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Short duration rainfall extremes in Ireland : influence of climatic variability

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Abstract

A widely-noted change in the North Atlantic circulation in the 1970s affected the spatial distribution and seasonal pattern of rainfall over Ireland. To examine if this was accompanied by a change on short duration precipitation extremes, multidecadal time series from the second half of the twentieth century of thirteen hourly precipitation stations in Ireland have been analysed for the occurrence of extreme values over several durations of up to 24 hours. Strong evidence was found for a change since the late 1970s in short duration rainfall depths, particularly in the west of the country. Precipitation depth-duration- frequency analyses over two sub-periods showed that at several locations, storm event magnitudes which corresponded to a 30 year return period before 1975 had a return period close to 10 years in the post-1975 period. The widespread increase in spring and autumn rainfall and the local increases in the frequencies and magnitudes of severe rainfalls have implications for engineering hydrology, flood risk analysis and water resources management. The necessity of using up-to-date data to derive design storm magnitudes is stressed, due to the possible influence of underlying climatic shifts. Furthermore, as non-stationarity has been demonstrated, the use of long timeseries extending beyond thirty years into the past will result in underestimation of storm intensities in many areas.

Keywords: Precipitation extremes; climate; nonstationarity; depth-duration-frequency; North Atlantic Oscillation.

1 Introduction

Annual precipitation totals in the Northern hemisphere midlatitudes showed an increasing trend in the twentieth century (Alexander et al., 2006). The global hydrologic and energy cycles are interlinked, therefore changes in the energy balances of the surface and troposphere result in changes to global mean evaporation and precipitation (Previdi and Liepert, 2008). Anthropogenic factors such as the decrease in abundance of atmospheric aerosols and increases in greenhouse gas concentrations observed in recent decades therefore have the potential to affect global precipitation, as well as surface and tropospheric temperature. Comparisons of global climate model simulations run with and without human influences have suggested that the increase in midlatitude precipitation recorded during the twentieth century was mainly due to anthropogenic factors and was unlikely to have been solely due to natural variability (Zhang et al., 2007; Previdi and Liepert, 2008). Satellite observations since 1987 have shown that, as global temperatures have increased, global mean precipitation has increased in parallel at a rate of 7.4 ± 2.6 % per ° C (Wentz et al., 2007).

Changing seasonal precipitation patterns have been accompanied by increases in the incidence of short duration, heavy rainfalls in many regions of the world and often it is these increases that are of the greatest concern (Trenberth et al., 2007; Peterson et al., 2008). An extreme rainfall event may be defined in relation to a reference distribution, for example the 90th percentile of rainday amounts. Alternatively, a probabilistic approach can be taken, defining event magnitudes by their expected recurrence interval or return period, which is the method employed here. Extreme precipitation events of short duration are hazardous to the built and natural environment, leading to flooding, degradation of water quality, overwhelming of drainage and waste water treatment facilities, increased emissions of greenhouse gases from saturated soils, and impairment of ecosystem functioning (White, 2001; Leahy et al., 2004, 2008; Jentsch and Beierkuhnlein, 2008). Extreme rainfalls can also contribute to soil erosion, and in countries with peatlands, such as Ireland, the destabilisation of large masses of peat on hillslopes may be triggered by heavy rain events, resulting in landslides and consequent pollution of surface waters (Dykes and Warburton, 2008).

Changes in regional atmospheric circulation patterns may affect local incidences of extreme precipitation as well as seasonal or annual rainfall totals (Queralt et al., 2009). The North Atlantic Oscillation (NAO) is a periodic change in the north-south differential in normalised mean sea level pressure between Iceland and the Azores and influences moist westerly airflows from the Atlantic to Europe (Visbeck et al., 2001). Scaife et al. (2008) related changes in incidences of temperature and precipitation extremes over Europe in the late twentieth century to a change in the seasonal strength of the NAO. The NAO and related large-scale circulation indices such as the Eastern Atlantic Oscillation have been proposed as drivers of climatic variability over Ireland (Murphy and Washington, 2001; Butler et al., 2007). Other periodic variations in Irish climate have been identified, for example Butler et al. (2007) used wavelet analysis to identify a 22-year cycle in seasonal rainfall and surface temperatures, ascribed to solar activity, and Mayes (2000) noted that the NAO is itself influenced by large-scale temperature patterns.

A recent reanalysis of long-term United Kingdom precipitation measurements has shown an upward trend from 1904, with the strongest rise occurring between 1970 and 1990, and a change in seasonal distribution of extreme precipitation events in most regions (Maraun et al., 2008). Work by Pauling and Paeth (2007) has shown that the mean winter precipitation over Ireland was higher in the period 1951-2000 than in the previous 450 years, and that the occurrence of extreme wet and dry winters also increased during this period. Allan et al. (2009) used British and Irish surface air pressure records to derive a record of severe storms between 1920 and 2004, and found a correlation between the incidence of severe storms in the January-March season and the NAO, but the strength of the correlation fluctuated on a decadal scale, from almost zero in 1950-1970 to a maximum value in 1970-1990. The strengthening of regional gradients of rainfall across Britain during the 1980s and 1990s has been noted to be coincidental with a more positive winter NAO and the associated increase in occurrence of westerly circulation patterns (Mayes, 2000). In Spain, Queralt et al. (2009) found regionally variable NAO influence on rainfall totals, extremes and frequencies.

Within Ireland, there are spatial variations in precipitation receipt which can be related to varying regional occurrence of different synoptic-scale airflow types, mean trajectories of storm tracks, and to local topography (Sweeney and O'Hare, 1992). Two studies combining observational and instrumental records of high wind events in Ireland showed an increase in storm occurrence in Dublin and Armagh during the 1970s and 1980s, and a decrease thereafter (Sweeney, 2000; Hickey, 2003). These studies also noted that trends of storminess in the last three decades of the twentieth century were spatially variable, with locations in the northwest of the country (Belmullet and Malin Head) registering an increase, and stations in the south and east (Armagh and Valentia) registering a decrease.

