ENVIRONMENTAL RESEARCH
LETTERS

ACCEPTED MANUSCRIPT • OPEN ACCESS

Abrupt drought termination in the British-Irish Isles driven by high atmospheric vapour transport

To cite this article before publication: Simon Parry *et al* 2023 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/acf145

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is **© 2023 The Author(s). Published by IOP Publishing Ltd**.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 4.0 licence, this Accepted Manuscript is available for reuse under a CC BY 4.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence https://creativecommons.org/licences/by/4.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the article online for updates and enhancements.

This content was downloaded from IP address 149.157.61.99 on 22/08/2023 at 12:07

IOP Publishing Environmental Research Letters
Journal **XX** (XXXX) XXXXXX https://doi.org/XXXX/XXXX

Abrupt drought termination in the British-Irish Isles driven by high atmospheric vapour transport

Simon Parry[1,2,*], David Lavers[3], Robert Wilby[2], Christel Prudhomme[3,1,2], Paul Wood[2], Conor Murphy[4] and Paul O'Connor[4]

[1] UK Centre for Ecology & Hydrology, Wallingford, UK
[2] Department of Geography, Loughborough University, Loughborough, UK
[3] European Centre for Medium-Range Weather Forecasts, Reading, UK
[4] Department of Geography, Maynooth University, Maynooth, Ireland
Email: spar@ceh.ac.uk

Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

During protracted dry spells, there is considerable interest from water managers, media and the public in when and how drought termination (DT) will occur. Robust answers to these questions require better understanding of the hydroclimatic drivers of DT than currently available. Integrated vapour transport (IVT) has been found to drive DT in western North America, but evidence elsewhere is lacking. To evaluate this association for the British-Irish Isles, Event Coincidence Analysis is applied to 354 catchments in the UK and Ireland over the period 1900-2010 using ERA-20C reanalysis IVT data and 7,589 DT events extracted from reconstructed river flow series. Linkages are identified for 53% of all DT events across all catchments. Associations are particularly strong for catchments in western and southern regions and in autumn and winter. In Western Scotland, 80% of autumn DTs are preceded by high IVT, whilst in southern England more than two thirds of winter DTs follow high IVT episodes. High IVT and DT are most strongly associated in less permeable, wetter upland catchments of western Britain, reflecting their maritime setting and orographic enhancement of prevailing south-westerly high IVT episodes. Although high IVT remains an important drought-terminating mechanism further east, it less frequently results in DT. Furthermore, the highest rates of DT occur with increasing IVT intensity, and the vast majority of the most abrupt DTs only occur following top decile IVT and under strongly positive North Atlantic Oscillation (NAO) conditions. Since IVT and NAO forecasts may be more skilful than those for rainfall which underpin current forecasting systems, incorporating these findings into such systems has potential to underpin enhanced forecasting of DTs. This could help to mitigate impacts of abrupt recoveries from drought including water quality issues and managing compound drought-flood hazards concurrently.

Keywords: drought recovery; integrated vapour transport; atmospheric rivers; event coincidence analysis; UK; Ireland

1 Introduction

Drought is a naturally recurring phenomenon influenced by a range of factors but ultimately caused by a prolonged lack of rainfall (Van Loon 2015). The UK and Ireland (hereafter jointly referred to as the British-Irish Isles; BII) have an extensive history of drought events over multiple centuries, despite reputations as relatively wet countries, which challenges public perceptions. Drought is an increasingly topical issue in the BII, due to the combined pressures of increasing populations and water demands plus climate change projections of more frequent and severe droughts (Parry et al. 2023; Meresa & Murphy 2023).

Drought termination (DT) – the return to normal quantities of water – is a critical drought phase (Parry et al. 2016a), and vital to avoiding the most damaging impacts and costly management interventions (Seneviratne & Ciais 2017). However, DT has generally received far less attention than other aspects of drought (Parry et al. 2016b) despite the compound occurrence of drought and flooding multiplying their impacts (Parry et al. 2013; Swain et al. 2018; He & Sheffield 2020; Seeley & Wordsworth 2021). Increasing abruptness of DTs has already been observed (Christian et al. 2015; Qiao et al. 2022), with climate change also impacting both historical (Michaelis et al. 2022) and future occurrences of DT (Chen & Wang 2022).

Relative to DT events, the likelihood of recovery from drought has received greater attention because of its relevance to water managers, decision makers and wider society during protracted droughts (Panu & Sharma 2002). These studies have addressed related questions such as when DT is likely to occur, how much precipitation this will require, and the likelihood of this occurring (e.g. Karl et al. 1987; Bell et al. 2013; Pan et al. 2013; Antofie et al. 2015). Associations between DT and hydroclimatic drivers including tropical cyclones (Lam et al. 2012; Kam et al. 2013), frontal systems (Maxwell et al. 2017), and atmospheric rivers (Dettinger, 2013; Maxwell et al. 2017) have been explored to some extent. However, there remains poor understanding of rainfall mechanisms that trigger DT (Schwalm et al. 2017), hindering progress in forecasting (Huang et al. 2015; Han & Singh 2021).

Atmospheric rivers (ARs) and their vertically-integrated horizontal water vapour transport (IVT) have received considerable attention over recent years as an important driver of intense rainfall and flooding in mid-latitude settings (Kingston et al. 2016; Nayak & Villarini 2017; Waliser & Guan 2017; Kamae et al. 2019; Esfandiari & Rezaei 2022; Guan et al. 2023), including western Europe (Lavers & Villarini 2013a; De Luca et al. 2017; Matthews et al. 2018). Despite the frequent occurrence of floods following droughts, linkages between DT and high IVT have not been explored sufficiently. IVT linkages to drought development have been assessed (Bennet & Kingston 2022) and most studies which have focused on DT are for North America. For instance, Maxwell et al. (2017) found that frontal storms were more important than ARs in the southern and eastern USA domain. In contrast, in western parts of the USA Dettinger (2013) found that ARs were responsible for up to two thirds of DTs. It is reasonable to anticipate that this might also apply to western Europe – a mid-latitude, maritime setting with upland areas close to coastlines that favour orographic enhancement.

High IVT and ARs are projected to become more frequent and intense under climate change (e.g. Dettinger 2011; Gao et al. 2016; Ramos et al. 2016; Espinoza et al. 2018; Curry et al. 2019), implying that they may become a more prevalent DT mechanism in future. Previous studies have assessed the influence on high IVT of different patterns of atmosphere-ocean circulation, including the North Atlantic Oscillation (Dhana Laskhmi & Satyanarayana 2020; Gonzales et al. 2022; Baek et al. 2023; Singh et al. 2023). Taken together these have potential to inform improved forecasting of DT and its impacts. Forecasts of IVT and NAO are more skilful than rainfall (Scaife et al. 2014; Lavers et al. 2016) hence they may yield more reliable outlooks at improved lead times than currently possible.

