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An evaluation of persistent meteorological drought using a homogeneous Island of Ireland precipitation network

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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,

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

69 hydrological or environmental drought (Wilhite and Glantz, 1985). Nonetheless, our

70 interrogation uses seasonal rainfall and persistence metrics not applied in the homogenization

71 process to quality-assure the integrity of series within the IIP network. We first reprise the

72 methods used to homogenise the IIP series and list other homogeneous rainfall products for

73 comparison. We then describe and apply statistical techniques for simulating occurrence and

74 persistence of below average rainfall across the IIP network. This leads into an account and

75 interpretation of the key findings before concluding with a few suggestions for further

76 research.

77

2. Data

78

79 Our analysis draws on several data sets. The homogeneous IIP network contains monthly

80 totals for 25 stations (Figure 1) covering the common years 1850 to 2010 (Noone *et al.,*

81 2015). Precipitation data underpinning the IIP network were drawn from four sources: long-

82 term series held by the Climatic Research Unit (UK) and Centre for Environmental Data

83 Archival (UK) updated to 2010 (16 stations); the record of Armagh Observatory (UK) (1

84 station); plus digital and paper records of varying completeness held by Met Éireann (IE) (8

85 stations). Raw data exist for all 25 stations from 1908; 23 from the 1890s; 19 from the 1880s;

86 and 8 in the 1850s. The longest continuous record is for Belfast which begins in 1812.

87 In preparation of the IIP network, for each station, detailed information about correction

88 factors, nearest neighbours, observer practices, meteorological site and gauge condition was

89 transcribed to a master file of meta-data to help interpret break points detected during

90 homogenisation. The HOMegenisation softwarE in R (HOMER) package (Mestre *et al*.,

91 2013) was used to detect and correct inhomogeneity in the monthly series and to infill/extend

92 records to the period 1850-2010 (see: Noone *et al*., 2015). HOMER compares differences

93 between candidate and reference sites within a network to identify likely break points that can

94 then be ratified against meta-data. Given the low density of long-term stations available for

95 IIP, at least 12 correlated reference stations for each candidate series were identified for

96 pairwise comparison and break detection. Annual correction factors were applied to

97 confirmed break points using an ANOVA model (Caussinus and Mestre, 2004; Mestre *et al*.,

98 2013; Venema *et al*. 2012). Missing data were infilled using the same method such that all

99 records start in 1850 with correction factors based on the adjustment amplitude applied until

100　the first detected change point of the series (Noone *et al*., 2015). Finally, the regional IIP

101　series was constructed as the un-weighted monthly mean of the 25 series.

102　Monthly precipitation totals for England and Wales (EWP), Scotland (SP) and Northern

103　Ireland (NIP) were obtained from the Met Office Hadley Centre. The EWP series begins in

104　1766, whereas SP and NIP start in 1931. All series are based on long-running meteorological

105　stations weighted to provide spatially and temporally homogeneous, area-averaged

106　precipitation totals (Alexander and Jones, 2001). These precipitation series were used

107　alongside the meta-data and archival material described above to quality check the

108　provenance of the IIP series and major dry-spells detected therein.

109

3. Methods

111　Following Wilby *et al*. (2015) the homogeneous IIP series were processed in four ways. First,

112　mean monthly precipitation totals were derived for a baseline period 1961-1990 with

113　averages consolidated into mean winter (October to March) and summer (April to September)

114　half years. Seasonal anomalies were then calculated for the 1850-2010 series relative to 1961-

115　1990 half-year means, recognising that spell lengths are sensitive to choice of baseline period

116　(Sen, 1980). As will be shown later, 1961-1990 was a relatively dry period. Therefore, any

117　negative anomalies referenced to this baseline are indeed noteworthy.

118　The number of stations with below average precipitation was counted for each half year to

119　establish the spatial coherence of dry-spells, accepting that this is a crude metric because of

120　the sparse and uneven distribution of sites (Figure 1). When more than two thirds of stations

121　in the IIP network report a dry season the event is regarded as widespread and unlikely to be

122　due to a local anomaly or suspect data. Dates of spells lasting three or more half-year seasons

123　were then cross-referenced to EWP and SP to establish coherence at the scale of the British-

124　Irish Isles.

125　Second, conditional dry-to-dry (Pdd) and wet-to-wet (Pww) first-order Markov model

126　transition probabilities were determined from series of seasonal anomalies. This involved

127　counting the frequency with which a below average season is followed by another dry season.

128　Pdd is the proportion of transitions that are dry-to-dry out of all transitions (i.e. dry-to-dry

129　plus dry-to-wet). Similarly, Pww was derived from the proportion of wet-to-wet transitions.

130   Unbroken dry- and wet-season runs were used to construct frequency distributions of spell

131   lengths and to identify the most persistent dry-spells in each record. Pdd and Pww were also

132   estimated for 30-year moving blocks to establish whether there has been any long-term

133   change in dry- and/or wet-spell persistence throughout the IIP, EWP, NIP and SP series.

