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Analysis of trends at some Irish rainfall stations

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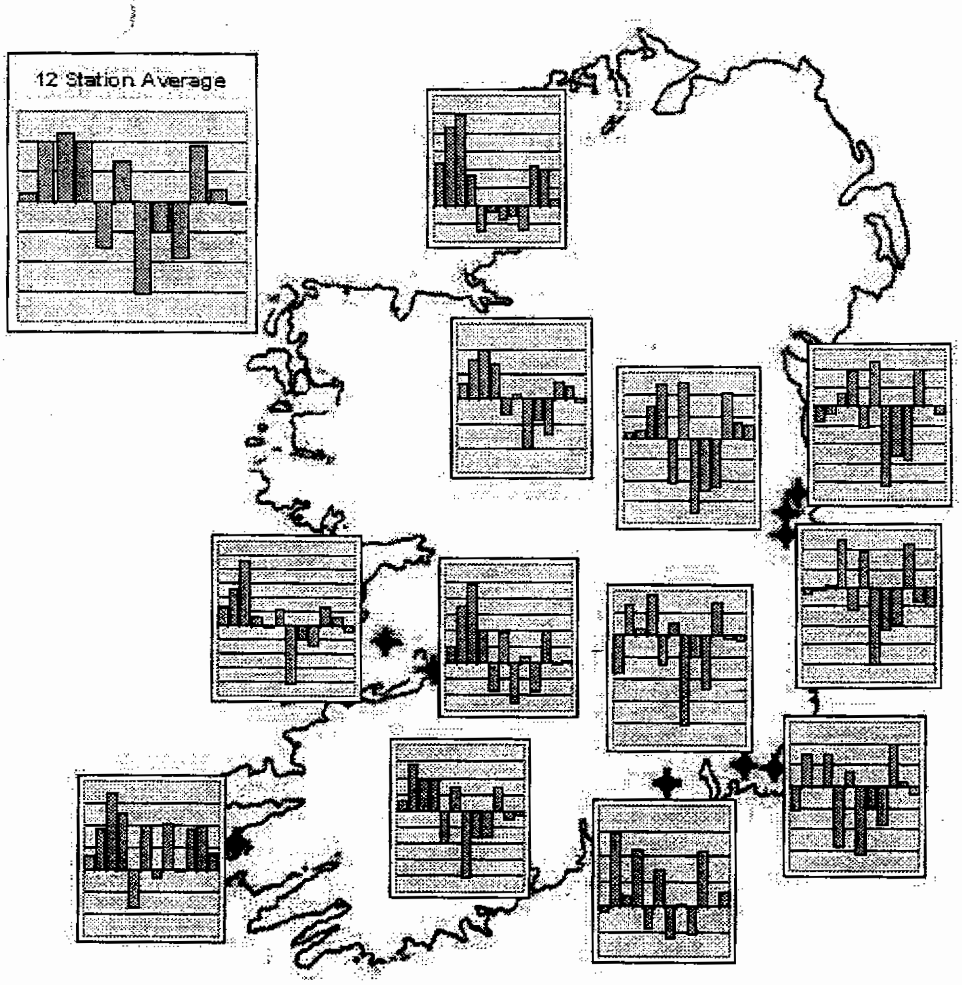

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Cover Diagram

Monthly (January to December) trends at the locations discussed in percent per decade. Horizontal lines are separated by units of 2% per decade. All graphs are either centred on location or immediately adjacent to the locations marked. Graph at top left is the average of all 12 stations. See section 2 (Monthly Data)

Analysis of trends at some Irish rainfall stations

Abstract

This report concerns a study of rainfall reports from 12 Irish locations covering a 59-year (708 months) period 1941 to 1999. The objective is to determine what changes, if any, have occurred in the character of Irish rainfall, as represented by these stations, during the period. Trends and variability of annual and monthly accumulations, numbers of rain days, numbers of wet days and greatest daily falls are reported. Annual maxima of rainfall of various durations from 15 minutes to 25 days at one station are also examined. Methods which were used to estimate missing data and, at one station, to correct some monthly accumulations are described.

Accumulations, rain-days and wet days are found to show significant increases at many stations in certain months (e.g. March) and decreases in others (e.g. July to September period). On the other hand, and perhaps surprisingly, November, December and January trends in the stations examined tend to be smaller and less significant.

Annual greatest daily falls show no significant trends but significant trends are found for some months (increasing trends at 3, 5 and 4 stations during March, April and June respectively and decreasing at 4 and 1 location for May and July respectively).

This investigation provides some support for the assertion that a change occurred in the character of Irish rainfall during the early 1970s.

Introduction

With increasing concerns about the *impacts* of climate change, whether it be anthropogenic or natural, in recent years the attention of climatologists is broadening to concerns about a wider range of issues than trends in mean temperatures. In particular, there is increasing concern about possible changes in the hydrological cycle. Many studies have been conducted into changes in rainfall accumulation over various periods, in the intensity of precipitation and in frequency of wet or dry spells. Amongst others, investigations have been carried out relating to the contiguous USA (Karl and Knight, 1998), Alaska (Stafford et al, 2000), Scandinavia (Førland et al., 1998), Belgium (Gellens, 2000), Italy (Brunetti et al, 2000, Brunetti et al, 2001), Australia (Suppiah and Hennesy, 1998), South Africa (Mason et al, 1999;), United Kingdom (Osborn et al., 2000; Mayes 1996; Thomson, 1999). Two interesting studies relating to the Western part of Ireland are Chandler and Wheater (1998a, 1998b).

The present investigation concerns monthly rainfalls, rain days, wet days and greatest daily falls from 12 Irish rainfall stations. Trends and variability within the 59-year series are investigated and a brief comparison of the 1941 to 1970 and the 1971 to 1999 data is presented. Seasonal references imply the spring = March, April, May convention.

After a brief discussion of the data and some issues relating to it, the paper is presented in the following order

Section 1 Analysis of Annual Accumulations for trend and variability
Section 2 Seasonal and Monthly analysis regarding trend and seasonality
Section 3 Investigation of annual and monthly rain days for trends, year-to-year variance and intensity trends
Section 4 Annual and monthly wet days analysis and comparison with rain days
Section 5 Extreme events
Section 6 Rainfall and the North Atlantic Oscillation
Section 7 Summary and discussion
Appendix I Metadata
Appendix II Correction procedure for Drumsna
Appendix III Details of some procedures employed

The Data

The Met Éireann climate database contains data from 1941 to date. There are also some electronic data files containing information pertaining to earlier periods such as monthly totals calculated from the paper record but which are not included in the formal database. For this study data was taken mostly from the MONTHLY_RAIN table. This table is constructed from the station returns and contains monthly totals, number of rain days, number of wet da ys and the greatest daily falls for each month and each station together with some indicator flags.

Only stations for which the database contained a full series of monthly rainfall totals from 1941 to 1999 inclusive were included in this study. The selection is therefore very restricted and is confined to 59 years of data from each of 12 stations. The stations examined are indicated in Fig 1 and in the Table 1.

Station	Name	Lat	Long	Elev
108	Foulkesmills	52 18 40	6 46 00	67m
305	Valentia Obs	51 56 23	10 14 40	7
417	Inagh	52 50 30	9 14 20	122
441	Glenties	54 47 25	8 17 10	44
518	Shannon	52 41 25	8 55 05	6
706	Mallow	52 11 25	8 39 00	94
915	Johnstown Cas	52 17 30	6 30 00	49
1529	Drumsna	53 54 40	8 00 00	45
1712	Knockaderry	52 12 35	7 16 15	71
1723	Phoenix Pk	53 21 50	6 20 50	49
1823	Glasnevin	53 22 15	6 16 20	21
1923	Glenasmole	53 14 20	6 22 00	158

Table 1. Station Details

In a very few cases values in the MONTHLY_RAIN table include estimates, or values for rain-days, wet-days or greatest daily falls (GDFs) were missing (see Appendix III). For a more complete study it would be preferable to use the tables containing the daily falls and apply a more sophisticated method of derivation of GDF (e.g. Brunetti et al, 2001b) and other data.

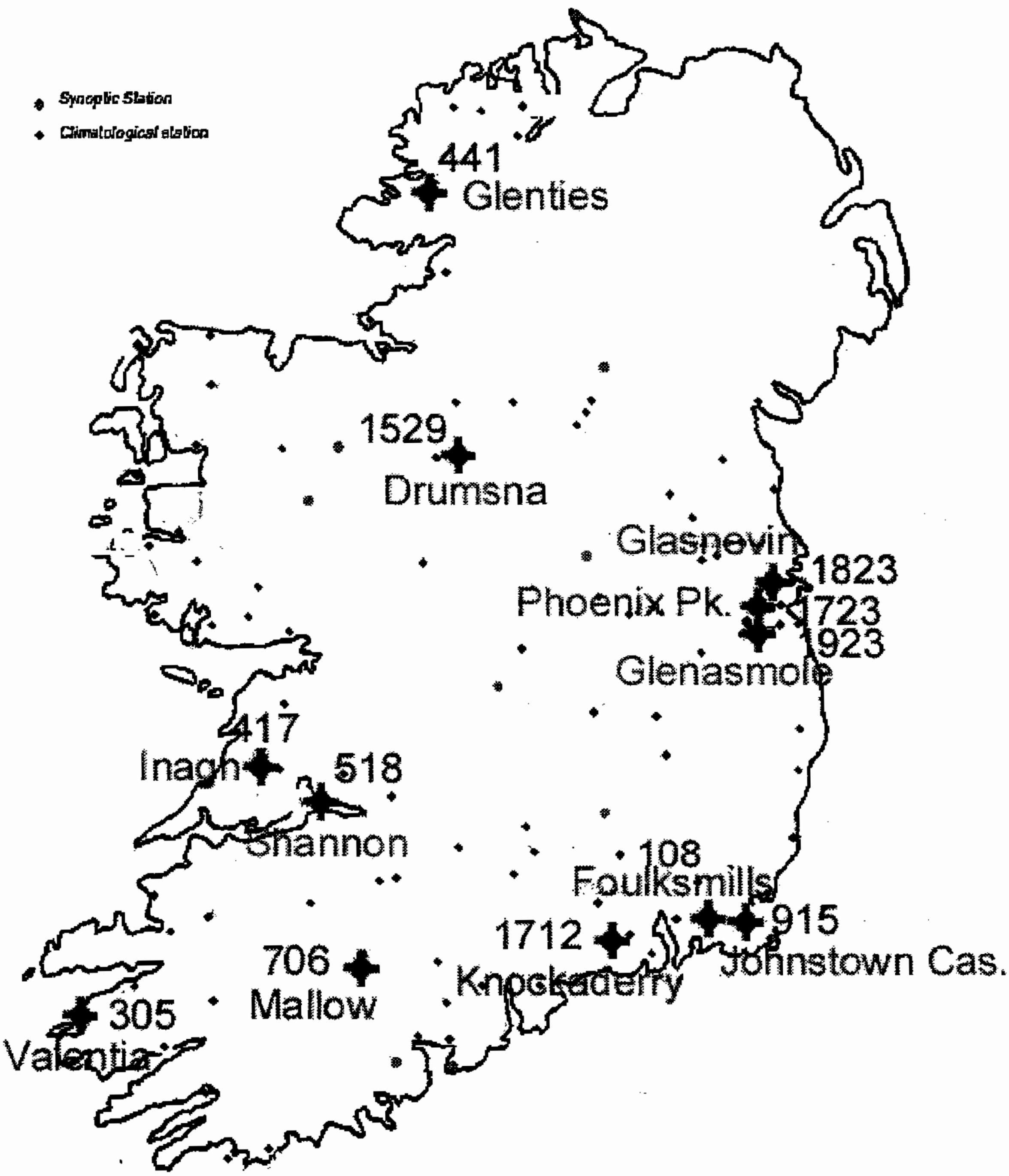

Fig 1. Stations used in this study overlaid on a map of the Met Éireann Climatological and Synoptic stations.

