THE UNIVERSITY *of* EDINBURGH
School of GeoSciences

Natural Hazards and Risk

North Atlantic Oscillation Influence on UK Precipitation

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Declaration

I declare that this report is my own work.

Contents

1 Introduction

The North Atlantic Oscillation (NAO) is one of the most significant patterns of atmospheric fluctuations observed in the higher latitudes of the Northern Hemisphere [1]. Particularly prominent during the winter months, the NAO plays a major role in dictating the climate across North America and Western Europe in terms of temperature, precipitation and wind [2].

Peaks and troughs in winter temperature were first documented in Greenland and Germany from 1709 - 1800 making the NAO one of the first discovered global weather patterns and is becoming a more and more popular subject of interest among meteorological modellers and statisticians due to its impact on weather patterns such as UK rainfall, see figure 1.

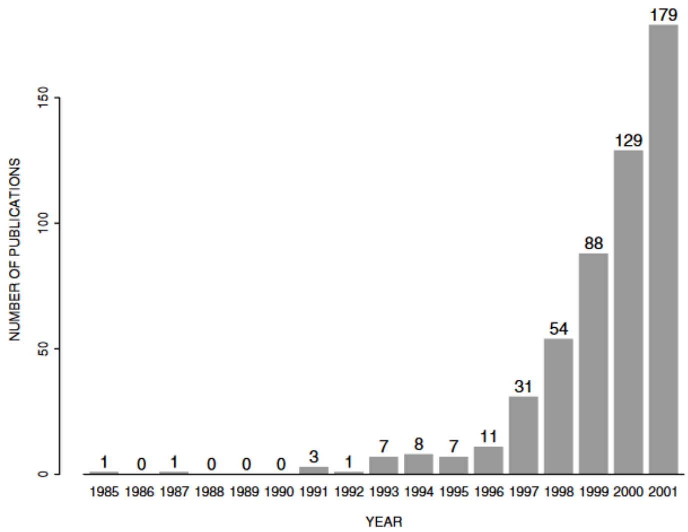


Figure 1: The increasing number of publications referring to the NAO in title or abstract by year [3]

Therefore, understanding and modelling the atmospheric dynamics associated with the NAO is extremely valuable as shown recent efforts using the Met Office's global climate model [4]. Another ongoing area of research is measuring the impacts on local climates. Here, the aim is to understand the influence the NAO has on UK precipitation.

1.1 NAO Index

There is a typical pressure difference between, the lower pressure, Icelandic Low and the, higher pressure, Azores High which determines the speed of westerly winds into Europe. We quantify the prominence of the NAO by defining the NAO index as how much greater this pressure difference is than expected. A positive NAO index (NAO+) means this pressure difference is greater than usual while a negative NAO index (NAO-) means this pressure difference is lesser than usual. NAO+ and NAO- tend to come in phases as shown in figure 2.

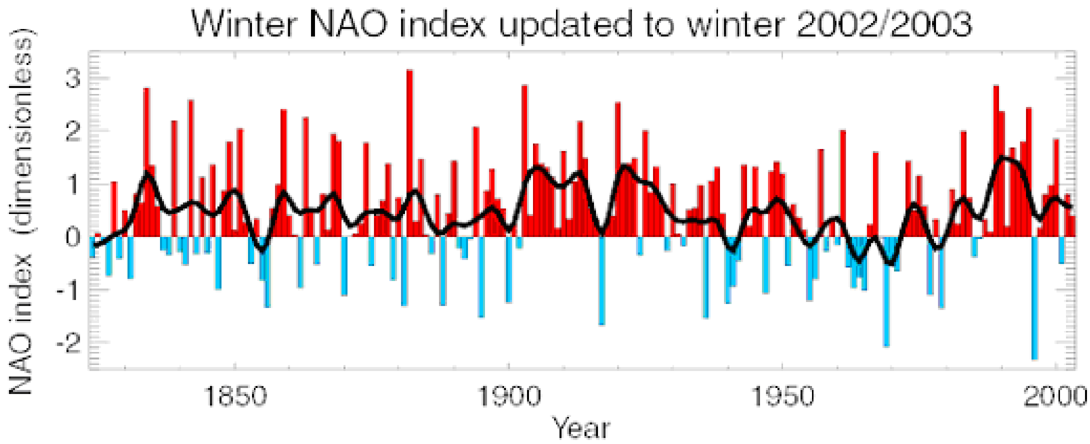


Figure 2: History of the NAO index 1823 - 2002 normalised to a mean value (December - March) over the whole period. The coloured bars show each annual value while the black curve shows a rolling average [5]

In the NAO+ phase, the greater pressure difference gives rise to stronger winds from the west directed more towards northern Europe [6], in turn, transporting increased moisture as shown in figure 3a. This has been shown to correlate with increased precipitation in the UK as displayed in figure 3b.

