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# Recent trends in diurnal variation of precipitation at Valentia on the west coast of Ireland

G. Kiely[a,*], J.D. Albertson[b], M.B. Parlange[c]

[a]*Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland*
[b]*Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA*
[c]*Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD, USA*

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**Abstract**

An investigation of 54 years of hourly precipitation at Valentia, on the south-west coast of Ireland, shows a change point in the annual amounts in the years around 1975 (identified by the Pettitt–Mann–Whitney statistic). This results in a 10% increase in the mean annual precipitation from a pre-1975 value of 1375 mm to a post-1975 value of 1507 mm. Most of that increase is absorbed in the months of March and October. The frequency of hourly precipitation in March in the post-1975 period is 57% greater than that of March in the pre-1975 period. However, the magnitude of the hourly intensity of precipitation in March for both periods was similar. Significant changes in wet hour frequency also occurred in October with no corresponding change in hourly intensity. These results compliment findings by others, that regions in Northern European latitudes have experienced an increase in precipitation since the mid-1970s. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* Precipitation; Change point; Occurrence; Diffusion; Frequency; Ireland

## 1. Introduction

Several climatic and hydrologic parameters, including precipitation (Demaree, 1990; Matyasovszky et al., 1993, 1994), air temperature (Jones, 1994), atmospheric circulation (Bardossy and Caspary, 1990; Bogardi et al., 1993; Trenberth, 1995), and stream runoff (Changnon and Demissie, 1996), have been studied for changing climate patterns either locally or globally. The impact of possible climate change on water resources in the UK has been examined by Wardlaw et al. (1996) and by Schumann (1993) in Germany. Sweeney (1985), Houghton and Cinneide (1976) and Sweeney and O'Hare (1992) have examined the changing synoptic origins of Irish precipitation and the geographical variations in precipitation yields and circulation types in Britain and Ireland. Bardossy and Caspary (1990) show that the changing atmospheric circulation in Western Europe, in the winter months, has led to increased precipitation on Northern Europe since the beginning of the 1970s. The change they identify is an increased frequency of "Westerlies". Kiely et al. (1998) have demonstrated the relationship between monthly sea level pressure (as an index to storm generation and direction) and precipitation amounts over Southern Ireland. Schonwiese et al. (1990) broadly indicate that for Ireland, precipitation has increased in winter and spring but there was no change for summer and

* Corresponding author. Fax: 00353 21 902965; e-mail: gkiely@ucc.ie

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autumn. In examining long time series of various parameters, several authors (Morrissey and Graham, 1996; Chen et al., 1996; Busuioc and Von Storch, 1996; Bardossy and Caspary, 1990) have identified a change point in time series of climatic parameters, occurring in the early 1970s. In evaluating the atmospheric moisture budget, Hurrell (1995) reveals coherent large-scale changes since about 1980 that are linked to recent dry conditions over Southern Europe and the Mediterranean and wetter than normal conditions in Northern Europe and Scandinavia. Intergovernmental Panel on Climate Change (IPCC) (1995) shows increased precipitation over land in high latitudes of the Northern Hemisphere, during the cold season.

Ireland has a temperate maritime (moist) climate influenced by the Atlantic ocean. Although the island is situated between 51.5° and 55.5° North Latitude, the warm Gulf stream adds a temperate effect on climate. The west coast of Ireland has a particularly moist climate, with the probability of wet days in winter as high as 80% and in summer as high as 50%. The prevailing wind direction on the south-west coast of Ireland is from the South-West.

The data set used in this study is the hourly precipitation time series, from 1940 to 1993, for Valentia on the south-west coast of Ireland (51°52′N, 10°23′W and 9 m above sea level). These data were collected by the Irish meteorological service who advise that there has been no change in the gauge surroundings for the duration of the time series. We first investigate the mean annual precipitation to see if there is a change point (at some year(s)) as others (e.g. Bardossy and Caspary, 1990) have found for other regions on the globe. Rather than looking for persistent trends in the time series, we investigate the presence (or lack) of a change point as this might suggest that the precipitation field has shifted into a different pattern.

