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Complete List of Authors:	Wilby, Rob; Loughborough University, Geography Noone, Simon; National University of Ireland Maynooth, Geography Murphy, Conor; National University of Ireland Maynooth, Geography Matthews, Tom; Liverpool John Moores University, School of Natural Sciences and Psychology Harrigan, Shaun; Maynooth University, Geography Broderick, Ciaran; National University of Ireland Maynooth, Geography
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An evaluation of persistent meteorological drought using a homogeneous Island of Ireland precipitation network

Wilby[1], R.L., Noone[2], S., Murphy[2], C., Matthews[3], T., Harrigan[2], S. and Broderick[2], C.

[1] Department of Geography, Loughborough University, LE11 3TU, UK

[2] Department of Geography, National University of Ireland Maynooth, Ireland

[3] School of Natural Sciences & Psychology, Liverpool John Moores University, L3 3AF, UK

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Corresponding author: Robert Wilby (email: r.l.wilby@lboro.ac.uk)

Abstract

This paper investigates the spatial and temporal properties of persistent meteorological droughts using the homogeneous Island of Ireland Precipitation (IIP) network. Relative to a 1961-1990 baseline period it is shown that the longest observed run of below average precipitation since the 1850s lasted up to 5 years (10 half-year seasons) at sites in southeast and east Ireland, or 3 years across the network as a whole. Dry- and wet-spell length distributions were represented by a first-order Markov model which yields realistic runs of below average rainfall for individual sites and IIP series. This model shows that there is relatively high likelihood (p=0.125) of a 5 year dry-spell at Dublin, and that near unbroken dry runs of 10 years or more are conceivable. We suggest that the IIP network and attendant rainfall deficit modelling provide credible data for stress testing water supply and drought plans under extreme conditions.

Key words:

Drought duration; Markov model; homogeneous rainfall series; water planning; Ireland.

1. Introduction

Drought is hardly synonymous with perceptions about the climate of Ireland. Nonetheless, the *Freeman's Journal*[1] provides numerous reports of potable water shortages in Dublin during severe dry spells over the period 1763-1924 and Barrington (1888) gives a rich account of impacts of the 1887 drought on Irish agriculture. Other notable events such as the pan-European drought of 1976 caused heat- and moisture-stress-related problems for Ireland's agricultural sector (Stead, 2014). Likewise, some future climate scenarios foresee loss of production for crops such as potatoes linked to rising temperatures and summer aridity (Holden *et al*., 2003); reduced grass growth and heat stress on livestock which could impact meat and dairy exports (Hunt *et al*., 2014); and decreased river flow in summer (Steele-Dunne *et al*., 2008; Bastola e*t al.*, 2011).

Given these vulnerabilities, surprisingly little has been published on the drought climatology of Ireland. O'Laoghog (1979) provides a summary of rainfall anomalies alongside impacts on agriculture and public water supply of the 1974-1976 drought. Brogan and Cunnane (2005) contend that 1976 may have witnessed the lowest recorded river flows since the 1930s. They also cite droughts in 1934, 1949, 1955, 1959, 1975, 1989, 1990, 1991 and 1995. MacCarthaigh (1996) compared 1995 with droughts back to 1975 whilst Dooge (1985) provides a synopsis of droughts in Irish history beginning with accounts in the Annals of Ulster and of Clonmacnoise (for the period AD 759 to 1408). Symons (1887) documents five droughts in the 1850s, two in the 1860s and three in the 1870s. Garcia-Suarez and Butler (2006) find periods with persistently negative annual Palmer Drought Severity Index at Armagh in the 1880s, 1890s, 1930s, 1970s and 1990s. Mandal (2011) estimated low flows for 125 Irish rivers using catchment properties. Aside from these sources, there is little quantitative information on which to base rigorous assessments of long-term drought risk and water planning for Ireland.

This *Short Communication* addresses this knowledge gap by using the homogeneous Island of Ireland Precipitation (IIP) network of Noone *et al*. (2015) to evaluate the *occurrence* and *persistence* of meteorological droughts since 1850. Here, a straightforward definition of drought is used for half-year periods or longer that have below average precipitation, at both site and regional scales. We accept that the term 'drought' is ambiguous and that runs of seasonal rainfall deficiency do not necessarily translate into periods of agricultural,

[1] *Freeman's Journal* available through Irish Newspaper Archives www.irishnewsarchive.com/

hydrological or environmental drought (Wilhite and Glantz, 1985). Nonetheless, our interrogation uses seasonal rainfall and persistence metrics not applied in the homogenization process to quality-assure the integrity of series within the IIP network. We first reprise the methods used to homogenise the IIP series and list other homogeneous rainfall products for comparison. We then describe and apply statistical techniques for simulating occurrence and persistence of below average rainfall across the IIP network. This leads into an account and interpretation of the key findings before concluding with a few suggestions for further research.

2. Data

Our analysis draws on several data sets. The homogeneous IIP network contains monthly totals for 25 stations (Figure 1) covering the common years 1850 to 2010 (Noone *et al.,* 2015). Precipitation data underpinning the IIP network were drawn from four sources: long-term series held by the Climatic Research Unit (UK) and Centre for Environmental Data Archival (UK) updated to 2010 (16 stations); the record of Armagh Observatory (UK) (1 station); plus digital and paper records of varying completeness held by Met Éireann (IE) (8 stations). Raw data exist for all 25 stations from 1908; 23 from the 1890s; 19 from the 1880s; and 8 in the 1850s. The longest continuous record is for Belfast which begins in 1812.

In preparation of the IIP network, for each station, detailed information about correction factors, nearest neighbours, observer practices, meteorological site and gauge condition was transcribed to a master file of meta-data to help interpret break points detected during homogenisation. The HOMegenisation softwarE in R (HOMER) package (Mestre *et al*., 2013) was used to detect and correct inhomogeneity in the monthly series and to infill/extend records to the period 1850-2010 (see: Noone *et al*., 2015). HOMER compares differences between candidate and reference sites within a network to identify likely break points that can then be ratified against meta-data. Given the low density of long-term stations available for IIP, at least 12 correlated reference stations for each candidate series were identified for pairwise comparison and break detection. Annual correction factors were applied to confirmed break points using an ANOVA model (Caussinus and Mestre, 2004; Mestre *et al*., 2013; Venema *et al*. 2012). Missing data were infilled using the same method such that all records start in 1850 with correction factors based on the adjustment amplitude applied until the first detected change point of the series (Noone *et al*., 2015). Finally, the regional IIP series was constructed as the un-weighted monthly mean of the 25 series.

