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Trends and variability in daily precipitation in Scotland

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Abstract

The objective of this research is to analyse temporal changes in historic rainfall variability across Scotland using different measures of variability. The CUSUM and sequential Mann-Kendall test applied to records from 28 weather stations with up to 80 years of daily precipitation data reveal the occurrence of abrupt changes in the rainfall trends. Most weather stations show a turning point between 1978 and 1985, although some stations situated in Eastern Scotland have more than one turning point. The temporal changes in rainfall variability across Scotland are presented using a number of measures of variability.

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Keywords: Climate variability; Rainfall; Scotland; Trends; Turning points

1. Introduction

The World Meteorological Organization (WMO) defines climate variability as variability inherent in the stationary stochastic process approximating the climate on scale of a few decades [1]. Climate variability is becoming a major concern for both water companies and policy makers [2]. There have been many studies worldwide on the impacts of climate variability on water resources. For example, increasing trends in temperature and decreasing trends in precipitation and riverflow have been observed in China [3], Korea [4], Japan [5], and New Zealand [6]. The effect of climate change on the hydrological regimes of Europe generally show an increasing trend in precipitation and runoff in northern Europe and a decreasing trend in southern Europe [7]. These continental trends in riverflow are reflected in the United Kingdom with statistically significant positive trends in annual runoff observed in a number of natural catchments across

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Scotland and the western regions of England and Wales, but with an indication of negative trends in eastern England [8].

Mayes [9] demonstrated that the precipitation gradient has been accentuated across the UK with the northwest becoming wetter, notably in the winter and the southeast drier, especially in the summer. This is consistent with a number of climatic studies focusing on Scotland, e.g. [10, 11], along with a trend towards greater flood risk in Western Scotland [12]. These changes in precipitation across the UK are also reflected in hydrological records [10, 13-17], and are projected to persist under climate change based on a number of modelling simulations [10, 18, 19]. In addition to those trends in the magnitude of rainfall, there is evidence of an increase in rainfall variability at different time-scales [14]. An increase in rainfall variability in the future and its subsequent impact on river flow could be problematic for water resource managers [10, 20]. Nonetheless, little research has been accomplished to date on changes in the variability of rainfall. Hence, the objective of this paper is to analyse temporal changes in historic rainfall variability across Scotland using various measures of variability.

A number of techniques have been used to measure rainfall variability at different time-scales with the most common measure being variance, an example of which is seen in Mitosek [21]. Another measure of variability is the winter to summer (w/s) ratio of precipitation and this technique has previously been used by Tosic [22] in Serbia and Montenegro, and Burt et al. [23] and Burt and Horton [24] in England, among others. Burt et al. [23] noted a trend towards wetter winters over the study period (1881-1995) in North-central England, whereas Burt and Horton [24] found no simple pattern to the changes in the w/s ratio for the period 1850-2004 at Durham; however, since the 1960s an increase in the w/s ratio was clearly evident. Other measures of rainfall variability are related to climate extremes, which received increasing attention since the 1995 report of the International Panel on Climate Change [25], as climate variability will impact on the frequency of extremes [10, 13-17]. Dry period characteristics have been used as a measure of variability, for example by Nasri & Modarres [26], Serra et al. [27], Gong et al. [28], and Schmidli & Frei [29] in Iran, Spain, China, and Switzerland, respectively. The analysis of rainfall characteristics, particularly the duration of dry spells is important to water resource managers due to the limited storage capacity of reservoirs. Trend analyses are dependent on the selected time period of analysis. For this reason, the Cumulative Sum (CUSUM) of the deviations from the mean is a technique that is widely used in hydrology for the identification of turning points in rainfall time series [30, 31]. Climate variability is important in the planning of major water infrastructure projects [32], nevertheless our understanding of rainfall variability is still limited.

2. Data and Methods

Daily precipitation data were obtained from the MIDAS Land Surface Observations Stations Data of the UK Meteorological Office and distributed through the British Atmospheric Data Centre (BADC). The weather stations were selected based on the length of their data records and the percentage of missing values. All selected time series have at least 30 years of data with no more than 5% missing values. The temporal records of the selected weather stations are given in Fig. 1.

Trend analyses were carried out using the non-parametric Mann-Kendall (MK) test. Non-parametric tests are more suitable than their parametric counterparts when the data do not meet the assumption of normality [33]. The trend detection technique was applied on precipitation totals and on the following measures of variability: variance, w/s ratio and annual number of dry days. A dry day was defined as a day with less than 0.2 mm of precipitation, as in Fowler [34].

