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Article

The Spatio-Temporal Influence of Atmospheric Circulations on Monthly Precipitation in Great Britain

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Abstract: It has long been understood that the North Atlantic Oscillation (NAO) is a key driver of regional climate in Great Britain and across Europe. However, studies have also noted that there is spatio-temporal variability in NAO-rainfall signatures which arguably limits its practical inclusion in water management. In this study we quantify, at high spatio-temporal resolution, the influence of a broader set of atmospheric circulations on monthly precipitation. Using Standardised Precipitation Indices for the Integrated Hydrological Unit (IHU) Groups of Great Britain we apply univariate and multivariate regression models to understand the potential of five atmospheric circulation indices to explain precipitation variability. As far as we are aware this represents the first high spatial and temporal resolution analysis quantifying the influence of a broad set of atmospheric circulations, both individually and in combination. We highlight the influence of each circulation and establish that the NAO only partially explains precipitation variability, especially in the southern regions and during the summer months, where circulations, such as the East Atlantic Pattern, also have an important influence. In summary, we suggest that there is significant explanatory value in looking beyond the NAO when seeking to understand hydroclimatological variability in Great Britain, and there is potential for future work to explore how this understanding can translate into the practical application of atmospheric circulation indices in water management.

Keywords: North Atlantic Oscillation; East Atlantic Pattern; Scandinavian Pattern; East Atlantic-West Russia Pattern; Polar/Eurasia Pattern; precipitation variability

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1. Introduction

Barnston and Livezey [1] identified a number of large-scale atmospheric-oceanic circulations (teleconnections) in the North Atlantic and European region. Subsequent studies have continued to explore how they interact and influence climate across various spatial and temporal scales. In particular, the North Atlantic Oscillation (NAO) has been identified as a key climatic driver [2,3], and strong associations between the phase and strength of the NAO and regional rainfall in Great Britain have been reported [4–6]. The NAO is defined by the difference in sea level pressure (SLP) between Iceland and the Azores [7] and fluctuates between positive (a greater than usual difference in SLP between Iceland the Azores) and negative (a weaker than usual difference in SLP between Iceland and the Azores) phases, quantified by North Atlantic Oscillation Indices (NAOI). Each phase of the NAO results in characteristic rainfall signatures in Great Britain [8]. Winter rainfall in the north-western regions, in particular, has a strong positive correlation with the NAOI [4,6,9,10], and whilst the NAO is weaker during the summer [11], negative NAOI-rainfall correlations across Great Britain have been reported [8,10,11]. The rainfall effect of the NAO propagates through the hydrological system [12] and relationships have been found with streamflow [13–17], groundwater [18,19] and water temperatures [20]. There is also potential to include the NAO into seasonal streamflow modelling and forecasting [21,22].

Whilst there are strong relationships between the NAO and rainfall (and subsequent hydrological variables), West et al. [23] found that NAO-rainfall signatures across Great Britain can vary over space and time. Whilst more temporally consistent and significant rainfall patterns were found in the north-west during winter, there was greater rainfall variability in the south and east [23]. Despite recent advancements in the skill of winter NAO forecasts [24,25], spatio-temporal variability in the NAO-rainfall effect is one of the limiting factors in the inclusion and application of the NAOI in water management [10,23,26].

Variability in NAO-rainfall signatures may be associated with other atmospheric circulations also influencing regional climate [8,23]. Based on the method of Barnston and Livezey [1], NOAA provide modelled monthly indices for different northern hemisphere circulations [27]. These have been used globally in studies exploring the impact of atmospheric circulations on climate, hydrology and the environment [28–33].

The East Atlantic Pattern (EA) is often defined as a monopole system, south of Iceland and west of Great Britain (≈55° N; 20–35° W) [1,34,35]. The EA is cited as the second most influential circulation affecting climate in the North Atlantic region, after the NAO [36,37]. Positive correlations between the EA and rainfall have been reported which are generally stronger in the southern regions of Great Britain and during winter [10,28,38]. The EA can influence the strength and location of the NAO dipoles [39,40] which results in different spatial distributions and volume of rainfall across Europe [35,38,41] and the likelihood of hydrological extremes [42,43]. Comas-Bru & McDermott [44] conclude that a combination of the NAO and EA may be able to explain winter climate variability more accurately across the North Atlantic region.

The Scandinavian Pattern (SCA) has a primary centre of action around the Scandinavian Peninsula and two secondary, oppositely signed, centres over the north-eastern Atlantic and central Siberia [45]. Originally referred to as the Eurasia-1 pattern, the SCA is the third leading mode of North Atlantic climate variability [1,44]. During winter, a positive SCA phase results in increased precipitation over southern Europe and the United Kingdom, and decreased precipitation over Scandinavia [45]. Like the EA, the SCA can affect the location and strength of the Azores High and Icelandic Low dipoles [40], subsequently influencing climatic variables such as temperature, rainfall and windspeed [44,46]. Rainfall deviations as a result of the phase of the SCA also propagate to streamflow in Scandinavia [33].

Two arguably lesser studied atmospheric circulations in the North Atlantic and European region include the East Atlantic-West Russia Pattern and the Polar/Eurasia Pattern. The East Atlantic-West Russia Pattern (EAWR) was originally referred to as the Eurasia-2 pattern by Barnston and Livezey [1]. Strong relationships between the EAWR and rainfall have been reported across the East Atlantic, Europe and the Mediterranean [47–49]. A positive phase of the EAWR results in drier conditions across Europe and the Mediterranean, whilst negative phases result in wetter conditions [50]. This relationship is strongest during the winter and decreases into late spring where there is no significant relationship [50]. The Polar/Eurasia Pattern (POL) is associated with variations in the circumpolar circulation with positive (negative) phases reflecting a stronger (weaker) polar vortex [1]. During winter POL has two action centres, over the Kara Sea and East Asia, and during summer an additional third centre over midlatitude Europe [1,51]. The POL influences climate predominately over Asia and eastern Europe [51] and may be linked to the NAO [52].

Whilst studies have explored the climatic effects of each of these atmospheric circulations, both individually and in various combinations, many have been undertaken at coarse spatial resolution across Europe and the North Atlantic, or have been restricted to the winter months (e.g., [35,40,44]). As far as we are aware, no study has yet explored at high resolution, the influence of all five of these circulations on monthly precipitation in Great Britain. This study aims to address this by firstly exploring how the circulations, both individually and in combination, are related to precipitation variability, and secondly how the relative importance of each circulation in influencing rainfall varies across space and time.

2. Methods

2.1. Data

As noted above, the NOAA Climate Prediction Centre [27] models monthly teleconnection indices, from 1950 onwards, based on the rotated principal component analysis approach of Barston and Livezey [1]. Such modelling approaches avoid limitations associated with indices derived from station-measured SLP data [53], principally the mobility of circulation action centres [40]. Monthly indices for the NAO, EA, SCA, EAWR and POL circulations were downloaded from NOAA for the period January 1950–December 2015, corresponding to the availability of the SPI time series described below.

To represent rainfall variability, Standardised Precipitation Index (SPI) time series were downloaded from the UK Centre for Ecology and Hydrology (CEH) aggregated for the Integrated Hydrological Unit (IHU) Groups of Great Britain [54]. These 105 IHU Groups are catchment-based zones and represent a useful basis for exploring spatial patterns, whilst retaining scale for water management relevance. The SPI time series had a one-month accumulation period (SPI-1), and were calculated by fitting a gamma distribution to historical Met Office 5 km rainfall grids with a standard period of 1961–2010 [54]. Monthly data (i.e., SPI with a one-month accumulation period) was chosen as to avoid the intra-/inter-seasonal dilution of teleconnection rainfall patterns [17]. The SPI-1 data are scaled from relative wetness (positive values) to dryness (negative values) allowing for an assessment of relative rainfall magnitude, or wet/dry severity, in a given month. The analysis period (January 1950–December 2015) therefore represents the greatest overlap across precipitation and circulation indices.

2.2. Regression Analysis

Stage 1 of the analysis quantifies the potential of each individual atmospheric circulations ability to infer precipitation variability across Great Britain. Univariate linear regression models were used to understand the strength of the relationship between the teleconnection index and SPI-1 time series for each calendar month across the IHU Groups. Based on these univariate models, the R^2 values were used to assess the strength of the relationship.

Stage 2 of the analysis explores whether atmospheric circulation indices, in combination, offer additional explanatory ability across space and time than indices in isolation. To do this a multiple linear regression model of all five atmospheric circulation indices was developed, with SPI-1 as the dependent variable. This was also undertaken for each calendar month and for all IHU Groups. Similar multiple regression models have been applied in understanding the combined effect of circulations in previous research [55]. As above, the R^2 values were used to evaluate the strength of the relationship, whilst the standardised coefficient (SC) (or beta coefficient) values for each teleconnection index gave an indication of the relative influence of each circulation in the model and the nature/directionality of the relationship with SPI-1. The SC values therefore identify the most influential atmospheric circulation affecting precipitation, its dominance relative to the other four circulations, and how this varies in space and time. Figure 1 describes the analytical stages undertaken in this study.

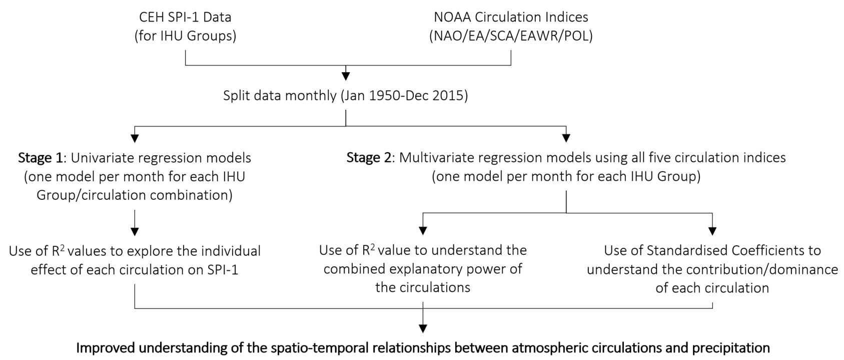

Figure 1. Flow chart summarizing the methodological stages of this study.

