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Climate change in Ireland from precipitation and streamflow observations

G. Kiely [1]

Civil and Environmental Engineering Department, University College Cork, Cork, Ireland

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Abstract

On the basis of General Circulation Model (GCM) experiments with increased CO_2, many parts of the northern latitudes including western Europe, are expected to have enhanced hydrologic cycles. Using observations of precipitation and streamflow from Ireland, we test for climatic and hydrologic change in this maritime climate of the northeast Atlantic. Five decades of hourly precipitation (at eight sites) and daily streamflow at four rivers in Ireland were investigated for patterns of climate variability. An increase in annual precipitation was found to occur after 1975. This increase in precipitation is most noticeable on the West of the island. Precipitation increases are significant in March and October and are associated with increases in the frequency of wet hours with no change in the hourly intensities. Analysis of streamflow data shows the same trends. Furthermore, analysis of extreme rainfall events show that a much greater proportion of extremes have occurred in the period since 1975. A change also occurred in the North Atlantic Oscillation (NAO) index around 1975. The increased NAO since 1975 is associated with increased westerly airflow circulation in the Northeast Atlantic and is correlated with the wetter climate in Ireland. These climatic changes have implications for water resources management particularly flood analysis and protection. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Climate change and its impact on water resources are basic questions that need to be addressed in terms of science and engineering as well as public policy. The Intergovernmental Panel on Climate Change (IPCC [17]) accepts that the Earth is experiencing warming since the late 19th century as well as a small positive (1%) global trend in precipitation over land. However, the IPCC report does not suggest whether natural or anthropogenic factors drive the change or which areas of the globe are likely to experience most change. In an effort to quantify climate change, scientists are investigating many aspects of the climate state variables of precipitation, temperature and sea level pressure. Brutsaert and Parlange [6], Karl et al. [21], on the basis of data analysis, agree that there is an enhanced hydrologic cycle in the last two decades, especially for some parts of the northern hemisphere. Increasing rates of precipitation with increasing rates of evaporation and runoff are the signatures of an enhanced hydrologic cycle. These findings are supported by General Circulation Model (GCM) numerical studies with increased CO_2 (e.g. Manabe [27]).

To detect and quantify climate change, much emphasis has been placed in recent years on the analysis of temperature variability [11,14–16,18]. Variations in precipitation over recent decades have been investigated in Refs. [5,9,10,19,25,28,32].

Katz and Parlange [22], Woolhiser et al. [41], Weare and Hoeschele [39], Wilson and Lettenmaier [40], and Kiely et al. [24], identified that patterns in atmospheric circulation (as exemplified by sea-level pressure, SLP) have significant effects on precipitation. Variability of SLP over recent decades has been studied in Refs. [1,2,23,37]. Bardossy and Caspary [1] and Busuioc and Von Storch [3] identified that changing atmospheric circulation patterns in western Europe produce more frequent westerlies leading to increased winter precipitation since the mid-1970s. Houghton and O'Cinneide [13], Sweeney [33] and Sweeney and O'Hare [34] investigated the changing synoptic pattern of Irish precipitation.

Variations in the North Atlantic Oscillation (NAO) have been used to explain increases/decreases in

[1] Tel.: +00353 21 902965; fax: +00353 21 902965; e-mail: gkiely@ucc.ie

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precipitation in western Europe [4,14,16,19,35]. Several authors [9,28] have identified change points in climate state parameters in the mid-1970s. Increases in precipitation, temperature and the NAO index have been documented since the mid-1970s [20]. Changnon and Demissie [8] detected changes in streamflow due to climate fluctuations and land use changes. McCabe [26] examined relations between atmospheric circulation and streamflow in the western US. Rowling [30] and Smith and Bennett [31] examined rainfall variability and its impact on streamflow and water management in Scotland. The impact of climate change on water resources in the UK has been examined by Wardlaw et al. [38] and in Germany by Schumann [36]. More recently, investigations of pan evaporation [6] over several decades suggest that pan evaporation is decreasing in those areas experiencing increased precipitation corresponding to an enhanced actual evaporation.

The objective of this paper is to study climate change in Ireland from precipitation and streamflow observations over the last five decades. Ireland has a temperate maritime climate moderated by the warm influence of the Gulf stream. The prevailing wind direction is from the southwest. Rain bearing winds come primarily from the Atlantic (on the southwest quadrant) and to a lesser extent from the northwest quadrant. Cold and dry weather comes from the east (continental Europe). The west of Ireland has a mean annual precipitation range 1000–1400 mm while the east has about 700 mm. Monthly precipitation on the west coast is about 150 mm in winter and about 50 mm in summer. On the east coast monthly precipitation is about 60 mm with little variation throughout the year. When Atlantic rain bearing storms encounter landfall and the mountains on the west coast, they deposit most of their moisture on the western half of the country.

Long-term precipitation data from eight sites and streamflow data from four sites around Ireland are used. We apply statistical tests to identify change point years in the full time series and analyse extreme values of the time series (pre the change point year and post the change point year). Trends in the NAO index are studied in relation to precipitation and streamflow changes. Fig. 1 and Tables 1 and 2 show the locations and lengths of the hourly precipitation and daily streamflow time series. Most of the data have a five-decade range (since 1940).

