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Updated Precipitation Series for the U.K. and Discussion of Recent Extremes

L. V. Alexander[1]* and P. D. Jones[2]†

[1]*Hadley Centre for Climate Prediction and Research, Met. Office, Bracknell, U.K.*
[2]*Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, U.K.*

Abstract: We present an automated method for updating existing long-running precipitation series in near-real time. Our analyses confirm the trend towards significantly drier summers in the south-east of England and significantly wetter winters in the west of Scotland. In 2000 England and Wales saw the wettest April since records began in 1766 and record-breaking daily precipitation in several regions in October led to the wettest autumn on record.

Keywords: Extreme events, precipitation trends, climate variability.

1. INTRODUCTION

Recent studies have shown significant changes in daily extreme rainfall events on both regional (Osborn *et al.*, 2000) and global (Groisman *et al.*, 1999; Frich *et al.*, in press) scales. The potential impacts of even slight shifts in the precipitation distribution on society and ecosystems have highlighted the increasing need to monitor daily precipitation online. However, long-running time-series such as England and Wales precipitation (EWP) (Wigley *et al.*, 1984) and Central England temperature (CET) (Parker *et al.*, 1992; Horton *et al.*, in press) are very time-consuming and complex to update because whenever an observing station moves or closes, a substitute has to be found to maintain the homogeneity of the series, so there is a significant delay before the series can be analysed thoroughly.

Jones and Conway (1997) used seven evenly distributed precipitation stations in each of the nine spatially coherent precipitation regions of the U.K. (Table 1) defined initially by Wigley *et al.* (1984) for England and Wales and extended nationwide by Gregory *et al.* (1991). The aim of this paper is to present a method for updating the regional and national series in near-real time. The method does not rely on the same set of stations remaining open within a region but it maintains the homogeneity of each regional precipitation series. The stations chosen send national climate messages (NCM) once or twice daily and have available monthly 1961–1990 averages. Some of the stations are automated: such precipitation data have disadvantages, for example a tipping bucket sensor may fail and only report zero rainfall values.

* lisa.alexander@metoffice.com
† p.jones@uea.ac.uk

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Table 1. The weighting factors defined for each spatially coherent precipitation region of the U.K. along with the approximate maximum number of stations in each region. A map of the boundaries of each region can be viewed on: http://www.metoffice.gov.uk/research/hadleycentre/pubs/posters/Alexander/divisionsd1.html

i	**Region**	ω_i	n
1	South-east England (SEE)	0.275	11
2	South-west England and south Wales (SWE)	0.288	15
3	Central and east England (CEE)	0.265	12
4	North-west England and north Wales (NWE)	0.128	10
5	North-east England (NEE)	0.158	11
6	South-west and south Scotland (SS)	0.379	6
7	North-west and north Scotland (NS)	0.270	8
8	East Scotland (ES)	0.529	6
9	Northern Ireland (NI)	0.955	7

Quality controls are therefore performed on the data before it is ingested into the Met. Office's database, MIDAS; e.g. a flag is raised if the NCM does not match hourly rainfall values that may also be produced from that station. Not all problems are detected operationally, however, so daily and monthly values are re-calculated on the 5th of each month with final quality control being performed a few months later. In spite of this, the automated daily values used operationally have not proved significantly different from the final quality controlled data. Furthermore, any random errors are reduced when individual stations' data are averaged into regional quantities. The method described below has been employed on a daily basis since 1997 although monthly values are available between 1961 and 1996. Updates for both EWP and CET are available on the Met. Office external website at: http://www.met-office.gov.uk/research/hadleycentre/obsdata/index.html

2. AVERAGING METHOD AND COMPARISON WITH PREVIOUS RESULTS

Calculating the regional precipitation series is a two-stage process. Firstly the relevant data are extracted nightly from MIDAS, but with a two-day time lag since the stations do not all report strictly in real time. Secondly, after the extraction process is complete, the daily precipitation totals from each station are collated, scaled by the ratio of the regional monthly normal [defined using the series developed by Jones and Conway (1997)] to the stations' monthly normal, and summed to obtain a regional total. Thus if N_i represents the average 1961–1990 monthly precipitation for region i and S_i represents the 1961–1990 average monthly precipitation for station j then a scaling factor f_{ij} is defined as:

$$f_{ij} = \frac{N_i}{S_j} \tag{1}$$

The scaling factor f_{ij} was chosen over area weighting to easily allow for different gauge configurations given that networks can change rapidly. This may become less useful in a fast-changing climate. The regions, however, are relatively small with most of the spatial variability of the 30-year annual totals determined by the unchanging orography and coastlines. Thus we feel its use is justified in this case.

