Spatio-Temporal Propagation of North Atlantic Oscillation (NAO) Rainfall Deviations to Streamflow in British Catchments

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Abstract

The North Atlantic Oscillation (NAO) teleconnection is often cited as the leading mode of climate variability in Great Britain. The NAO has been found to produce significant rainfall deviations which vary in space and time. The study sought to analyse the effect of the NAO at the catchment scale across a large number of catchments in Great Britain across a long study period (1900-2015). We first quantify the effect of the NAO on rainfall and streamflow at a monthly scale revealing distinctive spatio-temporal patterns under Positive and Negative phases of the NAO. Through comparison of correlation analyses we also explore whether catchment characteristics moderate the propagation of NAO-rainfall deviations to streamflow, and classify catchments based on their resilience and susceptibility to NAO-rainfall deviations. In summary our analyses combined contribute to an improved understanding of the hydrometeorological impact of the NAO in British catchments.

Keywords

North Atlantic Oscillation; NAO; Teleconnections; Rainfall-Flow Response; Great Britain

Introduction

The North Atlantic Oscillation (NAO) characterises some of the variability in the speed and latitude of the North Atlantic Jet Stream (Woollings *et al*., 2014) and has long been understood as the primary atmospheric-oceanic circulation (teleconnection) affecting climate in Great Britain (Hurrell & Van Loon, 1997; Rodwell *et al*., 1999; Folland *et al*., 2009; Rust *et al*., 2018). The NAO is commonly defined by the sea level pressure variation between the

Icelandic low-pressure action point and the Azores anticyclone. Depending on conditions at these locations the NAO fluctuates between Positive (NAO+) and Negative (NAO-) phases, quantified by the North Atlantic Oscillation Index (NAOI). A NAO+ phase represents a stronger than usual difference between the Icelandic Low and Azores High, whilst a NAO- phase represents a weaker than usual difference (Hurrell *et al.*, 2003).

Variability in the NAO can be explored across different temporal scales - multi-annual or sub-annual (daily/monthly/seasonal). Studies have examined the influence of sub-annual variations in the NAO on precipitation patterns in Great Britain, finding good correlations between the two (Wilby *et al.*, 1997; Folwer & Kilsby, 2002; West *et al.*, 2019a). Spatial patterns in the strength and direction of correlations vary seasonally. In the winter months rainfall in the north-western regions of Great Britain is strongly positively correlated with the NAO, while rainfall in the southern and eastern regions is generally negatively correlated (Simpson & Jones, 2014; Rust *et al.*, 2018). Therefore, NAO+ phases typically result in higher rainfall in the north-west, whilst NAO- phases result in drier conditions (West *et al.*, 2019a). Whilst the winter months are marked by this north-west/south-east NAO rainfall signature, in summer the rainfall response is more spatially consistent (West *et al.*, 2019a). Correlations are also typically negative between the NAOI and summer rainfall. This indicates that NAO+/- phases typically result in drier/wetter conditions respectively across the country (Folland *et al.*, 2009; Hall & Hanna, 2018), the inverse response is seen in winter rainfall in the north-western regions.

As the NAO influences rainfall, it stands to reason that there may also be a relationship between NAO phase and streamflow, as the changing rainfall distributions propagate through catchments (Kingston *et al.*, 2006). Investigating such climate-rainfall-streamflow

relationships is necessary to improve our understanding of hydrological responses and how these might change in the future (Lavers *et al*., 2010; Laize *et al*., 2010).

Studies have found NAO-flow relationships across the North Atlantic region. In North America, Kingston *et al.* (2007) and Berton *et al.* (2017) report significant correlations between the NAO and discharge in New England (alongside the Atlantic Multi-Decadal Oscillation). Significant NAO-flow relationships have also been identified in Europe. Generally, positive winter correlations are found in northern Europe, in particular in north-western UK and Scandinavia, and negative correlations in southern areas across the south-east of the UK, France, and the Mediterranean basin (Kingston *et al.,* 2009; Wrzesinski & Paluszkiewicz, 2011; Burt & Howden, 2013; Rust *et al.,*2021a). NAO signals have also been identified in groundwater hydrographs (Lavers *et al.,* 2015). For example, Rust *et al.* (2019) report an average of 21.7% of groundwater storage variability across various aquifers in Britain is relatable to 7-year NAO cycles, and higher for some chalk and sandstone borehole locations in southern England where the NAO periodicity is linked with up to 40% of the groundwater variability. Wilby & Johnson (2020) also report associations between the NAO and water temperatures which vary in space and time across England.