2. Statistics of precipitation

Several authors have developed statistical techniques for investigating change in time series [7,12,29]. For the precipitation and streamflow data sets, the annual, biannual, quarterly and monthly time series were computed and statistical tests were applied to identify a change in the mean. The Pettitt–Mann–Whitney and Mann–Whitney–Wilcoxon statistics were used to determine the year of change. The significance probability of the change point years was determined (see Appendix A). The statistics of occurrence and intensity of hourly precipitation and the statistics of extremes for the precipitation series pre and post the change point year were also computed.

2.1. Change point year and its significance probability

We identify change points (if they exist) in the mean of the annual (and biannual, quarterly and monthly) time series using the methods outlined in Appendix A. The objective is to determine in which year (or years) an abrupt change occurred in a single time series. Only results for one precipitation site (Belmullet) and one river site (Boyne) are presented in the figures and discussed in detail in this paper. The results for the other stations are summarized in the tables and are similar in terms of significant trends so they are not produced in the figures. Fig. 2, shows the annual precipitation series and its moving averages for Belmullet (on the west-coast). A change point in the annual precipitation at Belmullet is at 1975. Fig. 3, shows the cumulative sum and probability of change points (at Belmullet). Both methods indicate that the most probable change point year is in the mid-1970s. Table 3 shows the change point years and their significance probability for the eight precipitation stations for the annual, March and October time series. From these tables the period around 1975 is the most common change point year for most stations and so a change point year of 1975 is adopted in the remaining analysis for all stations. At Belmullet the average annual precipitation is 1150 mm for 1957–1996, 1090 mm for 1957–1975 and 1205 mm for 1976–1996. The post-1975 annual average is greater than the pre-1975 annual average by 10.6% at Belmullet.

2.2. Comparison of precipitation statistics pre- and post-1975

The precipitation statistics for the pre-1975 period (including 1975) are compared to the post-1975 (excluding 1975) period. For the west-coast stations (Valentia, Belmullet and Malin Head), the post-1975 period showed increases in the annual precipitation of 8.8–13%. In the bi-annual analysis (January–June), the results from Belmullet show an increase of 23.1% for the post-1975 period.

The mean monthly precipitation for the west-coast site of Belmullet is included in Fig. 4. The March increases observed in the post-1975 period is 46.2%. The October increase is 26.8%. March and October are the months with the largest increase. Long-term records at

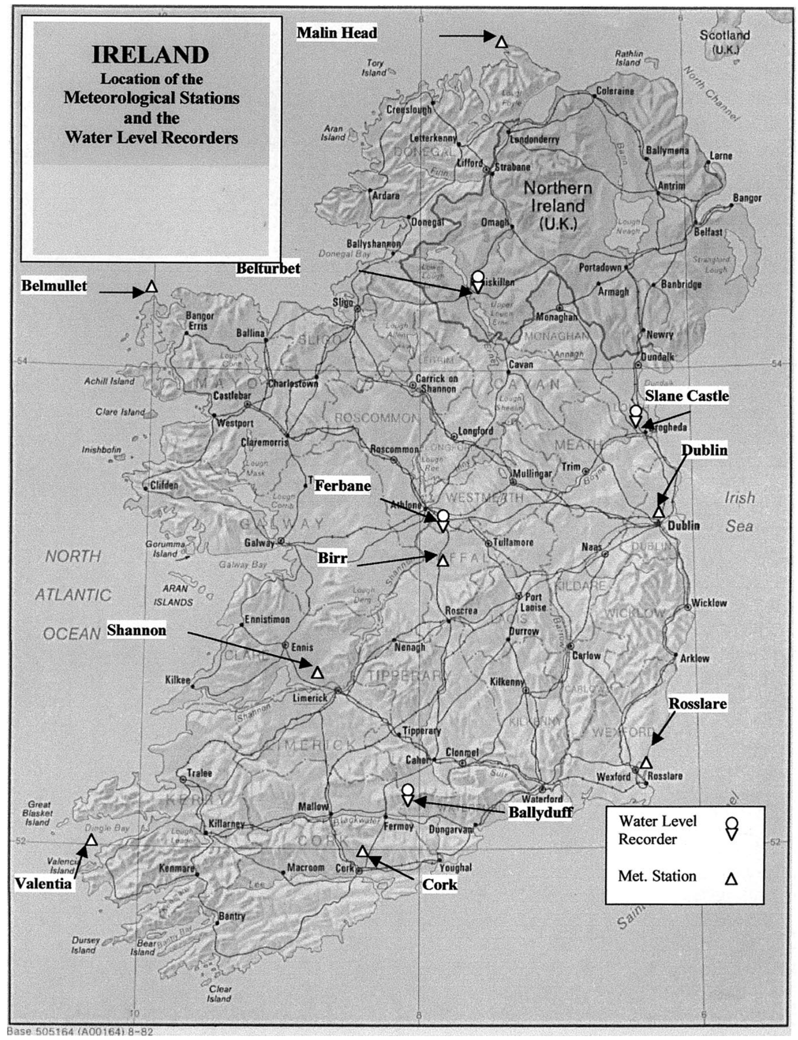

Fig. 1. Location map of precipitation and river flow stations.