Prior to this study, we were analysing the precipitation data with the view towards a rainfall–runoff model, when we observed changing trends in the precipitation time series that led on to this particular study. This study of hourly precipitation starts by examining the annual series for a change point year. We then split the original series into two: one for those years prior to the change point year and the second for those years after the change point year. We analyse the monthly mean precipitation for significant differences between the two series. We further examine the diurnal variations for each of the 12 months for both series and quantify the parameters of frequency of hourly precipitation and hourly precipitation intensity for those months with the most pronounced difference between both series. Significant change in these parameters, after a change point, has implications for precipitation modelling, especially extreme value modelling.

## 2. Analysis of change point in annual series

The problem addressed in this section is to determine the location (year(s)) of an abrupt change in a single time series of annual precipitation. Several statistical techniques have been used to identify shifts in single time series. A more complex form of this problem examined by Buishland (1984) is for the case of two related time series, e.g. streamflow and precipitation. For single series, the technique of cumulative sums is now routine, but has shortcomings if the series contains obvious outliers. Although cumulative sums are rather simple, they are seldom ideal for series where the change point might be considered "subtle". Hinkley (1970) derived likelihood ratios tests for a specified value of $t$, the change point, as well as for the estimation of $t$. Pettitt (1979) presented a form of the non-parametric Mann–Whitney two-sample test which is robust for continuous data. Three types of statistical methods were used by Changnon and Demissie (1996) in determining trends and change points in two related series of streamflow and precipitation: linear regression and the $t$-statistic to determine if the regression slope was significant at the 95% confidence interval; linear regression analysis of streamflow against precipitation; and the non-parametric "Kendall" Rank Correlation test, which is used to determine the direct trend and the residual trend in a time series. Matyasovszky (1992) used non-parametric regression methods for trend estimation of climatological time series. Bardossy and Caspary (1990) analysed European atmospheric circulation patterns using a low pass filter (the 10 year moving average) and also the form of the Mann–Whitney statistic presented by Pettitt. Solow (1987) applied a two-phase regression model in testing for climate change. In this study we examine the time series of annual precipitation using the combination

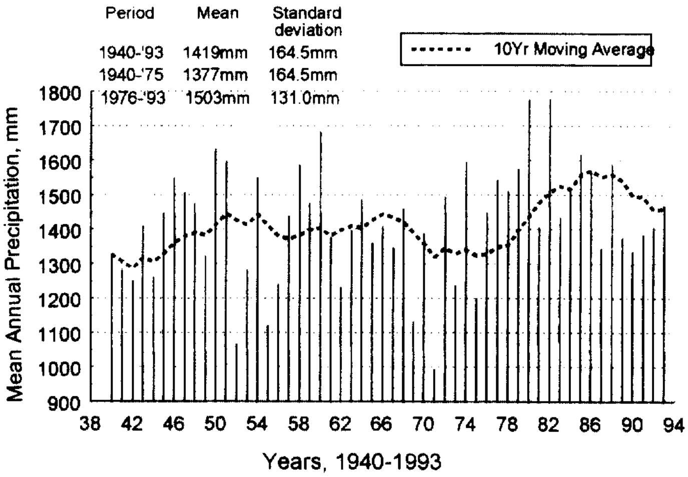


Fig. 1. Mean annual precipitation and its 10 year moving average at Valentia, 1940–1993.

of moving average technique and the Pettitt form of the Mann–Whitney statistic.

Fig. 1 presents the mean annual precipitation measured at Valentia from 1940 to 1993 and the 10 year moving average. While we can use the moving average to illustrate qualitatively the approximate change point(s) location, the time series is further analysed using non-parametric statistical tests to determine more precisely the change point (or change points). Specifically, we use the Pettitt–Mann–Whitney statistic which is briefly described as follows.

Let $T$ be the length of the time series (in our case 54 years) and let $t$ be the year of the most likely change point. We then consider our single time series of mean annual precipitation as two samples represented by $X_i \ldots, X_t$ and $X_{t+1} \ldots, X_T$. We first define the index,

$$V_t = \sum_{j=1}^{T} \operatorname{sgn}(X_t - X_j) \text{ for any } t \quad (1)$$

