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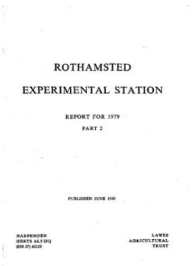
ROTHAMSTED RESEARCH

Rothamsted Experimental Station Report for 1979 Part 2



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Rothamsted and Woburn Weather: 1970–79

J. CROFT, A. T. DAY and T. WOODHEAD

Abstract

Means and extremes for several weather variables are presented for Rothamsted and Woburn for the decade 1970–79 and for various long-term periods. The decade recorded for some variables extremes that had not been equalled during a century or more, and its mean values provided new data points that allowed tests of earlier suggestions of long-term trends in rainfall and temperature. Some of the records merit further analysis, and recommendations are made for an appropriate programme.

Introduction

The decade 1970–79 included two summers, in 1975 and 1976, that were memorably warm and sunny, two winters, 1976/7 and 1978/9, that were memorably wet—the latter also memorably cold, and an autumn, in 1978, that was memorably dry. This present paper's survey of the decade's weather at Rothamsted and Woburn lends support to the memory, and compares the 1970–79 weather, in both its means and its extremes, with that which has gone before.

Many data are available for these comparisons. At Rothamsted, rainfall has been routinely measured since 1852, temperatures since 1878, and other elements from various later dates. Drawing on these routinely recorded data, and on data collected in research projects in field experiments, Penman presented in 1974 a very comprehensive survey of the Rothamsted data then existing. He indicated what instruments and what units of measurement had been used during what periods, considered the precisions and accuracies of the measurements, and gave a concise account of the importance to agriculture and to agricultural research of the various weather variables—including the less-widely recorded ones of net radiation, run-of-wind, drainage, and tank evaporation. For Woburn, as for Rothamsted, summaries of each year's weather are included in Parts 1 of the *Reports of Rothamsted Experimental Station*; but for Woburn, where observations began in 1895, there has been no synthesis and summary of these annual data such as Penman prepared for Rothamsted. The present paper therefore includes a rather full account of several decades of Woburn weather, but confines its treatment of Rothamsted data mainly to 1960–79, and repeats Penman's (1974) statistics only insofar as they require updating or are themselves needed to help interpret the 1970–79 data.

Radiation

Solar radiation: Rothamsted. Accurate recording of solar radiation at Rothamsted began in 1955, and monthly averages for daily values of total solar irradiance are shown, in Table 1, for the period 1956–79 and for the decades 1960–69 and 1970–79. On average, the ground-level irradiance in 1970–79 was about 5% higher than in 1960–69; the latter decade, as will be shown later, was the least sunny since sunshine recordings commenced, in 1892. Table 1 also shows the lowest and highest recorded monthly averages for daily irradiance. In the listing of the highest average irradiances, four of the entries appertain to 1976, two to 1979, and none to the 1960s. (Note that the 1956 data may be biased, and should be treated with caution.) The largest radiation total for a single day was

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TABLE 1

Rothamsted: average daily totals of solar irradiance ($MJ\ m^{-2}\ d^{-1}$)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
1956–79	2·1	4·0	7·6	11·3	15·7	17·5	15·6	13·0	9·7	5·6	2·7	1·6	8·9
1960–69	2·1	3·8	7·3	10·9	14·9	17·5	15·1	12·6	9·4	5·3	2·4	1·6	8·6
1970–79	1·9	3·9	7·5	11·2	16·2	17·4	16·0	13·4	10·1	5·7	3·0	1·7	9·0
Extreme months													
Least	1·4	2·0	5·2	8·2	13·4	14·1	12·3	9·9	7·9	4·2	1·7	1·0	
	1970	*1972*	1969	1966	*1975*	1956	1965	1968	1969	1960	1968	1969	
Most	3·0	6·4	11·5	13·3	18·0	21·1	19·2	15·3	12·0	6·9	3·8	2·1	
	1956	1956	1956	*1976*	*1977*	*1976*	*1976*	1959	*1979*	*1979*	*1977* *1978*	*1976*	
R_A	7·8	13·6	21·3	30·4	37·8	40·9	39·7	33·4	25·1	16·1	9·7	6·6	

