	-8.826 °C

		5 Year Return Level			10 Year Return Level			50 Year Return Level			100 Year Return Level		
Station	Year	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO
	1925-26	-14.271 °C	-9.752 °C	-5.233 °C	-16.313 °C	-11.241 °C	-6.169 °C	-20.111 °C	-14.01 °C	-7.909 °C	-21.468 °C	-15 °C	-8.531 °C
	1950-51	-13.977 °C	-9.457 °C	-4.938 °C	-16.018 °C	-10.946 °C	-5.874 °C	-19.816 °C	-13.716 °C	-7.615 °C	-21.174 °C	-14.705 °C	-8.237 °C
	1975-76	-13.682 °C	-9.163 °C	-4.644 °C	-15.724 °C	-10.652 °C	-5.579 °C	-19.522 °C	-13.421 °C	-7.32 °C	-20.879 °C	-14.41 °C	-7.942 °C
	2000-01	-13.387 °C	-8.868 °C	-4.349 °C	-15.429 °C	-10.357 °C	-5.285 °C	-19.227 °C	-13.126 °C	-7.025 °C	-20.584 °C	-14.116 °C	-7.647 °C
	2014-15	-13.222 °C	-8.703 °C	-4.184 °C	-15.264 °C	-10.192 °C	-5.12 °C	-19.062 °C	-12.961 °C	-6.86 °C	-20.419 °C	-13.951 °C	-7.482 °C
Rothampsted	All years	-15.077 °C	-10.253 °C	-5.923 °C	-17.353 °C	-11.872 °C	-6.884 °C	-21.661 °C	-14.936 °C	-8.703 °C	-23.228 °C	-16.05 °C	-9.365 °C
Leuchars	1925-26	-12.517 °C	-8.046 °C	-3.575 °C	-14.267 °C	-9.171 °C	-4.074 °C	-17.34 °C	-11.146 °C	-4.951 °C	-18.376 °C	-11.811 °C	-5.246 °C
	1950-51	-13.487 °C	-9.016 °C	-4.544 °C	-15.236 °C	-10.14 °C	-5.043 °C	-18.31 °C	-12.115 °C	-5.92 °C	-19.345 °C	-12.78 °C	-6.216 °C
	1975-76	-13.95 °C	-9.479 °C	-5.008 °C	-15.699 °C	-10.603 °C	-5.507 °C	-18.773 °C	-12.578 °C	-6.383 °C	-19.808 °C	-13.243 °C	-6.679 °C
	2000-01	-13.907 °C	-9.436 °C	-4.965 °C	-15.656 °C	-10.56 °C	-5.464 °C	-18.73 °C	-12.535 °C	-6.341 °C	-19.765 °C	-13.201 °C	-6.636 °C
	2014-15	-13.662 °C	-9.191 °C	-4.72 °C	-15.411 °C	-10.315 °C	-5.219 °C	-18.485 °C	-12.29 °C	-6.096 °C	-19.52 °C	-12.956 °C	-6.391 °C
Eskdalemuir	1954-55	-21.06 °C	-15.28 °C	-9.5 °C	-23.456 °C	-16.96 °C	-10.465 °C	-27.284 °C	-19.645 °C	-12.006 °C	-28.45 °C	-20.463 °C	-12.476 °C
	1975-76	-19.69 °C	-13.91 °C	-8.13 °C	-21.815 °C	-15.319 °C	-8.823 °C	-25.208 °C	-17.569 °C	-9.93 °C	-26.243 °C	-18.255 °C	-10.268 °C
	2000-01	-18.059 °C	-12.279 °C	-6.499 °C	-19.86 °C	-13.364 °C	-6.869 °C	-22.737 °C	-15.099 °C	-7.46 °C	-23.614 °C	-15.627 °C	-7.64 °C
	2014-15	-17.145 °C	-11.365 °C	-5.585 °C	-18.766 °C	-12.27 °C	-5.774 °C	-21.354 °C	-13.715 °C	-6.076 °C	-22.143 °C	-14.155 °C	-6.168 °C
Hastings	1950-51	-9.157 °C	-5.538 °C	-1.919 °C	-10.66 °C	-6.488 °C	-2.315 °C	-13.218 °C	-8.103 °C	-2.988 °C	-14.051 °C	-8.629 °C	-3.208 °C
	1975-76	-9.208 °C	-5.589 °C	-1.97 °C	-10.711 °C	-6.539 °C	-2.366 °C	-13.269 °C	-8.154 °C	-3.039 °C	-14.102 °C	-8.68 °C	-3.259 °C
	2000-01	-9.259 °C	-5.64 °C	-2.021 °C	-10.762 °C	-6.59 °C	-2.417 °C	-13.32 °C	-8.205 °C	-3.09 °C	-14.153 °C	-8.731 °C	-3.309 °C
	2014-15	-9.285 °C	-5.666 °C	-2.047 °C	-10.789 °C	-6.616 °C	-2.443 °C	-13.346 °C	-8.231 °C	-3.117 °C	-14.18 °C	-8.758 °C	-3.336 °C
Plymouth	1950-51	-8.429 °C	-5.488 °C	-2.547 °C	-9.481 °C	-6.214 °C	-2.948 °C	-11.154 °C	-7.369 °C	-3.584 °C	-11.662 °C	-7.72 °C	-3.778 °C