134   Third, as in Wilby (2007), Sharma and Panu (2012; 2014a;b) and Wilby *et al*. (2015), Pdd

135   and Pww transition probabilities based on 1850-2010 observations were used to

136   stochastically simulate series of seasons with above or below average rainfall. The process

137   begins by seeding with a uniform random number $r[0,1]$ to determine whether there is a

138   change from the initial state (assumed to be below average rainfall). If $r \leq$ Pdd the dry-spell

139   continues; if $r >$ Pdd then the new state is wet and Pww is applied at the next time step. In

140   this way, a single 10,000 season Markov model simulation was performed to generate a

141   distribution of synthetic spell lengths. The two-sample, nonparametric Kolmogorov-Smirnov

142   (KS) test was applied to determine whether the largest discrepancy (Dstat) between observed

143   and simulated cumulative distributions of spell-length was significantly ($p<0.05$) greater than

144   expected by chance.

145   Finally, 1000 boot-strap, Markov model simulations were performed to generate 100- and

146   160-year (i.e. 200 and 320 season) sequences for each site and region. Maximum dry- and

147   wet-spell lengths were retained from all 1000 realisations to construct distributions of

148   synthetic 100- and 160-year spells for comparison with observations. The 160-year event was

149   generated for equivalence with observed record lengths; the 100-year event enables

150   comparison with Wilby *et al*. (2015). Both sets of distributions were used to estimate

151   likelihoods of a 10-season spell with below average precipitation at each site. This provides

152   an upper bound (yet plausible) dry-spell that is much longer than the single season (1995)

153   design drought applied in, for example, the Dublin City Council (2010) Water Plan.

154

4. Results

156   Figure 2 shows seasonal anomalies as percentages of the 1961-1990 mean for IIP and EWP

157   since 1850. The IIP series is significantly correlated with both EWP (r = +0.75) and SP (r =

158   +0.57) (not shown). Seasonal anomalies of IIP vary between -40% (winter 1879/80) and

159   +49% (summer 1924). Most (84%) seasons lie within ±20% of the 1961-1990 average

160   precipitation. Overall, the driest 30-year period in IIP was 1884-1913 with 2% less

161   precipitation than 1961-1990. Hence, our chosen standard period was close to the very driest

162   continuous run in the IIP series and any negative anomalies would certainly have been

163   indicative of dry seasons. However, as noted at the outset, meteorological droughts do not

164   necessarily coincide with significant agricultural, water resource or environmental stress.

165   Nine dry-spells lasting longer than three seasons (and simultaneously occurring at more than

166   two thirds of stations) were identified (Table 1). Persistent events stand out in 1853-1856,

167   1886-1888 (followed shortly by 1892-1894) and 1970-1973 (tailed by 1974-1976). Dry spells

168   in the 1850s and late nineteenth century have been reported previously for Ireland

169   (Barrington, 1888; Symons, 1887; Tabony, 1980) and for England and Wales (Barker *et al*.,

170   2004; Burt and Howden, 2011; Burt and Horton, 2007; Jones *et al*., 2006; Marsh *et al*., 2007;

171   Wilby and Quinn, 2013). Likewise, dry-spells in the 1970s achieved notoriety for their

172   drought orders, rota cuts and standpipes across parts of south Wales, central and southern

173   England, water rationing in the Channel Islands, and even nightly shut-offs in Belfast (Rodda

174   and Marsh, 2011). Another noteworthy feature is the relatively quiet period 1908-1950 for

175   widespread, multi-year droughts (Table 1). Our criteria (i.e. two thirds of stations reporting

176   anomalies lasting at least three seasons) exclude well-known intense, but short-lived droughts

177   of 1921, 1933/34 and1941-1943 that are evident in both IIP and EWP (Marsh et al., 2007).

178   Overall, the longest unbroken runs of dry half-years in IIP were 14 seasons at Waterford

179   (1912-1919/1920); 12 at Cork Airport (1905-1911); 11 at both Markree Castle (1882-

180   1887/1888) and Mullingar (1904-1909) (Figure 3). All four dry-spells occurred prior to the

181   era of digital records (1941) but overlap with the coherent rainfall deficits (Table 1) of 1886-

182   1888 (at Markree Castle) and 1905-1907 (at Cork Airport and Mullingar). While no breaks in

183   this period were detected by Noone *et al*. (2015) the exceptionally long run of seasons with

184   below average precipitation at Waterford may be explained in part by documented

185   movements and sheltering of the rain gauge at Gortmore (used to bridge the record by

186   Tabony (1980)). Meta-data further signal that the Markree Castle gauge was 'leaking' and the

187   provenance of a 10 season dry spell at Belfast is questionable due to a large change of

188   correction factor applied by Tabony (1980) for bridging stations in the 1850s.

189   The most persistent dry-spell recorded anywhere in the IIP network since record digitisation

190   (1941) lasted 9 seasons at Cappoquin (1969-1973). This period partially overlaps with the

191   longest dry runs in the central and southeast part of the network covering Athboy, Birr Castle,

192   Drumsna, Enniscorthy, Foulkesmills, Portlaw and Roches Point (Table 2). The single season

193   drought in 1995 is noteworthy for the large precipitation anomaly (-35%) averaged across all

194   stations in the IIP network. The most recent 20 years have witnessed only a few single and

195   two season dry-spells (in 1996-97, 2001-02 and 2003-04) consistent with wetter and stormier

196   conditions (Sutton and Dong, 2012; Matthews *et al*., 2014; 2015).

