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Inter-decadal variability in daily rainfall at Durham (UK) since the 1850s

T. P. Burt[a]* and B. P. Horton[b]

[a] *Department of Geography, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK*
[b] *Sea Level Research Laboratory, Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA 19104-6316, USA*

Abstract:

Records of daily rainfall at Durham (UK) are analysed from 1850 to the present. The most notable wet period is the 1870s, followed by a protracted period of below-average rainfall. Other than the 1870s, summers tended to be much wetter than winters during the latter part of the 19th century. In the 20th century, summers had become drier and winters wetter. To analyse large daily totals, three thresholds, 15, 22.6, and 25 mm, are used. For all three indices, the frequency of large falls was highest from the 1860s to the 1880s, followed by a low frequency in the 1900s. Since then, the general trend has been for totals to gradually increase. There is a clear division for the annual total rainfall, number of heavy falls ($\geq$15 mm), and proportion of total rainfall provided by heavy falls in the winter (154 mm, 147 days, 12%, respectively) and spring (140 mm, 180 days, 16%) seasons in comparison to the summer (181 mm, 329 days, 28%) and autumn (186 mm, 304 days, 23%) seasons. However, since 1990, winter total rainfall (164 mm) has overtaken the summer total (154 mm). Furthermore, since 1990, heavy falls of rain in spring (23 days) and the proportion of total rainfall (26%) have overtaken summer heavy rain (17 days) and the proportions of rainfall in both summer (24%) and autumn (24%). In terms of heavy rainfall, winters have seen only a small increase in its relative importance, whereas its relative importance declined from the 1960s to the mid-1990s for summers. The widely recognised increase in the winter : summer ratio of rainfall since the 1960s is clearly evident. Overall, there has been a narrowing of the differences between seasons in terms of the frequency of heavy falls of rain in the 1990s. Copyright © 2006 Royal Meteorological Society

KEY WORDS rainfall; heavy falls of rain; seasonality

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CLIMATE CHANGE AND THE OCCURRENCE OF HEAVY RAINFALL

Under enhanced greenhouse conditions, climate model integrations suggest increases of both rainfall frequency and intensity in high latitudes of the Northern Hemisphere (e.g. McGuffie *et al.*, 1999; Palmer and Räisänen, 2002; Jones and Reid, 2001; New *et al.*, 2001; Semenov and Bengtsson, 2002; Ekström *et al.*, 2005; Fowler *et al.*, 2005). Earlier concerns about the difficulty in defining changes in daily rainfall from a global climate model, because of coarseness of the spatial scale (Arnell, 1996), are being overcome, and it is now feasible to derive an improved representation of extreme rainfall using regional climate models at a resolution of ~50 × 50 km (Jones and Reid, 2001; Hulme *et al.*, 2002; Huntingford *et al.*, 2003; Ekström *et al.*, 2005; Fowler *et al.*, 2005). In the UK (Jones and Conway, 1997; Osborn *et al.*, 2000; Osborn and Hulme, 2002; Fowler and Kilsby, 2003a,b), Europe (Brunetti *et al.*, 2000; Frei and Schar, 2001; Moberg and Jones, 2005), and worldwide (Iwashima and Yamamoto, 1993; Karl and Knight, 1998; Groisman *et al.*, 1999; Zhai *et al.*, 1999; New *et al.*, 2001), concerns regarding enhanced greenhouse conditions have been fuelled by the frequent occurrence of heavy rainfall and widespread flooding since 1990. For example, the autumn and winter of 2000–2001 saw the wettest months on record in the UK (Alexander and Jones, 2001; Marsh, 2001), with extensive flooding at many places across the country. Events such as the devastating floods at Boscastle in August 2004 (Doe, 2004), at Carlisle in January 2005, and on the North York Moors in June 2005 seem, to the general public at least, to confirm the link.

Jones and Conway (1997) updated the precipitation series for the British Isles following the studies of Wigley *et al.* (1984), Wigley and Jones (1987), and Gregory *et al.* (1991). However, this series did not include the Durham rainfall record. Jones and Conway (1997) concluded that from 1840 to 1995 there is evidence of a higher winter to summer precipitation totals in the 1990s following relatively high values in the 1860s and 1870s. Osborn *et al.* (2000) and Osborn and Hulme (2002) provide a more detailed spatial examination of heavy falls of rain,

* Correspondence to: T. P. Burt, Department of Geography, University of Durham, Science Laboratories, South Road, Durham DH1 3LE, UK. E-mail: t.p.burt@durham.ac.uk

as indicated by daily totals, for around 150 stations across the UK since 1961, together with a less comprehensive coverage for a much reduced number of gauges back to 1908 (including Durham). Osborn *et al*. (2000) showed that the intensity of daily precipitation amounts in the UK had changed over the period 1961–1995, becoming, on average, more intense in winter and less intense in summer. For the period 1961–2000, Osborn and Hulme (2002) showed that the recent increases in total winter precipitation were mainly due to an increase in the amount of precipitation on wet days, with a smaller contribution in the western UK from a trend towards more wet days. Results for summer showed almost the opposite trends: decreased precipitation totals because of both fewer wet days and reduced wet-day amounts. Osborn and Hulme (2002) also extended their analysis back to 1901 using a sparser network of weather stations.

The purpose here is to place the conclusions of Jones and Conway (1997), Osborn *et al*. (2000), and Osborn and Hulme (2002) in a long-term context using the daily rainfall record at Durham Observatory (UK); this record is very unusual in that it stretches back unbroken to the mid-1850s and, even rarer, is available as a computer file. This long record has been achieved using different gauges, but the location has remained the same and external influences were minimal owing to the lack of urban development close to the site. Thus, the Durham observations provide a homogeneous rainfall record (New *et al*., 2001). Although there are obvious limitations in using only a single record, this is offset by the rarity of such records for the 19th century. Indeed, Moberg and Jones (2005) stated that there is a clear need for more century-long observation records to allow a spatially more extensive analysis covering the whole of the European continent. The Durham observations described here comprise a considerably longer time series of daily rainfall than any others previously scrutinised. Thus, the Durham series provides an important resource for studying long-term regional rainfall variability, climate model evaluations, observed climate change against the background of natural variability, and the construction of climate scenarios for climate impact studies (e.g. Hulme, 1994; Hulme *et al*., 1999a,b).

