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

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

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E-mail: spar@ceh.ac.uk**Keywords:** drought recovery, integrated vapour transport, atmospheric rivers, event coincidence analysis, UK, IrelandSupplementary material for this article is available [online](#)**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 7589 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.

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 (Meresa and Murphy 2023, Parry *et al* 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 and 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 and Sheffield 2020, Seeley and 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 and 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 and 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 (ARs) (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 and Singh 2021).

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 and Villarini 2017, Waliser and Guan 2017, Kamae *et al* 2019, Esfandiari and Rezaei 2022, Guan *et al* 2023), including Western Europe (Lavers and 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 and 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

(NAO) (Dhana Laskhmi and 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 DT in the BII. The following research questions are addressed:

- How important is high IVT as a hydroclimatic driver of DT?
- 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 NAO influence characteristics of DT?

2. Data & methods

2.1. DT

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, 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 time step 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 DT 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 125 km) 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 occurring during identified drought events.

2.2.3. NAO 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 2(a)). 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 and 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 2(b)). 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 7589 events (SI figure 3) which generally terminate multi-year droughts.

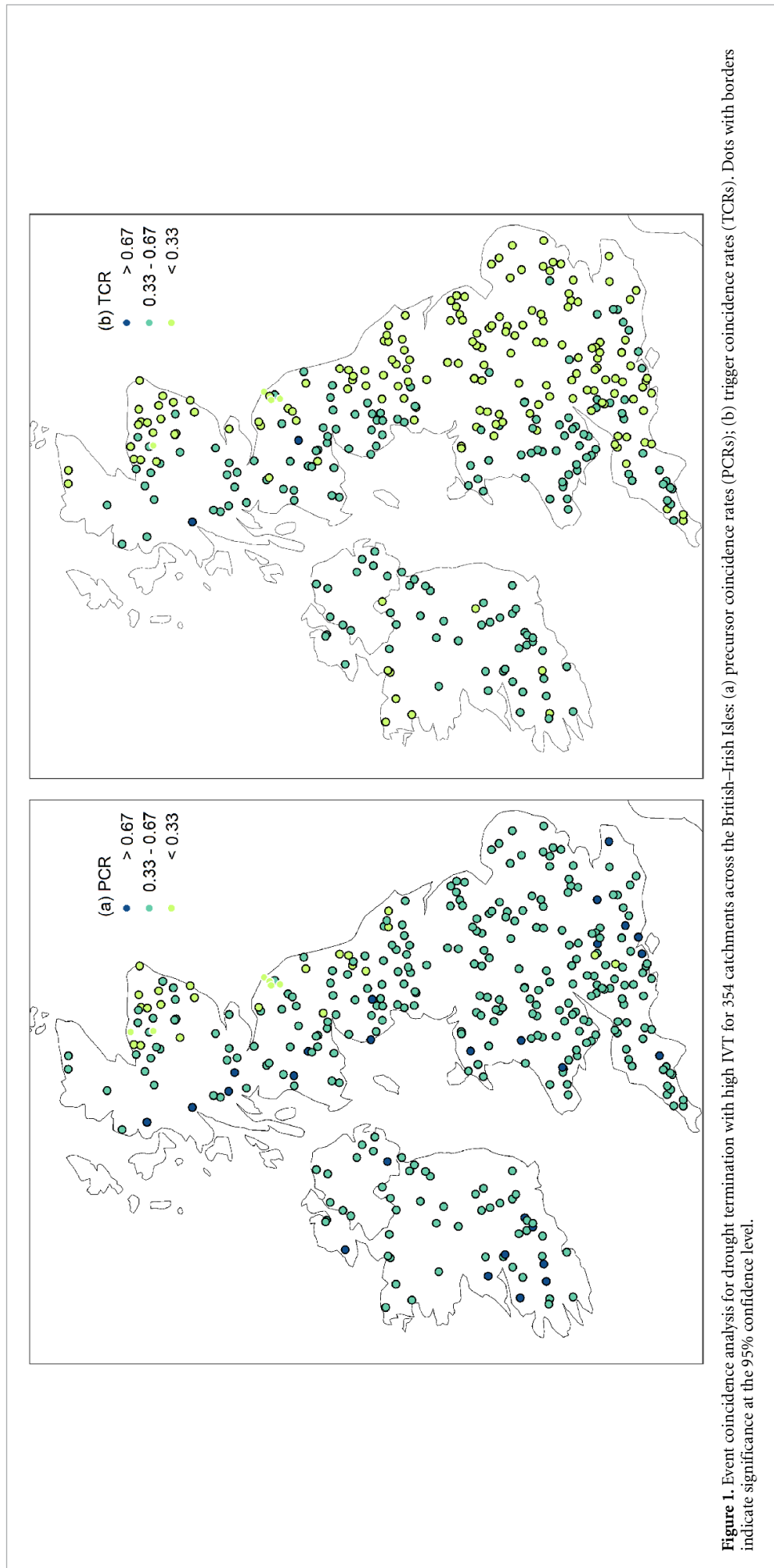
3.1. High IVT and DT

Highest PCR values (>0.67) are found in Western and Southern Britain, and south-western and northern parts of Ireland (figure 1(a)). Elsewhere, PCRs remain moderately high (0.33–0.67) in most catchments. Of the 12 hydroclimate regions identified for the BII, ten 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 1(b)). 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 7589 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 and 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 and North Wales, South-West England and 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 (figures 3(e) and (f)). TCRs correlate positively with catchment wetness (Spearman rank $r_s = 0.67$; $p < 0.001$) and, whereas a range of PCRs are exhibited for drier catchments, the wettest catchments all have PCRs exceeding 0.5 ($r_s = 0.24$; $p < 0.001$).

Elevation ('Max_Alt') is associated with TCR (figure 3(h), though to a lesser extent than for SAAR; figure 3(f)), but not with PCR (figure 3(g)). 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 ($r_s = 0.40$; $p < 0.001$) 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 ($r_s = -0.61$; $p < 0.001$; figure 3(b)). 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 3(a)). 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 3(c)), decreasing with distance north ($r_s = -0.30$; $p < 0.001$). 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 3(d)). 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 ($r_s = -0.36$; $p < 0.001$; figure 3(j)) but not so for PCRs (figure 3(i)). 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; figures 3(a), (c), (e), (g) and (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; figures 3(b), (d), (f), (h) and (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 figures 4(a)–(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 4(c)).

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 4(c)).

4. Discussion

This research sought to better understand the importance of high IVT as a potential driver of DT and its