Table 1
Location and altitude (above sea level) of the meteorological stations and length of the time-series

Station	Position/County	Altitude (Masl)	Length of the time series (day/month/year)
Valentia observatory	51.93°N/10.19°W Kerry	9	01.01.1940–30.09.1994
Shannon airport	52.70°N/8.90°W Clare	14	01.01.1946–30.09.1994
Belmullet	54.23°N/10.00°W Mayo	9	01.01.1957–31.12.1996
Malin head	55.37°N/7.30°W Donegal	20	01.01.1956–31.12.1996
Dublin airport	53.43°N/6.20°W Dublin	68	01.01.1942–31.12.1995
Birr	53.08°N/7.80°W Offaly	70	01.01.1955–31.12.1994
Rosslare	52.25°N/6.30°W Wexford	23	01.01.1957–31.12.1994
Cork airport	51.85°N/8.40° W Cork	153	01.04.1962–31.05.1996

Table 2
Location of the river water-level-recorders and length of the time-series

Station OPW	Gauging station – river	Catchment area (km^2)	Length of time-series
07 012	Slane Castle – river Boyne	2408	1941–1995
18 002	Ballyduff – Munster Blackwater	2338	1956–1995
25 006	Ferbane – river Brosna	1207	1950–1993
36 019	Belturbet – river Erne	1501	1958–1995

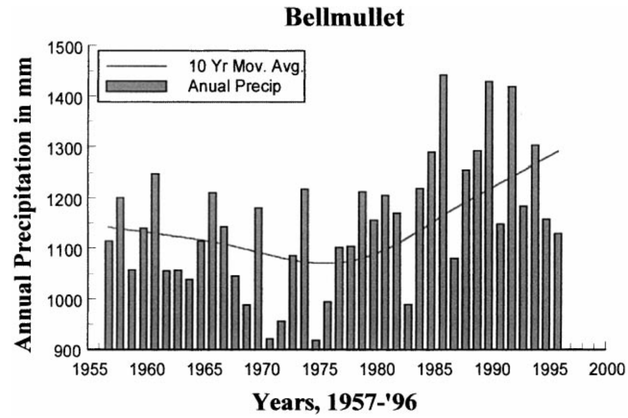

Fig. 2. Mean annual precipitation and 10 yr moving average at Bellmullet.

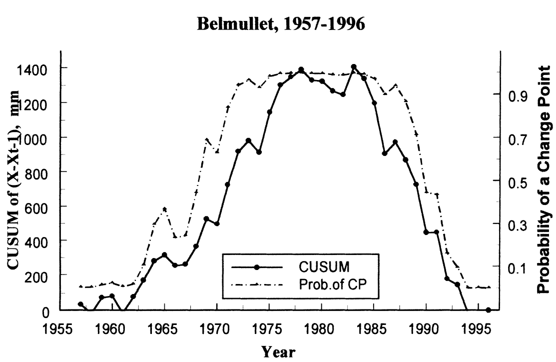

Fig. 3. Probability of change point and Cusum at Belmullet.

Valentia, 1861–1993, are very similar in annual and monthly statistics to the observations from 1940–1993.

The above results indicate that a significant increase in precipitation has occurred on the west-coast since about 1975. This appears as increases in the annual precipitation which in turn translates into increases in March and October. On the east-coast, the increases observed were not as large as those found on the west-coast. On the east side of the country, there was almost no increase in the post-1975 annual precipitation. However, there was a seasonal change with the months of March and October showing increases (see Table 4) while other months experienced decreased amounts of precipitation.

2.3. Hourly occurrence and intensity of precipitation

If there is a change point year (e.g. 1975), then Period I is defined as pre-1975 (including 1975) and Period II as post-1975 (excluding 1975). The statistics of the two periods are investigated to see if the more recent period holds evidence for change in hourly frequency and intensity of precipitation. For each of the twelve months, the diurnal variation of precipitation (hourly occurrence and hourly intensity) is investigated from the perspective of quantifying the relative differences between Period I and Period II. The occurrence (<1.0) or frequency of wet hours is defined as

$$Ow_k = \frac{\sum_{i=1}^{\text{ny}} \sum_{j=1}^{\text{nd}} \text{count}_{ijk}}{(\text{ny})(\text{nd})}, \tag{1}$$

where

$$\begin{aligned} \text{count}_{ijk} &= 1 \quad \text{for} \quad I_{ijk} \geqslant 0.2 \text{ mm/hr}, \\ \text{count}_{ijk} &= 0 \quad \text{for} \quad I_{ijk} < 0.2 \text{ mm/hr}, \end{aligned} \tag{2}$$

ny is the number of years of record, nd is the number of days in the (specific) month and I_{ijk} is the hourly intensity for year *i,* day *j* and hour *k* (for any of the 24 h of the day).

In the same way the hourly intensity is defined for each hour of the day (24 values of *k*) as

$$I_k = \frac{\sum_{i=1}^{\text{ny}} \sum_{j=1}^{\text{nd}} I_{ijk}}{(\text{ny})(\text{nd}_w)}, \tag{3}$$

where nd_w is the number of wet hour–days. The hourly occurrence and the intensity was computed for each of the 24 h of the day for each month. For presentation we fit the outcome of Eq. (1) as

$$y(x) = a + \sum_{\alpha=1}^{2} [b_\alpha \cos(2\pi\alpha x/24) + c_\alpha \sin(2\pi\alpha x/24)]. \tag{4}$$

The diurnal variation of occurrence (frequency) of wet hours for March at Belmullet is included in Fig. 5. This shows that on the west-coast there are significant increases in occurrence for the post-1975 period and when averaged over the daily cycle, the increase for Belmullet is 46.2%. The annual and monthly increases observed in Section 2.1 are translated into significant increases in the occurrence (of wet hours) particularly in March and October at all eight stations (see Table 4).

