

Regional rainfall response to the North Atlantic Oscillation (NAO) across Great Britain


Harry West, Nevil Quinn  and Michael Horswell

ABSTRACT

The North Atlantic Oscillation (NAO) has been long studied as the primary teleconnection affecting the 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 that there is a 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; and (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.

Key words | British climate, North Atlantic Oscillation, rainfall patterns, teleconnections, wet/dry continuum

Harry West (corresponding author)

Nevil Quinn 

Michael Horswell

Centre for Water, Communities and Resilience,
Department of Geography and Environmental
Management,
University of the West of England,
Bristol,
UK
E-mail: harry.west@uwe.ac.uk

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) have 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; De Luca *et al.* 2017; Huang *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 2013/2014 and the 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 the 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 the NAO on British and European climatic patterns (Comas-Bru & McDermott

2014; 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 NAO Index (NAOI) as a 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 the usual difference in the 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 the 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).

The impact of the NAOI phase during winter and summer is known to differ significantly (Folland *et al.* 2009; del Rio *et al.* 2011; Sun & Wang 2012). While the strength of regional correlations with rainfall of the winter (December, January, February (DJF)) NAO Index (NAOI_W) and summer (June, July, August (JJA)) NAO 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; Fowler & Kilsby 2002) and short record lengths (e.g. Fowler & Kilsby 2002; Afzal *et al.* 2015). Studies have also tended to focus on extremes rather than more general wet/dry patterns (e.g.

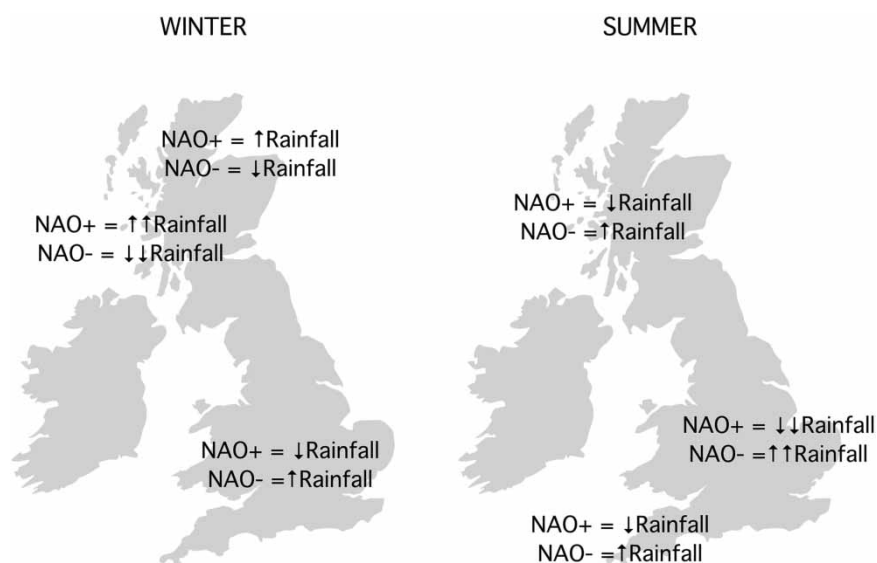


Figure 1 | Generalised NAO winter and summer rainfall patterns from previous studies (Wilby *et al.* 1997; Fowler & Kilsby 2002; Burt & Howden 2013; Kosanic *et al.* 2014; Simpson & Jones 2014; Afzal *et al.* 2015; Hall & Hanna 2018). A more detailed summary of these findings can be found in Table S1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

Simpson & Jones 2014) and have had a clear emphasis on the relationship between the 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 the NAO phase (Wilby *et al.* 1997; Fowler & Kilsby 2002). While relationships between winter rainfall and the 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 the 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 provides new opportunities for analysis of teleconnection drivers of rainfall. Similarly, the recent publication of the gridded Standardised Precipitation Index (SPI) time series (Tanguy *et al.* 2017) offers an additional advantage as the data are 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 (Irannezhad *et al.* 2015; Kingston *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 means that there is now a 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 SPI) 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 the NAO condition, the NAOI was used. This study makes use of two commonly used NAOI calculation methods: the station-based method (NAOI_{ST}) which calculates the index based on the fixed SLP station measured data, and the principal component analysis method (NAOI_{PC}) comprising a time series of the leading empirical orthogonal function 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–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 1 km grid and has a 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 5 km 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 a 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 of -1 to $+1$ (Tanguy *et al.* 2017).

Regional rainfall/SPI and NAOI correlations

The Met Office Climate Districts are 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 the correlation of regional mean monthly total rainfall/SPI and the NAOI. Mean monthly rainfall (based on GEAR data) and SPI were calculated by spatially averaging all gridded values within each climate district. The mean monthly rainfall/SPI for the study period are then correlated with the 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 the deviation of mean monthly rainfall and mean SPI-1

The 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. The NAO phase was defined as half the standard deviation plus/minus the long-term mean (after Berton *et al.* 2017). The NAO-positive phase was calculated to be NAOI >0.502 and -negative phase <-0.503 . Months with a NAOI_{PC} between these values represent an NAO neutral state. Each month in the GEAR and SPI-1 dataset was categorised using these values into being in either an 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 compared to when NAO is neutral.