This study aims to better understand the association between high IVT and hydrological drought termination in the BII. The following research questions are addressed:

- How important is high IVT as a hydroclimatic driver of drought termination?
- How does this association vary seasonally and spatially across the BII?
- How do catchment characteristics modulate these associations?
- How do high IVT intensity and the North Atlantic Oscillation influence characteristics of drought termination?

2 Data & Methods

2.1. Drought termination

2.1.1. Reconstructed river flows

Record lengths of reconstructed river flows far exceed those of observations, thus maximising the sample size of DT events for robust statistical analysis. Daily reconstructed river flows are available for 303 UK catchments for the period 1891-2015 (Smith et al. 2018; Smith et al. 2019), while monthly reconstructions are available for 51 Irish catchments during 1766-2010 (O'Connor et al. 2021). Reconstructed flows for the 1900-2010 timeframe were used, concurrent with that of the reanalysis product used to source IVT data. For the UK, daily flows were aggregated to monthly mean flows since a monthly timestep is sufficient for identifying robust DT.

The 354 catchments were grouped into 12 hydroclimatic regions (SI Figure 1) following previous hydrological studies in the BII (e.g. Harrigan et al. 2018; Quinn et al. 2021). Selected catchment characteristics hypothesised to modulate the hydroclimatic influence of high IVT on DT were extracted for all 354 study catchments (Marsh and Hannaford 2008; Mills et al. 2014), describing the location ('Longitude' and 'Latitude'), elevation ('Max_Alt'), wetness ('SAAR') and storage capacity (Base Flow Index, 'BFI') of catchments.

2.1.2. Identification and characterisation of DTs

For each catchment, DT events were identified objectively from monthly reconstructed flow series via the methodology described by Parry et al. (2016a; 2016b). Each drought event consists of drought development and DT phases, with the drought termination rate (DTR) quantifying how abruptly droughts terminate on average. For each catchment, monthly time series of DT were extracted from reconstructed flows. These were then converted into binary series: '1' corresponding to the final month of DT and '0' otherwise.

2.2. Integrated vapour transport

2.2.1. Reanalysis data

Reanalysis data were used herein because observations of IVT are unavailable and to ensure consistency of data across UK and Irish catchments. The ERA-20C reanalysis (Poli et al. 2016; grid resolution of 125km) spanning the period 1900-2010 was applied to maximise overlap with river flow reconstructions. For each catchment, data were extracted from the nearest grid cell to the catchment centroid.

2.2.2. Identification of high IVT episodes

High IVT was defined as monthly IVT falling within the upper quartile of seasonal mean IVT. Whilst a monthly time step cannot identify individual high IVT storm events which occur on single or multiple days, high monthly values are indicative of above average IVT and associated ARs within a given month. For each catchment, the resulting monthly binary time series of high IVT ('1' for instances of IVT within the upper quartile of the seasonal mean, and '0' otherwise) were filtered to include only those episodes of high IVT occuring during identified drought events.

2.2.3. North Atlantic Oscillation index data

Given the intensified flux of landfalling atmospheric water, it is hypothesised that both positive NAO and increased IVT could lead to higher DTRs (SI Figure 2a). In order to test this hypothesis, monthly NAO data spanning the 1900-2010 timeframe were sourced (Jones et al. 1997).

2.3. Event Coincidence Analysis

Event Coincidence Analysis (ECA; Donges et al. 2016) was applied (through the R package 'CoinCalc'; Siegmund et al. 2017) to all catchments to characterise associations between high IVT and DT during 1900-2010. ECA has been applied to independently-defined drought and flooding events (He & Sheffield 2020) but not yet potential drivers of DT. ECA reads in two binary time series of events that are hypothesised to be associated; in this instance, the binaries of DT and high IVT. Event series 'A' is the binary DT series and event series 'B' is the binary high IVT series, since this study assesses the importance of high IVT in driving DT. A window of *T* months is applied to detect occurrences of high IVT preceding DT. A value of T=2 was used to reflect the termination criteria of identified DT events (two months; Parry et al. 2016a, 2016b).

ECA yields two metrics that quantify associations between high IVT and DT. The Precursor Coincidence Rate (PCR) considers all occurrences of DT and quantifies how many are preceded by high IVT; PCR=1 (PCR=0) when every (no) DT is preceded by high IVT. Subtly different, the Trigger Coincidence Rate (TCR) considers all occurrences of high IVT during a drought and quantifies how many lead to DT; TCR=1 (TCR=0) when every (no) high IVT episode is followed by DT.

The relative values of PCR and TCR highlight important differences between catchments (SI Figure 2b). High PCR and low TCR suggests that high IVT is a frequent driver of DT but not every episode will result in DT. Conversely, low PCR and high TCR suggests that high IVT almost always results in DT, but these episodes occur less frequently and/or high IVT is one of a number of potential drivers.

Terciles were applied to indicate high (>0.67), moderate (0.33-0.67) and low (<0.33) values. PCRs and TCRs were evaluated for statistical significance whereby significance equates to a greater number of occurrences than expected by chance.

3 Results

Applying the DT methodology described above to monthly river flow time series spanning 1900-2010 for 354 catchments in the BII yielded 7,589 events (SI Figure 3) which generally terminate multi-year droughts.

3.1. High IVT and drought termination

Highest PCR values (>0.67) are found in western and southern Britain, and south-western and northern parts of Ireland (Figure 1a). Elsewhere, PCRs remain moderately high (0.33-0.67) in most catchments. Of the 12 hydroclimate regions identified for the BII, 10 have regional mean PCRs in the range 0.51-0.61 (SI Table 1). Low PCRs (<0.33) are restricted to eastern and particularly north-eastern Britain (SI Table 1). Nevertheless, PCRs are statistically significant in all but five catchments, suggesting that high IVT is a necessary driver of DT for most of the BII.

The spatial extent of high TCR values (>0.67) is much more constrained and generally limited to a dozen catchments in western Britain (Figure 1b). Moreover, the gradient of decreasing values – moving from west to east across Britain – is steeper for TCRs than PCRs. A similar gradient is not evident for the island of Ireland, with relatively uniform TCR values of 0.3-0.5. Low values (<0.33) are more widespread, encompassing many catchments in central, southern and particularly eastern Britain. Southern England and Anglian regions join Eastern Scotland and North-East England as outliers in regional mean TCRs (SI Table 1). Regardless, TCRs are statistically significant in all but four catchments.