DATA SOURCES AND METHODS

The 1840s was a critical period for the development of meteorology in the UK. A meteorological department was set up at Greenwich Royal Observatory in 1840, with James Glaisher as its first Superintendent of Meteorological Observations. Following this lead, several observatories in the north of England began their meteorological records in the same year, including the one at Durham University, where the observatory building was completed in 1841. Probably, meteorological observations began straight away, and the earliest surviving data are from 23 July 1843 (Kenworthy, 1985). Several authors have examined the meteorological records of Durham Observatory (the seminal paper is that of Manley, 1941), although these deal almost entirely with the temperature data and include little detail about the rainfall.

Durham Observatory is situated at 54°46′N, 1°36′W at an elevation of 102 m; the site is described in detail by Manley (1941). Unlike some other long-established observatories (e.g. the Radcliffe Observatory at Oxford), the Durham site has remained relatively unaltered since the 1840s; in particular, there has been no dense urban development close to the site.

The daily rainfall totals have always been measured at 09 : 00 h Greenwich Mean Time. There has, however, been a good deal of variety in gauge size and its height above ground level over the years. From 1852, a 12-inch (305 mm) diameter gauge was used, with its rim 4 feet 6 inches (1371 mm) above the ground. The 12-inch gauge was used until 1917, followed by an 8-inch (203 mm) gauge (with rim 1 foot (305 mm) above the ground) until 1948, and since then, a 5-inch (125 mm) gauge has been used (again with rim 1 foot above the ground). Since October 1999, an automatic weather station has been deployed, recording the totals hourly; the tipping bucket mechanism records rainfall amounts in 0.2 mm increments.

Summaries of the problems associated with sampling precipitation and the uncertainties inherent in estimating true precipitation from the rain gauge catch are well documented (e.g. Reynolds, 1965; Strangeways, 1996a,b). Data validity can be compromised by poor instrumental design or exposure, errors in observational interpretation, and changes in the type of rain gauge (Hanna, 1995; Tuomenvirta, 2001; Brunetti *et al*., 2004). It is clear that there was a good deal of experimentation at the Durham Observatory in the late 1860s and 1870s on rain gauge height and diameter (Joyce *et al*., 1998); at that stage there was no consensus on the desirable features of design and exposure of rain gauges (Reynolds, 1965). A note on the 1852 measurements is as follows: 'The rain gauge of which the record is here given is that one of two near the south fence, enclosed in a wooden casing. The receiving surface is 4 feet 6 inches above the ground.' A 4-foot gauge was used from 1886 and various heights, from 4 feet to 4 feet 8 inches, are recorded before that. In fact, it was not until 1917 that the gauge height at Durham was reduced from 4 feet to 1 foot. In the absence of any other information, we can only conclude that the gauges have been on the south lawn, in much the same location as it is today, since 1852.

In order to check the homogeneity of the Durham rainfall record, a number of methods were applied by Burt (in prep.), which were as described in Aguilar *et al*. (2003) and Linacre (1992). Comparative data were obtained from Oxford (records from 1767), Edinburgh (records from 1785), Malham Tarn (records from 1860), a variety of local gauges for which data are listed in successive volumes of *British Rainfall*, and the composite monthly regional rainfall record for north-east England (NEE) available from 1873 to the present (Alexander and Jones, 2001). Analysis of double mass curves and the use of ratio and first-difference time series have confirmed that the Durham record is entirely consistent with the others, except during the 1870s, a decade that has been the subject of particular scrutiny. As attested by the volumes of *British Rainfall* (Jones and Conway, 1997), the 1870s was clearly an unusually wet decade, particularly in some of the notable years such as 1872 and 1877, but the Durham results appear relatively higher than the results for nearby gauges (Burt, in prep.). Nothing in the original ledgers can explain these abnormally high totals, e.g. there is no mention of an unusually sited gauge. The Swed–Eisenhart Runs Test (Linacre, 1992) on a split series for Durham (1852–1928; 1929–2005) showed that the second half of the series is homogenous but the first half is not (at a 1% level of significance), which is probably because of the shift in the mean for the 1870s. The only period in which the NEE : Durham ratio (annual totals) falls below the value of 1 is 1874–1878 (Unfortunately, the NEE series starts one year too late to pick up the very wet year of 1872). Double mass analysis for accumulated totals at Durham and NEE indicates a breakpoint around 1879. We conclude that the Durham rainfall is homogenous from the 1880s and that the changes in the instrumentation (precise location, gauge height, orifice diameter) since then have not had any significant effect. Because the 1870s are of special interest in any long-term assessment, they are included here, but with the *caveat* that the recorded totals may be too high. Although it is relatively straightforward to adjust monthly and annual data (Aguilar *et al*., 2003; Burt, in prep.), the literature provides no guidance about how this adjustment should translate to daily totals, hence we have not sought to adjust the raw daily totals during the 1870s.

Although daily rainfall data are available from 1850, there are a number of missing months in 1854 and 1855. There is also some doubt about the totals for 1850 and 1851, which are very much larger than the other values in the record. For these reasons, the decadal analysis in this period starts with the 1860s. All decades run from xx01 to xx10. Following convention, winter is taken to be December, January, and February. Thus, winter 1861 starts with December 1860, which means that the 1860s start in December 1860 and ends in November 1870. The decadal analysis ends in November 2000, although in some cases the annual records are reported through to the end of 2004. The other seasons are defined using the same convention: spring (March, April, and May), summer (June, July, and August), and autumn (September, October, and November).