Quality and Homogeneity

Paper based station history files exist for all stations and some relevant extracts from these are given in Appendix 1. Such information is invaluable in making a judgement whether to accept, reject or correct reported data. In general, in the interest of objectivity, the monthly accumulations as available in the database were accepted at face value. However, in the course of the investigation, some anomalies were noted in one (Drumsna). On investigation, it was decided for the purpose of this study to replace a number of months' accumulation data for this station with corrected values as described in Appendix II. It is possible that a similar examination of the other stations would suggest some corrections should be applied for occasional months but this was not done.

The data is not homogenized but some absolute tests were done on the individual stations. The test of Abbe (Schoenwiese & Rapp, 1997; Conrad & Pollack, 1962) indicates that most stations are without significant inhomogeneities - see appendix III.

For the study of some of the monthly or longer accumulations, the data was in some cases 'normalised' by dividing by the relevant 1961 to 1990 normals.

1. Annual accumulations

Positive trends at most stations, especially in West.

Initially the annual accumulated totals for each station were examined for the period.

1.1 Variability

Annual totals for the individual stations varied over the period by over 40% from their respective 1961 to 1990 normals with standard deviations varying between 10.5% (Inagh) and 15.2% (Glasnevin). A positive correlation is noted between standard deviations and the 1961 to 1990 normal annual accumulations when expressed in absolute terms. When expressed in terms of percentage of normal, however, higher standard deviations are associated with lower annual normals.

The year-to-year changes when the 59 years are divided into two separate series (1941-1970 and 1971 – 1999) were examined. The stations in the Dublin area were found to have significantly lower year-to-year variance in the later series (probability of non-different variance < 5%, F-test). In these cases, the standard deviation was lower in the later series in terms of percent of the relevant means as well as in absolute values. Four other stations (Foulkesmills, Johnstown Castle, Knockaderry and Mallow) showed reducing variances and the remaining four (the more westerly stations) showed increasing variances. None of the last-mentioned 8 differences was significant.

Between-station variance shows a tendency to increase with time c.f. fig 2.

Examination of the between-station correlation ($\rho = \dfrac{Cov(x;y)}{\sigma_x \sigma_y}$) matrix for the normalised series shows the three geographically close stations in the SE well-correlated (>0.8) and the group of three in the Dublin also well correlated.

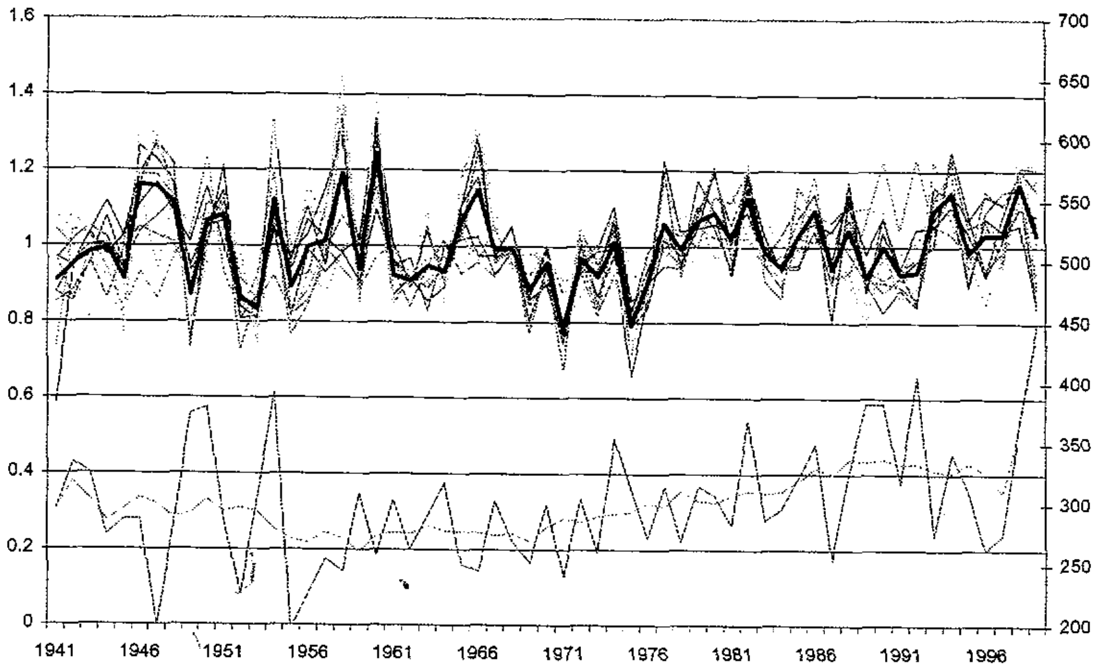

Fig 2. Normalised annual rainfall (i.e. annual accumulation divided by 1961-1990 average) for individual stations and average of 12 stations (Upper graphs and left hand axis). Between-station standard deviation of annual rainfall totals (mm) for 12 stations and 9-point smoothed values (Lower graphs and right hand axis).

1.2 **Trend** *Increasing annual rainfall, especially in the west, especially at wetter stations and especially since the early 1970s*

Over the period, 9 of the twelve stations had an increasing trend in rainfalls using the Kendall non-parametric (Knp see appendix III) trend test and 8 were increasing according to linear regression analysis.

Two of the stations' – Valentia and Glenties – positive trends were significant at more than the 98% level (Knp test) and Valentia, Glenties and Shannon had F-values

$\left(\frac{Trend}{Std\_error\_on\_trend}\right)^2$ in excess of 8, 10 and 3 respectively (linear regression). The

negative trends were all non-significant. Trend is obviously very dependent on where the series starts and ends. Two of the stations had their minima at the very start of the period (1941), one in 1949, two in the 1950s, three in 1971, 4 in 1975 and none in the 1980s or 1990s. Using sequential Knp analyses with varying length series all *starting in 1941* indicates some increase in most series during the 1940s but by the mid 1970s all station series show a negative trend. The trend then reverses, till by 1999 all series apart from the three mentioned (which showed very small trends) show a positive trend again. Reverse Knp analysis confirms the 1970s as a period during which the trend changes. This change is supported by the analysis of Kiely (1999) of accumulations of hourly and longer period rainfall from 8 Irish synoptic stations (including two of the stations dealt with in this study).

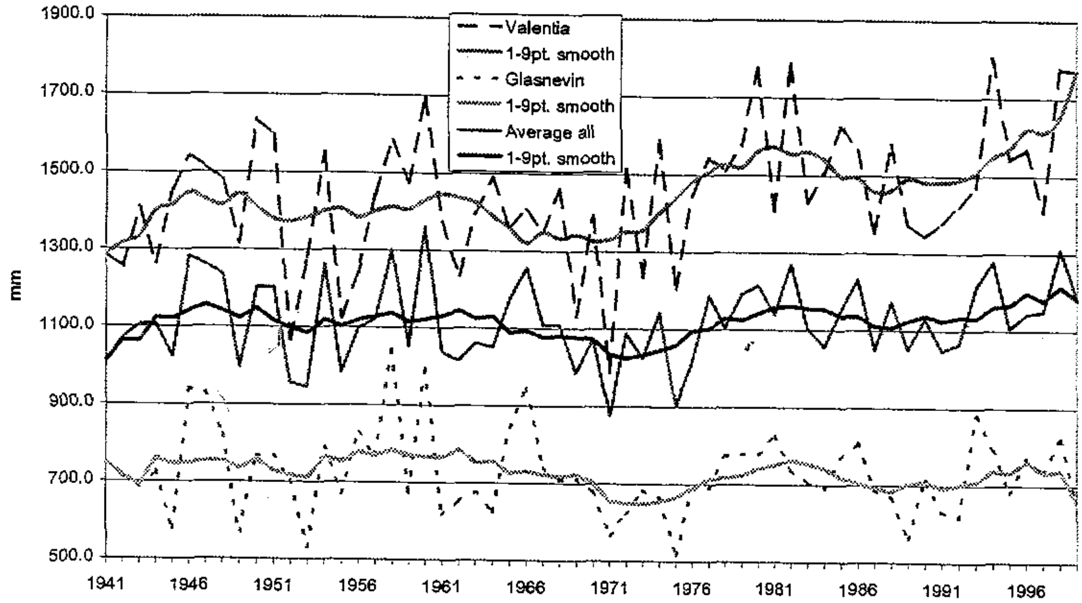

Fig 3 Annual accumulations for Valentia Observatory, Glasnevin and the 12-station average. 9-Point (less at both ends) smoothed values are also shown.

Fig 3 shows these features clearly.

Linear regression over the whole period indicates the following

	Station	Trend %/annum	Standard error +/-
Average		+0.06%	0.08
Max	Valentia	+0.25%	0.09
Min	Glasnevin	-0.09%	0.12

In general terms the trends tended to be larger (and more significant) and positive towards the west of the country with small positive or negative trends in the east and southeast. These figures should be compared with the trends (1.3% per decade with 95% confidence intervals +0.82 to +1.78%) in the 1946 to 1999 period of the ECA dataset containing 172 European stations (Klein Tank et al, in press 2002).

There is a positive correlation between the trend in the normalised annual totals and the 1961 to 1990 normals of rainfall accumulation of ρ =0.62. This indicates that those stations with greater annual rainfall show the larger increases (both in real terms and as a percentage of their normal) over the study period.

A number of stations examined here show statistically significant trends during the 59-year period. The positive trend in the past 25 years does stand out when viewed in the context of the Irish stations with rainfall records going back to the nineteenth century. However, Thomson (1999) in his examination of 30 Irish and UK stations concludes that the recent changes in the amount of precipitation do not stand out particularly from the natural variability of the last two centuries

2 Monthly Data

February, March, April becoming wetter; July, August, September drier

There is, of course, considerable between-station variation in the monthly accumulations. Taking the February data as an example, while the group of three stations in the Wexford area show between-station correlation coefficients above 0.95 and the three Dublin area stations are above 0.9, the lowest correlation in the sample is 0.4 between Glenties and Foulkesmills, separated by just under 300km.

Likewise, there is considerable variation between the stations in their trends over the 59 years.

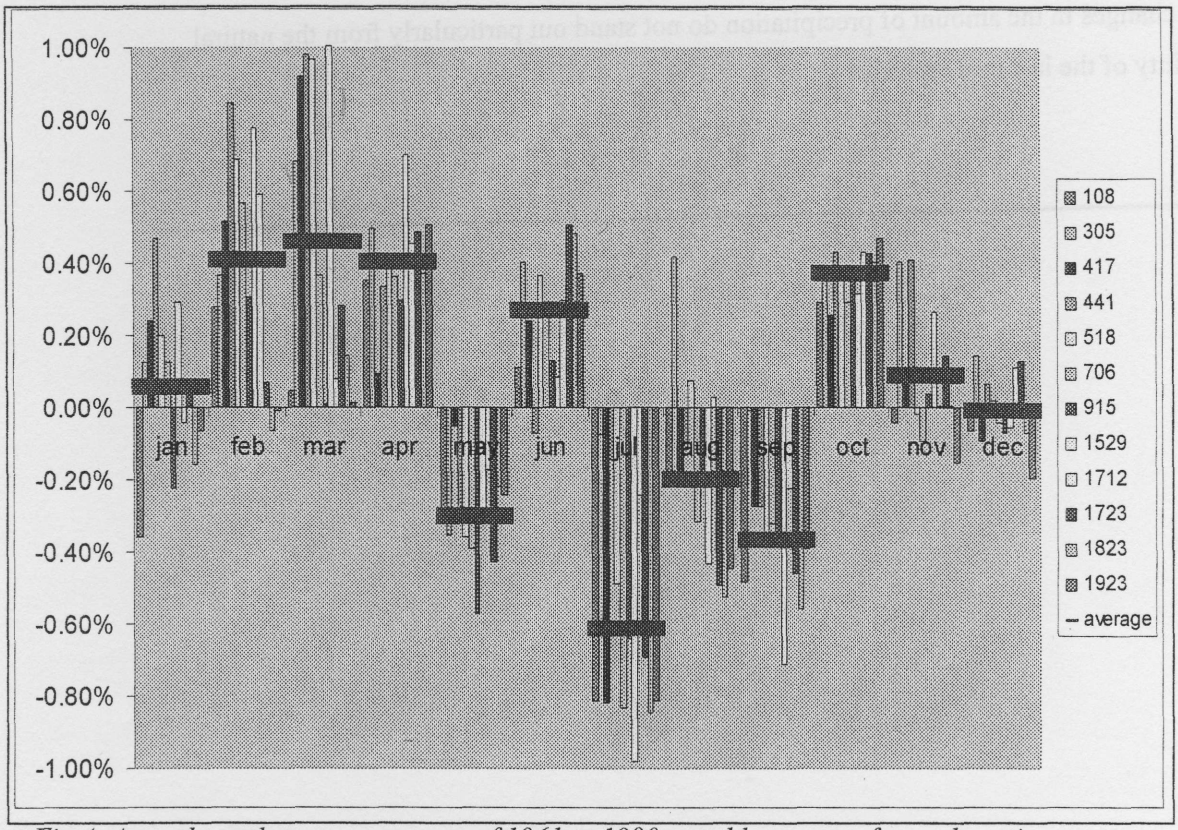

Fig 4. Annual trends as a percentage of 1961 to 1990 monthly average for each station. Individual stations as columns, average of 12 stations as horizontal bars. See cover graphs also.

