Regional Rainfall Response to the North Atlantic Oscillation (NAO) across Great Britain

Harry West, Nevil Quinn & Michael Horswell

Centre for Water, Communities & Resilience; Department of Geography & Environmental Management; University of the West of England, Bristol; United Kingdom.

Corresponding Author: Harry West (harry.west@uwe.ac.uk)

Abstract

The NAO has been long studied as the primary teleconnection affecting British and European climate. However, previous studies have focused on extremes or have been spatially and temporally limited. In recent years our ability to predict the NAO has improved. Also new research is emerging suggesting that the NAO is a key driver of hydrological extremes. These factors mean there is renewed value in enhancing our understanding of how the NAO influences general rainfall patterns. In this study we spatially analyse correlations between NAO indices and monthly rainfall data and the Standardised Precipitation Index. We also map mean monthly rainfall differences under NAO positive and negative conditions. Based on our results we identify three main observations: (I) there is sensitivity in the rainfall patterns to the chosen NAO index; (II) there is a clear winter north/west and south/east divide in rainfall patterns; (III) the NAO does have an effect on summer rainfall patterns, although the spatiality of these patterns is less distinctive than in winter. As far as we are aware this is the first national scale, monthly NAO-rainfall analysis undertaken for a long period.

Keywords

North Atlantic Oscillation; Rainfall Patterns; Teleconnections; British Climate; Wet/Dry Continuum

Introduction

Climate change is expected to significantly alter hydro-meteorological and climatological processes and patterns in Great Britain (Garner *et al.,* 2017; Kendon *et al.,* 2018), and understanding the characteristics and impacts of wet and dry extreme events remains a challenge (Jones *et al.,* 2014; Watts *et al.,* 2015; Parry *et al.,* 2016; Van Loon *et al.,* 2016). Oceanic-atmospheric circulation interactions (also referred to as teleconnections) are a key influence on regional climate (Wilby *et al.,* 1997; Rust *et al.,* 2018). Given the close interconnectedness of the climate and hydrological system, floods and droughts are inherently driven by larger scale meteorological processes and their interactions with local-scale catchment characteristics (Wilby & Quinn, 2013; Van Loon & Laaha, 2015; Barker *et al.,* 2016; Huang *et al.,* 2017; De Luca *et al.,* 2017). Furthering our understanding of the influence of teleconnections on local and regional climate is therefore key in water and climate resilience planning.

Weather in Great Britain is highly variable, often fluctuating between wet and dry conditions (e.g. the very wet winter of 2013/14 and dry summer of 2018). The North Atlantic Oscillation (NAO) characterises some of the variability of the North Atlantic jet stream and has been acknowledged as the primary teleconnection affecting British climate (Wilby *et al.,* 1997; Hurrell *et al.,* 2003). For example, Rodwell *et al.* (1999) suggested that the NAO is the single most important teleconnection influencing climate variability in the Northern Hemisphere, and Sweeney & O'Hare (1992) linked variations in precipitation to large scale NAO fluctuations across Europe. More recent studies continue to emphasise the influence of NAO on British and European climatic patterns (Comas-Bru & McDermott, 2014; Tsanus & Tapoglou, 2018; Varouchakis *et al.,* 2018). In a review of studies relating to hydro-meteorological signal control of the NAO, Rust *et al.* (2018) highlight the strong relationship (positive correlations) between the NAO and precipitation during winter months across Northern Europe.

The NAO can be defined in various ways but generally represents the sea level pressure (SLP) fluctuation between Iceland and the Azores that has been well defined in meteorology since the 19th Century (Hurrell *et al.,* 2003). Many studies use the North Atlantic Oscillation Index (NAOI) as quantitative measure of the pressure gradient between Iceland and the Azores (e.g. Simpson & Jones, 2014; Bonaccorso *et al.,* 2015; Spencer & Essery, 2016).

The NAO fluctuates between a positive and negative state; each state is known to produce characteristic climatic patterns over Great Britain and mainland Europe (Hall & Hanna, 2018; Rust *et al.,* 2018). A positive NAO (which represents stronger than usual difference in SLP between Iceland and the Azores), is generally associated with stormy and wet winter conditions as winds from the west dominate bringing warmer air and storms across the North Atlantic region. A negative NAO represents the reverse with a weaker than usual difference in SLP. Winds from the east and north-east are more frequent, bringing with them cold air, while the adjusted position of the jet stream leads to weaker and less frequent storms. As a result, Europe is more likely to experience cold, calm and dry winters (Hurrell *et al.,* 2003; Baker *et al.,* 2017). Many studies have associated fluctuations of the NAO to precipitation patterns in Great Britain specifically (Figure 1).