Analysis of heavy falls of rain, as indicated by daily totals, follows the analyses of Osborn *et al*. (2000) and Osborn and Hulme (2002), which were similar to those of Karl and Knight (1998), except that the thresholds used were determined by precipitation rather than frequency. In Osborn *et al*. (2000), a 'category (10)' threshold is identified: this is the daily rainfall total above which the top 10% of total rainfall has occurred. At Durham, this threshold is a daily total of 22.6 mm; considering the uncertainty about figures for the 1870s, this value was derived for the period 1881–2000. In a later paper, Osborn and Hulme (2002) also used an arbitrary threshold of 15 mm for convenience (Osborn, 2001); 22% of the total rainfall at Durham is derived from daily totals equalling or exceeding 15 mm. A 25-mm threshold is also used here; daily totals of 25 mm and above account for the upper 7.5% of total rainfall at Durham.

RESULTS

Annual rainfall and seasonal variability

Annual totals range from 415 mm (1989) to 1231 mm (1872), with a median of 676 mm and an interquartile range of 153 mm (584–737 mm). The most notable wet period is clearly the late 1860s and 1870s, followed by a protracted period of below-average rainfall around the turn of the century (Figure 1). Since the 1950s, the running mean shows a more frequent oscillation between wetter and drier spells.

There has been much interest recently on seasonal rainfall (e.g. Jones and Conway, 1997; Burt *et al*., 1998;

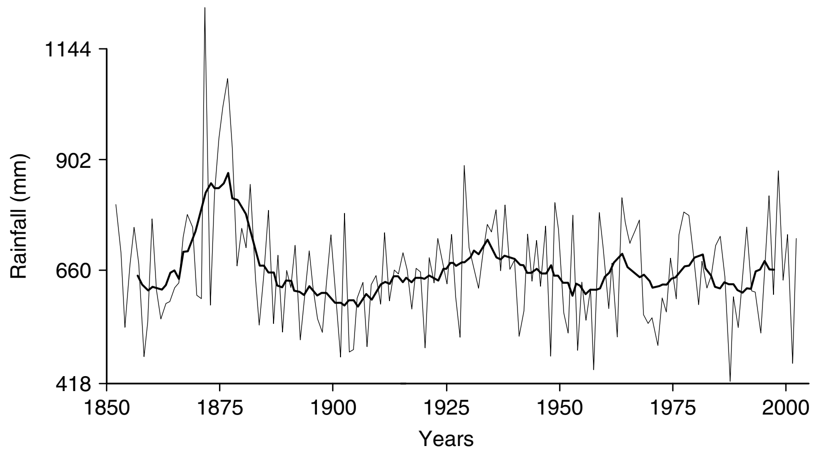

Figure 1. Annual rainfall totals for 1852–2004 at Durham, together with a decadal running mean. Grid lines are drawn at 2 standard deviations ($\sigma = 121$ mm) at the approximate mean value of 660 mm.

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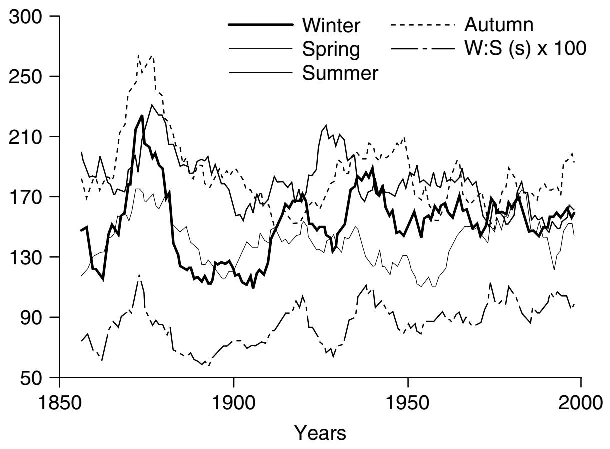

Figure 2. Seasonal rainfall at Durham using decadal running means. Also shown is the ratio of winter (DJF) to summer (JJA) rainfall (×100); this was calculated using the winter and summer running means shown in this figure, rather than the running mean of individual annual values (see text for further explanation).

Osborn and Hulme, 2002). There is a clear division in the mean seasonal rainfall totals at Durham between winter (154 mm) and spring (140 mm), and summer (181 mm) and autumn (186 mm). It is interesting to note that summers tended to be much wetter than winters during the latter part of the 19th Century, other than in the very wet 1870s. In the 20th Century, summers tended to become drier and winters tended to become generally wetter (Figure 2). This is reflected in the increasing values of the ratio since the minimum in 1893; the running mean has been greater than 1 since 1972 in all but two years (centred on 1984 and 1985). Except for the 1870s, autumn and summer rainfall totals were very close, through to ∼1930 (Figure 2). Since 1930, autumns have been wetter than summers more often than not, and were thus the wettest season of the years. Spring is usually the driest season, but this was not the case from the 1880s to the 1910s when winters were even drier than spring. Taken together, the data plotted in Figure 2 show that seasonal rainfall at Durham has shown considerable variability at the decadal timescale since the 1850s.