In general terms, positive trends are found in February, March, April and October with negative trends dominating in May, July, August and September. Both Knp and linear regression show positive trends for all stations in March, April and October and negative trends for all stations in May, July and September. Only one station (Valentia) shows a positive trend in August. This seems to be due mainly to the August rainfall (normalised by dividing by stations' 1961 to 1990 average) in the first two decades of the series being below the average of the other stations. The developments which occurred in the vicinity of Valentia during the 1960s (c.f. Appendix I) are not thought to have had any detectable impact on its rainfall. Comparing series up to and after 1975 Kiely (1999) also found March and October to be months of significant increases in precipitation

2.1 Significant trends

Using the Knp trend test, of the 144 series (12 stations, 12 months), 16 were found to be significant at the 90% level, 7 at the 95% level, and 4 at the 99% level. The last-mentioned four were the increasing trends at Shannon, Inagh, Drumsna and Glenties during March. The extra three at 95% level are negative trends for Foulkesmills and Glenasmole (July) and Drumsna (September). At 90% level, 7 stations showed a negative trend in July, five showed positive trends in March and there was one positive trend in February and one negative trend in each of May, August and September.

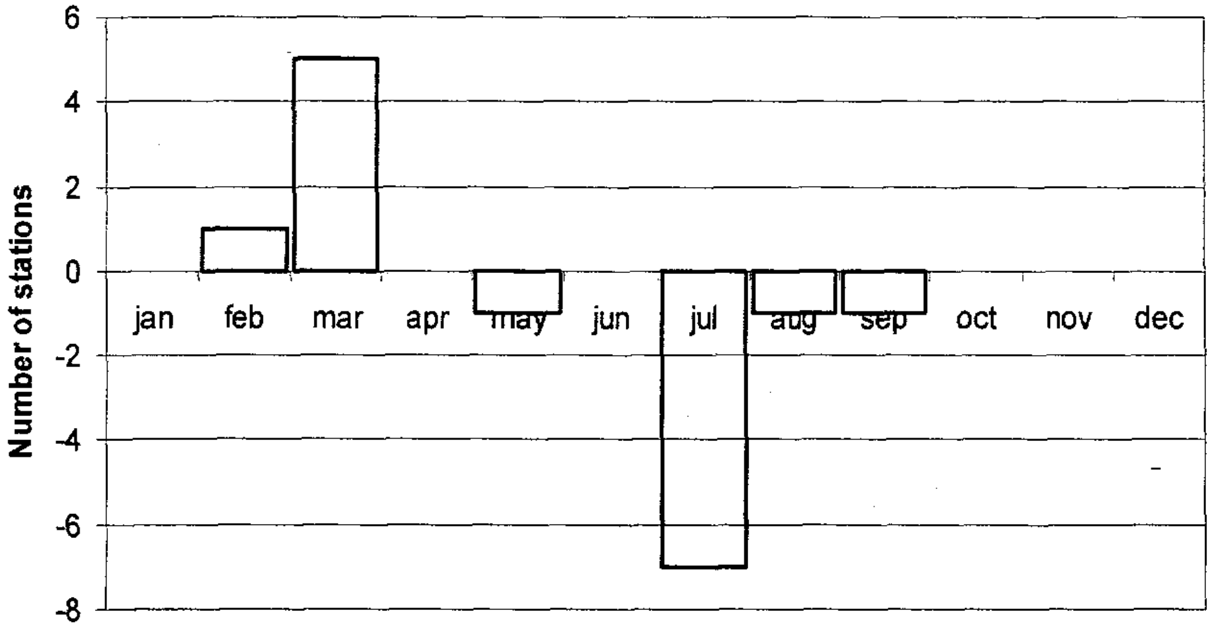

Fig 5. Numbers of stations with significant trends in rainfall accumulations for each month. Positive: numbers of stations with positive trends, negative: numbers of stations with negative trends. Kendall's non-parametric test with significance level > 90%.

Linear least squares regression indicates a significant (F>3) positive trend at 5 stations in March (>0.9% increase in rainfall per annum), two in February and one in April. A negative trend (F>3) averaging more than 0.8% per annum is found at 6 stations in July (the only month where all stations taken together shows a significant trend at this level) and at one station in September.

A number of authors have searched for seasonal precipitation changes. Strongest increasing trends in some other mid-latitude countries have been observed in the winter season. Wigley and Jones (1987) noted a statistically significant increase in the frequency of dry summers and wet springs over England and Wales during the 1976 – 1985 decade. However, this tendency was not continued during the subsequent five years (Gregory et al., 1991). Mayes (1996) examined a large number of British and Irish (33 Irish) records for the period 1941 to 1990 and found increasing precipitation in autumn, winter and early spring. The results of the present study differ somewhat from his over Ireland. For example, all 12 stations examined here show positive April trends, whereas his results would indicate a negative trend except for the stations in the East and southeast of the country. However, the fact that he worked mainly with differences between 1941 to 1970 accumulations and 1961 to 1990 accumulations and that the present study covers the (generally wetter) 1990s would probably account for any discrepancy.

The pattern reported here seems somewhat different from that in the UK also. For example the 1961 to 1995 period (reported by Osborne et al, 2000) in the UK shows strong increases in winter, weak in spring, weak decreases in summer and increases in autumn.

The corrections described for Drumsna made little difference to the significance of results in this study.

2.2 Seasonality

Variations in the seasonality of rainfall patterns was examined also using a relative Seasonality Index (SI, Walsh and Lawler, 1981) on a decadal basis.

$$SI = \frac{1}{\overline{R}} \sum_{n=1}^{n=12} \left| \overline{x_n} - \overline{R}/12 \right|$$

where

$\overline{x_n}$ is the mean rainfall of month n,

and

$\overline{R}$ is the mean annual rainfall.

This indicates the climate to be "equable but with a definite rainy season" in the 1970s and 1980s, but to have been "very equable" during the 1960s and 1990s at most stations examined. A small trend towards increased equability was detectable at most stations through the 59-year series. This trend could be better quantified by analysis of the series of annual SI.

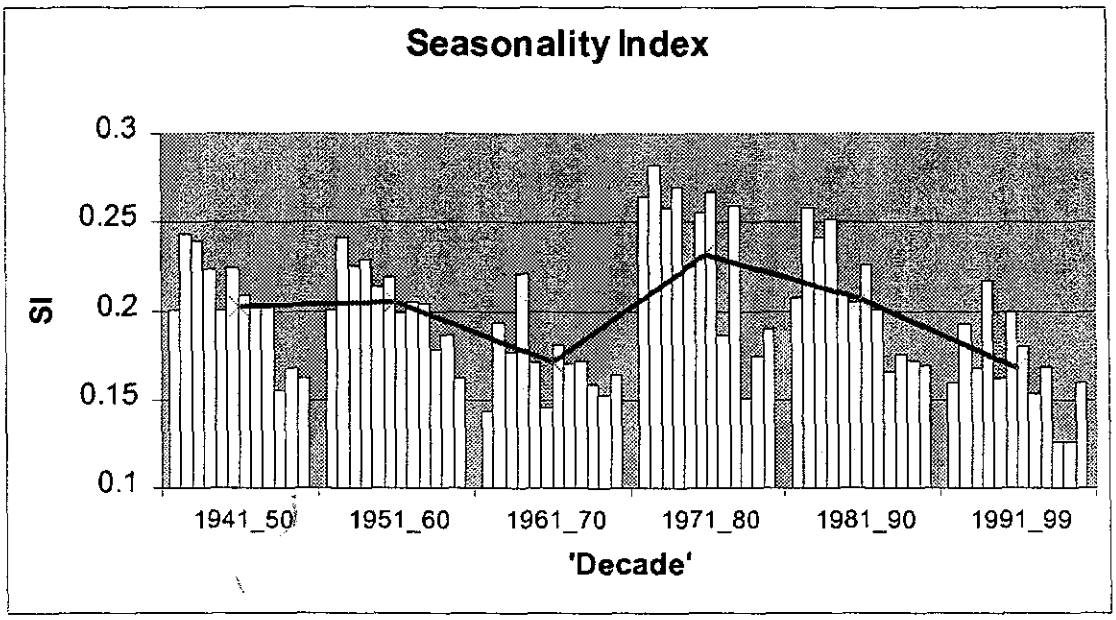

Fig 6 Seasonality Index by decade for each station (columns) and for average of 12 stations (heavy line).

Examination of the monthly series for the average of all 12 stations as a percentage of annual mean over the whole series shows the same general pattern as in Fig 1 of Logue 1978 (where rainfall for 1941 to 1970 for 11 stations including three of those dealt with here was examined). April is the driest month, February to July being the driest six months. Upon breaking the series into two, it is clear that the months of January, February, March and October during the 1971 to 1999 period had a greater proportion of the annual rainfall than in the earlier period. Nevertheless, February to July remains the drier six-month period of the year. If the trend apparent in fig. 7 continues, the dry half of the year can be expected to become April to September, This type of change is consistent with the findings of Thomson (1999). Examination of a larger number of longer-term precipitation stations in Britain and Ireland (Thomson, 1999) found no trend in the amplitude of the yearly precipitation cycle.

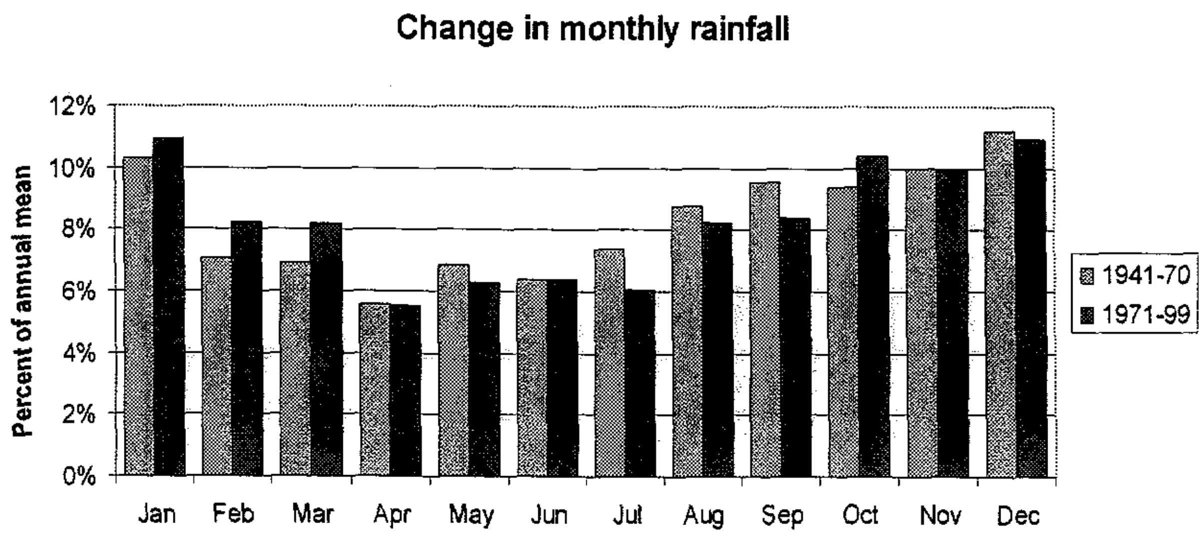

Fig 7 Percentage of annual rainfall occurring in each month for two sub-series.

