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LETTER

Oceanic conditions associated with Euro-Atlantic high pressure and UK drought

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Abstract

Persistent atmospheric high pressures can lead to long-lasting droughts and heatwaves with severe societal and environmental impacts, as evident in summer 2018 in Europe. It is known that oceanic and atmospheric features connected with the tropical Pacific influence the atmospheric circulation regimes over the North Atlantic/European sector leading to blocking high pressures in the cold season. Here we show that in the warm season, different combinations of sea surface temperatures in the North Pacific and the North Atlantic are associated with distinctly different atmospheric circulation patterns over northwest Europe some three months later. While most studies are restricted to atmospheric variables, for the UK we also investigate the hydrological impact and find that the effect of the preferred seasonal storm tracks is more clearly seen in regional streamflow observations than in precipitation, presumably because streamflows integrate the influences of precipitation and evapotranspiration. These relationships open up the possibility of skilful statistical forecasts for much of spring to autumn, which will usefully complement the currently available skilful winter forecasts based on general circulation models. Our results deliver new understanding of the truly global driving processes of UK droughts and highlight the potential for improved early warning for the wider European domain.

Introduction

Long-range dependencies between oceanic, atmospheric and hydrological variables over space and/or time (teleconnections) have been extensively explored for Europe for the cold season, when the inter-annual variability of influential forcings such as the North Atlantic Oscillation (NAO) is large. The effect of the NAO is well-known, with a positive (negative) NAO index being associated with mild and wet (cold and dry) conditions in western Europe (e.g. Scaife *et al* 2008, Svensson *et al* 2015). For winter, ocean-atmosphere features of the tropical Pacific Ocean have also been found to influence the atmospheric circulation regimes in the North Atlantic/European sector (e.g. Moron and Plaut 2003, Cassou *et al* 2004, Cassou 2008). An 'atmospheric bridge' concept has been proposed, whereby the extratropical atmosphere responds to perturbed tropical forcings during El Niño/Southern Oscillation (ENSO) events, and in turn influences the underlying extratropical ocean (e.g. Alexander *et al* 2002, Graf and Zanchettin (2012)). Exploring features of this bridge mechanism in all seasons, Lau and Nath (2001) found the strongest atmospheric response to occur in January-February, followed by peaks in the North Pacific and North Atlantic sea surface temperature (SST) signals one to two months later. Exploring the relationship in late winter, Zhang *et al* (2019) found a nonstationary relationship between the ENSO and the NAO, due to modulation by Atlantic sea surface temperatures. The negative ENSO-NAO correlation is significant only when the ENSO and the Atlantic Multidecadal Oscillation (AMO) are in phase.

The Westerly Index (Vicente-Serrano *et al* 2016) shows a strong relationship with drought variability in northern and central Europe throughout the year, but compared with winter, studies focussing on the European summer climate are fewer, and whereas teleconnections can be found in the cold season, they may be weaker or not at all discernible in the warm season (e.g. Lau and Nath 2001, Rimbu *et al* 2005, Ding *et al* 2011). However, Mikšovský *et al* (2019) suggest that sea surface temperatures in the Atlantic and, particularly, in the North Pacific Ocean are possible drivers of precipitation variability in the Czech Lands. Dong *et al* (2013) note that the dominant mode of the summer storm track variability in the Atlantic sector is characterised by a meridional shift of the storm track between two distinct paths, closely related to the summer NAO (SNAO), and that in addition to the atmosphere forcing the ocean, there is some evidence consistent with an ocean influence on the atmosphere. The AMO has been found to be partly related to the SNAO on interdecadal time scales (Folland *et al* 2009), and it has been argued that SSTs in the Atlantic Ocean, rather than those in the Indo-Pacific, exert the dominant influence on sea level pressure in the Atlantic region during boreal summer (Pohlmann and Latif 2005).

Sutton and Hodson (2003) suggest that the influence that the ENSO does have on North Atlantic sea level pressure variability may depend on the temperature state of the North Atlantic itself, as they found that the ENSO influence has been nonstationary over the last century. In the present study we investigate the association between North Pacific sea surface temperatures and northwest European climate and hydrology for different temperature states of the North Atlantic. Specifically, the influence on atmospheric pressure patterns aloft is explored, as well as the resulting effects on regional UK river flows and precipitation. The objective of the study is to understand the driving processes behind drought conditions, which could be beneficial for improving monitoring and early warning systems (e.g. Prudhomme *et al* 2017) as well as for improving stochastic methods increasingly used in long-term strategic water resources planning applications (e.g. Serinaldi and Kilsby 2012, Counsell *et al* 2017). Although the presented analysis focuses on northwest Europe and the UK, the wider results suggest the method could be usefully applied also in other parts of the world.

