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THE CLIMATE OF MALHAM TARN

T. P. BURT AND B. P. HORTON
Department of Geography, University of Durham
Science Laboratories, South Road, Durham DH1 3LE

ABSTRACT

The daily weather record at Malham Tarn is analysed for the period 1961–2000. In addition, monthly rainfall totals listed in British Rainfall are analysed for the period 1875–1906 and an annual rainfall series is reconstructed from 1860 to the present. Notwithstanding the sheltered nature of the Tarn House site, the Malham temperature record since 1961 fully reflects the regional, indeed global, pattern of warming, with an increase over the last four decades of 1° C in annual mean temperature. Winters show the greatest seasonal warming, and there have been noticeably fewer air and ground frosts in recent years. In contrast, there is no clear trend in rainfall totals over the study period, with several fluctuations between wetter and drier periods over the four decades. There has been a clear tendency towards drier summers and wetter winters recently; this stronger seasonality is reflected in the occurrence of heavy rainfall, with more winter days with heavy falls of rain in recent years, and, in marked contrast, far fewer very wet days in summer. In the late 19th century, total summer rainfall nearly equalled that received in winter, whereas by the late 20th century, winter rainfall was well in excess. During the study period there have been several droughts, with those in 1976 and 1995 being especially extreme. By contrast, rainfall totals in autumn 2000 broke all records.

INTRODUCTION

In November 1948, soon after the opening of Malham Tarn Field Centre (hereafter, referred to simply as ‘Malham’), a climatological station was established in association with the Meteorological Office, with readings being taken once a day at 09:00 hours GMT (Manley, 1957). These were not the first weather observations at Tarn House however, since rainfall data are listed in *British Rainfall* from 1870 to 1928. Most of the analyses presented here are based on daily data provided in computerised form to the Field Centre by the Meteorological Office for the period 1959-2000. A summary of the earlier observations is given in Manley (1957).

The weather station is located at an altitude of 395 m on the sloping lawn between the front of Tarn House (which faces just east of due south) and the Tarn itself. The site is sheltered to the north by the Scar, which rises steeply behind Tarn House and, to a lesser extent, by mature woodlands to the east and west. Proximity to the Tarn is an important element of the local microclimate, a point made by Manley (1957) and further elaborated below. Long, unbroken weather records for an upland site like Malham remain relatively rare in the UK and are, therefore, of some interest. However, local site characteristics must always be borne in mind since, for two places at the same altitude, the climate of a sheltered site like Malham must inevitably be subtly different from much more exposed locations.

TEMPERATURE

Table 1 summarises average temperatures at Malham Tarn since January 1959. Note that, in the very few instances where data for an individual month were missing, the average value for the month has been inserted. Monthly means are very little affected by occasional missing data, but even one missing month has a significant impact on the calculation of mean air temperature for a particular year.

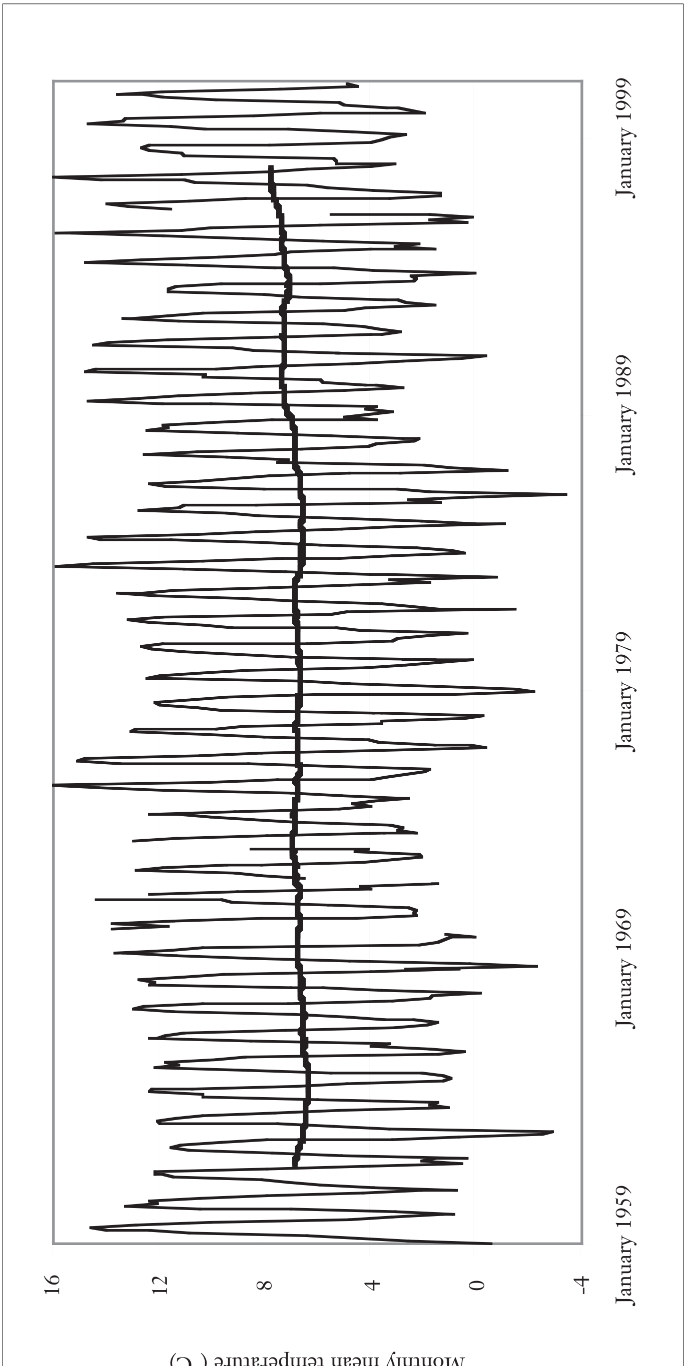

FIG. 1. Long-term temperature record for Malham Tarn since January 1959: monthly means with a 72-month running mean fitted.

TABLE 1. *Average temperatures at Malham Tarn Field Centre, 1959-2000.*

	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Mean air temperature (°C)	Standard deviation (MAT) (°C)	Average absolute maximum temperature (°C)	Average absolute minimum temperature (°C)
January	3.8	-0.8	1.5	1.5	8.3	-6.2
February	3.8	-0.8	1.5	1.9	8.1	-6.1
March	6.0	0.4	3.2	1.4	11.5	-4.5
April	8.9	2.1	5.5	1.1	15.6	-2.9
May	12.6	4.8	8.5	1.8	19.4	0.0
June	14.8	7.7	11.1	2.1	21.7	3.0
July	16.3	9.5	12.8	2.3	22.3	5.3
August	16.4	9.5	13.0	1.3	22.2	4.8
September	14.0	7.7	10.8	0.9	19.4	2.7
October	10.6	5.1	7.9	1.1	15.7	-0.7
November	6.6	1.8	4.2	1.2	11.4	-3.7
December	4.6	0.0	2.3	1.4	9.3	-5.6
Winter	*4.0*	*-0.6*	*1.7*	*1.2*	*9.9*	*-7.8*
Spring	*9.2*	*2.4*	*5.7*	*1.0*	*19.8*	*-4.8*
Summer	*15.8*	*8.9*	*12.3*	*1.5*	*23.8*	*2.8*
Autumn	*10.4*	*4.9*	*7.6*	*0.7*	*19.5*	*-3.9*
Year	**9.9**	**3.9**	**6.9**	**0.7**	**23.9**	**-8.3**