If n is the number of stations in region i, on any given day, then we define the daily precipitation total in the region as:

$$P_i = \frac{\sum_{j=1}^{n} R_{ij} f_{ij}}{n} \tag{2}$$

where R_{ij} is the daily precipitation total for station j in region i.

The "national" series are weighted averages of the regions, the weights ω_i having been determined by regression analysis (Wigley *et al.*, 1984; Gregory *et al.*, 1991). These weights are given in Table 1; the daily precipitation for England and Wales (EW), Scotland (S) and Northern Ireland (NI) are given by:

$$P_{EW} = \sum_{i=1}^{5} \omega_i P_i, \quad P_S = \sum_{i=6}^{8} \omega_i P_i \quad \text{and} \quad P_{NI} = \omega_9 P_9 \tag{3}$$

The monthly values for each region are simply defined as the sum of the daily values in that month.

Approximate maximum values of n are given for each region in Table 1. By definition n varies according to whether the requested data is available in MIDAS. We therefore performed tests to assess the sensitivity of our results to changes in n. On monthly timescales, taking SWE as an example as it has the greatest value of n, correlations of the cube root of precipitation between the standard ($n = 7$) series and random samples of the new series were in the range 0.87 and 0.97 for $n = 15$ and 0.58 and 0.89 for $n = 3$, the lowest acceptable value of n. The cube root of each series was used in order to reduce skewness.

To check the homogeneity of our method on monthly and annual timescales, the values were compared to the Climatic Research Unit (Jones and Conway, 1997) regional series over the period 1961–1995. The annual series for England and Wales (Figure 1) show that the old (Jones and Conway, 1997; Osborn *et al.*, 2000) and present methods are in excellent accord. In addition monthly and annual correlation coefficients between the old and new series for all regions are given in Table 2 and show high correlations between the two series in all regions. North-west Scotland (NS) does not have quite as good correlations as the other regions since this is where there is the greatest spatial variability of precipitation (Jones *et al.*, 1997). Also on monthly and annual time-scales (not shown) there is no significant trend in the difference between any corresponding national or regional series at the 95% level of confidence using restricted maximum likelihood regression analysis (e.g. Press *et al.* 1996).

On daily timescales it is harder to maintain homogeneity of the inter-daily variance and the results are much more sensitive to the numbers of stations in each region. As 1997 is the only year with daily precipitation estimated both from our operational technique and earlier studies [Jones and Conway's (1997) analyses updated during the development of the data used in Osborn *et al.* (2000)], we show absolute differences for England and Wales between the two series for 1997 in Figure 2. The maximum absolute daily difference in this region is 3.6 mm, with 92% of values within 1 mm and 83% within 0.5 mm; the correlation between the two daily series is 0.97. Corresponding analyses for the other series showed larger differences in some regions, most markedly in Scotland. In NS only 51% of

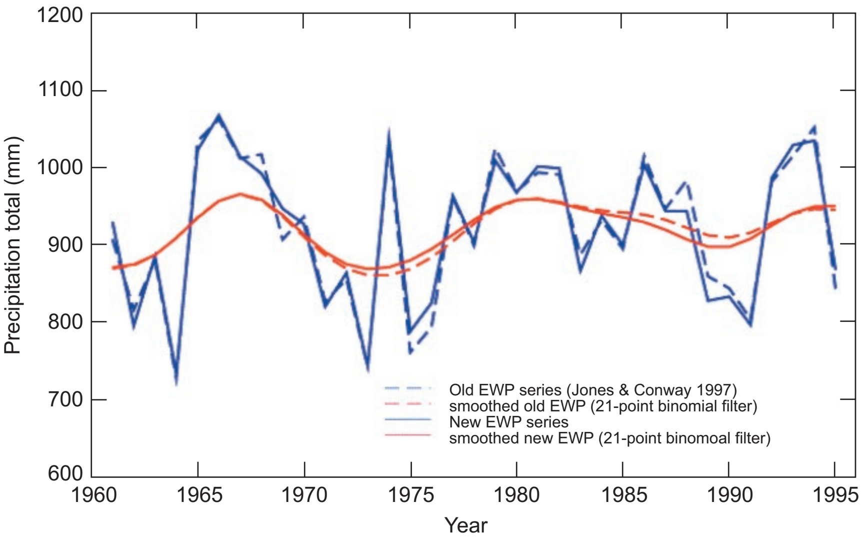

Figure 1. Comparison of old (Jones and Conway, 1997) and new (present study) versions of annual England and Wales Precipitation Series.