Data

Daily mean streamflows for 93 stations in the National Hydrological Monitoring Programme dataset (Dixon *et al* 2013) from the UK National River Flow Archive, http://nrfa.ceh.ac.uk/, (Marsh and Hannaford 2008) were used, aggregated into monthly means for 1961–2016, because few gauges have data before the 1960s. The mean monthly streamflows were log-transformed to make them more normally distributed, and then standardised separately for each calendar month by subtraction of the mean and division by the standard deviation for that month.

Precipitation data at a 5 km resolution, 1961–2015, from the UK Met Office gridded land surface climate observations dataset, https://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/index.html, (Perry and Hollis 2005) were used. Monthly values were derived from daily data for 1961–2000, whereas monthly data were used directly for 2001–2015. Daily data were used because a problem had been identified with the monthly data for the time period 1960–2000. No log-transform was applied as overall this did not make the precipitation data more normally distributed, but standardisation was carried out as for the streamflow data.

Unsmoothed monthly standardised Pacific Decadal Oscillation (PDO) indices, 1961–2016, available at http://research.jisao.washington.edu/pdo/PDO.latest.txt were used (Mantua *et al* 1997, Zhang *et al* 1997) were used, accessed via the NOAA PSD website at https://www.esrl.noaa.gov/psd/data/climateindices/list/. A positive value of the PDO means that SSTs in the eastern North Pacific are warmer than normal and that SSTs in the western Pacific are colder, and vice versa.

Monthly fields of geopotential heights at the 500 hPa pressure level (GPH), on a 2 by 2 degree grid, 1961–2012, from the 20th Century Reanalysis dataset v2 provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (Compo *et al* 2006), were used, downloaded from http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.pressure.mm.html.

The temperature state of the North Atlantic, 0–70°N, was characterised by three-month aggregations of the detrended but unsmoothed AMO time series (Enfield *et al* 2001) (https://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data; for methodology see https://www.esrl.noaa.gov/psd/data/timeseries/AMO/) derived by NOAA based on Kaplan SST V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/).

Methods

Statistical relationships between the PDO on the one hand, and worldwide GPH and UK streamflows and precipitation on the other hand, were investigated separately for the warm and cold temperature states of the North Atlantic as characterised by the AMO index. Concurrent and lagged correlation analyses and composite analysis were carried out for three-month aggregations of the data, starting in each of the 12 calendar months of the year. Because of the strong topographical and geological controls of precipitation and streamflow in the UK, precipitation and streamflow data were clustered into two and three regions, respectively.

The three-month seasonal values were calculated by averaging the already standardised monthly values over three consecutive months. Separately for each of the 12 calendar start months, the seasonal series were detrended and re-standardised to obtain a mean $= 0$ and a standard deviation $= 1$. An exception is the stratifying variable, the AMO, which was used as downloaded. Because the AMO index is predominantly in its negative phase during the study period 1961–2016, a stratification threshold of -0.05 rather than 0 was chosen, to obtain a more equal number of years in each of the two sets.

Each seasonal series was then analysed separately to avoid issues of temporal dependence. Even so, there is still some inter-annual dependence in the unsmoothed PDO series after stratification on AMO, for the three-month aggregations starting in March to June during the positive phase of the AMO. However, since there is no serial dependence in the streamflow, precipitation and GPH data, the temporal dependence in the PDO series does not affect the degrees of freedom, and hence the significance levels of the correlation analyses are still valid (see e.g. Pyper and Peterman 1998). A significance level of 5% for a one-sided test of non-parametric Spearman correlation was used for the analysis stratified on AMO. Concurrent and lagged Spearman correlation analyses were carried out using the function cor.test in the standard 'stats' package in the programming language R (R Core Team 2018). For the lagged analysis streamflow and precipitation were lagged 1, 2, 3, 4, 5, 6 and 7 months after the PDO.

A composite study of GPH for high and low PDO, stratified on AMO, was carried out. That is, for each AMO state separately, the difference in the mean between the two groups of GPH values (for each GPH grid cell separately) corresponding to PDO values greater than 0.5, and smaller than -0.5, standard deviations was calculated. This means there is about eight seasons in each of the two groups of GPH values. A two-sided Welch's t-test was applied for assessing 5% significance levels, using the function t.test in the 'stats' package in R (R Core Team 2018).