However, there is also evidence that NAO-rainfall patterns do not propagate into discharge because the characteristics of the catchment's moderate rainfall-flow transfer, making them less susceptible to NAO-driven rainfall variability. For example, Rust *et al.* (2021a) note that their identified 7-year NAO-flow relationship was found to be influenced by the response time of subsurface hydrological pathways. Phillips *et al.* (2003) investigated the relationship between atmospheric-oceanic circulations and discharge in two British catchments: the chalk-dominated Itchen in southern England and the impermeable Ewe in Scotland. The strongest

significant NAO-flow relationships were found in the Ewe catchment, especially in winter. Phillips *et al.* (2003) proposed this was due to its location in the north-west and the dominance of surface runoff pathways. Whilst the signal of the NAO in the Itchen was limited to the winter months; indicating that for the rest of the year its permeable bedrock and higher storage capacity means that the catchment is less susceptible to NAO-related rainfall variability due to a more sustained baseflow contribution.

Catchments which lack moderating characteristics, such as permeable bedrock, are more susceptible to NAO-driven rainfall variability, which can be further amplified by topography. Burt & Howden (2013) refer to the "double orographic enhancement" effect, where the NAO significantly increases the natural orographic enhancement of rainfall in upland areas of Britain. These enhanced NAO-rainfall signatures cascade down to streamflow; significant positive correlations were found across 86 flow gauge stations between the NAOI and seasonal river flow totals in winter, spring and autumn (Burt & Howden, 2013). The most significant correlations were found in upland areas in north-west Scotland. These close NAO-flow relationships suggest that catchments with certain characteristics lack the ability to moderate NAO-driven rainfall variability. These characteristics include steep topography, low infiltration rates (Sibley, 2010) and impermeable bedrock, such as the Ewe described previously (Phillips *et al.*, 2003).

Given the variation in catchment characteristics across Great Britain (Chiverton *et al.,* 2015), improving our understanding of the influence of the NAO on streamflow, may allow for more effective water management decisions to be taken. Furthering our understanding of NAO-flow spatio-temporal relationships is also timely because:

1. Our ability to the predict NAO variability across multiple temporal scales has notably improved in recent years (Baker *et al*., 2017; Parker *et al*., 2019; Athanasiadis *et al.,* 2020; Smith *et al.,* 2020).

2. Research continues to highlight the NAO's role in influencing hydrometeorological extreme events (Kingston *et al*., 2013; Burt & Howden, 2013; Tsanis & Tapoglou, 2019; Rust *et al*., 2019). Catchments with moderating characteristics may prove to be more resilient to NAO-related hydrometeorological extremes.

3. Research by the UK Centre for Ecology and Hydrology (CEH) suggests that the NAOI may be a useful addition to flow forecasting models and could improve forecasting skill particularly in the north and west of Britain (UK Hydrological Outlook, 2020). Similar evidence is developing in Irish flow modelling research (Donegan *et al.,* 2021).

As far as we are aware, no study has yet explored at a high spatial and temporal resolution NAO-rainfall-flow propagation in British catchments. The recent release of historic hydrometeorological modelled datasets from CEH offers a new opportunity to undertake such an analysis, which has not previously been possible over long historical time periods for a large number of catchments. There is therefore value in using these new long-term and large-scale datasets to enhance our spatio-temporal understanding of sub-annual relationships between the NAO and streamflow in Britain, and a need to assess the extent to which catchment characteristics can moderate the effect of NAO-related rainfall deviations on discharge.

This study aims to meet this need by:

- Quantifying long-term spatio-temporal relationships between the monthly NAO and rainfall and flows across 291 catchments in Great Britain.

- Evaluating spatio-temporal NAO-rainfall and NAO-flow relationships and identifying the moderating effect of catchment characteristics.

- Defining a classification which identifies catchments most resilient and most susceptible to NAO-rainfall deviations to improve catchment understanding.

Methods

Many sub-annual NAO studies have focused on winter (e.g. Hurrell, 1995; Kingston *et al*., 2006). However, Bower *et al*. (2004) noted the importance of examining catchment sensitivity to climatic drivers across a whole annual cycle, and West *et al*. (2019a) identify that the NAO rainfall spatial signature can vary markedly on a monthly basis. To avoid the recognised dilution of signatures across larger temporal scales, our study initially undertakes a monthly-scale analysis.