Kiely (1999) noted increasing annual precipitation and occurrence of extreme precipitation events in Ireland during the second half of the 20th century, particularly in the west of the country, with a change point evident in the mid-1970s. A change in the seasonal distribution of precipitation was also observed, coincident with a change in the seasonal pattern of the NAO, which has been widely noted (Werner et al., 2000; Visbeck et al., 2001). Regional climate model simulations for the period 2021-2060 have predicted an increase in extreme precipitation events, particularly in the southwest of the country (Steele-Dunne et al., 2008).

In the study of extreme rainfall events, a particular duration of interest, often referred to as an aggregation level, is first identified. The aggregation level depends on the hydrological response time of the system of interest, and has a lower limit of the time resolution of the available rainfall records. Aggregation levels measured in minutes or hours are suitable for design of sewers or for the study of small catchments. For studies of large catchment systems durations of several hours or days are of interest. A return period can be assigned to a rainfall event of a particular magnitude over a chosen duration. The return period may be calculated either through examination of annual maxima (AM) of precipitation at the chosen aggregation level, or using the peak-over-threshold method, also known as the partial duration series (PDS) method (Madsen et al., 1997). The PDS method is preferable to the AM method, particularly if return periods of less than 10 years are of interest, as the former preserves more extrema from the original time series (Willems, 2000). The concept of the return period is widely used in order to specify design storms, i.e. a system can be engineered to handle a 30-year storm, which is a storm of a magnitude expected to occur on average once every 30 years. However, any non-stationarities or trends in the underlying climatological regime may lead to over- or underestimation of design storm magnitudes (Ntegeka and Willems, 2008; Milly et al., 2008). The relationship between precipitation depth, event duration and occurrence frequency can be concisely described by an depth-duration-frequency (DDF) relation. Adamowski et al. (2009) used AM series of rainfall over several decades from stations in Ontario, Canada to examine the effect of underlying trends on precipitation DDFs and found that stations which exhibited increasing trends in annual maxima had apparently higher event intensities than stations without trends, particularly at the shorter aggregation levels.

In this study hourly precipitation records from thirteen sites through Ireland (Table 1) were examined with respect to: (a) interannual variability of total precipitation; (b) interannual variability of seasonal distribution of rainfall; (c) depth-duration-frequency (DDF) relationships for events of up to 24 hours' duration.

The study aims to examine the long-term variability of extreme rainfalls over Ireland under changing patterns of the North Atlantic circulation and seasonal precipitation distribution. A second aim is to study the effects of shifts in underlying patterns of rainfall extremes on calculated event return periods and DDFs.

2 Data

The thirteen hourly rainfall measurement sites are operated by Met Éireann, the Irish meteorological service, and are geographically dispersed throughout the Republic of

Ireland (Fig. 1 & Table 1). Ireland has a temperate maritime climate, and seasonal variation in surface air temperature is low ($\sim 10^\circ$ difference between mean January and July temperatures) due to the proximity of the Atlantic Ocean (Rohan, 1986). The topography is characterised by coastal mountain ranges surrounding a low-lying central plain. Rainfall was measured by the standard Met Éireann gauge with a funnel-shaped collector of 127 mm diameter (Rohan, 1986). The digitised rainfall records used for this study commenced at various times after 1939 (Table 1). For consistency only data from 1957 to 2008, which were available from almost all of the stations, were analysed. The records from Cork Airport and Casement commenced in 1962 and 1964 respectively, but are included in most of the analyses as they improve the spatial coverage. The record from the Knock station, which commenced in 1996, was considered too short to be useful for this study. The accompanying metadata indicated no changes in siting of stations during the records, although several stations were automated during the 1990s and subsequently no longer continuously attended. Seasonal values of the SW Iceland-Gibraltar NAO index were obtained from the formulation of Jones et al. (1997). Updated values of the index were downloaded from the internet site maintained by the University of East Anglia's Climatic Research Unit (2008).

3 Statistical Methods

An area-weighted time series of total annual precipitation was generated for the period 1965-2008, using the Thiessen polygon method and is presented in Fig. 2. The time series of annual total precipation from each station and the area-weighted precipitation were tested for the presence of a change point using the Pettitt-Mann-Whitney test (Pettit, 1979) and the cumulative sum method. A limitation of such tests is that they are capable of detecting a maximum of one change point, and do not deal well with autocorrelations or periodicities in the test series (Reeves et al., 2007). For the annual rainfall series under consideration here, autocorrelation and periodicity are unlikely to pose problems, but the presence of multiple change points cannot be ruled out. The cumulative sum test was bootstrapped to generate confidence intervals (Efron and Tibshirani, 1993), see the Appendix for further details. When near-contemporaneous change points were detected in a majority of rainfall series, all series were divided into two subseries corresponding to the periods before and after the common change point and the subsequent DDF analyses were performed on each subseries as well as on the full series.

Rainfall totals were calculated over 1, 3, 4, 6, 8, 12, 18 and 24 hour aggregation levels. These levels were chosen to cover a range of rain events from brief, convective storms of the order of one hour duration to moving frontal depressions delivering rainfall from several hours up to a day, and also to be useful for engineering purposes, from storm drain design (up to one hour) to fluvial flood mitigation measures (at the longer durations). For each duration only independent (i.e. completely non-overlapping) events were considered. The top 200 events of each duration category were then selected and ranked by magnitude. When change points were in annual precipitation amounts were detected by earlier analyses, this exercise was repeated for each time range (full time range, before change and after change). For brevity, only the top 20 results for selected intervals from the full Valentia record are presented here.