The cluster analyses of streamflow and precipitation data were carried out using the k-means method, seeded by the output from the complete linkage method (e.g. Gordon 1981), applied to data series of monthly anomalies standardised to have mean $= 0$ and standard deviation $= 1$. The clustering was carried out using the function hclust in the 'stats' package in R (R Core Team 2018). For each cluster, the median of the standardised flows (precipitation) for the gauges (grid cells) in each cluster were then used to represent the monthly streamflow (precipitation) anomaly for that cluster.

Results and discussion

Study area for hydrological impacts

The UK, like the rest of northwest Europe, is located in the belt of predominantly westerly winds, and displays strong windward and leeward effects in both precipitation and streamflow (e.g. Svensson and Jones 2002). Droughts affecting the lowland southeast of the UK generally extend into the neighbouring lowland parts of continental Europe. In contrast, the mountainous areas of northwest Scandinavia, the Alpine region and northwest Spain more rarely display spatially coherent droughts and events are generally of shorter duration (Hannaford *et al* 2011).

The topographical divide effectively separates the UK into two main regions (figure 1), a wetter, hillier Northwest and a drier, lowland South and East region. The regions reflect that the bulk of mid-latitude cyclones track northeastward across or to the north of the UK, resulting in heavy precipitation on the windward west-facing slopes, predominantly in autumn and winter. The more sheltered east of the country receives less rain (e.g. Barrow and Hulme 1997). In winter this rainfall distribution is typically associated with a positive NAO index (e.g. Svensson *et al* 2015). In summer, a negative SNAO index whose centres of action are slightly shifted and rotated compared with its winter counterpart, has a strong association with precipitation over all of the UK (and particularly the north) (e.g. Figures 1 and 6 of Folland *et al* 2009). Because some drift occurs across the topographical divide, headwaters of eastward-flowing rivers may still receive heavy rainfall, resulting in the Northwest region (based on cluster analysis) extending further eastward for streamflows (figure 1(a)) than for precipitation (figure 1(b)). As well as receiving rain in westerly airflow, wet periods in the south and east are also associated with precipitation falling in on-shore winds on the north side of depressions travelling eastwards on a more southerly track (Wheeler 1997). Persistence in storm tracks on seasonal time scales can result in very heavy precipitation and flooding, or in prolonged droughts.

A further separation into three regions is justified for streamflow, to capture the groundwater dominated catchments on permeable geology (particularly the Chalk) in parts of the southeast (figure 1(a)). In these catchments the streamflow response to rainfall can be delayed by months (e.g. Chiverton *et al* 2015), whereas in the fast-responding catchments in the northwest, runoff may occur within a matter of hours. Generally, the

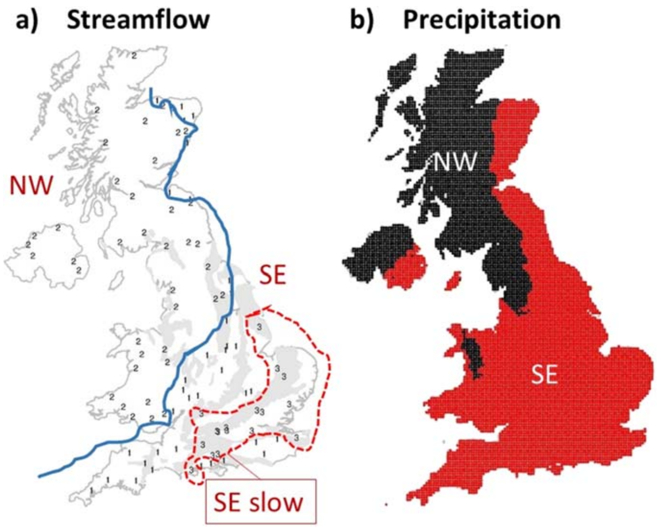

Figure 1. The UK divided into (a) three streamflow and (b) two precipitation regions. Aquifer outcrop areas are shaded grey in figure (a).

southeast is vulnerable to multi-year droughts arising from diminished groundwater recharge in successive seasons. This relatively dry region has a high water demand, resulting in significant pressure on water resources (Folland *et al* 2015). In the northwest, streamflow droughts tend to occur quickly and are of shorter duration (generally a few seasons) but can still have serious impacts due to the lack of groundwater storage.