Notes: (i) Values R_A for solar radiation at the outer limit of the earth's atmosphere, for latitude 52°N, are based on a solar constant of 135·3 mW cm^{-2} ($1{\cdot}353 \times 10^{-3}$ MJ $m^{-2}\ s^{-1}$ or 1·94 cal $cm^{-2}\ min^{-1}$).
(ii) Prior to 1959 radiation totals were obtained by planimeter, rather than electronic, integration of the radiation record.
(iii) Individual entries may be assumed accurate to ±5%; for comparisons within columns (but not rows) entries may be considered precise to ±2%.

31·6 MJ m^{-2}, recorded on 23 June 1977. This value, and indeed all the data in Table 1, may be compared with the corresponding values (R_A in Table 1) for the calculated intensity of shortwave irradiance at the outer limit of the earth's atmosphere.

(There are no radiation data for Woburn: irradiance is not routinely recorded there.)

Duration of bright sunshine: Rothamsted and Woburn. The strong correlation between solar irradiance and the duration of bright sunshine was reported and quantified in

TABLE 2

Rothamsted: hours of bright sunshine: means, extremes and 1970–79 values for monthly totals

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Monthly means													
1892–1979	51	67	115	150	194	202	191	180	144	103	62	45	1504
1970–79	42	63	106	129	196	201	190	180	148	103	74	45	1477
Extreme decades													
1960–69 (least)	48	59	109	128	175	203	165	155	132	93	54	48	1371
1900–09 (most)	62	72	113	173	197	195	228	204	158	101	63	42	1607
Extreme years													
1968 (least)	38	44	134	170	145	152	136	112	107	56	29	27	1149
1929 (most)	40	67	185	155	261	226	244	197	206	120	78	75	1854
Recent years													
1972	44	30	149	109	165	160	158	165	124	102	86	45	1377
1973	31	73	139	141	182	258	165	198	169	108	97	57	1618
1975	37	65	60	125	163	289	232	233	155	115	76	37	1587
1976	63	41	118	159	195	269	245	254	118	46	61	60	1629
Extreme months													
Least	23	22	59	85	124	116	91	99	84	46	26	16	
	1898	1940	1960	1966	1898	1923	1965	1912	1936	*1976*	1962	1969	
Most	88	106	206	271	280	289	316	271	223	154	104	76	
	1952	1939 *1970*	1907	1893	1922	*1975*	1911	1947	1911	1921	1923	1961	
Max. poss.	257	280	362	393	492	498	499	452	378	332	261	239	4443

Notes: (i) Monthly means for decades prior to 1970 may be read in Penman's (1974) Table 2.
(ii) Entries may be assumed accurate to ±1%.

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Penman's (1974) survey. Rothamsted observations of sunshine duration are summarised in Table 2, which is an updated and shortened version of Penman's (1974) Table 2. They show that the decade 1970–79 had sunshine averages, both for the individual months and for the year, that equate closely to the respective long-term means. No year in the decade had an annual total of sunshine that approached the extremes of 1854 h (in 1929) or of 1149 h (in 1968). The decade year that was least sunny was 1972 (with 1377 h); the sunniest was the drought year of 1976, whose total of 1629 h was nearly equalled by the 1618 h recorded in 1973; the other year with a notably sunny summer, 1975, had 1587 h. However, 1975 did include the sunniest June (289 h) since records began (Table 2). Contrarily, 1976 is listed not amongst the years for which some particular month was the sunniest on record, but as the year with the least sunny October. Nonetheless, in its summer 4 months (May to August) 1976 did receive a total of 963 hours of sunshine: almost 200 h greater than the corresponding long-term mean.