where $\operatorname{sgn}(x) = 1$, for $x > 0$

$\operatorname{sgn}(x) = 0$, for $x = 0$

and $\operatorname{sgn}(x) = -1$, for $x < 0$

Let a further index $U_t$ be defined as

$$U_t = \sum_{i=1}^{t} \sum_{j=1}^{T} \operatorname{sgn}(X_i - X_j) \quad (2)$$

A plot of $U_t$ against $t$ for a time series with no change point would result in a continually increasing value of $|U_t|$. However, if there is a change point (even a local change point) then $|U_t|$ would increase up to the change point and then begin to decrease. This increase followed by a decrease may occur several times in a time series, indicating several local change points. So there is still the question of determining the most significant change point. We can identify the most significant change point $t$ where the value of $|U_t|$ is maximum

$$K_T = \max_{1 \le t \le T} |U_t| \quad (3)$$

The probability of a change point being at the year where $|U_t|$ is a maximum is approximated (Pettitt, 1979) by

$$p = 1 - \exp\left[\frac{-6K_T^2}{T^3 + T^2}\right] \quad (4)$$

Applying Eqs. (1)–(4) to the annual time series, we obtain a change point at 1975 with an estimated probability of 0.949.

If we further introduce, for $1 \le t \le T$, the series

$$\hat{U}(t) = |U_t| \quad (5)$$

and define

$$P(t) = 1 - \exp\left[\frac{-6\hat{U}(t)^2}{T^3 + T^2}\right] \quad (6)$$

we now have a series of probabilities of significance for each year. For the Valentia time series of annual

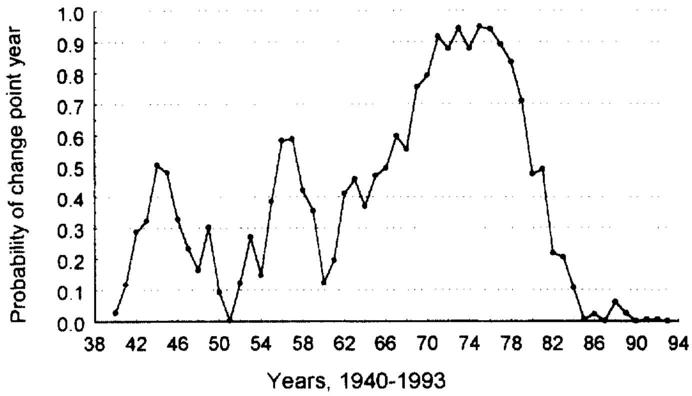


Fig. 2. The probability of a change point year, determined from Eq. (6).

precipitation the probabilities of significance for the years 1940 to 1993 are given in Fig. 2. While we take 1975 as the change point year, it is seen from Fig. 2 that a change point year 1971 or 1976 is almost of equal significance to 1975. So the change point is not an abrupt change at a single year but rather a strong change over a few years.

Table 1
Comparison of Mann–Whitney–Pettitt (MWP) and Mann–Whitney–Wilcoxon (MWW) tests (U = increase; D = decrease)

| Time series | MWP | MWW |
|---|---|---|
| **Annual** | **[a]75–U–0.949** | **(8) 1971–1978** |
| **Jan–June** | **71–U–0.900** | – |
| July–Dec | 75–U–0.776 | – |
| **Jan–Mar** | **71–U–0.971** | – |
| Apr–June | 57–U–0.520 | – |
| July–Sept | 79–U–0.333 | – |
| Oct–Dec | 75–U–0.907 | – |
| Jan | 68–U–0.44 | no |
| Feb | 65–U–0.710 | no |
| **Mar** | **75–U–0.990** | **(4) 71,73,75,76** |
| Apr | 70–D–0.641 | no |
| May | 86–D–0.461 | no |
| June | 75–U–0.520 | no |
| July | 64–D–0.695 | no |
| Aug | 77–U–0.641 | no |
| Sept | 83–D–0.400 | no |
| **Oct** | **74–U–0.869** | **(1) 74** |
| Nov | 58–U–0.369 | no |
| Dec | 75–U–0.669 | no |

[a] 75-U-.949 means, 1975 has an increase with a significance probability of 0.949.