Table 2. Correlations between Jones and Conway (1997) and the present regional and national precipitation. Results are based on monthly data between 1961 and 1995. See Table 1 for key

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Ann.
SEE	0.99	0.99	0.98	0.98	0.98	0.98	0.94	0.96	0.97	0.99	0.99	0.99	0.97
SWE	0.99	0.98	0.95	0.98	0.96	0.96	0.92	0.95	0.97	0.95	0.96	0.94	0.91
CEE	0.99	0.99	0.99	0.99	0.99	0.97	0.96	0.97	0.98	0.99	0.98	0.94	0.98
NWE	0.90	0.96	0.93	0.92	0.93	0.87	0.93	0.92	0.94	0.93	0.92	0.96	0.89
NEE	0.95	0.96	0.96	0.96	0.96	0.98	0.95	0.94	0.97	0.97	0.97	0.95	0.96
SS	0.97	0.97	0.94	0.95	0.97	0.94	0.95	0.96	0.97	0.97	0.96	0.97	0.95
NS	0.86	0.96	0.91	0.80	0.85	0.80	0.85	0.89	0.79	0.74	0.88	0.85	0.80
ES	0.80	0.95	0.90	0.90	0.93	0.97	0.94	0.98	0.95	0.95	0.93	0.89	0.93
NI	0.95	0.94	0.94	0.96	0.98	0.97	0.89	0.98	0.98	0.98	0.96	0.98	0.93
S	0.94	0.98	0.96	0.95	0.97	0.95	0.96	0.98	0.95	0.95	0.95	0.95	0.92
EW	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.98	0.98

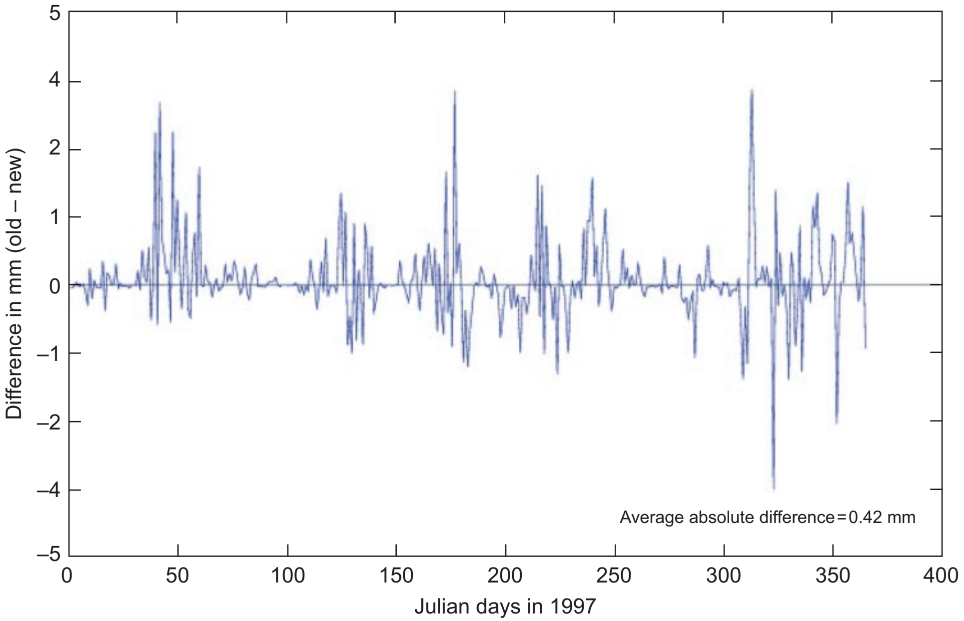

Figure 2. Differences in daily England and Wales Precipitation Series, 1997: Jones and Conway's 1997 technique updated during the development of Osborn et al. (2000) minus the present technique.

values were within 1 mm and 38% within 0.5 mm and the correlation was 0.87. This is to be expected given the variable orography of the north of Scotland and its much higher average precipitation compared to other regions. Analysis of the difference of the two series for England and Wales shows that there is an equal chance of accuracy for wet or dry daily events. Some of the regions, however, do appear to be less reliable in determining dry (<1 mm) events with the south-west England and south Wales (SWE) region less reliable in determining wet (>9 mm) events.