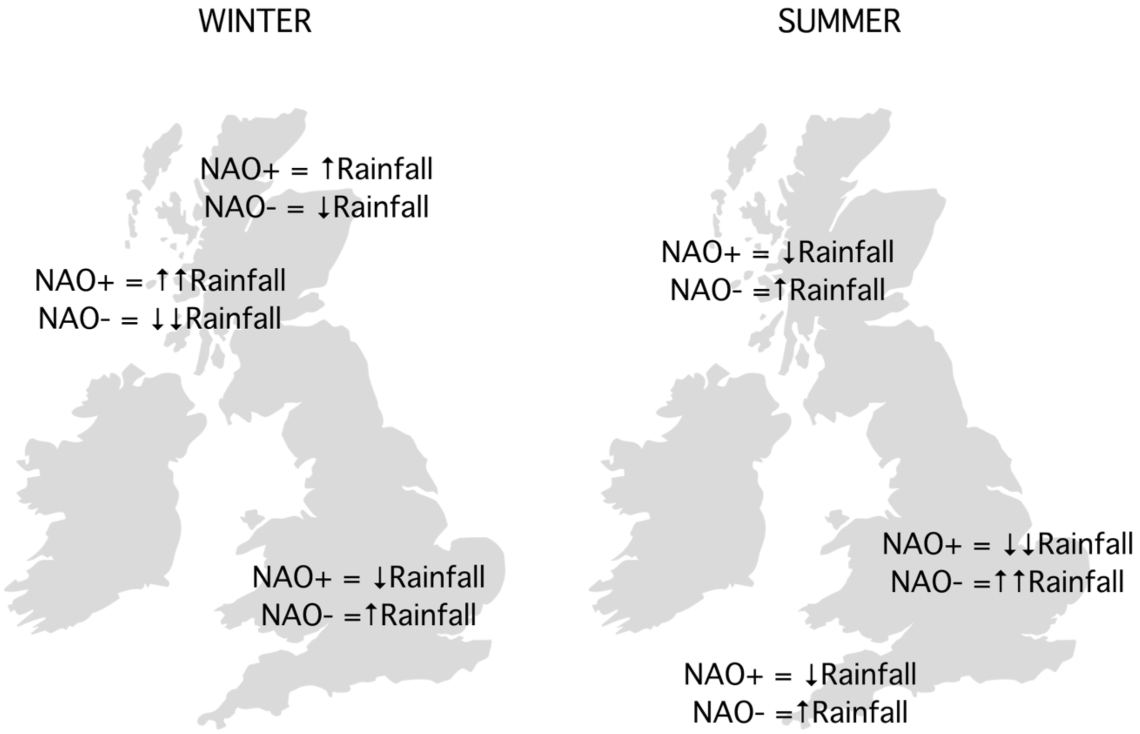

Figure 1: Generalised NAO winter and summer rainfall patterns from previous studies (Wilby *et al.,* 1997; Folwer & Kilsby, 2002; Burt & Howden, 2013; Kosanic *et al.,* 2014; Simpson & Jones, 2014; Afzal *et al.,* 2015; Hall & Hanna, 2018). A more detailed summary of these findings can be found in Table S1 in the Online Supplemental Material.

The impact of NAOI phase during winter and summer is known to differ significantly (Folland *et al.,* 2009; del Rio *et al.,* 2011; Sun & Wang, 2012). Whilst the strength of regional correlations with rainfall of the winter (DJF) North Atlantic Oscillation Index (NAOI_{W}) and summer (JJA) North Atlantic Oscillation Index (NAOI_{S}) vary across Great Britain, a general relationship is evident, particularly for the north/west of the country. There is a positive correlation between positive NAOI_{W} values and winter precipitation, and a negative correlation between positive NAOI_{S} values and summer precipitation. Conversely, negative NAOI_{S} values are correlated with higher summer precipitation, and negative NAOI_{W} values are associated with lower winter precipitation (Folland *et al.,* 2009; Simpson & Jones, 2014; Hall & Hanna, 2018).

Earlier analyses of relationships between NAOI and precipitation are typically based on precipitation data from relatively few sites (e.g. Wilby *et al.,* 1997; Folwer & Kilsby, 2002) and short record lengths (e.g. Folwer & Kilsby, 2002; Afzal *et al.,* 2015). Studies have also tended to focus on extremes rather than more general wet/dry patterns (e.g. Simpson & Jones, 2014) and have had a clear emphasis on the relationship between NAO and winter climate (e.g. Comas-Bru & McDermott, 2014; Rust *et al.,* 2018). This seems an understandable focus as intense and more frequent rainfall is typically associated with low pressure systems coming from the tropics – the movement of these systems being directly associated with NAO phase (Wilby *et al.,* 1997; Fowler & Kilsby, 2002). While relationships between winter rainfall and NAO are now well defined, the influence of the NAO on regional summer climates is less clear (Folland *et al.,* 2009) and is limited to some evidence suggesting negative correlations between NAOI and summer precipitation in all regions apart from north-west Scotland (Hall & Hanna, 2018).

The availability of nationally consistent gridded precipitation datasets, such as the Centre for Ecology and Hydrology (CEH) Gridded Estimates of Areal Rainfall (GEAR) dataset (Tanguy *et al.,* 2016), now provide new opportunities for analysis of teleconnection drivers of rainfall. Similarly, recent publication of gridded Standardised Precipitation Index (SPI) time series (Tanguy *et al.* 2017) offers an additional advantage as the data is conveniently scaled in relation to relative wetness and dryness over a specified rainfall accumulation period (Hannaford *et al.,* 2011). As a result, the SPI has been used to assess the spatial signature of teleconnections in rainfall in regions worldwide (Kingston *et al.,* 2015; Irannezhad *et al.,* 2015). The availability of these datasets is particularly important in helping develop a deeper understanding of the spatial structure of associations between North Atlantic teleconnections and precipitation, and any time-related/seasonal trends in this structure. Previous studies using similar spatially consistent data have tended to rely on UKCP09 estimates (e.g. Spencer & Essery, 2016), which are known to have limitations/pre-conditions for estimates of summer rainfall (Met Office, 2016). New understanding of the relationships between hydrological extremes and the NAO (Rust *et al.,* 2019), coupled with improvements in long-range NAO prediction ability (Scaife *et al.* 2014; Smith *et al.,* 2016; Baker *et al.,* 2017; Weisheimer *et al.,* 2017) and the potential for the NAOI to be used in hindcasting (Smith *et al.,* 2019), also mean there is now renewed value in developing a more complete understanding of how the NAO influences the spatial distribution of seasonal rainfall across Great Britain. Being able to infer more detailed regional rainfall responses in relation to predicted teleconnection behaviour would be of significant value in helping inform strategic responses to weather extremes (Palin *et al.,* 2016; Bell *et al.,* 2017; Clark *et al.,* 2017).

In this study we aim to examine the spatial distribution of rainfall (using both GEAR monthly rainfall estimates and the Standardised Precipitation Index) under positive and negative NAOI conditions. This represents the first monthly, nationally consistent spatial analysis undertaken for a long record (1899-2015, 117 water years) addressing the full wet/dry continuum.

Methods

Data

To represent NAO condition, the NAOI was used. This study makes use of two commonly used methods: the station-based method ($NAOI_{ST}$) which calculates the index based on fixed SLP station measured data, and the principal component analysis method ($NAOI_{PC}$) comprised of a time series of the leading empirical orthogonal function (EOF) of Atlantic SLP (Hurrell *et al.,* 2003). Both datasets were obtained from the US National Centre for Atmospheric Research (https://climatedataguide.ucar.edu/climate-data) at a monthly interval for the water years October 1899 to September 2015.