3. Results

3.1. Univariate Regression Models

Figure 2 shows the strength of the relationship (R^2 values) between the NAO index and SPI-1, which distinctly changes in space and time. The relationship between the NAO and SPI-1 is strongest during the winter months and in northern England and Wales and the Scottish regions. During summer the strength of the NAO SPI-1 relationship is weaker. Figure 3 shows the comparable R^2 values for the univariate EA regression model. Generally, the EA has a spatially and temporally consistent moderate relationship between the circulation index and SPI-1, which is weakest in the far north during winter and across large parts of the country in March, June and July.

Figure 2. R^2 values of the univariate regression model exploring the relationship between the NAO index and SPI-1 values across the IHU Groups. Climate Districts relate to the nine Met Office Climate Distracts of Great Britain–a spatial unit used in previous research [4,8,9,38].

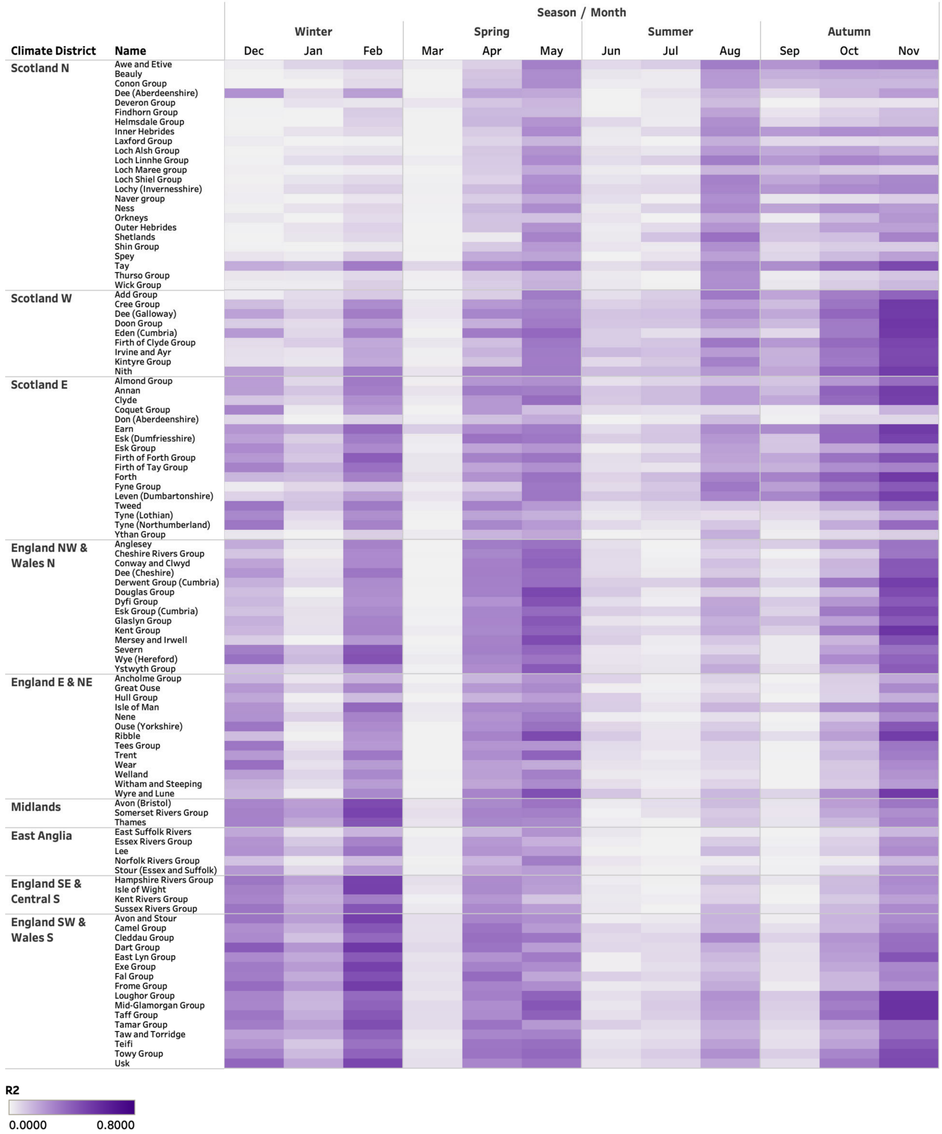

Figure 3. R^2 values of the univariate regression model exploring the relationship between the EA index and SPI-1 values across the IHU Groups.

The NAO and EA models have the strongest R^2 values between the circulation indices and SPI-1, relative to the univariate models for the SCA, EAWR and POL circulations-figures for which can be found Appendix A. The SCA generally has a weak relationship with SPI-1 across most of the country, with the exception of late winter–early autumn in the north of Scotland (Figure A1). Likewise, the EAWR R^2 values are generally weak, especially during the summer months. However, the EAWR does have a strong relationship with SPI-1 in the southern regions in January (Figure A2). The POL has a very weak relationship with SPI-1 across most of the year, especially during late spring and early summer (Figure A3).

3.2. Mutlivariate Regression Model

The results of the univariate regression analyses show that the ability of each circulation to explain precipitation varies in space and time, with the NAO and EA circulations generally having a stronger relationship with SPI-1. This stage of the analysis explores whether looking at the atmospheric circulation indices in combination offers greater explanatory ability than using the indices in isolation. Figure 4 shows the R^2 values of the multivariate regression model describing the strength of the relationship between a linear combination of the five circulation indices and SPI-1. In comparison to the univariate model outputs in Figures 2 and 3, and Figures A1–A3 (Appendix A), the multivariate model has more spatially and temporally consistent and stronger R^2 values. This indicates that there is additional value in looking at the combined effects of the atmospheric circulations in explaining precipitation variability, rather than considering circulations in isolation. The multiple regression model is notably stronger during the winter months across Great Britain, and there is improved performance in summer as well. The weakest relationship between the combined circulation indices and SPI-1 is found in March across England and Wales.

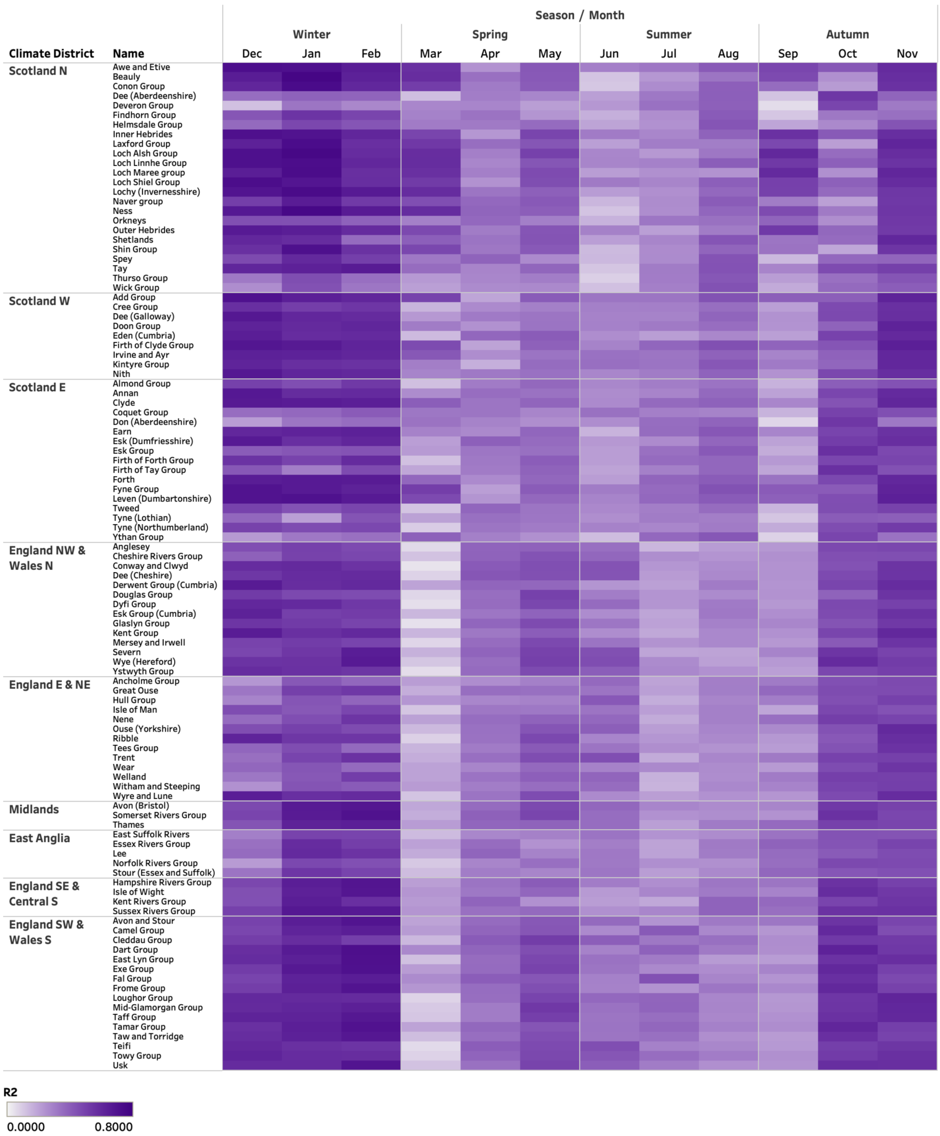

Figure 4. R^2 values of the multivariate regression model exploring the relationship between a combination of all five circulation indices and SPI-1 values across the IHU Groups.