For Woburn, although meterological observations began in 1895, the Lawes Agricultural Trust did not assume responsibility for them until 1926 and for this present survey data have been analysed for the 50 years 1930–79. The decade means and the 50-year means of sunshine duration, both for individual months and for annual totals, are shown in Table 3. Over the 40 years 1930–69, the Woburn and Rothamsted mean annual totals

TABLE 3

Woburn: hours of bright sunshine: means, extremes and 1970–79 values for monthly totals

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Overall mean 1930–79	50	64	115	140	183	198	180	171	135	101	61	44	1442
Decade means													
1930–39	50	70	131	130	166	194	178	184	133	102	56	37	1430
1940–49	51	65	116	171	205	205	191	182	138	106	62	50	1542
1950–59	54	70	116	156	185	189	192	170	136	102	59	45	1474
1960–69	53	57	111	125	177	208	162	153	131	97	57	48	1378
1970–79	42	56	100	118	183	192	178	167	138	99	71	41	1385
Extreme years													
1968 (least)	44	38	134	158	147	173	120	110	113	67	32	26	1162
1949 (most)	69	116	103	184	214	230	237	223	154	129	75	58	1792
Recent years													
1972	43	36	141	103	149	156	138	158	113	95	79	48	1259
1978	40	47	113	102	190	151	131	143	146	83	77	27	1250
1973	39	75	129	146	178	250	144	179	139	96	86	53	1514
1975	31	36	56	106	152	262	218	216	141	123	61	26	1428
1976	49	42	106	143	161	262	233	227	105	46	59	59	1492
Extreme months													
Least	31	25	56	85	106	110	96	110	70	46	30	19	
	1975	1940	*1975*	1961	1932	1953	1965	1968	1945	*1976*	1962	1930	
Most	87	116	190	233	250	276	261	267	197	148	96	78	
	1952	1949	1938	1942	1943	1957	1934	1947	1964	*1971*	*1971*	1962	
Max. poss.	256	279	362	393	493	499	500	453	378	332	260	238	4443

Note: Entries may be assumed accurate to ±1%.

differ by only 1 h in 1456 h—a remarkable agreement. But the Woburn 1970–79 mean annual total is less by some 6% than its Rothamsted counterpart—probably indicating that at Woburn the growth of trees has raised the sunshine recorder's horizon. Accepting

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the records as they are, the least sunny years of the decade at Woburn were 1972 and 1978, as were they also at Rothamsted, and the sunniest were 1973 and 1976—and the total for the latter, at 1492 h, might have been depressed by the rising of the horizon. The Table 3 entries for the month-by-month extremes, and their years of occurrence, show that in the decade, in 1971, were recorded the sunniest both of Octobers and Novembers, and that 1976, as for Rothamsted, is entered only for its October lack of sunshine. Nonetheless, for 1975 and 1976, the May to August sunshine totals were respectively 116 h (16%) and 161 h (21%) higher than the corresponding 50-year mean. In contrast, the winter that preceded the 1975 summer was, in its October–March total, memorably short of sunshine: short by some 138 h (32%) of its average value. (However, this low total may in part be due to the change of horizon—the corresponding Rothamsted total was 88 h (20%) less than its 1892–1979 mean.)

Temperature

Air temperature: Rothamsted and Woburn. Mean monthly and mean annual air temperatures for Rothamsted for the 102 years 1878–1979 and for the decades 1960–69 and 1970–79 are presented in Table 4. The 1970–79 decade, 0·2 K warmer than the 102-year