The clearest pattern to emerge is the relative increase in winter rainfall compared to summer rainfall since the 1890s. We have calculated the winter : summer ratio using the 'smoothed' winter and summer running means shown in Figure 2. If the ratio is calculated for each year and then a running mean calculated ('unsmoothed'), the calculated ratio becomes sensitive to extreme values; this was particularly the case for 1995 in which the actual ratio was 3.72, which is much higher than any other value in the series (Burt *et al.*, 1998). The use of an 'unsmoothed' ratio suggested that winters in the 1990s were 30% wetter than summers, when in fact the totals were very similar. The 'smoothed' ratio (Figure 2) shows that winter rainfall since 1972 has only twice been less than 90% of summer rainfall (decadal running means centred on 1984 and 1984), and indeed the ratio exceeded 100% for much of the 1970s and 1990s. Prior to the 1970s, winter : summer ratios above 90% were much less common, occurring only for 1868–1876, 1915–1921, and 1936–1945. Thus, before 1972, only 30 of the 115 years had the winter : summer ratios above 90%, whereas 25 of 27 years since then had ratios above 90%. Note that the winter : summer ratio fell below 70% between 1883 and 1896.

Heavy falls of rain: decadal results based on annual data

Only three decades have decadal totals that are outside the range of 6000–7000 mm: the dry 1900s fall below 6000 mm, the 1930s just exceed 7000 mm, and the very wet 1870s far exceed all others (Table I). The correlations in Table II show that all threshold indices are highly correlated with decadal rainfall totals, with the exception of the number of days that have totals exceeding 50 mm and where the numbers are too small to allow any meaningful result. Mean rainfall per rain day correlates significantly with the decadal total, but the number of rain days (daily totals ≥ 0.25 mm) does not. The percentage of total rainfall on rain days obtained from daily totals equalling or exceeding 15 mm correlates significantly with the decadal total, and the same is true for the 22.6-mm index. The results in Table II also show that, as the number of heavy falls increases, so too does the fraction of total rainfall resulting from such falls.

All three threshold indices have high totals in the first three decades of 1860s to 1880s. For the 22.6 and 25 mm thresholds, these totals are higher than any other value since then, and this is nearly true for the 15 mm threshold as well. All the three threshold index totals are lowest in the 1900s, and the general trend since then has been for the totals to increase, with the value of totals in the 1990s back to the level of the 1880s (15 mm) or nearly so (22.6 and 25 mm). The number of short-duration two-day totals (following Ekström *et al.*, 2005) equalling or exceeding 50 mm follows a broadly similar pattern, so too does the percentage of total rainfall obtained from heavy rainfall days, for both the 15 mm and 22.6 mm indices.

Heavy falls of rain: decadal results by season

Notwithstanding a fair amount of inter-decadal variation, the number of days per decade, by season, for which daily rainfall totals equalled or exceeded the 15 mm threshold (Figure 3, Table III) shows a broad trend, with heavy falls of rain becoming less common in summer and autumn. Following the peak in the 1870s, daily totals over 15 mm fell to a minimum in the period from the 1890s to the 1920s. In the 1930s and 1940s, the decadal total was ∼15 in winter, since then the winter decadal total had been ∼10. The spring total also reached a minimum in the 1920s, after which it remained steady at ∼12 until the 1990s, when it jumped to 23. In relation to the proportion of total seasonal rainfall from the daily totals that equal or exceed 15 mm (Table IV), the decadal patterns for each season look very similar to those shown in Figure 3. Thus, in general terms, as the number of heavy falls increases, so too does the proportion of seasonal rainfall from such falls. Over the period as a whole,

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Table I. Summary of daily rainfall at Durham since 1861, by decade.

	Total rainfall (mm)	Total number of rain days	Number of days with totals > = 15	Number of days with totals > = 22.6	Number of days with totals > = 25	Number of days with totals > = 50	Number of 2-day totals > = 50	Mean rainfall per rain day (mm/day)	% of total rainfall on raindays from daily totals = >22.6 mm	% of total rainfall on rain days from daily totals = >15 mm
1860s	6469	1476	80	31	23	1	6	4.38	14.9	27.7
1870s	8621	1729	117	48	37	1	18	5.84	18.1	31.0
1880s	6631	1716	71	30	23	1	6	3.84	14.0	24.3
1890s	6209	1845	63	19	14	2	8	3.34	9.9	22.0
1900s	5798	1686	52	9	6	2	4	4.62	5.8	18.6
1910s	6417	1783	53	14	9	0	2	3.52	6.2	17.6
1920s	6553	1815	54	23	16	1	5	3.75	10.9	18.7
1930s	7071	1739	79	22	13	1	2	4.27	9.3	23.0
1940s	6494	1648	68	20	15	2	6	3.89	9.7	22.2
1950s	6186	1658	56	16	8	0	2	3.29	7.9	18.1
1960s	6834	1868	72	30	21	0	2	4.24	12.7	23.4
1970s	6365	1613	60	23	16	3	8	3.91	12.0	21.5
1980s	6303	1614	62	17	14	1	1	3.81	8.2	21.2
1990s	6543	1644	73	25	18	1	10	3.99	12.0	24.0

Table II. Correlations between variables using data listed in Table I.

	Total rainfall (mm)	Total number of rain days	Number of days with totals > = 15	Number of days with totals > = 22.6	Number of days with totals > = 25	Number of days with totals > = 50	Number of 2-day totals > = 50	Mean rainfall per rain day (mm/day))	% of total rainfall on rain days from daily totals = >22.6 mm	% of total rainfall on rain days from daily totals = >15 mm
Total	1.00	–	–	–	–	–	–	–	–	–
Rain days	0.17	1.00	–	–	–	–	–	–	–	–
# >15	0.91	−0.09	1.00	–	–	–	–	–	–	–
# >22.6	0.87	−0.01	0.90	1.00	–	–	–	–	–	–
# >25	0.84	−0.04	0.89	0.98	1.00	–	–	–	–	–
# >50	−0.19	−0.26	−0.08	−0.12	−0.05	1.00	–	–	–	–
# 2-day >50	0.67	−0.06	0.73	0.72	0.75	0.33	1.00	–	–	–
mean/rain day	0.75	−0.11	0.80	0.68	0.69	0.07	0.63	1.00	–	–
%tot >22.6/total	0.72	−0.13	0.81	0.97	0.96	0.03	0.72	0.59	1.00	–
%tot >15/total	0.75	−0.25	0.93	0.90	0.91	0.04	0.71	0.72	0.90	1