Using the standardised coefficients (SC) of the circulation indices from the multiple regression analyses enables exploration of the strength and directionality (positive/negative) of these relationships. Figures 5–9 show the SC for each circulation index. The SC for the NAO (Figure 5) show the spatially and temporally variable nature of its relationship with precipitation. In the winter there is a positive relationship (green) with SPI-1, which is strongest in the north-western regions (also shown in the Figure 1). This indicates that positive phases of the NAO are associated with wetter conditions, and drier conditions with NAO negative phases. In Spring and Autumn more of a north-west/south-east spatial difference is observed, with positive SC in the north and negative SC (purple) in the south. Finally, the summer months show a negative relationship across most of the country between the NAO and SPI-1. This indicates the effect of the phase of the NAO on precipitation is opposite to winter in the summer months; with NAO positive (negative) phases associated with drier (wetter) conditions. For most of the year, the relationship remains relatively strong compared to the other indices.

Figure 6 shows the SC from the EA multivariate regression model. Whilst the relationship between the NAO and SPI-1 varies in directionality across space and time (Figure 5), the strength and the directionality of the EA's relationship with SPI-1 is more consistent. Figure 6 shows that the EA generally has a positive relationship with precipitation across most of the country; in other words, EA positive (negative) phases are associated with wetter (drier) conditions. The exception to this is in the north of Scotland during winter where weak and negative SC are observed (Figure 6).

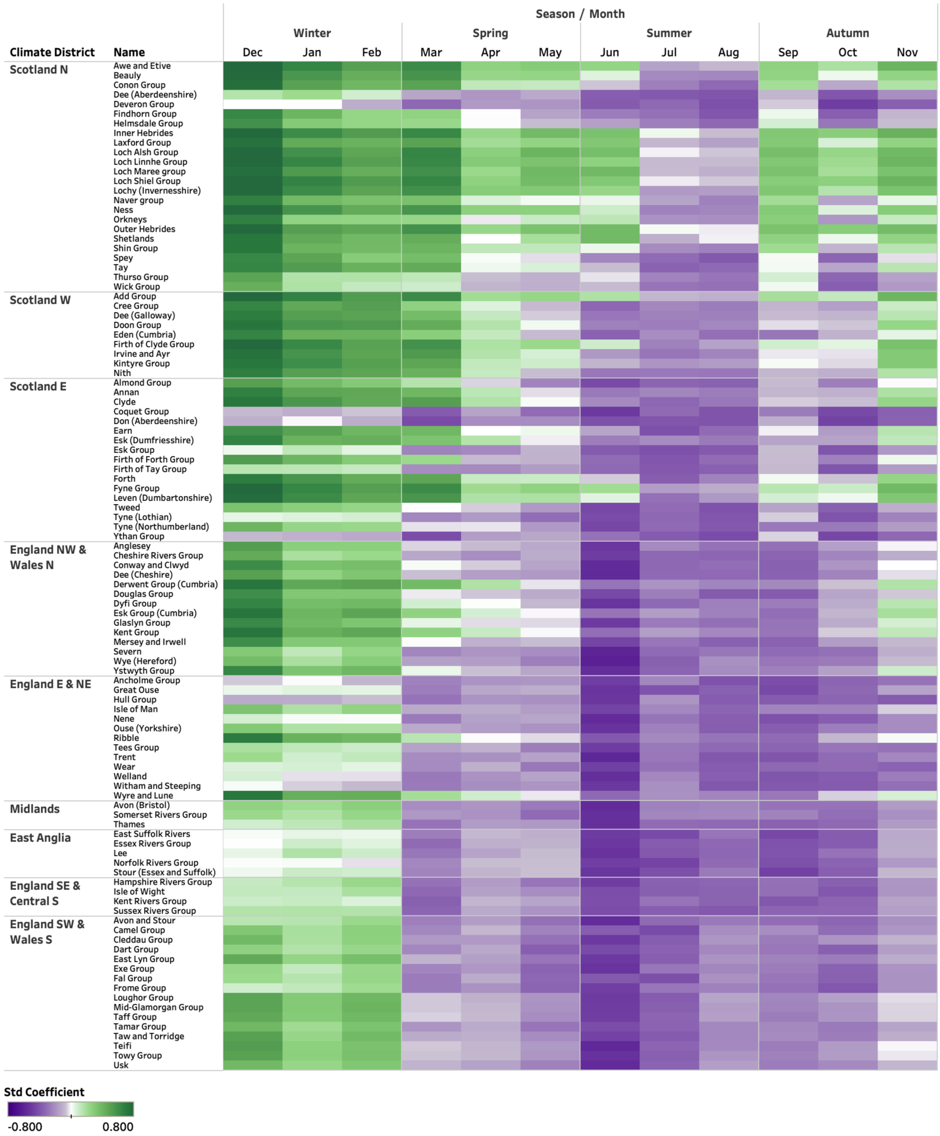

Figure 5. Standardised coefficient values for the NAO index from the multivariate regression model.

Like the NAO, the nature of the relationship between the SCA and precipitation has distinctive spatial differences across the year (Figure 7). For most of Great Britain, the relationship between the SCA and SPI-1 is positive, suggesting that SCA positive (negative) phases produce wetter (drier) conditions. However negative SC are observed in the north of Scotland, therefore indicating the opposite SCA phase-precipitation relationship. This negative pattern is observed in all months with consistent strength, except in December which has a weak positive directionality. Negative SC are also found in southern regions in January, February and July, although these are weaker than SC in Scotland.

Figures 8 and 9 show the SC for the EAWR and POL respectively. For the majority of the year both circulations have a negative relationship with precipitation, therefore positive phases of the EAWR and POL are more likely to result in drier conditions, and negative phases wetter conditions. Some months do have consistent positive SC, for example July and August in Figure 8, however these are weak. The EAWR has a stronger positive relationship in January and October, notably in the English and southern regions, and a weaker relationship during summer (similar to the pattern observed in the univariate analysis for the EAWR). The weaker POL SC (Figure 9) indicate that this circulation has a lesser influence on the model performance, and by inference precipitation variability, than the four other circulations (Figure 9). However, the POL SC are generally stronger in the summer than in the winter months.

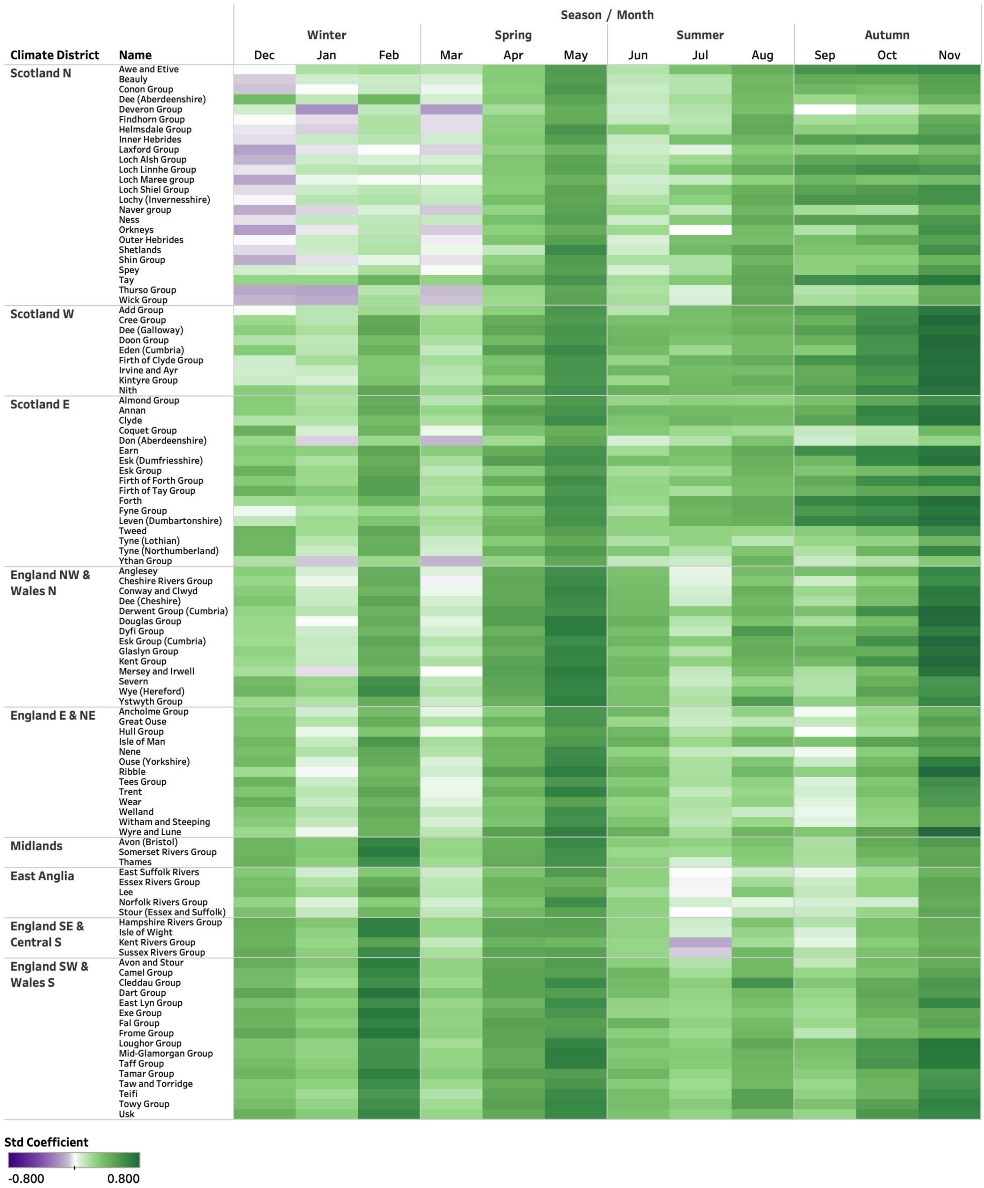

Figure 6. Standardised coefficient values for the EA index from the multivariate regression model.