Oceanic interactions resulting in atmospheric high pressure anomalies and drought

By analysing data separately for warm and cold temperature states of the North Atlantic, we find that the North Atlantic alters the association between the Pacific Ocean temperatures and European climate conditions. SSTs in the extratropical North Pacific show significant lagged relationships with atmospheric pressure patterns aloft over northwest Europe (figures 2, S1 and S2 is available online at stacks.iop.org/ERC/1/101001/mmedia), as well as with UK streamflow (figure 3) for much of spring to autumn. However, the nature of the relationship between the North Pacific SSTs and the European variables is diametrically opposite for the cold and the warm states of the North Atlantic. We use the AMO to describe the Atlantic SSTs, the PDO to describe the North Pacific SSTs, and the 500 mbar geopotential heights (GPH) to describe the pressure pattern aloft.

The change in the pressure pattern over Europe is part of a larger northern hemispheric circulation pattern that occurs during the boreal warm seasons (figures 2, S1 and S2). For a cold North Atlantic, the positive (negative) phase of the PDO is associated some three months later with positive (negative) pressure anomalies aloft over the Arctic, which extend southward over Greenland (the anomalies are of the opposite sign for the negative phase of the PDO throughout, and will not be mentioned further). An area of negative pressure anomalies covers much of western Europe and part of the nearby North Atlantic, resulting in a mid-latitude storm track that delivers higher than normal UK river flows, particularly in the southeast of the country (figure 3). However, when the North Atlantic is warm, the positive phase of the PDO tends to be associated with negative pressure anomalies aloft over the Arctic. The positive pressure anomalies over Greenland have also disappeared and instead positive anomalies now cover northwest Europe and part of the neighbouring North Atlantic. The area of negative anomalies over Europe is reduced in extent and shifted eastwards. This change in the circumpolar wave train results in atmospheric high pressure anomalies and drier than normal conditions over the UK. The location of the pressure centre over northwest Europe and the neighbouring North Atlantic is consistent with the mean sea level pressure centre associated with the SNAO (e.g. as shown in figure 1 of Folland *et al* 2009). Folland *et al* (2009) show the SNAO to have a slightly stronger association with precipitation in northern rather than southern Britain in July and August. We find the relationships between the PDO and streamflow to be of similar strength across the UK in these months (figure 3), whereas for spring and autumn relationships were generally stronger for the southeast than for the northwest. This suggests the preferred storm tracks may be slightly different in the transition seasons compared with summer.

The strongest relationships between North Pacific SSTs and UK streamflow occur when the streamflow is lagged about three months after the PDO (figure S5). The groundwater dominated catchments in the southeast respond more slowly to rainfall, and the strongest relationships between streamflow in these catchments and the PDO occur for slightly longer lags, about four to six months. As can be expected, the seasonal variation in the strength of the correlations is smoother than for the faster responding catchments.

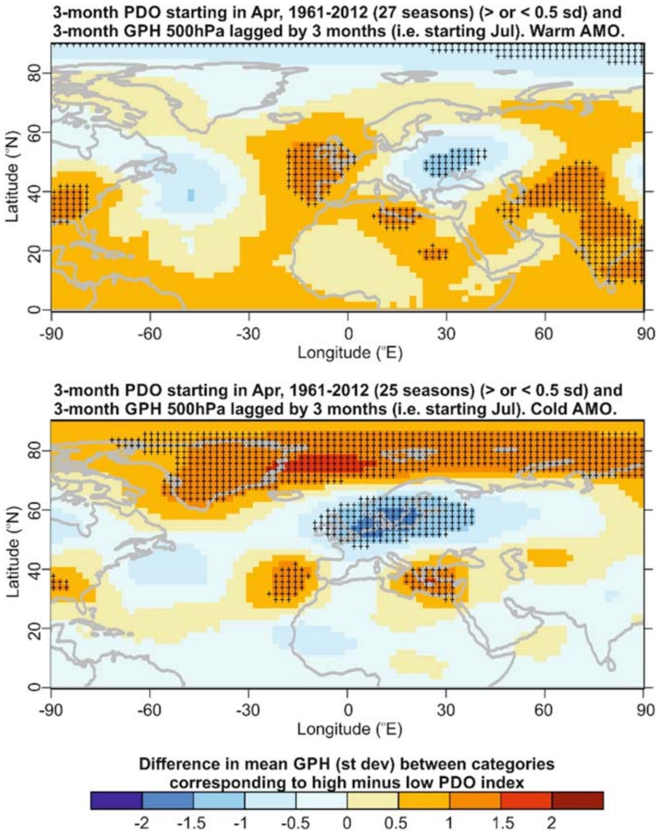

Figure 2. Example of composite analysis of GPH for PDO indices >0.5 or <−0.5 standard deviations, for a warm Atlantic (AMO $\geqslant -0.05$) (top), and for a cold Atlantic (AMO < -0.05) (bottom). GPH is lagged three months after PDO. The colour shows the difference in mean GPH (in units of standard deviations) for the two subsets, i.e. the mean GPH for seasons with high PDO indices minus the mean GPH for seasons with low PDO indices. Differences significant at the 5% level are stippled. See figures S1 and S2 for all calendar months.