3. ANALYSES OF REGIONAL RESULTS

Many analyses have already been performed on the data. In particular, Jones and Conway's (1997) update of the series to 1995 (see also Jones *et al*., 1997), concluded that the national precipitation series all showed trends towards wetter winters and drier summers. Our update of the series to the present day has confirmed that these results are still valid and in particular have shown the exceptional precipitation regimes of the 1990s. A poster showing some regional results was presented at the Royal Meteorological Society's Millennium Conference in July 2000 and can now be viewed on the website: http://www.metoffice.gov.uk/research/hadleycentre/pubs/posters/Alexander/index.html

Further analyses of recent trends and daily precipitation amounts are detailed below. All trends are calculated using a Mann–Kendall test (Press *et al*., 1996) and are significant at the 95% level of confidence unless otherwise stated.

England and Wales

Although Parker *et al.* (2000) stated that there was no significant increase in the annual number of heavy rain days in the England and Wales 1931–1999 daily record, on seasonal timescales precipitation totals have altered significantly (Figure. 3). Monthly regional results within England and Wales extend back to 1873. Since then there has been a significant decrease in the amount of rainfall in every region in July and August (e.g. Figure. 3a). Frich *et al.* (in press) defined the consecutive number of dry days (CDD) as the maximum number of consecutive days with less than 1 mm precipitation. However, analysis shows no significant increase in CDD in any region in July and August since the daily series began in 1931 at the start of a relatively dry epoch (Figure 3a). The recent decrease in July–August precipitation is associated with increased anti-cyclonic conditions during this time (not shown). The north-east of England shows a significant increase in winter (JFM) monthly precipitation (Figure 3b) and the most recent results show that 1998 and 2000 were the wettest springs (AMJ) respectively in this region since the monthly time-series began. Real-time monitoring has shown that there was a near-record breaking daily value of 28 mm on 3 June 2000 (Figure 3c) which contributed to the floods in the north of England. The Easter floods in the Midlands in 1998 were also captured and showed that the pattern was not uniform across England and Wales.

The national results date back even further to 1766 and show a significant increase in winter (JFM) and winter half-year (Oct.–Mar.) precipitation contrasting with a significant decrease in summer (JA) and summer half-year (Apr.–Sep.) precipitation. In particular 1995 was the driest high summer (JA) on record but also attained the accolade of being the second wettest winter (JFM). The automated results currently show that April 2000 with a monthly total of 143 mm was the wettest April in the 235-year England and Wales record (Figure 3d) contributing to Spring 2000 being the eighth wettest. The monthly England and Wales series is available at: http://www.metoffice.gov.uk/research/hadleycentre/CR_data/Monthly/HadEWP_act.txt

On daily times-scales, the widespread flooding in England and Wales in October 2000 can be linked with the 40 mm of rainfall that fell on average on the 29th of that month. Only the 42 mm that fell on 25 August 1986 was higher in the daily record which began in 1931. Daily values of 42 mm and 50 mm on 29 October 2000 in south-east England (SEE) and SWE respectively exceeded the previous October maximum daily values for those regions. However October 2000 (188 mm) was not as wet as October 1903 (218 mm) in the England and Wales series but autumn 2000 (502 mm) beat the previous record breaker of 1852 (455 mm).