Exploring the absolute SC values for each of the five atmospheric circulations in the multivariate regression model also enables evaluation of the relative dominance of each circulation, and how this varies in space and time. Figures A4–A8 in Appendix A show the SC plots, but with the colour indicative of the rank of the circulation relative to the other four (determined by the strength of the absolute SC). This is summarised in Figure 10, where the categorical colour classification shows the circulation with the strongest (highest ranking) absolute SC across the IHU Groups and all months.

During the winter months and early spring, the NAO is generally the dominant circulation influencing precipitation in the north west, with the SCA also having an influence in late winter and into spring and summer. In the southern and English regions, the EA is more influential. In the south, the EAWR is the most dominant circulation in January, with very strong (negative–as shown in Figure 8) absolute SC. In late spring the EA is the most influential pattern across most of the country, with the EAWR and SCA having a greater effect in a limited number of IHU Groups in the north. In the north, during summer, the SCA is more commonly the dominant circulation, with the EA and POL indices also being the most influential in some IHU Groups. In autumn, the EA is frequently the dominant pattern across large parts of Great Britain, with the EAWR also having a notable influence in the southern regions during October.

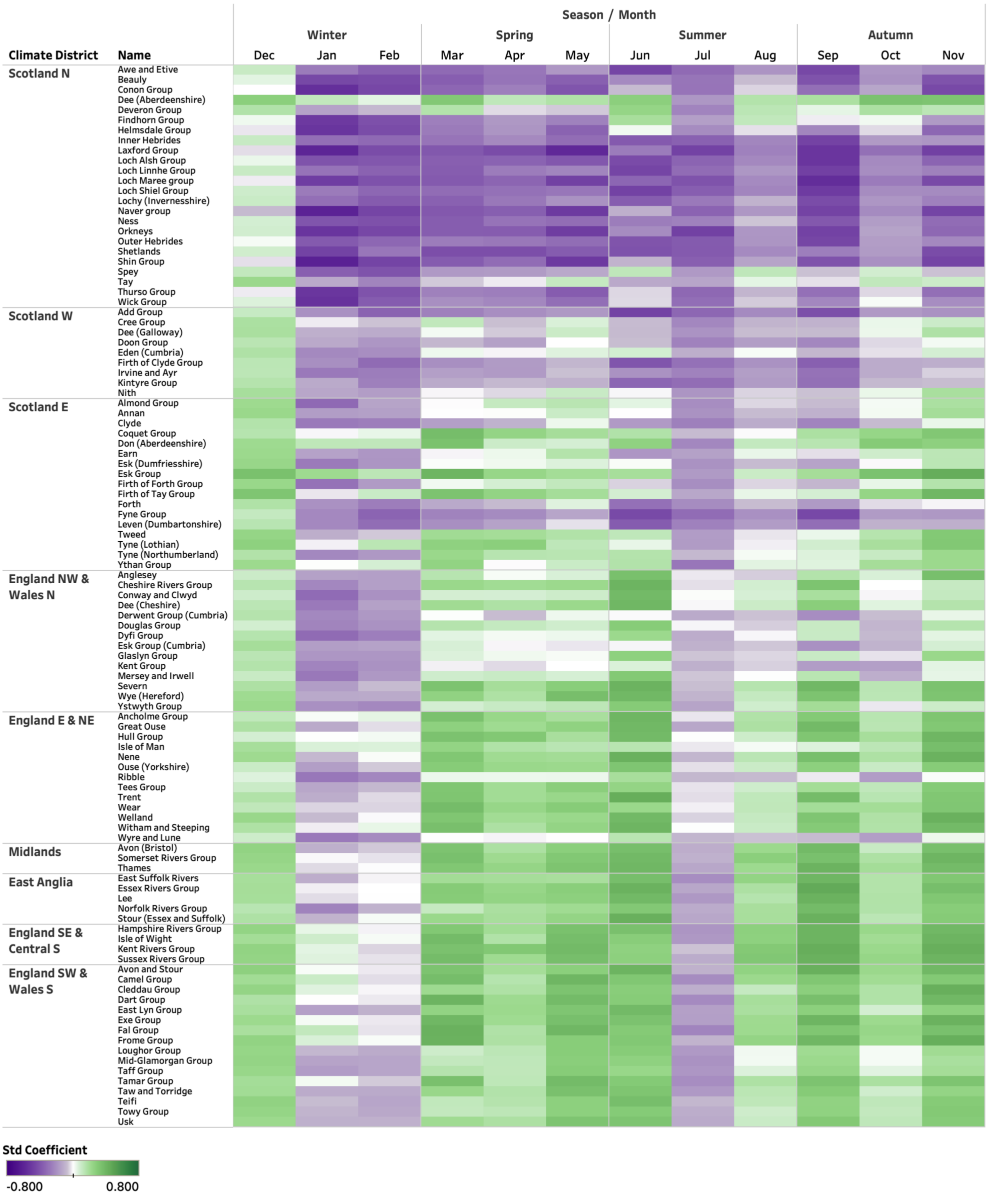

Figure 7. Standardised coefficient values for the SCA index from the multivariate regression model.

As in Figure 10, Figure 11 shows the strongest standardised coefficient values from Figures 5–9. Note that the size of the bar now indicates how dominant the circulation is relative to the circulation with the second highest SC (i.e., the absolute SC value of the dominant circulation minus the absolute SC of the second highest ranking circulation). The R^2 values of the multivariate regression model are typically stronger in the winter months than during summer (Figure 4). This is reflected in the plots where the magnitude of the SC (Figure 10), and the difference between circulation's relative influence (Figure 11), is lower in summer than in winter. For example, in Figure 10 it was identified that the most dominant circulation in the north-west during the winter months is the NAO. In Figure 11 we can see that the SC of the NAO are notably stronger than that of the other circulations. Therefore, the NAO has a clear and isolated influence on precipitation in this region. In contrast the NAO and EA typically play an important role across the country during the summer months (Figure 10). However, the relative dominance of each is much less than in winter (Figure 11).

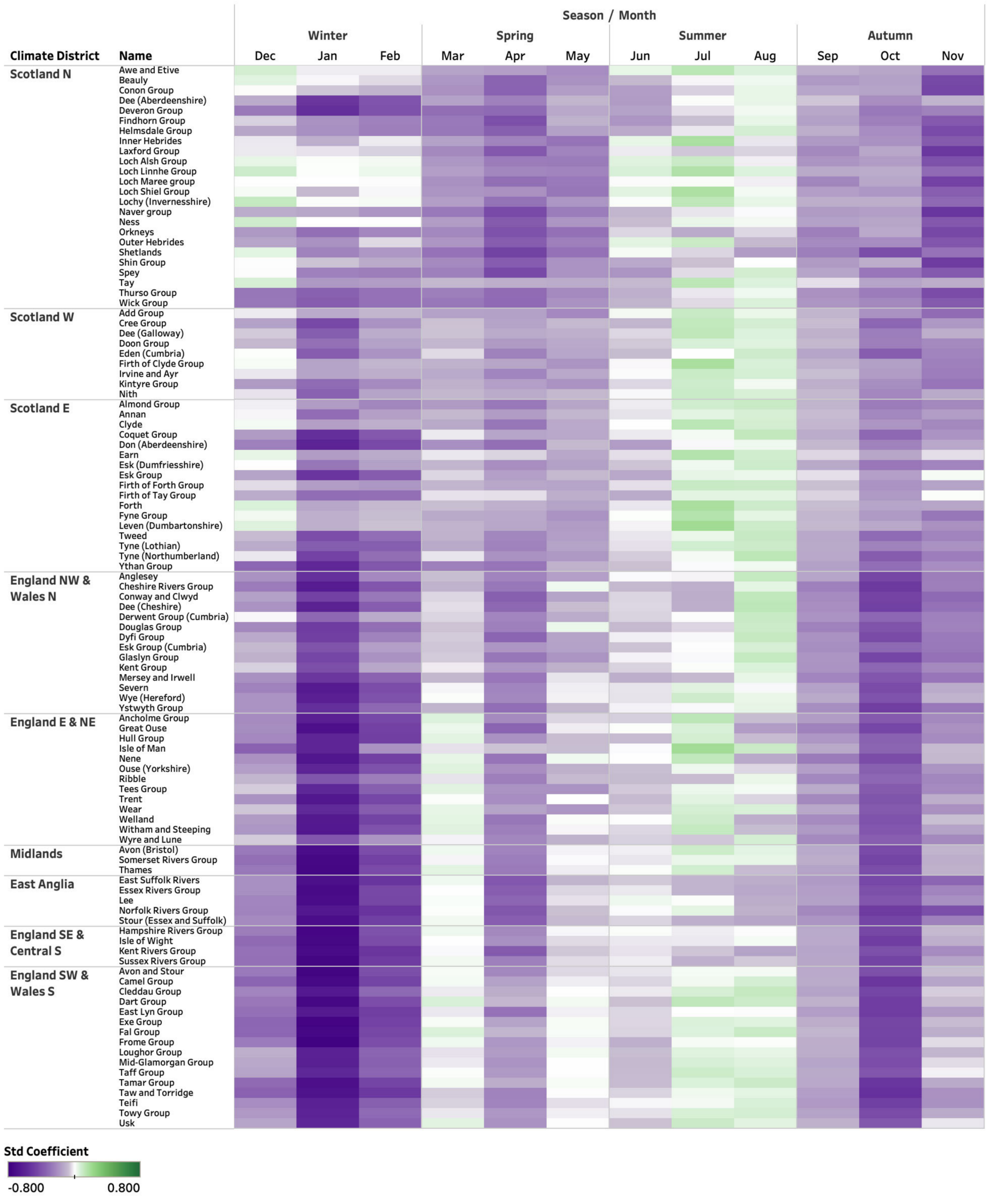

Figure 8. Standardised coefficient values for the EAWR index from the multivariate regression model.