Here, an attempt is made to verify these correlations between winter NAO Index and UK extreme monthly and daily maximum precipitation, using a data analysis approach. Monthly maximum precipitation, which can saturate the ground, is analysed first, followed by an analysis of daily maximum precipitation which can lead to flooding if coinciding with the monthly maximum.

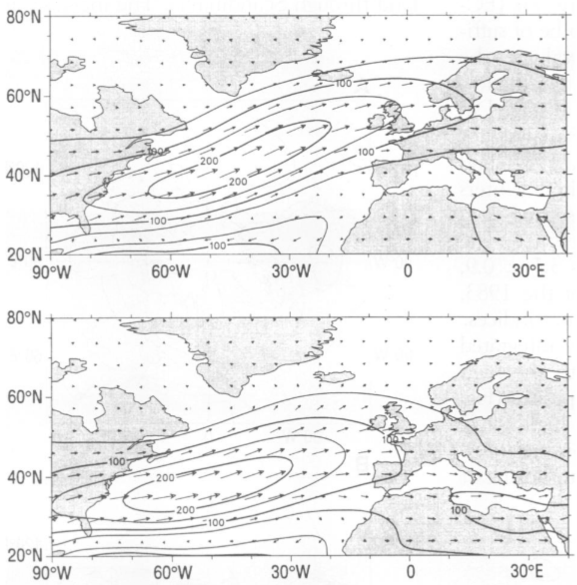
1.2 Datasets

The monthly NAO index time series are differences in sea level pressure, as measured by one station in Azores and another in Iceland, maintained by the University of East Anglia Climatic Research Unit [8]. The values are in units of standard deviations from the mean.

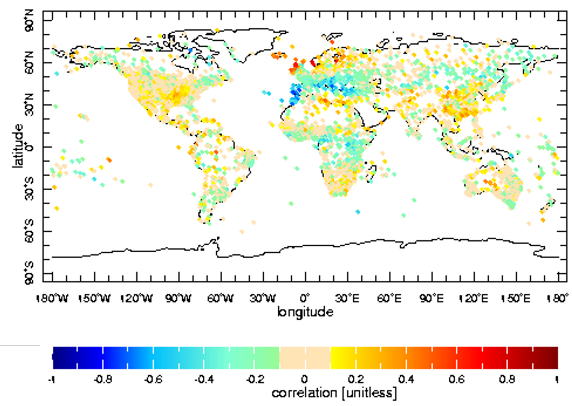
The monthly England/Wales and the daily Scotland precipitation values are maintained by the Met Office Hadley Centre [9]. These values are in units of mm.

2 Methods

To preprocess the NAO index data 1.2, all measurements preceding December 1830 and following March 2021 were dropped and then all months other than the winter months (December - March) were removed. The data was checked for any null values or artefacts from downloading the series but there were none found. The data was re-expressed by subtracting the mean of all remaining December values from each December value, the mean of all remaining January values from each January value etc. so each January value was now the deviation from a typical January. This would calibrate to the expected pattern of NAO indices within a winter which would make monthly extreme values more



(a)



(b)

Figure 3: (a) above is a contour plot of moisture transports for high NAO index winters while below is for normal or low NAO index winters showing the increased moisture transport across northern Europe [7]. (b) is a plot of NAO correlation with precipitation which shows the high correlation in northern Europe and the UK [6]

pronounced. For example, if NAO indices follow a trend of maxima in January and are decaying by March then, without this step, it may be less clear whether a high January value is high enough to be considered remarkable or is just typical of January. If there is no such pattern within each winter, the dataset is large enough that the mean of all Januaries would be similar to the mean of all winter months so little to no information is compromised. This gave the new timeseries shown in figure 4.