Monthly total rainfall values (1899-2015) were obtained from the CEH GEAR dataset (Tanguy *et al.,* 2016). GEAR provides interpolated monthly estimates of total rainfall on a 1km grid and has relatively complete spatial coverage of Great Britain. The rainfall estimates are derived from the Met Office national database of observed precipitation. The GEAR dataset was selected due to its high spatial resolution and long record period (when compared to similar UK rainfall datasets). The SPI, as defined by Mckee *et al.* (1993), was also sourced from CEH at monthly intervals (1899-2015) with a 1-month rainfall accumulation period (Tanguy *et al.,* 2017). This dataset is provided at 5km gridded spatial resolution and is derived based on the monthly GEAR dataset. The SPI is calculated by fitting a gamma distribution (Stagge *et al.,* 2015) to historical precipitation time series. The years 1961-2010 are used as the baseline for SPI calculation. The SPI is a standardised index, with positive values representing wetter than normal conditions for a given period, and negative values representing drier than normal conditions. The SPI is normally distributed with a mean of 0 (i.e. near-normal conditions) and standard deviation of 1. Theoretically values can range from -5 (extremely dry) to +5 (extremely wet), although approximately 95% of values occur within the range of -2 to +2, and 68% within the range -1 to +1 (Tanguy *et al*., 2017).

Regional Rainfall/SPI and NAOI Correlations

The Met Office Climate Districts are a commonly used in similar studies (e.g. Wilby *et al.,* 1997; Simpson & Jones, 2014), and as they represent areas of relatively homogeneous climate, were the chosen spatial unit of analysis for correlation of regional mean monthly total rainfall/SPI and NAOI. Mean monthly rainfall (based on GEAR data) and SPI were calculated by spatially averaging all gridded values within each climate district. Mean monthly rainfall/SPI for the study period are then correlated with NAOI calculated using both the ST and PC method for Great Britain. Exploratory analysis established normality and linear relationships, so a Pearson correlation was deemed appropriate. In our analysis we defined seasons as winter (DJF), spring (MAM), summer (JJA) and autumn (SON).

Calculation of Deviation of Mean Monthly Rainfall & Mean SPI-1

Monthly NAOI was classified into a state of positive, negative or neutral NAO phase. In light of the known limitations of the $NAOI_{ST}$ method of calculation, especially in the summer months (see Discussion), only the $NAOI_{PC}$ method was used for further analysis. NAO phase was defined as half the standard deviation plus/minus the long-term mean (after Berton *et al.,* 2017). NAO positive phase was calculated to be NAOI > 0.502, and negative phase <-0.503. Months with a NAOI_{PC} between these values represent a NAO neutral state. Each month in the GEAR and SPI-1 dataset was categorised using these values into being in either a NAO positive, NAO negative or NAO neutral state (Figure 3). For each month all datasets for a given phase were averaged on a cell-by-cell basis to produce a mean dataset for each month under each NAO condition. For the GEAR data the NAO positive/negative mean monthly datasets were then subtracted from the NAO neutral dataset for that month. This produced a final dataset to show deviation in mean monthly rainfall in the given phase from when NAO is neutral.

The deviation in mean monthly rainfall and mean SPI-1 values were then spatially averaged using the Met Office Climate Districts. In order to examine how similar each region's response to the NAO was over the study period, the mean deviation from neutral NAO conditions/mean monthly SPI of each district was then correlated against values from the other districts. Regions which are positively correlated suggest areas where rainfall displays similar NAO response, and vice-versa for negatively correlated regions.

Results

Regional Mean Correlations

Figure 2 show the results of the regional mean SPI/GEAR correlation analysis with NAOI_{ST} and NAOI_{PC}. Similar seasonal variations where produced using both rainfall measures (SPI and monthly GEAR data). Positive correlations suggest high SPI/GEAR values (i.e. high rainfall) when under NAO positive conditions and vice versa for NAO negative. While negative correlations are indicative of low SPI/GEAR values (i.e. low rainfall) when NAO is positive and vice versa for NAO negative. Significant positive correlations between NAOI_{ST} and monthly rainfall are found in the west of Great Britain, and particularly north, for all months between October and April. While significant correlations persist in 'Scotland North' and 'Scotland West' in spring (MAM), they are largely absent in England and Wales.

June is characterised by a marked gradient with most of England showing significant negative correlations. July and August are characterised by a notable lack of significant correlations between $NAOI_{ST}$ and the rainfall measures; with July largely having weak positive correlations and August a combination of weak positive and negative correlations. September through to November sees a change in the correlation strength; such as that by November, 'England East and North East', is the only region not showing a significant positive correlation.

$NAOI_{PC}$ produces similar spatial patterns to those described above; significant positive correlations are found for the north and west for the months of September through to May. During this time the central and southern regions fluctuate between positive and negative correlations (of varying significance). $NAOI_{PC}$ correlations vary from those gained through using $NAOI_{ST}$ in Spring (MAM), where more pronounced negative correlations are present in the central and southern regions. This signal is enhanced moving into the summer months where all of England, Wales and 'Scotland East' see significant negative correlations between SPI and $NAOI_{PC}$.