Monthly precipitation totals for England and Wales (EWP), Scotland (SP) and Northern Ireland (NIP) were obtained from the Met Office Hadley Centre. The EWP series begins in 1766, whereas SP and NIP start in 1931. All series are based on long-running meteorological stations weighted to provide spatially and temporally homogeneous, area-averaged precipitation totals (Alexander and Jones, 2001). These precipitation series were used alongside the meta-data and archival material described above to quality check the provenance of the IIP series and major dry-spells detected therein.

3. Methods

Following Wilby *et al*. (2015) the homogeneous IIP series were processed in four ways. First, mean monthly precipitation totals were derived for a baseline period 1961-1990 with averages consolidated into mean winter (October to March) and summer (April to September) half years. Seasonal anomalies were then calculated for the 1850-2010 series relative to 1961-1990 half-year means, recognising that spell lengths are sensitive to choice of baseline period (Sen, 1980). As will be shown later, 1961-1990 was a relatively dry period. Therefore, any negative anomalies referenced to this baseline are indeed noteworthy.

The number of stations with below average precipitation was counted for each half year to establish the spatial coherence of dry-spells, accepting that this is a crude metric because of the sparse and uneven distribution of sites (Figure 1). When more than two thirds of stations in the IIP network report a dry season the event is regarded as widespread and unlikely to be due to a local anomaly or suspect data. Dates of spells lasting three or more half-year seasons were then cross-referenced to EWP and SP to establish coherence at the scale of the British-Irish Isles.

Second, conditional dry-to-dry (Pdd) and wet-to-wet (Pww) first-order Markov model transition probabilities were determined from series of seasonal anomalies. This involved counting the frequency with which a below average season is followed by another dry season. Pdd is the proportion of transitions that are dry-to-dry out of all transitions (i.e. dry-to-dry plus dry-to-wet). Similarly, Pww was derived from the proportion of wet-to-wet transitions.

Unbroken dry- and wet-season runs were used to construct frequency distributions of spell lengths and to identify the most persistent dry-spells in each record. Pdd and Pww were also estimated for 30-year moving blocks to establish whether there has been any long-term change in dry- and/or wet-spell persistence throughout the IIP, EWP, NIP and SP series.

Third, as in Wilby (2007), Sharma and Panu (2012; 2014a;b) and Wilby *et al*. (2015), Pdd and Pww transition probabilities based on 1850-2010 observations were used to stochastically simulate series of seasons with above or below average rainfall. The process begins by seeding with a uniform random number $r[0,1]$ to determine whether there is a change from the initial state (assumed to be below average rainfall). If $r \leq$ Pdd the dry-spell continues; if $r >$ Pdd then the new state is wet and Pww is applied at the next time step. In this way, a single 10,000 season Markov model simulation was performed to generate a distribution of synthetic spell lengths. The two-sample, nonparametric Kolmogorov-Smirnov (KS) test was applied to determine whether the largest discrepancy (Dstat) between observed and simulated cumulative distributions of spell-length was significantly ($p<0.05$) greater than expected by chance.

Finally, 1000 boot-strap, Markov model simulations were performed to generate 100- and 160-year (i.e. 200 and 320 season) sequences for each site and region. Maximum dry- and wet-spell lengths were retained from all 1000 realisations to construct distributions of synthetic 100- and 160-year spells for comparison with observations. The 160-year event was generated for equivalence with observed record lengths; the 100-year event enables comparison with Wilby *et al*. (2015). Both sets of distributions were used to estimate likelihoods of a 10-season spell with below average precipitation at each site. This provides an upper bound (yet plausible) dry-spell that is much longer than the single season (1995) design drought applied in, for example, the Dublin City Council (2010) Water Plan.

4. Results

Figure 2 shows seasonal anomalies as percentages of the 1961-1990 mean for IIP and EWP since 1850. The IIP series is significantly correlated with both EWP (r = +0.75) and SP (r = +0.57) (not shown). Seasonal anomalies of IIP vary between -40% (winter 1879/80) and +49% (summer 1924). Most (84%) seasons lie within ±20% of the 1961-1990 average precipitation. Overall, the driest 30-year period in IIP was 1884-1913 with 2% less precipitation than 1961-

1990. Hence, our chosen standard period was close to the very driest continuous run in the IIP series and any negative anomalies would certainly have been indicative of dry seasons. However, as noted at the outset, meteorological droughts do not necessarily coincide with significant agricultural, water resource or environmental stress.

Nine dry-spells lasting longer than three seasons (and simultaneously occurring at more than two thirds of stations) were identified (Table 1). Persistent events stand out in 1853-1856, 1886-1888 (followed shortly by 1892-1894) and 1970-1973 (tailed by 1974-1976). Dry spells in the 1850s and late nineteenth century have been reported previously for Ireland (Barrington, 1888; Symons, 1887; Tabony, 1980) and for England and Wales (Barker *et al*., 2004; Burt and Howden, 2011; Burt and Horton, 2007; Jones *et al*., 2006; Marsh *et al*., 2007; Wilby and Quinn, 2013). Likewise, dry-spells in the 1970s achieved notoriety for their drought orders, rota cuts and standpipes across parts of south Wales, central and southern England, water rationing in the Channel Islands, and even nightly shut-offs in Belfast (Rodda and Marsh, 2011). Another noteworthy feature is the relatively quiet period 1908-1950 for widespread, multi-year droughts (Table 1). Our criteria (i.e. two thirds of stations reporting anomalies lasting at least three seasons) exclude well-known intense, but short-lived droughts of 1921, 1933/34 and1941-1943 that are evident in both IIP and EWP (Marsh et al., 2007).

Overall, the longest unbroken runs of dry half-years in IIP were 14 seasons at Waterford (1912-1919/1920); 12 at Cork Airport (1905-1911); 11 at both Markree Castle (1882-1887/1888) and Mullingar (1904-1909) (Figure 3). All four dry-spells occurred prior to the era of digital records (1941) but overlap with the coherent rainfall deficits (Table 1) of 1886-1888 (at Markree Castle) and 1905-1907 (at Cork Airport and Mullingar). While no breaks in this period were detected by Noone *et al*. (2015) the exceptionally long run of seasons with below average precipitation at Waterford may be explained in part by documented movements and sheltering of the rain gauge at Gortmore (used to bridge the record by Tabony (1980)). Meta-data further signal that the Markree Castle gauge was ‘leaking’ and the provenance of a 10 season dry spell at Belfast is questionable due to a large change of correction factor applied by Tabony (1980) for bridging stations in the 1850s.