The deviations 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 a similar NAO response and vice versa for negatively correlated regions.

RESULTS

Regional mean correlations

Figure 2 shows the results of the regional mean SPI correlation analysis with NAOI_{ST} and NAOI_{PC}. Similar seasonal variations were 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. 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 in the 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 to November sees a change in the correlation strength; such as that by

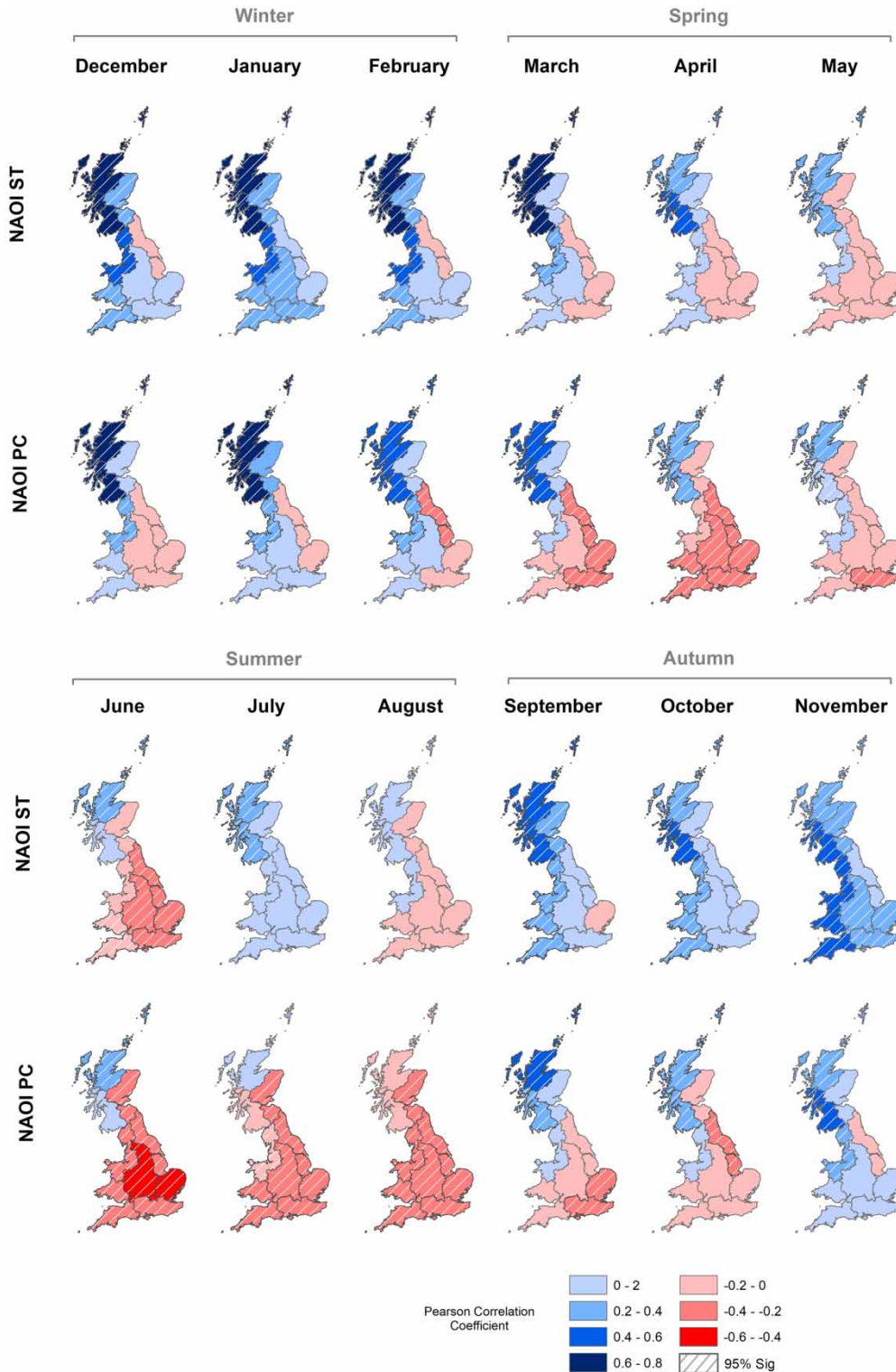


Figure 2 | Correlations between NAOI_{ST} and NAOI_{PC} with regional mean SPI-1. The two NAOI methods show similar patterns in the winter months (DJF), with strong positive correlations in the North. However, note that the significant differences observed between the two NAOIs in the summer months where 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).

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 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}.

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. The NAO-phase occurrence and intensity were clearly more pronounced during the winter (DJF) rather than summer (JJA) months, especially for NAO-positive.

Spatial patterns of deviation in mean monthly rainfall and mean SPI-1 under the NAO phase

Figure 4 shows the 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 also observed during the summer months (JJA). 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 ± 30 mm), 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 the 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 (DJF), 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 the 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.