When the year to year variations in the 1971 to 1999 series is compared to those of the previous 30 years, 10 months were found to show variability increasing at some stations and decreasing at others. The exceptions were August where all stations show increased variances and November, which shows decreased variance within the later series compared to the earlier. Three stations showed significant (<10% F-test) decreases in March and April and 4 in November. Six stations showed a significant increase in May and 5 in August.

2.3 Significantly wet months (SWMs)

For the definition of significantly wet month, the monthly rainfall was normalised as described in appendix III

A SWM was defined as a normalised value exceeding one.

The annual number of SWMs at the stations shows wide year-to-year variation. Taking all stations together and looking at the annual series, there is a maximum of 44, minimum of 2 and a mean of 22.2 significantly wet station months per annum (there is a potential for 144 significantly wet station months in a given year). In general terms the (smoothed) number of SWMs per year is high during the 1950s and early 1960s, falls to the series minimum around 1970, rising again to the series maximum in the mid-1990s. This pattern is very similar (as might be expected) to that of the annual accumulations mentioned in 1.2 above. Though the three highest values are in the early part of the series, overall there is an increasing trend in the numbers of SWMs of about 0.4% per annum. However, the statistical significance of this figure is not high (F=1.7 for linear regression).

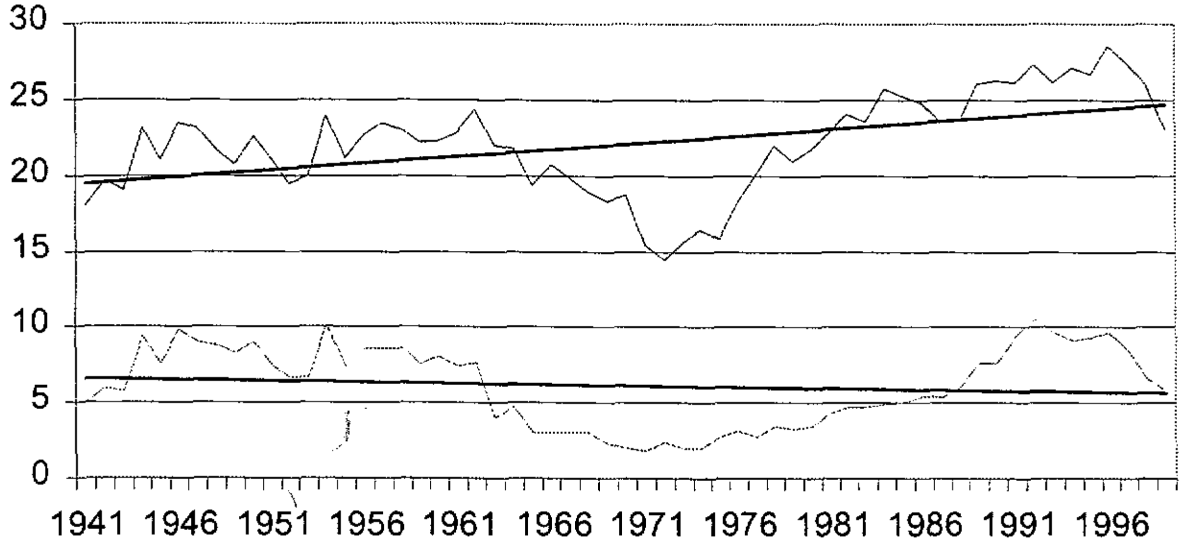

Fig 8. Upper graph: Number of significantly wet months (greater than or equal to one standard deviation from the 1941 to 1999 mean).
Lower graph: Total number of consecutive months greater than one standard deviation from the mean. In the latter graph, the number plotted is the sum of the maximum number of consecutive months at each station with rainfall of more than one standard deviation above the mean – isolated SWMs ignored.
Both graphs smoothed for clarity.

Sequences of two or more successive SWMs (which were assigned to the year containing the first month of the sequence) reach maximum in the late 1940s and the 1950s, minimum in the 1970s and another maximum in the early to mid 1990s. There is no significant trend in this case.

2.4 Years containing top and bottom five-percentiles

For each month, the three wettest years and the three driest years were identified for each station and noted in two (wet / dry) tables. The tables contained the number of stations observing one of their three wettest / driest years in that year (each calendar month considered separately). These would correspond approximately to the wettest five-percentile and the driest five-percentile. Thus for a given month we had 36 entries in each table. Most monthly entries were, of course, zero. The tables were aggregated into seasonal and annual numbers of wet (dry) years and temporal trends sought. Note that the seasonal totals were simply the sum of the entries in the relevant monthly table and thus, for a given year, simply represent the total entries in the top or bottom five-percentiles for the individual months. In this case, there were 108 (12stations by 3 extremes by 3 months) entries per seasonal series and 432 (12*3*12) for the annual series. Increasing trends in wet year counts were observed in all seasons, the largest being spring (Student's t=1.22 on slope, significance level about 88%) and annual (t=1.98, significant at 95% level). Interestingly, seasonal counts for dry years are

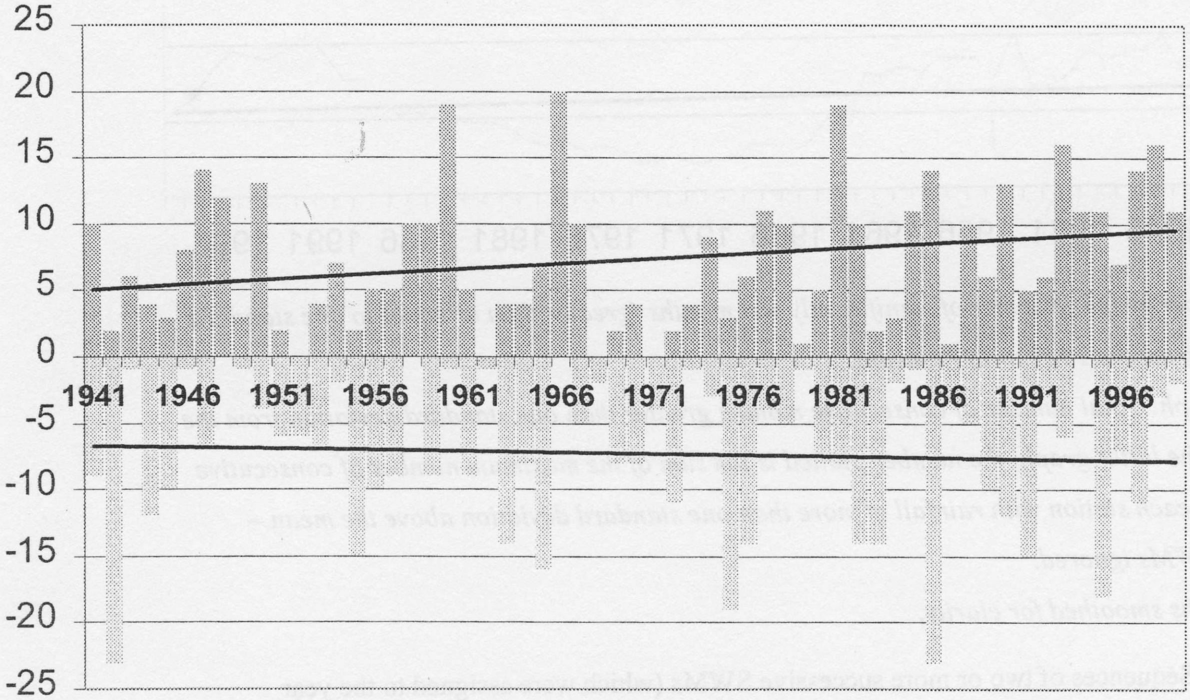

Fig 9. Annual number of station months in the top and bottom 'five-percentile'. Positive numbers: wet station months. Negative numbers: dry station months.

also increasing over the period for winter, spring and summer, though trends in all cases are smaller than for wet years and there is a small negative trend in the annual count. Only the annual wet year count trend is statistically significant at greater than 90%, with number of annual entries rising from about 5.1 at the beginning of the series to over 9.4 towards the end.

3 Rain Days

Monthly Rain Days (precipitation □ 0.2mm) were examined. Readings from almost all rainfall stations are now taken in mm with a resolution of 0.1mm. The change from inches (with resolution 0.01", equivalent to 0.254mm) to millimetres took place at most stations during the 1960s. Therefore, taking 0.01" as defining a rain day prior to changeover might indicate a potential for a discontinuity. Anything in excess of 0.005" might be expected to be coded as at least 0.01". The mm equivalent of these two figures (to the nearest 10th) would be 0.1 and 0.3. Thus some of the readings which with the more recent measuring cylinders would be read as 0.1mm, may in fact have been recorded as 0.01" and converted to rain days of 0.3mm. However, examination of the records of some stations for which the changeover date is on record do not seem to indicate any such discontinuity.

The data

Small amounts of data (17 figures out of 8,496 or 0.2%) were missing. More worrying was a somewhat larger number (0.7%) of reports of zero monthly rain days. Many of these (27) were clearly in error as there were daily falls in excess of 0.2mm quoted in the greatest daily falls field. In most of the other cases no greatest daily falls were in the table. For all these data, an estimate for the missing or incorrect rain-day data was based on an equation developed from a linear regression of available data for the rain days for the particular station using all other station data (c.f. appendix III).
This corrected rain day series was used throughout the analysis.

Analysis method

For each month of the year, the series of 59 values of number of rain days for each station (and also the average for all 12 stations) were examined. Some were plotted for visual inspection. All series of 59 numbers were analysed using Knp methods (Tau, Z and probability) and parametric methods (linear regression of number of rain days on year).

3.1 Year as a whole *Increasing number of rain days.*

The 12 stations showed a mean of 216 rain days per year over the period as shown in the table.

Station	Tau	Z	Prob	Signif.	Min	Max	mean	std_dev
108	-0.060	-0.6728	0.5011	49.89%	161	223	192	16
305	-0.097	-1.0817	0.2794	72.06%	205	277	241	16
417	0.316	3.5311	0.0004	**99.96%**	179	281	224	22
441	0.003	0.0331	0.9736	2.64%	218	302	258	18
518	0.032	0.3553	0.7224	27.76%	182	256	215	17
706	0.289	3.2354	0.0012	**99.88%**	169	267	214	21
915	0.014	0.1585	0.8741	12.59%	161	232	193	16
1529	0.017	0.1912	0.8484	15.16%	198	290	236	17
1712	-0.108	-1.2122	0.2255	77.45%	161	229	198	15
1723	-0.093	-1.0409	0.2979	70.21%	174	244	206	16
1823	0.052	0.5865	0.5575	44.25%	163	226	196	16
1923	0.159	1.7779	0.0754	**92.46%**	182	257	220	17
All	0.056	0.6283	0.5298	47.02%	186	244	216	14

Using the Knp analysis, 8 stations showed a positive trend, and four a negative one. This trend was significant at the 90% level for the positive trend at three stations, of which two (Inagh and Mallow) were significant at above the 99% level.

Using linear regression, 7 stations showed positive trend and five a negative one. Three stations had significant trends, as defined by F greater than 3. All three (Inagh, Mallow and Glenasmole) station trends were positive. These trends amounted to increases in annual number of rain days of 0.28%, 0.25% and 0.12% per annum (6, 5.5 and 2.6 days per decade) respectively. Linear regression of the average number of rain days for all 12 stations shows a 0.04% increasing trend but with an F value of only 0.77.

3.2 Individual months *Increasing numbers of rain days winter and early spring; decreasing numbers late summer, early autumn.*

Non-parametric analysis of the 12 stations for 12 months show approximately equal numbers of increasing trends (76) and decreasing trends (68). But of these, 8/14/22 were significant positive trends at 99%/95%/90% level, whereas only 2/4/11 of the negative trends were significant at these levels respectively. Thus it can be said that the significant trends were predominantly positive.