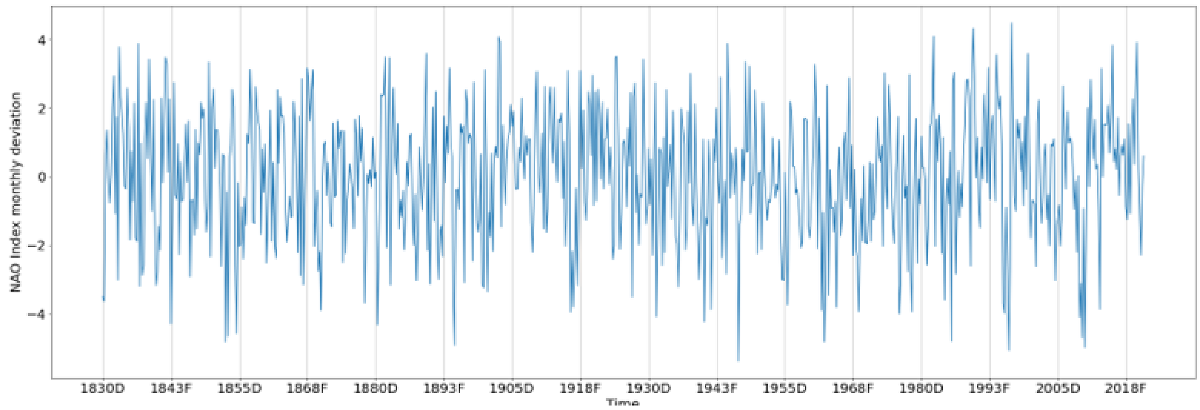


Figure 4: Monthly deviation in NAO index for winter months. Timescale on x-axis is discontinuous where D - Dec, J - Jan, F - Feb and M- Mar. Roughly scattered around the x-axis as expected but heights of peaks are relative to the average of the month they occur.

2.1 England/Wales Monthly Precipitation

The England/Wales monthly precipitation data 1.2 was cut to cover the same time range as the NAO data (Dec 1830 - Mar 2021 winter months only). A scatter plot was generated to visualise any correlation between NAO index and England/Wales monthly precipitation. The Pearson correlation coefficient was also calculated.

The precipitation data was then divided in two. One subset of values at months where the NAO index monthly deviation was positive or zero, called ‘pcppos’ data, and another subset of values at months where the NAO index monthly deviation was negative, called ‘pcpneg’ data. The two new data histograms were plotted on the same axes to visualise any differences in the two distributions.

The values of precipitation at percentiles ranging from 50th - 100th were recorded and the ratio of the number of pcppos events to the number of pcpneg events exceeding each precipitation was calculated and plotted to reveal if the tail of the distribution, meaning the highest precipitation events, contained more or less of the pcppos data subset.

2.2 Scotland Daily Precipitation

The same checks for null values were made on the Scotland daily precipitation data 1.2. There were null values but they were to be expected as they all fell on Feb 29th, April 31st etc so did not have to be cleaned up. The dataset spanned 91 years so selecting the annual maxima from these daily maxima gave a new distribution of 91 values. This distribution was fitted with a generalised extreme value distribution [10] using maximum likelihood estimation, by minimising negative log-likelihood, to estimate the; location parameter μ - where the distribution is centred; scale parameter σ - the spread of the distribution and the shape parameter ξ - the thickness of the tail. The parameter errors were estimated statistically by the fit as well as from a bootstrap resampling method. The fit was further evaluated by a P-P plot and a Q-Q plot [11].

The timeseries of the new annual maxima of daily maxima was plotted to identify any further trends and the return periods of three of the peaks were estimated using the fact that if $p(y > y_m) = \frac{1}{m}$, where y_m is the value of interest then m is the return period in years as block length is one year (annual values).

The analysis was all carried out in Python using standard libraries - NumPy, Pandas, SciPy and iminuit for curve fitting. The Scipy.stats.genextreme methods pdf, returning the probability density function, and cdf, returning the cumulative distribution function, were particularly useful for fitting and calculating the return periods respectively.

3 Results

3.1 England/Wales Monthly Precipitation

Monthly precipitation against NAO index is shown in figure 5 and looks like a cloud of points with no obvious correlation as rainfall is very variable. However, the points are not totally randomly distributed and this is confirmed upon calculating a Pearson correlation coefficient of 0.23 which is not negligible.