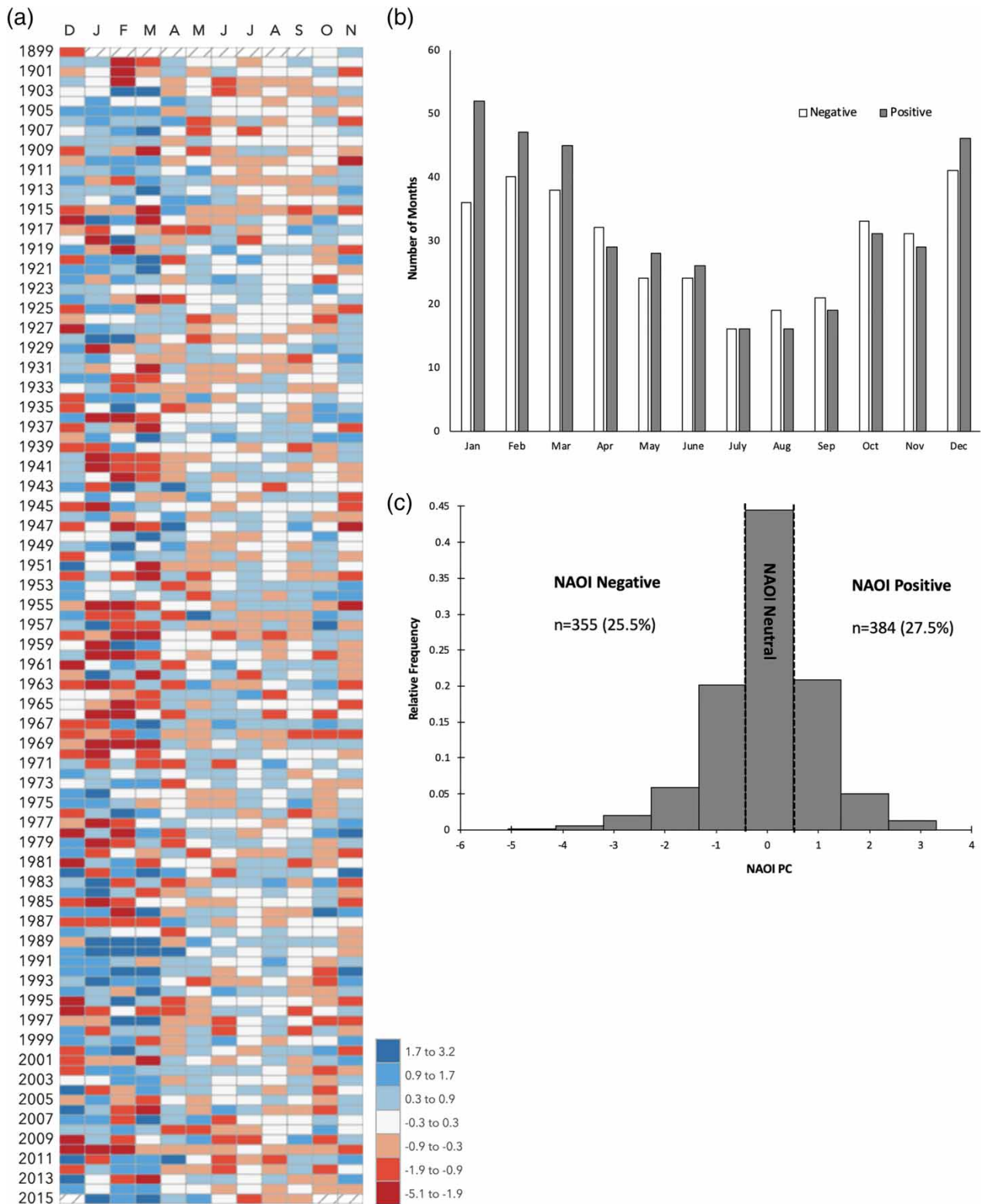


Figure 3 | (a) Heatmap showing the temporal distribution of NAO-phase occurrence and intensity, (b) the frequency of occurrence of each NAO phase per month and (c) the distribution of NAOI_{PC} classification over the study period (1899–2015).