Data & Pre-Analysis

NAO indices have long been used in similar research to quantify the NAO (Wilby *et al*., 1997; Folland *et al*., 2009; Rust *et al*., 2018, Hall and Hanna, 2018), however there is no fixed approach to defining the NAO (Hurrell & Deser, 2009) and the choice of NAO index (NAOI) can have a notable influence on subsequent analyses. To avoid the known limitations of summer NAO indices calculated using measured sea level pressure data (station-based indices) (Pokorná and Huth, 2015), an NAOI derived from a principal components (PC) analysis of the leading empirical orthogonal function of sea level pressure anomalies in the Atlantic region was used (Hurrell *et al*., 2003). PC-based indices are more accurate representations of spatial patterns of the NAO across a year (NCAR, 2020). PC-based NAO

Indices calculated at the monthly, seasonal (DJF and JJA) and annual scales were used in this study, downloaded for the period Jan 1900-Nov 2015 from the National Center for Atmospheric Research (NCAR, 2020).

The phase of the NAO can be defined in various ways, and classifying the monthly NAOI into Positive, Negative and Neutral phases allows for the identification of clear NAO Positive/Negative signals as weaker 'Neutral' conditions can be removed (Berton *et al.,* 2017). In this study the NAO phase was defined as half the standard deviation plus/minus the long-term mean of the NAOI (Berton *et al.*, 2017). NAO+ phases were defined as having a NAOI >0.502 and NAO- <-0.503. Months falling between this range were classified as NAO Neutral months.

In Stage 1 of our analysis the NAO signal in rainfall and flows at the catchment scale was quantified. For rainfall, the monthly 1km Gridded Estimates of Areal Rainfall (GEAR) dataset (Tanguy *et al.,* 2016) from CEH was spatially averaged for each of the 291 catchments across the analysis period (average rainfall was calculated by area-weighting the 1km gridded rainfall dataset (Equation 1)).

$$R = \sum_{i=1}^{n} r_i \left(\frac{a_i}{A}\right) \text{ (Equation 1)}$$

Where r_i is the rainfall value of the 1km pixel, a_i is the area of the 1km pixel which overlaps with the catchment boundary, and A is the total catchment area (a_i / A is the proportion of the catchment covered by each 1km pixel).

To represent streamflow a long-term historic dataset, also from CEH, was used. Reconstructions of daily river flows using the GR4J model for the 291 catchments across the analysis period (Jan 1900-Nov 2015) were extracted from a larger dataset (Smith *et al.*, 2018). This dataset has been evaluated for high, medium and low flows and found to produce quality representations of historic flows (Smith *et al.*, 2019). The data used in this study represented the best performing model from a 500-member ensemble (Smith *et al.*, 2018). Given its long historic record this dataset has been noted as allowing for large scale and long term spatio-temporal investigations which have previously not been possible (Smith *et al*., 2019). The daily reconstructed flows (m^3/s) were converted into monthly volumes (m^3) and normalised by catchment area (m^3/m^2) for each month in the 116-year record. We will refer to this value, representing monthly runoff volume per unit area, as the 'monthly flow index'.

In Stage 2, standardised indices for both precipitation and flows were used alongside the NAOI. Standardised indices were chosen for this stage of the analysis as they are scaled in relation to relative wetness/dryness (or high flows/low flows) over a specified accumulation period, and have been used in previous studies exploring the teleconnections between atmospheric-oceanic circulations and hydrometeorological signatures (Irannezhad *et al.,* 2015; Kingston *et al.,* 2015; West *et al.,* 2019a). To represent precipitation, we use the CEH 5km gridded Standardised Precipitation Index (SPI) dataset. The SPI dataset is normally distributed and has a standard period of 1961-2010 (Tanguy *et al.,* 2017). Area-weighted SPI values, with 1-month, 3-month and 12-month accumulation periods, were initially calculated for each of the 291 catchments (following Equation 1 substituting the 1km gridded rainfall values for the 5km gridded SPI). For flows, a similar Standardised Streamflow Index (SSI) dataset (Barker *et al.*, 2018) was used. This SSI data was calculated using the reconstructed flow dataset described above (Smith *et al.*, 2018) fitting a Tweedie distribution for a standard

period of 1961-2010 (aligning with the SPI) (Barker *et al.*, 2018). As with the SPI data, accumulation periods of 1-month, 3-months and 12-months were used. The range of datasets used, and the pre-analysis work, are summarised in Table 1 below.

<<INSERT TABLE 1 HERE>>

The first two research aims identified above lend themselves to two distinct analytical stages. The combined outputs of these stages allow for a comprehensive assessment of NAO-rainfall-flow propagation at a monthly scale across a large number of catchments, and an improved understanding of the hydrometeorological impact of the NAO across Great Britain.

<<INSERT FIGURE 1 HERE>>

Stage 1: Quantifying NAO-Rainfall and NAO-Flow Relationships

The first stage of the analysis sought to quantify NAO-rainfall and NAO-flow relationships across the 291 catchments using the monthly GEAR rainfall and monthly flow index (m^3/m^2) datasets described above:

1. The area-weighted rainfall for each month and each catchment was averaged under NAO Positive, Negative and Neutral conditions.