		5 Year Return Level			10 Year Return Level			50 Year Return Level			100 Year Return Level		
Station	Year	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO	Extreme Low NAO	Average NAO	Extreme High NAO
	1975-76	-8.159 °C	-5.218 °C	-2.277 °C	-9.211 °C	-5.944 °C	-2.678 °C	-10.884 °C	-7.099 °C	-3.314 °C	-11.392 °C	-7.45 °C	-3.508 °C
	2000-01	-7.889 °C	-4.948 °C	-2.008 °C	-8.941 °C	-5.674 °C	-2.408 °C	-10.614 °C	-6.829 °C	-3.045 °C	-11.122 °C	-7.18 °C	-3.238 °C
	2014-15	-7.749 °C	-4.808 °C	-1.867 °C	-8.8 °C	-5.534 °C	-2.267 °C	-10.474 °C	-6.689 °C	-2.904 °C	-10.982 °C	-7.04 °C	-3.097 °C
Stornoway	1883-84	-11.564 °C	-8.731 °C	-5.898 °C	-12.968 °C	-9.886 °C	-6.803 °C	-15.45 °C	-11.926 °C	-8.403 °C	-16.29 °C	-12.618 °C	-8.945 °C
	1900-01	-10.352 °C	-7.519 °C	-4.686 °C	-11.757 °C	-8.674 °C	-5.592 °C	-14.238 °C	-10.715 °C	-7.192 °C	-15.079 °C	-11.406 °C	-7.734 °C
	1925-26	-10.017 °C	-7.184 °C	-4.351 °C	-11.421 °C	-8.339 °C	-5.257 °C	-13.903 °C	-10.38 °C	-6.856 °C	-14.743 °C	-11.071 °C	-7.398 °C
	1950-51	-10.439 °C	-7.606 °C	-4.773 °C	-11.843 °C	-8.761 °C	-5.678 °C	-14.325 °C	-10.801 °C	-7.278 °C	-15.165 °C	-11.493 °C	-7.82 °C
	1975-76	-10.538 °C	-7.705 °C	-4.872 °C	-11.942 °C	-8.86 °C	-5.777 °C	-14.424 °C	-10.9 °C	-7.377 °C	-15.264 °C	-11.592 °C	-7.919 °C
	2000-01	-9.234 °C	-6.401 °C	-3.568 °C	-10.639 °C	-7.556 °C	-4.474 °C	-13.12 °C	-9.597 °C	-6.073 °C	-13.961 °C	-10.288 °C	-6.616 °C
	2014-15	-7.489 °C	-4.656 °C	-1.823 °C	-8.893 °C	-5.811 °C	-2.728 °C	-11.375 °C	-7.851 °C	-4.328 °C	-12.215 °C	-8.543 °C	-4.87 °C
Wick	1930-31	-10.512 °C	-7.718 °C	-4.923 °C	-11.53 °C	-8.646 °C	-5.762 °C	-13.044 °C	-10.027 °C	-7.009 °C	-13.472 °C	-10.417 °C	-7.362 °C
	1950-51	-11.755 °C	-8.96 °C	-6.165 °C	-12.772 °C	-9.888 °C	-7.004 °C	-14.287 °C	-11.269 °C	-8.252 °C	-14.714 °C	-11.659 °C	-8.604 °C
	1975-76	-12.362 °C	-9.568 °C	-6.773 °C	-13.38 °C	-10.496 °C	-7.612 °C	-14.894 °C	-11.877 °C	-8.859 °C	-15.322 °C	-12.266 °C	-9.211 °C
	2000-01	-11.518 °C	-8.723 °C	-5.929 °C	-12.536 °C	-9.652 °C	-6.767 °C	-14.05 °C	-11.032 °C	-8.015 °C	-14.477 °C	-11.422 °C	-8.367 °C
	2014-15	-10.115 °C	-7.32 °C	-4.526 °C	-11.133 °C	-8.248 °C	-5.364 °C	-12.647 °C	-9.629 °C	-6.612 °C	-13.074 °C	-10.019 °C	-6.964 °C