197   The relative quiescence of droughts since the 1990s is reflected by the moving average Pdd

198   and Pww indices (Figure 4). In particular, Pww shows non-stationary behaviour towards

199   more persistent wet-spells that is also evidenced by the EWP and SP series. The 30-year

200   mean Pww for IIP peaked in 2009 whereas Pdd is now lower than at any time since the

201   period 1938-1967, consistent with trends in SP. [Note that IIP and NIP are not independent

202   series because the former contains some records used to construct the latter. With this in

203   mind, the divergence in persistence behaviours over the last decade could reflect the

204   influence of the comparatively high density of stations within IIP along the east and southeast

205   seaboard].

206   The KS test indicates that simulated and observed spell distributions are statistically (p<0.05)

207   indistinguishable across all regional (Figure 5) and station (Figure 6) series. The model tends

208   to overstate the frequency of single-season dry-spells and underestimate the occurrence of

209   two-season events. Overall, the geometric distribution yielded by the Markov model provides

210   good representations of the observed dry-spell length distribution. The closest match for dry-

211   spells is for Shannon airport (KS = 0.017) and greatest discrepancy for Ardara (KS = 0.111).

212   Note, however, that the KS results are for the whole distribution whereas the fit to tails is

213   more relevant for estimating low frequency events. Validation data are limited for this part of

214   the distribution so we are restricted to assessing the ability of the model to generate the

215   maximum observed dry-spell length at each site.

216   Table 2 shows the extent to which bootstrap Markov model simulations replicate the most

217   extreme runs of dry-spells in the 160-year series. The model overestimates the duration of the

218   160-year dry-spell by less than one season at 7 sites and by more than one season at 2 sites.

219   The largest discrepancy is for Portlaw where the model simulates a 7.6 season dry-spell

220   compared with 5 season run in observations. Meta data suggest that some precipitation totals

221   are too high at this site due to incorrect conversion between inches and mm. Conversely, the

222   maximum observed dry-spell is underestimated by less than one season at 5 sites and more

223   than one season at 13 sites. The largest difference is at Waterford with 14 observed and 7.5

224 simulated seasons. As noted above, this mismatch may be explained by the likely under-catch
225 and site changes affecting the Waterford record.

226 The 160- and 100-year simulations also provide likelihoods for a 10-season dry-spell for each
227 site and region (Table 2). This outcome is over three times more likely across EWP (p=0.044)
228 than for IIP (p=0.012). To date, the maximum observed dry-spell for Dublin is 8 seasons
229 (1903-1907), however, the Markov model suggests a relatively high likelihood (p=0.125) of a
230 10-season run of rainfall deficiencies in a 160-year record. A slightly higher likelihood is
231 estimated for Markree Castle (p=0.127) but this could be due to fitting the model to a record
232 with possible rainfall under-catch in the early part of the series. On the other hand, a 10-
233 season dry-run is least likely at Armagh (p=0.008), Birr Castle (p=0.005), Foulkesmills
234 (p=0.008) and Roches Point (p=0.009).

235 Comparison of probability distributions for simulated maximum dry- and wet-spell lengths
236 reveals three distinct patterns (Figure 7). There are sites with greater dry-spell persistence
237 than wet-spell persistence (Dublin, Enniscorthy, Markree Castle, Mullingar, Phoenix Park);
238 sites where wet- and dry-spell lengths have similar likelihoods (Ardara, Athboy, Belfast,
239 Cork, Derry, Drumsna, Malin Head, Portlaw, Rathdrum, Strokestown, UC Galway,
240 Waterford); and sites where a given wet-spell length is more likely than the same length dry-
241 spell (Armagh, Birr, Cappoquinn, Foulkesmills, Killarney, Roches Point, Shannon, Valentia).
242 Across all sites and 100-year simulations, the longest dry-spell was generated for Dublin and
243 persisted 24 seasons (not shown in Figure 7). This might appear implausible but Dublin
244 observations contain near unbroken runs exceeding 20 seasons in 1850-1868 (26/36), 1928-
245 1946 (23/36) and 1961-1978 (23/35).

246

5. Discussion

248 Using 1961-1990 as the reference period (and excluding Waterford and Markree Castle for
249 reasons noted above) we found that the longest observed run of below average precipitation
250 persisted 12 seasons at Cork Airport (1905-1911). Noone *et al.* (2015) note that this record
251 was originally constructed by Tabony (1980) using a composite of stations with data prior to
252 1962 based on a lower elevation gauge at University College Cork. This station change is
253 thought to explain lower early seasonal totals and a detected break point in 1958. The break

254 was adjusted by Noone *et al.* (2015) but the same correction factor was applied across all
255 months which could affect dry run persistence for this station.