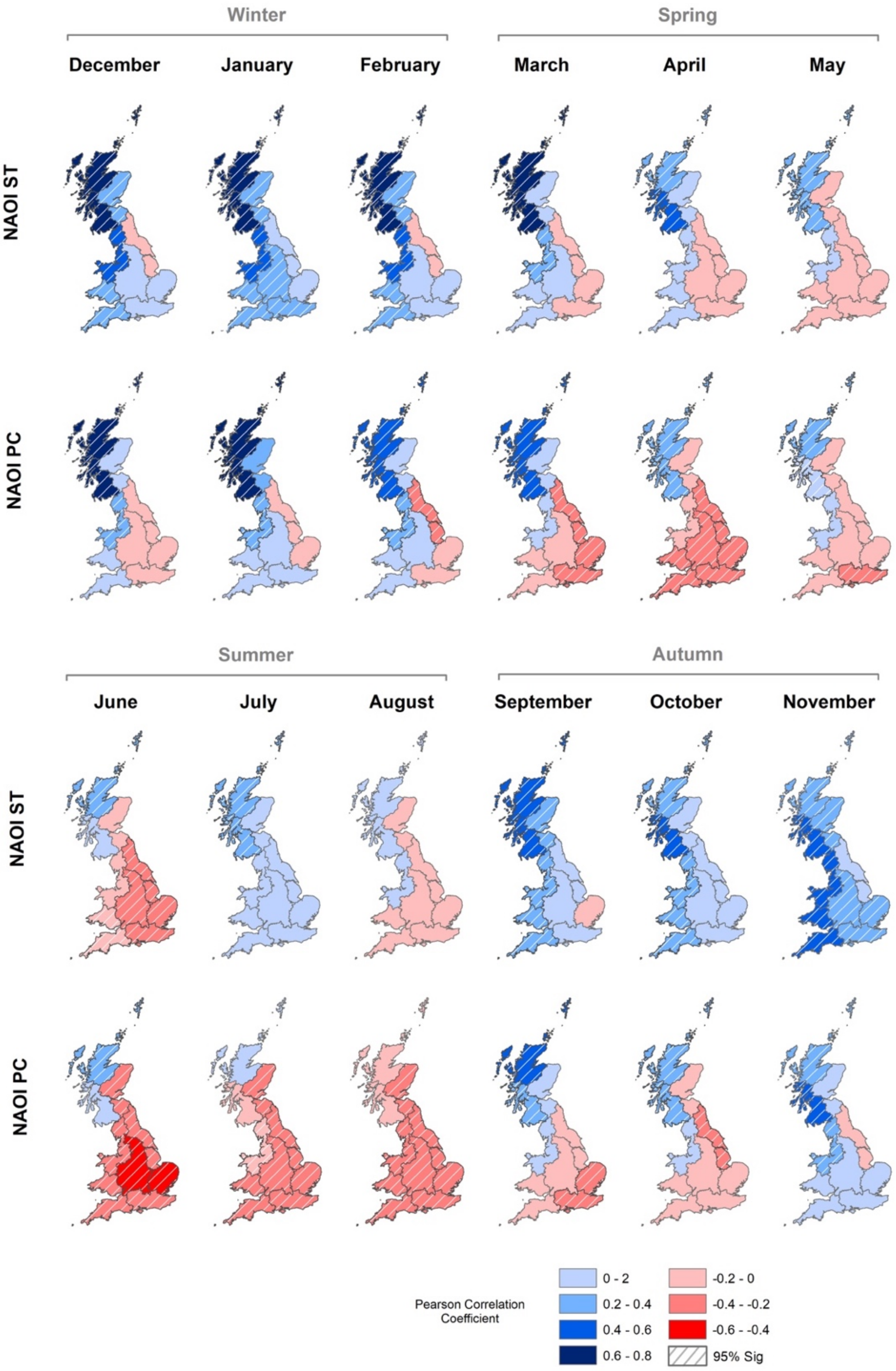

Figure 2: Correlations between NAOI ST/PC with regional mean SPI-1. The two NAOI methods show similar patterns in the winter months (DJF), with strong positive correlations in the North. However, note the significant differences observed between the two NAOI's in the summer months where stronger negative correlations are observed using NAOI$_{PC}$. Tabular data for this analysis can be found in the Online Supplemental Material (Tables S2 and S3).

NAO Phase Definition

Figure 3 shows the results of the NAO phase classification process using the method of Berton *et al.* (2017) on the $NAOI_{PC}$ time series. Based on our definition of phases, the NAO was in a positive or negative phase for approximately 53% of the time between October 1899 and September 2015. NAO phase occurrence and intensity was clearly more pronounced during the winter (DJF) rather than summer (JJA) months, especially for NAO positive.

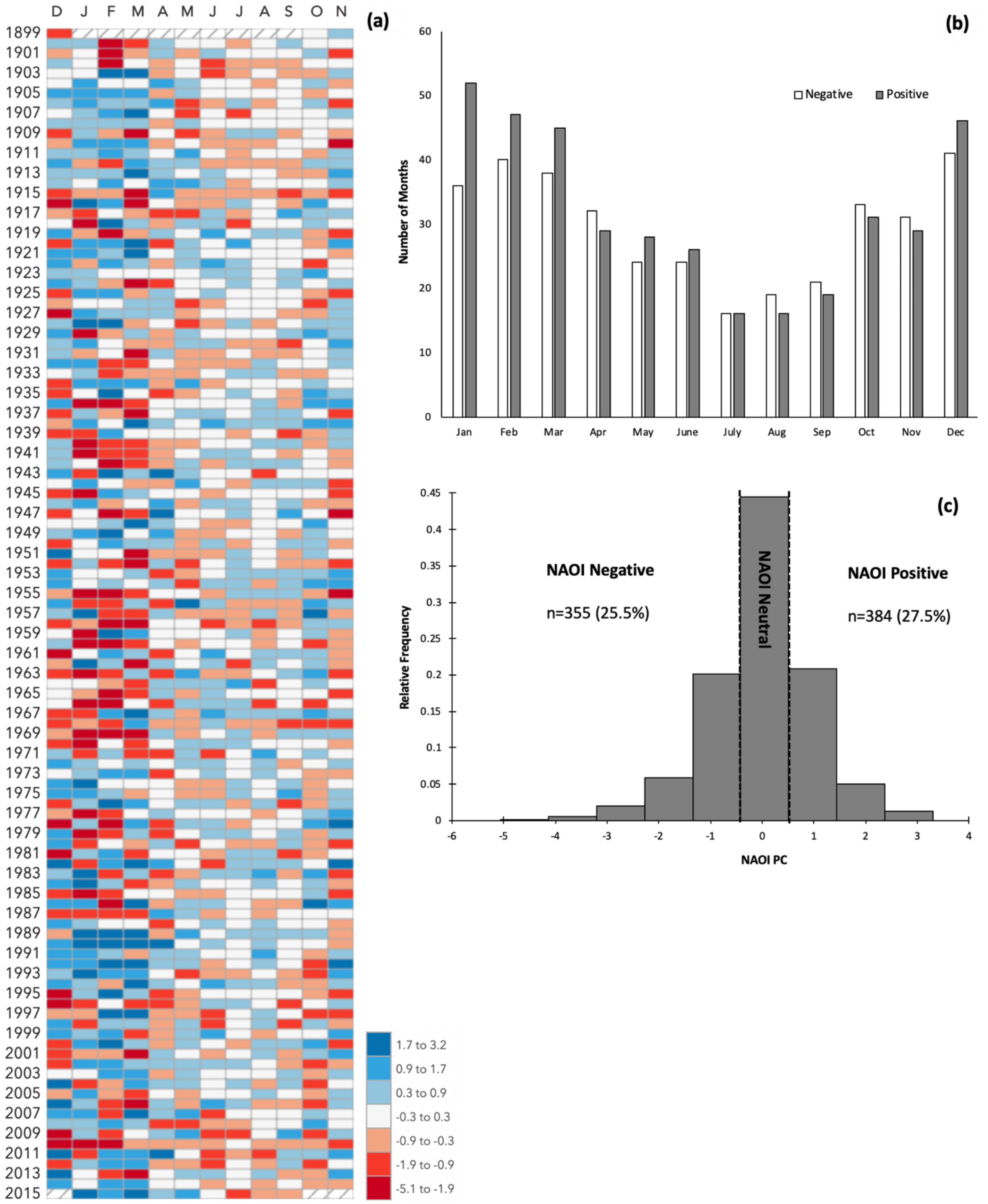

Figure 3: (a) Heatmap showing the temporal distribution of NAO phase occurrence and intensity, (b) frequency of occurrence of each NAO phase per month and (c) distribution of $NAOI_{PC}$ classification, over the study period (1899-2015).