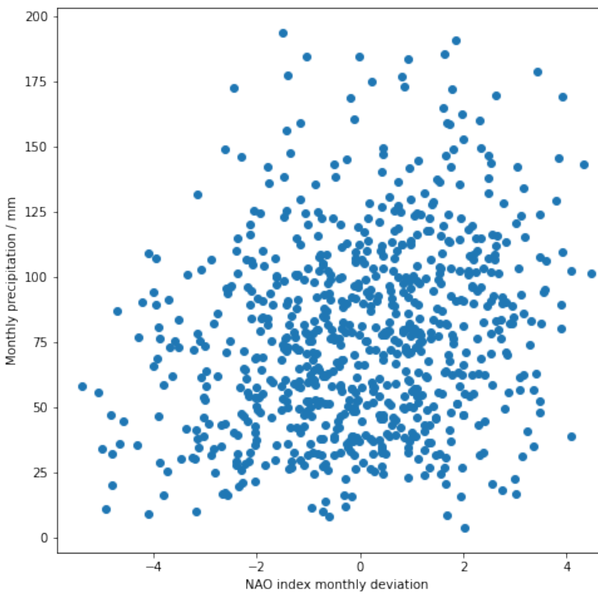
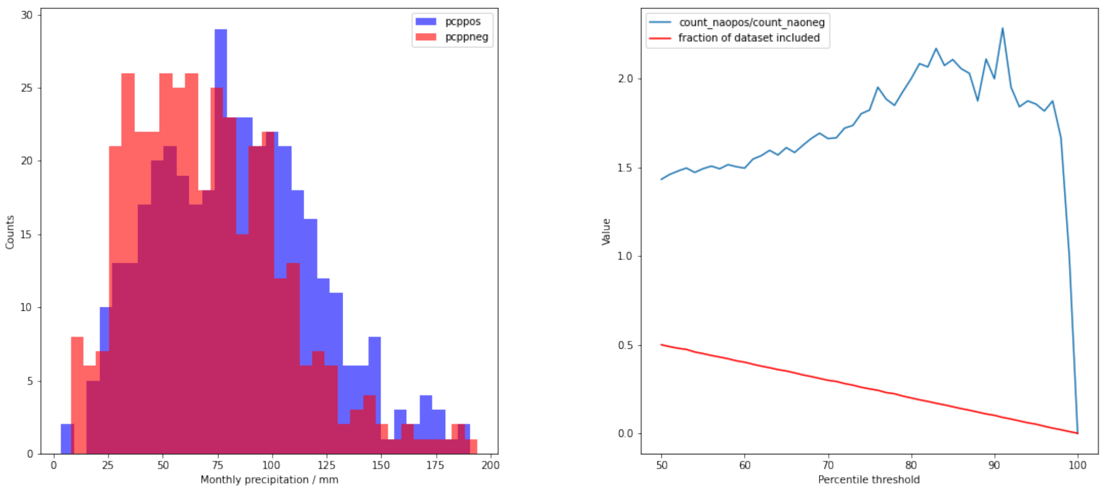


Figure 5: Monthly England/Wales precipitation against NAO index monthly deviation.

The distributions and ratio of pcppos and pcpneg data subsets are shown in figure

6. The distributions are clearly different and the pcppos distribution contains more high precipitation events which agrees with there being a positive correlation between winter NAO index and England/Wales precipitation. In figure 6b, at the 85th percentile the extra pcppos data points in the tail of the overall distribution is quantified as the ratio is 2.1 pcppos points to pcpneg point above the 85th percentile.

To further confirm that the pcppos and pcpneg distributions are different, a statistical test such as the Mann-Whitney U test [12] could be performed to obtain the p-value that these observed differences could be statistically expected assuming the underlying distributions were actually the same. This could be future work.



(a) (b)