Table 3
Results of the Pettitt–Mann–Whitney Test (change point year, increase (*I*) or decrease (*D*), probability of the change-point) for the Annual, March and October precipitation at the eight sites

Time	Cork	Valentia	Shannon	Belmullet	Malin head	Birr	Dublin	Rosslare
Annual	66 – *D*[a] – 0.59	75 – *I* – 0.95	51 – *D* – 0.59	78 – *I* – 0.998	77 – *I* – 0.98	68 – *D* – 0.88	68 – *D* – 0.52	67 – *D* – 0.69
Mar	75 – *I*[b] – 0.87	75 – *I* – 0.99	77 – *I* – 0.99	75 – *I* – 0.997	77 – *I* – 0.99	76 – *I* – 0.99	75 – *I* – 0.94	75 – *I* – 0.68
Oct	74 – *I* – 0.78	74 – *I* – 0.87	78 – *I* – 0.88	78 – *I* – 0.96	78 – *I* – 0.77	74 – *I* – 0.71	75 – *I* – 0.78	75 – *I* – 0.94

[a] *D* = decrease – variable decreases post the change point year.
[b] *I* = increase – variable increases post the change point year.

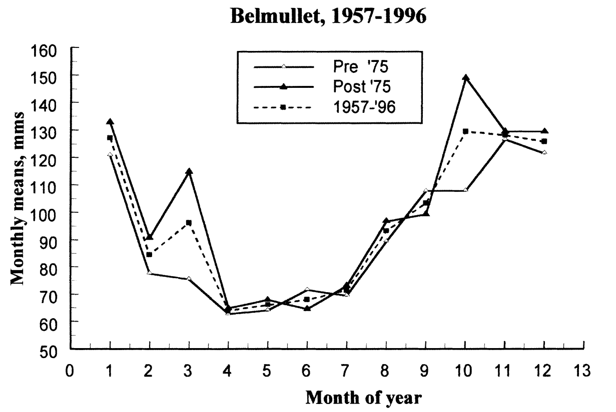

Fig. 4. Mean monthly precipitation at Belmullet for Period I, pre-1975; Period II, post-1975 and complete period (1956–1996).

There is almost no change in the hourly intensity (post the change point year) for any month for any of the stations.

2.4. Statistics of extremes

Extreme value analysis of precipitation was undertaken to determine if the extreme value statistics have changed since the mid-1970s. Changes in extreme value statistics are likely to have a particularly important impact on water resources. Increases in extremes (frequency and/or magnitude) are likely to lead to increased incidence of flooding. This may also lead to more frequent incidences of deterioration in river water quality due to more frequent non-point surface runoff.

Eight ($n = 8$) storm durations (1, 3, 4, 6, 8, 12, 18 and 24 h) were chosen. For each and every day (for the full time series) the single highest value for each duration (based on consecutive hours) was determined. For each location a partial series of length equal to 2.7 times the number of years of the series was used. So for each location three partial series were determined: one associated with the full period; the second associated with the period up to 1975; and the third period after 1975. For Valentia with a total series length of 54 yr the partial series used had 146 values ($\approx 2.7 \times 54$). These values were ranked and a comparison was made of the highest twenty values in the 1940–93, pre-1975 and post-1975 series.

Table 5, includes the ranked 20 highest values of the partial series for the full period (1940–1993) for Valentia for the eight durations of 1–24 h. For all durations a greater number of the ranked twenty values were found to occur in the post-1975 period. For instance, for the 24 h duration 15 of the highest 20 events were found to occur since 1975 even though the period length since 1975 was 18 yr by comparison with a length of 36 yr before 1975 (see the last two rows of Table 5). In Table 6, the highest 160 values (8 durations by 20 events each) for each station are partitioned into the pre- and post-1975 periods. For the west-coast sites (Valentia, Belmullet and Malin Head) a much greater number of the extreme events occurred since 1975. For example at Belmullet where the length of the series is 21 yr since 1975 and 19 yr before 1975, 102 of the 160 highest events (Table 6) are in the post-1975 period. This suggests that not only is there an increase in the depth of precipitation since 1975, but that there is also an increase in the number of extreme events.

In Fig. 6, a comparison of the percentage of extreme events (at all durations) by month for Belmullet is presented. Since 1975, at Belmullet increases in the percentage of extreme events in August, September and October are observed. The increase for the post-1975 period in October is 24%.

2.5. Intensity–duration–frequency analysis

While the analysis of the previous section quantifies the increased frequency of storms since 1975, additional interest is in determining if there are increases in the 'Intensity–duration–frequency' curves associated with the post-1975 period. For this purpose the partial series concept is used rather than the single value per year concept. The objective in this section is to produce intensity–duration–frequency (IDF) curves comparing the full series (for Valentia, 1940–1993) with the post-1975 series. It is assumed the IDF relationship (rain-depth as a function of return period) has the form of

$$h_n(T_n) = u_p + w_p(\ln T_n), \tag{5}$$

Table 4
Occurrence of a 'wet hour' (daily mean value for March and October) for the period pre- and post-1975 and the increase in percent (note that all stations show an increase for the post-1975 period; see Section 3, for definitions)