Scotland and Northern Ireland

For Scotland and Northern Ireland, Gregory et al. (1991), only developed series back to 1931, so analyses are limited to this shorter record. The western part of Scotland has shown a dramatic increase in winter half-year (Oct.–Mar.) precipitation totals (see also: http://www.metoffice.gov.uk/research/hadleycentre/pubs/posters/Alexander/index.html)

Figure 4 shows the significant increase (99% significance level) in the number of days exceeding the 95th percentile of 1961–1990 daily precipitation, in Oct.– Mar. in south-west Scotland. (N.B. Percentiles were calculated using a simple ranking method given the large amount of daily data over this 30-year base period.) Note that every year in the 1990's has exceeded the average long-term (1931–1999) number of "heavy" precipitation days. The annual sequence of maximum 5-day precipitation totals (not shown) also shows a significant increase (90% significance level) over the analysis period. Both results can be partly linked to a much more positive phase of the North Atlantic Oscillation (Hurrell and Van Loon, 1997; Osborn and Jones, 2000). This pattern shows up in other regions of the U.K. but not to such a significant extent. The northern and eastern regions of Scotland also show a significant decrease in summer (JA) precipitation totals.

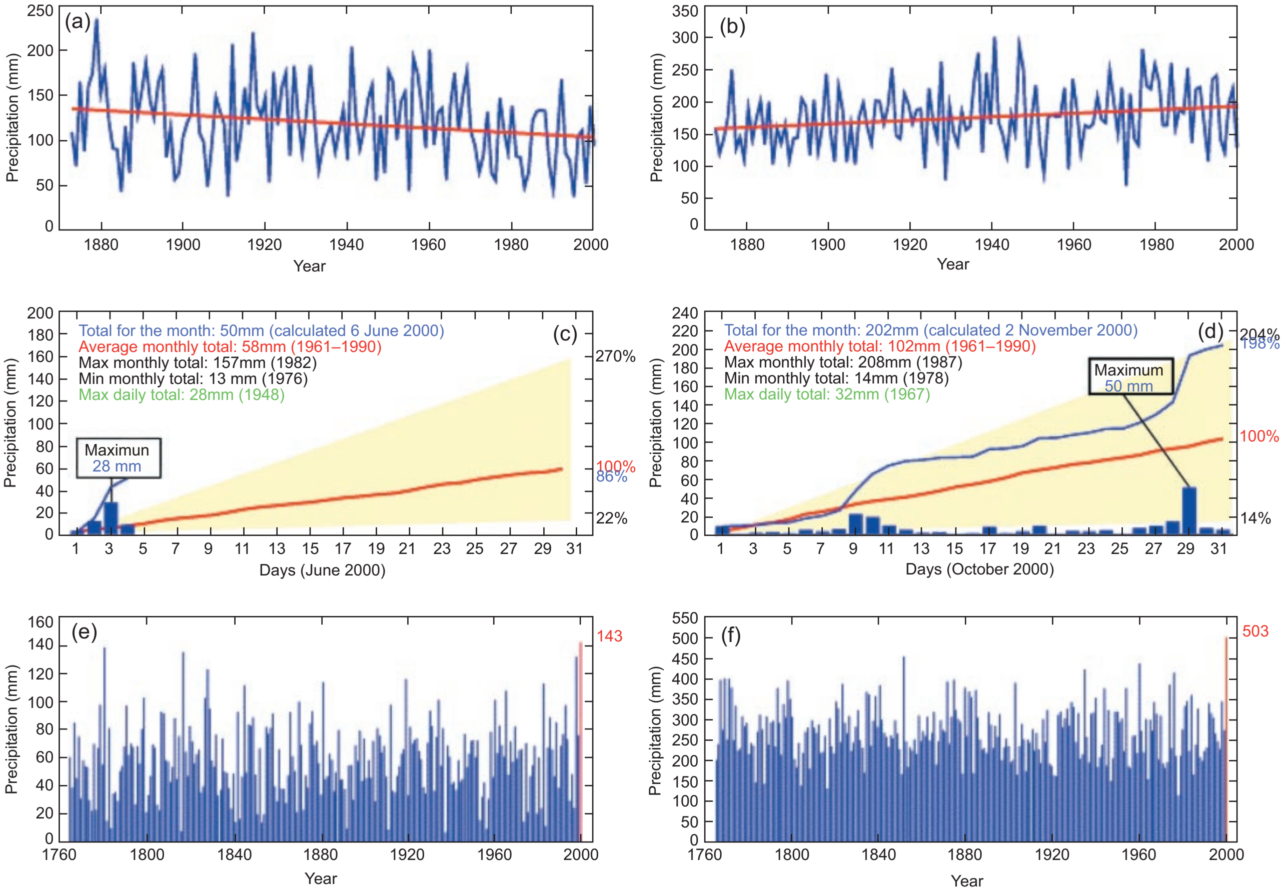

Figure 3. (a) Monthly south-east England high summer (JA) precipitation totals are fitted with a least squares trend line. The downward trend is significant at the 95% significance level. (b) As (a) only showing north-east England monthly winter (JFM) precipitation totals. The upward trend is significant at the 95% significance level. (c) Graphics that were available on http://www.metoffice.gov.uk/research/hadleycentre/CR_data/Daily/HadNEEP_act_graph.gif on 6 June 2000 showing near