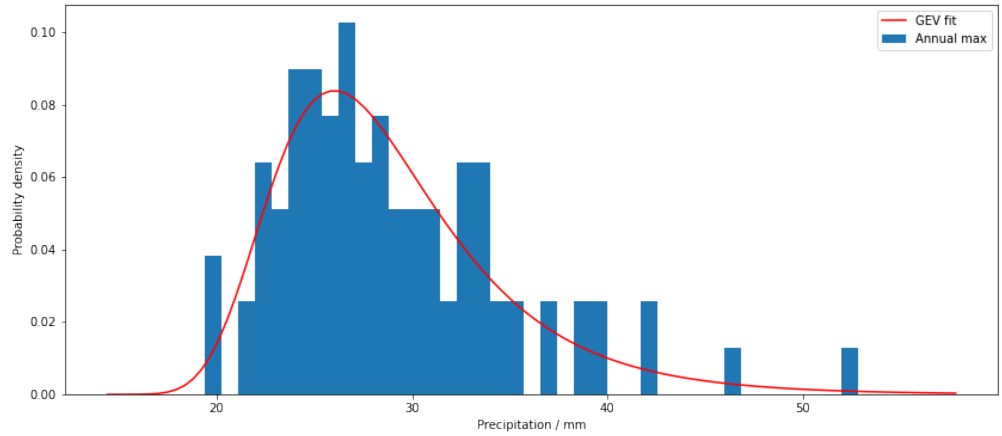
Figure 6: (a) Blue is the pcppos distribution and red is the pcpneg distribution which shows that the precipitation values in the pcppos distribution are typically greater than those in the pcpneg distribution. (b) confirms this by showing the ratios by percentile, the red line shows the fraction of the overall dataset included in the calculation ie more values make the calculation more reliable. Hence, 85th percentile gives the maximum ratio without excluding too many points.

3.2 Scotland Daily Precipitation

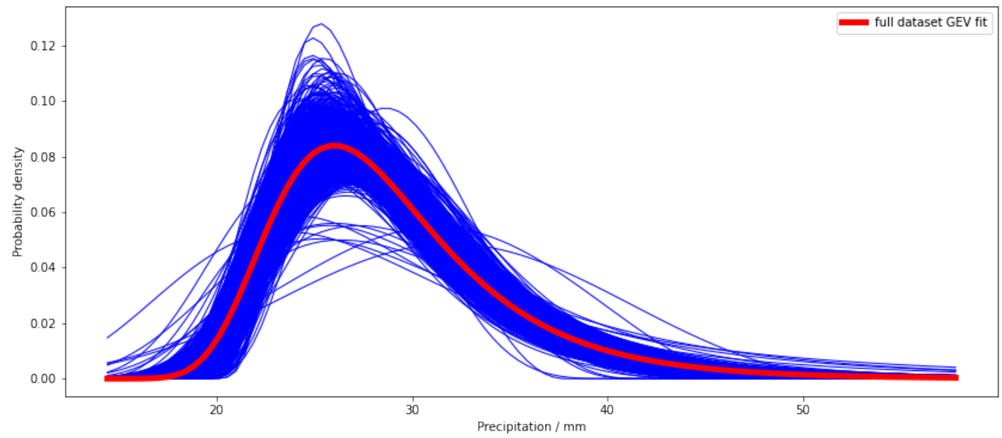
The results of the maximum likelihood fit gave:

$$\mu = 26.2 \pm 0.08$$
$$\sigma = 4.4 \pm 0.5$$
$$\xi = -0.05 \pm 0.08$$

The tail shape $\xi < 0$ corresponds to a Weibull distribution. This is not typical for precipitation values [13]. However, the error of 0.08 is significant and makes the estimate for the tail shape less reliable and the data could actually follow a Gumbel distribution ($\xi = 0$) or even a Frechet distribution ($\xi > 0$). Here the block length is a year so taking a shorter block length would increase the number of data points the fit is based on which would help get a more reliable fit especially in the tail, where we find the fewest data points. However, it has to be clear that the values are still extreme enough to follow a GEV distribution. The bootstrap method generated distributions of plausible μ, σ and ξ by respampling the data 1000 times and fitting each time. The bootstrap errors, $\Delta\mu, \Delta\sigma$ and $\Delta\xi$ were the standard deviation of there respective distributions - $0.5, 0.5$ and 0.11. This is further evidence that the tail shape ξ is not confidently estimated.



(a)

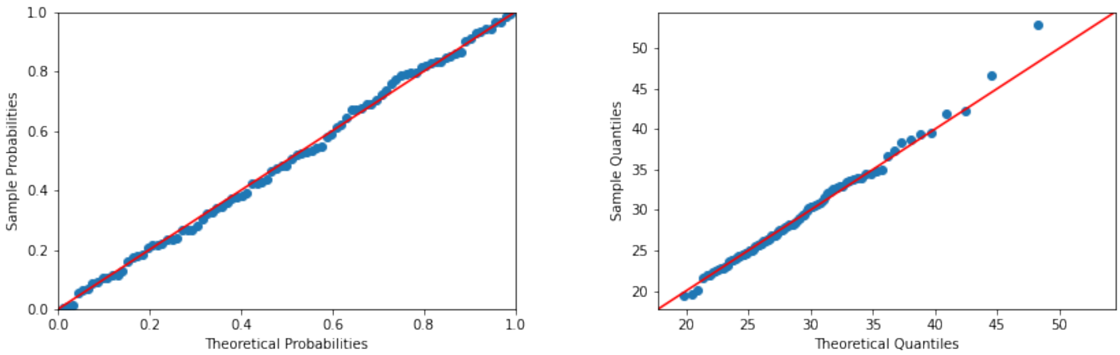


(b)