Month	Period	Valentia	Belmullet	Malin head	Cork	Dublin	Birr	Shannon	Rosslare
March	Pre-1975	0.105	0.104	0.093	0.092	0.061	0.069	0.077	0.075
	Post 1975	0.165	0.152	0.129	0.129	0.079	0.101	0.111	0.087
	Increase	+57.1%	+46.2%	+38.7%	+40.2%	+29.5%	+46.4%	+44.2%	+16.0%
October	Pre 1975	0.132	0.123	0.117	0.097	0.063	0.083	0.089	0.072
	Post 1975	0.165	0.156	0.139	0.118	0.080	0.098	0.119	0.099
	Increase	+25.0%	+26.8%	+18.8%	+21.6%	+27.0%	+18.1%	+33.7%	+37.5%

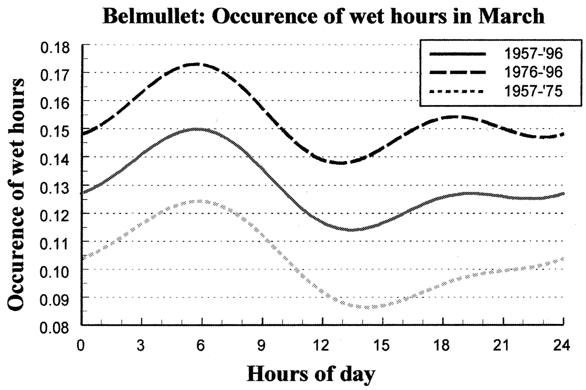

Fig. 5. Occurrence of 'wet-hours' in March at Belmullet for Period I, pre-1975; Period II, post-1975 and complete period (1956–1996).

where $h_n(T_n)$ is the rain-depth in mm, for a return period of T_n yr (for each of n durations), and u_p and w_p are parameters (to be determined) of the distribution function. Return period is defined (in years) as:

$$T_n = \frac{L + 0.2}{k - 0.4}\left(\frac{M}{L}\right), \tag{6}$$

where M is the length of the series (in years) and L is the number of values in the partial series. The parameter $k = 1$ for the highest value of the partial series and $k = L$ for the lowest value of the partial series. The parameters u_p and w_p are determined as follows:

$$w_p = \frac{\sum_{k=1}^{L}(h_{nk}\ln T_{nk}) - L\overline{h_n \ln T_n}}{\sum_{k=1}^{L}(\ln T_{nk})^2 - L\left(\overline{\ln T_n}\right)^2}, \tag{7}$$

$$u_p = \overline{h_n} - w_p(\overline{\ln T_n}) \tag{8}$$

where

$$\overline{h_n} = \frac{1}{L}\sum_{k=1}^{L} h_{nk} \quad \text{and} \quad \overline{\ln T_n} = \frac{1}{L}\sum_{k=1}^{L}\ln h_{nk}.$$

Eq. (5) is used to determine the rain-depth as a function of return period (for each duration) and is extended to be a function of both return period and duration as

$$h_n(T_n, D) = a_u + b_u \ln D + (a_w + b_w \ln D)\ln T_n, \tag{9}$$

Table 5
Distribution of highest 20 values in mms (in the full time series) for 8 durations of the partial series at Valentia. There are approximately twice as many high values in the post-1975 period

Rank	1 h	3 h	4 h	6 h	8 h	12 h	18 h	24 h
1	24	43.8	46.3	56.1	68	79.9	95.7	117.6
2	19.6	36.7	43.2	53.2	60.1	79	94.1	95.8
3	18.9	34.2	42.3	49	59.5	70.5	86.1	88.8
4	17.2	34.2	41.8	47.9	54.7	64.2	75.7	87.8
5	16.6	32.1	35.6	46	52.2	62.8	75.2	82.9
6	16.5	31.6	34.4	44.1	49.6	62.2	70.9	80.9
7	16.4	29.5	34.3	43.7	49.4	60.8	69.8	79
8	16	29.4	32.9	43.4	49	58.5	68.6	78
9	15.8	29.3	32.7	41.2	46.7	55.1	68.4	74.1
10	15.7	29.2	32.4	39.8	45.9	54.5	64.6	71.4
11	15.2	28.4	32.2	37.6	45.4	54.2	61.9	70.5
12	15.1	28	31.6	36.9	44.6	53.6	60.9	69.9
13	14.7	27.7	31.6	36.7	43.3	52.7	60.9	69.9
14	14.6	27.2	31.2	36.6	40.8	52.5	60.8	66.1
15	14.6	27.1	31	36.5	40.4	52.4	60.8	64.9
16	14	26.8	31	36.4	40.3	50.9	60.2	64.8
17	13.6	26.6	30.7	36.2	39.2	50.9	59.7	64.6
18	13.6	26.4	29.7	34.3	39.2	50.7	59.6	64.6
19	13.4	26.3	29.7	34.1	39.1	50.5	58.3	63
20	13	25.2	29.6	34	37.6	48.2	58.3	62.6
1940–1975	9	6	6	7	9	6	8	5
1976–1993	11	14	14	13	11	14	12	15

Table 6
Distribution of the 160 highest extreme-events for the eight time-intervals

	Valentia	Belmullet	Malin head	Shannon	Birr	Dublin	Rosslare	Cork
α	0.53	1.05	1.00	0.63	0.86	0.56	1.06	1.42
up to 1975	56	58	62	**113**	78	**84**	**89**	72
since 1976	**104**	**102**	**98**	47	**82**	76	71	**88**

α is calculated as the length of the time-series post-1975 divided by the length pre-1975. As indicated in Table 5, there are also many more extreme events in the post-1975 period.