256 The next longest run lasted 11 seasons at Mullingar (1904-1909) but, again, Noone *et al*.
257 (2015) report break points in 1937 and 1950 that could be due to a station change in the latter
258 case. Correction of the 1950 break resulted in a large downward adjustment, again potentially
259 affecting dry run persistence. The 10 season dry-spell at Belfast (1853-1858) has already
260 been queried, so the longest run now becomes 9 seasons at Ardara (1927-1932), Cappoquinn
261 (1969-1973), Phoenix Park (1903-1908) and Strokestown (1919-1912) (Table 2). The Ardara
262 record is based on a composite of stations with a small amplitude break point in 1983. While
263 Strokestown has been bridged from 1961, the years 1908-1961 represent a stable period in
264 the record (Noone *et al*., 2015). No breaks were detected for Cappoquinn and there are no
265 issues of note from metadata. There are documented station moves early in the record at
266 Phoenix Park but these pre-date the identified dry run and a station inspection in 1903 noted a
267 very clear/open site. Therefore, having accounted for break points, station/instrument changes
268 and reported measurement errors the most credible, conservative upper bound continuous
269 dry-spell length for the IIP network is 9 seasons.

270 Our sub-annual analysis interrogated data that were homogenized at annual scales and thus
271 represents a stringent test of the IIP network. Anecdotal accounts, proxy sources and data
272 from neighbouring regions, all provide a basis for quality assuring our catalogue of
273 widespread multi-year rainfall deficits (Table 1). We find issues with two stations (Waterford
274 and Markree Castle) that were not picked up in the annual homogenisation of Noone *et al*.
275 (2015). While the confounding issues identified by metadata may have negligible effect at
276 annual resolution they can evidently become important when examining long duration
277 rainfall deficits. Additionally, suspicion is raised at Cork, Mullingar and Belfast that high
278 persistence of negative rainfall anomalies may be an artefact of using a single correction
279 factor equally across several months. Both issues arise despite application of best-practice
280 methods for homogenisation and emphasise the need for cautious use of homogenous series,
281 particularly when examining sequences of sub-annual extremes. [Note that snowfall is only a
282 small component of total precipitation across Ireland and thus any underestimation normally
283 associated with snowy climates is a minor concern]. Our analysis shows how metadata are
284 critical for increasing confidence in the authenticity of long-term precipitation indices.

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

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

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

309

6. Conclusions

311 We have investigated the spatial and temporal properties of long-lasting negative rainfall
312 anomalies across the Island of Ireland at site and regional scales with half-year granularity.
313 Our aim was to create the first coherent picture of multi-season rainfall deficit occurrence and
314 persistence across the region and, in the process, subject the IIP network to stringent
315 appraisal. Our preliminary analysis has highlighted the immense value of carefully

316 cataloguing station meta-data – an essential resource for interpreting break-points and
317 exceptional runs of below/above average precipitation. We acknowledge that interpretations
318 of spatial patterns are hindered by the sparse and uneven distribution of sites, as well as by
319 the range of issues picked up by meta-data, so we were restricted to describing three types of
320 spell-length regime. Further work is needed to determine whether these regimes form
321 coherent clusters in space.

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

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

342 We have only begun to speculate about the underlying physical drivers of dry-spells lasting 5
343 or even 10 years. This is an area of active research, not least because of the potential to apply
344 such insights to long range drought forecasting (Folland et al., 2015; Kingston et al., 2015).
345 Assembling homogeneous meteorological records from paper and digital records (with
346 accompanying meta-data) is a laborious but critical part of this process. Creation of the IIP
347 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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459 **Tables**

460

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

Period	Number of seasons		
	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

464

465   **Table 2** Observed maximum dry-spell duration (seasons) compared with simulated mean
466   160- and 100-year events at each site as well as for IIP, NIP, EWP and SP. Likelihoods of a
467   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

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470 **Figures**

471

472 **Figure 1** Map of station locations
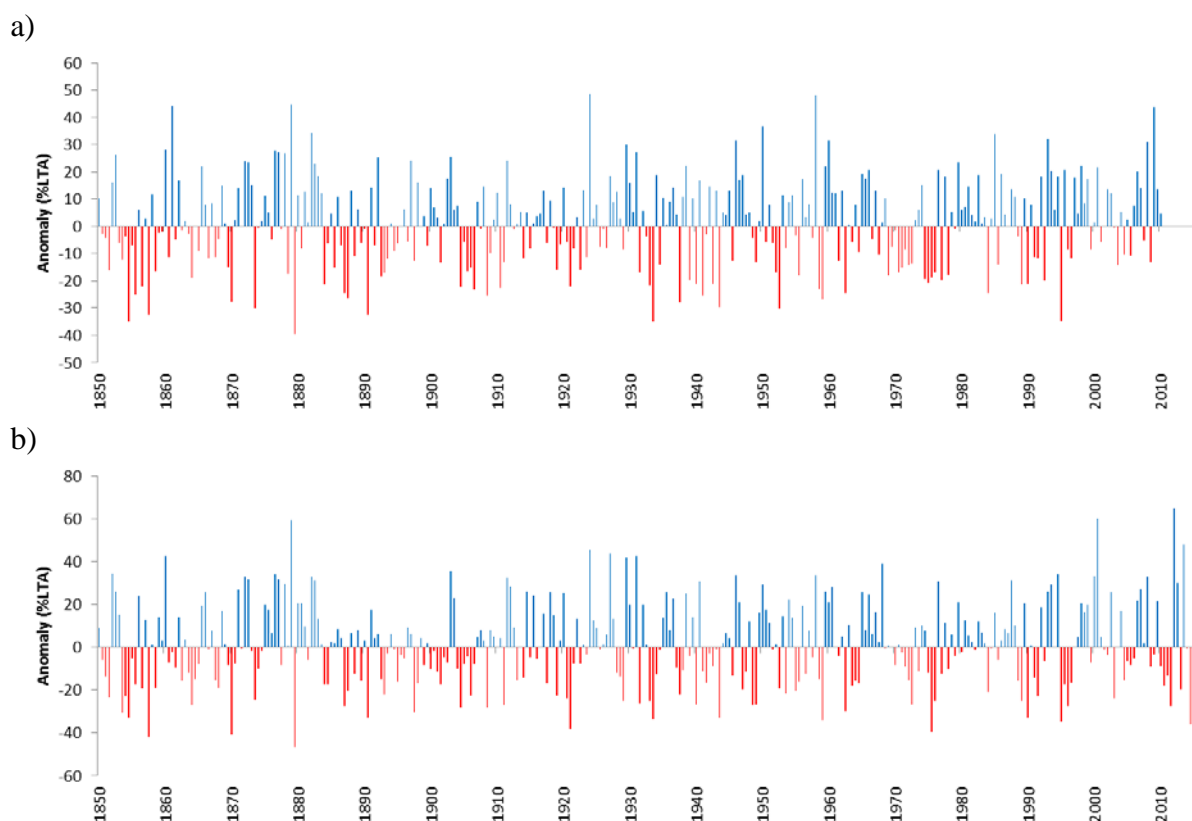
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a)