Spatial Patterns of Deviation in Mean Monthly Rainfall & Mean SPI-1 under NAO phase

Figure 4 show NAO phase dependent deviation in mean monthly rainfall (calculated as the difference from mean monthly rainfall under NAO neutral conditions). Clear regional and seasonal differences are observed in both NAO positive and negative phases. The most notable deviations in rainfall occur in the north of Great Britain during the winter months (DJF) (in particular in Scotland North and Scotland West). These regions receive significantly more or less rainfall under NAO positive or negative conditions respectively. These conditions are inverted in the south/east of Great Britain, with these regions seeing decreases/increases under NAO positive/negative, however to a lesser extent compared to the north. This creates a strong winter spatial signal in rainfall under the two NAO conditions, with the north/west and south/east showing clear regional differences. The magnitude of the deviation is also different in terms of enhanced wetness/dryness; NAO positive tends to produce wetter conditions than NAO negative does dry. This suggests that the enhancing effect on rainfall is more marked than the dampening effect. Only small changes in rainfall under NAO conditions were found in southern Great Britain throughout winter. Moving into Spring (MAM) this spatial pattern is largely retained, although the magnitude of the deviation in rainfall decreases with time.

Significant differences in rainfall are observed during the summer months (JJA) also. However, the relative increases/decreases in rainfall under NAO positive/negative are broadly inverted when compared to the winter months (DJF). The NAO spatial signature now seems more apparent in the southern and central regions, with NAO positive resulting in notably drier conditions, and NAO negative producing wetter conditions (up to approximately +/- 30mm), most notably in July and August in South West England and South Wales. The clear north/west and south/east spatial divide in rainfall patterns observed in the winter months becomes less pronounced, with the central and southern regions of Great Britain being more homogeneous in their rainfall response, and much of the country displaying a similar rainfall deviation to these regions. In the autumn months (SON), the patterns in rainfall deviation start to invert again becoming more similar to those described above in winter and the regional differences in NAO rainfall response become more discernible.

Figure 5 shows the comparable analysis undertaken using mean monthly SPI-1 data. As with the deviation in monthly rainfall analysis discussed above, notable seasonal and spatial patterns in wet/dry conditions are present when NAO is in either a positive or negative phase. During the winter (DFJ) the north has significantly high/low SPI values, representing wetter than normal/drier than normal conditions under positive/negative NAO. Mean SPI-1 values follow a similar winter spatial pattern to the monthly deviation analysis – a clear north/west and south/east difference in NAO response. While during the summer months (JJA) this pattern is broadly inverted and more homogeneous spatially so that the central and southern regions experience the most notable drier/wetter conditions under NAO positive/negative, with the rest of the country experiencing similar conditions.

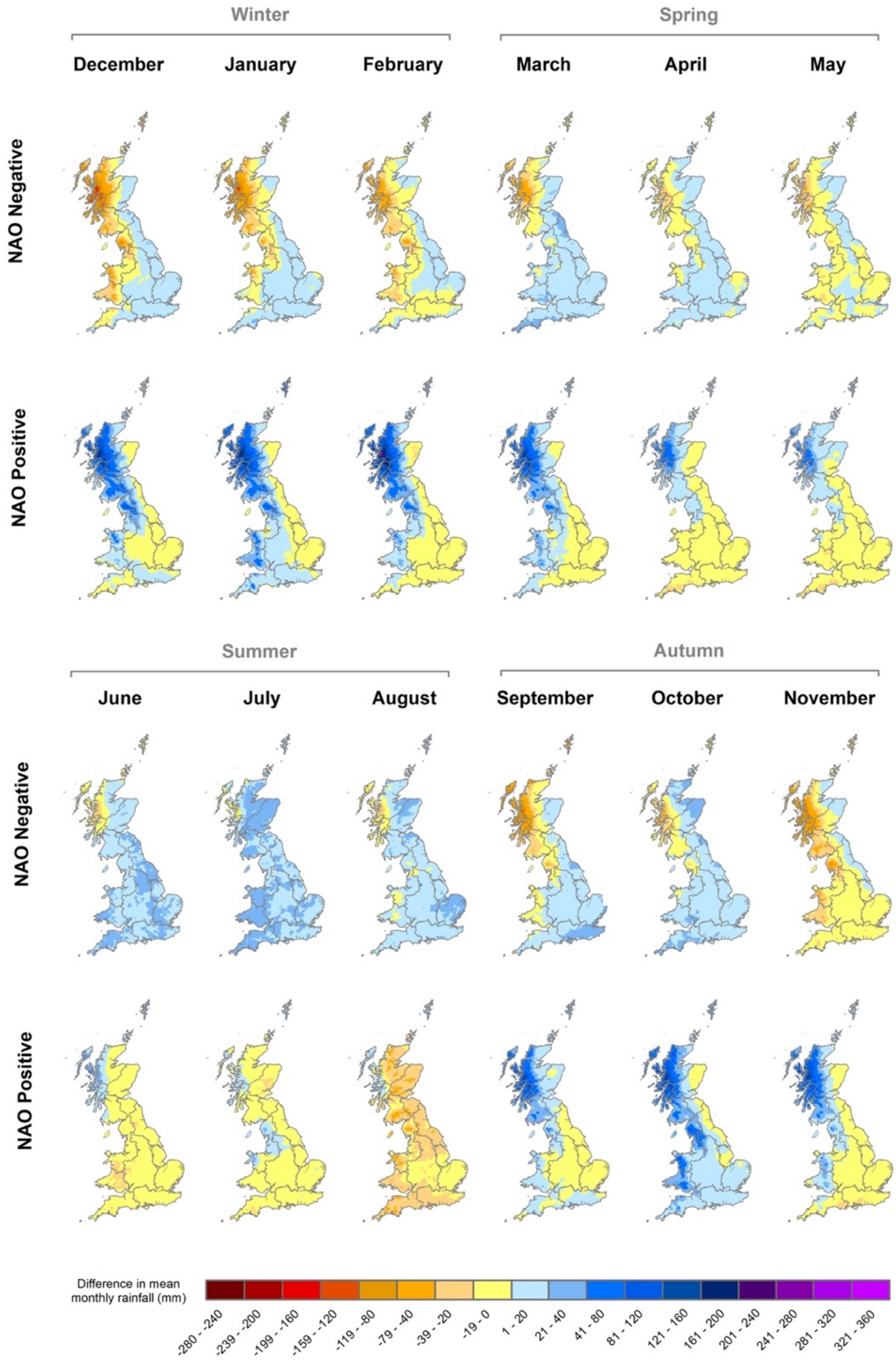

Figure 4: Difference in mean monthly rainfall values (mm) under NAO phase for the period October 1899-September 2015. Note the significant increase/decrease in rainfall in the North/West during the winter months, and the wetter/drier conditions observed during the summer months under NAO positive/negative (GEAR data from Tanguy *et al.,* 2016). Tabular data for this analysis can be found in the Online Supplemental Material (Table S4).