Regardless of the phase of the AMO, for much of the year the PDO tends to have a positive association with pressure anomalies aloft along the equator, particularly the tropical Pacific for both the concurrent and lagged analysis (figures S1–S4). At interannual time scales the PDO has been found to be driven by the ENSO and the Aleutian low (e.g. Schneider and Cornuelle 2005), and to be lagged behind the ENSO by 1–2 months (e.g. Nidheesh *et al* 2017). Although the symmetry in the pressure patterns in the northern and southern hemispheres, particularly for the Pacific region for the concurrent analysis (figures S3 and S4), suggest that the global pressure patterns are ultimately driven by conditions in the tropics, there is no strong direct link between UK streamflows and the ENSO itself (e.g. with the Southern Oscillation Index, results not shown). Presumably the relationship is modified by the temperature conditions of the mid-latitude seas, particularly the North Atlantic. Even so, the long-range dependence seen between the PDO and the northwest European GPH and streamflows may still originate in the tropical Pacific Ocean, being the result of an atmospheric bridge akin to that described by Lau and Nath (2001). That is, the extratropical atmosphere responds to perturbed tropical forcing during ENSO events and in turn influences the underlying extratropical oceans not only in the Pacific but also in the Atlantic. The time lags involved in the present study are longer than the one to two months suggested by Lau and Nath (2001), but their study focused on ENSO events in boreal winter. It may be that tropical anomalies of more moderate magnitudes, occurring in seasons with generally smaller Atlantic pressure variability than in winter, require longer seasonal aggregation times to reach a quasi-equilibrium in the influence on the atmospheric circulation aloft over Europe. The response-time between precipitation falling and streamflow being generated will also play a part in some catchments.

On decadal time scales the AMO and PDO have been shown to influence the South American monsoon region (e.g. Krishnamurthy and Misra 2011), and more recently also to affect precipitation in Chile (Valdés-Pineda *et al* 2018). On a seasonal time scale, figures S1 and S2 suggest that in austral winter (PDO aggregations starting in April to September) the southern part of South America is affected by the AMO in a similar way to northwest Europe, as correlations between GPH anomalies over southern South America and the PDO three months earlier have the opposite sign for the two phases of the AMO. That is, SSTs in the South Atlantic modulate the atmospheric circulation pattern over South America that evolved accounting for South Pacific