Table 11: probability of experiencing an extreme temperature (as given by the 85th, 90th and 95th quantile of temperature data) in any given year for extreme positive, average and negative phase of the NAO index

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
	Temp	***-10 ºC***	***-15 ºC***	***-20 ºC***	***-10 ºC***	***-15 ºC***	***-20 ºC***	***-10 ºC***	***-15 ºC***	***-20 ºC***
Balmoral	1920-21	0.69	0.21	0.03	0.53	0.04	0.00	0.12	0.00	0.00
	1950-51	0.74	0.29	0.08	0.63	0.13	0.01	0.40	0.00	0.00
	1975-76	0.75	0.33	0.10	0.66	0.18	0.02	0.48	0.02	0.00
	2000-01	0.76	0.33	0.11	0.67	0.18	0.02	0.49	0.02	0.00
	2014-15	0.75	0.33	0.10	0.66	0.18	0.02	0.48	0.02	0.00
	Temp	***-1 ºC***	***-4 ºC***	***-6 ºC***	***-1 ºC***	***-4 ºC***	***-6 ºC***	***-1 ºC***	***-4 ºC***	***-6 ºC***
Bude	All years	1.00	0.56	0.30	1.00	0.39	0.12	1.00	0.08	0.00
	Temp	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***
Craibstone	All years	0.14	0.00	0.00	0.05	0.10	0.06	0.03	0.01	0.00
	Temp	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***
Durham	1880-81	0.59	0.47	0.36	0.22	0.13	0.08	0.01	0.00	0.00
	1900-01	0.55	0.43	0.33	0.19	0.11	0.06	0.01	0.00	0.00
	1925-26	0.50	0.39	0.29	0.16	0.09	0.05	0.00	0.00	0.00
	1950-51	0.46	0.35	0.25	0.13	0.07	0.04	0.00	0.00	0.00
	1975-76	0.41	0.31	0.22	0.10	0.06	0.03	0.00	0.00	0.00
	2000-01	0.37	0.27	0.19	0.08	0.04	0.02	0.00	0.00	0.00

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
	2014-15	0.35	0.25	0.18	0.07	0.04	0.02	0.00	0.00	0.00
	Temp	***-10 ºC***	***-11 ºC***	***-14ºC***	***-10 ºC***	***-11 ºC***	***-14ºC***	***-10 ºC***	***-11 ºC***	***-14ºC***
Oxford	1853-54	0.22	0.17	0.07	0.10	0.06	0.01	0.00	0.00	0.00
	1875-76	0.22	0.17	0.06	0.09	0.06	0.01	0.00	0.00	0.00
	1900-01	0.22	0.16	0.06	0.09	0.06	0.01	0.00	0.00	0.00
	1925-26	0.21	0.16	0.06	0.09	0.05	0.01	0.00	0.00	0.00
	1950-51	0.21	0.16	0.06	0.08	0.05	0.01	0.00	0.00	0.00
	1975-76	0.21	0.15	0.06	0.08	0.05	0.01	0.00	0.00	0.00
	2000-01	0.20	0.15	0.05	0.08	0.04	0.01	0.00	0.00	0.00
	2014-15	0.20	0.15	0.05	0.07	0.04	0.01	0.00	0.00	0.00
	Temp	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***	***-11 ºC***	***-12 ºC***	***-13ºC***
Rothampsted	All years	0.183193	0.139111	0.10459	0.066669	0.041434	0.024977	0.001557	0.000321	4.45E-05
	Temp	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***
Leuchars	1925-26	0.14	0.10	0.07	0.02	0.01	0.00	0.00	0.00	0.00
	1950-51	0.16	0.11	0.08	0.03	0.01	0.01	0.00	0.00	0.00
	1975-76	0.16	0.12	0.09	0.04	0.02	0.01	0.00	0.00	0.00
	2000-01	0.16	0.12	0.09	0.04	0.02	0.01	0.00	0.00	0.00
	2014-15	0.16	0.12	0.08	0.03	0.02	0.01	0.00	0.00	0.00
	Temp	***-15 ºC***	***-16 ºC***	***-17ºC***	***-15 ºC***	***-16 ºC***	***-17ºC***	***-15 ºC***	***-16 ºC***	***-17ºC***