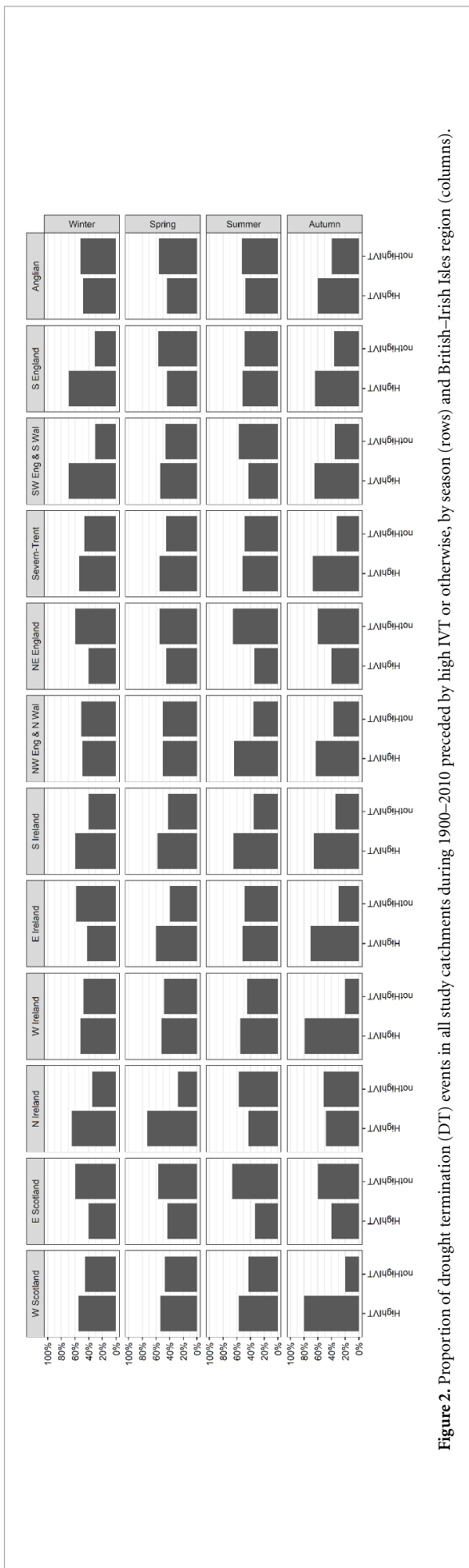


Figure 2. Proportion of drought termination (DT) events in all study catchments during 1900–2010 preceded by high IVT or otherwise, by season (rows) and British–Irish Isles region (columns).

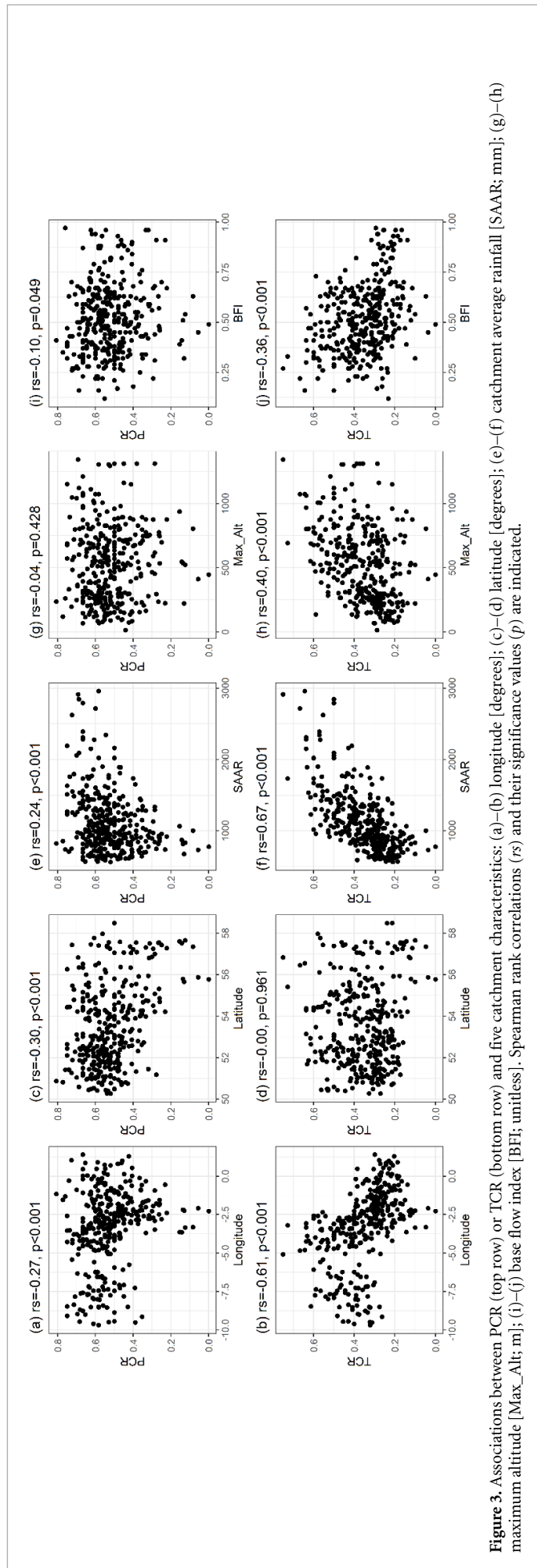


Figure 3. Associations between PCR (top row) or TCR (bottom row) and five catchment characteristics: (a)–(b) longitude [degrees]; (c)–(d) latitude [degrees]; (e)–(f) catchment average rainfall [SAAR; mm]; (g)–(h) maximum altitude [Max_Alt; m]; (i)–(j) base flow index [BFI; unitless]. Spearman rank correlations (r_s) and their significance values (p) are indicated.