Malham's upland location is immediately apparent in a mean air temperature (MAT) of 6.9 °C, noticeably cooler than Manchester Airport[1] (MAT 9.4 °C, altitude 75 m) to the south west and Durham (MAT 8.6 °C, altitude 102 m) to the north east. Manley (1957) makes the important point that Malham is some 0.2 °C warmer than might be expected, given its altitude, because of local factors, including aspect, shelter and the warming effect of the Tarn. Thus, Malham is only a little cooler than Eskdalemuir (MAT 7.2 °C, altitude 242 m) in the Southern Uplands, despite 150 m difference in altitude. Comparing Malham with nearby Slaidburn (MAT 8.0 °C, altitude 192 m), the mean lapse rate between the two sites is 0.54 °C/ 100 m, whereas the mean lapse rate between Malham and Moor House[2] (MAT 5.2 °C, altitude 556 m) is 1 °C/ 100 m. Manley (1957) notes that the decrease in temperature with altitude is more a function of lower maxima than lower minima. Cold air drainage at night means that an upland site, like Malham, is very often no colder than the surrounding lowlands, whereas in the day, the combined effect of normal lapse rates and increased cloudiness mean that an upland site can be distinctly cooler. This is borne out by comparing Slaidburn with Malham: mean maximum temperatures are 1.5 °C lower at Malham, but mean minimum temperatures are only 0.8 °C lower.

The annual range of mean monthly temperature at Malham Tarn (11.5 °C) is larger than at Slapton Ley in Devon (10.4 °C), where there is strong oceanic influence (Burt &

FOOTNOTES

1. Temperature data for other sites are taken from Tout (1976), Tufnell (1997), Wheeler (1997) and Holden & Adamson (2002).
2. The mean lapse rate between Moor House and Carlisle is 0.70 °C and between Moor House and Durham is 0.74 °C. Although it is hard to generalise given the paucity of stations in the uplands, it does appear that Malham Tarn is not a safe station to use in calculations of lapse rates because, as Manley (1957) pointed out, it is slightly warmer than expected owing to local microclimatic factors.

TABLE 2. *The occurrence of extreme air temperatures at Malham Tarn Field Centre, 1959-2000. Also given is the occurrence of grass minimum temperatures below 0 °C.*

	Average number of days with air maximum below 0 °C	Average number of days with air minimum below 0 °C	Average number of days with grass minimum below 0 °C	Average number of days with air maximum above 20 °C	Total number of days with air maximum above 25 °C
January	4	19	24	0	0
February	4	17	21	0	0
March	1	15	22	0	0
April	>0	7	17	0	0
May	0	1	9	1	0
June	0	>0	2	3	5
July	0	0	1	4	10
August	0	0	1	4	15
September	0	>0	3	1	1
October	0	2	8	0	0
November	0	10	17	0	0
December	2	16	22	0	0
Winter	*10*	*52*	*66*	*0*	*0*
Spring	*1*	*23*	*46*	*1*	*0*
Summer	*0*	*0*	*4*	*11*	*30*
Autumn	*0*	*11*	*28*	*1*	*1*
Year	**12**	**86**	**145**	**12**	**31**

Horton, 2001), but smaller than at more continental locations like Heathrow (13.7 °C: Tout, 1976). August is the warmest month at Malham, although July is almost equally warm. January and February are the coldest months. Mean air temperature only exceeds 6 °C (the lower limit for grass growth) between May and October. Monthly temperatures are least variable in the autumn and early winter, reflecting the strength and consistency of westerly winds at that season. February, June and July have the largest standard deviations, indicating that variation between oceanic and continental circulation is more likely at those times. The warmest year on record at Malham was 1997 with a mean air temperature of 8.2 °C, more than two standard deviations above the 1959-2000 mean. Clearly, 1997 was an exceptional year by any standards, with only two months (January and June) being below average temperature.

Further aspects of Malham's upland climate are indicated in Table 2. There are, on average, 86 air frosts a year; this is less than at Eskdalemuir (105: Tout, 1976) despite Malham's greater altitude, and may reflect the ameliorating influence of the Tarn and the sheltered location of Tarn House. However, there are considerably fewer air frosts than at Moor House (131: Manley, 1970). Only July and August have remained totally free of air frosts since 1959; four have occurred in June and three in September (hence the >0 symbol in Table 2). There are also 12 days per year on average when maximum air temperature fails to rise above zero. As with air frosts, the average number of ground frosts per year (145: Table 2) is lower than expected. Nevertheless, ground frosts can occur in every month of the year at Malham. It should be noted, however, that the mean value disguises a notable decrease in the number of ground frosts per year over the last four decades, a matter returned to below. As expected, the number of really warm days at Malham is limited: on

TABLE 3. *Extreme air temperatures recorded at Malham Tarn Field Centre, 1959-2000.*

	Highest maximum (°C)	Lowest maximum (°C)	Highest minimum (°C)	Lowest minimum (°C)
January	11.1 (1971)	-7.4 (1987)	7.5 (1998)	-11.5 (1987)
February	13.0 (1993)	-5.7 (1979)	8.5 (1998)	-13.0 (1986)
March	18.9 (1965)	-2.8 (1965)	9.0 (1990)	-11.1 (1965)
April	21.0 (1999)	-0.1 (1981)	9.9 (1980)	-6.1 (1968)
May	22.8 (1965)	3.3 (1968)	13.1 (1992)	-4.2 (1979)
June	27.2 (1976)	7.1 (1977)	16.3 (1980)	-1.1 (1975)
July	28.0 (1983)	9.4 (1964)	16.2 (1976)	1.7 (1965)
August	28.2 (1990)	9.9 (1979)	16.8 (1997)	2.2 (1964)
September	25.0 (1959)	6.2 (1974)	14.0 (1999)	-1.0 (1985)
October	21.1 (1959)	2.9 (1992)	13.1 (1983)	-4.9 (1975)
November	15.2 (1989)	-2.8 (1969)	9.9 (1996)	-9.2 (1993)
December	11.6 (1985)	-6.0 (1978)	8.7 (1987)	-12.6 (1999)

average, temperatures exceed 20 °C on only 12 days each year. Although, on average, nearly every year has one day with a maximum temperature above 25 °C, in fact this mean figure is seriously misleading: temperatures have failed to reach 25 °C in 31 out of 42 years. Of the 31 days since 1959 when temperatures have exceeded 25 °C, ten were in 1995 and six in 1976. Table 3 shows extreme air temperatures at Malham. The lowest recorded temperature at Malham Tarn is -13 °C on 11th February 1986 and the highest is 28.2 °C on 3rd August 1990.