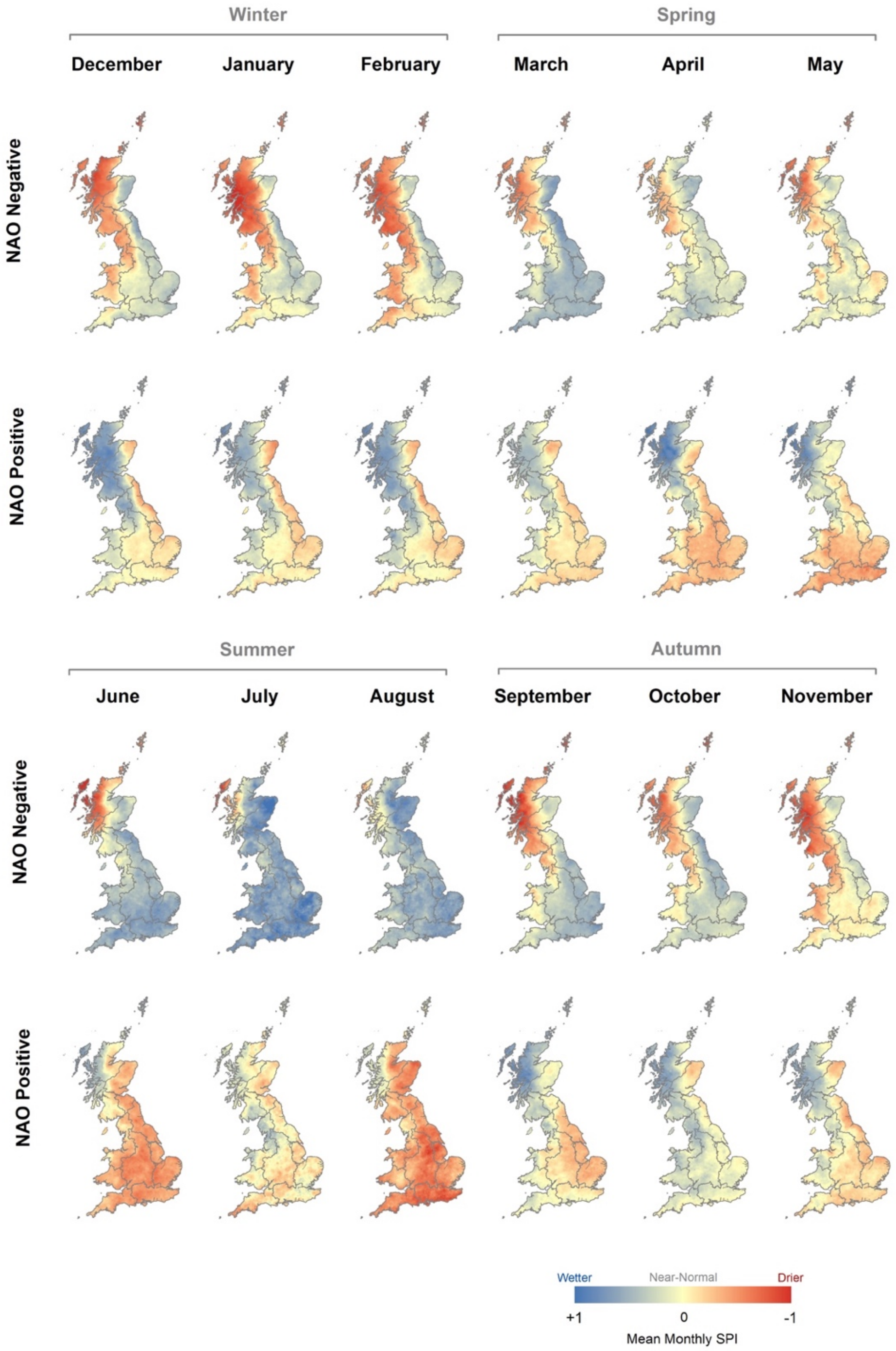

Figure 5: Mean monthly SPI-1 under NAO conditions for the period October 1899-September 2015. Note the significantly wetter/drier conditions in the North/West during the winter months, and the wetter/ drier conditions observed during the summer months under NAO positive/negative. (SPI data from Tanguy *et al.,* 2017). Tabular data for this analysis can be found in the Online Supplemental Material (Table S5).

Figure 6 shows the results of the correlation analysis to assess the similarity of each regions response to NAO positive/negative conditions (derived using both the mean monthly rainfall deviation data and mean SPI-1 data). Regions which show positive correlations in their spatial mean rainfall deviation or SPI-1 respond to the NAO in a similar way (i.e. they are wetter or drier by a similar magnitude), while regions which are negatively correlated show where differences occur in regional response to NAO fluctuation. Similar spatial patterns in correlation are present using both mean monthly rainfall deviation (from the GEAR dataset) and mean monthly SPI-1.

‘Scotland North’ and ‘Scotland West’ are strongly positively correlated at the 95% confidence level, these regions are also positively correlated with ‘England North West and North Wales’. This suggests that these regions respond to the NAO in a similar manner. A clear grouping is also evident in the positive correlations around the South East of Great Britain, with ‘East Anglia’ and ‘England South East and Central South’ showing similar responses. Based on these regional groupings of positive correlations, the north/west and south/east divide present in the previous analysis is clearly shown in the correlation maps, most notably in the southern regions negative correlation with ‘Scotland North’ and ‘Scotland West’.

However, the clear spatial signature is only evident in the correlations between certain regions. Some regions, such as ‘Scotland East’, ‘South Wales and England South West’, and the ‘Midlands’ show consistent significant positive correlations with almost all other regions. This suggests that these regions respond in a similar way to the NAO and tend to follow the general pattern in deviation/mean SPI-1 as the rest of country.