record-breaking daily June value of 28.0 mm in north-east England on 3 June. The previous recorded maximum daily value in this region was 28.5 mm on 2 June 1948. (Note that the first four days of the month had already reached 86% of the average total for June). (d) As (c) only showing the graphics available for the south-west of England and Wales on 2 November 2000. The extreme record-breaking daily rainfall on 29 October is clearly shown, beating the previous record in 1967 by 18 mm. (e) Bar chart showing that April 2000 was the wettest in the 235-year England and Wales record with 143 mm. (f) Bar chart showing that autumn 2000 was the wettest in the 235-year England and Wales record with 503 mm.

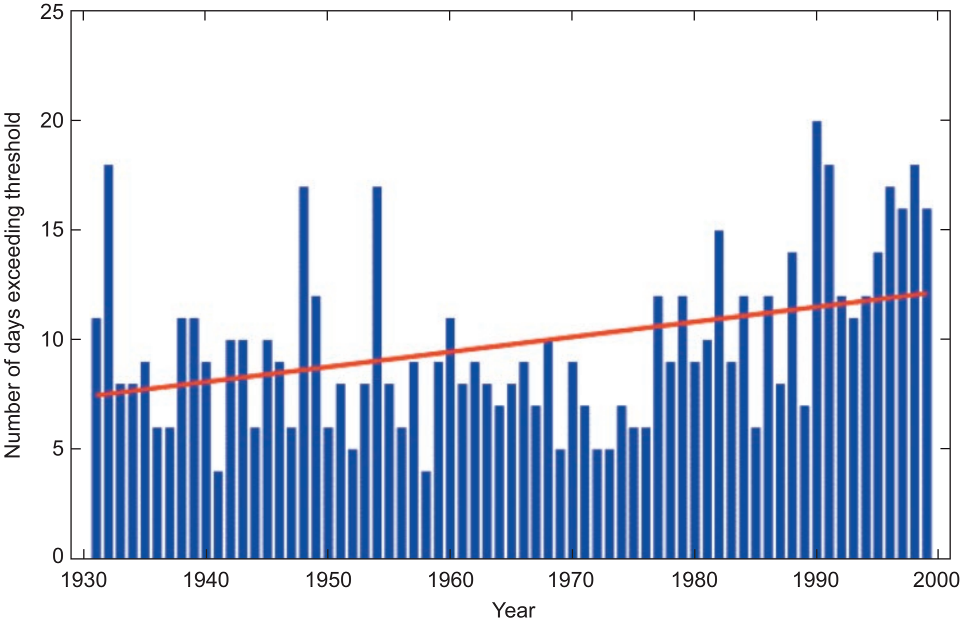

Figure 4. Number of days above 95th percentile of the 1961–1990 daily precipitation for south-west Scotland, October to March.

Scotland as a whole has been showing a significant trend towards wetter winters and drier summers whilst Northern Ireland shows a significant decreasing trend in summer months, particularly in July (see: http://www.metoffice.gov.uk/research/hadleycentre/pubs/posters/Alexander/index.html)

4. CONCLUSIONS

A major advantage of our automated analysis is the ability to isolate "record breakers" shortly after they happen. The regional and national time-series can also be monitored and analysed in near-real time with daily updated graphics available at : http://www.metoffice.gov.uk/research/hadleycentre/CR_data/Daily/

Further analysis needs to be performed on the time-series on daily timescales to confirm its homogeneity with earlier analyses (e.g. Gregory et al., 1991; Jones and Conway, 1997). The automation process could potentially accelerate research into the changing variability of U.K. precipitation totals and extreme events.

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