The sequential MK trend test detects significant or abrupt changes in a time series. To see the change in trend with time, the sequential values $u(t)$ and $u'(t)$ were developed from the progressive analysis of the MK test [35]. The sequential behaviour of $u(t)$ fluctuates around zero as it is a standardized variable. The following steps were used by Partal and Kahya [35] to develop a time series:

1. The magnitudes of x_j annual mean time series, (j=1, ..., n) are compared with x_k, (k=1, ..., j-1). For each comparison, the number of cases $x_j > x_k$ is counted and denoted by n_j.
2. The test statistic *t* is then given by equation

$$t_j = \sum_{1}^{j} n_j \tag{1}$$

3. The mean and variance of the test statistic are

$$E(t) = \frac{n(n-1)}{4} \; and \; \text{var}(t_j) = [j(j-1)(2j+5)]/72 \tag{2}$$

4. Then the sequential values of statistic *u(t)* are calculated using

$$u(t) = \frac{t_j - E(t)}{\sqrt{Var(t_j)}} \tag{3}$$

Similarly, the values of *u'(t)* are computed backwards, starting from the end of time series [35].

The CUSUM procedure adapted from Wayne [36] has been used in this study for indicating changes in trend. A sudden change in the direction of CUSUM indicates a sudden shift in the trend. The CUSUM was calculated on both precipitation totals and the measures of variability.