3.2. Seasonal variations

Of the 7,589 DTs identified across all 354 study catchments in the BII, 53% are preceded by high IVT, although important seasonal variations exist. Across all catchments, DTs preceded by high IVT are more frequent in autumn/winter than in spring/summer. In autumn, IVT-driven events comprise substantially more than half of all DTs for 9/12 hydroclimatic regions. In Western Scotland, 80% of autumn DTs are preceded by high IVT. In winter, for South-West England & South Wales and Southern England, more than two thirds of all DTs are preceded by high IVT (Figure 2). In spring and summer, the importance of high IVT in driving DT is less striking, although in half of the regions IVT-driven DTs outnumber those unrelated to high IVT for each season.

The majority of DTs in Western Scotland, Severn-Trent, Western Ireland and Southern Ireland are preceded by high IVT regardless of season (Figure 2). This is also true for three of the four seasons in Northern Ireland, Eastern Ireland, North-West England & North Wales, South-West England & South Wales, and Southern England. The year-round importance of high IVT is particularly noticeable for the island of Ireland. The only regions for which high IVT precedes less than half of DTs in all seasons are Eastern Scotland and North-East England.

3.3. IVT-DT and catchment characteristics

Average rainfall ('SAAR') has the greatest association with each ECA metric (Figure 3e-f). TCRs correlate positively with catchment wetness (Spearman Rank $rs=0.67$; $p<0.001$) and, whereas a range of PCRs are exhibited for drier catchments, the wettest catchments all have PCRs exceeding 0.5 ($rs=0.24$; $p<0.001$).

Elevation ('Max_Alt') is associated with TCR (Figure 3h, though to a lesser extent than for SAAR; Figure 3f), but not with PCR (Figure 3g). Nevertheless, there are relatively fewer low PCR and TCR values for catchments with high maximum altitudes (compared to lower altitude catchments). Higher TCRs in higher elevation catchments ($rs=0.40$; $p<0.001$) suggest that a single occurrence of high IVT during a drought is more likely to lead to DT.

TCR decreases strongly with increasing longitude (distance east) across the BII ($rs=-0.61$; $p<0.001$; Figure 3b). Irish catchments (longitudes of -10.0 to -5.0) all have moderate to high PCRs and TCRs, with PCRs less than 0.4 and TCRs less than 0.2 almost entirely restricted to eastern catchments of the BII. Similarly, for catchments east of longitude -2.5, TCRs appear to be truncated with no catchments exceeding 0.4 (the same pattern is not evident for PCRs; Figure 3a). These results indicate a stronger association between high IVT and DT in western catchments of the BII.

The opposite is true for latitude. PCRs are more strongly correlated with latitude (Figure 3c), decreasing with distance north ($rs=-0.30$; $p<0.001$). At lower latitudes (further south in the BII), there are relatively few catchments with PCRs less than 0.4, and an increasing range of PCRs in catchments further north (increasing latitude). Conversely, there is no signal for TCR with latitude (Figure 3d). Higher PCRs at lower latitudes (further south) suggests that episodes of high IVT frequently lead to DT, whereas this is not necessarily the case further north.

Catchment storage ('BFI') has a modest association with TCRs ($rs=-0.36$; $p<0.001$; Figure 3j) but not so for PCRs (Figure 3i). TCRs are strongly truncated at values of 0.3 for BFIs exceeding 0.75. The limited correlation between BFI and PCRs suggests that high IVT is just as likely to precede DT regardless of catchment storage. However, the limits placed on TCRs in high BFI catchments suggests that multiple high IVT episodes occur before DT.

Taken together, a coherent narrative emerges linking high IVT and DT in different catchment types. High IVT frequently precedes DT in wetter catchments, and those further west and south, but is less likely to precede DT in drier catchments and those further north and east (PCRs; Figure 3a,c,e,g,i). Similarly, mid-drought high IVT episodes more frequently lead directly to DT in wetter, upland and/or western catchments, with high IVT less likely to lead to DT in drier, lowland and/or eastern catchments, particularly those with more substantial catchment storage (TCRs; Figure 3b,d,f,h,j).

3.4. Influence of NAO and IVT intensity on DT characteristics

The NAO plays a key role in influencing the intensity of high IVT. Across all DT events preceded by high IVT in all study catchments, strong positive NAO conditions ($NAO>2.0$) favour the occurrence of higher intensity IVT episodes (as evidenced by higher NAO values with increasing IVT intensity in Figure 4a-c). Furthermore, it is clear that an increasingly high intensity of IVT influences the upper limit of DTR that can be realised (Figure 4). The upper limit of DTRs increases markedly with IVT threshold (particularly for IVT above the 90th percentile). The majority of the highest DTR values (>100% month^{-1}) are associated with the highest IVT values (Figure 4c).

Taken together, these findings confirm that positive NAO triggers higher IVT and that increased IVT, in turn, produces the highest DTRs. Whilst a range of DTRs is plausible for all positive NAO values and for all high IVT values, the highest DTRs (i.e. the most abrupt terminations) are almost entirely limited to episodes of high IVT above the 90th percentile during strongly positive NAO conditions (Figure 4c).

4 Discussion

This research sought to better understand the importance of high IVT as a potential driver of DT and its spatial and seasonal variations across the BII. High IVT is very influential in driving DTs (especially in autumn and winter; Figure 2), consistent with findings from previous studies (Debbage et al. 2017; Nayak & Villarini 2017; Dettinger et al. 2018; Akbary et al. 2019; Sharma & Dery 2019). Summer associations are limited by less intense high IVT-derived rainfall (Champion et al. 2015).

TCRs vary more markedly with a stronger association with catchment characteristics but PCRs are relatively higher across a range of catchment characteristics (Figure 3). This suggests that high IVT is an important trigger for DT in most catchments, but that in some catchments not every episode of high IVT will lead to DT (where TCRs are lower). Where PCRs and TCRs are lower, it also implies that other hydroclimatic drivers largely unrelated to high IVT may be more influential in driving DT, an aspect which would require further research.

The catchment characteristic with the strongest correlation with the ECA metrics is catchment average rainfall (Figure 3e-f). High IVT is most responsible for DT in the wettest regions, likely explained by lower potential evapotranspiration and wetter shallower soils meaning such catchments are more responsive to rainfall inputs (e.g. McCabe & Wolock 2016). Catchment maximum elevation is also found to be influential on TCRs (Figure 3h). It is likely that the orographic enhancement of plumes of high IVT over the higher ground of western Britain and Ireland (Burt & Howden 2013; Griffith et al. 2020) produces a swifter response and thus higher TCRs (i.e. a greater proportion of high IVT episodes result in DT). Orographic enhancement of high IVT has also been cited as a controlling factor in other parts of the world (e.g. Neiman et al. 2008).