2. The average rainfall depth under NAO+ conditions was then divided by the average rainfall depth under NAO- conditions for the respective catchments and months.

3. This 'Phase-Rainfall' ratio represents the change in rainfall depth between NAO+ and NAO- phases. A value of close to one indicates that the catchment averaged rainfall does not vary between phases, whereas increasing deviations either side of one indicate successively larger rainfall differences between the two phases. A Phase-

Rainfall ratio of two would mean that rainfall doubles in NAO+ relative to NAO-phases, and conversely a ratio of 0.5 would mean NAO+ rainfall is half that of NAO-conditions.

4. A similar 'Phase-Flow' ratio was constructed on the basis of the ratio of the catchment area normalised flow (i.e. the monthly flow index defined above) between NAO+ and NAO- phases.

These phase ratios quantify the relative influence of the NAO on rainfall and flows for each month and across all 291 catchments, allowing for the identification of spatio-temporal NAO-rainfall and NAO-flow signatures.

Stage 2: Comparing NAO-Rainfall and NAO-Flow Signatures

Stage 2 of the analysis sought to compare rainfall and flow responses to the NAO to assess whether catchment characteristics moderate the propagation of NAO-rainfall deviations through to streamflow, and to explore how this varies in space and time. Spearman Rank correlation tests were undertaken between the monthly NAOI and catchment-weighted SPI1 (SPI with a 1-month accumulation period) and NAOI and SSI1.

These two sets of monthly correlations for the 291 catchments were used as separate inputs to a space-time clustering algorithm (Esri, 2020). This analysis grouped together catchments with similar monthly NAOI-SPI1/NAOI-SSI1 correlation coefficients across the year. The clustering used a k-means algorithm, with spatially random starting seeds. The correlation coefficient values similarity across catchments was assessed using the Euclidean distance between the time series values (the square root of the sum of squared differences in coefficient values across time) (Esri, 2020). Rather than specify a fixed number of clusters to

classify the catchments, the algorithm determined an optimal number of clusters. To do this, 90 space-time clustering solutions were produced, each containing between two and ten catchment clusters. These clustering solutions were then evaluated using the pseudo-F statistic. This value is a measure of within-cluster similarity and between-cluster difference, in other words how distinct each cluster is from another. The clustering solution with the highest pseudo-F statistic was identified as the optimal clustering output (Esri, 2020). For both sets of correlation time series, the algorithm determined the optimal number of clusters to be four.

The outputs of these analyses were two datasets which presented clusters of catchments with similar NAOI-SPI1/NAOI-SSI1 correlations across the year. These datasets were spatially overlaid to identify unique combinations of clusters from the two space-time clustering analyses. .This resulted in a final classification where 'Catchment Groups' could be identified based on similar NAO-rainfall (represented by the NAOI-SPI1 correlation cluster membership) and NAO-flow (represented by the NAOI-SSI1 correlation cluster membership) responses.

The local catchment characteristics of each Catchment Group (the unique combination of SPI and SSI clustering results) were then explored. Catchment characteristics influence the hydrological processes within each catchment, and the efficiency of the rainfall-streamflow transfer – for example impermeable geology increasing the speed of runoff resulting in shorter flow response times. Box plots presenting the range of various catchment characteristics (including altitude, landcover, geology and the Base-Flow Index (BFI)) were produced for each Catchment Group. We acknowledge that in this study we have only looked at catchment size, landcover, topography and geology and have not accounted for the

potential compounding effects of inter-basin transfers, flood attenuation measures or other human alterations of the catchment system.

It stands to reason that in catchments with similar NAOI-SPI and NAOI-SSI correlations the characteristics potentially have little moderating effect on runoff - therefore flows in these catchments are likely to be susceptible to NAO-rainfall deviations. Meanwhile in catchments where NAOI-SPI correlations are not replicated between NAOI-SSI, the characteristics have a potentially greater effect on moderating runoff and slowing the flow response time –these catchments are therefore likely to be less susceptible/more resilient to NAO-rainfall deviations (Figure 2).

<<INSERT FIGURE 2 HERE>>

The final stage of the analysis sought to establish whether the spatio-temporal patterns in NAO response identified at the monthly scale where present at other (sub-)annual timescales. To explore relationships at the seasonal (3-monthly) time scale, Spearman correlations were run between the winter NAOI (DJF) and February SPI3/SSI3 and between the summer NAOI (JJA) and August SPI3/SSI3. At the annual scale a final set of correlations were run between the annual NAOI and SPI12/SSI12 for December. These additional sets of correlations were plotted for the Catchment Groups identified earlier allowing an evaluation of consistency in NAO rainfall and flow responses across multiple time scales.