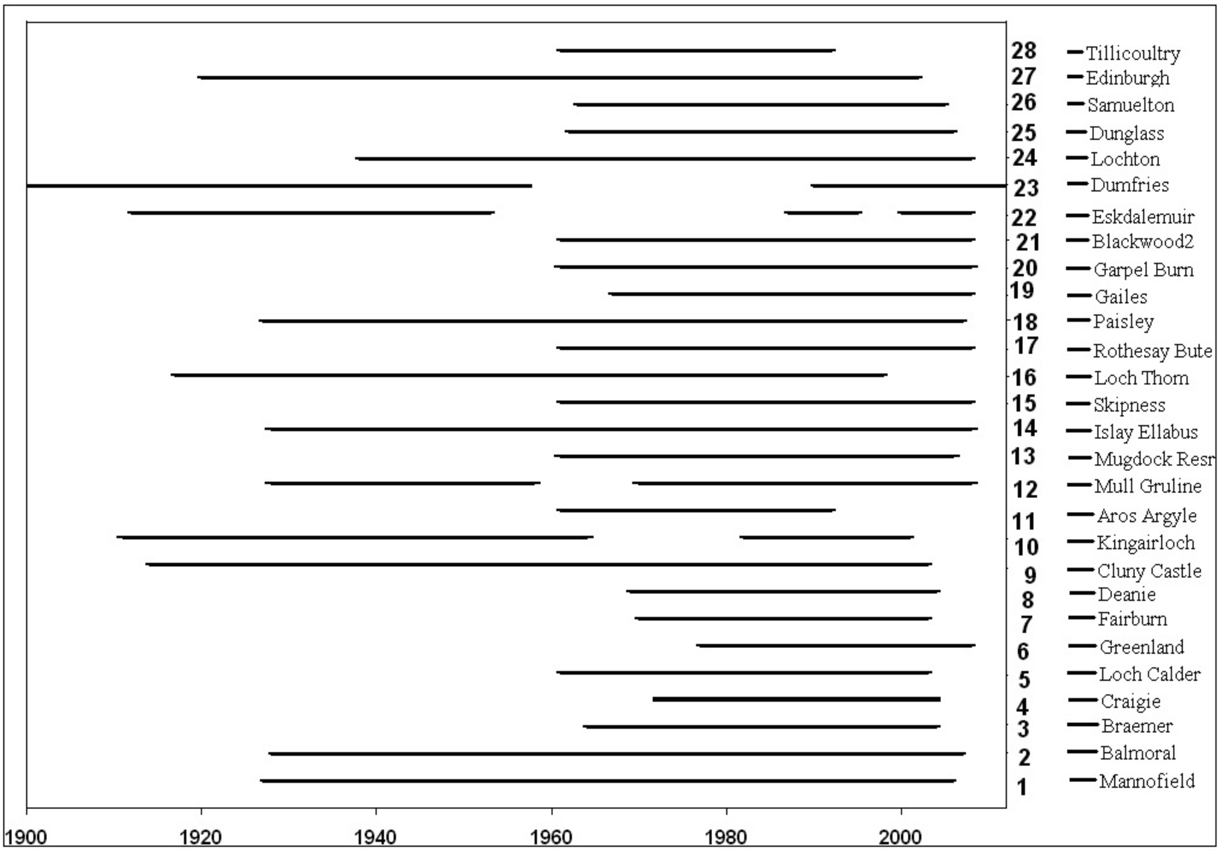

Fig. 1: Chronogram of data records

3. Results

3.1. Trends in daily precipitation

There have been changes in the magnitude of rainfall in Scotland during the study period but these changes have not been unidirectional. Most weather stations in Scotland showed an increasing trend in rainfall with the exception of one station in the East, which showed a decreasing trend over the entire period (Table 1).

The CUSUM and sequential MK test reveal one turning point in the precipitation trends at the weather stations situated in the West and South-West of Scotland and more than one turning point in the other regions, as illustrated at Paisley and Balmoral in the Western and Eastern parts of Scotland, respectively (Figs. 2 & 3). Fig. 4 displays the spatial distribution of the weather stations across Scotland on the basis of the number of turning points in the precipitation trends.

3.2. Variability index and trends in rainfall variability

The different measures of variability were combined into a variability index (X) which was calculated from the sum of the mean value of each variability parameter at each weather station divided by the mean value for all stations, i.e.:

$$X_i = V_i/V_m + WS_i/WS_m + D_i/D_m + CR_i/CR_m \tag{4}$$

where V = variance, WS = winter/summer ratio, D = mean length of dry period, CR= CUSUM range and the subscript i refers to each station and m refers to the mean for all stations. Table 2 shows an example of three stations; Garpel Burn representing most weather stations from South-west and North-west region with variability index from 1.25 and above; Paisley representing most of the stations from West region with a variability index from 1.0 to 1.25, and Balmoral representing most of the stations from North and East region with a variability index below 1.0. The spatial distribution of the variability index for all weather stations is shown in Fig. 4, which indicates that most weather stations in the West and South-west, which exhibit higher rainfall variability, also show an abrupt change in trend in the w/s ratio and the variance around 1980. Most of the stations in the Northern and the Eastern parts of the country, which showed more than one turning point also showed less variability as compared to the other regions (Fig. 4).

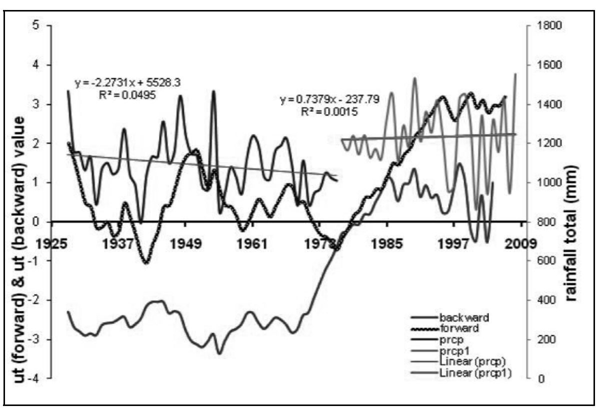

Fig. 2 Sequential MK test on daily precipitation totals at Paisley for the period 1928-2008. Also displayed are the trendlines estimated using the ordinary least squares technique.