In addition to the Mann–Whitney–Pettitt (MWP) statistic we use the Mann–Whitney–Wilcoxon (MWW) statistic (Wilks, 1995, p. 138), and summarize the results of both in Table 1. Both tests broadly indicate similar results. In Table 1, MWP indicates that the probability of a change point year is highest in 1975 while MWW indicates that the change is between 1971 and 1978. For the three months, January to March, the MWP statistic indicates that the change point year is 1971. Similarly for the months October to December, the MWP statistic indicates the change point year as 1975. In Table 1, we also include the MWP and MWW statistics for each month and show that March and October have the highest probabilities of change in 1975 and 1974 respectively. On this basis we chose 1975 as the change point year.

With a change point defined at year 1975 the mean annual precipitation increases from 1377 mm (pre-75) to 1503 mm (post-75). This increase of nearly 10% is statistically highly significant. Using the $t$-test, there was a statistically significant difference between the means of the two samples (pre- and post-1975) at the 99.0% confidence level (Table 2).

Fig. 3 presents the mean monthly precipitation for the pre-1975 and post-1975 time series. The key observations from Fig. 3 are that in the post-1975 period the monthly mean precipitation for March increased by 57% and for October by 24%. There was less change in the other months.

## 3. Analysis of diurnal variation

Diurnal variation of precipitation has been

Table 2
The confidence levels ($t$-test) associated with the difference in means of the average hourly occurrences between the pre-1975 and post-1975 series

| Month | Pre-1975 | Post-1975 | Difference in means (%) | Confidence level (%) |
|---|---|---|---|---|
| Jan | – | – | – | < 90 |
| Feb | 0.132 | 0.146 | + 10.6 | > 99 |
| Mar | 0.105 | 0.165 | + 57.1 | > 99 |
| Apr | – | – | – | < 90 |
| May | – | – | – | < 90 |
| June | 0.084 | 0.097 | + 15.5 | > 95 |
| July | 0.091 | 0.080 | – 12.1 | > 98 |
| Aug | – | – | – | < 90 |
| Sept | 0.120 | 0.110 | – 8.3 | > 98 |
| Oct | 0.132 | 0.165 | + 25.0 | > 99 |
| Nov | – | – | – | < 90 |
| Dec | 0.164 | 0.174 | + 6.1 | > 97 |

examined by several authors (e.g. Landin and Bosart, 1989; Sharma et al., 1991; Tucker, 1993). Wallace (1975) in looking at diurnal variations of precipitation over the US identified phase shifts between the amplitude and frequency. In some regions there are pronounced seasonal differences in the character of the diurnal variability. Over much of Western Europe winter precipitation exhibits a nocturnal rainfall maximum while during summer the maximum occurs during the afternoon. There has been interest in quantifying the diurnal variation (if it exists). There are different diurnal variation characteristics over continents and over oceans, and maritime countries like Ireland will tend to follow the diurnal characteristics of oceanic areas. In examining diurnal variations it is relevant to look at both frequency of wet hours and also intensity as these are not necessarily in phase. The statistics we use to examine the diurnal variation of (hourly) precipitation include: occurrence (frequency) of a wet hour; mean and variance of intensity of wet hours; and temporal correlations of occurrence or intensity between wet hours. In this paper we concentrate on the parameters of occurrence of a wet hour and the intensity of the wet hour. We define a wet hour as having a precipitation intensity greater or equal to 0.25 mm $h^{-1}$ (1/100 in $h^{-1}$). We define the occurrence (or frequency of a wet hour) as follows. Consider a single month (e.g. January) and further, consider a

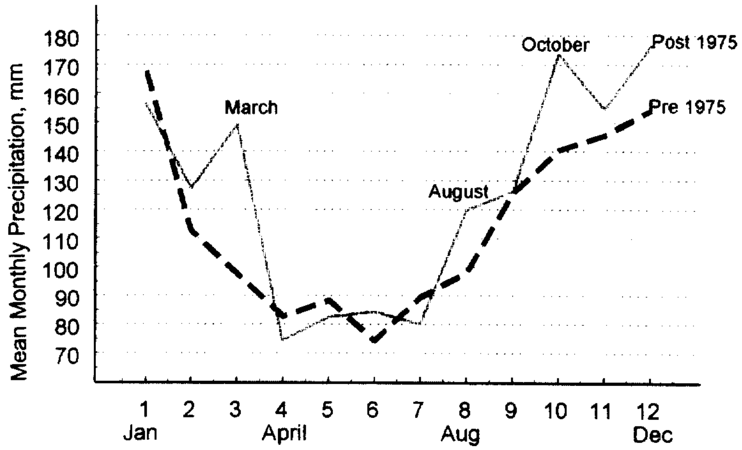


Fig. 3. Monthly precipitation at Valentia, for the pre-1975 and post-1975 time series.