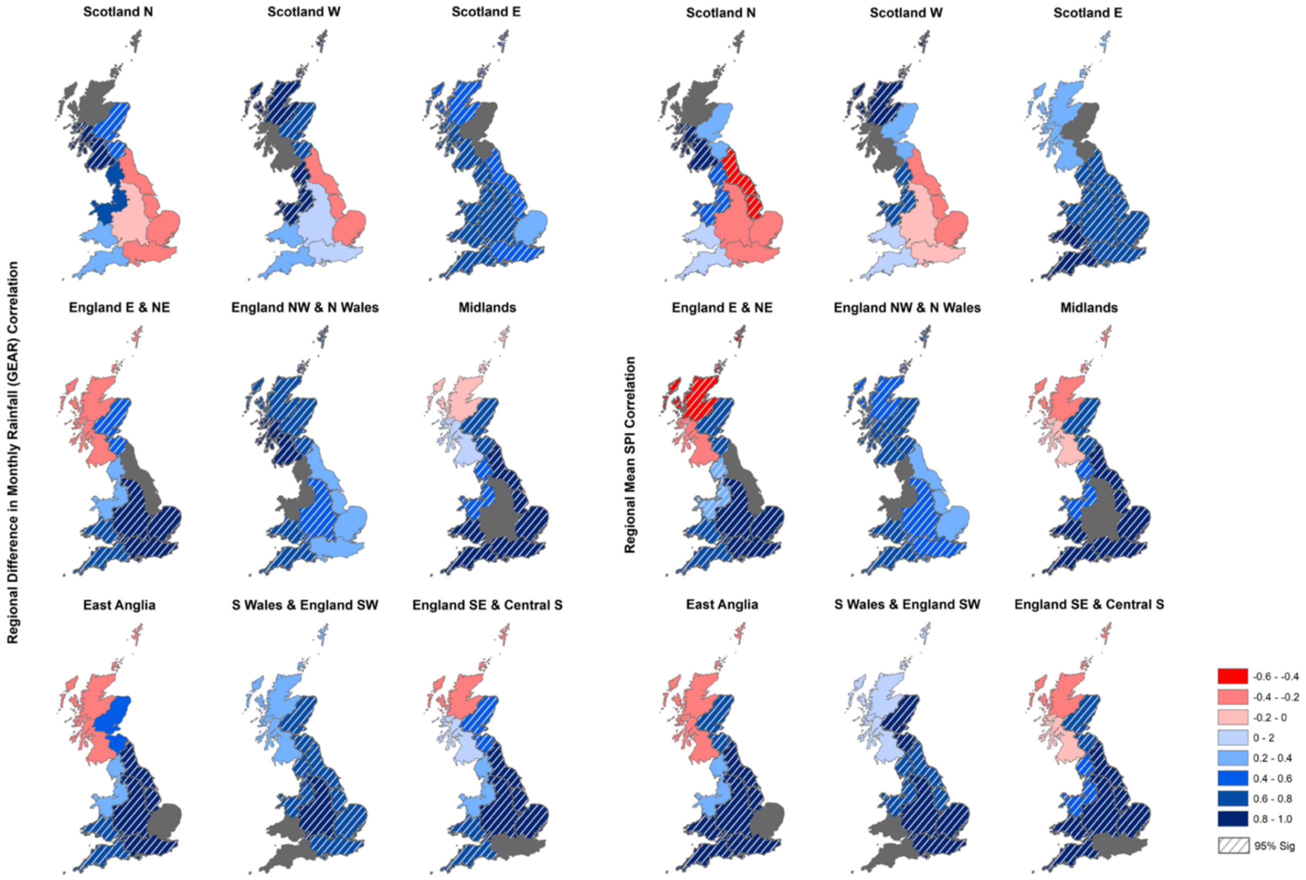

Figure 6: Spatial representation of Pearson Correlation Coefficient values for assessing the similarity of rainfall response across the 9 Met Office Climate Districts. Note the positive correlations of the north-western/south-eastern regions, and the negative correlations between Scotland and the Southern/Central regions. Block grey areas indicate the region used as the independent variable in the correlation analysis. Tabular data for this analysis can be found in the Online Supplemental Material (Tables S6 and S7).

Discussion

This research set out to examine the spatiality of rainfall patterns under NAO positive and negative conditions using nationally consistent, high resolution datasets (Tanguy *et al.,* 2016; Tanguy *et al.,* 2017). This extends previous NAO rainfall studies based in Great Britain as it considers the full wet/dry continuum, rather than just weather extremes, across a full year, rather than just the winter months, and is not restricted in terms of available data as we use spatially consistent gridded datasets rather than analysis based on selected stations/regions. A range of methods were implemented to achieve this, and based on the convergence of evidence in the results, we identify three main observations: (I) the sensitivity of spatial rainfall analysis to the chosen NAOI calculation method; (II) the clear north/west and south/east divide in rainfall signatures under NAO positive and negative conditions during the winter months; (III) the NAO does appear to have some influence over summer (JJA) rainfall, although the spatiality of these patterns is less distinctive when compared to winter. These will now be discussed in turn.

The first observation relates to the use of different NAOI measures; in our study namely the decision to use $NAOI_{ST}$ or $NAOI_{PC}$. Pearson correlation analysis was undertaken using both SPI-1 and monthly GEAR data against both NAOI measures (Figure 2). While the two measures generally produced similar spatial patterns in correlation strength during the winter months, notable differences were observed during spring (MAM) and summer (JJA). $NAOI_{PC}$ produced significant strong negative correlations in the southern and central regions during this period; while the $NAOI_{ST}$ method produced much weaker correlations which were not significant. This implies that if $NAOI_{ST}$ is used then under positive NAO much of the country is wetter than average, and drier under NAO negative. However, if $NAOI_{PC}$ is used then this pattern is the opposite. Therefore, had the later analysis to examine rainfall spatiality been undertaken using the $NAOI_{ST}$ method, it is likely that the results would have been far less conclusive as those gained from the $NAOI_{PC}$ method (Kosanic *et al.,* 2014).