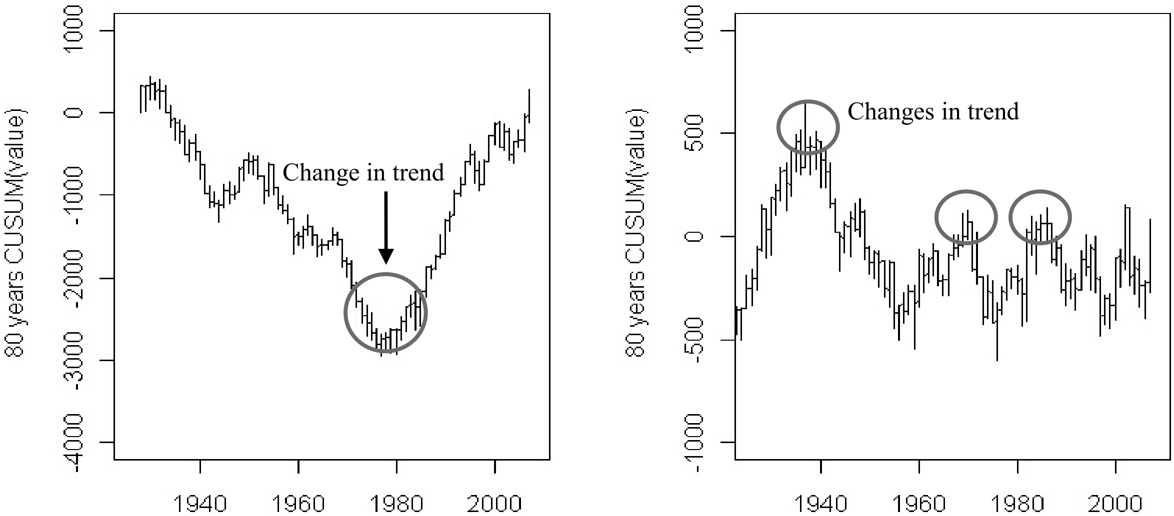

Fig. 3: CUSUM plot of daily precipitation at Paisley (left) and Balmoral (right) for the period 1928-2008

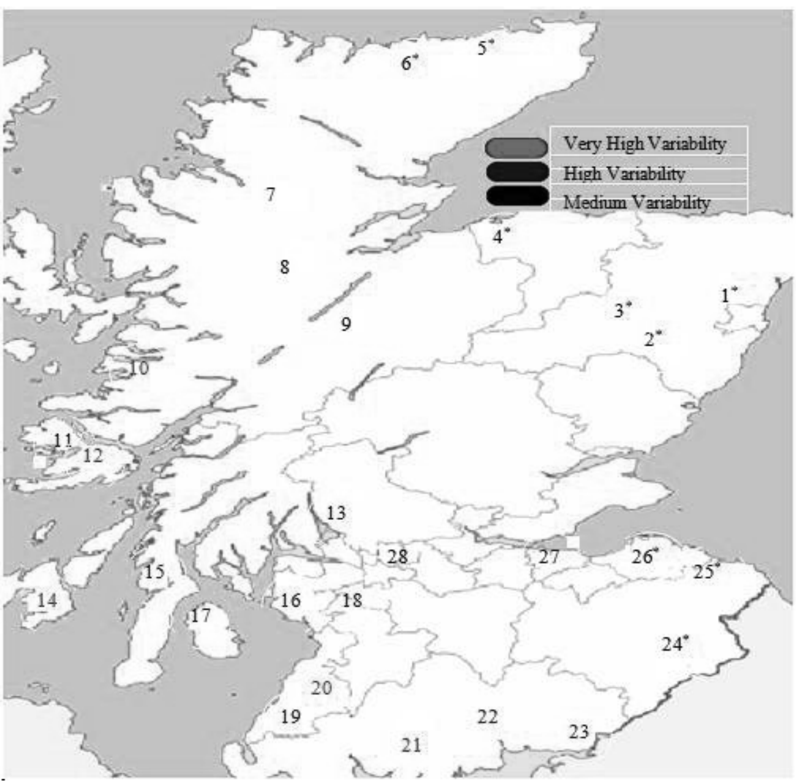

Fig. 4: Rainfall variability in Scotland based on a composite index of rainfall variability. Also shown are the weather stations with more than one turning points in the rainfall time series (*) as explained in the text.

Although statistically significant increasing trends in rainfall variability were observed in the West and South-west of Scotland, the trends have not been temporally consistent. The sequential MK test revealed turning points between 1978 and 1985 with rainfall variability showing a decreasing trend since the 1980s in both the variance and the w/s ratio (Figs. 5 & 6). In the East, no statistically significant trends were detected in either the variance or the w/s ratio of precipitation (Table 1).

The variance of rainfall on a seasonal basis in the West also showed a sudden change in trend during the winter and autumn seasons around 1980, explaining the change of trend observed at the same time at the annual time-scale; while little or no significant change in trend are observed at weather stations in the North and East (Fig. 7).

Some stations showed significant trends in the annual number of dry days (Table 1); the trends were mostly decreasing but with some increasing. As an example, Fig. 8 illustrates the decreasing and increasing trends respectively in the annual number of dry days at Islay Ellabus in Western Scotland and at Balmoral in the East. The figure also shows that the maximum dry period length varied in a similar manner.