Table 4 shows mean temperatures at Malham by decade. For mean air temperature (Table 4a), the 1970s were a little warmer than the 1960s, with warmer winters but cooler summers (notwithstanding the very warm summers of 1975 and 1976). By contrast, the 1980s saw summers warm up but winters cool a little. In the 1990s, an exceptionally warm decade everywhere (Houghton, 2001), all four seasons were much warmer than in the previous decade. Of the ten warmest years at Malham, five have occurred since 1991 (with 1989 and 1990 also appearing in the top ten). Overall, comparing the 1960s with the 1990s, Malham Tarn was 0.8 °C warmer in the 1990s, with winter showing by far the largest increase (1.3 °C); spring and summer both warmed up by 0.8 °C, but autumn only by 0.4 °C. Tables 4b and 4c show that, again comparing the 1960s to the 1990s, maximum temperatures have risen more than minimum temperatures, in direct contrast to results from Moor House, which is further north and higher (Holden & Adamson, 2002). As with mean air temperature, the increases range from greatest to least in the order: winter, spring, summer, autumn. Because maximum temperatures have tended to increase more, the mean diurnal range has also increased, notably in winter. The warming signal is underlined by data for ground frosts (Table 4d). Over the last four decades, there has been a very significant decrease in ground frosts in all seasons, and thus for the year as a whole. There has been a smaller but still important decrease in numbers of air frosts (Table 4e) with only three quarters the number in the 1990s compared with the 1960s. Remarkably, the number of ground frosts in the 1990s was only about two thirds of the number experienced in the 1960s. This implies that the recent warming may have a particularly significant impact on soil temperatures and vegetation growth in sensitive marginal upland locations like Malham.

Given the range of mean monthly air temperatures (11.5 °C, Table 1), an increase of 0.8 °C (just over one standard deviation) over four decades is a subtle signal within a rather noisy record (Fig. 1). Nevertheless, the warming signal is clear and significant. This is

TABLE 4. *Mean temperatures (°C) at Malham Tarn by decade.*

(a) Mean air temperature				
	1960s	**1970s**	**1980s**	**1990s**
winter	1.0	1.9	1.7	2.4
spring	5.3	5.5	5.7	6.2
summer	12.1	12.4	12.4	12.9
autumn	7.5	7.5	7.5	7.9
year	6.5	6.8	6.8	7.3
		Difference between		
		1960s and 1970s	**1970s and 1980s**	**1980s and 1990s**
winter		0.9	-0.2	0.6
spring		0.1	0.2	0.5
summer		-0.5	0.8	0.4
autumn		0.0	0.0	0.3
year		0.1	0.2	0.5
(b) Mean minimum temperature				
	1960s	**1970s**	**1980s**	**1990s**
winter	3.2	3.6	4.2	4.8
spring	8.6	8.8	9.1	9.6
summer	15.6	15.4	16.0	16.4
autumn	10.1	10.2	10.4	10.6
year	9.4	9.5	9.9	10.4
(c) Mean minimum temperature				
	1960s	**1970s**	**1980s**	**1990s**
winter	-1.2	-0.7	-0.8	0.0
spring	2.1	2.1	2.2	3.1
summer	8.6	8.6	8.9	9.3
autumn	4.9	4.8	4.6	5.1
year	3.6	3.7	3.7	4.4
(d) Ground frosts				
	1960s	**1970s**	**1980s**	**1990s**
winter	77	68	65	59
spring	55	50	47	36
summer	8	3	2	3
autumn	34	28	26	24
year	173	149	139	121
(e) Air frosts				
year	99	84	87	76

underlined by correlations between mean air temperature and year number. Few correlations are significant for individual months, and winter is the only season to show significant warming ($r = 0.33$, $p = 0.031$). However, the increase in annual mean temperature is strongly significant ($r = 0.39$, $p = 0.01$); the regression coefficient indicates an average rate of warming of 0.025 °C per annum, or 1 °C every 40 years.

TABLE 5. *Rainfall statistics for Malham Tarn, 1961-2000 compared with the mean for 1875-1906.*

	Mean total (mm)	Standard deviation	Coefficient of variation	No of rain days (>=0.25 mm)	No of wet days (>=1 mm)	Wettest	(year)	Driest	(year)	Mean 1875-1906
January	156.4	67.9	43.4	21	18	287.2	(1984)	13.6	(1997)	140.2
February	111.6	64.7	58.0	17	14	268.0	(1997)	11.0	(1986)	104.0
March	127.6	60.3	47.2	19	46	320.5	(1981)	26.3	(1993)	120.2
April	97.6	46.1	47.3	17	14	172.4	(1993)	2.5	(1980)	86.1
May	90.6	47.3	52.2	15	13	179.9	(1993)	21.8	(1970)	84.2
June	96.2	46.2	48.0	16	14	229.7	(1991)	24.3	(1975)	93.0
July	98.2	44.0	44.9	16	13	214.1	(1988)	19.6	(1982)	126.1
August	125.2	56.6	45.3	17	15	260.1	(1985)	24.6	(1995)	154.2
September	134.3	58.3	43.4	17	15	279.2	(1968)	32.2	(1986)	119.5
October	151.0	75.9	50.3	19	16	328.9	(2000)	45.1	(1993)	152.0
November	152.6	62.9	41.2	21	18	292.9	(2000)	63.6	(1993)	144.2
December	167.0	76.7	45.9	20	17	322.9	(1979)	42.1	(1963)	147.0
Winter	*434.1*	*132.5*	*30.8*	*58*	*49*	*690.8*	*(1995)*	*163.9*	*(1964)*	*392.7*
Spring	*315.9*	*85.2*	*27.0*	*51*	*43*	*485.6*	*(1981)*	*128.1*	*(1984)*	*293.7*
Summer	*319.6*	*88.7*	*27.8*	*48*	*41*	*510.6*	*(1985)*	*121.7*	*(1995)*	*373.4*
Autumn	*438.0*	*127.4*	*29.1*	*57*	*49*	*861.4*	*(2000)*	*253.3*	*(1995)*	*414.4*
Year	1502.4	209.9	14.0	213	180	2096.0	(2000)	1124.5	(1975)	1470.7

PRECIPITATION

The first mention of rainfall being measured at Malham Tarn appears in G. J. Symon's *British Rainfall* for 1870. Shaw (1957) reports that a 5-inch gauge "provided out of the funds of the British Association" was set up with its rim 13 inches above the ground at an estimated height of 1,250 feet (381 m) above sea level. From 1877 onwards (to 1928 when the record ceases), the gauge altitude is given as 1,296 feet (395 m). It is now impossible to know what difference this change of location made and any possible errors arising from this move are therefore ignored here. A further complication (not discussed by Shaw) is that two different gauges were used over the years: an 8-inch gauge was used from 1892 to 1925 as well as the 5-inch already mentioned (as recorded in the annual volumes of *British Rainfall*). Indeed, no 5-inch gauge totals are given for 1907-1912 inclusive; we have accordingly used the 8-inch annual totals to estimate the 5-inch totals for these years and have (unlike Shaw) ignored the monthly figures for 1907-8 since these are not from the 5-inch gauge. In practice, the two gauges catch very similar amounts and the correlation between the two records is very high ($r = 0.998$). Like Shaw (1957), we have infilled the missing period between 1929 and 1949 using data from nearby gauges: Winterburn-Longhill (215 m, $r = 0.938$), Winterburn-Brownhill (293 m, $r = 0.958$) and Grimwith reservoir (297 m, $r = 0.847$). In addition, because an excellent and long record exists for nearby Arncliffe Vicarage (1860-1916), it has been possible to reconstruct the annual Malham record back to 1860 ($r = 0.935$).