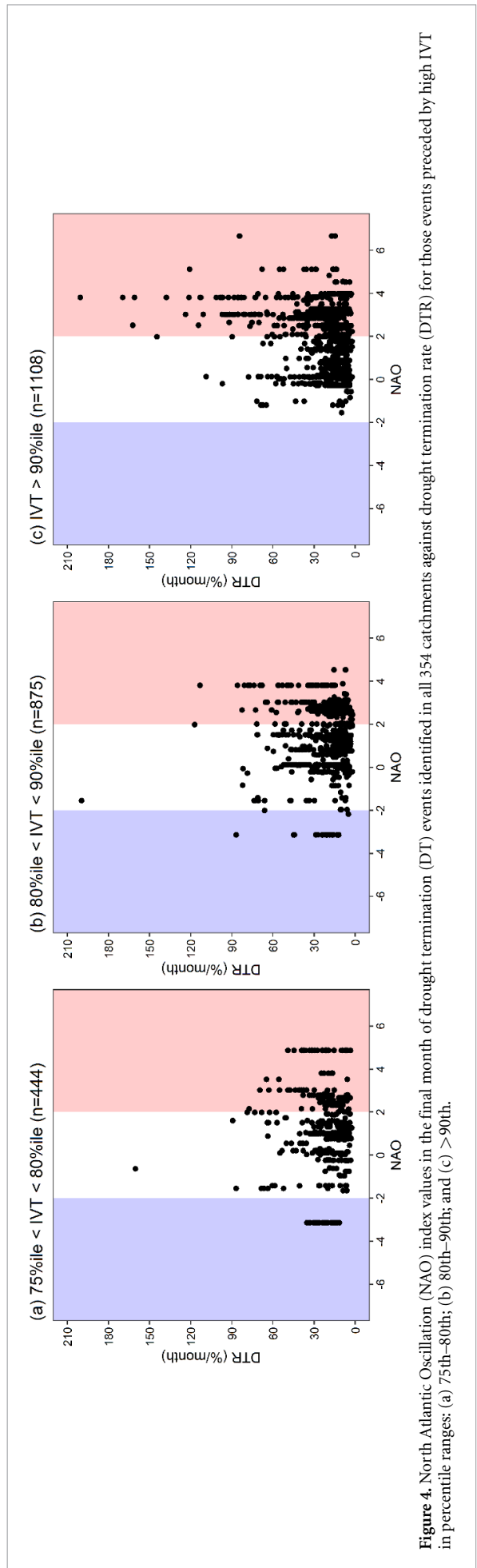


Figure 4. North Atlantic Oscillation (NAO) index values in the final month of drought termination (DT) events identified in all 354 catchments against drought termination rate (DTR) for those events preceded by high IVT in percentile ranges: (a) 75th-80th; (b) 80th-90th; and (c) >90th.

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 and Villarini 2017, Dettinger *et al* 2018, Akbary *et al* 2019, Sharma and 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 hydro-climatic 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 (figures 3(e) and (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 and Wolock 2016). Catchment maximum elevation is also found to be influential on TCRs (figure 3(h)). It is likely that the orographic enhancement of plumes of high IVT over the higher ground of Western Britain and Ireland (Burt and 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 (figures 3(a) and (b)). Both PCRs (figure 1(a)) and especially TCRs (figure 1(b)) 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 and 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 and 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 (figures 3(c) and (d)).

In general, high IVT less often leads to DT in drier lowland catchments (figures 3(e)–(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 and 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 ~1600 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, 2017, Scaife *et al* 2016, Hall *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 and 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 and Villarini 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.

Data availability statement

The DOI datasets are available from two different locations:

For UK data: <https://doi.org/10.5285/f710bed1-e564-47bf-b82c-4c2a2fe2810e>.

For Ireland data: <https://doi.org/10.1594/PANGAEA.914306>.

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