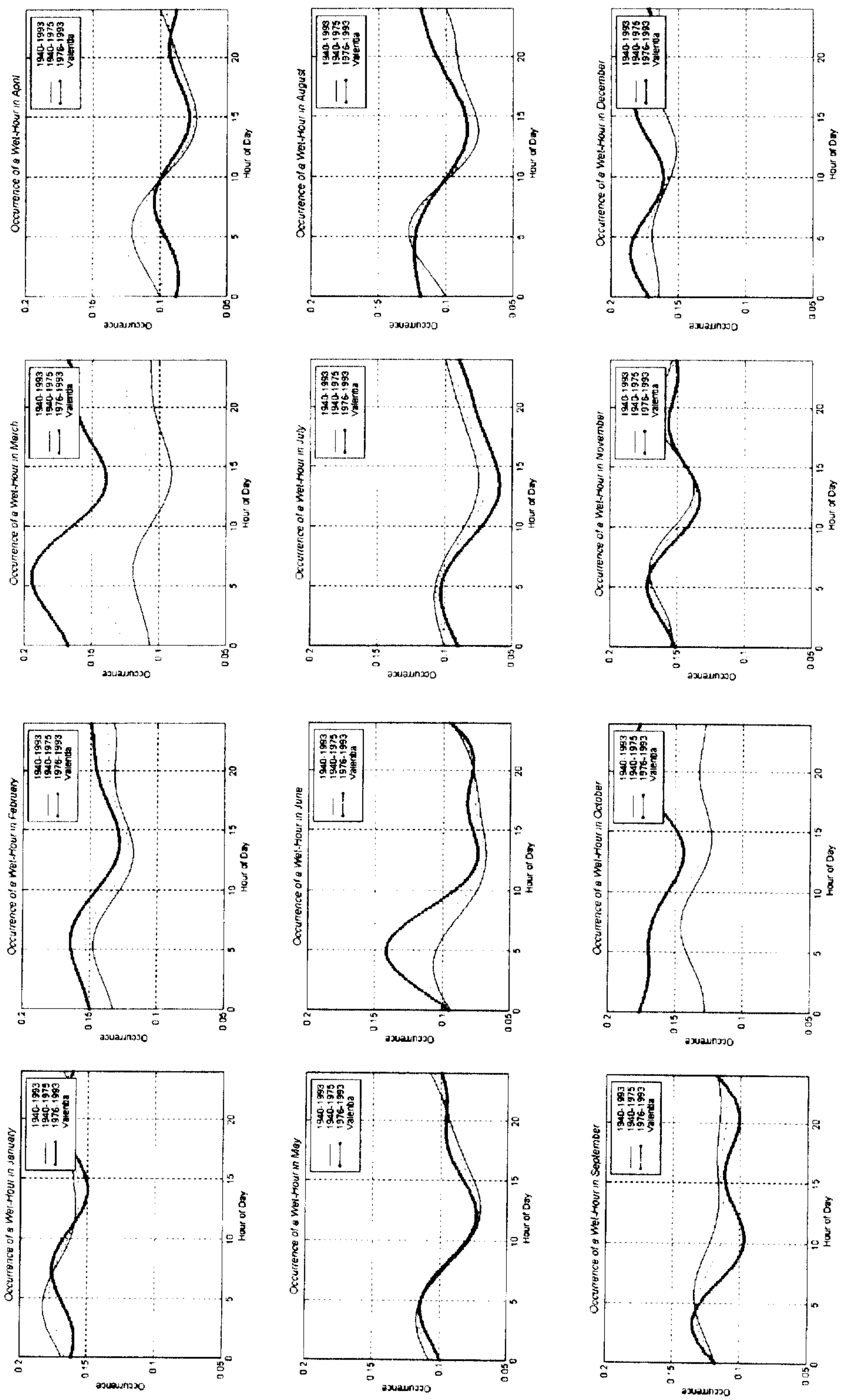


Fig. 4. The occurrence of precipitation for all 12 months for the three time series: 1940–1993, pre-1975 and post-1975.

single hour (e.g. 9 a.m. to 10 a.m.). We interrogate all the 9 a.m. to 10 a.m. periods in all the March months in the record and count the number of wet hours and the total number of hours (wet plus dry). We divide the number of wet hours by the total number of hours to obtain the frequency of wet 9 a.m. to 10 a.m. hours in the series. We repeat for all 24 hours to complete the January computation. Furthermore, we repeat the above for the 12 months.