The distribution of the extreme values of a quantity x, above a certain threshold value, may be described by a Generalised Pareto (GP) distribution (Picklands, 1975). This distribution has been widely used to describe extremes of precipitation, e.g. Svensson et al. (2007); Ntegeka and Willems (2008); Muller et al. (2009); AghaKouchak and Nasrollahi (2010).

$$G(x) = 1 - \left(1 - \xi \frac{x}{\beta}\right)^{-1/\xi} \quad (\xi \neq 0; x > 0) \tag{1}$$

The shape of the GP distribution $G(x)$, Eqn. 1, is defined by the values of the shape parameter ξ and the scale parameter β, and the exceedance x is constrained to positive values. The behaviour of the tail of the distribution is governed by the value of ξ, with positive values indicating a heavy tail, or a higher frequency of extreme values than the exponential distribution. If ξ = 0, Eqn. 1 becomes the exponential distribution.

$$T_r = \frac{n}{t(1 - F(x))} \tag{2}$$

The return period, T_r, is defined by Eqn. 2, and is specified in years; n is the length of the precipitation record in years; t is the number of extrema used to derive the distribution; $F(x)$ is the distribution of extreme values.

The suitability of a particular extreme value distribution for describing an observed series of extrema can be visually and analytically examined by the use of a quantile-quantile or Q-Q plot, in which the theoretical quantiles of an assumed distribution are plotted against quantiles of the observed events. If the relationship between the empirical and theoretical values remains linear for even the largest observed values, then it is an indication that the chosen theoretical distribution is an accurate description of the tail behaviour of the empirical distribution. Examples of Q-Q plots are shown in Fig. 3 where quantiles of an exponential distribution are plotted against observed extrema for four different aggregation levels at the Belmullet, Mullingar and Valentia stations.

Finally, precipitation depth-duration-frequency curves were computed for several locations compared across the three time ranges (full series, pre-change point, post-change point). The PDS approach was used to derive DDFs over the specified aggregation levels. Routines developed in the Matlab programming environment (Mathworks, USA), including functions from the Matlab statistical toolbox and the EVIM toolbox developed by Gençay et al. (2001) were used to fit GP distributions to the observed distributions of extreme values over defined depth thresholds, x_t, for each aggregation level. The value t is referred to as the order of the threshold, and corresponds to the position of the threshold rainfall amount in the ranked list of extrema.

The threshold was separately determined for each aggregation level. A methodology based on the stability of the Hill estimator of the GP shape parameter ξ (Eqn. 3) with increasing threshold order was developed to select the optimal threshold in each case (Hill, 1975; Gençay et al., 2001). Firstly, the PDS were ranked in descending order by magnitude, then the Hill estimator was calculated for each value of the threshold order t, increasing from one (highest threshold amount) to 200, the final value in the PDS (lowest threshold amount). The optimal threshold is deemed to be that value where the Hill estimator becomes stable with increasing t. In this case, stability was determined by calculating the coefficient of variation of $\hat{\xi}$ (ratio of $\sigma_{\hat{\xi}}$ to $\bar{\hat{\xi}}$) within a moving window of nine orders, scanned across the Hill plot (Fig. 4). The optimal threshold is determined to be the central value of the first window where the coefficient of variation is less than 1%. Although the value of 1% and the window size are arbitrary choices, the method was found to converge well across all the series. After identification of the optimal threshold, the GP distribution was recalibrated to the truncated PDS using maximum likelihood estimation. The Hill estimator of ξ is defined as:

$$\hat{\xi} = \frac{1}{t-1} \sum_{i=1}^{t-1} \ln{(x_{i,N})} - \ln, (x_{t,N})\, (t \geq 2) \tag{3}$$

where N is the sample size.

The results of the PDS analyses were used to derive the DDFs for return periods of 10 and 30 years. For the purposes of illustration, continuous DDF curves as a function of aggregation level D were fitted using a logarithmic function after Stalmann and Pecher (1985):

$$x(D) = u_p + w_p \ln{(D)} \tag{4}$$

where x_n is the precipitation depth (in mm) corresponding to a return period T_r (years) and u_p, w_p are parameters determined by curve fitting.

4 Results and Discussion

4.1 Interannual variability of NAO and annual and seasonal precipitation

The series of winter (December-February) values of the NAO index values (1950-2000; Table 2) exhibited a change point at 1980 with greater than 95% probability (from the cumulative sum test), The Mann-Pettit-Whitney test, which tended to return more conservative probability estimates, indicated a change at 1979, with just 87% probability.

Both tests revealed significant change points in the time series of annual total precipitation from several of the stations (Table 2). Measurement stations on the west coast had the strongest evidence ($P >$ 0.95) of change points: Belmullet, Claremorris, Malin Head and Valentia. Of these stations, the change points occurred between 1975 and 1978, with the exception of Belmullet, where the change point year was determined to be 1983. A very high ($P >$ 0.99) probability was associated with the Belmullet and Valentia change points. No significant change points were detected for stations in the remainder of the country, or for the Shannon station which is near the west coast.

Examination of the post-1975 change in rainfall amounts (Table 3) reveals that the change is largest in several stations on the western seaboard (*i.e.* Belmullet, Claremorris and Valentia), and is less evident for inland stations or stations near the east coast. The seven highest annual Valentia precipitation totals for the entire measurement period occurred after 1975, and are listed in Table 4. The five lowest annual totals occurred before 1975. Although average total annual rainfall for some stations was almost the same before and after 1975, all stations recorded an increase in mean rainfall depth for the April-June and July-September seasons. Percentage changes for the months of March and October were positive for all stations, and almost all stations, with the exception of three stations on the west coast, showed a decrease in July rainfall after 1975. The decrease was most pronounced in the midlands, east and southeast.