Despite the strong association between elevation and rainfall across the BII, associations with TCRs are weaker for elevation (non-existent for PCRs) than for rainfall. Whilst there are west-east gradients for both rainfall and elevation, the western uplands cast a rain shadow effect inhibiting rainfall totals. Although high elevation is an important explanatory factor linking high IVT with DT (e.g. Neiman et al. 2008), it is not necessarily elevation which best reflects this pattern.

Longitude was also found to be an important factor (Figure 3a-b). Both PCRs (Figure 1a) and especially TCRs (Figure 1b) are higher in western than eastern catchments (SI Table 1). This is most likely explained by the prevailing south-westerly direction from which plumes of high IVT arrive in the BII (Griffith et al. 2020). It also explains why Irish catchments tend to have both high PCRs and TCRs despite lacking the same higher elevations which promote orographic enhancement and higher rainfall totals in western Britain. This mirrors previous findings of stronger associations in western maritime settings of other countries (Dhana Laskhmi & Satyanarayana 2020; Singh et al. 2023).

The importance of catchment wetness, elevation and the location of the wettest and highest elevation catchments along the same western maritime setting in which plumes of high IVT make landfall is highlighted by the lack of seasonality in associations between high IVT and DT. For regions comprising the entirety of the western maritime BII, high IVT is an important driver of DT in all seasons (SI Table 1). The dominance in autumn/winter is consistent with previous findings in similar western upland maritime settings, attributed to the increased effectiveness of orographic enhancement (Neiman et al. 2008; Burt & Howden 2013; Khouakhi et al. 2022).

DT in catchments in eastern Scotland and north-east England are least correlated with high IVT (Figure 1). This is probably also attributable to the presence of the rain shadow cast by western uplands over north-eastern regions and reducing the influence of south-westerly airflows on DT (Malby et al. 2007). This is borne out by steeper west-east gradients in PCRs and TCRs in the north than further south (Figure 3c-d).

In general, high IVT less often leads to DT in drier lowland catchments (Figure 3e-h). More frequently characterised by higher rates of evapotranspiration, higher soil moisture deficits, and more substantial subsurface storage, these catchments are generally less responsive to rainfall inputs. This suggests that multiple episodes of high IVT might be necessary to trigger DT, resulting in reduced TCRs. Such catchments are also subject to higher surface and groundwater abstractions to meet water demands – an additional factor confounding DT occurrence. Whilst abstractions are higher today than in the early 20th century, the reconstructed river flow data used herein were calibrated over recent decades, incorporating current artificial influences and extrapolating them over the entire time series.

In addition to the influence of catchment properties, the intensity of IVT and the NAO are also found to coincide with the occurrence of particularly abrupt DTs (Figure 4). Strong positive NAO favouring the prevalence of higher intensity IVT episodes is consistent with previous findings in north-west Europe. Positive NAO conditions were found to promote the development of ARs that draw atmospheric moisture from subtropical sources under a south-westerly airflow (Stohl et al. 2008). It is perhaps no surprise that abrupt DTs are more prevalent under positive NAO conditions, which generally bring more winter storms, higher IVT, increased rainfall and higher temperatures across the BII and Northern Europe (Li et al. 2020; Barnes et al. 2022). Even within the UK there are spatio-temporal variations in the influence of NAO on rainfall and river flows, with positive NAO found to be more important primarily in the north-west and in winter (West et al. 2021). By extension, given the influence of positive NAO, negative NAO may also suppress rainfall; the relative sequencing of negative (dry) and positive (wet) NAO phases (e.g. Burt & Howden 2013; West et al. 2022) is a potential mechanism of DT.

These findings have important implications for forecasting DTs. Catchments with high PCRs and TCRs are those in which DT is most likely to be successfully forecast, as most DTs are triggered by high IVT and most mid-drought high IVT episodes result in DT. Such conditions are most prevalent in autumn/winter in western parts of the BII. Only one of the study catchments falls within the highest tercile of both PCR and TCR; the Nevis drains the slopes of the highest peak in the BII and is the sixth wettest of ~1,600 catchments in the UK (Marsh and Hannaford 2008).

For more than 90% of study catchments, PCR values exceed TCR values, meaning that whilst high IVT tends to lead to DT, not every high IVT episode results in DT. Lower TCR values could act to limit the forecasting potential of high IVT. Where values of TCR are lower, it is more likely that a given high IVT episode will not result in DT (a ‘false alarm’ in a forecasting context). Confounding factors that weaken the IVT-DT association (such as catchment storage, higher evaporative demand and soil moisture deficits, artificial influences) are consistent with previous findings in the UK (Lavers et al. 2012).

Nevertheless, whilst there are important regional, seasonal and catchment-specific controls on the extent to which high IVT associates with DT, these findings demonstrate the potential for forecasting. Despite recent improvements in the skill of medium-term rainfall forecasts (e.g. Scaife et al. 2014), forecasts of IVT and NAO over a similar timeframe show greater skill, particularly at longer lead times (e.g. Lavers et al. 2016; Scaife et al. 2016; Hall et al. 2017; Lavers et al. 2017; Weisheimer et al. 2017). Combining this skill with the insights gained herein offers scope to forecast DTs and therefore both better manage droughts and minimise negative impacts of destructive DT events (Han & Singh 2021; Ficklin et al. 2022).

5 Conclusion

This study has provided the science that might potentially underpin enhanced forecasting of DTs in the BII. Subsequent research is required to more formally evaluate the success of hindcasts of sub-seasonal IVT and NAO outlooks. Such evaluations would provide formal skill assessments which could inform the confidence with which decision-makers, water managers and other stakeholders might utilise forecasts. The UK Hydrological Outlook (Prudhomme et al. 2017) is an existing forecasting system which could operationalise enhanced DT forecasting capabilities.

Given the strength of associations between high IVT and DT identified herein for the BII, as well as findings on the importance of high IVT in triggering flooding elsewhere in western Europe (e.g. Stohl et al. 2008; Lavers et al. 2013a), a natural successor study could explore the extent to which findings are similar elsewhere in the region. The development of reconstructed flow series in other countries (e.g. Caillouet et al. 2017 for France) offers tantalising potential to underpin enhanced forecasting of DTs across the region.

Acknowledgements

The authors would like to acknowledge Tom Matthews and Lena Tallaksen for their constructive comments on aspects of this research. Funding for this research was provided by the Learning & Development programme at the UK Centre for Ecology & Hydrology, as well as the Natural Environment Research Council (NERC) grant ‘Climate change in the Arctic-North Atlantic Region and Impacts on the UK (CANARI)’ (NERC grant reference NE/W004984/1).