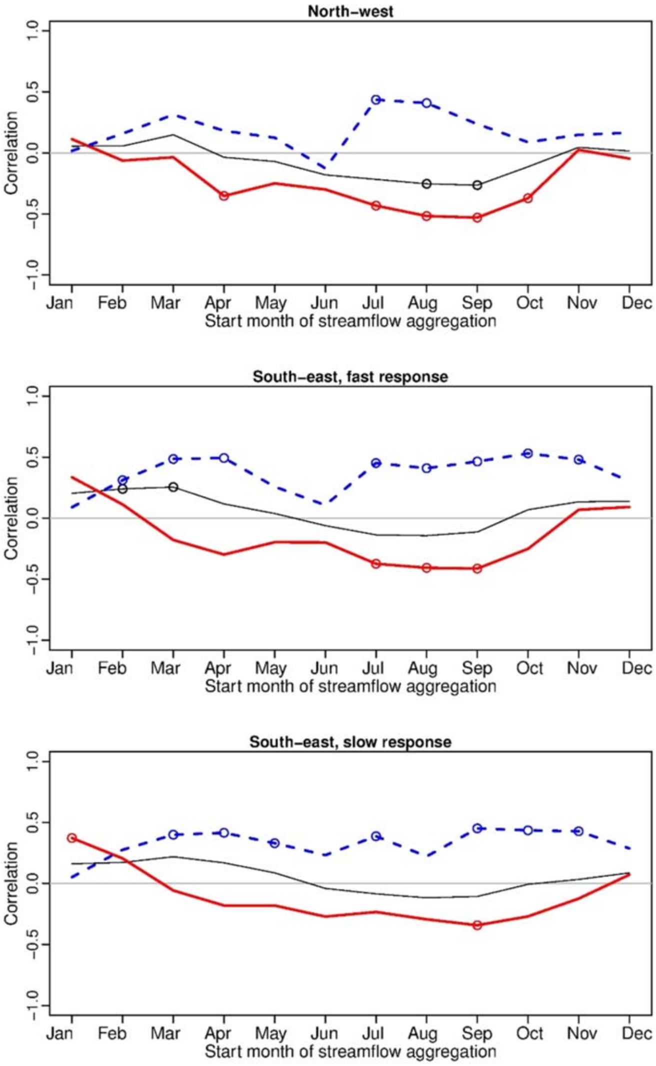

Figure 3. Correlations between three-month aggregations of PDO and streamflow, with streamflow lagged three months after the PDO, for three different UK regions, 1961–2016. The correlations are stratified on AMO phase: AMO < -0.05 (dashed blue line); AMO $\geqslant -0.05$ (thick solid red line); all AMO regardless of phase (thin solid black line). Significant correlations are circled.

SSTs upstream in the circumpolar wave train. The PDO is the North Pacific node of the Pacific-wide Interdecadal Pacific Oscillation, which displays strong symmetry in SSTs north and south of the equator (Henley *et al* 2015). Further, the temperature anomalies in the South Atlantic are negatively correlated with the North Atlantic AMO (figure 1(b) of Enfield *et al* 2001). It is possible that a stronger relationship may be observed for GPH anomalies over South America if the analysis were stratified on the South Atlantic SSTs rather than on the AMO, and a southern hemisphere-specific version of the Interdecadal Pacific Oscillation were used rather than the PDO, although this is outside the scope of the present study.

The lagged relationship between the PDO and UK precipitation is weaker than that for streamflow (figure 4), and is generally even weaker for concurrent observations. The higher correlations for streamflow likely occurs because it not only depends on precipitation, but also integrates the effect of increased evapotranspiration in the catchment during high pressure periods in the warm season. Using a longer precipitation record from 1900–2015 results in even poorer relationships with the PDO (not shown). Assuming that the PDO is driven from the tropical Pacific, this may be because the ENSO variability was comparatively weak between about 1920 and 1960 (Sutton and Hodson 2003).

Concluding remarks

Zhou *et al* (2015) note that observational and modelling studies present complex and sometimes controversial results regarding the vertical structure and sign of the atmospheric response to mid-latitude, as opposed to tropical, Pacific SST anomalies. For much of the warm part of the year, we find significant relationships between

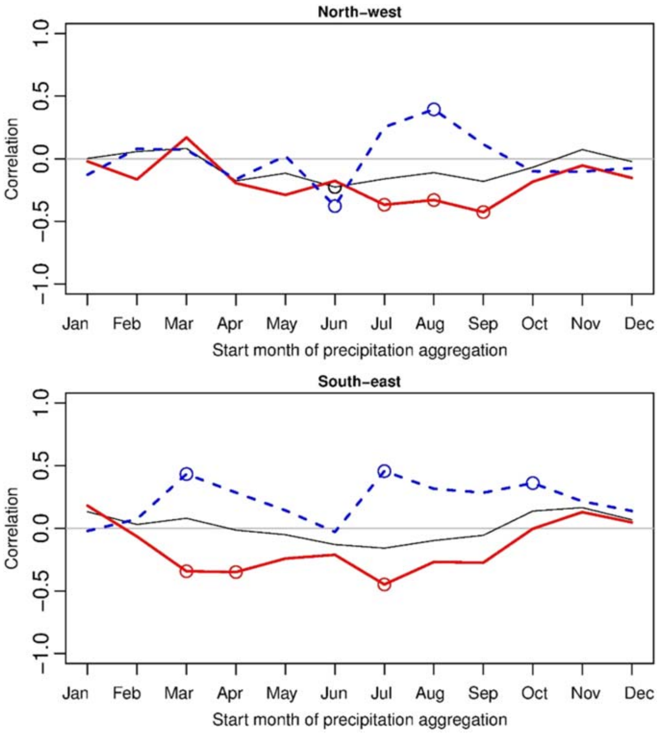

Figure 4. As figure 3, but for the two precipitation regions, 1961–2015.