TABLE 4

Rothamsted: mean air temperature (°C): average and extreme values

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Monthly means													
1878–1979	2·9	3·4	5·2	7·7	11·1	14·1	15·9	15·6	13·4	9·7	5·8	3·7	9·0
1960–69	2·5	3·1	5·2	8·0	11·1	14·2	15·3	15·2	13·6	10·6	5·6	2·8	8·9
1970–79	3·4	3·6	5·1	7·3	11·0	13·9	16·0	16·0	13·5	10·2	6·1	4·6	9·2
Coldest year													
(1879)	−1·2	3·1	4·6	5·9	8·4	13·5	13·9	15·1	12·6	8·6	3·3	−0·8	7·3
Recent cool years													
1972	3·1	3·9	6·4	8·0	10·5	11·7	15·5	15·1	11·7	10·5	5·7	5·1	8·9
1979	−1·3	0·7	4·3	7·6	10·3	13·6	15·9	15·0	13·4	11·0	5·9	5·2	8·5
Hottest year													
(1949)	4·6	4·8	4·3	9·7	10·4	14·5	17·4	17·0	16·9	11·7	5·9	5·2	10·2
Recent warm years													
1975	6·1	4·3	4·4	8·1	9·5	14·2	17·4	18·7	13·7	9·4	5·5	4·0	9·6
1976	4·9	4·0	4·5	7·6	12·1	17·2	18·5	17·5	13·5	10·5	5·7	1·5	9·8
Lowest minimum (monthly average)													
	−6·1	−6·3	−2·0	0·3	4·1	7·2	9·4	9·2	7·1	2·3	−0·5	−4·3	
	1963	1895	1883	1917	1902	1916	1907	1887	1912	1888	1923	1890	
Highest maximum (monthly average)													
	9·4	10·0	14·1	17·3	19·0	23·7	25·1	24·8	22·2	17·5	11·8	9·9	
	1916	1914	1938	1893	1947	*1976*	*1976*	*1975*	1929	1921	1913	1912	

Notes: (i) Mean annual temperatures for decades prior to 1960 may be read from Penman's (1974) Fig. 5.
(ii) Some data for hottest day and coldest night temperatures are included in Penman's (1974) Table 4.
(iii) Entries may be assumed accurate to ±0·1 K.

average, ranks with 1930–39 and 1950–59 as a decade only 0·1 K cooler than the warmest (1940–49) since records began. Thus Penman's suggestion (1974, Fig. 5) of a secular trend of temperatures decreasing after the 1940s is not continued into the 1970s. In the 1970–79 decade, mean temperature was high, in large measure, because of the warm years 1975 and 1976, each within 0·6 K of the two hottest recorded years: 1921 and 1949. Indeed, average maximum temperatures in June and July 1976 and in August 1975 were the highest

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recorded, exceeding maxima that had respectively been unsurpassed since 1893, 1921 and 1911. In the 1976 summer, in particular, the record temperatures resulted in part from the combination (over much of western Europe) of a shortage of rain with the high (but not the highest-recorded) sunshine totals. Thus the ground received large inputs of solar energy, of which rather little could be dissipated by evaporation and transpiration, and the larger part was therefore used in convective heating of the lower atmosphere. Furthermore, south-easterly winds prevailed over southern Britain, and these, already convectively warmed during a 1000 km traverse of north-west Europe, helped further to maintain the high air temperatures over England: temperatures that at Rothamsted rose as high as 33·0°C on 26 June 1976 (the hottest June day on record, and only 0·3 K cooler than the 102-year maximum achieved on 9 August 1911 and 19 August 1932) and as high as 32·0°C on 7 August 1975. So far as minimum temperatures are concerned, no day or month in 1970–79 was so cold as the extremes amongst its fore-runners, but the June and September of 1972 were only 0·3 and 0·4 K warmer respectively than the coldest of Junes (1916) and Septembers (1912), and the January of 1979 only 1·3 K warmer than the coldest January (1963).

For Woburn, Table 5 shows the mean air temperatures for the period 1930–79 and for