The most persistent dry-spell recorded anywhere in the IIP network since record digitisation (1941) lasted 9 seasons at Cappoquin (1969-1973). This period partially overlaps with the longest dry runs in the central and southeast part of the network covering Athboy, Birr Castle, Drumsna, Enniscorthy, Foulkesmills, Portlaw and Roches Point (Table 2). The single season drought in 1995 is noteworthy for the large precipitation anomaly (-35%) averaged across all stations in the IIP network. The most recent 20 years have witnessed only a few single and two season dry-spells (in 1996-97, 2001-02 and 2003-04) consistent with wetter and stormier conditions (Sutton and Dong, 2012; Matthews *et al*., 2014; 2015).

The relative quiescence of droughts since the 1990s is reflected by the moving average Pdd and Pww indices (Figure 4). In particular, Pww shows non-stationary behaviour towards more persistent wet-spells that is also evidenced by the EWP and SP series. The 30-year mean Pww for IIP peaked in 2009 whereas Pdd is now lower than at any time since the period 1938-1967, consistent with trends in SP. [Note that IIP and NIP are not independent series because the former contains some records used to construct the latter. With this in mind, the divergence in persistence behaviours over the last decade could reflect the influence of the comparatively high density of stations within IIP along the east and southeast seaboard].

The KS test indicates that simulated and observed spell distributions are statistically ($p<0.05$) indistinguishable across all regional (Figure 5) and station (Figure 6) series. The model tends to overstate the frequency of single-season dry-spells and underestimate the occurrence of two-season events. Overall, the geometric distribution yielded by the Markov model provides good representations of the observed dry-spell length distribution. The closest match for dry-spells is for Shannon airport (KS = 0.017) and greatest discrepancy for Ardara (KS = 0.111). Note, however, that the KS results are for the whole distribution whereas the fit to tails is more relevant for estimating low frequency events. Validation data are limited for this part of the distribution so we are restricted to assessing the ability of the model to generate the maximum observed dry-spell length at each site.

Table 2 shows the extent to which bootstrap Markov model simulations replicate the most extreme runs of dry-spells in the 160-year series. The model overestimates the duration of the 160-year dry-spell by less than one season at 7 sites and by more than one season at 2 sites. The largest discrepancy is for Portlaw where the model simulates a 7.6 season dry-spell compared with 5 season run in observations. Meta data suggest that some precipitation totals are too high at this site due to incorrect conversion between inches and mm. Conversely, the maximum observed dry-spell is underestimated by less than one season at 5 sites and more than one season at 13 sites. The largest difference is at Waterford with 14 observed and 7.5 simulated seasons. As noted above, this mismatch may be explained by the likely under-catch and site changes affecting the Waterford record.

The 160- and 100-year simulations also provide likelihoods for a 10-season dry-spell for each site and region (Table 2). This outcome is over three times more likely across EWP (p=0.044) than for IIP (p=0.012). To date, the maximum observed dry-spell for Dublin is 8 seasons (1903-1907), however, the Markov model suggests a relatively high likelihood (p=0.125) of a 10-season run of rainfall deficiencies in a 160-year record. A slightly higher likelihood is estimated for Markree Castle (p=0.127) but this could be due to fitting the model to a record with possible rainfall under-catch in the early part of the series. On the other hand, a 10-season dry-run is least likely at Armagh (p=0.008), Birr Castle (p=0.005), Foulkesmills (p=0.008) and Roches Point (p=0.009).

Comparison of probability distributions for simulated maximum dry- and wet-spell lengths reveals three distinct patterns (Figure 7). There are sites with greater dry-spell persistence than wet-spell persistence (Dublin, Enniscorthy, Markree Castle, Mullingar, Phoenix Park); sites where wet- and dry-spell lengths have similar likelihoods (Ardara, Athboy, Belfast, Cork, Derry, Drumsna, Malin Head, Portlaw, Rathdrum, Strokestown, UC Galway, Waterford); and sites where a given wet-spell length is more likely than the same length dry-spell (Armagh, Birr, Cappoquinn, Foulkesmills, Killarney, Roches Point, Shannon, Valentia). Across all sites and 100-year simulations, the longest dry-spell was generated for Dublin and persisted 24 seasons (not shown in Figure 7). This might appear implausible but Dublin observations contain near unbroken runs exceeding 20 seasons in 1850-1868 (26/36), 1928-1946 (23/36) and 1961-1978 (23/35).

5. Discussion

Using 1961-1990 as the reference period (and excluding Waterford and Markree Castle for reasons noted above) we found that the longest observed run of below average precipitation persisted 12 seasons at Cork Airport (1905-1911). Noone *et al.* (2015) note that this record was originally constructed by Tabony (1980) using a composite of stations with data prior to 1962 based on a lower elevation gauge at University College Cork. This station change is thought to explain lower early seasonal totals and a detected break point in 1958. The break was adjusted by Noone *et al.* (2015) but the same correction factor was applied across all months which could affect dry run persistence for this station.

The next longest run lasted 11 seasons at Mullingar (1904-1909) but, again, Noone *et al*. (2015) report break points in 1937 and 1950 that could be due to a station change in the latter case. Correction of the 1950 break resulted in a large downward adjustment, again potentially affecting dry run persistence. The 10 season dry-spell at Belfast (1853-1858) has already been queried, so the longest run now becomes 9 seasons at Ardara (1927-1932), Cappoquinn (1969-1973), Phoenix Park (1903-1908) and Strokestown (1919-1912) (Table 2). The Ardara record is based on a composite of stations with a small amplitude break point in 1983. While Strokestown has been bridged from 1961, the years 1908-1961 represent a stable period in the record (Noone *et al*., 2015). No breaks were detected for Cappoquinn and there are no issues of note from metadata. There are documented station moves early in the record at Phoenix Park but these pre-date the identified dry run and a station inspection in 1903 noted a very clear/open site. Therefore, having accounted for break points, station/instrument changes and reported measurement errors the most credible, conservative upper bound continuous dry-spell length for the IIP network is 9 seasons.