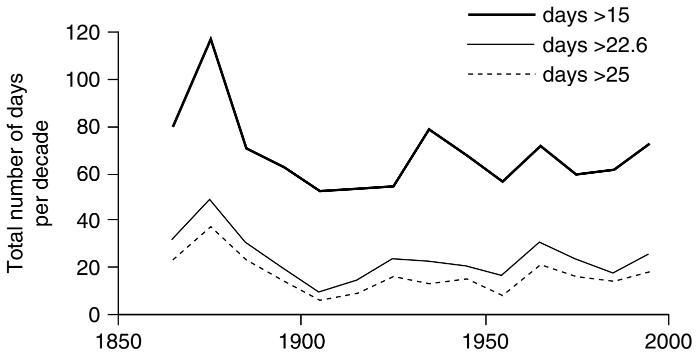

Figure 3. Total number of days per decade when daily rainfall equals or exceeds a given threshold (15, 22.6, and 25 mm).

Table III. The number of days, per decade, for which daily rainfall totals equalled or exceeded 15 mm and 25 mm.

	Winter		Spring		Summer		Autumn		Annual		Winter : summer ratio	
	15 mm	25 mm	15 mm	25 mm	15 mm	25 mm	15 mm	25 mm	15 mm	25 mm	15 mm	25 mm
1861–1870	12	2	20	2	24	11	23	6	80	23	0.50	0.18
1871–1880	27	9	19	7	33	9	38	13	117	37	0.82	1.00
1881–1890	10	2	13	1	27	15	23	6	71	23	0.37	0.13
1891–1900	4	2	9	0	23	5	26	7	63	14	0.17	0.40
1901–1910	5	0	10	1	20	2	18	3	52	6	0.25	∼
1911–1920	6	0	13	1	16	5	18	3	53	9	0.38	∼
1921–1930	5	2	4	1	32	11	13	2	54	16	0.16	0.18
1931–1940	15	1	14	1	26	5	23	6	79	13	0.58	0.20
1941–1950	16	3	6	1	20	5	26	6	68	15	0.80	0.60
1951–1960	9	1	12	3	20	2	16	2	56	8	0.45	0.50
1961–1970	8	4	13	1	27	10	24	6	72	21	0.30	0.40
1971–1980	11	2	12	3	25	6	12	5	60	16	0.44	0.33
1981–1990	9	1	12	3	19	3	20	6	62	14	0.47	0.33
1991–2000	10	1	23	5	17	5	24	8	73	18	0.59	0.20
Total	147	30	180	30	329	94	304	79	960	233		

Table IV. Fraction of the seasonal rainfall total provided for each decade by daily falls equalling or exceeding 15 mm.

	Winter	Spring	Summer	Autumn	Annual
1861–1870	14.8	25.1	33.0	25.5	27.7
1871–1880	25.0	21.6	33.8	30.0	31.0
1881–1890	13.9	17.6	35.2	23.6	24.3
1891–1900	6.1	13.5	25.9	30.7	22.0
1901–1910	5.6	13.5	23.6	21.6	18.6
1911–1920	7.0	14.4	20.9	22.3	17.6
1921–1930	6.0	7.4	32.7	16.0	18.7
1931–1940	12.7	18.5	30.9	24.7	23.0
1941–1950	16.5	8.3	24.5	26.3	22.2
1951–1960	11.9	18.3	23.3	16.6	18.1
1961–1970	10.3	16.1	34.5	27.3	23.4
1971–1980	10.4	14.3	29.4	16.5	21.5
1981–1990	12.1	11.8	25.7	22.4	21.2
1991–2000	10.6	26.1	23.7	24.2	24.0
Mean	11.6	16.2	28.4	23.4	22.4

there is no simple pattern to the winter : summer ratio, but the increase noted by Osborn *et al*. (2000) and Osborn and Hulme (2002) since the 1960s is clearly evident. In Durham's case, this is because of a decline in heavy summer rainfall rather than any increase in heavy falls in winter.

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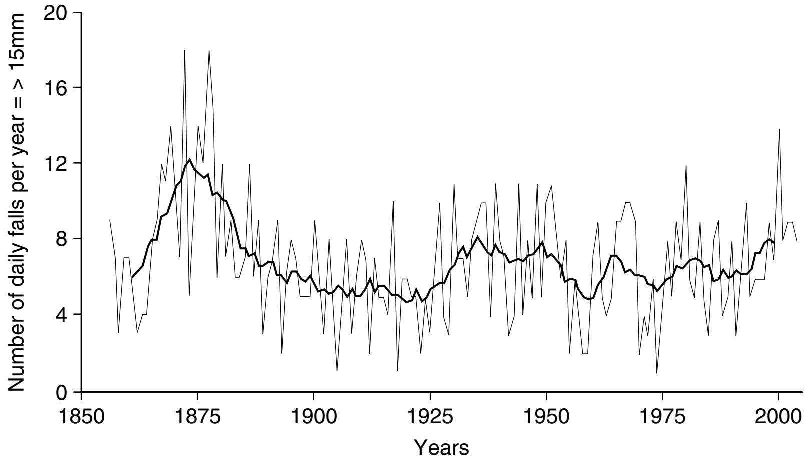

Figure 4. Number of days each year when the rainfall total equals or exceeds 15 mm, together with a decadal running mean.