b)

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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.
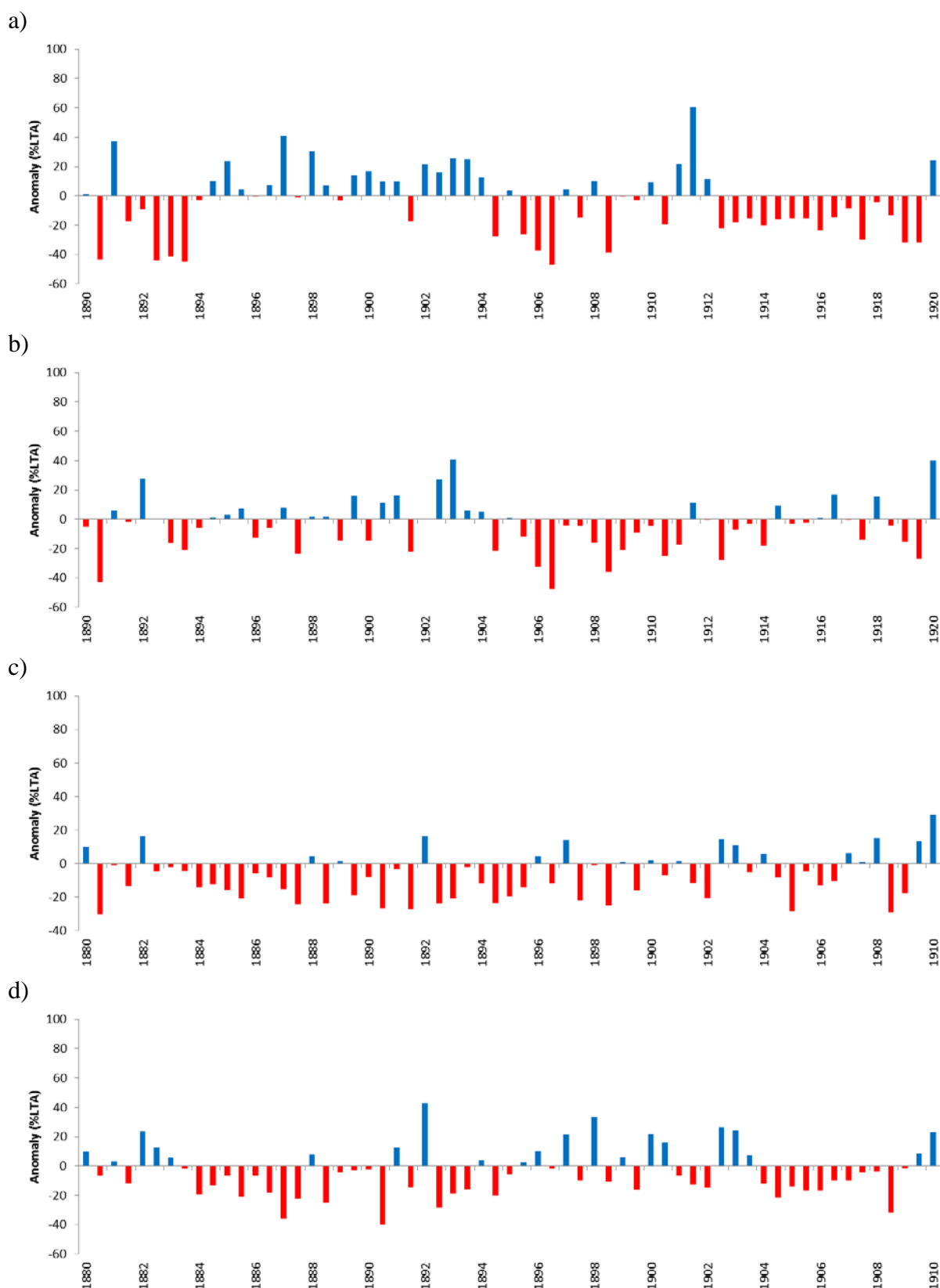