Although our figures correlate well with Shaw's for the period 1929-49 ($r = 0.759$), hers have a wider range, one effect of which would be to make 1933 the 2nd driest year on record. Our estimation places 1933 only 17th lowest, which may be too cautious, but is derived from a very high correlation with the Winterburn-Brownhill gauge. When the Council for the Promotion of Field Studies (now the Field Studies Council) began making rainfall observations again at Malham Tarn in 1950, the new gauge was placed very nearly on the old site (Shaw, 1957). We have annual totals from 1950 and daily data from 1961;

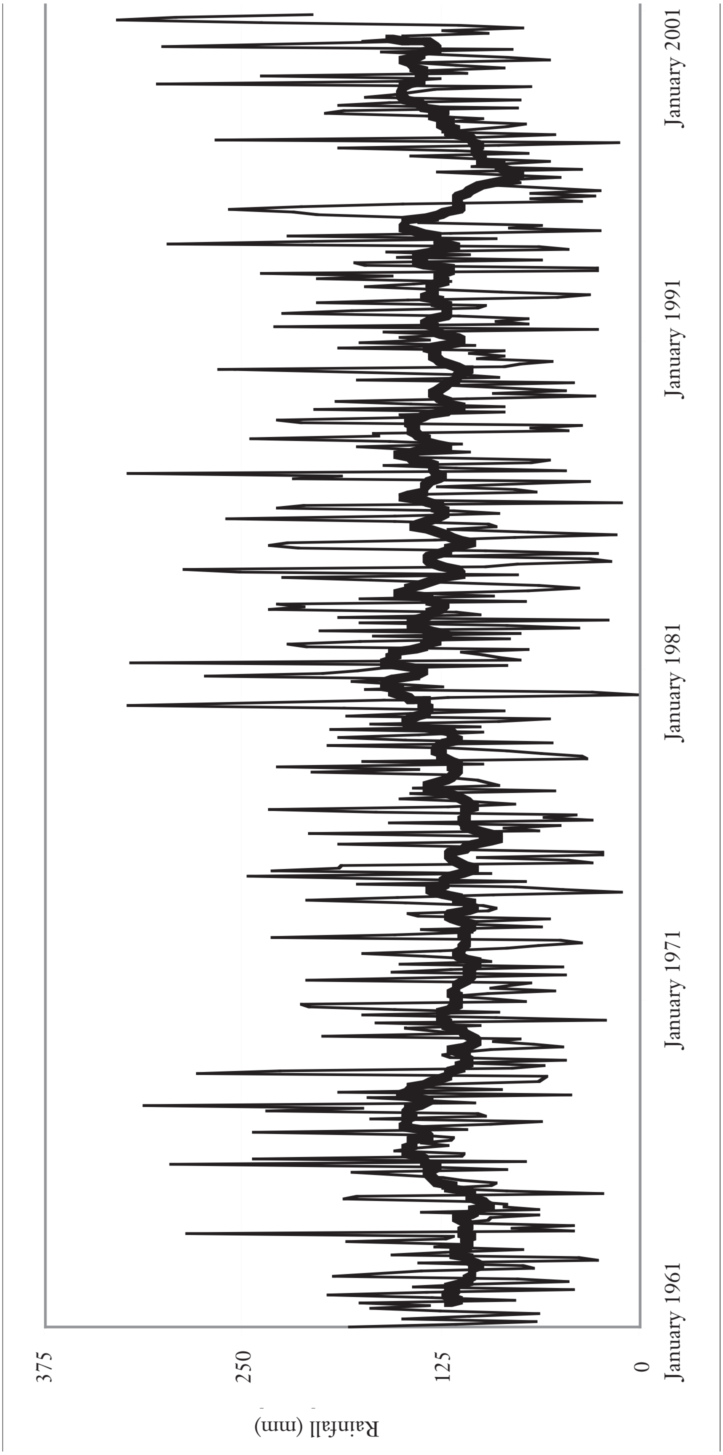

FIG. 2. Monthly rainfall at Malham Tarn since January 1961 with an 18-month running mean fitted.

TABLE 6. *Driest and wettest years and seasons at Malham Tarn, 1961-2000. Also shown are figures for the ratio of winter (DJF) to summer (JJA) rainfall.*

Year		Winter		Spring		Summer		Autumn		DJF/JJA	
(a) Driest											
1124.5	1975	163.9	1964	128.1	1984	121.7	1995	253.3	1995	0.44	1985
1153.2	1995	206.3	1963	154.1	1974	130.6	1976	267.8	1993	0.48	1963
1155.4	1964	221.6	1969	154.9	1980	171.9	1983	277.4	1964	0.62	1964
1188.6	1971	223.8	1985	172.6	1975	210.1	1969	278.5	1962	0.79	1971
1207.1	1969	267.4	1996	217.1	1990	246.7	1984	285.6	1973	0.83	1961
(b) Wettest											
1748.5	1967	620.1	2000	421.7	1968	437.5	1967	590.8	1967	2.14	1990
1758.3	1988	633.6	1980	423.7	1998	458.7	1998	610.5	1981	2.58	1984
1774.3	1979	634.2	1990	443.7	1986	479.4	1980	613.8	1980	2.83	1976
1797.9	1998	636.3	1984	464.1	1979	480.1	1988	671.2	1984	2.98	1983
2096.0	2000	690.8	1995	485.6	1981	510.6	1985	861.4	2000	5.68	1995

the latter comprise the main focus for our analysis here. Monthly totals for January and February 1979, the only missing months in the record, have been estimated using data from Blackmoorfoot (Burt, 1999).

Rainfall statistics are given in Table 5. The rainfall regime at Malham Tarn is typical of an upland site in the UK, exhibiting strong seasonality with peak rainfall in the period October to January. Even so, monthly averages for the 'drier' period, April to July, all exceed 90 mm! Apart from February and May, the degree of variability is fairly similar throughout the year. As might be expected, there is a very wide range when all months are considered, from the driest month (April 1980 – 2.5 mm) to the wettest (October 2000 - 328.9 mm). In terms of seasons, 29 % of annual rainfall comes in winter and 30 % in autumn, with 21 % in both spring and summer. The annual average of 1502 mm is a typical value for this elevation in the Pennine hills (Burt, 1980) where the degree of orographic enhancement is not as great as in higher hills nearer the western coast, such as the Lake District or Snowdonia.

Fig. 2 shows monthly rainfall at Malham Tarn since January 1961. Note that mean monthly rainfall at Malham is exactly 125 mm. An 18-month running mean has been added since this best emphasises protracted wet or dry periods, in particular prolonged droughts where there is a dry winter between two dry summers. No simple trend is apparent over the four decades. It is apparent that the early 1960s, the late 1960s plus the first half of the 1970s, and the mid-1990s were all drier than normal, while the mid-1960s, the late 1970s through to the early 1990s, and the late 1990s were all wetter than normal. Even so, these broad generalisations hide shorter-term departures from the mean. The driest calendar year since 1961 was 1975 (1124.5 mm, Table 5), although the remarkably dry year of 1887 (1049 mm) easily remains the overall record holder for a calendar year. The wettest year since 1961 was 2000 (2096 mm), a year of exceptional flooding in north east England, beating the 1928 total by over 100 mm. Since 1961, the wettest winter on record was December 1994 – February 1995 (listed by convention as 1995 in Table 5), and (after the 9th driest spring) there followed the driest summer on record (1961-2000). Autumn 1995 was also the driest on record, the 1995-96 winter 5th driest, and spring 1996 6th driest (all since 1961). Even with average summer rainfall in 1996, drought conditions remained critical in the Pennines, and it was only late in 1996 and into 1997 that matters began to improve. The famous drought of 1975-76 does not quite compare with the 1995-96