Results

Stage 1: Quantifying NAO-Rainfall and NAO-Flow Relationships

Figures 3 and 4 present the monthly Phase-Rainfall and Phase-Flow ratios, which quantify the influence of NAO+ and NAO- phases. The results show clear monthly and seasonal differences in the strength and distribution of the NAO's hydrometeorological signature. In both figures, values greater than one indicate that average monthly rainfall/flows are higher under NAO+ than NAO-. While values less than one indicate average rainfall/flows are lower under NAO+. Catchments were the NAO+/- change is minimal (i.e., within 25% - 0.75-1.25) are shaded yellow.

During the winter months a general north-west and south-east pattern can be observed in the rainfall and flow response to NAO+ and NAO- phases. Catchments in the north-west see a significant uplift in rainfall under NAO+ phases which cascades down to streamflow in catchments. During winter some north-west catchments see flows 1.5-2.0 times higher during NAO+ phases, while flows in the majority of the southern/eastern catchments are within 25% change between the two NAO phases.

In spring and early summer, the rainfall and flow signatures start to differ, and the distinct winter spatial pattern generally becomes more homogeneous. Throughout summer, an NAO+ phase results in consistent reductions in rainfall (25-50%) compared to an NAO- phase. Whilst this is reflected in some catchments, many are within 25% deviation and catchments where flows are reduced by 25-50% (0.5-0.75) in June and July are dispersed throughout the country. However, in August the majority of the 291 catchments see a 25-50% reduction, with some catchments where flows are more than halved (0-0.5) under an NAO+ phase compared to NAO-.

<<INSERT FIGURE 3 HERE>>

Stage 2: Comparing NAO-Rainfall and NAO-Flow Patterns

Figure 5 presents two sets of time-series clusters, representing monthly correlations between the NAOI and SPI1, and NAOI and SSI1. As in the Phase-Rainfall analysis above, the correlations between NAOI and SPI1 show a clear spatio-temporal response to the NAO in rainfall patterns. Across all months there is a clustering of values north-west/south-east across the country, with the greatest between-cluster differences observed in the winter months (represented by the average value plot for the NAOI-SPI1 correlations). In winter a similar space-time signal can be observed in the NAOI-SSI1 correlations. In summer the between-cluster differences are minimal for the NAOI-SSI1 correlations, resulting in a less spatially distinctive space-time clustering, in particular in the central and southern region.

The two cluster datasets mapped in Figure 5 were combined to identify unique combinations of clusters from the two space-time clustering analyses (Table 2). In total eight combinations (out of a possible 16) were found which we refer to as 'Catchment Groups'. Catchment Groups represent a collection of catchments with similar NAOI-SPI and NAOI-SSI correlation time series. These groupings are mapped in Figure 6, alongside box-plots presenting the range of the monthly NAOI-SPI1 and NAOI-SSI1 correlations for each Group.

Within each Group, similar winter NAO-rainfall and NAO-flow responses can be observed. For example, the largest Catchment Group (8) is concentrated along the north-western coastline. As previously described these areas see significant increases/decreases in winter flows under NAO+/- conditions which tend to mirror the NAO-rainfall signatures. However, notable differences across other Catchment Groups (in particular Groups 1-5) can be seen in the summer months. For example, catchments within Group 1, concentrated in central/southern England, have negative correlations between NAOI-SPI1, which are not replicated in the NAOI-SSI1 correlations.

Seasonal and Annual Correlation Analyses

To evaluate the consistency of the monthly NAO-rainfall and NAO-flow responses at seasonal and annual scales, further sets of correlations were calculated and evaluated for the Catchment Groups (Figure 7). Winter correlations between the 3-month NAOI (DJF) and February SPI3/SSI3 show a very similar response to the monthly NAO-SPI/-SSI correlations (Figure 6), with the most notable positive correlations being observed in Group 8 in the north-west. In the summer months moderately stronger and relatively consistent NAOI-SPI3 negative correlations are observed across Groups 1-7. At the annual scale the NAO-rainfall and NAO-flow correlations show a similar pattern to that observed in winter - catchments in Group 8 continue to show positive correlations with the NAOI, while catchments for the majority of the country in Groups 1-6, show weak annual correlations for both SPI12 and SSI12.

Discussion

Monthly NAO-Rainfall and NAO-Flow Relationships

The first aim of this study was to quantify the sub-annual spatio-temporal relationships between the NAO, rainfall and streamflow in Great Britain. This was analysed through the calculation and mapping of two ratios (Phase-Rainfall and Phase-Flow), representing the change in average monthly rainfall or flows between NAO+ and NAO- phases, respectively.