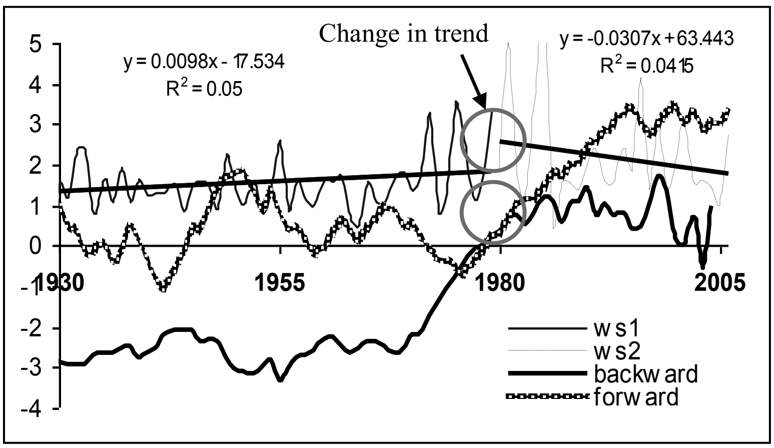

Fig. 5: Sequential MK test on the w/s ratio of precipitation at Paisley for the period 1928-2008. Also displayed are the trendlines estimated using the ordinary least squares technique.

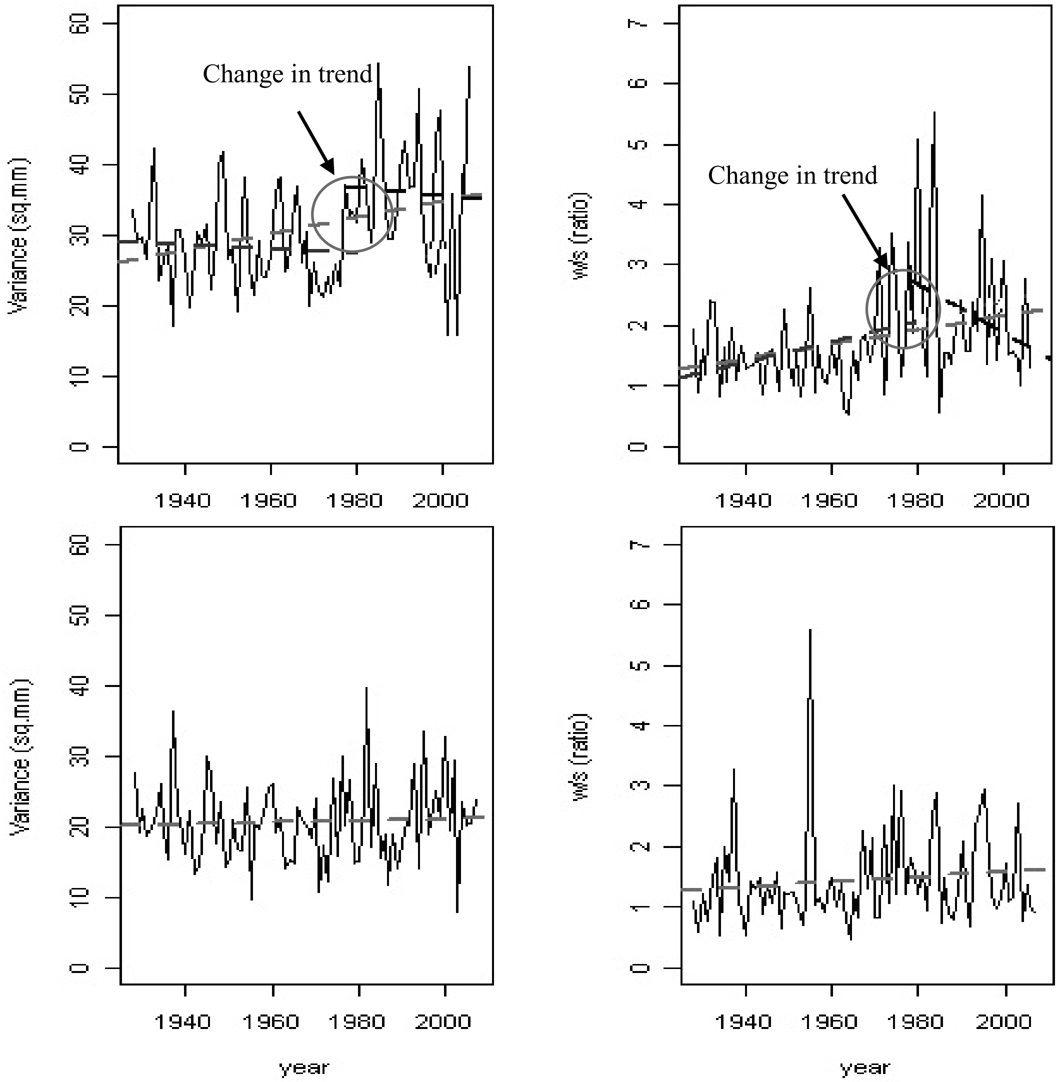

Fig. 6: Annual variance (left) and w/s ratio (right) of daily precipitation at Paisley (top) and Balmoral (bottom) for the period 1928-2008.