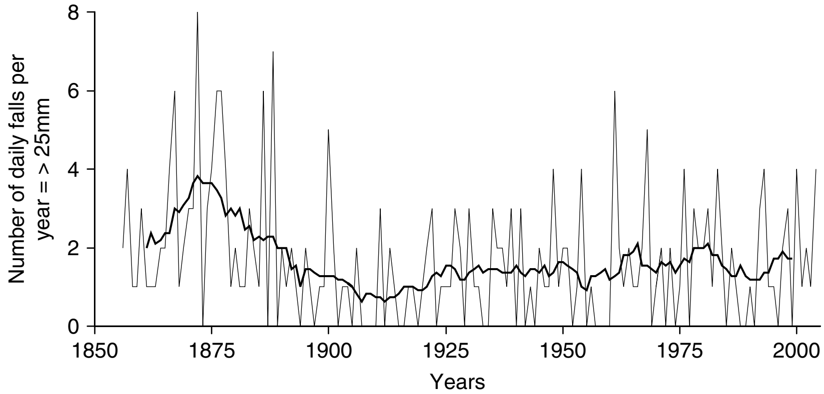

Figure 5. Number of days each year when rainfall total equals or exceeds 25 mm, together with a decadal running mean.

A broadly similar pattern is seen for the 25 mm threshold, with a general long-term decline in heavy falls in summer and a gradual increase through the 20th century in spring and summer. Since the 1960s, both summer and winter have shown a decline in the 25 mm threshold, but its winter : summer ratio has, nevertheless, increased. Both autumn and spring have seen increases over these four decades.

Numbers of heavy falls of rain: annual results

From 1867 to 1883, the decadal running mean of the number of days when rainfall total was greater or equal to 15 mm exceeded eight; thereafter it goes above eight only in 1935 and again in 1998 (Figure 4). The decadal increase from the 1970s to the 1990s (Table I) is seen to be an uneven pattern, but the transition from the low point in 1974 through to the peak in 2000 is a bigger shift than any such occurrence since the period 1921–1935; the increase in neither of these periods compares with the increase seen between 1862 and 1873. The total of 14 days rainfall in 2000 was the highest since 1878. The pattern for the 25 mm (Figure 5) and 15 mm thresholds is very similar through to the 1920s; thereafter, there is less variability for the 25 mm than for the 15 mm threshold and a more steady increase, from around 1 day per year having a rainfall exceeding 25 mm in the 1920s to nearly 2 days per year for the 1990s. It is not possible to calculate a winter : summer ratio for each year because a number of years have zero values. For this reason, Figure 6 shows the decadal running means for winter, summer, and the 'smoothed' winter : summer ratio on the basis of the decadal running means for the period 1855–2004. Only for the decade that is centred on 1873 does the ratio exceed one. It falls below 0.5 in 1883 and, apart from 1918, does not exceed 0.5 again until 1933, thereafter remaining above this figure until 1953. Only since 1986 has the ratio consistently been above 0.5, reaching 0.72 twice in the late 1990s. The early 2000s has shown a modest increase in heavy summer falls of rain and the ratio has subsequently fallen again.

The proportion of total rainfall from heavy falls of rain by season

There is a contrast between the late 19th and early 20th centuries regarding the proportion of total rainfall from heavy falls of rain during the winter season (Figure 7(a)). From the 1930s through the 1950s, the proportion of winter rainfall supplied by daily totals equalling or exceeding 15 mm was ∼15%; the proportion fell again in the 1960s but has gradually increased since then. This

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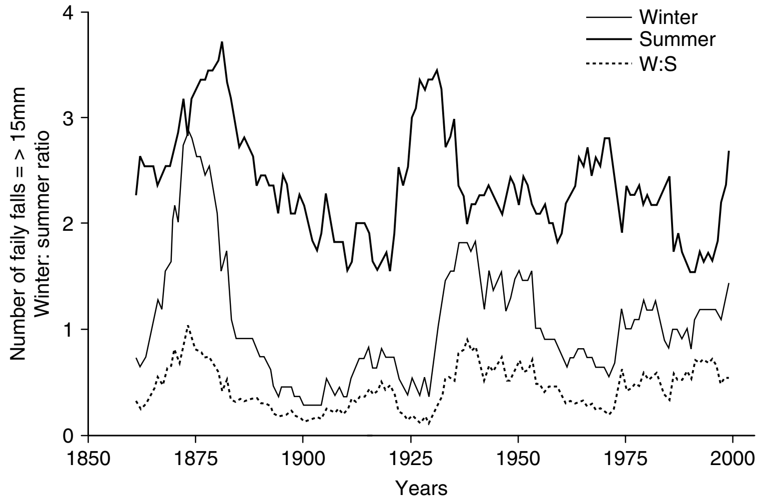

Figure 6. Number of days in winter and summer each year when rainfall total equals or exceeds 15 mm, together with a decadal running mean. Also shown is the ratio of winter (DJF) to summer (JJA) rainfall.

pattern is closely mirrored by the trend in the number of daily falls equalling or exceeding the 15 mm threshold. The pattern in spring (Figure 7(b)) is very similar to that for winter, except that it lacks such a large increase between the 1930s and 1950s.

The summer pattern (Figure 7(c)) is broadly similar to that of the winter pattern through to 1920, but tends to an opposite response from then onwards. The rise in the pattern in the 1920s predates that for winter in the 1930s, and then, unlike in winter, gradually falls till the end of the 1950s. It rises again in the 1960s before falling steadily through to the mid-1990s; this corresponds to the response identified by Osborn *et al.* (2000), Osborn and Hulme (2002), and Fowler and Kilsby (2003). The proportion of summer rainfall provided by large daily falls has again increased rather sharply recently, having been particularly influenced by the 2001 value (63.5%), which is only exceeded by the value for 1867 (63.6%). The pattern for autumn (Figure 7(d)) has elements of both the winter and summer curves. It is the only season to show an increase since ∼1900. Since 1960, the proportion has remained very steady for autumn, unlike for the other three seasons.