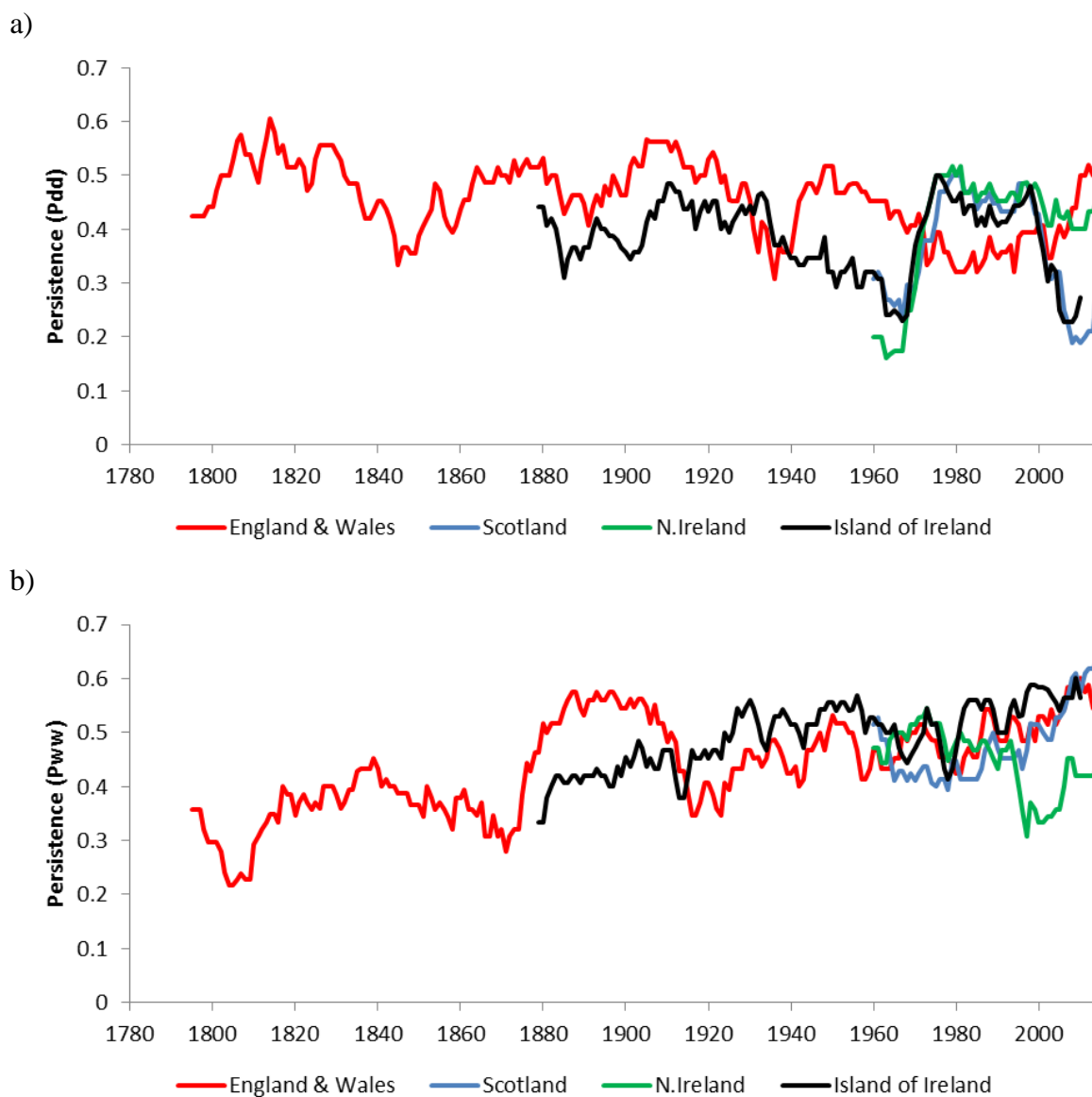
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a)

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c)