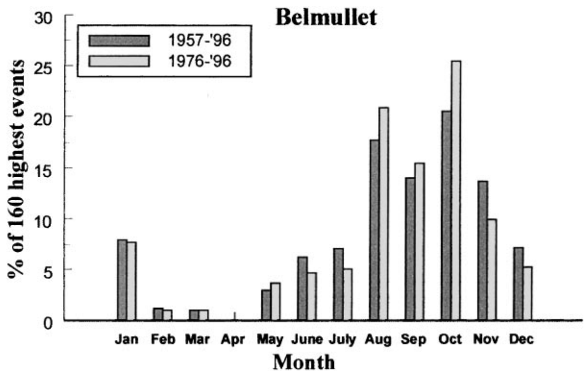

Fig. 6. Distribution of the 160 highest extreme events during the year (in %) for the complete and partial time series (post-1975) at Belmullet.

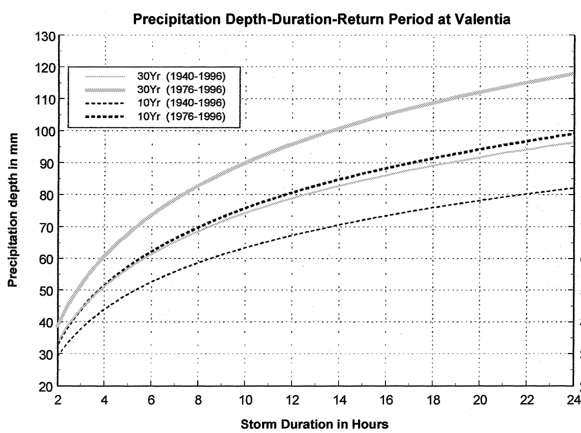

Fig. 7. Precipitation depth–duration–frequency for Valentia for the complete (1940–1993) and partial time series (post-1975).

$$b_u = \frac{\sum_{j=1}^{n} \left(u_j - \overline{u}\right).\left(\ln D_j - \overline{\ln D}\right)}{\sum_{j=1}^{n} \left(\ln D_j - \overline{\ln D}\right)^2}, \quad (10)$$

$$a_u = \overline{u} - b_u \overline{\ln D}. \quad (11)$$

In Eq. (9), the parameters a_w and b_w are determined in the same way as b_u and a_u, by replacing u_j and $\overline{u}$ with w_j and $\overline{w}$ in Eqs. (10) and (11). Further parameter definitions are in Ref. [42].

The precipitation depth–duration–return period curves for Valentia are shown for the full period (1940–1993) by comparison with the post-1975 period (see Fig. 7). Precipitation depth rather than intensity is used here for convenience. The 30 and 10 yr return periods are shown. At low durations and low return periods, there is little difference in the precipitation depth between the periods 1940–1993 and post-1975. At the higher durations (e.g. 24 h) and higher return periods (e.g. 30 yr) the difference is significant. For the period 1940–1993, the estimated precipitation depth for the 30 yr (return period), 24 hr (duration) storm is 91 mm. For the post-1975 period the estimate is 114 mm (a 25% increase). Furthermore, it is seen in Fig. 7, that the 30 yr return period curve for 1940–1996, is slightly less than the 10 yr return period curve for the post-1975 period. In other words, what used to be the 30 yr storm depth is now approximately the 10 yr storm. This has ominous implications for flood management.

3. Statistics of river discharge

The change point analysis of Section 2.1 (and Appendix A) was applied to the daily river flow data from four sites in Ireland. Table 7 and Fig. 8 include some results. The annual mean daily flows for the period 1958–1995 for the river Boyne are presented in Fig. 8 along with the 10 yr moving average. It is clear there is a corresponding change point year around the mid-1970s as found with the precipitation records. Also in Fig. 8, the mean daily flows for March are presented for the same period along with its moving average. Again it seen that there is a change point year near the mid-1970s.

Table 7 includes the results of change point analysis for the four rivers. Three of the river flow sites show a change point year in the annual mean daily flow near 1975, followed by an increase in flow magnitudes. All four river sites show a change point year near 1975 for March flows, followed by an increase in flows. The increase since the mid-1970s is particularly significant for the Boyne at Slane castle.

In summary, the analysis of precipitation and streamflow show that these variables experience a change in the mid-1970s, after which both precipitation and streamflow increase.

4. Connection to NAO

The above analysis show that both precipitation and river flow in Ireland experienced a change point year

Table 7
Results of the Pettitt–Mann–Whitney Test (change point year, increase (*I*) or decrease (*D*), probability of the change-point) for the four river stations

Time	River Erne at Belturbet	River Boyne at Slane	River Blackwater at Ballyduff	Brosna at Ferbane
Annual	1978 – *I* – 0.872	1978 – *I* – 0.996	1976 – *I* – 0.756	–
March	1976 – *I* – 0.994	1976 – *I* – 0.999	1975 – *I* – 0.835	1976 – *I* – 0.998
October	1968 – *D* – 0.979	1968 – *I* – 0.718	–	1968 – *I* – 0.915