DISCUSSION

The long daily rainfall record for Durham indicates a good deal of variability in heavy falls of rain – as indicated by daily totals – over the decadal time scale. The most notable contrast is between the very wet period centred in the 1870s and the protracted period of below-average rainfall that followed the turn of the century. Through the 20th century, summers have tended to become drier and winters wetter. Similarly, Jones and Conway (1997) have concluded that, from 1840 to 1995, the British Isles and Ireland show trends towards wetter winters and winter half-years (November to April) and drier summers, with the trends being strongest in Scotland. For example, Jones and Conway noted that six of the ten wettest winter half-years have occurred for Scotland from 1987 to 1995 and only 1990–1991 was not an extreme year. Changes in the total Durham rainfall for over 150 years are generally reflected in both the number of heavy falls of rain and the proportion of total rainfall provided by those heavy falls. For all three threshold indices, totals were high in the first three decades, 1860s to 1880s; in contrast, totals fell to their lowest in the 1900s. Since then, the general trend has been for the number of heavy falls to increase, with totals in the 1990s back to the level of the 1880s (15 mm) or nearly so (22.6 and 25 mm). As Table II shows, as the number of heavy falls increases, so too does the fraction of total rainfall resulting from them. For most of the study period, the seasonal order for total rainfall, number of heavy falls, and the proportion of total rainfall provided by heavy falls have been as follows: spring <= winter < summer <= autumn. However, winter and spring have recently overtaken summer in terms of total rainfall; spring has overtaken summer in terms of heavy falls of rain and both summer and autumn in terms of the proportion of total rainfall provided by heavy falls. For Durham at least (which may not be typical of wetter, more western sites in the UK), there seems to have been a narrowing of the differences between seasons in the 1990s.

Durham's location to the east of the Pennine Hills implies that it is not an ideal location to observe some of the changes noted by Osborn *et al.* (2000) and Osborn and Hulme (2002); in particular, the increased frequency and contribution of heavy falls in winter over north-west Britain. In Durham's case, increase in the winter : summer ratio since the 1960s has been because of a decline in heavy summer rainfall rather than any increase in heavy falls in winter. Judging by Figure 2(f) given in Osborn and Hulme (2002), it is unusual for the Durham region to not have a stronger increase in heavy winter rainfall in the period 1961–1995. Why this should be

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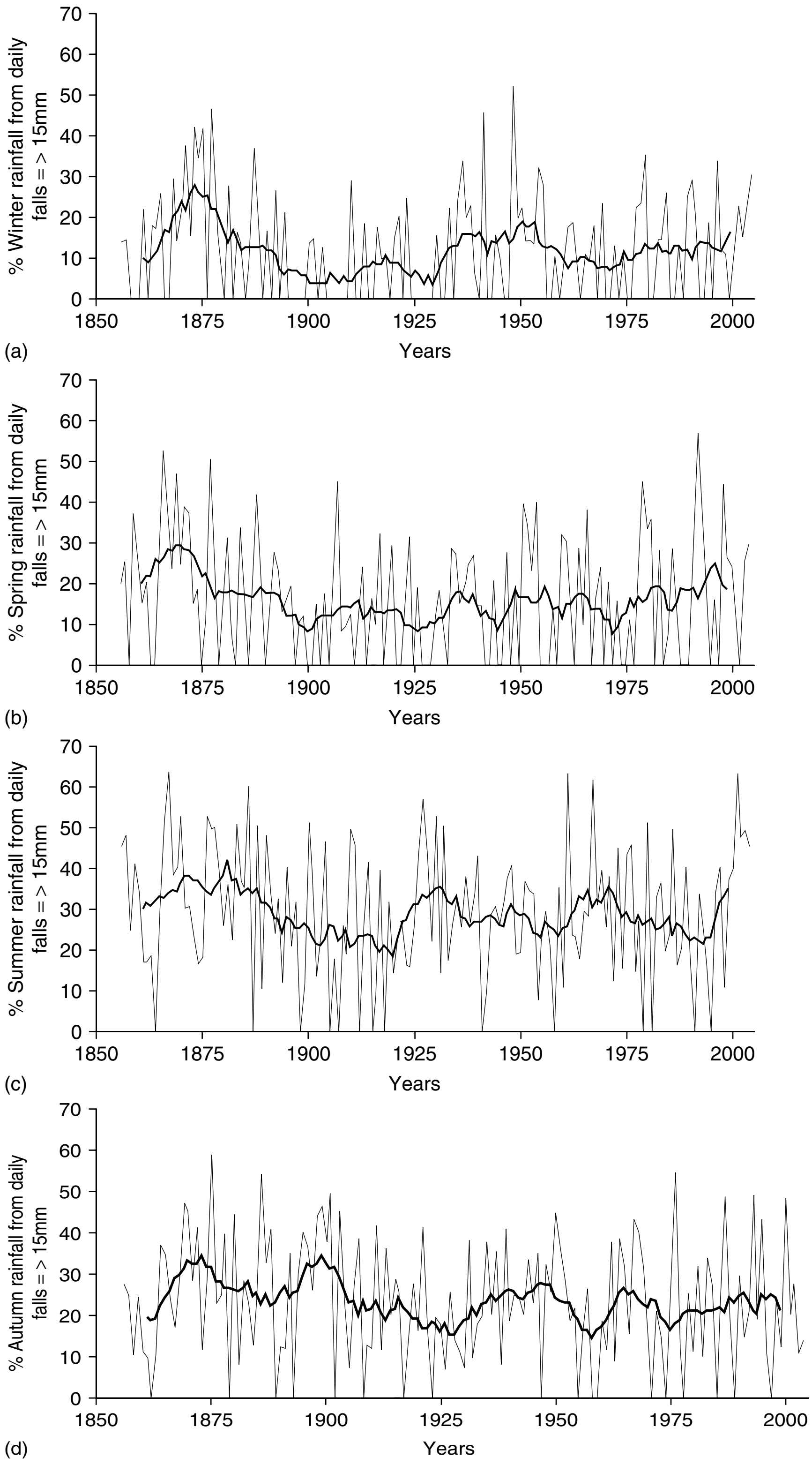