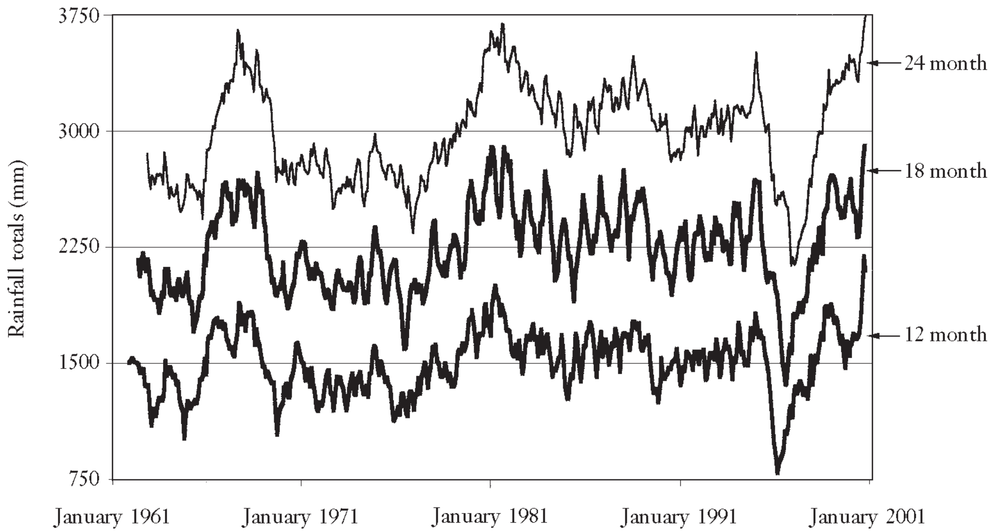

FIG. 3. Malham Tarn rainfall: 12-month, 18-month and 24-month totals since January 1961. In each case, totals are plotted for the last month in the period.

drought at Malham therefore, either in terms of severity or length; nor indeed does the 1887 drought (see below). As Table 6 shows, despite the very wet start to the year, 1995 ended up 2nd driest on record, only marginally wetter than 1975. As it happens, 1996 was the 6th driest year on record (1221 mm). Not surprisingly therefore, the driest 12-month period since 1961 was the period April 1995 – March 1996 with only 785.6 mm (52 % of the long-term mean).

Fig. 3 shows the changing pattern of rainfall over varying periods of time. A running total for a given period up to and including the month in question is calculated for periods of 12, 18 and 24 months. In general, wet and dry periods show up on all three plots, but the longer-period totals emphasise different aspects of the record. The more severe droughts only stand out when 18-month totals are used, since these invariably involve two dry summers with a dry winter sandwiched between. On the 12-month plot, 1975-76 appears no worse than several other events, for example. The 24-month totals are too long to show all but the most severe droughts but are very useful for assessing protracted periods of above-average rainfall. The transformation from April 1997 to December 2000 is particularly noteworthy, and the accumulated totals reached at the end of 2000 broke all records.

Table 5 includes mean data for the period 1875-1906. Mean annual rainfall (1471 mm) is only a little less than for 1961-2000 (1502 mm) but there is an interesting shift in the seasonal pattern: winter rainfall is lower in the earlier period (27 % compared to 29 %) and the same applies in spring rainfall (from 21 % to 20 %) and autumn (from 30 % to 28 %). In contrast, summer rainfall is higher in the late 19th century, 25 % of the annual total compared to 21 % for the late 20th century. A feature of climate change in the last third of the 20th century has been the tendency for drier summers and wetter winters (Jones & Conway, 1997; Burt *et al.*, 1998; Burt, 1999). The ratio of winter to summer rainfall in the period 1875-1906 was 1.05 whereas for 1961-2000 it was 1.36 (See below for further discussion of this ratio). In the earlier period, the maximum winter: summer ratio for an individual year was 2.93 in 1899. This value has been beaten twice between 1961 and 2000:

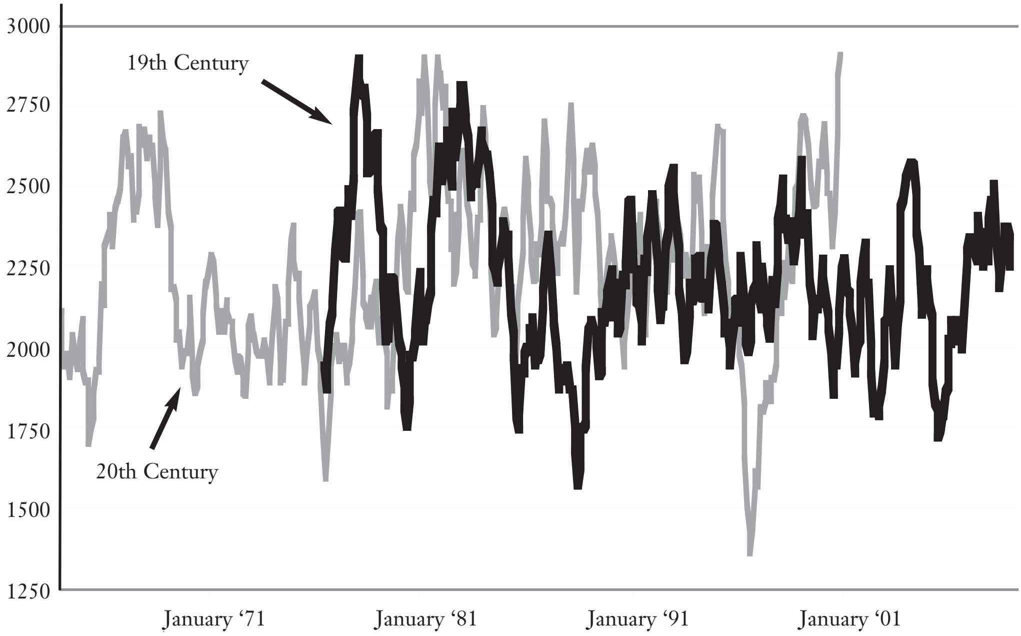

FIG. 4 Monthly rainfall (mm) at Malham Tarn in the 19th and 20th centuries.
The periods in shown are 1875-1906 and 1961 to 2000.

in 1983 (2.98) and most remarkably in 1995 (5.68) when the contrast between winter and summer rainfall was way beyond anything seen before (*cf.* Burt *et al.*, 1998).

Fig. 4 superimposes the 19th and 20th century records, showing 18-month totals up to and including the month in question. There seems little to choose between the two periods in terms of variability. The peak 18-month totals for January 1878 (2899.6 mm), April 1981 (2889.4 mm), November 1981 (2896.6 mm) and December 2000 (2906.5 mm) are all within a few millimetres of one another. There is no drought in the earlier record as severe and protracted as the 1995-96 drought, although that for 1887-8 was as extreme as 1975-6 and a little longer lasting. The driest 12-month period in the 19th century record was February 1887 – January 1888 inclusive with 1026.4 mm (a good deal higher therefore than the April 1995 – March 1996 drought mentioned earlier).

Fig. 5 shows the entire reconstructed annual rainfall record for Malham Tarn from 1860 to 2000 together with a decadal running mean. Extremes within the time series have already been commented upon. Unlike the long-term temperature record (Houghton, 2001), there is no simple trend for rainfall. Decadal averages range from 1378 mm (centred on 1973) to 1645 mm (centred on 1927).