4.2 Precipitation depth-duration-frequency

The method of identifying the optimal threshold for fitting GP distributions typically selected orders in the range 40-160, with a reduction in threshold order with increasing aggregation levels (e.g. Figs. 4, 5), indicating that fewer extrema were needed to fit distributions at higher aggregation levels. From examination of the parameters of the fitted GP distributions, in most records ξ values were around 0.2 for lower aggregation levels, declining to less than 0.1 at the higher aggregation levels, and becoming negative in some cases. This general pattern of decreasing ξ with aggregation level indicates that the tails of the fitted GP distributions become less fat as the aggregation level increases. The values of β tended to increase with aggregation level up to 12 hours and remain relatively constant thereafter. The example shown in Fig. 5, based on Valentia data, is typical, with a high order (low threshold rainfall) for the one hour level and lower orders thereafter. The shape parameter ξ is reasonably constant with increasing aggregation level in this case, with two higher values returned at the 6 and 24 hour aggregation levels. It is therefore possible that storms of different synoptic origins are responsible for rainfall events over different durations at this location.

The highest 24-hour event magnitudes, of up to 117.6 mm, were recorded at the Valentia station (Table 4). The highest magnitudes of 24-hour rainfall events were much lower at several non-coastal stations (e.g. Birr: 61.0 mm; Kilkenny: 66.4 mm, Clones: 76.8 mm). However, no clear spatial pattern emerges, with some stations on the western coast exhibiting lower values and high values at some eastern stations. When the records were split into two periods, separate depth-duration-frequency analyses showed an increase in storm event magnitude for return periods of 30 years at some stations after 1975 (e.g. Valentia, Dublin Airport and Belmullet), and decreases at other stations, notably Claremorris (Table 5). For many stations the changes were small ($<$ 5 mm) at all aggregation levels (see Fig. 6 for a set of sample DDF curves) and in the case of two locations there was insufficient pre-1976 data to reliably calculate the 30 year event magnitude.

Kiely (1999) used rainfall records up to 1995 to calculate that a storm at Valentia with a 10 year return period post-1975 was of the same magnitude as an event with a 30 year return period pre-1975. This study, with over 10 years of additional observations now available, reinforces this result. The DDF analyses of the Valentia observations shows that rainfall events of duration five hours or longer with a 10 year return period in the post-1975 record are almost as large as similar magnitude to events with a 30 year return period in the record up to 1975 (Fig. 7). A similar change is evident at Dublin Airport in 1975. By contrast, the DDF relationships for Malin Head remain almost unchanged after 1975 and there is little change in the Belmullet or Casement (not shown) DDF curves, despite the latter station's proximity to Dublin Airport. A spatial pattern of a east to west gradient of increasing variability since 1975 might be reasonably expected given the typical northwestward trajectories of Atlantic storms, which make landfall on the west coast, where the local topography then precipitates rainfall. However, as with the results of the Canadian study on trends and short duration extremes of (Adamowski et al., 2009), the spatially variable results presented here show that the change in frequencies of extreme events cannot be simply described in this manner. Local variations in factors such as exposure or orography may be responsible for some of the differences in precipitation receipt between stations, for example Shannon is less susceptible than other western locations to incoming southwesterly rain storms as it is shielded by elevated areas to the south.

For all the aggregation levels examined in the Valentia event analysis, more than half of the twenty largest events occurred after 1975 (Table 4). For the longer durations, post-1975 events occupy most of the topmost rankings (e.g. all five largest 12, 18 and 24 h events occurred in the period after 1975.)

5 Conclusions

A remarkable increase in March and October rainfall occurred in 1975 across the entire study area, and a corresponding decrease in July rainfall occurred at all but three stations. These changes are contemporaneous with a noted change in the December-January-February value of the NAO index. These results notwithstanding, changes in short duration rainfall extrema in Ireland over the last half century show considerable spatial variation. In general, annual totals and seasonal distributions of rainfall have changed most in the west and northwest. However, increases in frequency and magnitude of extreme rainfalls do not always coincide with increases in annual total rainfall. For example, the Dublin Airport station in the east has shown increased storm frequency and severity since 1975, while the Malin Head station in the extreme northwest has shown almost no change. The mid 1970s change point in precipitation observations remains the most significant change in the extended records.

These findings highlight the importance of considering local post-1975 records when analysing flood risk, designing storm drains or planning water resources management schemes in Ireland. Engineers should also reassess the adequacy of existing infrastructure, given the changes in rainfall depth-duration-frequency in recent decades. Particularly in the west of the country, the main risk appears to be due to increases in spring and autumn rainfall coupled with, in some locations, increased storm severity and frequency. The combination of increases in seasonal precipitation receipt and short duration extremes is of particular concern, because heavy antecedent rainfall over several weeks can affect how catchments respond to short duration extreme events, leading to greater risk of flooding or events such as peat slides.

It is often presumed that, for the purposes of estimating design storms for engineering works, the longer the dataset, the more accurate the result. These results demonstrate that this is not necessarily the case when the underlying climatic regime is non-stationary. Over much of the area studied here, using longer precipitation time series, dating back to periods before the mid-1970s may actually result in a considerable underestimation of storm magnitudes for a given return period.

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Appendix : Bootstrapped change point test

N versions of the time series, randomly resampled (with replacement) from the original series with replacement were created for this purpose. For a series of n observations, the series of cumulative sums, S_i (Eqn. A.1), was calculated for the original time series and then compared against cumulative sums for the N resampled series, where N = 10,000. Each S_i is calculated over the partial series of x, from 1 to the value of the index i. The mean of the complete series is denoted by $\bar{x}$.

$$S_i = \sum_{j=1}^{i} (x_i - \bar{x}), i = 1 \mathinner{..} n \tag{A.1}$$

The estimator $S_\triangle \equiv$ (max(S) - min(S)) (where S is the value of the cumulative sum) was used to generate confidence intervals for the change point. The value of the estimator for the original time series, $S_{\triangle,0}$, is compared against the estimator values, $S_{\triangle,k}$, for the N versions of the resampled time series (Eqn. A.2). A confidence estimate, P, is defined as the ratio of the number of instances of $S_{\triangle,k}$ of the resampled series exceeding the $S_{\triangle,0}$ of the original series to N (Eqn. A.3.) P is analogous to the probability of detection of a change of the strength detected in the original series, $S_{\triangle,0}$, by chance, in resampled realisations of the same series.

$$\phi_k = \begin{cases} 1 & (S_{\triangle,0} \quad > \quad S_{\triangle,k}) \\ 0 & (S_{\triangle,0} \quad <= \quad S_{\triangle,k}) \end{cases} \tag{A.2}$$

$$P = \frac{\sum_{k=1}^{N} \phi_k}{N} \tag{A.3}$$

For each station, change point tests were carried out on the series of annual total precipitation and for each of the twelve multi-annual series of monthly total precipitation.