Consequently, during the winter months individual circulations can have a dominant and significant impact on regional precipitation, such as the NAO in the north west and EAWR in the southern regions during January. However, in the southern regions throughout most of the year, and in Scotland during spring, summer and autumn, precipitation variability is potentially better explained through looking at a combination of atmospheric circulations.

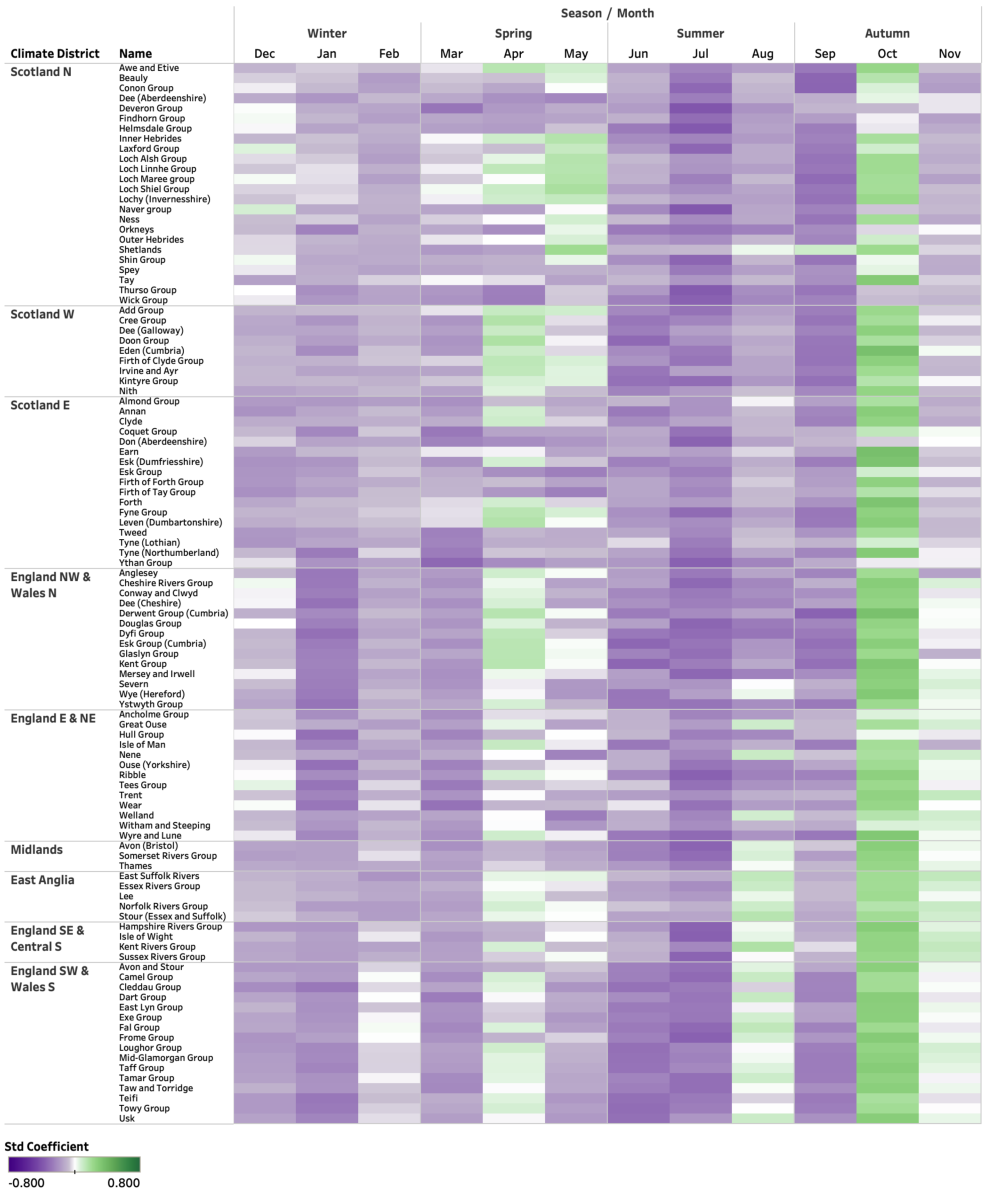

Figure 9. Standardised coefficient values for the POL index from the multivariate regression model.

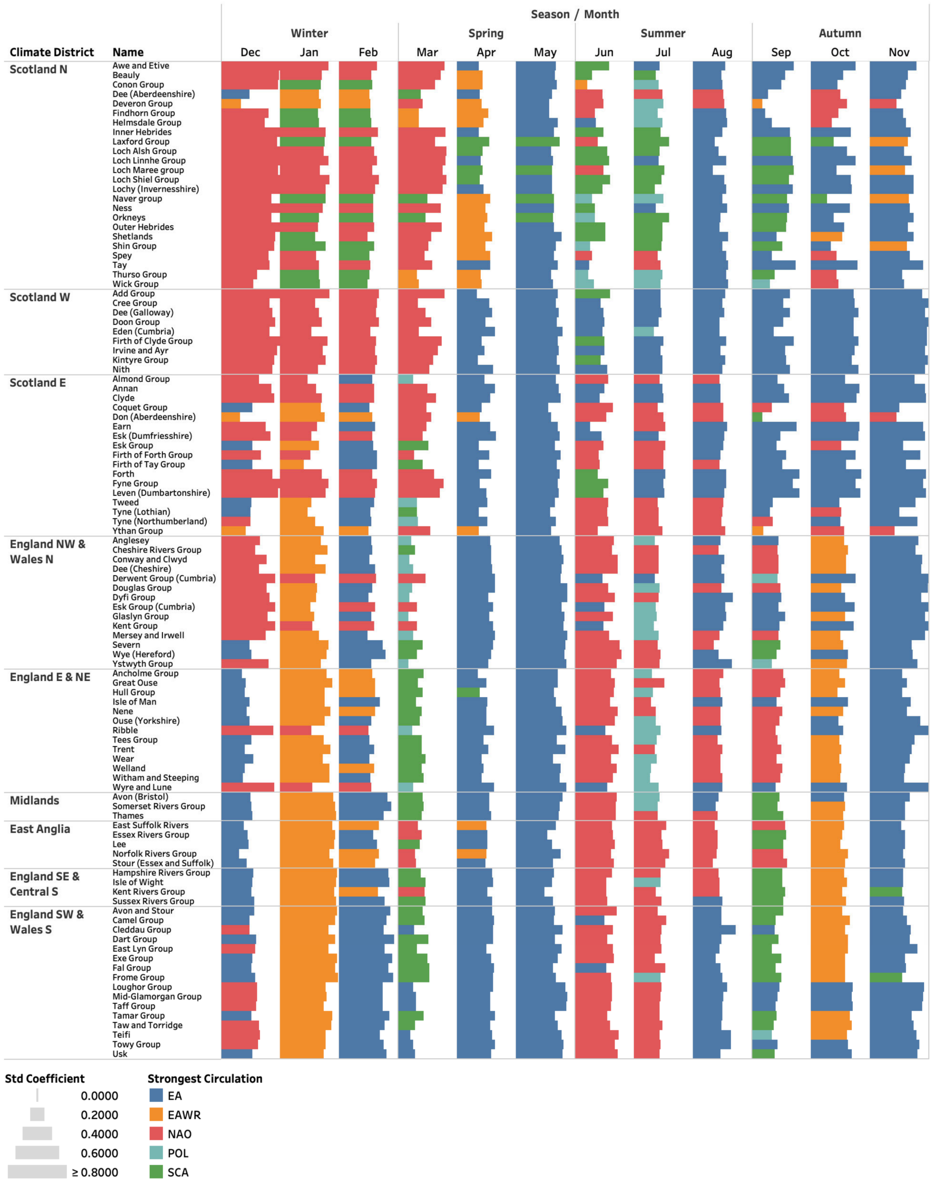

Figure 10. The strongest standardised coefficient values from Figures 5–9. Colour indicates which circulation is the most influential in the multivariate regression (i.e., the circulation with the strongest absolute SC value). The size of the bar is based on the absolute SC value.