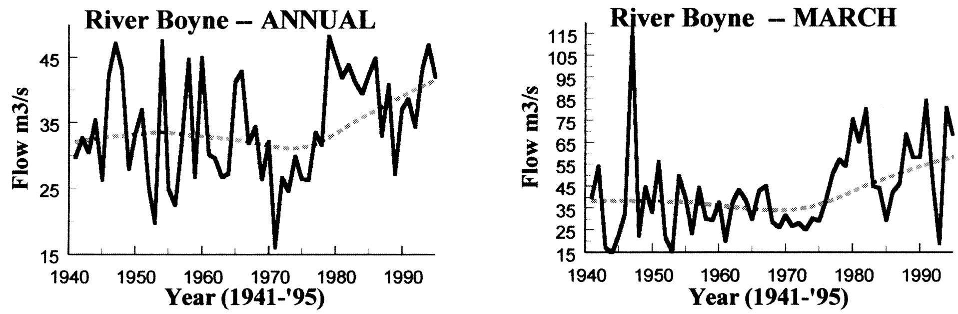

Fig. 8. Mean annual and monthly flow in m^3/s, (in March) and the 10 yr moving average at Slane Castle on the Boyne river.

near the mid-1970s. Since that time, annual and monthly (March and October) precipitation has increased especially on the west-coast sites. Furthermore, this change has been accompanied by an increase in the frequency of wet hours in some months (mainly March and October). An increase has been identified not only in the frequency of extreme events since 1975 but also an increase in the rain depth for most storm durations and return periods. River flows mimic the above trends for precipitation.

The teleconnection likely to affect countries bordering the north east Atlantic is the North Atlantic Oscillation (NAO), [20]. This is a large-scale alternation of atmospheric mass with centres of action near the Icelandic low and the Azores high. It is the dominant mode of atmospheric behaviour in the north Atlantic throughout the year, though it is most pronounced throughout the winter and accounts for more than one-third of the total variance in sea-level pressure [4]. The NAO index as defined by Hurrell [14,15] uses sea-level pressure anomalies from Lisbon and Stykkisholmur (Iceland). The index from Ref. [20] uses records from Gibralter and SW Iceland. A high positive index pattern indicating strong mid-latitude westerlies, is characterised by an intense Iceland low with a strong Azores ridge to its south, while during low (negative) index periods the signals of these anomalies are reversed.

The Jones form of NAO index for March is presented in Fig. 9 along with its 10 yr moving average. There is a change point in the mid-1970s. Table 8 includes the results of the Pettitt–Mann–Whitney (change point) test for the NAO index. For the March NAO index, this shows that there is a significance probability (see Appendix A) of 0.98 that a change point occurred in 1975 and that since 1975 there has been an increase in the index. It is also seen in Table 8, that the annual NAO index shows a change point in 1961. The index decreases after 1961. The point to note is that while the annual NAO signal is weak, the signal in the individual months like March and October is strong.

The NAO analysis suggests that there are increased westerlies in March and October (those months with strong NAO signals) which bring increased precipitation to Ireland. This change occurred in the mid-1970s.

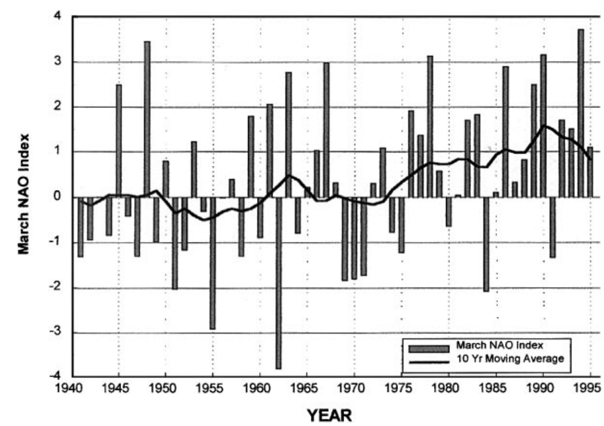

Fig. 9. The NAO index for March since 1940 and its 10 yr moving average.

Table 8
Pettitt–Mann–Whitney test for NAO index

Time series	1940–1995
March	1975 – *I* – 0.980
Jan-Mar	1972 – *I* – 0.981
Dec-Mar	1981 – *I* – 0.988
Year	1961 – *D* – 0.723

5. Summary

Long-term records at eight precipitation sites and four river flow sites around Ireland were examined for evidence of climate change. At all the precipitation and streamflow sites, there was a change point around the mid-1970s after which the precipitation (and streamflow) increased. Since 1975, there has been an increase in the annual precipitation of about 10% on the west-coast and the bulk of this increase was in the months of March and October. March increases were as high as 60%, while October increases were of the order of 30%. For both March and October, it was found that the monthly increases showed as increases in the occurrence (frequency) of wet hours. There was almost no change in the hourly intensity.

Extreme precipitation events were analysed and the results for the full series (1940–1995) are compared with results for the post-1975 period. For the west coast, it was found that approximately 75% of the extreme events (of the ranked 20 events) occurred since 1975, even though there were 18 yr since 1975 and 36 yr before 1975. At the highest event durations (24 h), it was found that the magnitude of the post-1975 events were about 25% higher than similar events from the full period (1940–1995). New precipitation depth–duration–return period curves for both the full period and for the post-1975 period were produced. These curves show that at low durations and low return periods there was little difference between the two periods. At the high return periods (e.g. 30 yr) and the high durations (e.g. 24 h) there was a significant increase in the magnitude of the raindepths. At Valentia the comparative magnitudes were 91 and 114 mm. This increase of 25% is highly significant (where significant is defined by the t-test at the 99% confidence level). Similar but not so significant increases were determined for the other west-coast sites. It was found that the higher magnitude extreme events are now occurring more frequently in the months of September and October.