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Station	**Latitude** ° ′ N	**Longitude** ° ′ W	**Elevation** m a.s.l.	**Start**	**Distance from coast** km
Belmullet	54°14′	10°0′	11	1957	< 5
Birr	53°5′	7°53′	73	1955	69
Casement	53°18′	6°26′	94	1964	17
Claremorris	53°43′	8°59′	71	1939	40
Clones	54°11′	7°48′	89	1951	66
Cork Airport	51°51′	8°29′	153	1962	7
Dublin Airport	53°26′	6°14′	68	1942	9
Kilkenny	52°40′	7°16′	66	1957	67
Malin Head	55°22′	7°20′	22	1956	<5
Mullingar	53°32′	7°22′	104	1950	77
Rosslare	52°15′	6°20′	26	1957	<5
Shannon Airport	52°42′	8°55′	14	1946	<5
Valentia	51°56′	10°15′	11	1940	<5

Table 1: Location, elevation, distance from coast and start dates of records for each station.

	C_{cusum}	P_{cusum}	C_{MPW}	P_{MPW}
NAO (DJF)	1980	0.99	1979	0.87
Belmullet	1983	1.00	1983	1.00
Birr	1989	0.70	1960	0.81
Casement	1977	0.75	2005	0.79
Claremorris	1978	0.98	1978	0.97
Clones	1978	0.81	1952	0.71
Cork Airport	1975	0.67	1975	0.39
Dublin Airport	1977	0.49	1944	0.15
Kilkenny	1992	0.55	2005	0.16
Malin Head	1978	0.97	1978	0.94
Mullingar	1978	0.92	1978	0.69
Rosslare	1966	0.39	1957	0.32
Shannon Airport	1976	0.85	1976	0.67
Valentia	1975	1.00	1975	0.99
Area-weighted average	1976	0.99	1978	0.88

Table 2: Change points (C) and probabilities (P) from the bootstrapped cumulative sum (cusum) and the Mann-Pettit-Whitney (MPW) test of the winter (December-February) value of the NAO index, for annual precipitation totals for each measurement station and for the area-weighted annual average precipitation over the entire study area.

	Annual	**JFM**	**AMJ**	**JAS**	**OND**	**March**	**July**	**October**
Belmullet	11	19	4	1	16	37	9	36
Birr	1	13	0	-13	4	33	-20	20
Casement	6	7	4	3	13	26	-10	38
Claremorris	8	22	2	-12	15	46	-12	21
Clones	4	16	0	-7	7	43	-7	19
Cork Airport	4	4	-2	-1	23	30	-7	35
Dublin Airport	1	4	6	-16	12	16	-17	40
Kilkenny	1	4	0	-8	10	35	-17	34
Malin Head	7	21	-1	4	9	30	6	19
Mullingar	4	19	7	-12	6	44	-19	19
Rosslare	1	1	-3	-15	16	17	-25	48
Shannon Airport	4	20	4	-10	6	39	-5	27
Valentia	12	14	11	4	17	36	1	26

Table 3: Percentage change in total annual, seasonal, March, July and October precipitation from pre-1975 to post-1975 period.

	1 hour		**3 hour**		**6 hour**		**12 hour**		**18 hour**		**24 hour**	
Rank	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**
1	24	24	43.8	43.8	56.1	56.1	79.9	79.9	95.7	95.7	117.6	117.6
2	21.1	21.1	36.7	34.2	53.2	53.2	79	79	94.1	94.1	95.8	95.8
3	19.6	18.9	34.2	34.2	49	49	70.5	70.5	86.1	86.1	88.8	88.8
4	18.9	17.2	34.2	32.1	47.9	47.9	64.2	64.2	75.7	75.7	87.8	87.8
5	17.2	16.4	32.1	31.6	46	44.1	62.2	62.2	75.2	75.2	80.9	80.9
6	17.2	15.8	31.6	29.3	44.1	43.7	60.8	60.8	70.9	69.8	79	71.4
7	16.6	15.3	29.5	28.4	43.7	43.4	58.5	54.5	69.8	68.6	71.4	69.9
8	16.5	15.1	29.4	28.3	43.4	42.6	55.1	53.7	68.6	61.7	69.9	66.1
9	16.4	14.7	29.3	28.1	42.6	37.6	54.5	52.5	61.9	60.9	69.9	64.1
10	16.4	14.6	29.2	28	41.2	37.2	53.7	52.4	61.7	60.8	66.1	60.9
11	16	14.3	28.4	27.7	39.8	36.7	52.7	51.1	60.9	55.7	64.9	58
12	15.8	14	28.3	27.2	37.6	36.6	52.5	50.5	60.9	55.6	64.6	56.3
13	15.7	14	28.1	26.8	37.2	36.2	52.4	50.4	60.8	55.6	64.1	56.3
14	15.3	14	28	26.6	36.9	34.1	51.1	50.4	59.7	55.3	62.2	56.2
15	15.2	13.6	27.7	26.4	36.7	34	50.9	48.2	58.3	55	60.9	56
16	15.1	13.6	27.2	26.3	36.6	33.8	50.9	46.6	55.7	54.1	58.5	55.6
17	14.7	13.4	27.1	24.6	36.5	33	50.5	46.4	55.6	53.6	58	55.2
18	14.6	13	26.8	24.5	36.4	32.8	50.5	45.2	55.6	52.4	56.9	54.4
19	14.6	12.8	26.6	24.2	36.2	32.6	50.4	45.2	55.3	51.9	56.7	54.1
20	14.3	12.8	26.4	24.1	34.3	32.2	50.4	45.1	55	51.6	56.3	53.4

Table 4: Ranked highest rainfall amounts (in mm) over 1, 3, 6, 12, 18 and 24 hours from Valentia for (a) the full record (1940-2005) and (b) 1976-2008.