References

Akbary M, Salimi S, Hosseini S and Hosseini M 2019 Spatio-temporal changes of atmospheric rivers in the Middle East and North Africa region *International Journal of Climatology* **39** 3976-3986

Antofie T, Naumann G, Spinoni J and Vogt J 2015 Estimating the water needed to end the drought or reduce the drought severity in the Carpathian region *Hydrol. Earth Syst. Sci.* **19** 177–193

Baek S, Battalio J and Lora J 2023 Atmospheric river variability over the last millennium driven by annular modes *AGU Advances* **4** e2022AV000834

Barnes A, Svensson C and Kjeldsen T 2022 North Atlantic air pressure and temperature conditions associated with heavy rainfall in Great Britain *International Journal of Climatology* **42** 3190–3207

Bell V, Davies H, Kay A, Marsh T, Brookshaw A and Jenkins A 2013 Developing a large-scale water-balance approach to seasonal forecasting: application to the 2012 drought in Britain *Hydrological Processes* **27** 3003-3012

Bennet M and Kingston D 2022 Spatial patterns of atmospheric vapour transport and their connection to drought in New Zealand *International Journal of Climatology* **42** 5661–5681

Burt T and Howden N 2013 North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain *Water Resources Research* **49** 3504-3515

Caillouet L, Vidal J-P, Sauquet E, Devers A and Graff B 2017 Ensemble reconstruction of spatio-temporal extreme low-flow events in France since 1871 *Hydrol. Earth Syst. Sci.* **21** 2923–2951

Champion A, Allan R and Lavers, D 2015 Atmospheric rivers do not explain UK summer extreme rainfall *Journal of Geophysical Research: Atmospheres* **120** 6731-6741

Chen H and Wang S 2022 Accelerated transition between dry and wet periods in a warming climate *Geophysical Research Letters* **49** e2022GL099766

Christian J, Christian K and Basara J 2015 Drought and Pluvial Dipole Events within the Great Plains of the United States *J. Appl. Meteor. Climatol.* **54** 1886–1898

Curry C, Islam S, Zwiers F and Déry S 2019 Atmospheric rivers increase future flood risk in Western Canada's largest Pacific river *Geophysical Research Letters* **46** 1651-1661

De Luca P, Hillier J, Wilby R, Quinn N and Harrigan S 2017 Extreme multi-basin flooding linked with extra-tropical cyclones *Environmental Research Letters* **12** 114009

Debbage N, Miller P, Poore S, Morano K, Mote T and Marshall Shepherd J 2017 A climatology of atmospheric river interactions with the southeastern United States coastline *International Journal of Climatology* **37** 4077-4091

Dettinger M 2011 Climate change, atmospheric rivers, and floods in California–a multimodel analysis of storm frequency and magnitude changes *Journal of the American Water Resources Association* **47** 514-523

Dettinger M 2013 Atmospheric rivers as drought busters on the US West Coast *Journal of Hydrometeorology* **14** 1721-1732

Dettinger M, Ralph F and Rutz J 2018 Empirical return periods of the most intense vapor transports during historical atmospheric river landfalls on the US West Coast *Journal of Hydrometeorology* **19** 1363-1377

Dhana Laskhmi D and Satyanarayana 2020 A Climatology of landfalling atmospheric Rivers and associated heavy precipitation over the Indian coastal regions *Int J Climatol.* **40** 5616– 5633

Donges J, Schleussner C, Siegmund J and Donner R 2016 Event coincidence analysis for quantifying statistical interrelationships between event time series *The European Physical Journal Special Topics* **225** 471-487

Esfandiari N and Rezaei M 2022 Automatic detection, classification, and long-term investigation of temporal–spatial changes of atmospheric rivers in the Middle East *International Journal of Climatology* **42** 7730–7750

Espinoza V, Waliser D, Guan B, Lavers D and Ralph F 2018 Global analysis of climate change projection effects on atmospheric rivers *Geophysical Research Letters* **45** 4299-4308

D, Null S, Abatzoglou J, Novick K and Myers D 2022 Hydrological intensification will increase the complexity of water resource management *Earth's Future* **10** e2021EF002487

Gao Y, Lu J and Leung L 2016 Uncertainties in projecting future changes in atmospheric rivers and their impacts on heavy precipitation over Europe *Journal of Climate* **29** 6711-6726

Gonzales K, Swain D, Roop H and Diffenbaugh N 2022 Quantifying the relationship between atmospheric river origin conditions and landfall temperature *Journal of Geophysical Research: Atmospheres* **127** e2022JD037284

Griffith H, Wade A, Lavers D and Watts G 2020 Atmospheric river orientation determines flood occurrence *Hydrological Processes* **34** 4547-4555

Guan B, Waliser D and Ralph F 2023 Global application of the atmospheric river scale *Journal of Geophysical Research: Atmospheres* **128** e2022JD037180

Hall R, Scaife A, Hanna E, Jones J and Erdélyi R 2017 Simple Statistical Probabilistic Forecasts of the Winter NAO *Weather and Forecasting* **32** 1585-1601

Han J and Singh V 2021 Impacts of Rossby wave packets and atmospheric rivers on meteorological drought in the continental United States *Water Resources Research* **57** e2021WR029966

Harrigan S, Prudhomme C, Parry S, Smith K and Tanguy M 2018 Benchmarking ensemble streamflow prediction skill in the UK *Hydrol. Earth Syst. Sci.* **22** 2023–2039

He X and Sheffield J 2020 Lagged compound occurrence of droughts and pluvials globally over the past seven decades *Geophysical Research Letters* **47** e2020GL087924

Huang S, Huang Q, Chang J, Zhu Y, Leng G and Xing L 2015 Drought structure based on a nonparametric multivariate standardized drought index across the Yellow River basin, China *Journal of Hydrology* **530** 127-136

Jones P, Jonsson T and Wheeler D 1997 Extension to the North Atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland *Int. J. Climatol.* **17** 1433-1450

Kam J, Sheffield J, Yuan X and Wood E 2013 The Influence of Atlantic Tropical Cyclones on Drought over the Eastern United States *J. Climate* **26** 3067–3086

Kamae Y, Mei W and Xie S 2019 Ocean warming pattern effects on future changes in East Asian atmospheric rivers *Environmental Research Letters* **14** 054019

Karl T, Quinlan F and Ezell D 1987 Drought Termination and Amelioration: Its Climatological Probability *Journal of Climate and Applied Meteorology* **26** 1198-1209

Khouakhi A, Driouech F, Slater L, Waine T, Chafki O, Chehbouni A and Raji O 2022 Atmospheric rivers and associated extreme rainfall over Morocco *International Journal of Climatology* **42** 7766–7778