The 24-hour rainfall day (24 hours from 09:00 GMT in the UK) is by far the most convenient, and therefore the most common, time period over which to measure rainfall totals (Atkinson & Smithson, 1976). As already noted, this is the observation period at Malham Tarn Field Centre, and although this means we have no knowledge of shorter-period intensities (which may be important for processes like soil erosion), nevertheless daily totals still provide a meaningful timescale for analysis, especially in relation to flood generation.

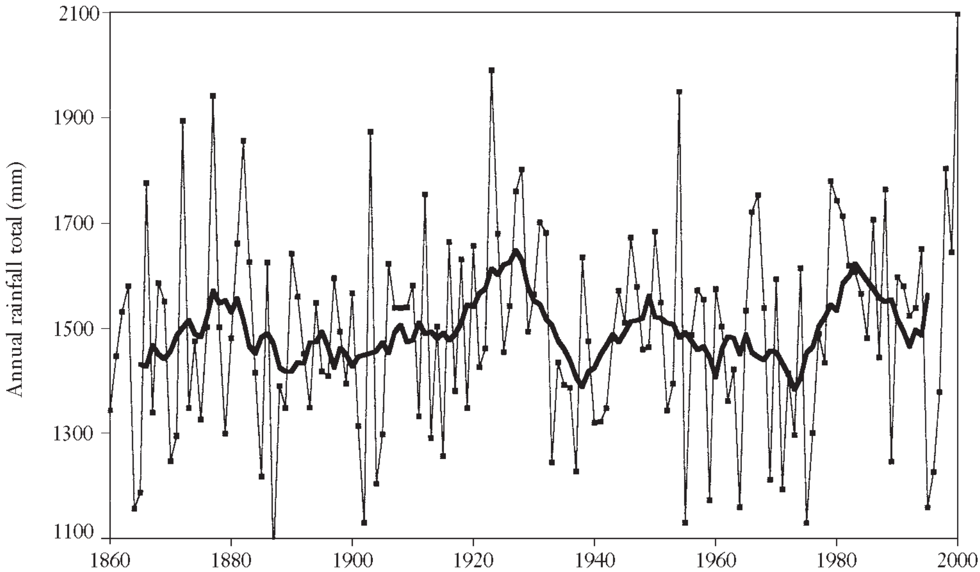

FIG. 5 The reconstructed annual rainfall record for Malham Tarn, 1860-2000.

Table 7 gives the number of days each decade with rainfall equalling or exceeding various thresholds, and the mean rainfall total for each category. In summer there has been little change in either the number of rain days (> 0.25 mm) or the number of wet days (=> 1mm). It is, however, of some interest that the number of heavy falls (=> 15 mm and => 25 mm) has fallen significantly since the 1960s (especially in the 1990s), whereas the mean amount occurring in such heavy falls has not changed. Total summer rainfall has fallen by nearly 10% and a much smaller fraction of this now occurs in large falls. By contrast, winter rainfall has increased considerably since the 1960s and a larger proportion now occurs in heavy falls. The number of days in each category has increased in winter, but the increase in the number of large falls is of most significance, especially given the importance of the Pennines as a source of flood runoff to the surrounding lowlands. As in summer, it is again notable that the mean size of heavy falls has not changed; it is the number of such days that has increased. Further analysis of heavy falls has been conducted following the methods of Osborn *et al.* (2000) and Osborn & Hulme (2002). The percentage of seasonal rainfall (excluding days with < 0.3 mm) from falls equal or exceeding a given threshold are shown in Figs 6 and 7. Taking the somewhat arbitrary threshold of 15 mm (Osborn & Hulme, 2002), on average 47% of winter rainfall and 40% of summer rainfall comes from such falls.

Fig. 6 shows that the proportion of total summer rainfall from falls => 15 mm declined significantly during the 1990s. By contrast, the percentage of winter rainfall from falls => 15 mm rose steadily from the early 1970s to the early 1990s but has declined in recent years. Osborn *et al.* (2000) used an upper decile threshold in preference to an arbitrary total such as 15 mm: the upper decile threshold is the daily rainfall total (for the whole period in question) above which the top 10% of total rainfall has occurred. For Malham, the summer threshold is 28.4 mm and the winter threshold is 33.1 mm; these represent just 1.1% and 1.8% of all rain days respectively (i.e. the top 10% of total rainfall is produced on a very

TABLE 7. *Number of days each decade with rain equal to or exceeding a given threshold and the mean rainfall total on those days.*

	Summer				Winter			
	1960s	**1970s**	**1980s**	**1990s**	**1960s**	**1970s**	**1980s**	**1990s**
>0.25 mm number	494	442	503	485	551	556	581	601
mean rainfall	6.8	7	6.5	6.2	6.7	7.2	8.1	7.9
=>1 mm number	410	385	429	416	442	468	518	503
mean rainfall	8.1	7.9	7.6	7.2	8.2	8.4	9	9.4
=>15 mm number	60	64	55	43	65	81	99	95
mean rainfall	23.4	21.4	24.5	21.8	24.4	22.4	23.1	23.6
%seasonal rainfall	41.8	44.3	40.8	30.8	42.9	45.4	48.7	47
=>25 mm number	20	15	24	9	21	19	27	28
mean rainfall	32	30.8	31.8	32.8	34.5	33.4	34.2	34.1
%seasonal rainfall	19.1	14.9	23.1	9.7	19.6	15.8	19.7	20

Winter: summer rainfall ratios by decade

	1960s	**1970s**	**1980s**	**1990s**
total winter rainfall	3786	4134	4698	4743
total summer rainfall	3349	3097	3299	3038
ratio	1.13	1.33	1.42	1.56

small number of days, as might be expected). Fig. 7 shows the percentage of summer and winter rainfall produced from daily falls above the upper decile threshold. Results largely mirror those shown on Fig. 6: the complete lack of very large summer falls during most of the 1990s is in strong contrast to the high proportion of winter rainfall coming in very heavy falls in the early 1990s. Although only 11% of total rainfall in both seasons comes in such falls, their importance for flood generation, especially in winter, is great.

WIND AND SUNSHINE

Observations of wind speed and direction, based on standard Met Office protocols, are available, with very few gaps, from 25th April 1961; the computerised data provided by the Meteorological Office ran to the end of January 1998. Such data are subject to observer error, both in terms of judging wind direction and wind speed (using the Beaufort Scale), and of course, a single observation at 09:00 GMT cannot provide an accurate summary of conditions throughout the whole 24-hour period. Nevertheless, when collated over a long period, such results can still provide a reasonably reliable picture of conditions at a site.

Long-term mean wind speed, based on 09:00 observations is exactly 9 knots. There is a relatively small range in monthly means from 8.2 kt in July to 9.9 kt in December. Fig. 8 shows annual mean wind speeds together with a decadal running mean. It is clear that mean wind speeds have dropped significantly since the 1970s, from a peak of 10.6 kt (centred on 1975) down to 7.7 kt (centred on 1992). It is possible that this reflects a regional decrease in wind speed but seems more likely to be the result of increased shelter from maturing woodland to the east and west of the weather station.