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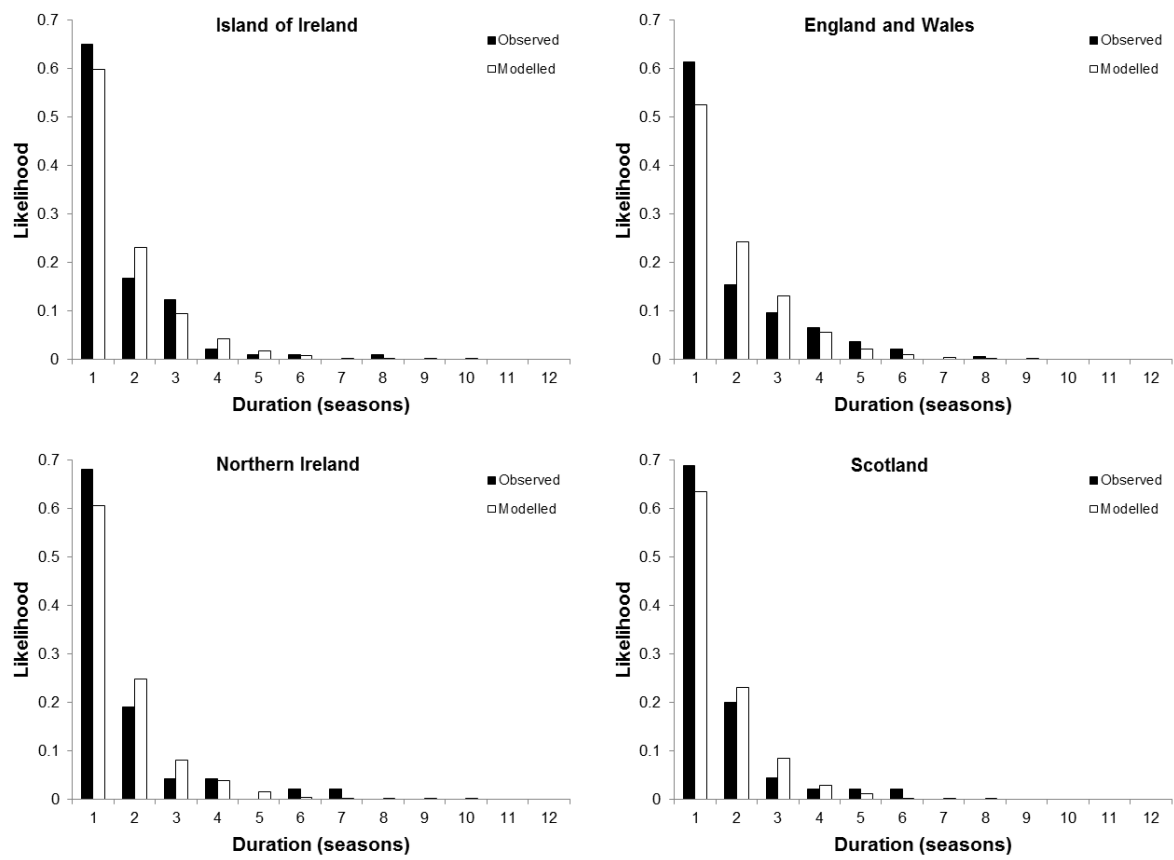
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486   **Figure 4** a) Dry-to-dry (Pdd) and b) wet-to-wet (Pww) season persistence for the Island of
487   Ireland, Northern Ireland, England and Wales, and Scotland. All series are based on 30-year
488   moving windows with anomalies referenced to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