Our sub-annual analysis interrogated data that were homogenized at annual scales and thus represents a stringent test of the IIP network. Anecdotal accounts, proxy sources and data from neighbouring regions, all provide a basis for quality assuring our catalogue of widespread multi-year rainfall deficits (Table 1). We find issues with two stations (Waterford and Markree Castle) that were not picked up in the annual homogenisation of Noone *et al*. (2015). While the confounding issues identified by metadata may have negligible effect at annual resolution they can evidently become important when examining long duration rainfall deficits. Additionally, suspicion is raised at Cork, Mullingar and Belfast that high persistence of negative rainfall anomalies may be an artefact of using a single correction factor equally across several months. Both issues arise despite application of best-practice methods for homogenisation and emphasise the need for cautious use of homogenous series, particularly when examining sequences of sub-annual extremes. [Note that snowfall is only a small component of total precipitation across Ireland and thus any underestimation normally associated with snowy climates is a minor concern]. Our analysis shows how metadata are critical for increasing confidence in the authenticity of long-term precipitation indices.

There is strong independent evidence of persistent, regional droughts in the 1850s and 1880s but bridging and homogenization techniques increase dependency between records as the network density decreases further back in time. This is particularly the case for the 1850s where only eight stations were active; by the 1880s this increases to 19. Thus, greater drought coherence would be expected at the beginning of the IIP series than at the end due to the smaller number of active stations. Hence, when evaluating the realism of Markov model simulations there is ambiguity about whether inability to replicate dry-spells (>10 seasons) at some sites is due to model deficiency, uncertainty in homogenized data, or both.

There is plenty of scope for developing more elaborate Markov model simulations for Ireland. For example, seasonal Pdd and Pww parameters could be conditioned by the phase of the North Atlantic Oscillation, Atlantic Multidecadal Oscillation, or El Niño Southern Oscillation to replicate low-frequency variations (evident in Figure 4) and hence more realistic clustering of dry-spells at decadal time-scales (e.g. Wilby et al., 2002). The distribution of seasonal precipitation anomalies could be simulated using gamma or normal functions. There is also scope for multi-site simulation of meteorological drought occurrence and severity across the network as a whole and/or within homogeneous precipitation regions. Such tools could be used to simulate groundwater recharge, river flow and reservoir levels for vulnerable water supply zones, as well as for assessing potential environmental stress.

An important finding of our analysis is that recent decades have been relatively benign in terms of widespread, multi-year sequences of below average rainfall in Ireland. This reflects a return to generally stormier and wetter summers since the 1990s (Matthews et al., 2015). Nonetheless, there is no room for complacency about drought risk given rising water demands. Routinely updating the Pdd and Pww indices offers a simple way of tracking the long-term propensity for seasonal rainfall deficits in Ireland.

6. Conclusions

We have investigated the spatial and temporal properties of long-lasting negative rainfall anomalies across the Island of Ireland at site and regional scales with half-year granularity. Our aim was to create the first coherent picture of multi-season rainfall deficit occurrence and persistence across the region and, in the process, subject the IIP network to stringent appraisal. Our preliminary analysis has highlighted the immense value of carefully cataloguing station meta-data – an essential resource for interpreting break-points and exceptional runs of below/above average precipitation. We acknowledge that interpretations of spatial patterns are hindered by the sparse and uneven distribution of sites, as well as by the range of issues picked up by meta-data, so we were restricted to describing three types of spell-length regime. Further work is needed to determine whether these regimes form coherent clusters in space.

Overall, we find that the Island of Ireland is surprisingly prone to runs of seasonal rainfall deficiency and that major dry spells in the 1850s, 1880s and 1970s were far more persistent than any episodes experienced in the last 40 years. These events could provide useful analogues for stress testing the robustness of water supply and drought plans; a practice that is finding favour elsewhere (e.g. Spraggs *et al*., 2015). As Irish Water embarks on a period of major investment in water infrastructure, stress testing designs against episodes with negative rainfall anomalies lasting up to 9 seasons offers an altogether different risk assessment than ability to cope with single season deficiencies. We also show that there is relatively high likelihood (p=0.125) of a continuous 5 year (10 season) dry-spell at Dublin, a region in which population growth and aging infrastructure has resulted in a water system operating at the edge of its capacity.

In practice, water resource system vulnerability depends on a host of factors including the type(s) of resource (i.e. groundwater, river intake, reservoir, or combination of sources); amount of raw and treated water storage; connectivity of the system linking points of supply to demand; water quality and treatment constraints. Such issues would clearly modulate any assessment of droughts based on the analysis of meteorological data alone. Homogenised rainfall series would need to be fed into more elaborate rainfall-runoff models and then, in turn, simulated inflows input to water system models. Markov modelling, as demonstrated for IIP, offers a way of generating severe drought sequences for evaluating water supply system performance under combinations of long duration and intense rainfall deficits.

We have only begun to speculate about the underlying physical drivers of dry-spells lasting 5 or even 10 years. This is an area of active research, not least because of the potential to apply such insights to long range drought forecasting (Folland *et al*., 2015; Kingston *et al*., 2015). Assembling homogeneous meteorological records from paper and digital records (with accompanying meta-data) is a laborious but critical part of this process. Creation of the IIP series (Noone *et al*., 2015), reference networks for river flow (Murphy *et al*., 2013) and attendant analytical tools (Wilby *et al*., 2015) is bringing together ingredients needed for a deeper understanding of multi-decadal hydroclimatic variability and change at a sentinel location of Europe.

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Tables

Table 1 Periods with more than 2/3 of all IIP stations reporting below average seasonal rainfall for at least three continuous seasons compared with dry-spell lengths in IIP, EWP and SP. Note that NIP was not included because of the risk of double-counting with IIP.

	Number of seasons		
Period	**IIP**	**EWP**	**SP**
1853-1856	6	5	-
1858-1860	3	1	-
1886-1888	3	2	-
1892-1894	3	3	-
1905-1907	3	3	-
1951-1953	3	2	2
1962-1964	3	3	3
1970-1973	5	4	5
1974-1976	4	3	3

Table 2 Observed maximum dry-spell duration (seasons) compared with simulated mean 160- and 100-year events at each site as well as for IIP, NIP, EWP and SP. Likelihoods of a simulated 10-season dry-spell are also given.