In Figs 4 and 5, we present the diurnal variation of hourly occurrence and hourly precipitation for the 12 months. For presentation we fit the data to a two-frequency sum of sine and cosine functions

$$y(x)=a+\sum_{k=1}^{2}[b_k\cos(2\pi kx/24)+c_k\sin(2\pi kx/24)] \tag{7}$$

Fig. 4 presents the diurnal variation of occurrence for the 12 months. March is the month that stands out with most change. There is an increase (post-1975) in the occurrence for March for all 24 hours. The post-1975 occurrence has a mean of approximately 0.165 (16.5% of the March hours are wet) by comparison with approximately 0.105 for the pre-1975 time series. This increase of approximately 57.1% is significant at a confidence level greater than 99%. In Fig. 4 we see that there is an increase (post-1975) in the occurrence for October for all 24 hours. The average post-1975 occurrence is approximately 0.165 by comparison with approximately 0.132 for the pre-1975 time series. This increase of approximately 25.0% is statistically significant at greater than the 99% confidence level. Not much change is noted for the other months between the pre- and post-1975 occurrences.

Fig. 5 presents the diurnal variation of intensity for the 12 months. The intensity of hourly precipitation for March varies from 0.95 to 1.25 mm $h^{-1}$. The hourly intensities are similar for the pre-1975 and post-1975 series. In general there is not much change in the intensities between the pre- and post-1975 series.

The increase observed in the monthly mean for March and October (Fig. 3) is absorbed by an increase mainly by an increase in occurrence and not in hourly intensity.

It is also noted that the hourly occurrences for the summer month of August are essentially identical in magnitude and shape and the increase in monthly precipitation is accommodated mainly in the intensity.

Fig. 4 shows that there is a sinusoidal shape to the diurnal variation of occurrence for March, with two occurrence peaks: one at about 6 a.m. and the second around 8 p.m. There is a low value at about 2 p.m. The peaks of intensity for March (Fig. 5) are at about 4–6 a.m. and 4–6 p.m., with two lows at about 10–12 a.m. and 10–12 p.m. So there is a phase shift of about 2–3 hours with the intensity peaks (and troughs) preceding the occurrence peaks and troughs.

A key observation from Figs 3–5 is that the most significant fraction of the annual increase in the post-1975 series is concentrated in the month of March (and to a lesser extent October) and that this increase is manifested mainly in an increase in the occurrence and not in the hourly intensity.

## 4. Discussion and conclusions

We have presented an analysis of hourly precipitation data (1940–1993) from a site on the south-west coast of Ireland. This analyses shows that there was a change point in the mean annual precipitation time series in the years around 1975. For the months of October and March when most change in the monthly amounts of precipitation was experienced, the Mann–Whitney–Pettitt and Mann–Whitney–Wilcoxon statistics identify the year of most likely change to be around 1975. The increase in mean annual precipitation since 1975 has been 10%. This increase has been concentrated largely in the month of March and to a lesser extent in the month of October. The other months, particularly the summer months, show less change in the mean monthly precipitation. Analyses of the diurnal variation of each month, with regard to hourly occurrence and mean hourly intensity show that for March (and October) the increase found in the post-1975 time series is concentrated in the hourly occurrence, with little change in the hourly mean intensity. It is also noted that the hourly occurrences for the summer month of August are essentially identical in magnitude and shape and the increase in monthly precipitation is accommodated mainly in the intensity. Finally, it is also interesting that the shape of