Table 1: Results of the MK trend test on precipitation amounts and three measures of variability for the entire data record

Weather station	Map no.	**Daily rainfall**		**Variance**		**w/s ratio**		**No. dry days per year**	
		Kendall's tau	p-value	Kendall's tau	p-value	Kendall's tau	p-value	Kendall's tau	p-value
Mannofield	01	**-0.18**	**0.01**	-0.07	0.30	0.07	0.35	0.56	0.22
Balmoral	02	<0.01	0.97	0.02	0.75	0.08	0.28	**0.23**	**<0.01**
Braemar	03	**0.20**	**0.04**	**0.26**	**0.01**	0.15	0.14	**-0.24**	**0.02**
Craggie	04	0.20	0.11	0.21	0.09	0.08	0.49	0.03	0.78
Loch Calder	05	**0.19**	**0.05**	0.14	0.18	0.19	0.06	**-0.28**	**<0.01**
Greenland	06	**0.26**	**0.03**	0.10	0.42	0.08	0.48	-0.23	0.06
Fairburn	07	**0.26**	**0.02**	**0.26**	**0.03**	0.16	0.17	**-0.52**	**<0.01**
Deanie	08	**0.62**	**<0.01**	**0.61**	**<0.01**	0.22	0.05	-0.05	0.65
Cluny Castle	09	0.03	0.65	0.07	0.29	**0.15**	**0.04**	-0.05	0.65
Kingairloch	10	-0.01	0.90	0.05	0.54	**-0.20**	**0.03**	-0.14	0.12
Aros	11	**0.27**	**0.03**	0.15	0.21	0.18	0.14	0.17	0.16
Mul-Gruline	12	**0.20**	**0.05**	0.12	0.26	-0.03	0.77	0.15	0.16
Mugdock	13	**0.27**	**<0.01**	**0.28**	**<0.01**	-012	0.90	-0.10	0.31
Islay Ellabus	14	**0.23**	**<0.01**	**0.16**	**0.03**	0.05	0.43	**-0.20**	**<0.01**
Skipness	15	**0.31**	**<0.01**	**0.27**	**<0.01**	0.12	0.21	**-0.26**	**<0.01**
Loch Thom	16	0.06	0.39	0.06	0.42	0.08	0.28	**0.56**	**<0.01**
Rothesay	17	**0.22**	**0.02**	0.12	0.22	0.09	0.32	0.15	0.11
Paisley	18	**0.21**	**0.01**	**0.19**	**0.01**	**0.17**	**0.01**	0.04	0.57
Gailes Air	19	**0.28**	**<0.01**	**0.22**	**0.04**	0.03	0.74	-0.14	0.17
Garpel Burn	20	0.58	0.09	0.57	0.09	**0.20**	**0.03**	-0.16	0.11
Blackwood	21	**0.58**	**<0.01**	**0.58**	**<0.01**	**0.20**	**0.04**	**-0.29**	**<0.01**
Eskdalemuir	22	0.05	0.63	0.18	0.08	**-0.21**	**0.04**	0.21	0.10
Dumfries	23	**0.31**	**<0.01**	**0.18**	**0.01**	0.20	0.07	**0.31**	**<0.01**
Lochton	24	0.06	0.39	0.09	0.23	0.13	0.08	0.01	0.81
Dunglass	25	0.02	0.79	0.06	0.52	0.07	0.47	**-0.39**	**<0.01**
Samuelton	26	0.17	0.10	0.14	0.18	0.17	0.10	-0.03	0.77
Edinburgh	27	**0.13**	**0.05**	**0.24**	**<0.01**	**0.16**	**<0.01**	0.40	0.34
Tillicoultry	28	**0.26**	**0.03**	0.13	0.29	0.17	0.18	-0.08	0.50

The values in bold indicate trends that are statistically significant at the 95% confidence level

Table 2: Variability index calculated on a selected number of weather stations.