The poor representation of summer NAO has been noted as a key limitation of the station-based method of NAOI calculation (Pokorná & Huth, 2015). The main limitation being the mobility of the dipoles of the NAO across any given year (Jung *et al.,* 2003; Bernanová & Huth, 2008). During the summer months the main pressure ‘action points’ of the NAO (the Azores high and Icelandic low) move away from the position of the in-situ monitoring stations, measurements from which are used to calculate $NAOI_{ST}$, due to a combination of factors including the East Atlantic and Scandinavian teleconnections (Hurrell & Van Loon, 1997; Moore *et al.,* 2013), which have also been attributed to UK meteorological patterns (Comas-Bru & McDermott, 2014; Zubiate *et al.,* 2017). Based on our correlation analysis, and the potential mis-representation of summer rainfall patterns under NAO conditions, we support the conclusions of Hurrell & Deser (2009) who suggest there is no unique or universally accepted way to define the NAO, and those of Pokorná & Huth (2015) who advise caution in the selection of NAO representative indices and recommend non-station-based methods of calculation for summer NAO representation due to circulation spatial variability.

The spatial analysis of rainfall patterns under NAO positive and negative phase inform our second and third main observations. The accepted general understanding of NAO impact on rainfall across Great Britain during the winter months is to associate winter storms with NAO positive, and colder/drier winters with NAO negative indices (Visbeck *et al.,* 2001). Our analysis of both deviation in mean monthly rainfall and mean SPI-1 values show a clear north/west and south/east spatial divide in response to NAO during the winter months; implying a less spatially generalisable response than suggested above. The north/west of Great Britain in particular sees rainfall patterns significantly alter under different NAO phases. Under NAO positive these regions see notable increases in monthly rainfall, while under NAO negative there is a notable decrease. Although to a smaller magnitude, the opposite response is observed in the southern and eastern region. This clear winter spatial pattern in rainfall under NAO positive/negative conditions is also evident in the regional correlation analysis; where the northern and western regions are positively correlated with each other, but negatively correlated with the southern and eastern regions. This winter spatial pattern has been observed in other studies over shorter timescales using station-based measurements of rainfall, thus indicating some long-term consistency in this pattern (Wilby *et al.,* 1997; Folwer & Kilsby, 2002; Burt & Howden, 2013; Simpson & Jones, 2014). Although this winter pattern coincides with upland/lowland topographic patterns, which may enhance rainfall under NAO positive conditions (Burt & Howden, 2013), the notable dry conditions under NAO negative suggests that the interaction between NAO and local characteristics is far more complex. Having an understanding of the generalisable winter NAO rainfall pattern is significant given that in recent years notable advances have been made in our ability to predict winter NAO phase months in advance (Baker *et al.,* 2017; Weisheimer *et al.,* 2017 Hall *et al.,* 2017). For example, being able to say with some degree confidence that the NAO will remain in a negative condition over the winter months, will allow for early warning water shortage systems in Scotland to be triggered to ensure consistent supply in the upcoming dry period.

The clear spatial pattern during winter which reverses under the two different NAO conditions is likely associated with the location of storm tracks due to altered jet stream location (Visbeck *et al.,* 2001). Long term storm track analysis (mid-Holocene) suggest that a NAO positive phase is characterised by a stronger and more northerly/easterly storm track across the Atlantic (Trigo, 2006; Brayshaw *et al.,* 2010). This NAO driven pattern is evident in both precipitation and wind speed records (Burningham & French, 2013).

Our analysis shows that the NAO winter spatial pattern continues into Spring (MAM), gradually decreasing in discernibility over time; this is explainable by the SLP anomalies associated with winter NAO tending to persist into Spring across the Atlantic region (Herceg-Bulić & Kucharski, 2014). This change in NAO rainfall signature over time brings into focus our final main observation. Moving into summer (JJA) the spatial pattern of rainfall under both positive and negative NAO is far less distinctive and more homogenous (Figures 4 and 5). Some regional differences are observable, with the central and southern regions showing the most notable deviation from normal conditions.

However, the general direction of this deviation under NAO positive and negative conditions is broadly inverted during summer when compared to winter. NAO positive now produces relatively homogenous dry conditions, and NAO negative produces wetter conditions. Alongside the NAO, it is likely that high SPI values (high rainfall) are associated with convective storms during the summer months (Kendon *et al.,* 2014). As these systems are small in their spatial influence this may partly explain the dispersed summer rainfall patterns in Figure 4 and Figure 5.

Conclusion

As the primary teleconnection affecting British climate, the NAO has been well researched (Wilby *et al.,* 1997; Folwer & Kilsby, 2002; Burt & Howden, 2013). However, many studies have focused on winter climate and weather extremes and have been based on a limited number of in-situ measurements/regions. This study set out to examine the spatial signatures of NAO phase dependent precipitation, using nationally consistent datasets. Through correlation and spatial analysis we draw attention to three observations regarding regional response in rainfall patterns to the NAO: (I) the sensitivity of any analysis to the chosen NAOI. (II) The clear north/west and south/east divide in rainfall signatures during the winter months. (III) The NAO does appear to have some influence over summer rainfall, although the spatiality of these patterns is less distinctive when compared to winter patterns.

Our results extend the understanding of the NAO's influence on rainfall patterns in Great Britain and suggest that, now more than ever, there is potential to improve our predictive ability of teleconnections and precipitation, allowing for better informed water management decisions. This is important given the potential future impacts of climate change on hydro-meteorological conditions in Great Britain (Watts *et al.,* 2015). In relation to seasonal forecasting and climate projections, this work shows some potential and adds to the growing evidence finding value of including the NAOI in model simulations (Baker *et al.,* 2017; Smith *et al.,* 2019).

It is important to note that our work uses gridded rainfall from the CEH-GEAR dataset, which over the period shows variability in the number of rainfall stations used for interpolation. Therefore, an avenue for future research would be to repeat similar analysis using more temporally consistent Met Office MIDAS (Met Office Integrated Data Archive System) rainfall. The use of the new CEH SPI data (Tanguy *et al.,* 2017) also has potential for future research in this area; due to the calculation of multiple accumulation periods ranging from 3-24 months. Future research could utilise these longer periods to establish whether there is any lagged effect of the NAO on rainfall patterns. It is also important to note that the NAO cannot explain all of the rainfall spatio-temporal patterns in the UK. NAO rainfall spatial signatures have been found to show variable levels of consistency over long records (West *et al.,* 2019), and extreme events have been found to occur due to the interaction of multiple teleconnections (Rust *et al.*, 2019). There is therefore still a future need to consider the NAO's interaction with and the general influence of other teleconnections on weather and climate in Great Britain to further improve our predictive capability of seasonal rainfall patterns (Comas-Bru & McDermott, 2014; Hall & Hanna, 2018).

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