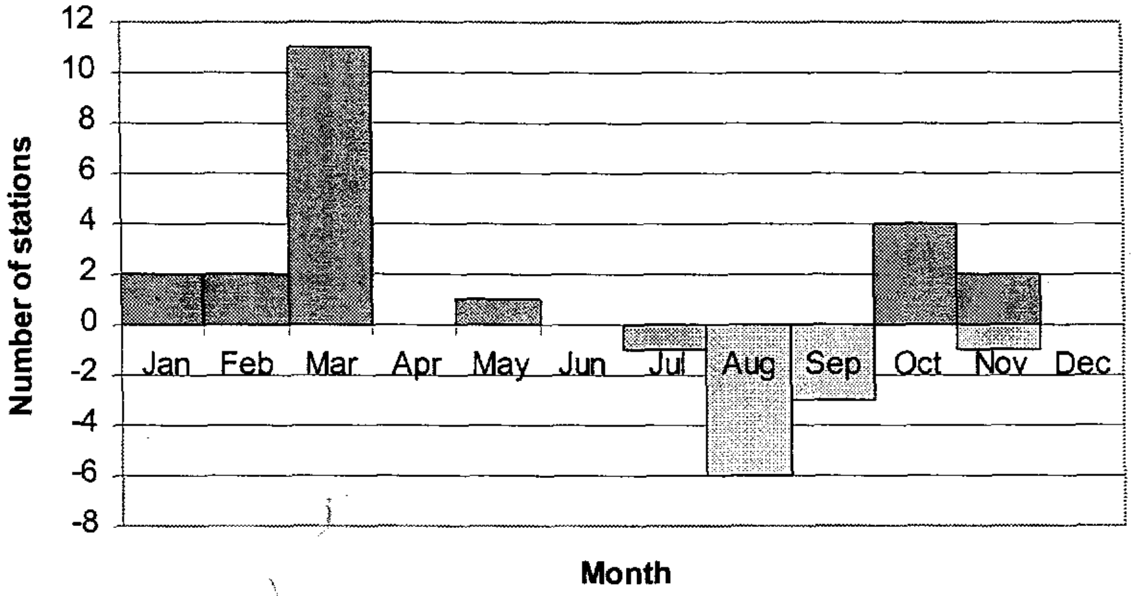

Fig 10. Number of stations showing significant (90% Kendall) trends over the 1941 to 1999 period in each month. Negative numbers are the number of stations with decreasing trends in rain days.

Fig 10 shows the positive trends tended to occur in late winter / early spring whereas the negative trends were predominantly in the late summer. March was the month with the most positive trends and August had the most negative ones. While 11 of 12 stations showing a positive trend in March (at 90% level, 9 of which were significant at the 95% level) might appear a very significant result, it should be pointed out that synoptic systems are responsible for much of the rainfall in Ireland and the scale of many such systems is such that they would be expected to effect most of the stations – i.e. there is a lack of independence amongst the stations. Some spot checks were done for a number of months to see how the rain-day count correlated between different stations. Correlation coefficients (as defined above in section 1.1) between stations were generally above 0.7 (sometimes considerably higher) and rarely below 0.6.

No formal sensitivity study was undertaken of these results to see how much they would be affected by a short series of wet or dry months (Augusts or Marches, for example). However, it should be mentioned that the March rain days (averaging for all 12 stations) during 1996 to 1999 inclusive were all below the 1941 to 1999 average – the positive trends were due mostly to the fact that only two of the twenty years 1976 to 1995 dipped below the March average. On the other hand, a general trend downwards in the all-station average raindays appears to be evident in August on visual inspection of the complete series.

Looking at the 12-station average number of rain days there is a +0.63% per annum (1.1 days per decade) trend in March. The standard error on this linear trend is less than 0.2%. The corresponding figure for the negative trend in August is –0.28% with a standard error of 0.22%. The strongest March trend was at Inagh with +1.08% (2 days per decade) and standard error 0.21%. In August the station with the strongest negative trend is Knockaderry with –0.64% per annum (1 day per decade) and standard error 0.27%.

3.3 Changes in the mean *More rain days per annum in the past three decades than earlier*

March, the month with the most significant trends, shows little or no trend in the annual number of rain days up to the middle of the series, a strong rise during the 1970s and insignificant trends thereafter. The mean annual number of rain days (from all 12 stations for March) is 16.3 in the period 1941 to 1970 and 20.0 for the remainder of the series. The hypothesis that the means are equal (as opposed to the later series being greater) is rejected at the 99% confidence level for 8 of the 12 stations and for the average of all for March. The exceptions are Foulkesmills, Johnstown Castle and Phoenix Park, where the hypothesis is rejected at the 95% level and Knockaderry for which the hypothesis would be rejected with about 85% confidence. Change-point analysis (West, R.W and Ogden, R.T., 1997) indicates 1975 as the year where the change took place with a March mean of 16.1 rain days before and 21.1 days after the change.

While the transition is less obvious, the mean number of rain days in the second half of the series for September is generally less than the first half. In this case, the one-tailed hypothesis of equality can be rejected with 95% confidence for four stations and for a further two using 90% confidence. Change-point analysis (West, R.W and Ogden, R.T., 1997) indicates 1985 as the year where the most significant change took place in the September all-station rain-days with a mean of 18.5 rain days before and 15.9 days after the change.

3.4 Variance changes *Increasing year-to-year variation in spring, reducing variation in late autumn.*

Initial graphical inspection of some of the series seemed to show an increasing year-to-year variation during the second half of the series. Therefore the variances in two sub-series for each month and each station were analysed. These were the 30-year series 1941 to 1970 and the 29-year series 1971 to 1999. In each case the variances of the two series were compared. The F-test was used to test the hypothesis that the sets of variances were not different. Looking at the yearly totals of rain days, the hypothesis is rejected at the 10% level for one station (Glenties) which shows the later variance to be lower. The hypothesis is rejected at the 10% level for one station in January, three in April (two of which are rejected at the 5% level), one in May, all showing higher variances in the later period. On the other hand, three stations show a reducing variance (hypothesis rejected at 10%, two of which at the 5% level) in November.

3.5 Intensity variations *Some significant changes observed in April to July*

A proper study of rainfall intensity requires the use of data with temporal resolutions from minutes to days, as opposed to the monthly resolution employed generally in this investigation. However, a crude indicator of intensity is the monthly (or annual) accumulation divided by the number of rain-days. These rain-day mean fall figures were examined. They are generally quite noisy.

The mean intensity (with the meaning used here) over the whole period for the average of all 12 stations is 5.2 mm per rain day with a standard deviation of 0.2. The largest value is 7.3 for Inagh and the lowest is 3.7 for Phoenix Park. For all stations taken together, rainfall for each of the six months February to July was less intense (minimum 4.2 mm per rain day in April) than for the other six months of the year (maximum 5.7 mm in October and December).

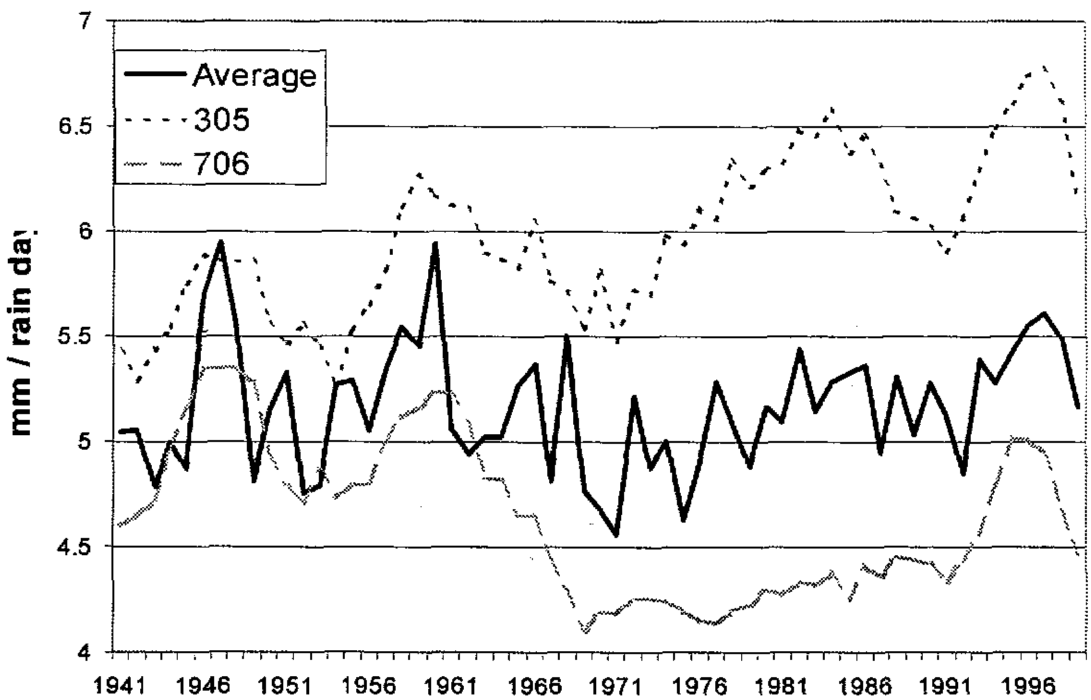

Fig 11. 'Intensity' of rainfall expressed as mm/rain day. Average of all 12 stations, station with the strongest significant positive trend (Valentia) and the strongest significant negative trend (Mallow).

Looking at the year as a whole there is no significant trend in the data for all stations taken together. However, prior to 1971 the intensities are more variable but with a slight downward trend whereas after this date there is less year-to-year variation and a definite upward trend. Regarding the year-to-year variability, the series prior to 1971 has a higher variance than those from 1971 onwards for all six stations where the hypothesis of equal variances is rejected at the 90% level (F-test). Linear regression over the whole 59 year period showed up statistically significant trends, both positive and negative, at individual stations with no obvious relationship between trend sign and location.

Taking all stations together, the months October to February inclusive all show positive trends in intensity but none of these is statistically significant. April and June have significant positive trends (F>2) and May and July have significant negative trends. This confirms what can be seen from a direct comparison of the percentage trends for changes in monthly rainfall accumulations – the (positive and the negative) trends in monthly accumulations result more from changes in accumulations on rain days than from trends in the numbers of rain days.

4 Wet Days

Monthly Wet Days (precipitation □ 1.0mm) were examined using the same methods as in the case of the rain days.

The data

In this case 0.2% (17) of the data was missing and 0.82% (70) was zero. Six of the zero reports were deemed to be correct on the basis of consistency checks, reducing the 0.82% to 0.75%. Apart from these six cases, the multiple linear regression procedure as described in appendix III was used to provide estimates of the missing data and the same analysis procedure was employed.

4.1 Year as a whole *Some negative trends*

77% of rain days were also wet days. Using the non-parametric test, as can be seen in the table, 7 stations showed a positive trend and five trends were negative – interestingly only 5 of the stations' trends were of the same sign as for rain days.

Station	Tau	Z	Prob	signif.	Min	Max	mean	Std_dev
108	-0.126	-1.406	0.160	84.03%	110	176	144	14
305	0.028	0.316	0.752	24.77%	155	229	188	16
417	0.016	0.178	0.859	14.12%	170	238	203	17
441	0.055	0.619	0.536	46.43%	176	248	215	17
518	0.062	0.694	0.488	51.23%	124	194	161	15
706	-0.094	-1.050	0.294	70.61%	131	195	164	15
915	-0.148	-1.660	0.097	90.31%	110	175	146	15
1529	-0.013	-0.146	0.884	11.59%	136	208	178	16
1712	0.092	1.028	0.304	69.62%	114	180	148	15
1723	0.092	1.029	0.304	69.65%	108	168	142	14
1823	0.005	0.059	0.953	4.73%	94	160	133	14
1923	-0.145	-1.616	0.106	89.40%	138	221	170	16
All	-0.001	-0.013	0.990	1.04%	137	191	166	13

Interestingly also, only one station's trend for the annual series was significant at the 90% level (the negative trend at Johnstown Castle).