Kim J, Moon H, Guan B, et al. 2021 Precipitation characteristics related to atmospheric rivers in East Asia *Int J Climatol.* **41** E2244–E2257

Kingston D, Lavers D and Hannah D 2016 Floods in the Southern Alps of New Zealand: the importance of atmospheric rivers *Hydrological Processes* **30** 5063-5070

Lam H, Kok M and Shum K 2012 Benefits from typhoons–the Hong Kong perspective *Weather* **67** 16-21

Lavers D, Villarini G, Allan R, Wood E and Wade A 2012 The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale climatic circulation *Journal of Geophysical Research: Atmospheres* **117** D20

Lavers D and Villarini G 2013a The nexus between atmospheric rivers and extreme precipitation across Europe *Geophysical Research Letters* **40** 3259-3264

Lavers D and Villarini G 2013b Atmospheric rivers and flooding over the central United States *Journal of Climate* **26** 7829-7836

Lavers D, Pappenberger F, Richardson D and Zsoter E 2016 ECMWF extreme forecast index for water vapor transport: a forecast tool for atmospheric rivers and extreme precipitation *Geophysical Research Letters* **43** 11852–11858

Lavers D, Zsoter E, Richardson D and Pappenberger F 2017 An assessment of the ECMWF extreme forecast index for water vapor transport during boreal winter *Weather and Forecasting* **32** 1667–1674

Li M, Yao Y, Simmonds I, Luo D, Zhong L and Chen X 2020 Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018 *Environ Res Lett* **15**

Malby A, Whyatt J, Timmis R, Wilby R and Orr H 2007 Long-term variations in orographic rainfall: analysis and implications for upland catchments *Hydrological Sciences Journal* **52** 276-291

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

Matthews T, Murphy C, McCarthy G, Broderick C and Wilby R 2018 Super Storm Desmond: a process-based assessment *Environmental Research Letters* **13** 014024

Maxwell J, Knapp P, Ortegren J, Ficklin D and Soulé P 2017 Changes in the mechanisms causing rapid drought cessation in the southeastern United States *Geophysical Research Letters* **44** 12476-12483

McCabe G and Wolock D 2016 Variability and trends in runoff efficiency in the conterminous United States *Journal of the American Water Resources Association* **52** 1046-1055

Meresa H and Murphy C 2023 Climate change impacts on the frequency, magnitude and duration of meteorological droughts for the island of Ireland using SPI and SPEI *International Journal of Climatology* (in review)

Michaelis A, Gershunov A, Weyant A, Fish M, Shulgina T and Ralph F 2022 Atmospheric river precipitation enhanced by climate change: A case study of the storm that contributed to California's Oroville Dam crisis *Earth's Future* **10** e2021EF002537

Mills P, Nicholson O and Reed D 2014 Flood studies update technical research report (Volume IV. Physical catchment descriptors) Office of Public Works

Nayak M and Villarini G 2017 A long-term perspective of the hydroclimatological impacts of atmospheric rivers over the central United States *Water Resources Research* **53** 1144-1166

Neiman P, Ralph F, Wick G, Lundquist J and Dettinger M 2008 Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations *Journal of Hydrometeorology* **9** 22-47

O'Connor P, Murphy C, Matthews T and Wilby R 2021 Reconstructed monthly river flows for Irish catchments 1766–2016 *Geoscience Data Journal* **8** 34-54

Pan M, Yuan X and Wood E 2013 A probabilistic framework for assessing drought recovery *Geophysical Research Letters* **40** 3637-3642

Panu U and Sharma T 2002 Challenges in drought research: some perspectives and future directions *Hydrological Sciences Journal* **47** S19-S30

Parry S, Marsh T and Kendon M 2013 2012: from drought to floods in England and Wales *Weather* **68** 268–274

Parry S, Prudhomme C, Wilby R and Wood P 2016a Drought termination: Concept and characterisation *Progress in Physical Geography* **40** 743-767

Parry S, Wilby R, Prudhomme C and Wood P 2016b A systematic assessment of drought termination in the United Kingdom *Hydrology and Earth System Sciences* **20** 4265-4281

Parry S, Mackay J, Chitson T, Hannaford J, Bell V, Facer-Childs K, Kay A, Lane R, Moore R, Turner S and Wallbank J 2023 Divergent future drought projections in UK river flows and groundwater levels *Hydrology and Earth System Sciences Discussions* 1-36

Poli P, Hersbach H, Dee D, Berrisford P, Simmons A, Vitart F, Laloyaux P, Tan D, Peubey C, Thépaut J and Trémolet Y 2016 ERA-20C: An atmospheric reanalysis of the twentieth century *Journal of Climate* **29** 4083-4097

Prudhomme C, Hannaford J, Harrigan S, Boorman D, Knight J, Bell V, Jackson C, Svensson C, Parry S, Bachiller-Jareno N and Davies H 2017 Hydrological Outlook UK: an operational streamflow and groundwater level forecasting system at monthly to seasonal time scales *Hydrological Sciences Journal* **62** 2753-2768

Qiao Y, Xu W, Meng C, Liao X and Qin L 2022 Increasingly dry/wet abrupt alternation events in a warmer world: Observed evidence from China during 1980–2019 *International Journal of Climatology* **42** 6429– 6440

Quinn D, Murphy C, Wilby R, Matthews T, Broderick C, Golian S, Donegan S and Harrigan S 2021 Benchmarking seasonal forecasting skill using river flow persistence in Irish catchments *Hydrological Sciences Journal* **66** 672-688

Ramos A, Tomé R, Trigo R, Liberato M and Pinto J 2016 Projected changes in atmospheric rivers affecting Europe in CMIP5 models *Geophysical Research Letters* **43** 9315-9323

Scaife A, Arribas A, Blockley E, Brookshaw A, Clark R, Dunstone N, Eade R, Fereday D, Folland C, Gordon M and Hermanson L 2014 Skillful long-range prediction of European and North American winters *Geophysical Research Letters* **41** 2514-2519

Scaife A, Karpechko A, Baldwin M, Brookshaw A, Butler A, Eade R, Gordon M, MacLachlan C, Martin N, Dunstone N and Smith D 2016 Seasonal winter forecasts and the stratosphere *Atmos. Sci. Lett.* **17** 51-56

Schwalm C, Anderegg W, Michalak A, Fisher J, Biondi F, Koch G, Litvak M, Ogle K, Shaw J, Wolf A, Huntzinger D, Schaefer K, Cook R, Wei Y, Fang Y, Hayes D, Huang M, Jain A and Tian H 2017 Global patterns of drought recovery *Nature* **548** 202

Seeley J and Wordsworth R 2021 Episodic deluges in simulated hothouse climates *Nature* **599** 74–79