Table 8 shows the relation between wind speed and direction during the 1990s. Data have been sorted into six directional classes and four speed categories; the percentages falling in each category are tabulated. It is notable that calm conditions are relatively rare,

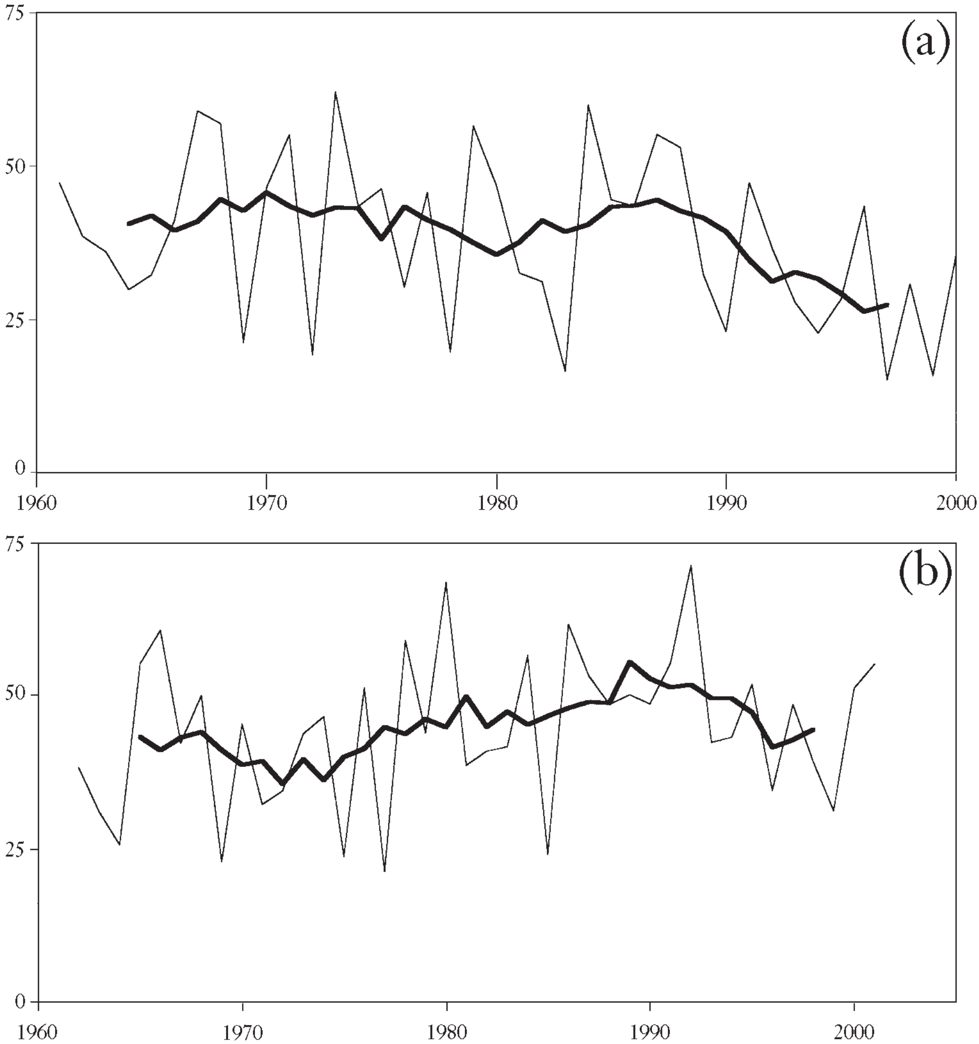

FIG. 6 Percentage of seasonal rainfall each year in daily falls of 15 mm or more: (a) summer; (b) winter.

with nearly half the occasions exceeding 11 kt. Wind directions from the west (250° – 300°) are easily the most common, with very similar frequencies for winds from easterly and southerly directions. Winds from the northern sector (310° – 060°) were observed on only 7.6% of occasions; probably this underestimates the true situation and reflects the sheltered nature of the Tarn House site.

There are no data for hours of bright sunshine at Malham but the Environment Agency has operated solar and net radiation gauges since the early 1990s. Fig. 9 shows mean daily solar radiation by month since January 1993. The annual cycle is remarkably similar from year to year, with poor summers like 1993 not appearing much worse than the hot summer of 1995, for example. We have not attempted to convert these solar radiation values into hours of bright sunshine, but this should be possible using algorithms being developed by, inter alia, the UK's Environmental Change Network.

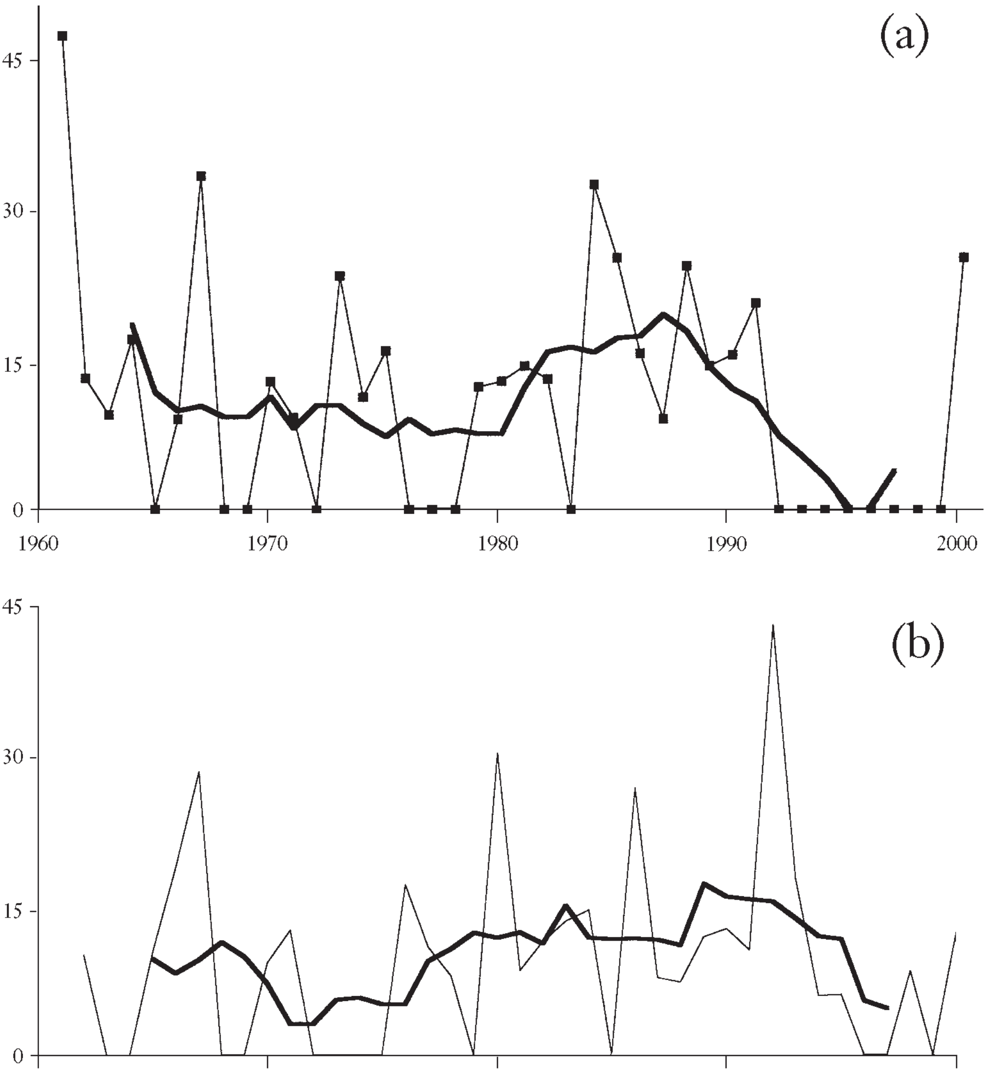

FIG. 7 Percentage of seasonal rainfall at Malham Tarn each year in daily falls equalling or exceeding the upper decile threshold: (a) summer (28.4 mm threshold); (b) winter (33.1 mm threshold).