Stations	No on map	Variance Index V_i/V_m	w/s Index WS_i/WS_m	CUSUM Index CR_i/CR_m	Dry Days Index D_i/D_m	Variability Index (X)*
Balmoral	2	0.57	0.95	0.75	1.00	0.82
Paisley	18	0.81	1.16	1.41	1.06	1.11
Garpel Burn	20	1.78	1.31	2.7	0.89	1.67

* The variability index (X) of all stations was calculated by dividing the mean variability of each station by the average of all stations variability index.

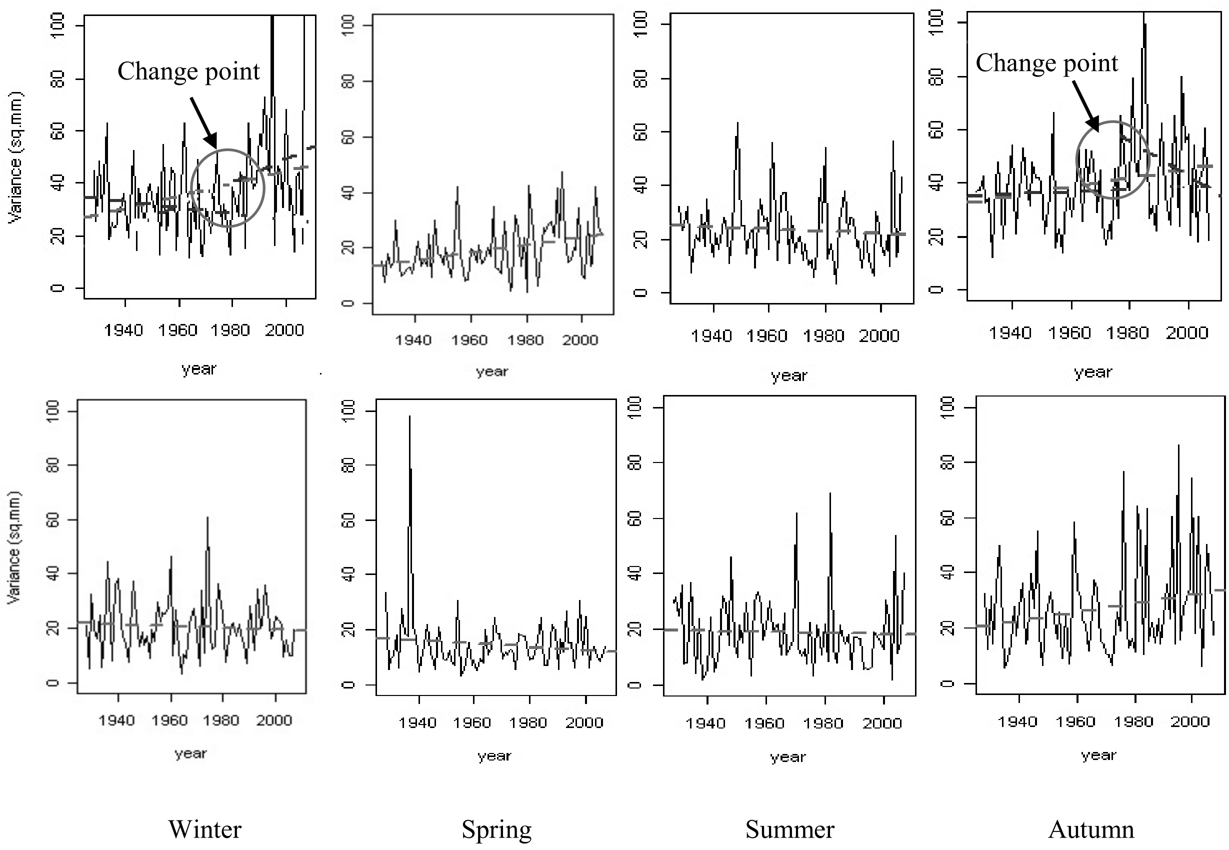

Fig. 7: Variance of daily precipitation at the seasonal time-scale at Paisley (top) and Balmoral (bottom) for the period 1928-2008.