TABLE 5

Woburn: mean air temperature (°C): average and extreme values

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Overall mean 1930–79	3·2	3·4	5·4	7·9	11·1	14·2	16·0	15·8	13·6	10·1	6·3	4·0	9·3
Decade means													
1930–39	4·0	3·7	5·5	7·7	10·9	14·5	16·2	16·3	13·6	9·3	6·4	3·8	9·3
1940–49	2·2	3·2	5·4	9·0	11·2	14·5	16·4	16·1	14·1	10·1	6·3	4·2	9·4
1950–59	3·0	3·1	5·6	7·9	11·2	14·3	16·2	15·8	13·5	9·9	6·3	4·5	9·3
1960–69	2·8	3·4	5·4	8·0	11·0	14·3	15·4	15·2	13·4	10·7	5·9	3·0	9·1
1970–79	3·6	3·5	5·2	7·2	10·9	13·7	15·9	15·8	13·5	10·2	6·5	4·9	9·2
Coldest year (1963)	−3·9	−1·9	5·7	8·3	10·3	14·5	14·6	14·1	12·5	10·7	8·1	1·9	7·9
Recent cool years													
1972	3·5	4·1	6·5	8·1	10·5	11·9	15·3	15·0	11·4	10·1	6·0	5·3	9·0
1979	−0·9	0·7	4·6	7·7	10·7	13·4	16·1	15·3	13·5	10·7	6·5	5·6	8·7
Hottest year (1949)	4·9	5·2	4·4	9·9	10·5	14·7	17·4	17·0	16·8	11·5	6·0	5·7	10·3
Recent warm years													
1975	6·6	3·9	4·5	8·3	9·5	13·9	17·4	18·4	13·6	9·8	5·5	4·1	9·6
1976	5·4	4·2	4·5	7·8	12·3	17·3	18·3	16·9	13·4	10·8	5·9	1·6	9·8
Lowest minimum (monthly average)	−7·0	−5·4	−2·1	0·2	3·6	7·0	9·3	8·1	6·7	3·2	0·4	−2·7	
	1963	1947	1962	1938	1941	*1977*	1963	1956	1952	1931	1952	1962	
Highest maximum (monthly average)	9·4	10.5	14·5	15·4	18·8	24·0	25·2	25·2	21·8	16·7	12·1	10·2	
	1975	1945	1938	1945	1947	*1976*	*1976*	1947	1949	1959	1938	*1974*	
Coldest night (1930–79)	−20·0	−20·6	−15·0	−7·2	−6·8	−0·5	1·7	1·7	−2·2	−7·8	−8·9	−13·3	
	1963	1947	1947	1968	*1971*	1962	1965	1955 1964	1969	1931	1952	1946	
Hottest day (1930–79)	14·4	16·7	22·8	25·5	29·5	33·3	32·7	33·9	29·5	25·0	19·5	14·9	
	1930 1953	1959	1968	1945	1944 1947 1953	*1976*	*1976*	1932	1949	1959 1969	1938	*1979*	

Note: Entries may be assumed accurate to ±0·1 K.

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the decades that comprise it. Temperatures (1930–79) average 0·1 K higher than at Rothamsted, and from 1930 the decade means show for both sites the same trend with time. As would be expected, in the 1970–79 decade the coolest and warmest years at Woburn (1972, 1979 and 1975, 1976) were the same years as at Rothamsted. However, in the two warm summers Woburn tended to have slightly lower mean temperatures, but slightly higher monthly mean maxima and lower mean minima, than did Rothamsted. These average maxima and minima (Table 5) show, too, that within the 50-year record the decade 1970–79 included the warmest January, June, July and December days and the coolest June nights. And the hottest day of the decade, 26 June 1976, was, at 33·3°C, only 0·6 K below the highest-recorded maximum (33·9°C on 19 August 1932); the decade also realised the hottest July day on record: 3 July 1976, the warmest December day: 4 December 1979, and the coldest May night: 2 May 1971. (These data are listed in the lower part of Table 5—a Woburn complement of Penman's (1974, Table 4) data for Rothamsted.)

Soil temperature: Rothamsted and Woburn. Soil temperatures at both Rothamsted and Woburn are measured at 09.00 h G.M.T. at various depths under bare soil and under grass. For the Rothamsted readings under grass, a detailed analysis for 1960–69 data was included in Penman's (1974) survey, and showed that on a monthly mean comparison the temperature of the soil at 10 cm depth was within 0·5 K of the mean air temperature in the screen. This present summary is concerned with the soil temperatures under bare soil, at 10 cm depth; and monthly values for decade means and for recent warm and cool years are presented in Table 6 for Rothamsted and in Table 7 for Woburn.