Seneviratne S and Ciais P 2017 Environmental science: Trends in ecosystem recovery from drought *Nature* **548** 164

Sharma A and Déry S 2019 Variability and trends of landfalling atmospheric rivers along the Pacific Coast of northwestern North America *International Journal of Climatology* **40** 544– 558

Siegmund J, Siegmund N and Donner R 2017 CoinCalc—A new R package for quantifying simultaneities of event series *Computers & Geosciences* **98** 64-72

Singh S, Kumar Goyal M and Jha S 2023 Role of large-scale climate oscillations in precipitation extremes associated with atmospheric rivers: nonstationary framework *Hydrological Sciences Journal* **68** 395-411

Smith K, Tanguy M, Hannaford J and Prudhomme C 2018 Historic reconstructions of daily river flow for 303 UK catchments (1891-2015) NERC Environmental Information Data Centre doi:10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e

Smith K, Barker L, Tanguy M, Parry S, Harrigan S, Legg T, Prudhomme C and Hannaford J 2019 A multi-objective ensemble approach to hydrological modelling in the UK: an application to historic drought reconstruction *Hydrol. Earth Syst. Sci.* **23** 3247–3268

Stohl A, Forster C and Sodemann H 2008 Remote sources of water vapor forming precipitation on the Norwegian west coast at 60 N–a tale of hurricanes and an atmospheric river *Journal of Geophysical Research: Atmospheres* **113** D5

Swain D, Langenbrunner B, Neelin J and Hall A 2018 Increasing precipitation volatility in twenty-first-century California *Nature Climate Change* **8** 427

Van Loon A 2015 Hydrological drought explained *Wiley Interdisciplinary Reviews: Water* **2** 359-392

Waliser D and Guan B 2017 Extreme winds and precipitation during landfall of atmospheric rivers *Nature Geoscience* **10** 179

Weisheimer A, Schaller N, O'Reilly C, MacLeod D and Palmer T 2017 Atmospheric seasonal forecasts of the twentieth century: multi-decadal variability in predictive skill of the winter North Atlantic Oscillation (NAO) and their potential value for extreme event attribution *Q.J.R. Meteorol. Soc* **143** 917-926

West H, Quinn N and Horswell M 2021 Monthly Rainfall Signatures of the North Atlantic Oscillation and East Atlantic Pattern in Great Britain *Atmosphere* **12** 1533

West H, Quinn N and Horswell M 2022 The Influence of the North Atlantic Oscillation and East Atlantic Pattern on Drought in British Catchments *Frontiers in Environmental Science* **10** 231

Figure 1 -- Event Coincidence Analysis for drought termination with high IVT for 354 catchments across the British-Irish Isles: (a) Precursor Coincidence Rates (PCRs); (b) Trigger Coincidence Rates (TCRs). Dots with borders indicate significance at the 95% confidence level.

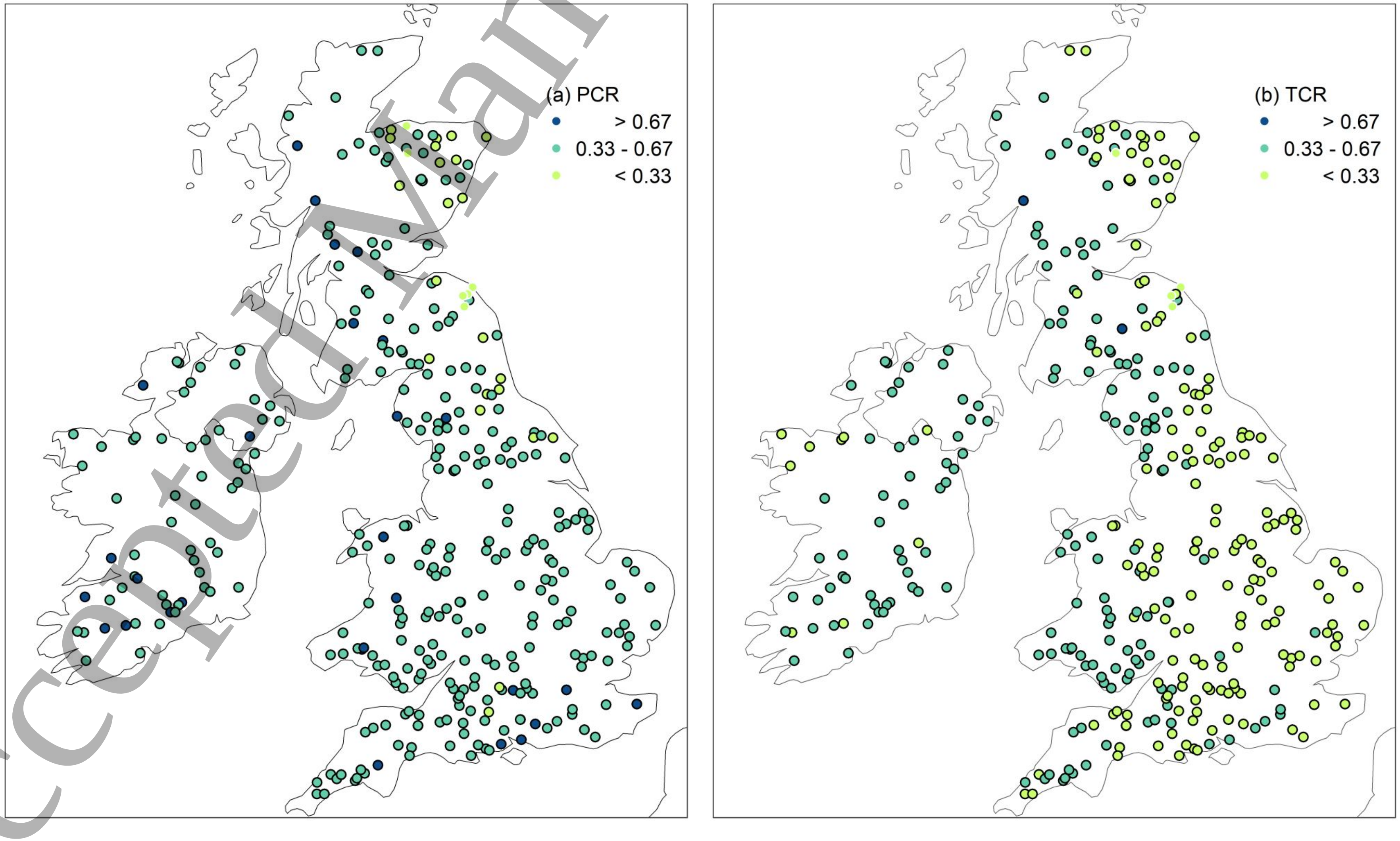

Figure 2 -- Proportion of drought termination (DT) events in all study catchments during 1900-2010 preceded by high IVT or otherwise, by season (rows) and British-Irish Isles region (columns).