The magnitude of the NAOI is notably strong in the winter months, and these strong NAO+ and NAO- phases result in characteristic hydrometeorological patterns in Great Britain (Wilby *et al.,* 1997; Folwer & Kilsby, 2002; Folland *et al.,* 2009; West *et al*., 2019a). Winter months are characterised by a north-west and south-east divide in the relationship between NAO and rainfall/streamflow, which we quantify using our Phase-Rainfall and Phase-Flow ratios. Catchments in the north-west see significant uplift in rainfall under NAO+ conditions (relative to NAO- conditions) which propagates through to higher streamflow. In some catchments, flows are as much as doubled when the NAO is positive compared to when it is negative. Less discernible differences between the two NAO phases are observed in both rainfall and flows in the south-east.

Whilst the magnitude of the NAOI is weaker in the summer months compared to winter (Folland *et al.,* 2009), our Phase-Rainfall and Phase-Flow ratios show that the NAO also has a quantifiable effect on rainfall and streamflow in the summer months. However, the NAO+/-wet/dry response is the opposite to that in winter. NAO+ conditions can result in lower summer flows, with the strongest NAO+ summer flow signature being observed in August.

During August, under average NAO+ conditions, a large number of catchments see a flow reduction of 25-50% compared to when the NAO is negative, and in some catchments, flows are more than halved.

The Moderating Effect of Catchment Characteristics

The second aim of this study was to compare correlations between the NAOI and rainfall (quantified by the SPI) and NAOI and streamflow (quantified by the SSI). We also explored whether catchment characteristics moderate the propagation of NAO-rainfall deviations through the hydrological cycle to influence discharge. The transfer of rainfall to streamflow is influenced by a number of different variables in British catchments (Chiverton *et al.,* 2015; Barker *et al.,* 2016; Rust *et al.,* 2021a) and Figure 8 explores a range of catchment characteristics datasets for the Catchment Groups identified in Figure 6 and Table 2.

<<INSERT FIGURE 8 HERE>>

Catchments in the north-western regions, as discussed earlier, are highly responsive to winter NAO-driven rainfall (generally in Groups 7 and 8). This is partly associated with their geographic location in relation to the influence of the NAO in the North-Atlantic region. The phase of the NAO has been found to drive the location of storm tracks across the Atlantic (Visbeck *et al.,* 2011; Brayshaw *et al.,* 2010). Given their location along the north-western coastline these catchments are likely to have strong NAO-rainfall relationships, as have been noted in previous studies (e.g. Rust *et al.,* 2018; West *et al.,* 2019a). In terms of their physical characteristics these catchments have low-medium Base Flow Index (BFI) values. This is likely a result of their relatively high low permeability bedrock coverage restricting slower groundwater flow pathways and catchment storage capacity. Notably these catchments are

also high altitude (Figure 8) which is significant given that the NAO has been found to amplify the natural orographic enhancement of rainfall in upland regions of Great Britain (Burt & Howden, 2013). These factors suggest that in the winter months these catchments do not have the characteristics necessary to moderate NAO-rainfall deviations, therefore the NAO-rainfall and NAO-flow patterns are similar (Figures 3, 4, and 6).

In contrast to Group 8, catchments in Group 1, which are located in central/southern England, have very weak NAO-rainfall and NAO-flow correlations. During the summer months moderate and consistent negative correlations between NAOI and SPI1 are present. This is also observed in the GEAR rainfall analysis where much of the country sees a 25-50% reduction in rainfall under NAO+ phases relative to NAO-, a pattern also observed in other studies (Folland *et al.,* 2009; West *et al.,* 2019a). However, these negative NAOI-SPI1 correlations are not replicated in flows. Summer NAOI-SSI1 correlations for Group 1 are very weak. These catchments have high/very high BFI values, are low-lying and have high coverage of highly permeable superficial deposits and bedrock geologies. We suggest as a result of these local characteristics they are able to moderate the propagation of NAO-rainfall deviations through the catchment. For example, a 25-50% decrease in rainfall under NAO+ conditions described above, is not transferred to a similar reduction in discharge.

Comparison Across Temporal Scales

While catchments in the north and west typically show strong SSI1 relationships with short SPI accumulation periods, catchments in the central and southern regions (generally Catchment Groups 1, 3 and 4) have been found to have the strongest SPI-SSI1 correlations when SPI accumulation periods greater than one-month have been used (Barker *et al.,* 2016; West *et al.,* 2019b). This raises the question as to whether the catchments identified as being

able to moderate monthly NAO rainfall deviations (especially in the summer months), remain able to do so at longer seasonal/annual scales.