Linear regression indicates 8 positive trends and 4 negative ones. Using the F > 2 criterion, two stations (Johnstown Castle and Glenasmole) had significant trends, both of which were negative. These amount to an annual trend of –0.13% and –0.11% per annum in annual number of wet days. There is no indication of a trend for all stations taken together.

4.2 Comparison of Annual Rain days and Annual Wet Days *Increasing frequency of light rain days*

These results for those wet day trends of statistical significance differ markedly from the rain days trends in that the former are negative and the latter positive. The difference between rain-day count and wet-day count was examined. This is the number of days with light (□ 0.2mm and < 1.0mm) rain, with an all-station annual average of about 50 days. As might be expected there is a small but significant (F=8.8) positive trend amounting to 0.19% per annum equivalent to about one extra light rain day per annum per decade.

4.3 Individual Months *Increasing numbers of wet days in March, decreasing in August, September*

For all 144 analyses, there were 67 positive trends and 77 negative ones. There were 5 / 9 / 12 positive and 1 / 6 / 14 negative trends significant at the 99% / 95% / 90 % level respectively. As with the rain days, the positive trends dominate in the case of the more highly significant trends, but the dominance is not as marked and in the case of 90% significance level, there are more negative trends.

March dominated in the case of positive trends (8 stations at the 90% level) with three

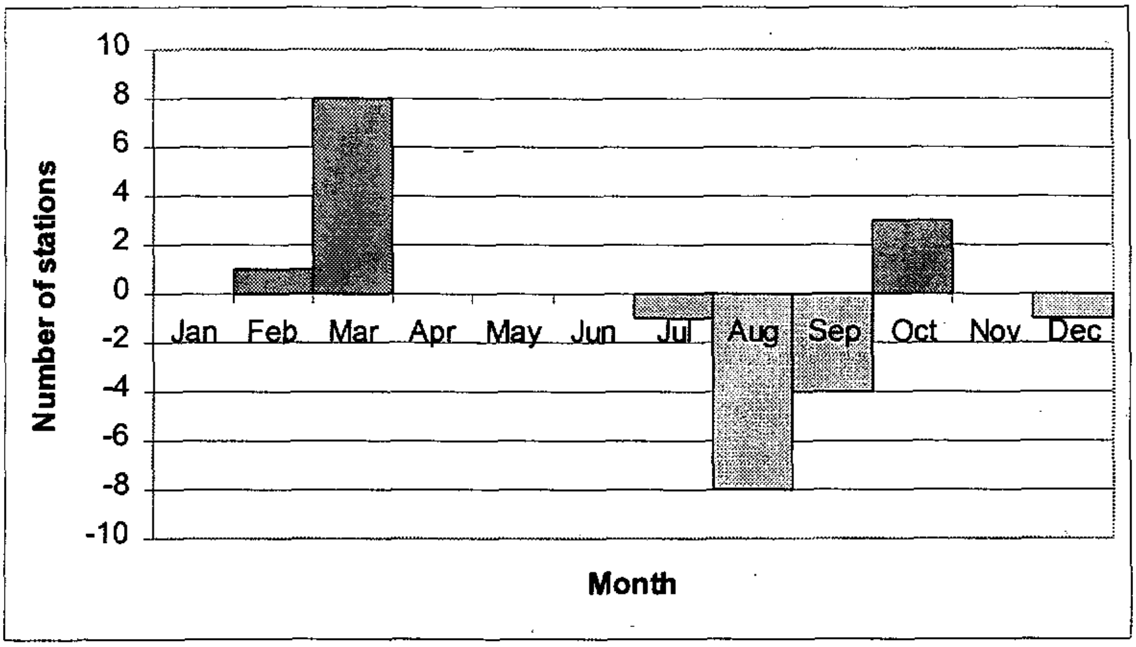

Fig 12. Number of stations showing significant (90% Kendall) wet day trends over the 1941 to 1999 period in each month. Negative numbers are the number of stations with decreasing trends in wet days.

in October and one in February. August and September dominated in the negative trends (8 and 4 stations respectively at the 90% level) with one in each of July and December.

Looking at the graphed results for March (the month of most positive trends), the positive trend is due mostly to the dominance of above normal numbers of wet days during the 20-year period 1976 to 1995. The March linear trend for the average number of wet days for all 12 stations amounts to+0.6% per annum (0.8 days per decade) with standard error of 0.2%. The stations with the strongest linear trend in March (Glenties and Drumsna) each amount to +0.9% per annum (about 1.5 days per decade) with standard error of 0.2%.

In the case of August, the average station wet days trend is –0.41% (about –0.5 days per decade) with standard error of 0.25%, while the strongest station trend is –0.7% per annum (-0.8 days per decade) with standard error of 0.3% at Johnstown Castle.

5 Extreme rainfalls

5.1 Greatest Daily Falls (gdf) *Maximum falls becoming heavier in March, April and June, lighter in May*

Extreme rainfall is of interest for building and infrastructure design, agriculture and of river flooding, amongst other things. While many studies have found an increasing trend in annual, seasonal and monthly rainfall accumulations in various countries around the world, there is increasing evidence that in many cases heavy or extreme rainfall events are contributing disproportionately to this increase (IPCC, 2001).

GDF is regularly extracted from the Met Éireann's rainfall data and stored in the MONTHLY_RAIN table. In the case of the 12 stations studied here, there were 104 (1.2%) missing values. The reason for most of these omissions is outlined in appendix III. The multiple linear regression procedure (appendix III) was used to fill in missing days. As mentioned previously, the procedure of examining the daily records and applying a procedure such as that outlined in Brunetti et al, 2001b or recreating some of them by a re-examination of the original records, may be preferable in the case of GDF. It is considered that application of the regression procedure with the relatively small number of missing da ta did not introduce any significant bias.

The 59-year series of gdf was examined for each station for each month and for the maximum gdf for all stations taken together.

For the year as a whole, 5 stations show an increasing trend in GDF and seven are decreasing. None of these trends is significant at the 90% level using the Knp test, though linear regression would seem to show significant trends at two locations – a positive trend at Valentia (F=2.4; c.f. also Valentia graph shown at the European Climate Assessment site http://www.knmi.nl/samenw/eca/index.html) and a negative one at Mallow (F=2.7). Taking the maximum GDF from the 12 stations, there is an increasing but non-significant trend of 0.17 mm/annum.

Maximum annual gdf (i.e. the series constructed from the 59 values of the maximum for a given month from all 12 stations together) shows an increasing trend for 9 of the 12 months. The increasing trend is significant at the 99% (Knp) level for June and at the 95% level for March. The negative trend in May is significant at the 95% level. The strongest of these trends amounts to +0.24mm/annum for June.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Positive	4	5	10	11	0	11	1	6	1	11	11	5	5
Negative	8	7	2	1	12	1	11	6	11	1	1	7	7
+90%	0	0	3	5	0	4	0	0	0	0	0	0	0
-90%	0	0	0	0	4	0	1	0	0	0	0	0	0

From the table, it can be seen that, in terms of significant trends (here taken as at the 90% level), positive trends dominate in March, April and June, with negative trends showing in May and July.

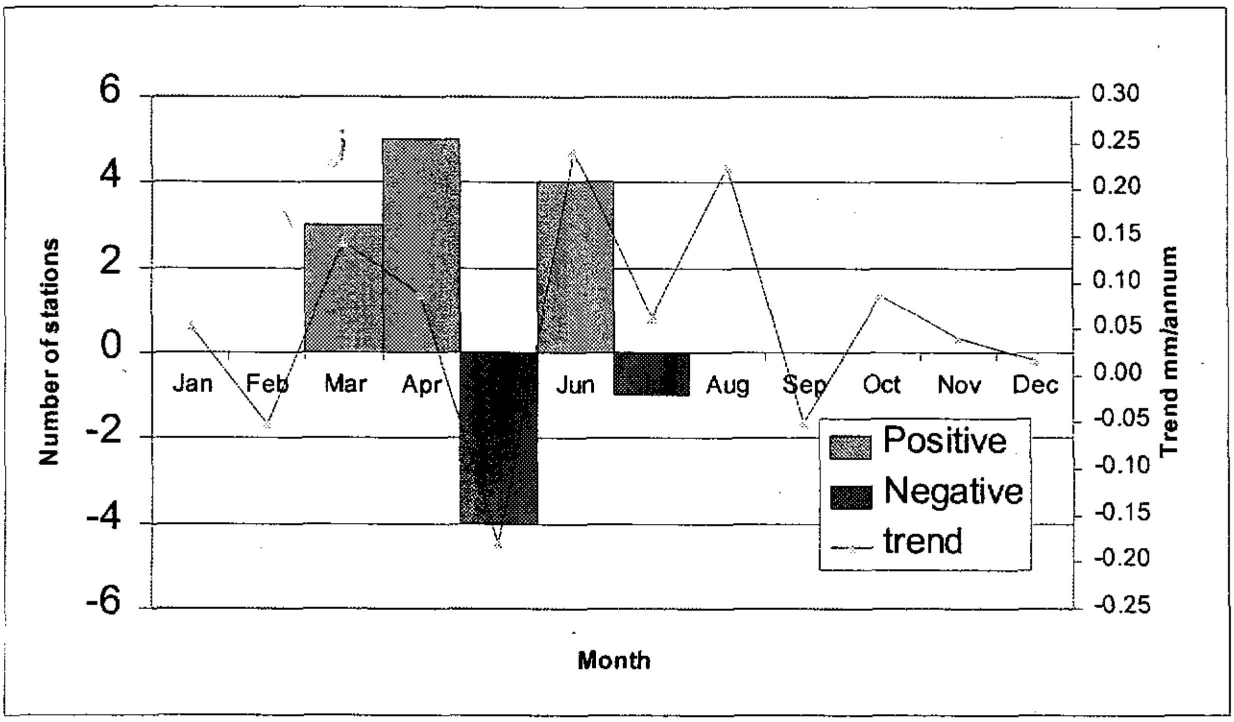

Fig 13. Number of stations showing significant (90% Kendall) Greatest Daily Fall (GDF) trends over the 1941 to 1999 period in each month (vertical bars and left hand axis). Negative numbers are the number of stations with decreasing GDF trends. Trend in maximum GDF (mm/annum; line and right hand axis)

5.2 Other Durations at Valentia *Heavy falls becoming heavier at Valentia.*

Reports for station 305 (Valentia Observatory) were extracted from the relevant database tables and the annual rainfall maxima for various durations were examined. These durations include 15, 30, 60, 120, 180, 240, 360, 720 and 1440 minutes from the maxfalls table (data originally extracted from rain recorder charts). Designation in terms of minutes used for convenience. As this table is constructed to contain the incidences of occurrences of exceedence of certain thresholds, there was one year (1990) in which no annual maxima were available for 360, 720 and 1440 minutes. In addition, the maxfalls data was available only from 1958 onwards. Annual maxima were extracted from the HOURLY table for 1, 2, 3, 4, 6, 12, 24 and 48 hours durations starting in 1941. From the 1941 to 1999 DAILY_RAIN table, annual maxima were extracted for 1, 2, 5, 10 and 25 days.