Figure 7. The proportion of total rainfall from heavy falls of rain by season.

so is not clear, but it may relate to stronger and more frequent westerly and south-westerly flows over the UK in winter (Osborn *et al.*, 2000); these flows tend to produce heavier rainfall on the western side of the country but not to the east of the Pennine Hills. Indeed, Fowler *et al*. (2005) using regional climate model integrations suggested that regions on the leeward side of the areas of high elevation, such as north-east England, show a classic 'rain-shadow' effect with very small increases in simulated mean annual rainfall. In this respect, Durham may be more like some of the East Anglian stations than the upland stations close to the west. Osborn and Hulme (2002) show (in Figure 3(f) in their work) that the decline in heavy summer rainfall at Durham was larger than at

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many stations, which again seems to reflect Durham's lowland, eastern location. Thus, while the tendency for wetter winters and drier summers seen throughout the UK is clear at Durham (Figure 2), in terms of heavy rainfall, winters have not shown any increase in the relative importance of heavy rainfall, while for summers the relative importance of heavy rainfall declined.

It is beyond the scope of this paper to investigate the reasons for the various changes in the heavy falls of rain at Durham over the last 150 years. However, it is likely that these relate to changes in circulation patterns in the North Atlantic, in particular, the strength of the North Atlantic Oscillation (NAO) and the relative frequency of different weather types crossing the north-east of England (Hurrell, 1995; Osborn *et al*., 2000; Marshall *et al*., 2001; Hurrell *et al*., 2003; Haylock and Goodess, 2004). Positive values of the NAO indicate stronger than average westerly circulation over the British Isles (Jones and Conway, 1997). This relationship is stronger in the Northern Hemisphere winter than summer (Hurrell and van Loon, 1997; New *et al*., 2001); from November to April, positive values of the NAO imply a warm and wet winter for northern Europe and dry winters for southern Europe. Negative values of the NAO imply that the opposite will occur. For example, relatively low rainfall in Durham during the 1995–1996 winter coincided with a strongly negative NAO index. Jones and Conway (1997) noted a similar change in precipitation for Scotland, suggesting that the 1995–1996 winter was reminiscent of winters in the 1960s and a few winters in the late 1970s. In the absence of a more detailed analysis, it can only be concluded here that there have been some relatively large changes in the incidence of heavy falls of rain and in their seasonal occurrences. In relation to the attempts to model climate change at a regional scale, it is important to be able to down-scale to a seasonal timescale and to be able to generate realistic daily rainfall distributions (Fowler *et al*., 2005). The results reported here does not suggest any simple relation to the enhanced greenhouse conditions over the last century and a half (e.g. New *et al*., 2001); indeed, the long-term temperature record appears to be much less noisy than the rainfall record at the decadal time scale (Burt and Horton, 2001, 2003). It is also not fully clear whether the experience of recent decades is necessarily a good guide for climatic behaviour in the near future. In recent years, the four seasons have become much more similar at Durham in terms of the occurrence of heavy falls of rain. This seems a possible scenario for a warmer world, with heavy falls more likely throughout the year, even if some seasons become drier as a whole and others get wetter. Climate model runs under enhanced greenhouse conditions suggest that, at the global scale, a warming world will see increases in the intensity of precipitation extremes compared with mean precipitation changes (Kharin and Zwiers, 2000; Semenov and Bengtsson, 2002; Hegerl *et al*., 2004).The results from Durham seem to be consistent with those given in Ekström *et al*. (2005) (Figure 8 in their work), where grid box analysis showed that NEE might well experience relatively large increases in the magnitude of 1-day falls for return periods of 10 and 50 years. On the other hand, regional frequency analysis suggested that NEE might see lesser increases than some other parts of the UK. Either way, Ekström *et al*. (2005) note that their results, derived from the HadRM3H model, indicate much lower increases in extreme rainfall event magnitude than the earlier estimates using the HadRM2 model, which were much more akin to the observations from the 1990s (Fowler and Kilsby, 2003). This suggests that the increase in the number of heavy falls of rain seen at Durham (Figure 4) between the 1960s and the 1990s may not continue into a future warmer world.

CONCLUSIONS

1. Seasonal rainfall at Durham has shown considerable variability at the decadal timescale since the 1850s. The clearest pattern to emerge is the relative increase in winter rainfall compared to summer rainfall since the 1890s: from the mid-1970s, winter and summer rainfall totals have been very similar, something not experienced since the very wet 1870s.
2. All three threshold indices have high totals in the first three decades of 1860s to 1880s. Totals are lowest in the 1900s and the general trend since then has been for the totals to increase, with the totals in the 1990s back to the level of the 1880s (15 mm) or nearly at that level (22.6 and 25 mm).
3. There is no simple pattern to the changes in the winter : summer ratio at Durham. However, an increase since the 1960s is clearly evident. In the case of Durham, this is because of a decline in heavy summer rainfall rather than any increase in heavy falls in winter.
4. The most dramatic increase in the number of days when rainfall total equalled or exceeded 15 mm happened between 1862 and 1873. There were also increases from 1921 to 1935 and from 1974 to 2000.
5. The proportion of total winter rainfall from heavy falls of rain gradually increased through the 20th century, whereas summer rainfall tended to move in the opposite direction, at least until very recently.
6. The lowland and eastern location of Durham implies that it is not an ideal place to observe the increased frequency and contribution of heavy falls in winter noted by Osborn *et al*. (2000) and Osborn and Hulme (2002). It can, however, offer a very long daily rainfall record that can be used to observe the decadal scale changes in the patterns of heavy rainfall. It would be interesting if the daily rainfall analysis presented here could be repeated for a much wetter, western location over a similar period of 150 years.

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