In winter the similarity in the seasonal and monthly analyses (Figures 6 and 7) suggests that these catchments in the north-west remain unable to moderate to winter NAO rainfall deviations at the monthly and seasonal scales. In the summer, the majority of catchments in the central and southern regions were identified as being able to moderate monthly NAO-rainfall deviations due to their characteristics (notably NAO Positive low rainfall summers). These catchments show similar moderating ability at the seasonal scale as the 3-month NAOI (JJA) negative correlations with August SPI3 are not replicated in NAOI-SSI3 correlations. In other words, the moderating characteristics of these Catchments Groups (such as their altitude, elevation and geologies – Figure 8) result in limited propagation of summer NAO rainfall signatures at both the monthly and 3-monthly timescales.

The annual scale correlations between the annual NAOI and SPI12/SSI12 showed similar patterns to those observed in the winter months. This reinforces the importance of looking across a full annual cycle when exploring climate signatures in rainfall and flow datasets discussed in the introduction (Bower *et al.,* 2004), as the summer patterns in rainfall, which are variably replicated in flows, are not fully represented at this temporal scale. This observation also reinforces the growing evidence base of distinct NAO summer signatures in Great Britain (Folland *et al.,* 2009; Hall & Hanna, 2018; West *et al.,* 2019a). Table 3 provides a summary of the multi-scale correlation analyses for the Catchment Groups.

<<INSERT TABLE 3 HERE>>

It should be noted that spatio-temporal variability in NAO rainfall signatures has been observed in other studies (West *et al.,* 2021 Rust *et al.*, 2021b) and deviations in rainfall across Great Britain and Europe have also been attributed to other atmospheric-circulations, such as the East Atlantic Pattern and Scandinavian Pattern (Comas-Bru and McDermott, 2014; Mellado-Cano *et al.,* 2019). There is therefore scope to apply the long-term historic flow datasets used in this study to further understand NAO signature variability and the impact of other circulations on regional hydrology in Great Britain.

Conclusion

This study sought to firstly explore sub-annual NAO hydrometeorological signatures in 291 catchments across Great Britain. Through comparative analyses based on historic rainfall and flow datasets we identify distinctive spatio-temporal flow responses of the NAO at the monthly scale across a long time period (1900-2015). In particular we note the spatial divide in NAO-flow response in winter compared with the more spatially consistent summer patterns.

Secondly, we sought to understand the extent to which local catchment characteristics might be able to moderate sub-annual NAO-rainfall-flow propagation. Through comparative analysis of rainfall and flow datasets we present a new understanding of the spatio-temporal variable nature of the propagation of NAO variability to flows as a result of the moderating effect of catchment characteristics. For example, catchments in the north-western regions of Britain, due their location, topography and geology typically show strong relationships between NAOI and rainfall, which during winter, persist as correlations between NAOI and flows. The similarity of the two responses leads to a conclusion that these catchments have limited ability to moderate NAO-rainfall deviations in winter. Meanwhile during summer, we

note that NAO rainfall signatures are present, for example the 25-50% reduction in rainfall under NAO+ phases relative to NAO- phases. However, for a large number of catchments in the central and southern regions of Britain these signatures are not replicated in flows. These catchments are relatively flat, low-lying and have highly permeable geologies. We therefore conclude that these catchments characteristics moderate the propagation of NAO-rainfall deviations during the summer. As far as we are aware this study represents the first large spatial and temporal scale analysis of the sub-annual influence of the NAO on streamflow in Britain and presents new evidence as to the variable nature of the propagation of NAO variability to flows as a result of moderating catchment characteristics.

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Tables

Table 1: Datasets used in this study and associated pre-analysis work

Name	Source	Pre-Analysis	Scale
Stage 1:			
North Atlantic Oscillation Index (NAOI)	National Center for Atmospheric Research (NCAR, 2020)	Monthly data categorised into Positive, Negative and Neutral phases.	National scale, monthly index.
Gridded Estimates of Aerial Rainfall (GEAR) (1km x 1km grid)	(Tanguy *et al.,* 2016)	Area weighted per catchment.	Catchment scale, monthly data.
Historic Flows (at gauging station site)	(Smith *et al*., 2019)	Converted to monthly volumes and catchment area-normalised (referred to as the 'monthly flow index')	Catchment scale, monthly data.
Stage 2:			
North Atlantic Oscillation Index (NAOI)	National Center for Atmospheric Research (NCAR, 2020)	NA	National scale, monthly, seasonal (DDF and JJA) and annual indices.

Standardised Precipitation Index (SPI) (1km x 1km grid)	(Tanguy *et al.,* 2017)	Area weighted per catchment.	Catchment scale, 1-month, 3-month and 12-month accumulation periods.
Standardised Streamflow Index (SSI) (at gauging station site)	(Barker *et al.*, 2018)	NA	Catchment scale, 1-month accumulation period.
Various Catchment Characteristics Data	National River Flow Archive	Catchment characteristics were cross-correlated and any factors significantly and strongly related to one-another were removed from the analysis.	Catchment scale.