Output Table for Valentia (305)

Italic: t >1.5 **Bold t >1.7** ***Italic & Bold t > 2***

Years	Duration	Kendall Z	Significance level	Annual trend % (of 61-90 aver)	std err	1961-1990 Average
1958 - 1999	15 minutes			**0.9%**	0.51%	6.6
1958 - 1999	30 minutes			0.6%	0.42%	9.3
1958 - 1999	60 minutes			0.4%	0.35%	13.4
1941 - 1999	1 hour	0.876	61.9%	0.2%	0.21%	12.5
1958 - 1999	120 minutes			*0.5%*	0.31%	19.9
1941 - 1999	2 hours	0.949	65.8%	0.2%	0.20%	19.3
1958 - 1999	180 minutes			*0.5%*	0.30%	24.4
1941 - 1999	3 hours	0.926	64.6%	0.3%	0.18%	23.9
1958 - 1999	240 minutes			*0.5%*	0.30%	27.8
1941 - 1999	4 hours	0.636	47.5%	0.2%	0.17%	27.7
1958 - 1999	360 minutes			**0.5%**	0.31%	33.3
1941 - 1999	6 hours	1.035	69.9%	0.3%	0.18%	33.1
1958 - 1999	720 minutes			0.4%	0.34%	45.1
1941 - 1999	12 hours	1.453	85.4%	**0.4%**	0.20%	44.7
1958 - 1999	1440 minutes			0.4%	0.39%	55.5
1941 - 1999	24 hours	1.505	86.8%	**0.4%**	0.22%	55.3
1941 - 1999	1 day	1.101	72.9%	*0.4%*	0.25%	49.2
1941 - 1999	48 hours	2.103	96.5%	**0.4%**	0.21%	68.0
1941 - 1999	2 day	1.728	91.6%	**0.4%**	0.21%	64.8
1941 - 1999	5 day	1.898	94.2%	***0.3%***	0.14%	93.9
1941 - 1999	10 day	1.151	75.0%	*0.2%*	0.13%	135.5
1941 - 1999	25 day	1.368	82.9%	**0.2%**	0.11%	231.2

The table shows the results of the investigation. Knp tests on the 59-year series show increasing trends for all though only 2-day, 5-day and 48-hour duration trends are significant at the 90% level. Application of least squares linear regression to all the series shows a positive trend at all durations. In almost all cases the trends are greater than the standard error of the trends and the trends are significant at the 95% level for durations of 15 and 360 minutes, 12, 24 and 48 hours, 2, 5 and 25 days.

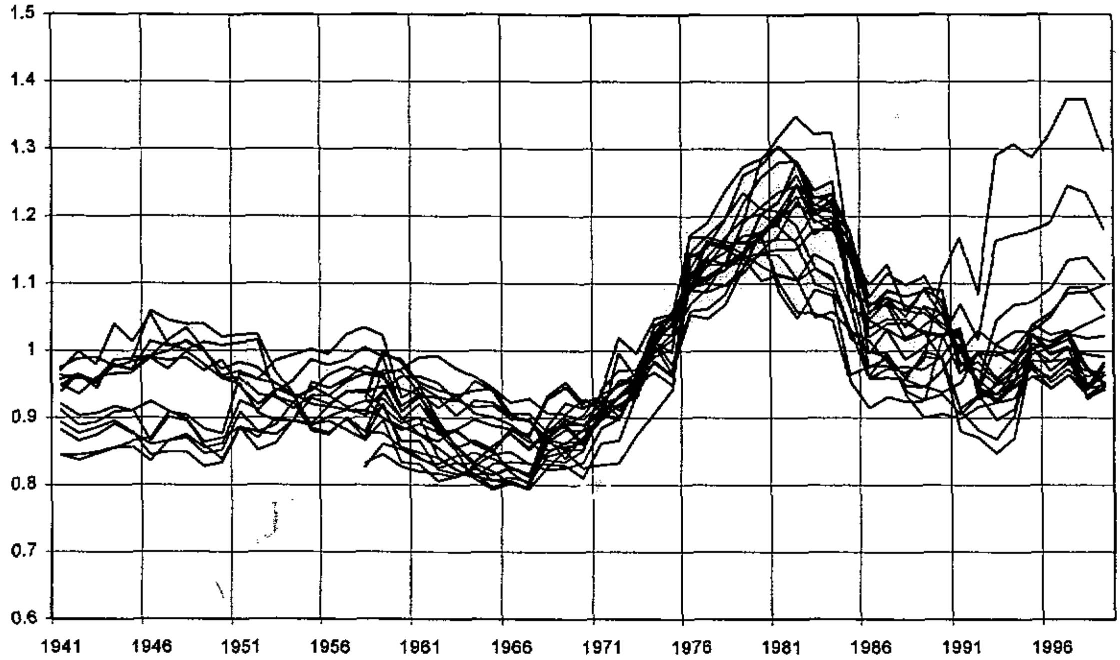

Fig 14. Valentia annual maximum rainfall for various durations. Actual values divided by the mean of 1961 to 1990 values for the particular duration. 9-point smoothing.

Fig 14 shows a tendency for the annual maxima for most durations to decrease between 1941 and about 1967, rising strongly to a maximum around 1982, falling for the remainder of the 1980s and then followed, generally, by no major changes in the 1990s. The exceptions which stand out in the 90s are the 15 and 30-minute falls which rise strongly.

It should be noted that these trends are for Valentia only. In the examination of the GDF above, the 12 annual series for the stations showed both positive and negative trends and (based on the magnitude of Student's t) Valentia had the strongest positive trend while the negative trend at station Mallow (Mallow) was even stronger. Likewise, of the stations examined Valentia was the one with the strongest trend in annual accumulations.

6 Rainfall and the North Atlantic Oscillation

There is a suggestion that the North Atlantic Oscillation has a significant effect on rainfall. A brief examination of the correlation between the NAO index (c.f. http://www.cru.uea.ac.uk/cru/data/nao.htm) and some of the figures analysed above was undertaken. The following table shows the correlation coefficient between the NAO and the annual variables mentioned.

Station:	108	305	417	441	518	706	915	1529	1712	1723	1823	1923
Annual accum	-0.09	0.19	0.46	0.53	0.30	0.04	-0.06	0.34	-0.10	-0.11	-0.10	-0.10
Annual GDF	-0.11	-0.12	-0.14	0.00	-0.18	-0.12	-0.14	-0.15	-0.05	-0.03	-0.07	-0.17
Annual wet-days	0.11	0.50	0.49	0.51	0.46	0.17	0.07	0.53	0.18	0.02	0.08	0.16

The larger correlations with annual accumulations tend to be positive, especially in the western half of the country. In the east the correlations tend to be negative but smaller. Though the correlation coefficients between NAO and annual greatest daily rainfall are relatively small, they are generally negative – i.e. years with stronger westerly gradients in the North Atlantic tend to have lower GDFs. As might be expected, annual numbers of wet days correlate positively with the NAO index. Again, this correlation is highest in the west of the country. In general terms, the signs of the correlations in the table above fit well with the fact that eastward-moving Atlantic frontal systems dominate our weather and that convective systems are most active in the East and Southeast of the country.

Examination of the correlation between NAO index and monthly rainfall accumulations shows a number of statistically significant positive correlations. No significant correlations occur in the summer months (JJA). All other months show some significance at some stations. For example, Valentia, Drumsna, Glenties, Shannon and Inagh - the western stations - all show positive correlations (>99% significance) during the months of December, January and February. Indeed, there seems to be some predictive skill in the use of the NAO index for certain months. A significant negative correlation was found between March rainfall and February NAO index at 9 of the 12 stations. Regression of March rainfall on February NAO index for Mallow, for example, yields the following equation

$$Rain\ (mm) = 76.3 - 8.16*(Feb\ NAO\ index)$$

With a standard error of 32.8 mm. There is scope for further work in this area.

7. Summary and Discussion

The following are the major findings of this report: -

- Most stations show an increasing trend in annual accumulations over the 1941 to 1999 period

59-year annual rainfall trends vary from about –1% to +2.5% per decade. As might be expected from this, more of the top 5-percentile of wet months tend to occur later in the annual series. Similarly, the annual number of station months exceeding the mean for the particular station and month by one standard deviation shows an increasing trend.

- Monthly totals are generally increasing in February, March and April and decreasing in July, August and September.

Most winter trends are small and variable. This result is somewhat surprising as many reports for other mid-latitude countries show strongest increasing trend in winter. Many climate change models show strongest future increases in winter and decreases in summer. One example is the Hadley model HadCM2 using the medium high scenario (1% GHG growth per annum) coarse mesh model (UKCIP, 1998). In the grid box which covers the south of Ireland, the mean of four runs shows for the 30 year period around the middle of the present century increased annual rainfall (+4% compared to 1961-1990), increased winter (+12%) and Autumn (+10%) falls and reduced precipitation in spring (-1%) and summer (-9%).

- The large number of significant positive trends in March and negative ones in September is particularly striking in the case of both rain days and wet days.

- Greatest daily falls for the year as a whole show small trends but some individual months show significant (March, April and June positive and May negative) trends.

- Three stations have significant increasing trends in annual number of rain days

A further 5 have non-significant increasing trends with the remaining 4 showing non-significant decreases. The average (of the 12 stations – mean 216 days) annual number of rain days shows a statistically non-significant increasing trend. Wet days (average 166) show a small and non-significant decrease. Light rain days (□ 0.2mm and < 1.0mm) show a significant increasing trend.

- There are indications of a change occurring around the early 1970s – a change in trend of annual accumulations, in the number of significantly wet months, rain per wet day, year-to-year variance etc.

- Standard deviations of annual accumulation of rainfall for the stations examined vary from 10.5% to 15.2% of the 59-year means.

- At Valentia maximum falls of all durations show an increasing trend Valentia was the only station examined for all durations from 15 minutes to 25 days. All durations show a strongly increasing trend in the 1970s and a fall in the 1980s.

- Rainfall is well correlated positively with the North Atlantic Oscillation Index, especially outside of winter months and especially in the West of Ireland.

- There are some significant correlations between monthly rainfall and NAO Index for the previous month.

The negative correlations between March rainfall and February index are worthy of further study.

No conclusive evidence of increasing occurrence of heavy rain is detectable from the trend of GDFs. However, a fuller study of this might better be performed using the numbers of exceedences of particular thresholds of daily and other duration rainfalls. Looking at the annual maxima series for various durations at Valentia, there is clearly a positive trend. However, it should be pointed out that in several respects Valentia appears to be an outlier of the 12 stations examined.

It should be noted that the stations are not evenly distributed around the country. Therefore, station averages which are quoted should not be taken as representing averages for the country. A much larger set of (homogenised) series – perhaps with results transformed to regular grids – is required for a comprehensive study of rainfall representative of the country as a whole or over sub-regions.

Another cautionary note is that the period dealt with here is 1941 to 1999. As discussed in section 1.2, for a relatively short period (59 years) trends can be quite sensitive to values in the early and late part of the series. To put this period in context, the trends in a few stations for which longer series of monthly falls are tabulated were examined. At Valentia (using data starting in 1861) the smoothed annual totals were decreasing till near 1970, at which time this trend reversed. Trends within a moving 59-year window are predominantly negative till those ending in the mid-1970s after which all 59-year trends are increasingly positive. At another coastal station, Malin Head in the North with tabulated data from 1890 onwards, the smoothed trends are all positive, with the smallest 59-year trends being those ending in the mid-1980s after which the trends become large again. On the other hand, the Phoenix Park data (also tabulated from 1890 onwards) indicate the smallest 59-year trends towards the end of the series but with only one year showing a negative 59-year trend (that ending 1997). The overall 110-year trend is, like Malin's, positive and statistically significant. On the other hand, the Valentia 139-year trend is not significant. These three stations, together with the long series for Markree Castle and Birr, all show marked local or whole-series minima near 1971, followed by notable rises.

The rain-day analysis (and consequently the light rain analysis dealt with in section 4.2) needs also to be taken with a certain degree of wariness. Measurement of light rain is particularly sensitive to wind strength, instrument design and exposure, relative humidity etc. Therefore the monthly or annual rain-day count will have considerable uncertainties which will be a function of other meteorological elements and of minor changes in instrument exposure.

Many climate change models predict decreases in summer rainfall and winter increases in mid-latitudes and this pattern has been detected already in many studies. While there is definite evidence of decreasing summer rainfalls in the stations examined in the present study, there is little evidence of any trend in November, December or January, whereas strong positive trends are evident in February, March and April. This study and others would seem to indicate that a change in the nature of rainfall occurred during the (early) 1970s and that therefore the 1961 to 1990 normals may not be the most appropriate reference baseline period for a search for anthropogenic climate change effects. A similar suggestion has been made by Mayes (1996).

Study of the nature of changes in Irish rainfall could be enhanced by extracting data from daily records from a larger number of stations and by examining the changes in accumulations falling into various frequency or amount percentiles.