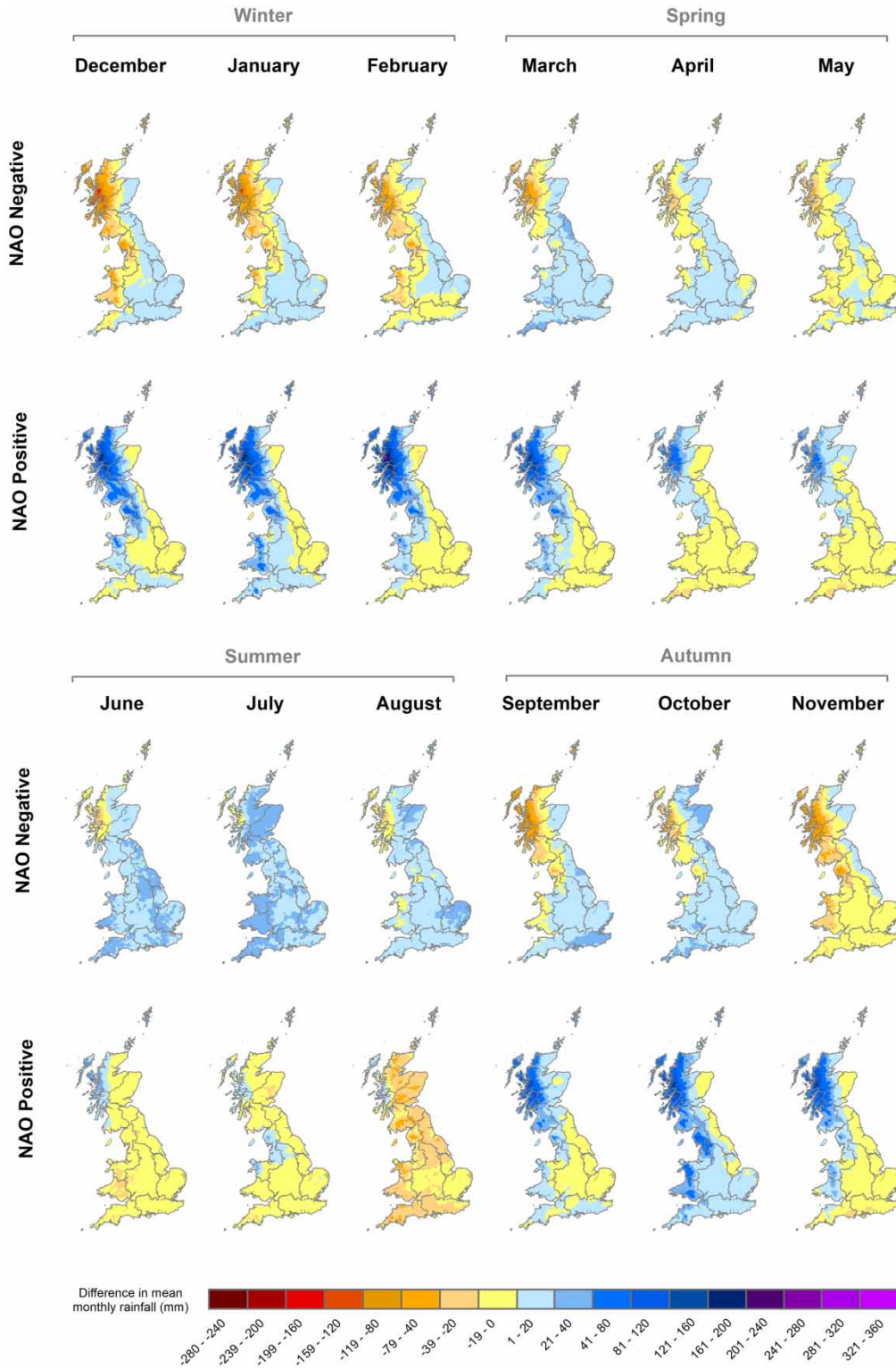


Figure 4 | Difference in mean monthly rainfall values (mm) under the NAO phase for the period October 1899–September 2015. Note the significant increase/decrease in rainfall in the north/west during the winter months and the wetter/drier conditions observed during the summer months under NAO-positive/negative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