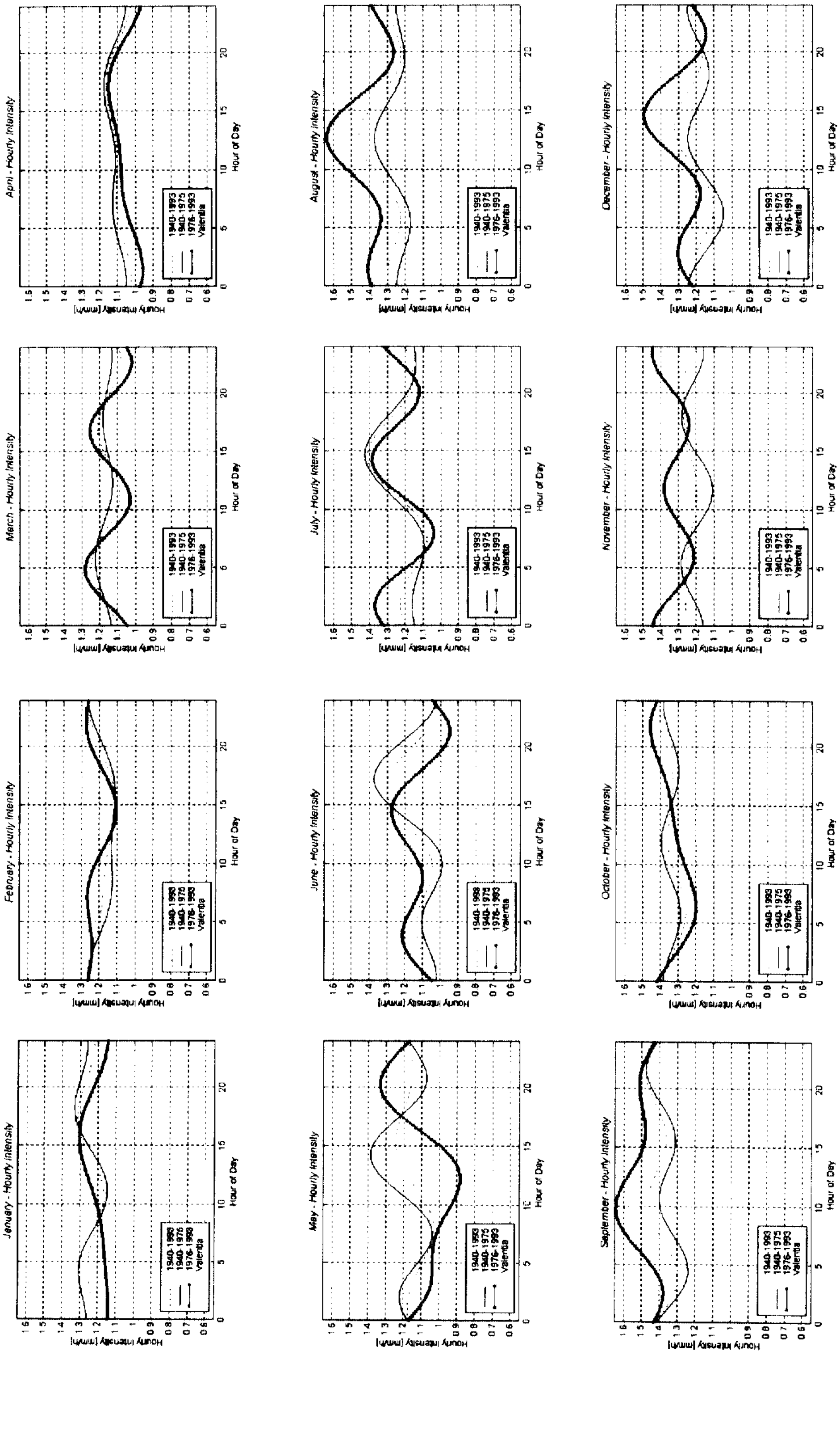


Fig. 5. The hourly intensity of precipitation for all 12 months for the three time series: 1940–1993, pre-1975 and post-1975.

the diurnal variation for hourly occurrence for March and October is broadly sinusoidal with peaks around midnight or early morning and troughs at about 2 p.m. However, there are phase shifts between occurrence and intensity. The two peak intensities for March occur in the early morning and late afternoon.

We have not addressed the question of why this clear-cut change in precipitation has occurred. Bardossy and Caspary (1990) and Sweeney (1985) have identified an increase in westerly winds in North-West Europe with a decrease in Northerlies and Easterlies in recent decades and show the correlation with increased precipitation.

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