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Appendix I Some Metadata examples

108 Foulkesmills (officially opened 1/1/1873)

30/8/1939	Non-standard gauge (bad condition – very shallow funnel since 1887) read between 1000 and 1100 clock time. Trees 100' high 300' distant.
24/6/53	No change in exposure. Gauge in good order
13/6/1959	New gauge issued to replace non-standard funnel.
Sep-Oct 1960	Gauge moved to new position
29/3/1977	Holly tree has grown too high near gauge. Gauge moved c 30'
28/5/1987	Gauge Replaced

305 Valentia (1866)

16/5/1963	Factory built in industrial estate, 350m SE of anemometer, several more units followed between 1975 and 1990
12/9/1965	Spruce trees planted around Variometer house, 100m W of anemometer, 150m S of enclosure
24/4/1993	Some trees removed from Variometer house
11/6/1997	Community college (12m high, 72m long) commenced, 150m N of anemometer, 3m below the level of adjacent Observatory ground.
15/2/1999	New enclosure / observations room. New Dines Syphon Rain Recorder. New 5" raingauge. New Casella tipping raingauge.

417 Inagh (1897)

29/05/1943	New gauge
15/06/1995	New gauge

441 Glenties (21/12/1923)

10/03/1948, 21/09/1966, 08/04/1976	New gauges
03/10/1967	New site for instruments

706 Mallow (1/1/1925)

29/04/1952	New gauge 6074/51
09/07/1993	Gauge moved to new location

915 Johnstown Castle (1/1/1914)

08/04/1964	New site
29/09/1981	New site - (close to old site)
1999 –2000	Trees planted around enclosure (not (yet) interfering)

1529 Drumsna Albert Lock (1876)

16/6/1942	New gauge (from c 14 months parallel readings. New 54% more!)
01/08/1943	Readings from old gauge ceased
31/1/1969, 7/12/1971, 30/11/1972	New gauges
22/10/1997	Gauge moved 3 yards.

1712 Knockaderry, Co.Waterford (01/01/1886)

01/01/1929	Gauge moved to new position, figures prior to 1929 are unreliable
23/06/1993, 23/06/2000	New gauges

1823 Glasnevin, Dublin (01/01/1829 Station opened)

01/08/1950	New site

1923 Glenasmole, Co Dublin (1885 Station opened)

10/04/1986	New gauge

Appendix II Correction procedure for Drumsna (station 1529) 1941 to 1999 rainfalls

In the course of the study of trends in monthly rainfall from all stations in the database which had a complete 1941 to 1999 record, it was noticed that some of the Drumsna reports seemed to stand out as different. This seemed to be due to anomalously low values early in the series. Other stations may have some dubious results elsewhere in the series but their trends over the whole series did not cause them to stand out. As a matter of fact, the worst years indicated in the report below for Drumsna did not become apparent till the investigation below was begun, presumably because they were located towards the middle of the temporal series.

Each of the 12 months examined separately.
Stations selected as predictors which

a) are in the same catchment
b) contained sufficient reports for the month being examined such that at least a total of 50 (of 59) months, which included predictand and all predictors, were available for regression.

This left three predictor stations (1729, 1829 and 1929).

Generally 1829 was the best predictor and 1929 the least significant. All three were retained.

Linear regression of Drumsna on the other three was performed for each month (53 to 57 points in each case). Residuals were examined for anomalies. The residuals are scattered around zero with an approximately normal distribution. Thus for a given monthly series, about 17 would be expected to be more than one standard deviation from zero and about four more than two standard deviations (15 and four are the actual observed average figures). For this analysis, an Excel add-in, Essential Regression, was used because of its comprehensive range of facilities.

(Subjective part:) There may be valid reasons to consider positive residuals differently from negative ones. For example, problems at an individual station will most often show up as a reduction in its rainfall accumulation (a negative residual). To some degree such a problem in the predictor stations will not be apparent, or if so will be less significant, in the regression equation (assuming station problems are not correlated with one another) but not at the predictand station. However, real problems at a station would in most cases persist for a period. A decision was made to reject Drumsna observations whenever two consecutive months' residuals departed from zero by more than 1.5 times the standard deviation for that month.

In all cases of rejection by this criterion, the residuals were negative. The following months were indicated as candidates for rejection:

1942	Apr, May
1954	May, Jun, Jul
1964	Mar, Apr
1967	Jan, Feb, Sep, Oct, Nov
1968	Jan, Mar, Apr, May, Aug, Sep, Oct, Nov

The following is an extract from the station metadata file:

16/06/1942	New Gauge MS 163/40.
31/01/1969	New gauge MS 4102/46
07/12/1971	New gauge MS 6731/53
30/11/1972	New gauge MS 5259/50
21/01/1981	New observer
22/10/1997	Gauge moved to new position (three yards from original position)

There was a problem with the gauge during 1941 and 1942. The statistical procedure employed here showed negative residuals on 15 of the 17 months preceding the installation of the new gauge in 1942, though only two months met the criteria for rejection. There were some comparative studies done at the time which would seem to point to the rejection of all months for this period. There seems to have been no similar comparison done at the time of installation of the new gauge in January 1969, but this present investigation suggests that most of the months in the preceding two years should be rejected.

It is not standard practice to replace observations in the database tables with estimates (as opposed to some cases where estimates made from surrounding days and stations may replace missing observations). For the purpose of searching for trends, however, it is appropriate to make some adjustments when they can be well founded. This would be part of a major homogenisation project. In the present case, it was decided to remove the months mentioned for 1942, 1954 and 1964 and all of 1967 and 1968 (except December 1968 – it may be that the new gauge was unofficially being used for this month), redo the regression and replace the observed values with calculated ones.

For the redoing of the regression, the NAG Excel add-in was used because of the ease with which observations could be excluded.

The table below shows the result of the adjustments

Comment

It is not proposed that data in the database be replaced with values by this type of method. However, when searching for trends etc., it seems reasonable to do some preliminary processing of data in suspect cases.

It is likely that some poor data will still get through. For example, the 1941 Drumsna data in the present case still seems anomalously low. In order to objectively trap and correct smaller errors which may persist over a longer period, a procedure of the type used here would need to be applied to aggregated months (seasons or years) as well as individual months. In this way, smaller but more persistent errors may show up as significant.

The method will obviously replace some valid data (possibly March and/or April 1964 in this case, for example). To guard against this, it seems reasonable to adjust only non-fitting data during some period preceding some physical change or corrective action at the station. The station files do not often indicate what problem was being experienced, when it began and so on, but if an instrument (a raingauge in this case) is replaced then it is likely that a problem with readings had been experienced for some preceding period. If this is confirmed by a statistical analysis then such data should be replaced by calculated values where possible.

Better tools are required for this type of analysis. Procedures such as those described above are very labour intensive. While software could be developed in-house to speed up the process, there would still be a considerable amount of manual intervention and procedures would still need to be done on a station by station basis. Some element of spatial analysis capability as might be available within a GIS would enable a degree of 'parallel processing'.

Calculated Values

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1942				47.2	100.0							
1954					98.5	79.0	135.8					
1964			105.3	75.3								
1967	62.4	75.0	78.5	36.3	112.3	36.7	82.2	85.1	118.2	173.5	67.7	75.0
1968	136.8	27.7	71.1	57.2	68.0	97.6	18.8	91.6	130.9	152.3	110.2	

Reported values												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1942				28.4	63.0							
1954					75.3	55.5	90.7					
1964			84.7	60.1								
1967	35.3	44.6	61.3	28.8	106.2	32.7	84.5	84.5	79.6	117.0	35.4	57.0
1968	102.6	17.9	37.0	34.5	49.2	81.4	29.3	62.9	100.5	113.2	72.6	

Difference (Calculated – Reported)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1942				18.8	37.0							
1954					23.2	23.5	45.1					
1964			20.6	15.2								
1967	27.1	30.4	17.2	7.5	6.1	4.0	-2.3	0.6	38.6	56.5	32.3	18.0
1968	34.2	9.8	34.1	22.7	18.8	16.2	-10.5	28.7	30.4	39.1	37.6	

Appendix III Technical aspects of procedures used

Estimates in the database

As mentioned in the introduction, a small number of the monthly data in the database table include estimates of daily rain. The most common cause of this is when accumulation of rainfall for two or more days is reported by the station. In such a case, the rainfall QC operator will not normally distribute the accumulation between the days in question. The only exception would be when only two days are accumulated and he is confident that one of those was dry. On some occasions when multi-day accumulations are reported the operator may be confident enough to say that a particular missed day would have been a rain day or a wet day. In such a situation he may not assign an actual amount to the day and, if the multi-day accumulation is sufficiently large to indicate one of the missed days may have contained the greatest daily fall for the month, there may be no greatest daily fall entered in the table for that month.

Homogeneity tests

The procedure applied for testing the homogeneity of the annual series was that outlined by Schoenwiese & Rapp (1997). The linear trend is first removed from the data. For homogeneity at any particular station the following test should be true

$$1-\frac{1}{\sqrt{n-1}} \leq \frac{2A}{B} \leq 1+\frac{1}{\sqrt{n-1}}$$

Where

$$A=\sum_{i=1}^{n}(r_i-\bar{r})^2$$

$$B=\sum_{i=1}^{n}((r_i-\bar{r})-(r_{i+1}-\bar{r}))^2$$

r_i is the rainfall in year I (with $r_{n+1} = r_n$)

$\bar{r}$ is the mean of the (detrended) annual rainfall

n is the number of observations,

All stations except Drumsna passed the test.

Statistical tests

In general, the Kendall non-parametric (Knp) test was used to determine the existence and significance of trends. This test, described in most statistics textbooks which cover non-parametric methods, involves comparison of each term in the series with those preceding it and producing a figure based only on the sum of the signs of the differences. The resulting test statistic is normally referred to as τ, the Greek letter tau, or Z where Z is the number of standard deviations between τ and its expectation.

$$Z = \frac{\tau - E(\tau)}{\sqrt{\text{var}(\tau)}}$$

For determination of the magnitude of trends, standard linear regression was used.

Significance of correlation coefficients (section 6 above) was assessed using the Student t test and the Fisher transformation method, where,

$$t = \frac{\rho\sqrt{n-2}}{\sqrt{1-\rho^2}}$$

and

$$z = \frac{1/2 \ln\left[\frac{1+\rho}{1-\rho}\right]}{\sqrt{n-3}}$$

where

ρ is the correlation coefficient as previously defined,

n is the number of observations.

These statistics can then be compared to tabulated values to estimate the significance of the correlation coefficients. In the present case where n=59, values of ρ in excess of about 0.21 or 0.31 correspond to significance of difference from zero of at least 95% and 99% respectively.

Replacing missing data

As mentioned above, some station months had rain-days, wet-days and / or GDF missing. It was decided to use data calculated using multiple regression techniques in place of these missing figures. The NAG Excel add-in MULT_LIN_REG was used. A different equation was used for each 'predictand' station (i.e. the station with missing data for that month) and each month of the year using all other stations reports as predictors. Tests indicate this gives a reasonably accurate result. R squared for regression fit was in most cases higher than 0.9. In the development of the equations, occasions with zeros or missing data in either predictor or predictand stations were excluded. On the very rare occasions where more than one station report was missing for a given month, an iterative procedure was applied to provide the missing values. A regression equation was developed for one station predictand and applied using an estimated value for the other missing station. Then an equation was developed with the second station as predictand and applied including the previously calculated value for the first station. This second station value was in turn used to provide an improved value for the first missing report. In most cases it was found that the procedure did not have to be further repeated.

Definition of significantly wet months

For each station and each month of the year the mean and standard deviation for the 59 values was found. The normalised rainfall for each of the 59 months was then defined as

$$\frac{\left(R_{sm} - \overline{R_{sm}}\right)}{\sigma_{sm}}$$

where

R_{sm} is the month's rainfall for the particular station for the year,

$\overline{R_{sm}}$ is the mean monthly rainfall for the station and month,

σ_{sm} is the standard deviation of the rainfalls for the station and month.

Thus, for this purpose 144 different means and standard deviations are used. While it is recognised that monthly rainfall is not normally distributed, 'normalising' in this way ensures that it is reasonable to compare values for different stations and months. [14.8% of monthly normalised rainfalls exceeded + 1, 3.4% exceeded 2 while 16.1% were less than –1 but only 0.98% were below –2. Apart from the last mentioned, these percentages are close to what would be expected for normally distributed data]

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