Record	Observed Maximum event		Simulated 160-year event		Simulated 100-year event	
	Period(s)	Length (seasons)	Length (seasons)	Likelihood (10 season)	Length (seasons)	Likelihood (10 season)
Ardara	1927-32	9	6.7	0.028	6.1	0.017
Armagh	1892-95	7	5.5	0.008	5.1	0.002
Athboy	1969-73	8	7.0	0.044	6.4	0.027
Belfast	1853-58	10	7.4	0.058	6.6	0.029
Birr Castle	1970-73	5	5.2	0.005	4.7	0.001
Cappoquin	1969-73	9	6.4	0.021	5.8	0.015
Cork Airport	1905-11	12	7.8	0.086	7.1	0.045
Derry	1885-88	6	6.3	0.022	5.7	0.014
Drumsna	1966-70	7	6.6	0.024	6.0	0.018
Dublin Airport	1903-07	8	8.7	0.125	7.8	0.069
Enniscorthy	1969-73	8	7.8	0.068	7.0	0.057
Foulkesmills	1969-73	8	5.6	0.008	5.2	0.001
Killarney	1853-56, 1939-42	6	5.8	0.010	5.2	0.005
Malin Head	1950-54	7	6.9	0.033	6.3	0.022
Markree Castle	1882-88	11	8.6	0.127	7.9	0.089
Mullingar	1904-09	11	8.0	0.111	7.3	0.065
Phoenix Park	1903-08	9	7.9	0.070	7.2	0.053
Portlaw	1855-58, 1888-91, 1904-07, 1948-50, 1969-71, 2003-06	5	7.6	0.067	7.0	0.046
Rathdrum	1853-56	6	6.3	0.017	5.8	0.015
Roches Point	1941-43, 1961-63, 1969-71, 1974-76, 1990-92	4	5.7	0.009	5.2	0.008
Shannon Airport	1904-07	6	6.8	0.032	6.2	0.018
Strokestown	1919-22	9	6.2	0.027	5.8	0.008
UC Galway	1887-91	7	7.2	0.048	6.6	0.033
Valentia	1908-11, 1970-73	6	6.6	0.023	6.0	0.021
Waterford	1912-20	14	7.5	0.061	6.9	0.048
IIP	1969-73	8	6.0	0.012	5.6	0.009
NIP	1970-73	7	6.0	0.014	5.5	0.009
EWP	1900-03, 1904-07, 1941-44	8	7.0	0.044	6.5	0.034
SP	1970-73	6	5.6	0.008	5.0	0.004

Figures

Figure 1 Map of station locations

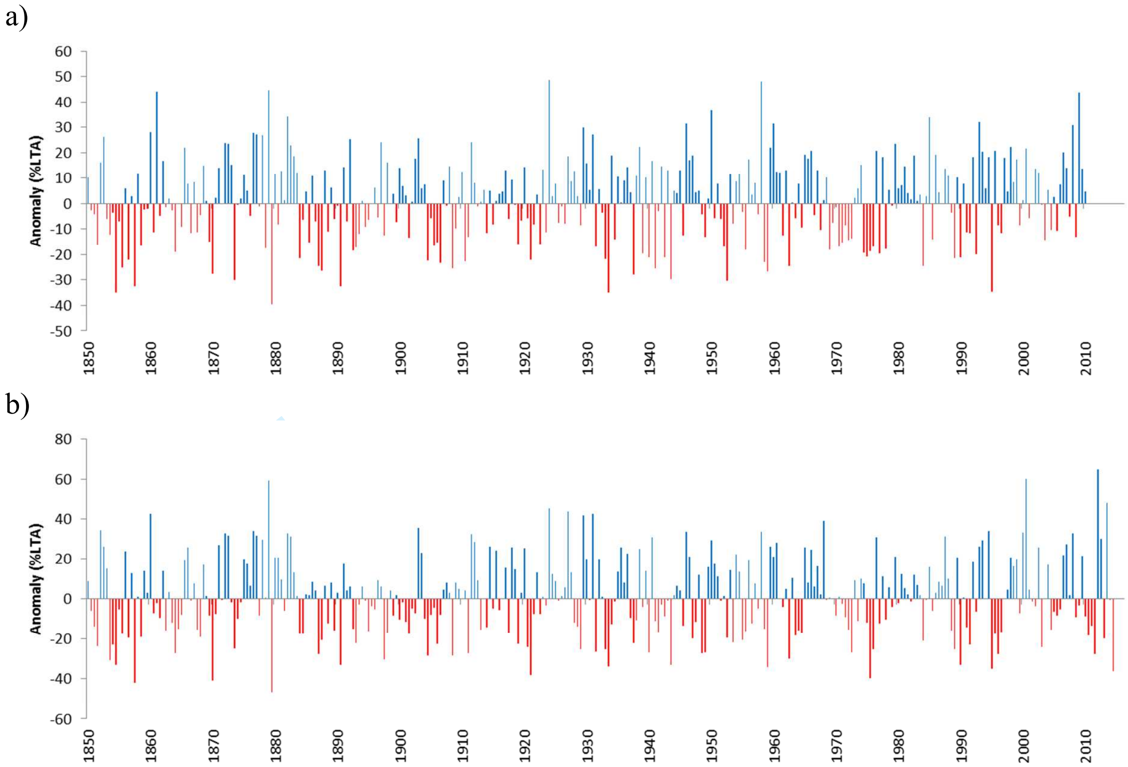

Figure 2 Above (**blue**) and below (**red**) long-term average precipitation totals in winter (October to March) and summer (April to September) half years (seasons) across a) the Island of Ireland and b) England and Wales for the years 1850-2010. All deviations are percentage anomalies with respect to the 1961-1990 mean.