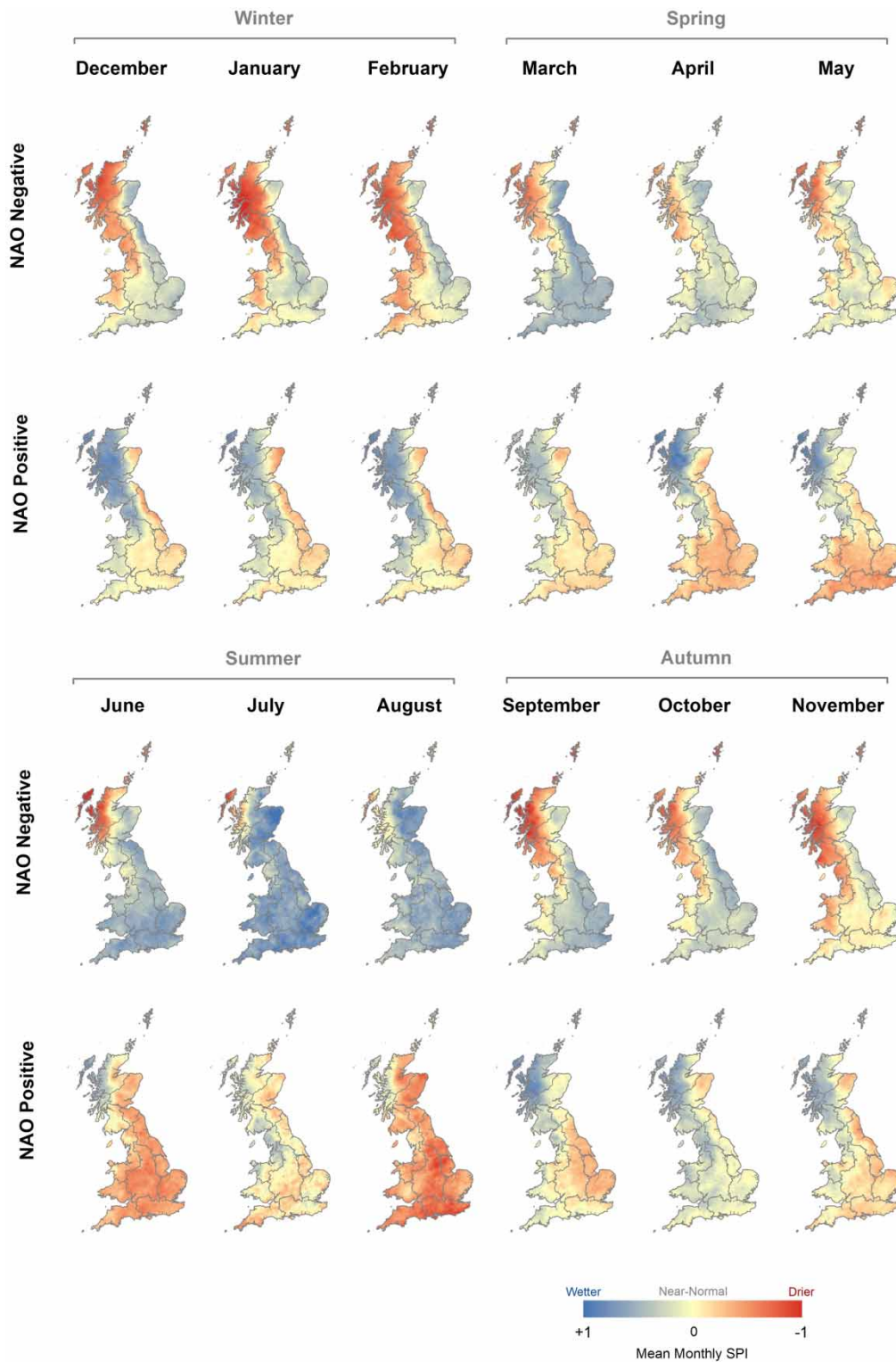


Figure 5 | Mean monthly SPI-1 under NAO conditions for the period October 1899–September 2015. Note the significantly wetter/drier conditions in the north/west during the winter months and the wetter/ drier conditions observed during the summer months under NAO positive/negative. (SPI data from Tanguy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

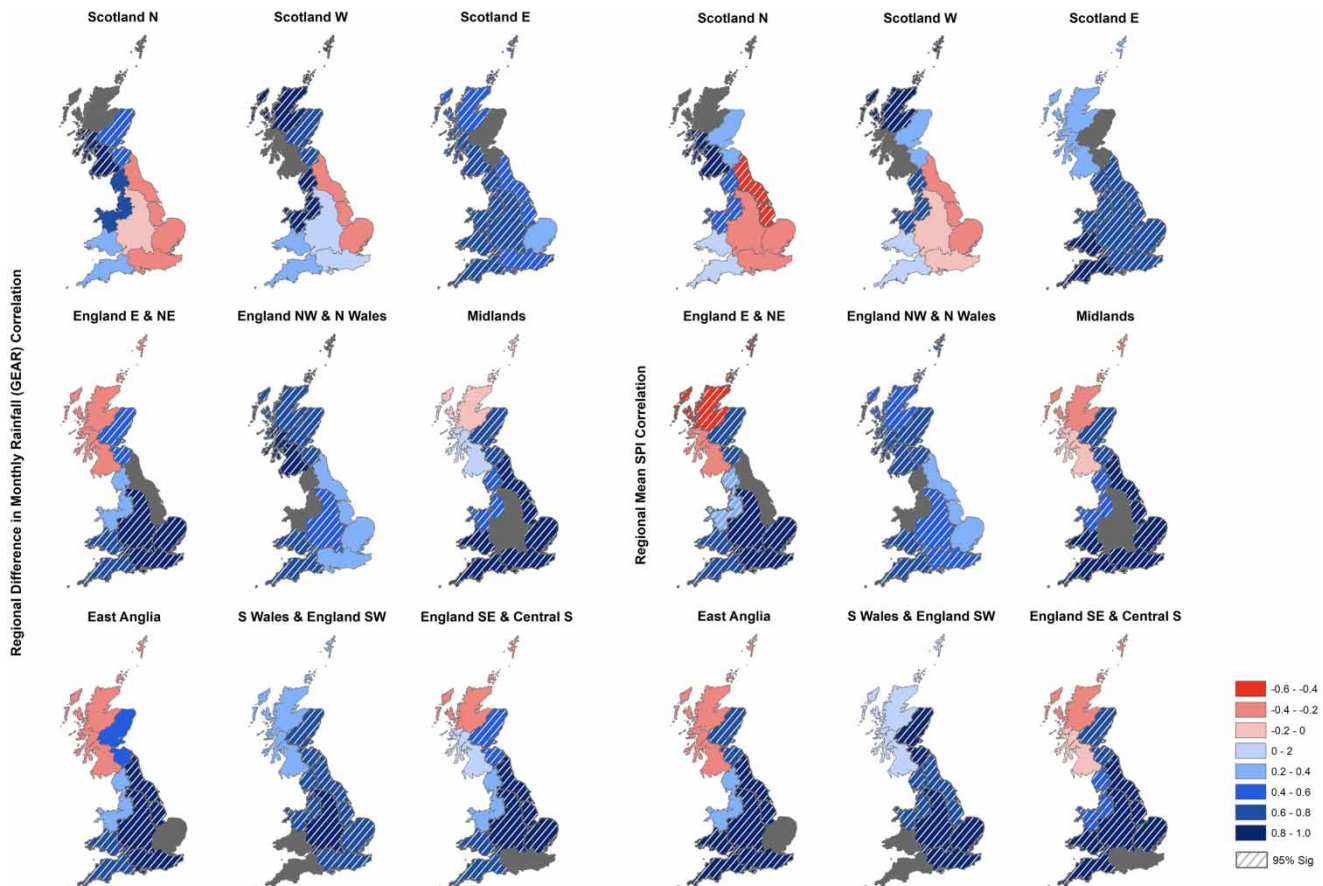


Figure 6 | Spatial representation of Pearson correlation coefficient values for assessing the similarity of rainfall response across the nine Met Office Climate Districts. Note the positive correlations of the north-western/south-eastern regions and the negative correlations between Scotland and the 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).