UK climate and mid-latitude rather than tropical Pacific Ocean SSTs, provided that the analysis is carried out separately for the warm and cold phases of the AMO. The present study shows how the atmospheric response in the northeast Atlantic sector is completely altered by the temperature state of the North Atlantic, causing atmospheric anomalies of the opposite sign. This stresses the importance of a truly global perspective in attempting to unravel the drivers of drought in any given region, and highlights the need to get both the mid-latitude Pacific and Atlantic SSTs correct for global climate modelling of European weather in the warm season. The fact that the relationship between streamflows and the PDO is stronger when the streamflows are lagged three months after the PDO, rather than for the concurrent analysis, also opens up the possibility for simple statistical forecasting methods on a seasonal time scale. Regional Atlantic SSTs may provide further predictors, as shown by for example Osso *et al* (2018) who related European summer precipitation to SSTs in the preceding spring. Variable selection may be aided by the 'stable teleconnections' methodology described by, for example, Ionita *et al* (2008), to avoid problems with non-stationarities. The results of the present study suggest that skilful early warning of northwest European hydrological drought (or persistent wetness) conditions may be possible with relatively long lead times for much of spring to autumn. Streamflow, rather than precipitation, showed a stronger relationship with the PDO, presumably because it integrates also the effect of increased evapotranspiration during high pressure periods in the warm season.

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References

Alexander M A, Bladé I, Newman M, Lanzante J R, Lau N-C and Scott J D 2002 The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans *J Climate* **15** 2205–31

Barrow E and Hulme M 1997 Describing the surface climate of the British Isles *Climates of the British Isles—Past, Present and Future* ed M Hulme and E Barrow (London, UK: Routledge) pp 33–62

Cassou C 2008 Intraseasonal interaction between the Madden-Julian Oscillation and the North Atlantic Oscillation *Nature* **455** 523–7

Cassou C, Terray L, Hurrell J W and Deser C 2004 North Atlantic winter climate regimes: spatial asymmetry, stationarity with time, and oceanic forcing *J Climate* **17** 1055–68

Chiverton A, Hannaford J, Holman I, Corstanje R, Prudhomme C, Bloomfield J and Hess T M 2015 Which catchment characteristics control the temporal dependence structure of daily river flows ? *Hydrol Process* **29** 1353–69

Compo G P, Whitaker J S and Sardeshmukh P D 2006 Feasibility of a 100 year reanalysis using only surface pressure data *B Am Meteteorol Soc* **87** 175–90

Counsell C, Hunt D and Ledbetter R 2017 Drought vulnerability framework *Report 17/WR/02/12* (London, UK: UK Water Industry Research Limited)

Ding Q, Wang B, Wallace J M and Branstator G 2011 Tropical–extratropical teleconnections in boreal summer: observed interannual variability *J Climate* **24** 1878–96

Dixon H, Hannaford J and Fry M J 2013 The effective management of national hydrometric data: experiences from the United Kingdom *Hydrol Sci J* **58** 1383–99

Dong B, Sutton R T, Woollings T and Hodges K 2013 Variability of the North Atlantic summer storm track: mechanisms and impacts on European climate *Env Res Let* **8** 034037

Enfield D B, Mestas-Nuñez A M and Trimble P J 2001 The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US *Geophys Res Lett* **28** 2077–80

Folland C K, Hannaford J, Bloomfield J P, Kendon M, Svensson C, Marchant B P, Prior J and Wallace E 2015 Multi-annual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half year *Hydrol Earth Syst Sci* **19** 2353–75

Folland C K, Knight J, Linderholm H W, Fereday D, Ineson S and Hurrell J W 2009 The summer North Atlantic Oscillation: past, present, and future *J Climate* **22** 1082–103

Gordon A D 1981 *Classification* (London, UK: Chapman and Hall)

Graf H-F and Zanchettin D 2012 Central Pacific El Niño, the 'subtropical bridge,' and Eurasian climate *J Geophys Res* **117** D01102

Hannaford J, Lloyd-Hughes B, Keef C, Parry S and Prudhomme C 2011 Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit *Hydrol Process* **25** 1146–62

Henley B J, Gergis J, Karoly D J, Power S, Kennedy J and Folland C K 2015 A tripole index for the Interdecadal Pacific Oscillation *Clim Dyn* **45** 3077–90

Ionita M, Lohmann G and Rimbu N 2008 Prediction of spring Elbe discharge based on stable teleconnections with winter global temperature and precipitation *J Clim* **21** 6215–26

Krishnamurthy V and Misra V 2011 Daily atmospheric variability in the South American monsoon system *Clim Dyn* **37** 803–19

Lau N-C and Nath M J 2001 Impact of ENSO on SST variability in the North Paceific and North Atlantic: seasonal dependence and role of extratropical sea-air coupling *J Clim* **14** 2846–66