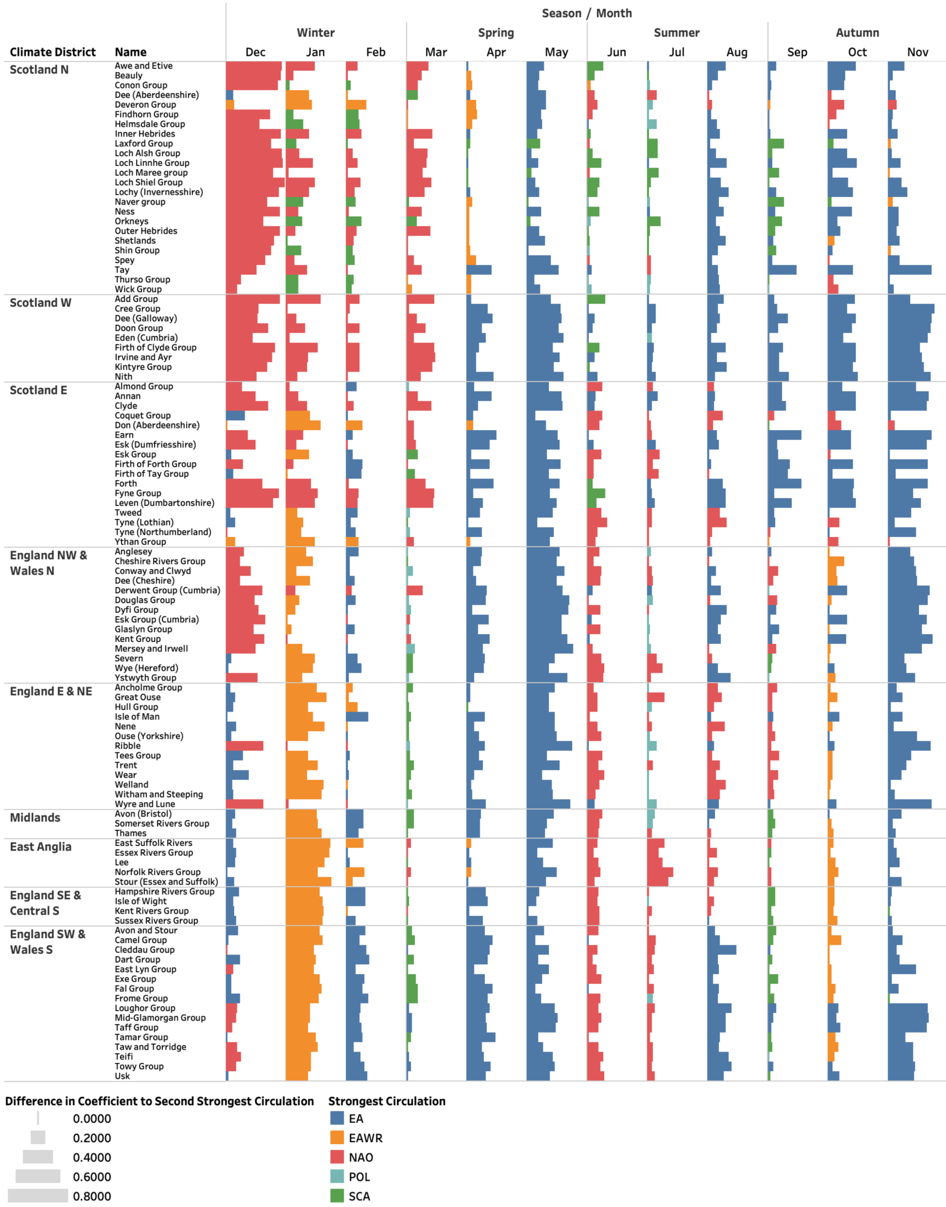

Figure 11. The strongest standardised coefficient values from Figures 5–9. Colour indicates which circulation is the most influential in the multivariate regression (i.e., the circulation with the strongest absolute SC value). The size of the bar is based on the difference in absolute SC between the dominant and second most influential circulation.

4. Discussion

This study explores, at a high spatial and temporal resolution, the relative influence North Atlantic/European atmospheric circulations on precipitation variability in Great Britain. Previous studies have either tended to focus on only one or a small number of these circulations, have been limited temporally to the winter, or undertaken using station-based or coarse spatial resolution modelled datasets (e.g., [10,15,28,35,40,44]). To address these limitations, we considered five key atmospheric circulations, using high resolution SPI-1 data for the IHU Groups of Great Britain [54], at a monthly scale. Through univariate and multivariate regression models we show the spatial and temporal variation in the relative influence of five atmospheric circulations on precipitation in Great Britain–the NAO, EA, SCA, EAWR and POL.

The NAO influences regional rainfall across Great Britain, particularly in the north-west [4,6,8] where local topography can also enhance the NAO-rainfall effect [15]. This is shown in our analyses where strong positive relationships between the NAO and SPI-1 are observed in winter (Figures 2 and 5). The phase of the NAO influences the location and strength of the North Atlantic jet stream [7]; positive phases result in southerly jet stream bringing warm and moist conditions to Great Britain, meanwhile negative phases result in a northerly jet stream, resulting in colder and drier winters [7] with greater snowfall in the north-west [56]. This understanding of physical processes corresponds with the positive (Figure 5) and dominant relationship (Figure 10) between the NAO and precipitation in the north-west during winter.

Whilst the dominance of the NAO in the north-west during winter is well-known [4,6,8,15], the influence of the other circulations is much less understood, especially during the NAO's weaker summer state [11]. This study highlights a consistent and moderately strong positive EA-precipitation relationship (Figure 6) and negative EAWR-precipitation relationship (Figure 8), which corroborates findings exploring the impact of these two circulations [10,28,38,50]. This reinforces the EA's role as the second leading mode of climate variability [1,40,44] and therefore its strong influence on precipitation across Great Britain throughout the year (Figure 10).

In this study we find that the SCA can also have a dominant and important influence on rainfall in Great Britain (Figure 10), with a weak positive and stronger negative relationship in the southern and far northern regions, respectively. Bueh & Nakamura [45] reported positive relationships between the SCA and precipitation over southern Europe and negative relationships over Scandinavia; corresponding to our observed north/south SC variation for the SCA (Figure 7). Our analysis of the SC values, however, indicates that the SCA is more frequently the dominant circulation in the north compared to the south (Figure 10), however it is relatively less influential compared to the NAO and EA (Figure 11). This demonstrates the SCA's role as the third mode of climate variability [1,40,44]. The SC values for the POL circulation are consistently low throughout the year in our analysis (Figure 9), although they are moderately stronger in the summer, possibly associated with the additional and third centre of action of the circulation over midlatitude Europe [1].

Our analysis shows that each circulation has a spatially and temporally variable influence on regional precipitation in Great Britain. Importantly, the results from the multiple regression analysis indicate that by looking at the atmospheric circulations in combination, rather than in isolation (for example the univariate regression models in Figures 2 and 3), will provide a more complete description of precipitation variability. This is particularly true of the NAO and EA circulations [35,38], and for the southern regions in winter and across the country during summer, where there is notably less difference between the dominant and second most influential circulation (Figure 11).

Research has long highlighted the importance of the NAO in driving regional climate [4,6,7]. However significant variability in NAO-rainfall signatures has also been reported, in particular, for southern England [23]. Despite advancements in our understanding of how NAO-rainfall deviations propagate through the hydrological cycle [16,17], such variability in NAO-rainfall signatures is a limiting factor in being able to use the NAOI in water and environmental management decision making, even as more skillful forecasts are increasingly available [10]. We suggest that some of this spatio-temporal variability may be explained by looking at the strength and phase of other atmospheric circulations such as the EA. Consequently, there is the potential to incorporate and apply a broader range of monthly climate indices to explain, and possibly predict, precipitation variability (and subsequently hydrological variability). However, additional research is required to translate the findings of this study into useful predictive tools for application in water management. However, at present the utility of this may be limited given that recent advancements in teleconnection forecasting have been reported for the NAO [24,25].

5. Conclusions

As far as we are aware this study represents the first attempt to explore at high resolution the relative influence of five atmospheric circulations on monthly precipitation variability across Great Britain, both individually and in combination. Historically, many studies have focused on the NAO as the key driver of regional precipitation, and subsequently streamflow and groundwater levels. However, our analyses reveal the variable influence of a broader range of circulations on regional precipitation, and by inference, catchment hydrology.

Importantly this study demonstrates how the NAO may only partially explain precipitation variability, especially in the southern regions and during the summer months, where circulations such as the EA also have an important influence. There is scope for future research to continue to develop our understanding of the impact of these circulations on rainfall (and its propagation through the hydrological cycle) at high spatial and temporal resolution using increasingly available long-term atmospheric circulation and hydrometeorological datasets. There is also potential to explore how circulation-driven precipitation interacts with local precipitation influences, such as topography [15] and landcover which might also influence the spatio-temporal rainfall patterns observed in this study.

We suggest that there is significant explanatory value in looking beyond the NAO when seeking to explore climatological and hydrological variability in Great Britain. An aim of future research might be to explore how the understanding presented in this study may be used in a predictive capacity in water management practice; however, we acknowledge the associated limitations, most notably the lack of accurate annual forecasts for all five atmospheric circulations.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1. R^2 values of the univariate regression model exploring the relationship between the SCA index and SPI-1 values across the IHU Groups.

Figure A2. R^2 values of the univariate regression model exploring the relationship between the EAWR index and SPI-1 values across the IHU Groups.

Figure A3. R^2 values of the univariate regression model exploring the relationship between the POL index and SPI-1 values across the IHU Groups.