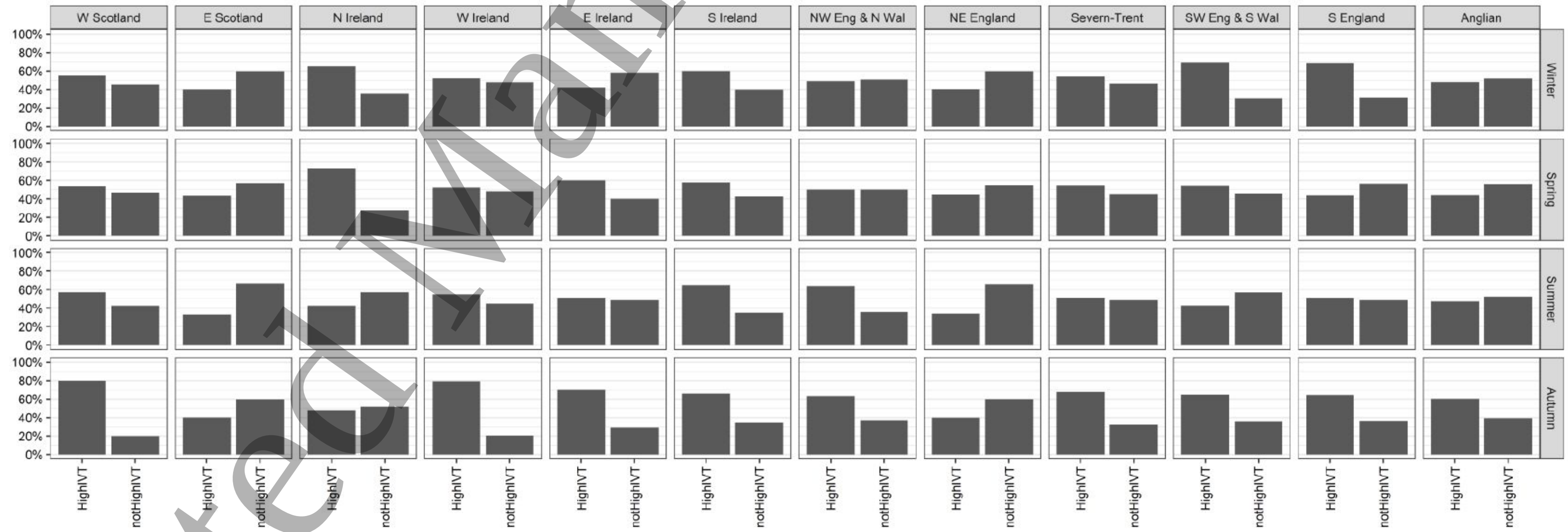

Figure 3 -- Associations between PCR (top row) or TCR (bottom row) and five catchment characteristics: (a)-(b) Longitude [degrees]; (c)-(d) Latitude [degrees]; (e)-(f) catchment average rainfall [SAAR; mm]; (g)-(h) maximum altitude [Max_Alt; m]; (i)-(j) Base Flow Index [BFI; unitless]. Spearman rank correlations (rs) and their significance values (p) are indicated.

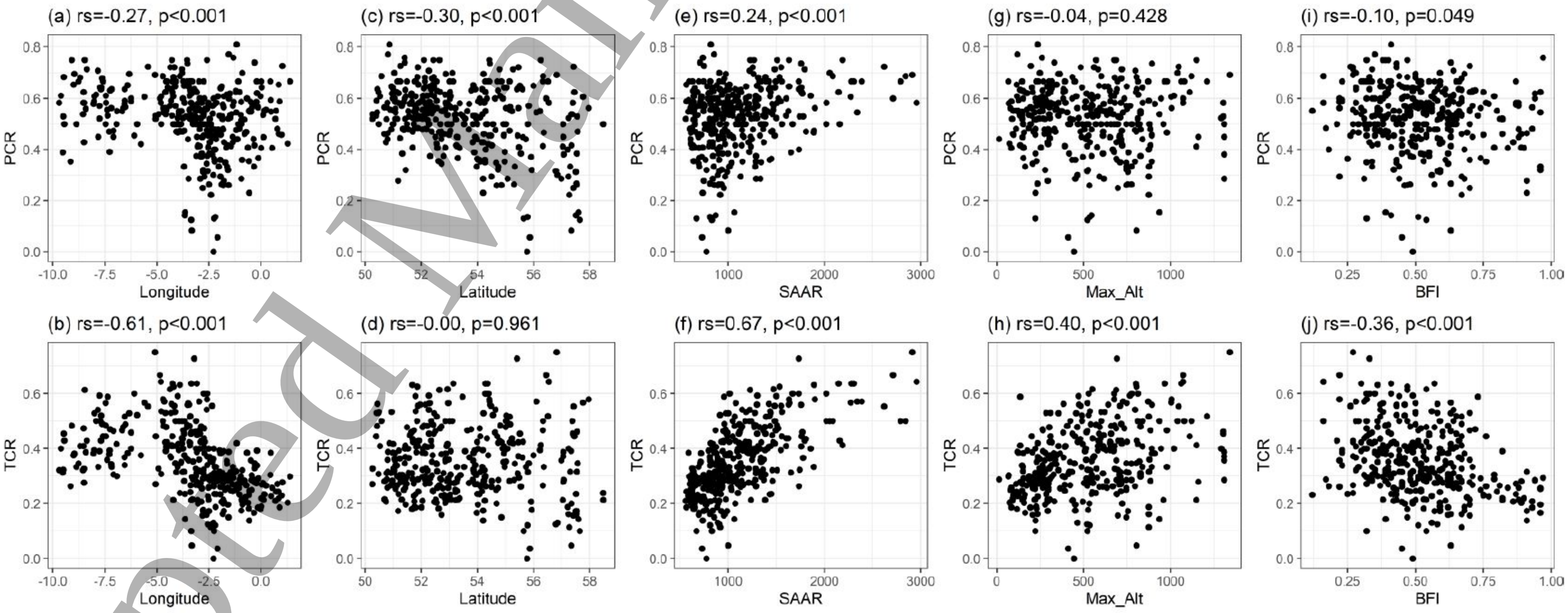

Figure 4 -- North Atlantic Oscillation (NAO) index values in the final month of drought termination (DT) events identified in all 354 catchments against drought termination rate (DTR) for those events preceded by high IVT in percentile ranges: (a) 75th-80th; (b) 80th-90th; and (c) >90th.