TABLE 8. *Percentage occurrence of wind speed and direction at Malham Tarn in the 1990s.*

Speed/Direction	010°-060°	070°-120°	130°-180°	190°-240°	250°-300°	310°-360°	Sum
0 - 3 kt	0.9	2.5	3.2	2.2	3.9	1.4	14.1
4 - 10 kt	1.9	9.2	8.6	5.4	13.1	1.4	39.5
11 - 21 kt	0.8	6.5	5.4	7.0	15.7	0.8	36.3
> 22 kt	0.2	0.8	0.6	2.2	6.1	0.2	10.1
Sum	3.9	19.1	17.8	16.7	38.8	3.7	100.0

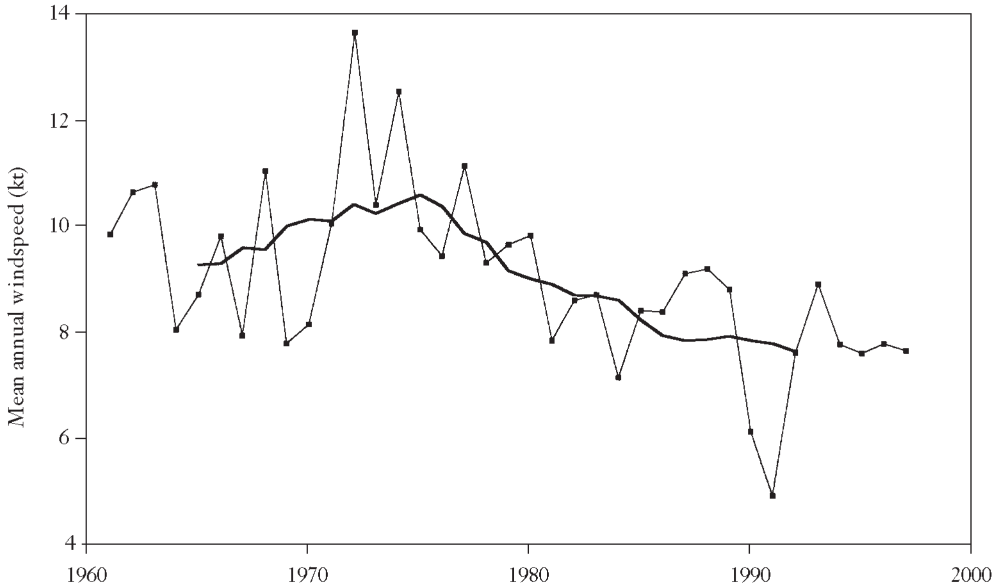

FIG. 8 Annual mean wind speed at Malham Tarn House since 1961.

CONCLUSIONS

The sheltered site of the Tarn House climatological station is reflected in the results presented here; in particular, temperatures and wind speeds are probably not entirely indicative of conditions on the nearby open moorland. Be that as it may, the Malham temperature record since 1961 fully reflects the regional, indeed global, pattern of warming, with an increase over this period of 1° C in mean temperature. Of the seasons, autumn has shown the least increase, and winter the largest. Maximum temperatures have tended to increase more than minimum temperatures, in contrast to Moor House (Holden & Adamson, 2002), but even so, the impact of warming on the frequency of both air and ground frost has been very evident.

In contrast to temperature, no simple trend in rainfall is apparent, with both wetter and drier periods across the four decades. Most notable has been the tendency towards wetter winters and drier summers; this stronger seasonality is reflected in the analysis of extreme daily rainfall, with more days with heavy falls of rain in winter in recent years, and, in marked contrast, far fewer very wet days in summer. It has also been possible to take a much longer perspective on the Malham Tarn rainfall record, by comparing observations for the period 1875-1906 with the post-1961 data. Most notable has been the seasonal shift in rainfall: summer rainfall almost equalled the winter total in the late 19th century, whereas in the late 20th century, mean winter rainfall was well in excess of mean summer rainfall. As discussed above, there have been several droughts during the study period, with those in 1976 and 1995 being especially extreme. By contrast, rainfall totals in autumn 2000 broke all records

These changes in climate have important implications both for the moorland environment around Malham itself and for lowland areas further afield. On the moors, significant warming means a longer growing season and less harsh winter conditions. Mean

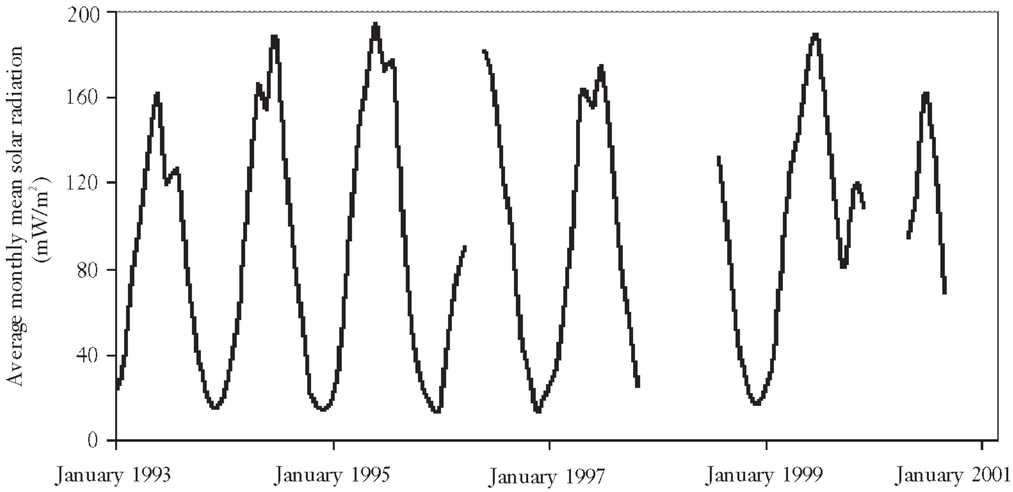

FIG. 9. Annual monthly mean solar radiation (mW/m^2) at Malham Tarn since 1993. Data supplied to the Field Centre by the Environment Agency.

air temperature in spring now exceeds 6°C, suggesting an earlier start to the growing season than 40 years ago. We were not able to analyse data for 'days with snow lying' but almost certainly these will have declined in number since the relatively cold decade of the 1960s. As far as the increased seasonality of heavy rainfall is concerned, it is the increased number of days with heavy rainfall in winter that is of most interest, given the importance of the Pennine hills as headwater catchments for many large rivers such as the Aire and Wharfe. The increased frequency of heavy rainfall in the uplands, when combined with adverse changes in catchment conditions, such as the widespread draining ("gripping") of peaty moorland soils, seems bound to result in increased flood hazard in the surrounding valleys.

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