Analyses of river flows at four sites also showed a change point in the mid-1970s with flow increases since 1975. The analysis of precipitation and streamflow show that these variables experienced a change in the mid-1970s, after which time both precipitation and streamflow increase which correspond with the NAO index change point (1975). The index has become increasingly positive since 1975. An increase in the index, indicates an increase in westerlies resulting in more rain over Ireland. The increase in rain depths and increase in river flows correlates with the increase in the NAO index. It is clear that Ireland is experiencing an enhanced hydrologic cycle of increased precipitation and steamflow and this enhancement began in the mid-1970s.

The implications of this enhanced hydrologic cycle particularly on the west of the island are critical with regard to flood management. Managers of lakes, rivers, reservoirs and dams need to take this changing climate into consideration. The disastrous flooding in the west and south of Ireland in the last twenty years is the result of the enhanced hydrologic cycle. If the trend persists, managers and engineers involved in water resource and flood control should consider climate change in their designs. Higher precipitation magnitudes result from extreme value analysis if the shorter time series (since 1975) is used rather than the full periods (e.g. since 1940).

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Appendix A

Initial estimates of the trends in the mean annual precipitation were determined using a low pass filter (10 yr moving average, MA) defined as

$$MA_t = \frac{1}{2L}\left(\frac{1}{2}x_{t-L} + \sum_{j=-(L-1)}^{L-1} x_{t+j} + \frac{1}{2}x_{t+L}\right), \quad \text{(A1)}$$

where x_t is the mean annual precipitation at year t and $L = 5$. The mean annual precipitation and the 10 yr moving average are shown in Fig. 2 for the west coast site of Belmullet.

The nonparametric Mann–Whitney–Pettitt Test [29] was used to identify the change-point (year/years) in the different time series (annual, half-yearly, quarterly and monthly) and is briefly described in the following.

The time series (length $T; x_1, \dots, x_T$) is considered as two samples represented by $x_1, \dots, x_t$ and $x_{t+1}, \dots, x_T$. The indices $V(t)$ and $U(t)$ are calculated from

$$V_{t,T} = \sum_{j=1}^{T} \operatorname{sgn}(x_t - x_j), \quad \text{(A2)}$$

$$U_{t,T} = U_{t-1,T} + V_{t,T} \quad \text{for} \quad t = 2, T, \quad \text{(A3)}$$

$$U_{1,T} = V_{1,T}, \quad \text{(A4)}$$

$$\begin{aligned} \operatorname{sgn}(x) &= 1, \quad \text{for} \quad x > 0, \\ \operatorname{sgn}(x) &= 0, \quad \text{for} \quad x = 0, \\ \operatorname{sgn}(x) &= -1, \quad \text{for} \quad x < 0. \end{aligned} \quad \text{(A5)}$$

The most significant change-point is found where the value $|U_{t,T}|$ is maximum:

$$K_T = \max |U_{t,T}| \quad \text{(A6)}$$

The approximate significance probability $p(t)$ for a change-point is

$$p(t) = 1 - \exp\left(\frac{-6U_{t,T}^2}{T^3 + T^2}\right). \quad \text{(A7)}$$

The probability for a change-point for all the time series (annual, bi-annual, quarterly and monthly) was computed for all eight sites (altogether 152 time series) and determined the year with the most significant change-point. The results for the eight precipitation sites are presented in Table 3.

The Mann–Whitney–Wilcoxon Test statistic allows us to test the hypothesis that the means of two samples are equal. The hypothesis of equal means is rejected if

$$|Z_c| > u_{1-\alpha/2}, \tag{A8}$$

where $u_{1-\alpha/2}$ is the '$1-\alpha/2$ quantile' of the standard normal distribution (we choose a significance level of $\alpha = 0.05$). The index Z_c is calculated as follows:

$$Z_c = \frac{w - \frac{n(T+1)}{2}}{\sqrt{\frac{n(T-n)(T+1)}{12}}}. \tag{A9}$$

To compute the variable w the single time series (of T elements) is divided into two new series with the elements: $[x_1, \ldots, x_m]$ and $[y_1, \ldots, y_{n-m}]$. Each of these two time series should contain at least eight elements [29]. The variable w is the sum of the ranks $r(x_i)$ of the elements of first series $[x_1, \ldots, x_m]$ which is defined by rearranging the elements of both series (x and y) in increasing order.

$$w = \sum_{i=1}^{m} r(x_i). \tag{A10}$$

The cumulative sum technique was also used to detect changes in the mean value of a sequence of observations ordered in time. This has shortcomings if the time series contains obvious outliers. The 'cumsum' is

$$S_i = \sum_{i=1}^{i} (x_i - k), \tag{A11}$$

where k was chosen to be the average of the time-series.

We computed the cumulative sum for the time series and the results confirm the change points which were detected with the Pettitt–Mann–Whitney and the Mann–Whitney–Wilcoxon Test. Using this technique the hypothesis of no change in the mean value is rejected if $\max|Si|$ becomes too large.

The results of this analysis show that a significant change point year occurred at about 1975.

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