	1957-1975			1976-2008			All		
	lwr	mid	upr	lwr	mid	upr	lwr	mid	upr
Belmullet	42.5	54.8	82.2	54.4	70.0	103.5	52.9	67.3	100.8
Birr	38.2	44.8	56.5	42.9	56.8	85.1	47.1	51.9	83.0
Casement	-	-	-	61.1	88.2	148.1	62.8	82.8	126.8
Claremorris	51.6	76.1	141.6	49.5	58.3	72.6	48.5	66.5	62.7
Clones	42.1	51.6	67.8	45.4	67.9	126.2	50.9	59.9	112.8
Cork Airport	-	-	-	64.6	80.3	110.4	75.4	85.5	112.1
Dublin Airport	46.8	60.3	87.9	57.0	77.6	118.9	63.4	70.2	97.0
Kilkenny	39.1	51.5	86.7	46.2	59.5	96.0	41.6	58.2	92.5
Malin Head	44.9	61.3	98.5	46.5	62.7	106.0	49.9	62.2	98.3
Mullingar	47.2	64.7	103.2	48.4	68.7	124.3	47.0	67.4	114.7
Rosslare	58.3	90.8	177.2	58.8	79.0	123.3	65.4	83.1	125.7
Shannon Airport	42.8	54.9	83.2	41.5	47.2	57.4	38.8	51.4	52.0
Valentia	59.4	70.9	92.0	73.9	99.0	150.2	69.4	89.2	91.3

Table 5: Calculated event magnitudes [mm] for a 30 year return period for the 24 hour aggregation level calculated using pre-1975 data, post-1975 data and the full record. The lower and upper confidence limits (at the 95% level) are based on the maximum likelihood estimates of the GP distribution parameters.

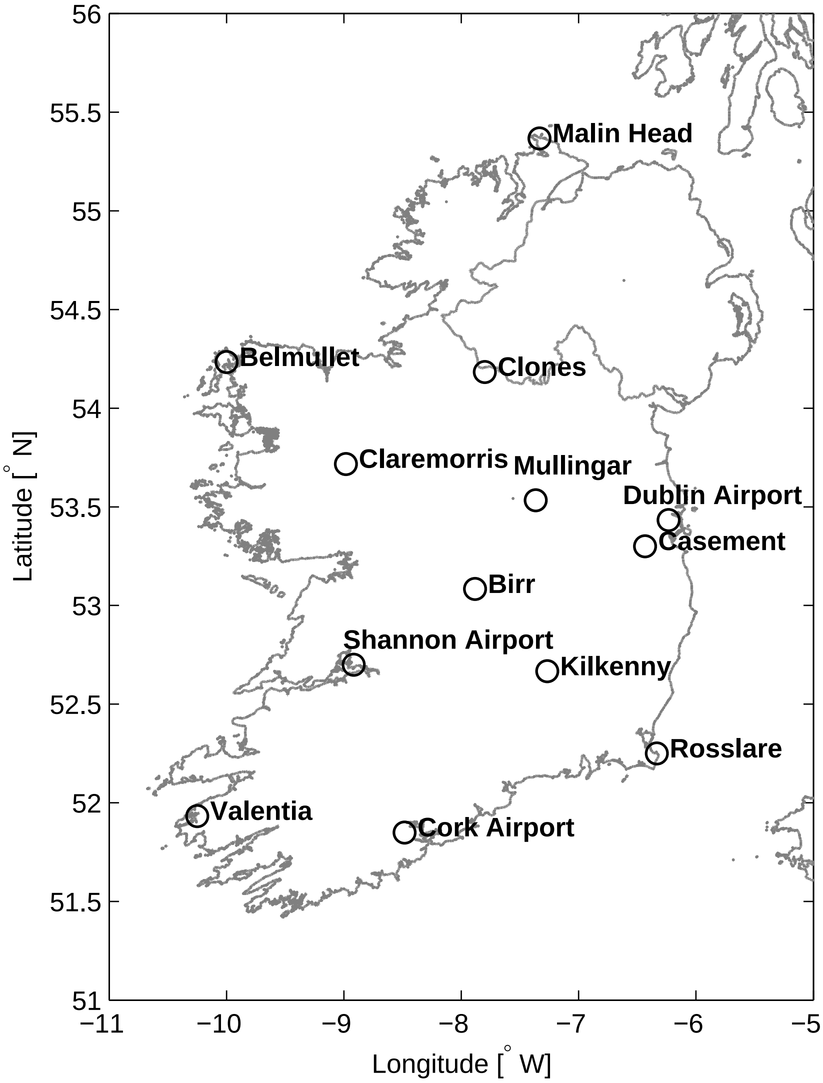

Figure 1: Map of Ireland showing hourly precipitation measurement locations used in this study.

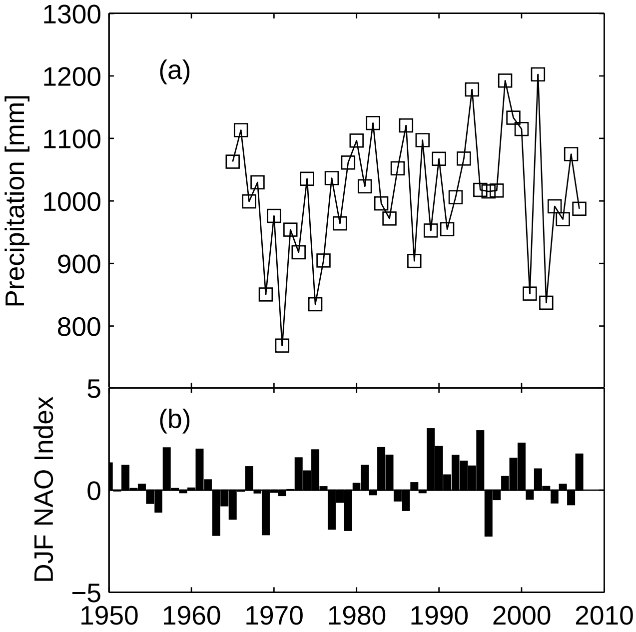

Figure 2: Area-weighted mean annual precipitation (calendar year) and the winter (DJF) value of the NAO index.