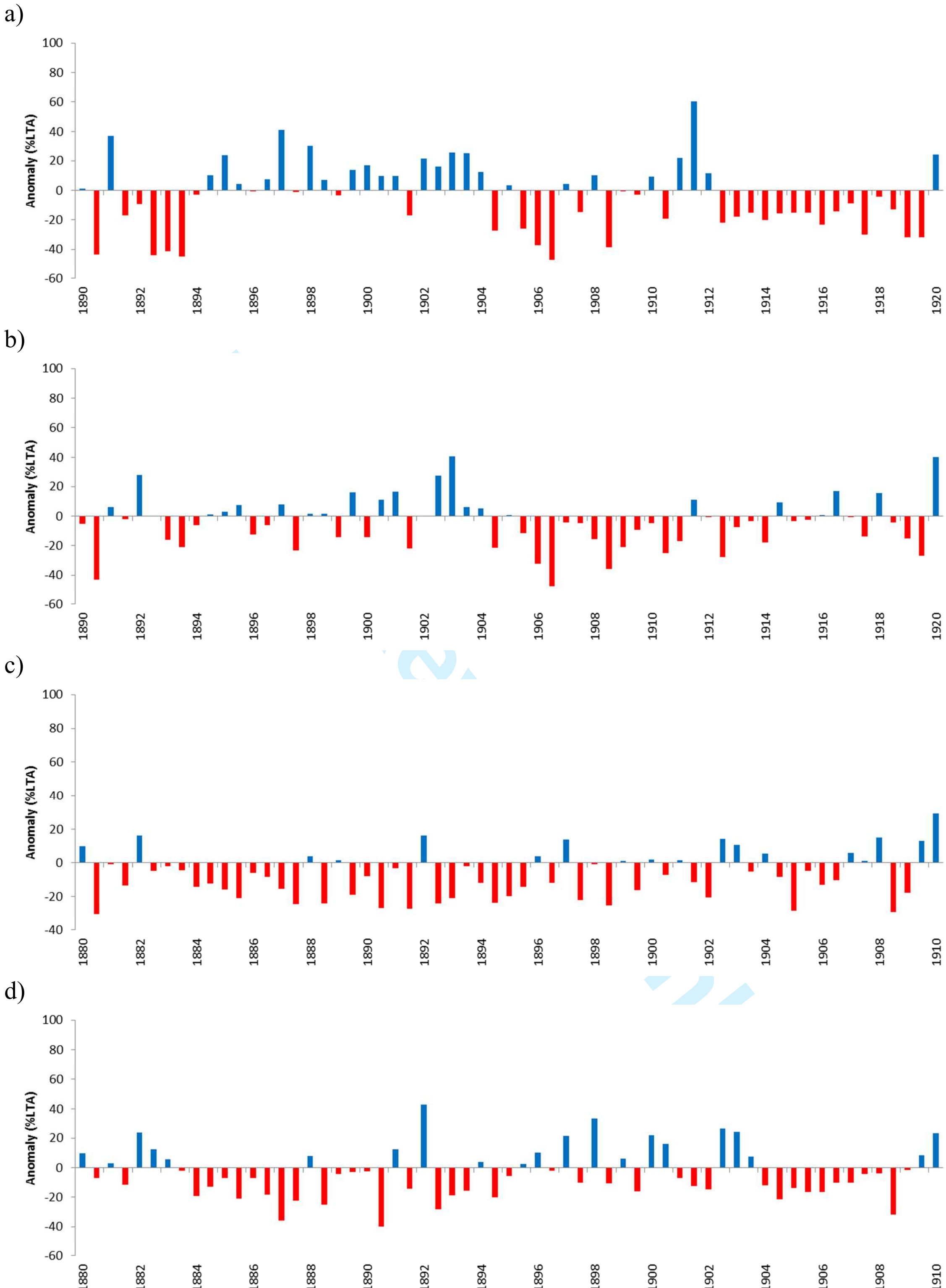

Figure 3 Long-run dry-spells at a) Waterford (1912-1919/1920), b) Cork Airport (1905-1911), c) Markree Castle (1882-1887/1888) and d) Mullingar (1904-1909)