Figure 6 shows the results of the correlation analysis to assess the similarity of each region's 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 the 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 the country.

DISCUSSION

This research sets out to examine the spatiality of rainfall patterns under NAO-positive and -negative conditions using nationally consistent, high-resolution datasets (Tanguy *et al.* 2016, 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; and (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 is the mobility of the dipoles of the NAO across any given year (Jung *et al.* 2003; Beranová & 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 misrepresentation of summer rainfall patterns under NAO conditions, we support the conclusions of Hurrell & Deser (2009) who suggest that 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 informs 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 deviations in mean monthly rainfall and mean SPI-1 values shows 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 regions. 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 time-scales using station-based measurements of rainfall, thus

indicating some long-term consistency in this pattern (Wilby *et al.* 1997; Fowler & 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 suggest 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; Hall *et al.* 2017; Weisheimer *et al.* 2017). For example, being able to say with some degree of 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) suggests 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 the 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 Figures 4 and 5.

CONCLUSION

As the primary teleconnection affecting the British climate, the NAO has been well researched (Wilby *et al.* 1997; Fowler & 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 sets 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; and (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 to 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).

ACKNOWLEDGEMENTS

We thank the two anonymous reviewers, whose constructive comments and suggestions have allowed us to strengthen this manuscript and clarify our argument.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at <https://doi.org/10.2166/nh.2019.015>.

REFERENCES

- Afzal, M., Gagnon, A. S. & Mansell, M. G. 2015 Changes in the variability and periodicity of precipitation in Scotland. *Theoretical and Applied Climatology* **119**, 135–159.
- Baker, L. H., Shaffrey, L. C. & Scaife, A. A. 2017 Improved seasonal prediction of UK regional precipitation using atmospheric circulation. *International Journal of Climatology* **38** (51), 437–453.
- Barker, L. J., Hannaford, J., Chiverton, A. & Svensson, C. 2016 From meteorological to hydrological drought using standardised indicators. *Hydrology and Earth System Science* **20**, 2483–2505.
- Bell, V. A., Davies, H. N., Kay, A. L., Brookshaw, A. & Scaife, A. A. 2017 A national-scale seasonal hydrological forecast system: development and evaluation over Britain. *Hydrology and Earth System Sciences* **21**, 4681–4691.
- Beranová, R. & Huth, R. 2008 Time variations of the effects of circulation variability modes on European temperature and precipitation in winter. *International Journal of Climatology* **28** (2), 139–158.
- Berton, R., Driscoll, C. T. & Adamowski, J. F. 2017 The near-term prediction of drought and flooding conditions in the northeastern United States based on extreme phases of AMO and NAO. *Journal of Hydrology* **553**, 130–141.
- Bonaccorso, B., Cancelliere, A. & Rossi, G. 2015 Probabilistic forecasting of drought class transitions in Sicily (Italy) using Standardised Precipitation Index and North Atlantic Oscillation Index. *Journal of Hydrology* **526**, 136–150.
- Brayshaw, D. J., Hoskins, B. & Black, E. 2010 Some physical drivers of changes in the winter storm tracks over the North Atlantic and Mediterranean during the Holocene. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* **366** (1931), 5185–5223.
- Burningham, H. & French, J. 2013 Is the NAO winter index a reliable proxy for wind climate and storminess in northwest Europe? *International Journal of Climatology* **33**, 2036–2049.
- Burt, T. & Howden, N. 2013 North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. *Water Resources Research* **49**, 3504–3515.
- Clark, R. T., Bett, P. E., Thornton, H. E. & Scaife, A. A. 2017 Skilful seasonal predications for the European energy industry. *Environmental Research Letters* **12**, 024002.
- Comas-Bru, L. & McDermott, F. 2014 Impacts of the EA and SCA patterns on the European twentieth century NAO – winter climate relationship. *Quarterly Journal of the Royal Meteorological Society* **140**, 354–363.
- De Luca, P., Hillier, J. K., Wilby, R. L., Quinn, N. W. & Harrigan, S. 2017 Extreme multi-basin flooding linked with extra-tropical cyclones. *Environmental Research Letters* **12**, 114009.
- del Rio, S., Herrero, L., Pinto-Gomes, C. & Penas, A. 2011 Spatial analysis of mean temperature trends in Spain over the period 1961–2006. *Global Planetary Change* **78** (1–2), 65–75.
- Folland, C. K., Knight, J., Linderholm, H. W., Fereday, D., Ineson, S. & Hurrell, J. W. 2009 The summer North Atlantic Oscillation: past, present and future. *Journal of Climate* **22**, 1082–1103.
- Fowler, H. J. & Kilsby, C. G. 2002 Precipitation and the North Atlantic Oscillation: a study of climatic variability in Northern England. *International Journal of Climatology* **22**, 843–866.
- Garner, G., Hannah, D. & Watts, G. 2017 Climate change and water in the UK: recent scientific evidence for past and future change. *Progress in Physical Geography* **41** (2), 154–170.
- Hall, R. J. & Hanna, E. 2018 North Atlantic circulation indices: links with summer and winter temperature and precipitation and implications for seasonal forecasting. *International Journal of Climatology* **38** (S1), 660–677.