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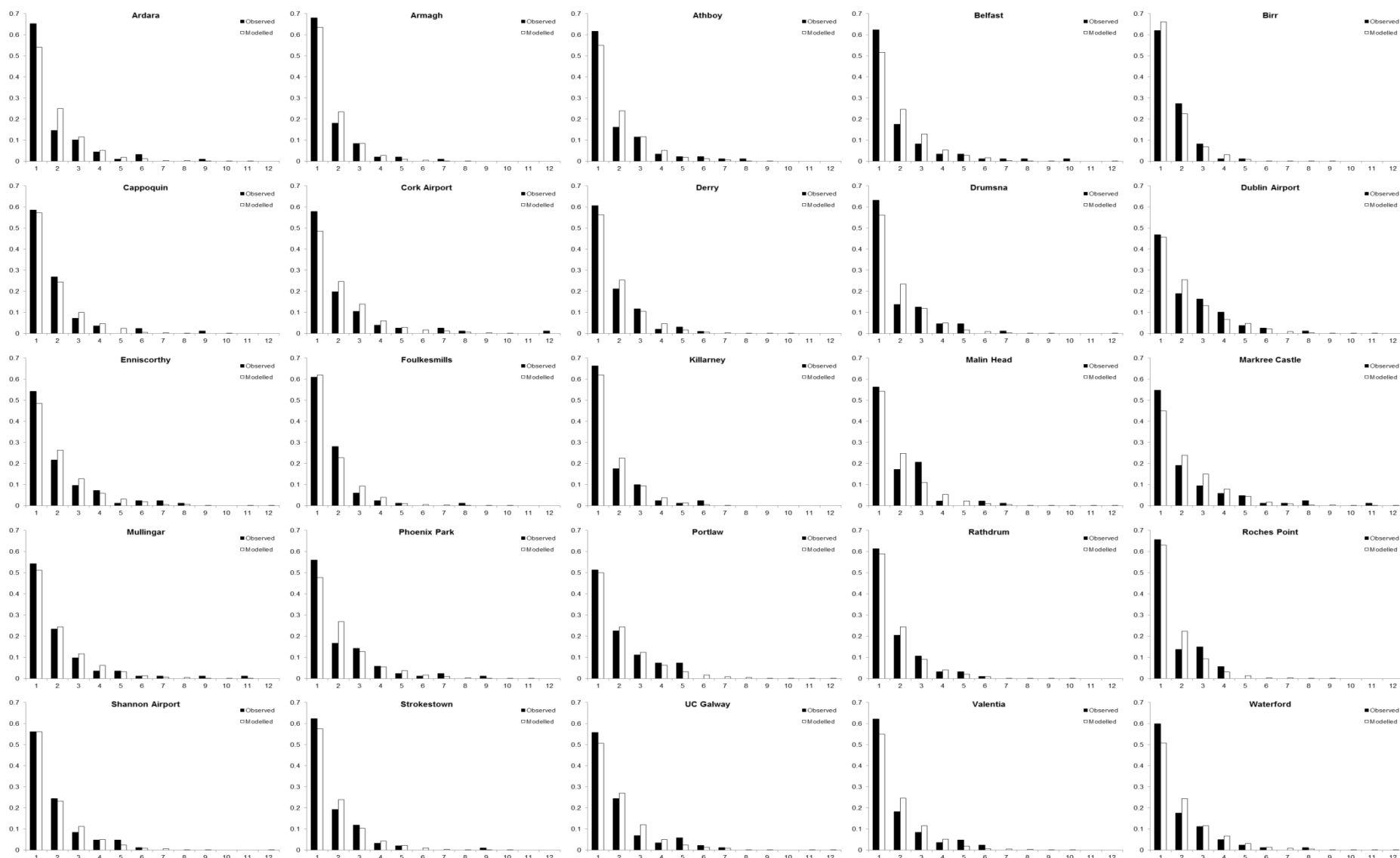
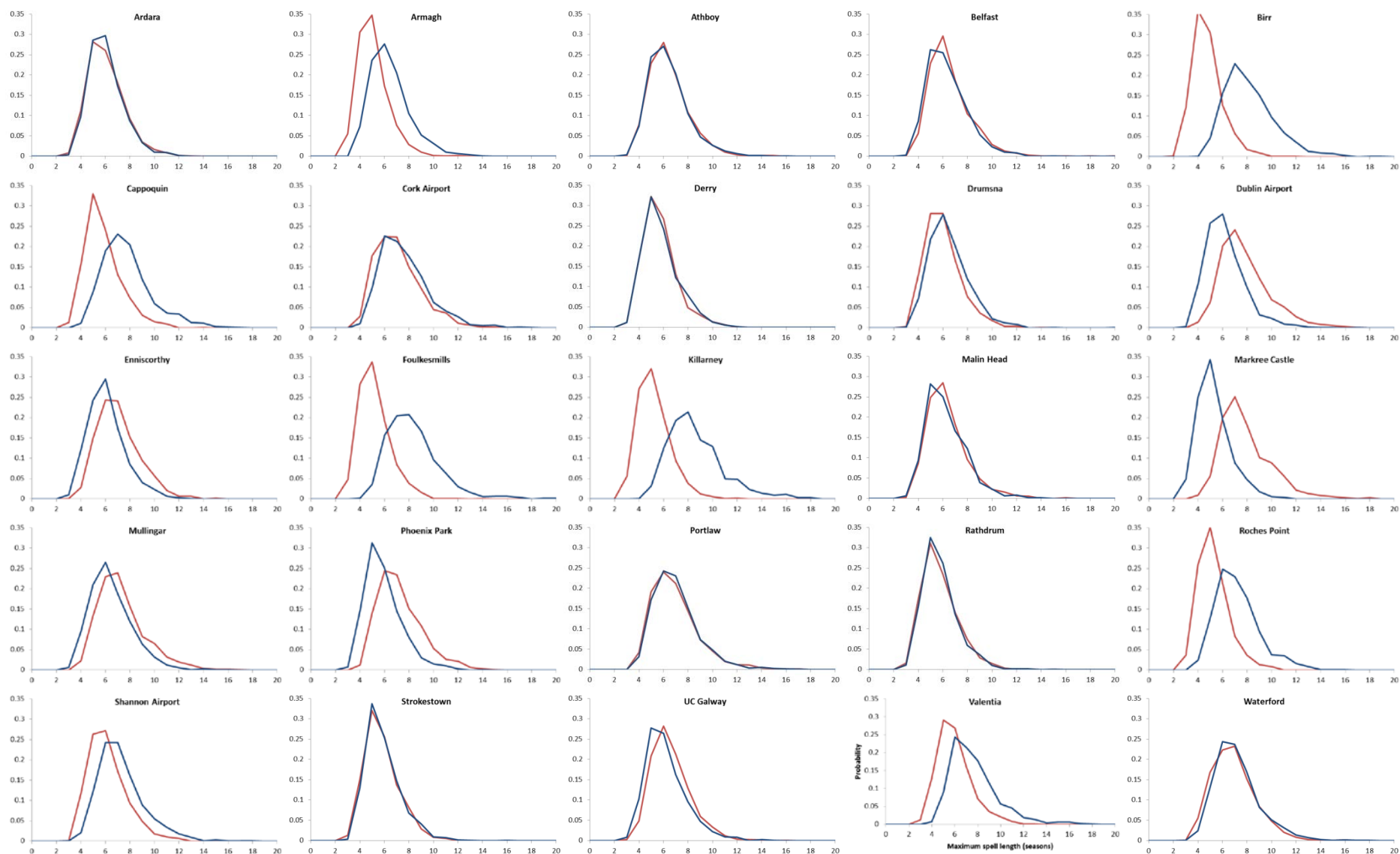**Figure 6** As in Fig.5 but 25 sites across the Island of Ireland.

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