Mantua N J, Hare S R, Zhang Y, Wallace J M and Francis R C 1997 A Pacific interdecadal climate oscillation with impacts on salmon production *B Am Meteorol Soc* **78** 1069–79

Marsh T J and Hannaford J 2008 *UK Hydrometric Register. Hydrological data UK series* (Wallingford, UK: Centre for Ecology & Hydrology)

Mikšovský J, Brázdil R, Trnka M and Pišoft P 2019 Long-term variability of drought indices in the Czech Lands and effects of external forcings and large-scale climate variability modes *Clim Past* **15** 827–47

Moron V and Plaut G 2003 The impact of El Niño-Southern Oscillation upon weather regimes over Europe and the North Atlantic during boreal winter *Int J Climatol* **23** 363–79

Nidheesh A G, Lengaigne M, Vialard J, Izumo T, Unnikrishnan A S and Cassou C 2017 Influence of ENSO on the Pacific decadal oscillation in CMIP models *Clim Dyn* **49** 3309–26

Osso A, Sutton R, Shaffrey L and Dong B 2018 Observational evidence of European summer weather patterns predictable from spring *P Natl Acad Sci USA* **115** 59–63

Perry M and Hollis D 2005 The generation of monthly gridded datasets for a range of climatic variables over the UK *Int J Climatol* **25** 1041–54

Pohlmann H and Latif M 2005 Atlantic versus Indo-Pacific influence on Atlantic-European climate *Geophys Res Lett* **32** L05707

Prudhomme C *et al* 2017 Hydrological Outlook UK: an operational streamflow and groundwater level forecasting system at monthly to seasonal time scales *Hydrol Sci J* **62** 2753–68

Pyper B J and Peterman R M 1998 Comparison of methods to account for autocorrelation in correlation analyses of fish data *Can J Fish Aquat Sci* **55** 2127–40

R Core Team 2018 R: A Language and Environment for Statistical Computing (Vienna, Austria: R Foundation for Statistical Computing https://R-project.org)

Rimbu N, Dima M, Lohmann G and Musat I 2005 Seasonal prediction of Danube flow variability based on stable teleconnection with sea surface temperature *Geophys Res Lett* **32** L21704

Scaife A A, Folland C K, Alexander L V, Moberg A and Knight J R 2008 European climate extremes and the North Atlantic Oscillation *J Climate* **21** 72–83

Schneider N and Cornuelle B D 2005 The forcing of the Pacific Decadal Oscillation *J Climate* **18** 4355–73

Serinaldi F and Kilsby C G 2012 A modular class of multisite monthly rainfall generators for water resource management and impact studies *J Hydrol* **464–465** 528–40

Sutton R T and Hodson D L R 2003 Influence of the ocean on North Atlantic climate variability 1871-1999 *J Climate* **16** 3296–313

Svensson C, Brookshaw A, Scaife A A, Bell V A, Mackay J D, Jackson C R, Davies H N, Arribas A and Williams A 2015 Long range forecasts of UK winter river flow *Environ Res Lett* **10** 064006 (8 pp.)

Svensson C and Jones D A 2002 Dependence between extreme sea surge, river flow and precipitation in eastern Britain *Int J Climatol* **22** 1149–68

Valdés-Pineda R, Cañón J and Valdés J B 2018 Multi-decadal 40- to 60-year cycles of precipitation variability in Chile (South America) and their relationship to the AMO and PDO signals *J Hydrol* **556** 1153–70

Vicente-Serrano S M, García-Herrera R, Barriopedro D, Azorin-Molina C, López-Moreno J I, Martín-Hernández N, Tomás-Burguera M, Gimeno L and Nieto R 2016 The Westerly Index as complementary indicator of the North Atlantic oscillation in explaining drought variability across Europe *Clim Dyn* **47** 845–63

Wheeler D 1997 North-east England and Yorkshire *Regional Climates of the British Isles* ed D Wheeler and J Mayes (London: Routledge) pp 158–80

Zhang W, Mei X, Geng X, Turner A G and Jin F-F 2019 A Nonstationary ENSO-NAO relationship due to AMO modulation *J Climate* **32** 33–43

Zhang Y, Wallace J M and Battisti D S 1997 ENSO-like interdecadal variability: 1900-93 *J Climate* **10** 1004–20

Zhou G, Latif M, Greatbatch R J and Park W 2015 Atmospheric response to the North Pacific enabled by daily sea surface temperature variability *Geophys Res Lett* **42** 7732–9