Figure 7: (a) The annual maxima of daily maximum precipitation data histogram overlayed with a maximum likelihood fit. (b) The same dataset resampled 1000 times, allowing the same value to be sampled multiple times, and a fit carried out for each with the original fit in red.

The quality of the fit was evaluated by percentile-percentile (P-P) and quantile-

quantile (Q-Q) probability plots given in figure 8. The 45° line in each would be a perfect fit where scanning across the percentiles and quantiles of the real sample distribution and the theoretical distribution from the fit always gives the same number of events. The P-P plot looks good while we do see in the high end of the Q-Q plot that the tail thickness may be underestimated as for the last point, the sample distribution counts reach the top quantile before the theoretical distribution as maximum precipitation increases.



(a) (b)

Figure 8: (a) The P-P plot evaluating the fit. (b) The Q-Q plot evaluating the fit. The red 45 ° lines would be given by an ideal fit. In the Q-Q plot we see the discrepancy in the tail of the distribution ie. high quantiles.

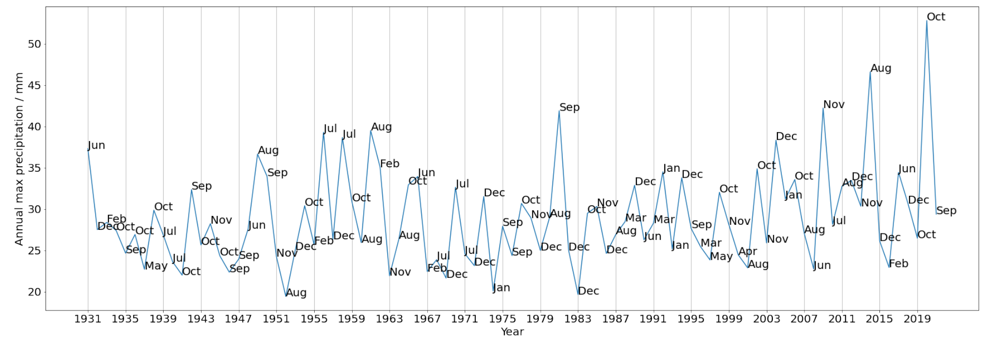
The timeseries of the wettest day in year is shown in figure 9. By visual inspection, there is a slight increasing trend that is more noticeable in recent years as all three of the highest maxima are later than 2007. Two of the highest peaks occurred in September 1981 and October 2020 with return periods of 29 years and 211 years respectively, so very rare events.

Unexpectedly, the wettest days rarely occurred in winter months other than December. The peak in December 2004 had a return period of 14 years but the England/Wales maximum monthly precipitation in that time was only 63.8 mm which is quite unremarkable. The winter NAO index monthly deviation at this time was 0.89 so slightly higher than a typical December. Floods in Scotland in September 1981 [14] and October 2020 are well documented - the October 2020 maximum occurred on the 3rd October at the peak of Storm Alex [15].