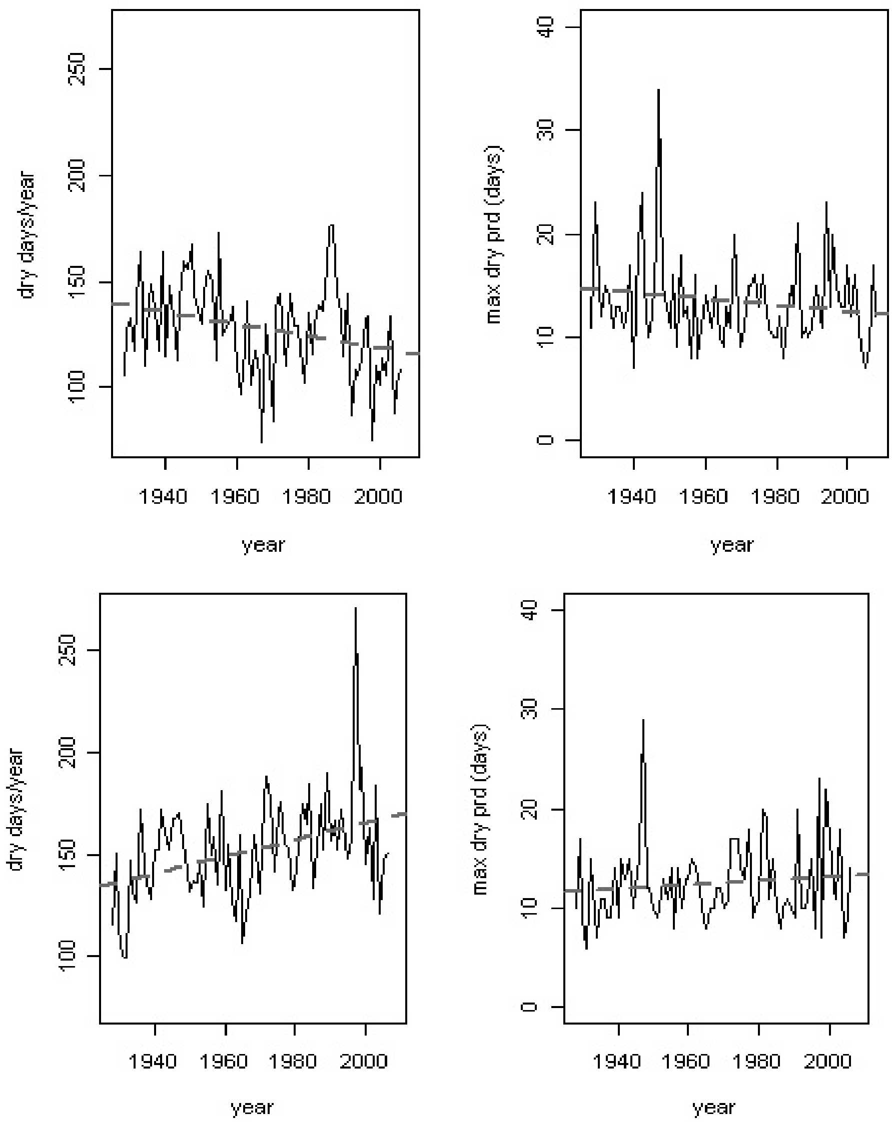

Fig. 8: Annual number of dry days and maximum dry period length at Islay Ellabus (top) and Balmoral (bottom) for the period 1928-2008.

4. Conclusion:

This study examined the variability in daily precipitation at 28 weather stations across Scotland with record lengths varying from 30 to 80 years. The findings reveal that the increasing trends in rainfall amounts reported by many authors have not been temporally continuous. Rather, many stations situated in the West of Scotland showed an abrupt change in precipitation amounts around 1980. It was also noted that there was a spatial pattern in average rainfall variability. Three regions with different rainfall variability patterns were identified with the highest variability observed in the West and South-west regions. Weather stations situated in the West and South-west of Scotland also showed increasing trends in rainfall variability as measured by the variance and the w/s ratio. At most weather stations there was an abrupt change in the trend of rainfall variability around 1978-1985; nonetheless, some stations, especially in the North and East, showed no single change. Significant increasing and decreasing trends were observed in the number of annual dry days and the annual maximum dry period length across Scotland, but further work using a consistent time-period of analysis is required to derive any spatial pattern.

Future changes in rainfall variability could have an impact on the reliability of the water supply systems. The work presented here will be extended to examine the variability in future rainfall using UKCP09 climate change scenarios and a hydrological model will be used to investigate the reliability of the water supply of different case study regions with contrasting amounts of water storage.

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