- Hall, R. J., Jones, J. M., Hanna, E., Scaife, A. A. & Erdélyi, R. 2017 Drivers and potential predictability of summer North Atlantic polar front jet variability. *Climate Dynamics* **48**, 3869–3887.
- Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S. & Prudhomme, C. 2011 Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. *Hydrological Processes* **25**, 1146–1162.
- Herceg-Bulić, I. & Kucharski, F. 2014 North Atlantic SSTs as a link between wintertime NAO and the following spring climate. *Journal of Climate* **27** (1), 186–201.
- Huang, S., Li, P., Huang, Q., Leng, G., Hou, B. & Ma, L. 2017 The propagation from meteorological to hydrological drought and its potential influence factors. *Journal of Hydrology* **547**, 184–195.
- Hurrell, J. W. & Deser, C. 2009 North Atlantic climate variability: the role of the North Atlantic Oscillation. *Journal of Marine Systems* **78**, 28–41.
- Hurrell, J. W. & Van Loon, H. 1997 Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change* **36** (3–4), 301–326.
- Hurrell, J. W., Kushnir, Y., Ottersen, G. & Visbeck, M. 2003 An overview of the North Atlantic Oscillation. In: *The North Atlantic Oscillation: Climate Significance and Environmental Impact*, AGU Geophysical Monograph Series, 134 (J. W. Hurrell, Y. Kushnir, G. Ottersen & M. Visbeck, eds). American Geophysical Union, Washington, 1–35. doi:10.1029/134GM01
- Irannezhad, M., Torabi Haghighi, A., Chen, D. & Kløve, B. 2015 Variability in dryness and wetness in central Finland and the role of teleconnection patterns. *Theoretical and Applied Climatology* **122** (3–4), 471–486.
- Jones, M. R., Blenkinsop, S., Fowler, H. J. & Kilsby, C. G. 2014 Objective classification of extreme rainfall for the UK and updated estimates of trends in regional extreme rainfall. *International Journal of Climatology* **34**, 751–765.
- Jung, T., Hilmer, M., Ruprecht, E., Kleppek, S., Gulev, S. K. & Zolina, O. 2003 Characteristics of the recent eastward shift of interannual NAO variability. *Journal of Climate* **16**, 3371–3382.
- Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C. & Senior, C. A. 2014 Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change* **4**, 570–576.
- Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A. & Legg, T. 2018 State of the UK climate 2017. *International Journal of Climatology* **38** (S2), 1–35.
- Kingston, D. G., Stagge, J. H., Tallaksen, L. M. & Hannah, D. M. 2015 European-scale drought: understanding connections between atmospheric circulation and meteorological drought indices. *Journal of Climate* **28** (2), 505–516.
- Kosanic, A., Harrison, S., Anderson, K. & Kavcic, I. 2014 Present and historical climate variability in South West England. *Climatic Change* **124**, 221–237.
- McKee, T. B., Doesken, N. J. & Kleist, J. 1995 The relationship of drought frequency and duration to time scales. In: *Eighth Conference on Applied Climatology*, January 17–22, 1993, Anaheim, California.
- Met Office 2016 Is UKCP09 Still and Appropriate Tool for Adaption Planning? *Land Projections*. Available from: <http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=88738&filetype=pdf> (accessed 03 May 2018).
- Moore, G. W. K., Renfrew, I. A. & Pickart, R. S. 2013 Multidecadal variability of the North Atlantic Oscillation. *Journal of Climate* **26** (8), 2453–2466.
- Palin, E. J., Scaife, A. A., Wallace, E., Pope, E. C. D., Arribas, A. & Brookshaw, A. 2016 Skillful seasonal forecasts of winter disruption to the UK transport system. *Journal of Applied Meteorology and Climatology* **55**, 325–344.
- Parry, S., Prudhomme, C., Wilby, R. L. & Wood, P. J. 2016 Drought termination: concept and characterisation. *Progress in Physical Geography* **40** (6), 743–767.
- Pokorná, L. & Huth, R. 2015 Climate impacts of the NAO are sensitive to how the NAO is defined. *Theoretical and Applied Climatology* **119** (3–4), 639–652.
- Rodwell, M. J., Rowell, D. P. & Folland, C. K. 1999 Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. *Nature* **398**, 320–323.
- Rust, W., Holman, I., Corstanje, R., Bloomfield, J. & Cuthbert, M. 2018 A conceptual model for climatic teleconnection signal control on groundwater variability in Europe. *Earth-Science Reviews* **177**, 164–174.
- Rust, W., Holman, I., Bloomfield, J., Cuthbert, M. & Corstanje, R. 2019 Understanding the potential of climate teleconnections to project future groundwater drought. *Hydrology and Earth System Sciences Discussions*. doi:10.5194/hess-2019-119.
- Scaife, A. A., Arribas, A., Blockley, E., Brookshaw, A., Clark, R. T., Dunstone, N., Eade, R., Fereday, D., Folland, C. K., Gordon, M., Hermanson, L., Knight, J. R., Lea, D. J., MacLachlan, C., Maidens, A., Martin, M., Peterson, A. K., Smith, D., Vellinga, M., Wallace, E., Waters, J. & Williams, A. 2014 Skillful long-range prediction of European and North American winters. *Geophysical Research Letters* **41**, 2514–2519.
- Simpson, I. R. & Jones, P. D. 2014 Analysis of UK precipitation extremes derived from Met Office Gridded Data. *International Journal of Climatology* **34**, 2438–2449.
- Smith, K., Stringer, N., Tanguy, M., Eastman, M., Dadson, S. & Knight, J. 2019 Improving winter ensemble streamflow predicting in the UK using North Atlantic Oscillation analogues. In: *European Geosciences Union General Assembly*, April 7–12, 2019, Vienna, Austria.
- Smith, D. M., Scaife, A. A., Eade, R. & Knight, J. R. 2016 Seasonal to decadal prediction of the winter North Atlantic Oscillation: emerging capability and future prospects. *Quarterly Journal of the Royal Meteorological Society* **142**, 611–617.
- Spencer, M. & Essery, R. 2016 Scottish snow cover dependence on the North Atlantic Oscillation index. *Hydrology Research* **47** (3), 619–629.

- Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., Van Loon, A. F. & Stahl, K. 2015 Candidate distributions for climatological drought indices (SPI and SPEI). *International Journal of Climatology* **35** (13), 4027–4040.
- Sun, J. & Wang, H. 2012 Changes of the connection between the summer North Atlantic Oscillation and the East Asian summer rainfall. *Journal of Geophysical Research* **117**, D08110.
- Sweeney, J. C. & O'Hare, G. P. 1992 Geographical variations in precipitation yields and circulation types in Britain and Ireland. *Transactions of the Institute of British Geographers* **17** (4), 448–463.
- Tanguy, M., Dixon, H., Prosdocimi, I., Morris, D. G. & Keller, V. D. J. 2016 Gridded estimates of daily and monthly areal rainfall for the United Kingdom (1890–2015) [CEH GEAR]. NERC Environmental Information Centre. doi:10.5285/33604ea0-c238-4488-813d-0ad9ab7c51ca.
- Tanguy, M., Fry, M., Svensson, C. & Hannaford, J. 2017 Historic gridded standardized precipitation index for the United Kingdom 1862–2015 (generated using gamma distribution with standard period 1961–2010) v4. NERC Environmental Information Centre. doi:10.5285/233090b2-1d14-4eb9-9f9c-3923ea2350ff.
- Trigo, I. F. 2006 Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a comparison between ERA-40 and NCEP/NCAR reanalyses. *Climate Dynamics* **26** (2–3), 127–143.
- Van Loon, A. F. & Laaha, G. 2015 Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology* **526**, 3–14.
- Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangelcroft, S., Wanders, N., Gleeson, T., Van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T. & Van Lanen, H. A. J. 2016 Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences* **20**, 3631–3650.
- Varouchakis, E. A., Corzo, G. A., Karatzas, G. P. & Kotsopoulou, A. 2018 Spatio-temporal analysis of annual rainfall in Crete, Greece. *Acta Geophysica* **66** (3), 319–328.
- Visbeck, M. H., Hurrell, J. H., Polvani, L. & Cullen, H. M. 2001 The North Atlantic Oscillation: past, present and future. *Proceedings of the National Academy of Sciences of the United States of America* **98** (23), 12876–12877.
- Watts, G., Hannah, D. M. & Watkinson, A. 2015 Introduction to the special issue on the impact of climate change on water in the UK. *Progress in Physical Geography* **39** (1), 3–5.
- Weisheimer, A., Schaller, N., O'Reilly, C., MacLeod, D. A. & Palmer, T. 2017 Atmospheric seasonal forecasts of the twentieth century: multi-decadal variability in predictive skills of the winter North Atlantic Oscillation (NAO) and their potential value for extreme event attribution. *Quarterly Journal of the Royal Meteorological Society* **143**, 917–926.
- West, H., Quinn, N. & Horswell, M. 2019 A space-time geostatistical approach to exploring the stationarity of North Atlantic Oscillation driven wet/dry conditions in Great Britain. In *European Geosciences Union General Assembly*, April 7–12, 2019, Vienna, Austria.
- Wilby, R. L. & Quinn, N. W. 2013 Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. *Journal of Hydrology* **487**, 109–121.
- Wilby, R. L., O'Hare, G. & Barnsley, N. 1997 The North Atlantic Oscillation and British Isles climate variability. *Weather* **52** (9), 266–276.
- Zubiate, L., McDermott, F., Sweeney, C. & O'Malley, M. 2017 Spatial variability in winter NAO – wind speed relationships in western Europe linked to concomitant states of the East Atlantic and Scandinavian patterns. *Quarterly Journal of the Royal Meteorological Society* **143**, 552–562.

First received 8 February 2019; accepted in revised form 9 May 2019. Available online 25 May 2019