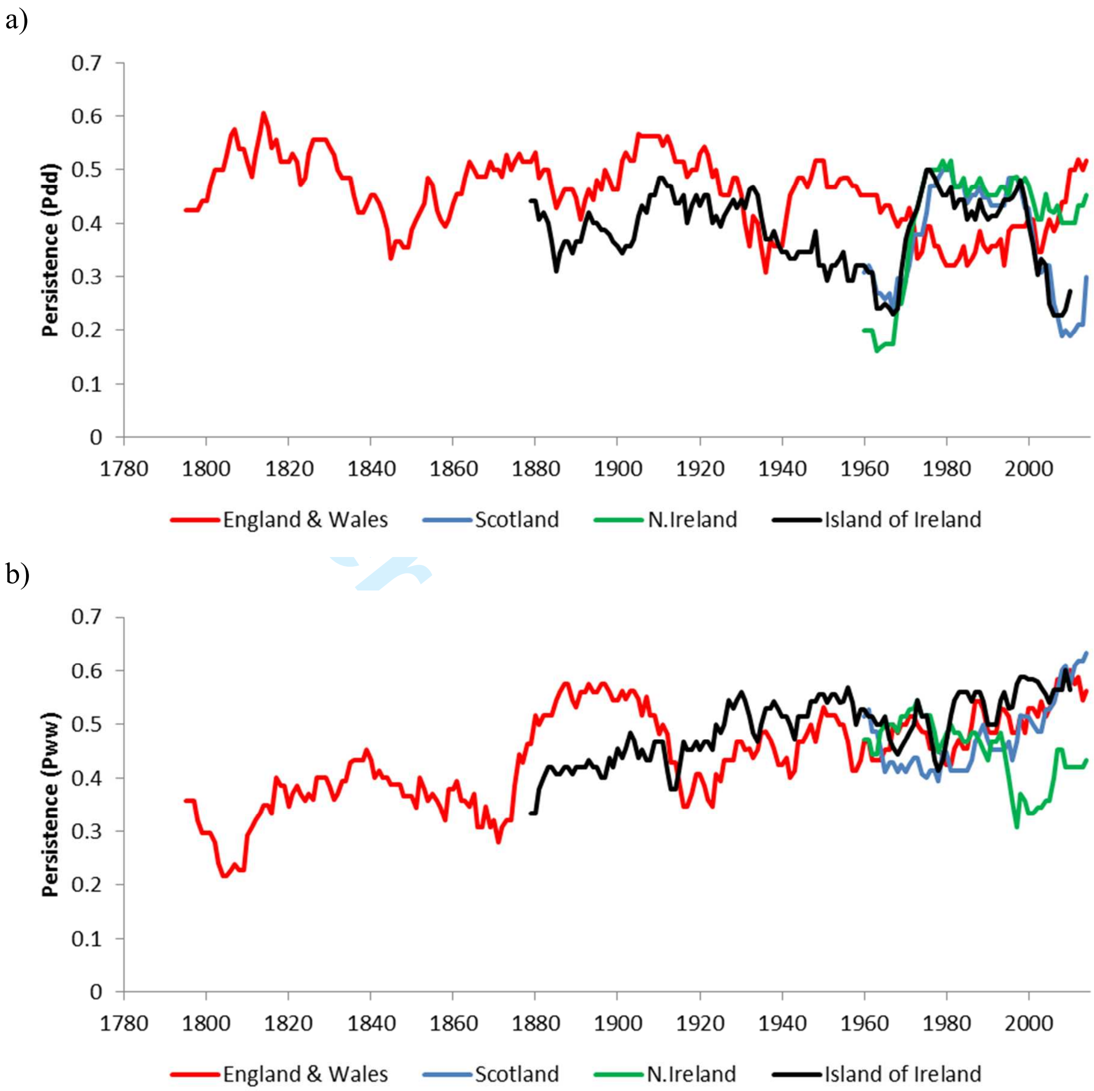

Figure 4 a) Dry-to-dry (Pdd) and b) wet-to-wet (Pww) season persistence for the Island of Ireland, Northern Ireland, England and Wales, and Scotland. All series are based on 30-year moving windows with anomalies referenced to the 1961-1990 mean. Adapted from Wilby et al. (2015).

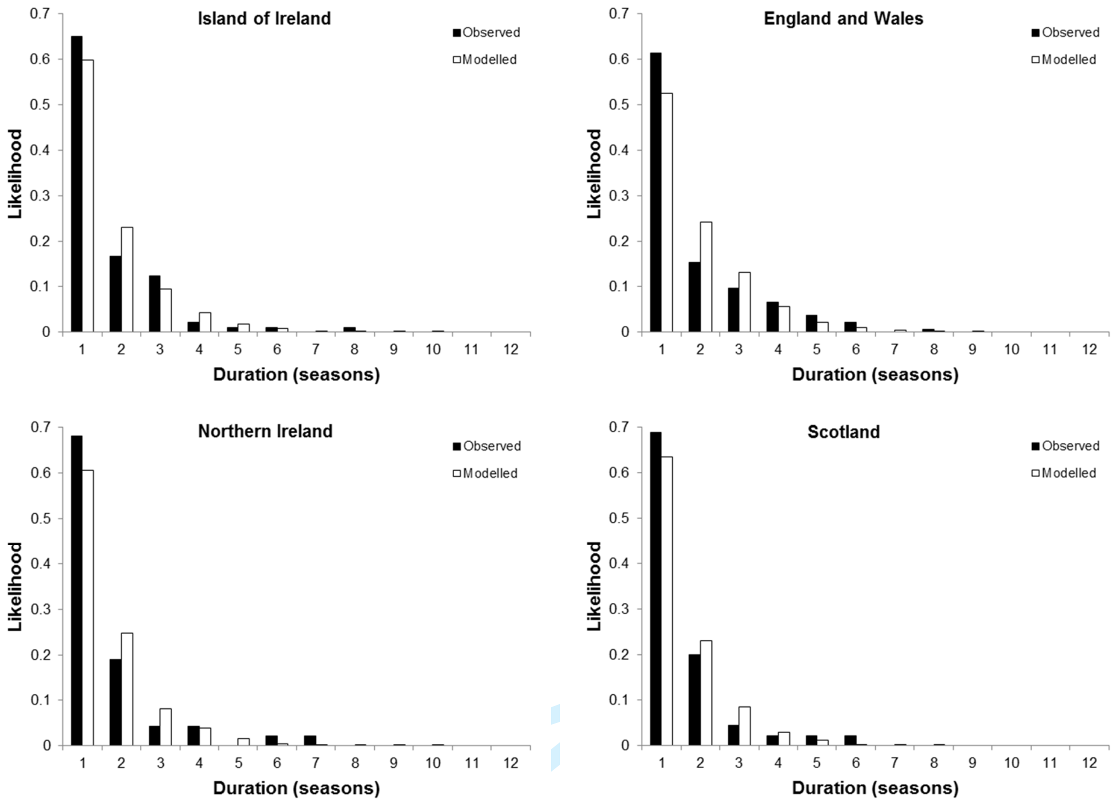

Figure 5 Observed and modelled likelihood of dry-spells of duration 1 to 12 seasons in the Island of Ireland (1850-2010), Northern Ireland (1931-2014), England and Wales (1766-2014) and Scotland (1931-2014). Adapted from Wilby et al. (2015).