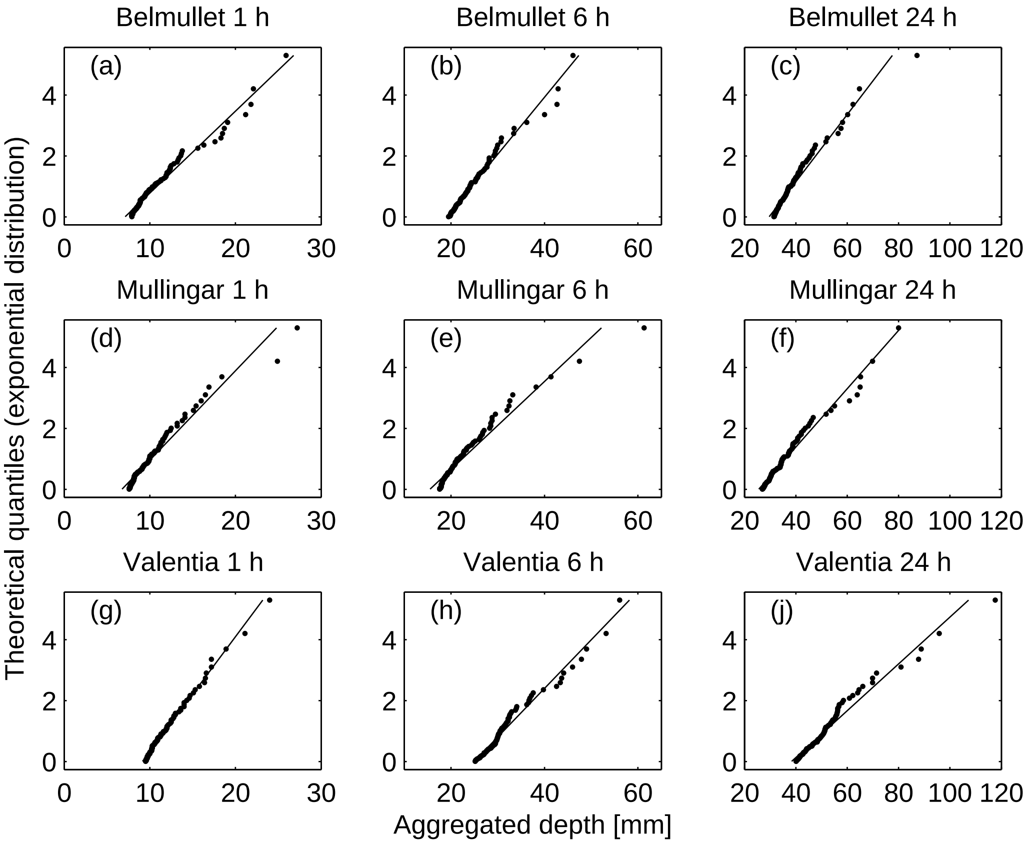

Figure 3: Q-Q plots of quantiles derived from an exponential distribution ($\xi = 0$) against empirical extrema observed at Belmullet, Mullingar and Valentia over aggregation levels of 1, 6 and 24 hours.

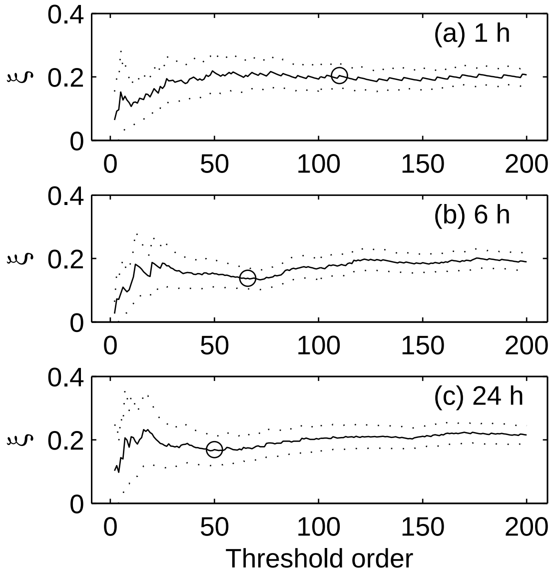

Figure 4: Sample Hill plots of the ξ estimator versus threshold order for three aggregation levels of the Valentia record, indicating the optimal threshold orders (circled).