Table 2: Cluster Combinations Identified in the Catchment Group Analysis.

NAOI-SPI Cluster	NAOI-SSI Cluster	Catchment Group Identifier	Number of Catchments
3	3	1	21
4	3	2	43
3	4	3	57
4	4	4	12
3	2	5	37
2	2	6	23
2	1	7	29
1	1	8	69

Table 3: Summary of the multi-scale correlation analyses for the 8 Catchment Groups (Groups are mapped Figure 5, and characteristics inferred from Figure 7).

Catchment Group	Correlation Patterns/Characteristics
1 (Higher Summer Resilience)	• In winter and at the annual scale there is little evidence of NAO signatures in rainfall or flows in these catchments. • In the summer months (and seasonal scale) moderate negative correlations with rainfall are not replicated in flows. • **Suggests geology and altitude characteristics are able to the moderate NAO rainfall influence in summer months.**
2 (Higher Summer Resilience)	• In winter and at an annual scale there are some weak-moderate negative correlations between the NAO and rainfall. This is generally well replicated in flows. • In the summer months (and seasonal scale) moderate negative correlations with rainfall are not replicated in flows. • **Suggests geology and altitude moderate NAO rainfall deviations in summer, however this is not the case in winter.**
3 and 4 (Higher Summer Resilience)	• In winter and at an annual scale there is little evidence of NAO signatures in rainfall or flows in these catchments. • In the summer months (and seasonal scale) moderate negative correlations with rainfall are not (fully) replicated in flows. • **Suggests geology (deposits) and altitude moderate NAO rainfall influence in summer months.**
5	• In winter and at an annual scale there is little evidence of NAO signatures in rainfall or flows in these catchments.

(Higher Summer Resilience)	• In summer months (and seasonal scale) moderate negative correlations with rainfall are not (fully) replicated in flows. There are moderate SSI correlations in August at the monthly scale however. • **Suggests variable geology and altitude (high BFI) offer moderating ability in early summer.**
6 (Potential Summer Resilience)	• In winter and at an annual scale there is some, but little, evidence of NAO signatures in rainfall and flows in these catchments. • In early summer moderate negative correlations with rainfall are not (fully) replicated in flows. In August and when looking seasonally some moderate correlations are replicated. • **Suggests these catchments have some moderating properties in summer. Although location and altitude might overcome this in late summer or after persistent NAO influence.**
7 (Higher Susceptibility)	• In winter and at the annual scale similar weak-positive correlations are observed in both rainfall and flows. • Weak-moderate negative rainfall correlations in summer are relatively well replicated in flows. • **Suggests catchment characteristics and location results in limited ability to moderate to NAO rainfall deviations, and monthly flows follow rainfall.**
8 (Higher Susceptibility)	• In winter and at the annual scale similar moderate/strong correlations are observed in both rainfall and flows. • In early summer rainfall and flow correlations are weak. Some moderate August correlations.

	• **Suggests catchment characteristics and location results in limited or no ability to moderate to NAO rainfall deviations, and monthly flows follow rainfall.**

Figure Captions

Figure 1: Flow Chart Summarising the Key Stages of the Analysis

Figure 2: Interpretation of the correlation results in relation to the effect of local catchment characteristics.

Figure 3: Monthly Phase-Rainfall Ratios showing change in catchment area-weighted rainfall between NAO+ and NAO- phases.

Figure 4: Monthly Phase-Flow Ratios showing change in runoff per unit area (m^3/m^2) (Monthly Flow Index) between NAO+ and NAO- phases.

Figure 5: Space-time clusters for the NAOI-SPI1 and NAOI-SSI1 correlation analyses. The cluster colour on each map is the colour of the line in the respective graph. The plots represent the average value per cluster for each calendar month.

Figure 6: Catchment groupings identified in Table 2. Box plots represent the range of NAOI-SPI1/-SSI1 correlations for each grouping. There is no association between the symbology of the Catchment Groups and box plots. Low correlations (-0.2 – 0.2) are greyed out.

Figure 7: Seasonal and annual correlations for the 8 Catchment Groups between the 3-monthly/annual NAOI and SPI/SSI with longer accumulation periods.

Figure 8: The Base Flow Index (BFI) and a range of local characteristics of the Catchment Groupings in Figure 5. Colours for the characteristics are not associated with the BFI or map of Catchment Groups. Catchment characteristics with variable units and values are plotted using a z-score standardisation.

Disclosure Statement