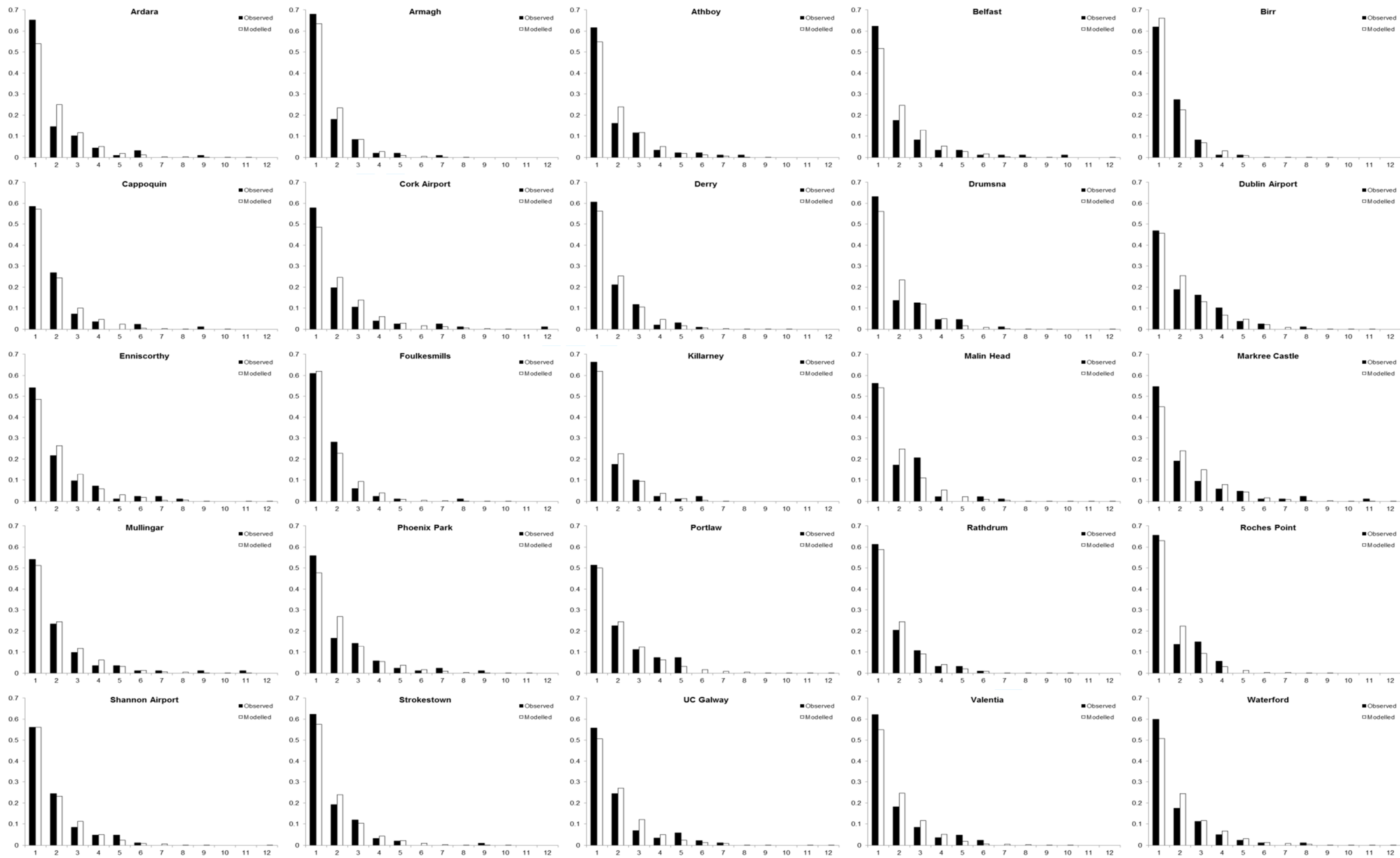

Figure 6 As in Fig.5 but 25 sites across the Island of Ireland.

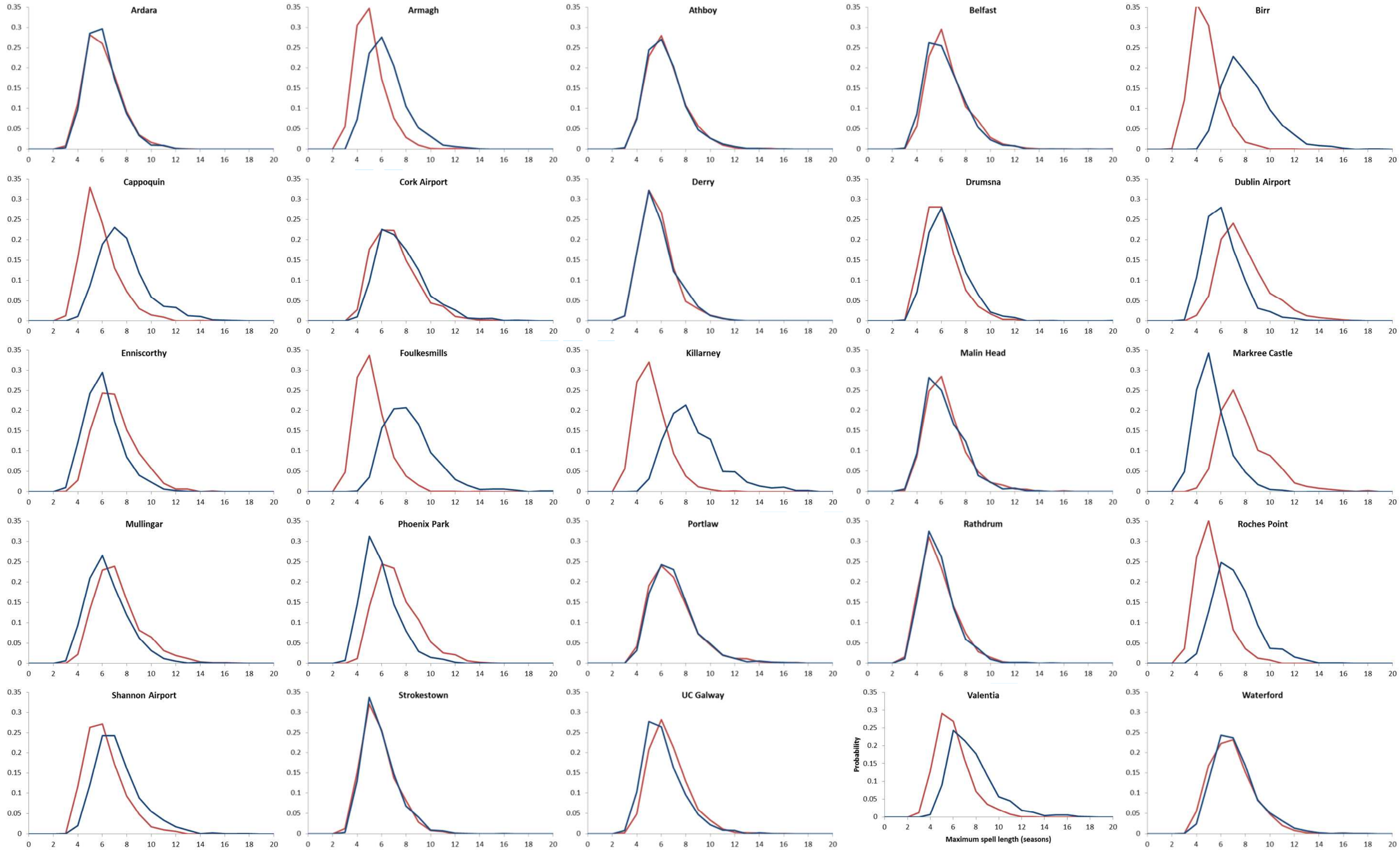

Figure 7 Probability distributions of maximum simulated 100-year dry- (red lines) and wet- (blue lines) spells for Island of Ireland sites.