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
Eskdalemuir	1954-55	0.13	0.10	0.07	0.06	0.04	0.02	0.01	0.00	0.00
	1975-76	0.12	0.09	0.06	0.05	0.03	0.02	0.01	0.00	0.00
	2000-01	0.11	0.08	0.05	0.04	0.02	0.01	0.00	0.00	0.00
	2014-15	0.10	0.07	0.05	0.04	0.02	0.01	0.00	0.00	0.00
	Temp	***-6 ºC***	***-7 ºC***	***-8ºC***	***-6 ºC***	***-7 ºC***	***-8ºC***	***-6 ºC***	***-7 ºC***	***-8ºC***
Hastings	1950-51	0.26	0.18	0.12	0.07	0.03	0.01	0.00	0.00	0.00
	1975-76	0.26	0.18	0.12	0.07	0.03	0.01	0.00	0.00	0.00
	2000-01	0.26	0.18	0.12	0.08	0.03	0.01	0.00	0.00	0.00
	2014-15	0.26	0.18	0.12	0.08	0.03	0.01	0.00	0.00	0.00
	Temp	***-5 ºC***	***-6 ºC***	***-7ºC***	***-5 ºC***	***-6 ºC***	***-7ºC***	***-5 ºC***	***-6 ºC***	***-7ºC***
Plymouth	1950-51	0.17	0.11	0.27	0.04	0.01	0.09	0.00	0.00	0.00
	1975-76	0.17	0.10	0.26	0.03	0.01	0.08	0.00	0.00	0.00
	2000-01	0.16	0.09	0.25	0.03	0.01	0.07	0.00	0.00	0.00
	2014-15	0.15	0.09	0.24	0.02	0.00	0.07	0.00	0.00	0.00
	Temp	***-8 ºC***	***-9 ºC***	***-10ºC***	***-8 ºC***	***-9 ºC***	***-10ºC***	***-8 ºC***	***-9 ºC***	***-10ºC***
Stornoway	1883-84	0.15	0.10	0.07	0.07	0.04	0.02	0.01	0.00	0.00
	1900-01	0.13	0.09	0.05	0.05	0.03	0.01	0.01	0.00	0.00
	1925-26	0.13	0.08	0.05	0.05	0.02	0.01	0.00	0.00	0.00
	1950-51	0.13	0.09	0.06	0.06	0.03	0.01	0.01	0.00	0.00

Station	Year	Extreme Low NAO (extremely cold winter)			Average NAO (average winter)			Extreme High NAO (extremely warm winter)		
	1975-76	0.14	0.09	0.06	0.06	0.03	0.01	0.01	0.00	0.00
	2000-01	0.11	0.07	0.04	0.04	0.02	0.01	0.00	0.00	0.00
	2014-15	0.08	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00
	Temp	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***	***-10 ºC***	***-11 ºC***	***-12ºC***
Wick	1930-31	0.08	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.00
	1950-51	0.11	0.07	0.04	0.03	0.01	0.00	0.00	0.00	0.00
	1975-76	0.12	0.08	0.04	0.04	0.02	0.00	0.00	0.00	0.00
	2000-01	0.10	0.06	0.03	0.02	0.01	0.00	0.00	0.00	0.00
	2014-15	0.07	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00