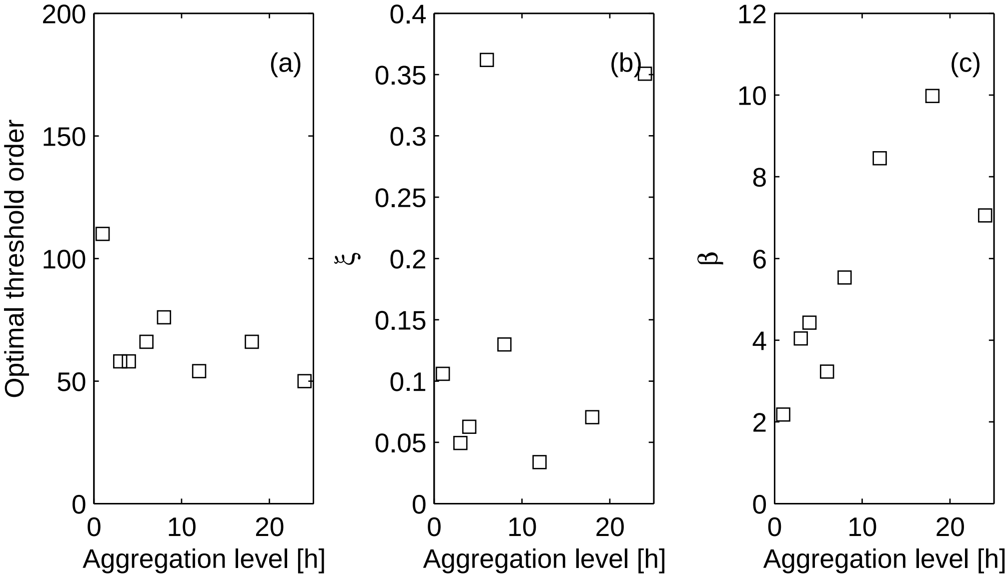

Figure 5: Optimal threshold orders and GP distribution parameters ξ and β versus aggregation level for the post-1975 period data from Valentia.

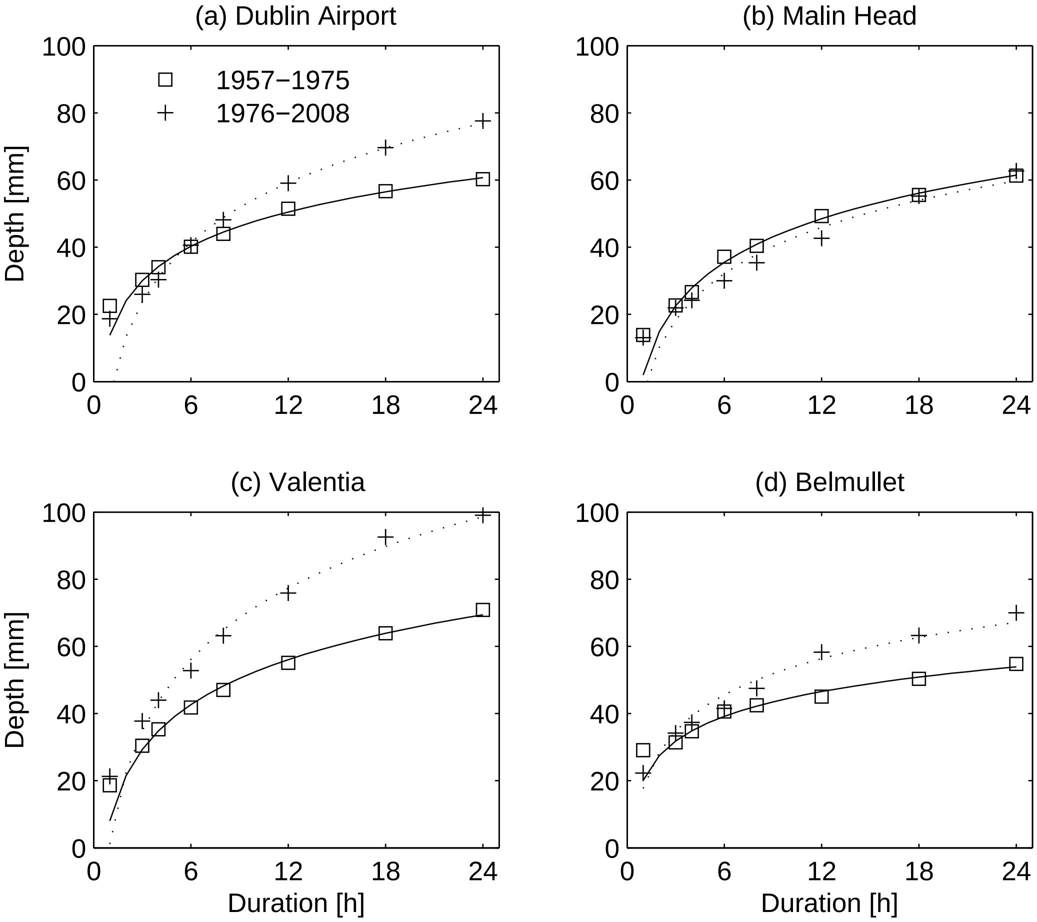

Figure 6: Precipitation depth-duration-frequency curves for a 30 year return period derived from data recorded during the intervals 1940-1975 and 1976-2008 for four stations. The markers show the values of the inverse of the fitted GP functions at the given aggregation levels; the lines show logarithmic fits to the series of inverted GP values.

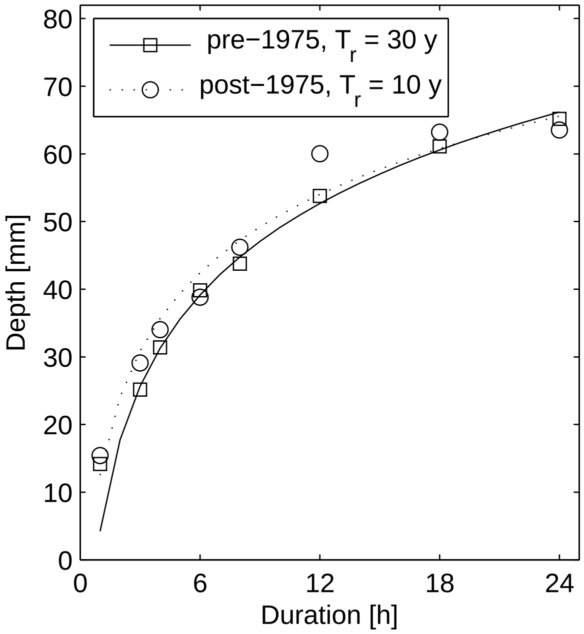

Figure 7: Comparison of DDF curves for 10 year return period events up to 1975 and 30 year events after 1976 at Valentia.