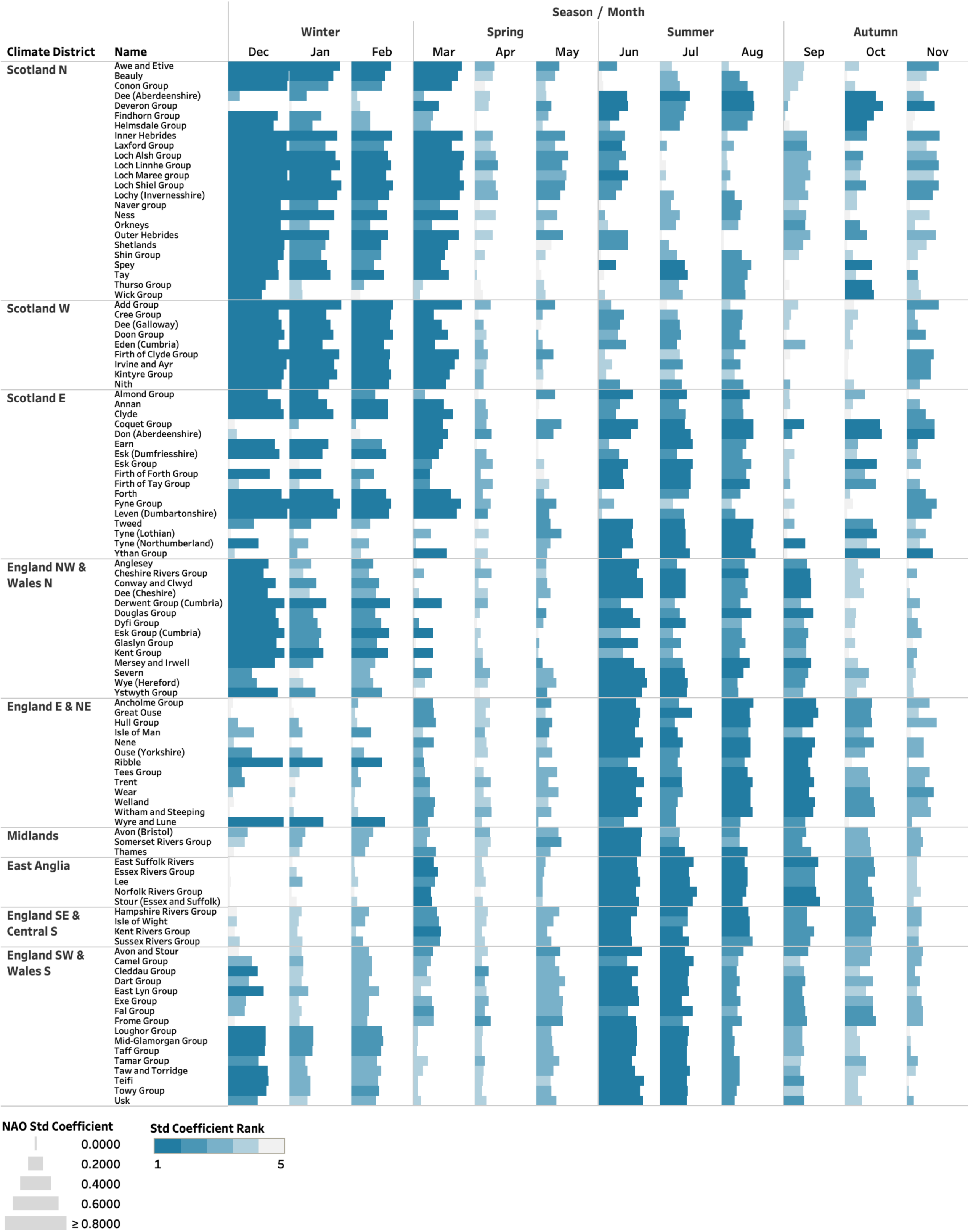

Figure A4. Rank of the NAO Standardised Coefficient. Colour represents the rank, with darker colours signifying greater influence (higher rank). Size is dependent on the magnitude of the SC.

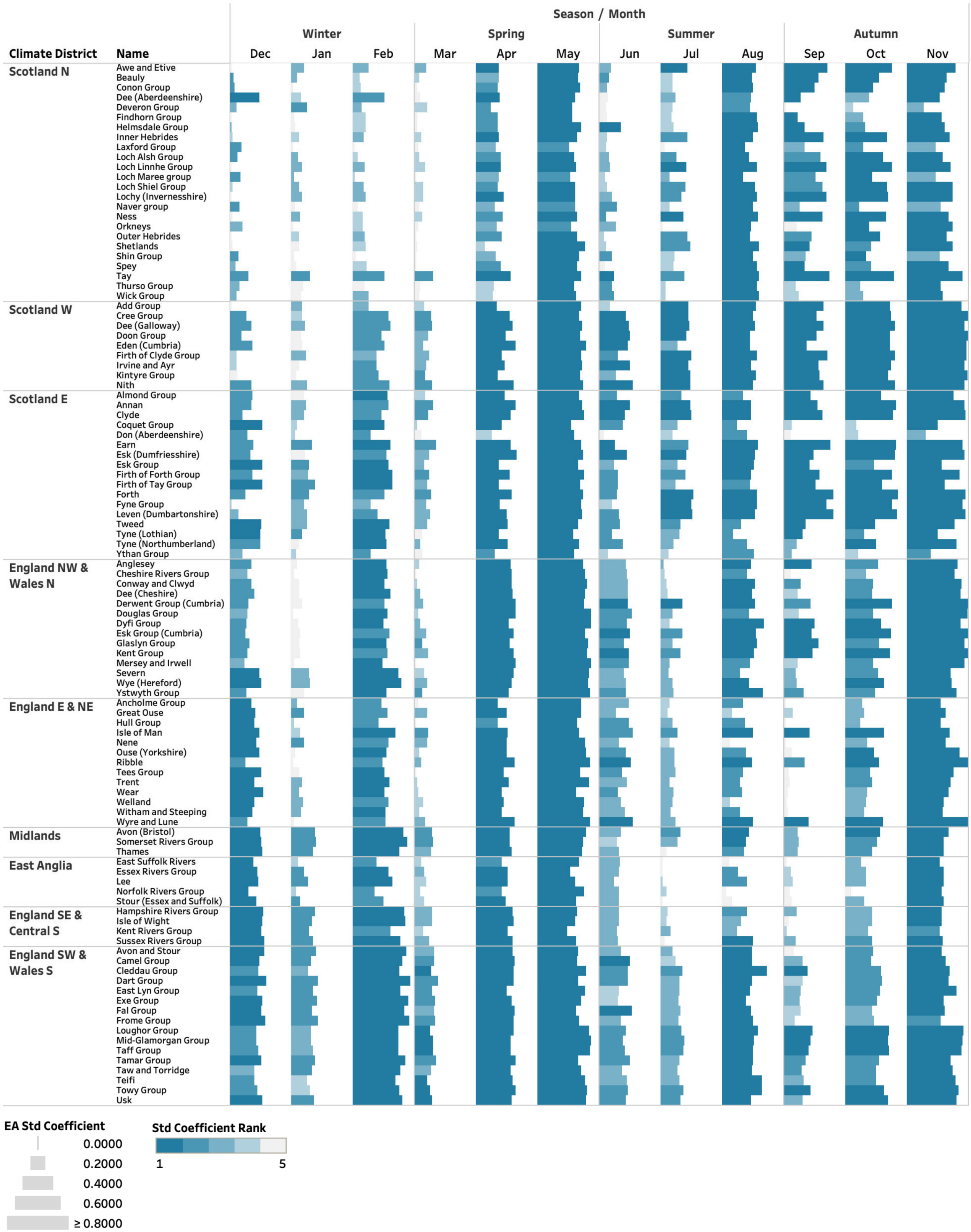

Figure A5. Rank of the EA Standardised Coefficient. Colour represents the rank, with darker colours signifying greater influence (higher rank). Size is dependent on the magnitude of the SC.

Figure A6. Rank of the SCA Standardised Coefficient. Colour represents the rank, with darker colours signifying greater influence (higher rank). Size is dependent on the magnitude of the SC.

Figure A7. Rank of the EAWR Standardised Coefficient. Colour represents the rank, with darker colours signifying greater influence (higher rank). Size is dependent on the magnitude of the SC.

Figure A8. Rank of the POL Standardised Coefficient. Colour represents the rank, with darker colours signifying greater influence (higher rank). Size is dependent on the magnitude of the SC.

References

1. Barnston, A.G.; Livezey, R.E. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Weather Rev.* **1987**, *115*, 1083–1126. [CrossRef]
2. Hurrell, J.W.; Van Loon, H. Decadal variations in climate associated with the North Atlantic Oscillation. *Clim. Change* **1997**, *36*, 301–326. [CrossRef]
3. Rodwell, M.J.; Rowell, D.P.; Folland, C.K. Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature* **1999**, *398*, 320–323. [CrossRef]
4. Wilby, R.L.; O'Hare, G.; Barnsley, N. The North Atlantic Oscillation and British Isles climate variability. *Weather* **1997**, *52*, 266–276. [CrossRef]
5. Folwer, H.J.; Kilsby, C.G. Precipitation and the North Atlantic Oscillation: A study of climate variability in Northern England. *Int. J. Climatol.* **2002**, *22*, 843–866.
6. Rust, W.; Holman, I.; Corstanje, R.; Bloomfield, J.; Cuthbert, M. A conceptual model for climatic teleconnection signal control on groundwater variability in Europe. *Earth-Sci. Rev.* **2018**, *177*, 164–174. [CrossRef]
7. Hurrell, J.W.; Kushnir, Y.; Ottersen, G.; Visbeck, M. (Eds.) An overview of the North Atlantic Oscillation. In *The North Atlantic Oscillation: Climate Significance and Environmental Impact*; AGU Physical Monograph Series: Washington, DC, USA, 2003; Volume 134.
8. West, H.; Quinn, N.; Horswell, M. Regional rainfall response to the North Atlantic Oscillation (NAO) across Great Britain. *Hydrol. Res.* **2019**, *50*, 1549–1563. [CrossRef]
9. Simpson, I.R.; Jones, P.D. Analysis of UK precipitation extremes derived from Met Office Gridded Data. *Int. J. Climatol.* **2014**, *34*, 2438–2449. [CrossRef]
10. Hall, R.J.; Hanna, E. North Atlantic circulation indices: Links with summer and winter temperature and precipitation and implications for seasonal forecasting. *Int. J. Climatol.* **2018**, *38*, 660–667. [CrossRef]
11. Folland, C.K.; Knight, J.; Linderholm, H.W.; Fereday, D.; Ineson, S.; Hurrell, J.W. The summer North Atlantic Oscillation: Past, present and future. *J. Clim.* **2009**, *22*, 1082–1103. [CrossRef]
12. Kingston, D.G.; Lawler, M.; McGregor, G.R. Linkages between atmospheric circulation, climate and streamflow in the North Atlantic: Research prospects. *Prog. Phys. Geogr.* **2006**, *30*, 143–174. [CrossRef]
13. Kingston, D.G.; Hannah, D.M.; Lawler, M.; McGregor, G.R. Climate-river flow relationships across montane and lowland environments in northern Europe. *Hydrol. Process.* **2009**, *23*, 985–996. [CrossRef]
14. Wrzesinski, D.; Paluszkiewicz, R. Spatial differences in the impact of the North Atlantic Oscillation on the flow of rivers in Europe. *Hydrol. Res.* **2011**, *42*, 30–39. [CrossRef]
15. Burt, T.; Howden, N. North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. *Water Resour. Res.* **2013**, *49*, 3504–3515. [CrossRef]
16. Rust, W.; Cuthbert, M.; Bloomfield, J.; Corstanje, R.; Howden, N.; Holman, I. Exploring the role of hydrological pathways in modulating multi-annual climate teleconnection periodicities from UK rainfall to streamflow. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 2233–2237. [CrossRef]
17. West, H.; Quinn, N.; Horswell, M. Spatio-temporal propagation of North Atlantic Oscillation (NAO) rainfall deviations to streamflow in British catchments. *Hydrol. Sci. J.* **2022**. [CrossRef]
18. Lavers, D.; Hannah, D.M.; Bradley, C. Connecting large-scale atmospheric circulation, river flow and groundwater levels in a chalk catchment in southern England. *J. Hydrol.* **2015**, *523*, 179–189. [CrossRef]
19. Rust, W.; Holman, I.; Bloomfield, J.; Cuthbert, M.; Corstanje, R. Understanding the potential of climate teleconnections to project future groundwater drought. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 3233–3245. [CrossRef]
20. Wilby, R.L.; Johnson, M.F. Climate Variability and Implications for Keeping Rivers Cool in England. *Clim. Risk Manag.* **2020**, *30*, 100259. [CrossRef]
21. UK Hydrological Outlook. December 2020. Available online: http://www.hydoutuk.net/files/2816/0743/4122/2020_12_HO_Complete.pdf (accessed on 14 December 2020).
22. Donegan, S.; Murphy, C.; Harrigan, S.; Broderick, C.; Golian, S.; Knight, J.; Matthews, T.; Prudhomme, C.; Quinn, D.F.; Scaife, A.A.; et al. Conditioning Ensemble Streamflow Prediction with the North Atlantic Oscillation improves skill at longer lead times. *Hydrol. Earth Syst. Sci.* **2021**, *25*, 4159–4183. [CrossRef]
23. West, H.; Quinn, N.; Horswell, M. Spatio-Temporal Variability in North Atlantic Oscillation (NAO) Monthly Rainfall Signatures in Great Britain. *Atmosphere* **2021**, *12*, 763. [CrossRef]
24. Smith, D.M.; Scaife, A.A.; Eade, R.; Athanasiadis, P.; Bellucci, A.; Bethke, I.; Bilbao, R.; Borchert, L.F.; Caron, L.-P.; Counillon, F.; et al. North Atlantic climate far more predictable than models imply. *Nature* **2020**, *583*, 796–800. [CrossRef] [PubMed]
25. Athanasiadis, P.J.; Yeager, S.; Kwon, Y.-O.; Bellucci, A.; Smith, D.W.; Tibaldi, S. Decadal predictability of North Atlantic blocking and the NAO. *NPJ Clim. Atmos. Sci.* **2020**, *3*, 20. [CrossRef]
26. Rust, W.; Bloomfield, J.; Cuthbert, M.; Corstanje, R.; Holman, I. Non-stationary control of the NAO on European rainfall and its implications for water resource management. *Hydrol. Process.* **2021**, *35*, e14099. [CrossRef]
27. NOAA Climate Prediction Centre—Northern Hemisphere Teleconnections. Available online: https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml (accessed on 16 January 2022).
28. Casanueva, A.; Rodríguez-Puebla, C.; Frías, M.D.; González-Reviriego, N. Variability of extreme precipitation over Europe and its relationships with teleconnections patterns. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 709–725. [CrossRef]