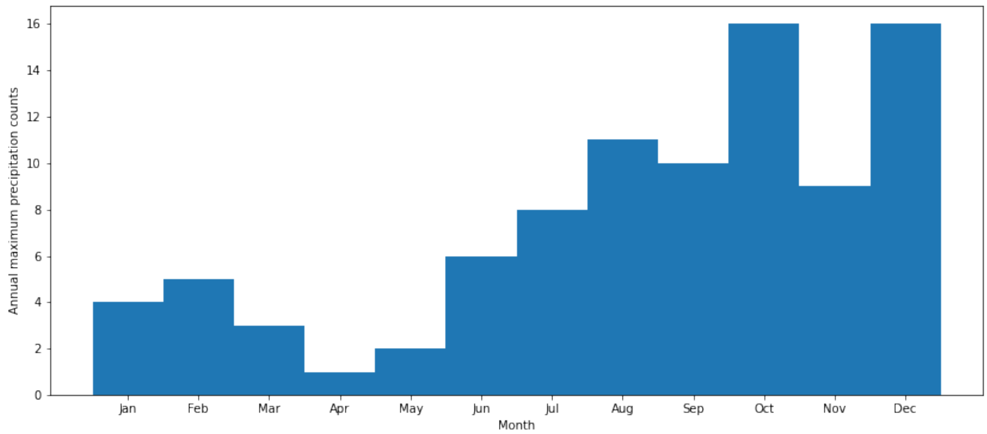
4 Summary

In conclusion, despite high variability in rainfall, the NAO does influence UK precipitation. This was revealed by finding a mild correlation between winter NAO index monthly deviation and England/Wales precipitation monthly maxima. Also, from inspecting pcppos and pcpneg distributions, the higher precipitation monthly maxima often occurred when the NAO index was higher than usual.

A GEV model has been fitted to Scotland annual maxima of daily maximum precipitation data. However, the true tail shape of the underlying distribution is still unclear.



(a)



(b)

Figure 9: (a) Timeseries of wettest day in a year. (b) Distribution of months wettest days in year occurred in.

The return periods for some of the most extreme maxima have been estimated using the fit and aligned with media reports on floods and storms in some cases. There is no evidence that when we zoom in to particular extreme precipitation events, they were caused by high NAO perhaps due to the natural variability in rainfall, other factors or the poor estimation of the tail shape.

References

[1] James W. Hurrell, Yochanan Kushnir, Geir Ottersen, and Martin Visbeck. *An Overview of the North Atlantic Oscillation*, pages 1–35. American Geophysical Union (AGU), 2003. 2

[2] North atlantic oscillation, Met Office. https://www.metoffice.gov.uk/weather/learn-about/weather/atmosphere/north-atlantic-oscillation. Accessed 10th March 2022. 2

[3] David B. Stephenson, Heinz Wanner, Stefan Brönnimann, and Jürg Luterbacher. *The History of Scientific Research on the North Atlantic Oscillation*, pages 37–50. American Geophysical Union (AGU), 2003. 2

[4] A. A. Scaife and Arribas et al. Skillful long-range prediction of european and north american winters. *Geophysical Research Letters*, 41(7):2514–2519, 2014. 2

[5] Nao index for the period 1823 - 2002, European Envoronment Agency. https://www.eea.europa.eu/data-and-maps/figures. Accessed 10th March 2022. 3

[6] North atlantic oscillation, Columbia Climate School. https://www.ldeo.columbia.edu/res/pi/NAO/. Accessed 10th March 2022. 3, 4

[7] James W. Hurrell. Decadal trends in the north atlantic oscillation: Regional temperatures and precipitation. *Science*, 269(5224):676–679, 1995. 4

[8] P. D. Jones, T. Jonsson, and D. Wheeler. Extension to the north atlantic oscillation using early instrumental pressure observations from gibraltar and south-west iceland. *International Journal of Climatology*, 17(13):1433–1450, 1997. 3

[9] L.V. Alexander and P.D. Jones. Updated precipitation series for the u.k. and discussion of recent extremes. *Atmospheric Science Letters*, 1(2):142–150, 2000. 3

[10] Generalized exterme value distribution, Wikipedia. https://en.wikipedia.org/wiki/Generalized_extreme_value_distribution. Accessed 10th March 2022. 6

[11] Probability plot, Wikipedia. https://en.wikipedia.org/wiki/Probability_plot. Accessed 10th March 2022. 6

[12] H. B. Mann and D. R. Whitney. On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other. *The Annals of Mathematical Statistics*, 18(1):50 – 60, 1947. 7

[13] Naima Boudrissa, Hassen Cheraitia, and Lotfi Halimi. Modelling maximum daily yearly rainfall in northern algeria using generalized extreme value distributions from 1936 to 2009. *Meteorological Applications*, 24(1):114–119, 2017. 7

[14] M. C. Acreman. The significance of the flood of september 1981 on the ardessie burn, wester ross. *Scottish Geographical Magazine*, 99(3):150–161, 1983. 9

[15] Storm alex and heavy rain 2 to 4 october 202, Met Office. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2020/2020_09_storm_alex_1.pdf. Accessed 10th March 2022. 9