29. Irannezhad, M.; Haghihgi, A.T.; Chen, D.; Kløve, B. Variability in dryness and wetness in central Finland and the role of teleconnection patterns. *Theor. Appl. Climatol.* **2015**, *122*, 471–486. [CrossRef]
30. Bednorz, E.; Czernecki, B.; Tomczyk, A.M.; Półrolniczak, M. If not NAO then what? Regional circulation patterns governing summer air temperatures in Poland. *Theor. Appl. Climatol.* **2018**, *136*, 1325–1337. [CrossRef]
31. Bednorz, E.; Tomczyk, A.M. Influence of macroscale and regional circulation patterns on low- and high-frequency sea level variability in the Baltic Sea. *Theor. Appl. Climatol.* **2021**, *144*, 115–125. [CrossRef]
32. Amini, M.; Ghadami, M.; Fathian, F.; Modarres, R. Teleconnections between oceanic-atmospheric indices over Iran using quantile regressions. *Hydrol. Sci. J.* **2020**, *65*, 2286–2295. [CrossRef]
33. Uvo, C.B.; Foster, K.; Olsson, J. The spatio-temporal influence of atmospheric teleconnection patterns on hydrology in Sweden. *J. Hydrol. Reg. Stud.* **2021**, *34*, 100782. [CrossRef]
34. Moore, G.W.K.; Renfrew, I.A. Cold European winters: Interplay between the NAO and the East Atlantic mode. *Atmos. Sci. Lett.* **2012**, *13*, 1–8. [CrossRef]
35. Mellado-Cano, J.; Barriopedro, D.; Garcia-Herrera, R.; Trigo, R.M.; Hernandez, A. Examining the North Atlantic Oscillation, East Atlantic Pattern jet variability since 1685. *J. Clim.* **2019**, *32*, 6285–6298. [CrossRef]
36. Mikhailova, N.V.; Yurovsky, A.V. The East Atlantic Oscillation: Mechanism and Impact on the European Climate in Winter. *Phys. Oceanogr.* **2016**, *2016*, 25–33. [CrossRef]
37. Maidens, A.; Knight, J.R.; Scaife, A.A. Tropical and stratospheric influences in winter atmospheric circulation patterns in the North Atlantic sector. *Environ. Res. Lett.* **2021**, *16*, 024035. [CrossRef]
38. West, H.; Quinn, N.; Horswell, M. Monthly rainfall signatures of the North Atlantic Oscillation and East Atlantic Pattern in Great Britain. *Atmosphere* **2021**, *12*, 1533. [CrossRef]
39. Moore, G.W.K.; Pikart, R.S.; Renfrew, I.A. Complexities in the climate of the subpolar North Atlantic: A case study from the winter of 2007. *Q. J. R. Meteorol. Soc.* **2011**, *137*, 757–767. [CrossRef]
40. Moore, G.W.K.; Renfrew, I.A.; Pickart, R.S. Multidecadal mobility of the North Atlantic Oscillation. *J. Clim.* **2013**, *26*, 2453–2466. [CrossRef]
41. Rodrigo, F.S. Exploring combined influences of seasonal East Atlantic (EA) and North Atlantic Oscillation (NAO) on the temperature-precipitation relationship in the Iberian Peninsula. *Geosciences* **2021**, *11*, 211. [CrossRef]
42. Chen, M.; Papadikis, K.; Jun, C. An investigation on the non-stationarity of flood frequency across the UK. *J. Hydrol.* **2021**, *597*, 126309. [CrossRef]
43. West, H.; Quinn, N.; Horswell, M. The Influence of the North Atlantic Oscillation & East Atlantic Pattern on Drought in British Catchments. *Front. Environ. Sci.* **2022**. [CrossRef]
44. Comas-Bru, L.; McDermott, F. Impacts of the EA and SCA patterns on the European twentieth century NAO–winter climate relationship. *Q. J. R. Meteorol. Soc.* **2014**, *140*, 354–363. [CrossRef]
45. Bueh, C.; Nakamura, H. Scandinavian pattern and its climatic impact. *Q. J. R. Meteorol. Soc.* **2007**, *133*, 2117–2131. [CrossRef]
46. Zubiate, L.; McDermott, F.; Sweeney, C.; O'Malley, M. Spatial variability in winter NAO-wind speed relationships in western Europe linked to concomitant states of the East Atlantic and Scandinavian Patterns. *Q. J. R. Meteorol. Soc.* **2017**, *143*, 552–562. [CrossRef]
47. Krichak, S.O.; Alpert, P. Decadal trends of main Eurasian oscillations and the Mediterranean precipitation. *Theor. Appl. Climatol.* **2002**, *72*, 209–220. [CrossRef]
48. Krichak, S.O.; Alpert, P. Decadal trends in the East Atlantic-West Russia Pattern and Mediterranean precipitation. *Int. J. Climatol.* **2005**, *25*, 183–192. [CrossRef]
49. Caroletti, G.N.; Coscarelli, R.; Caloiero, T. A sub-regional approach to the influence analysis of teleconnection patterns on precipitation in Calabria (southern Italy). *Int. J. Climatol.* **2021**, *41*, 4574–4586. [CrossRef]
50. Ionita, M. The impact of the East Atlantic/Western Russia Pattern on the hydroclimatology of Europe from mid-winter to late spring. *Climate* **2014**, *2*, 296–309. [CrossRef]
51. Gao, N.; Bueh, C.; Xie, Z.; Gong, Y. A novel identification of the Polar/Eurasia Pattern and its weather impact in May. *J. Meteorol. Res.* **2019**, *33*, 810–825. [CrossRef]
52. Balling, R.C., Jr.; Goodrich, G.B. Interannual variations in the local spatial autocorrelation of tropospheric temperatures. *Theor. Appl. Climatol.* **2011**, *103*, 451–457. [CrossRef]
53. Pokorna, L.; Huth, R. Climate impacts of the NAO are sensitive to how the NAO is defined. *Theor. Appl. Climatol.* **2015**, *119*, 639652. [CrossRef]
54. Tanguy, M.; Fry, M.; Svensson, C.; Hannaford, J. Historic Standardised Precipitation Index time series for IHU Groups (1862–2015). *NERC Environ. Inf. Cent.* **2017**. [CrossRef]
55. Chun, K.P.; Dieppois, B.; Qing, H.; Sidibe, M.; Eden, J.; Paturel, J.-E.; Mahe, G.; Rouche, N.; Klaus, J.; Conway, D. Identifying drivers of streamflow extremes in West Africa to inform a nonstationary prediction model. *Weather Clim. Extrem.* **2021**, *33*, 100346. [CrossRef]
56. Spencer, M.; Essery, R. Scottish snow cover dependence on the North Atlantic Oscillation index. *Hydrol. Res.* **2016**, *47*, 619–629. [CrossRef]