TABLE 6

Rothamsted: mean monthly soil temperature (°C) at 10 cm depth under bare soil

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Decade means													
1960–69	2·3	2·6	3·8	7·2	11·3	15·5	16·5	15·4	13·2	9·8	5·2	2·6	8·8
1970–79	3·1	2·6	3·9	6·5	11·2	15·1	17·1	16·1	12·9	9·2	5·4	4·0	8·9
Recent years													
1975	4·9	3·2	3·6	7·0	10·1	15·9	18·5	19·1	13·3	8·9	4·9	3·5	9·4
1976	4·1	3·0	3·7	7·4	12·4	18·3	20·1	18·0	13·1	10·3	5·0	1·4	9·7
1979	0·8	0·6	3·0	6·3	10·2	14·7	17·7	14·7	13·1	10·1	5·2	4·6	8·4

Notes: (i) Soil temperatures are read at 09.00 h G.M.T.
(ii) Entries may be assumed accurate to ±0·1 K.

At Rothamsted, the decades 1960–69 and 1970–79 had very similar annual mean soil temperatures that were respectively 0·1 and 0·3 K below the corresponding mean air temperatures (Table 4). In both decades, midsummer soil temperatures were about 1 K higher, and during the rest of the year about 0·5 K lower, than their associated mean air temperatures. (A fuller description of the relation of soil to air temperature, and of the effects of measurement time and phase delay, is included in Penman's (1974) survey.) Within the 20 years 1960–79, soil temperatures were highest in summer 1976, with 24·2°C recorded on 28 June, and with a July monthly mean of 20·1°C (all measurements at 09.00 h G.M.T.). Lowest monthly mean soil temperatures since 1960 and since 1970 were respectively experienced in February 1963 (0·0°C) and in February 1979 (0·6°C). Lowest daily values were, in 1960–69, the −3·3°C recorded on 24 December 1963, and in 1970–79 the −1·7°C of 7 January 1970. For Woburn, data for the decade 1970–79 only are presented. The decade means bear a relation to the corresponding air temperatures similar to that reported for Rothamsted, and, expectedly, the decade's highest soil tem-

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TABLE 7

Woburn: mean monthly soil temperature (°C) at 10 cm depth under bare soil

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Decade means													
1970–79	3·3	2·6	4·1	6·9	11·5	15·6	17·3	16·2	12·8	9·3	5·6	4·1	9·1
Recent years													
1975	5·1	3·5	3·9	7·3	10·7	16·4	18·8	19·0	12·8	8·7	5·0	3·8	9·6
1976	4·4	3·2	3·7	7·3	12·0	18·6	20·1	17·8	13·1	10·2	5·1	1·4	9·7
1979	0·9	0·9	3·3	6·7	10·3	15·0	17·1	15·0	13·1	10·0	5·5	4·5	8·5

Notes: (i) Soil temperatures are read at 09.00 h G.M.T.
(ii) Entries may be assumed accurate to ±0·1 K.

peratures occurred during 1976, with 24·0°C recorded on 26 June and with a July mean of 20·1°C. The decade's lowest daily value was −1·1°C, on 2 December 1973, and its lowest monthly mean 0·9°C, recorded for both January and February 1979.

Rainfall

Rothamsted rainfall. Table 8 lists the mean monthly and mean annual Rothamsted rainfalls, as registered by the 1/1000 acre (4·05 m²) raingauge, for the 127 years 1853–1979. Means, by the same gauge, for the decades 1960–69 and 1970–79 are also shown: the latter decade is seen to have been drier than average by some 19 mm (2·6%). The 1/1000 acre gauge is of a shape and of sufficient size that its catch of rainfall may be assumed to be little affected by the distortion of the wind pattern that any gauge necessarily produces near the perimeter of its orifice. For the Meteorological Office Mark II raingauge, of 5 inch (12·7 cm) diameter and conventionally exposed with its rim 0·30 m above ground level, such an assumption of an unbiased catch is known to be not justified. To minimise this bias in a Mark II gauge catch, recommendations were made that the gauge be surrounded by a circular turf wall, 1·5 m radius and 0·30 m high. The rainfalls recorded by a 5 inch gauge conventionally mounted, and by a 5 inch gauge surrounded by a turf wall, are in Table 8 compared with the corresponding 1/1000 acre gauge catches for the

TABLE 8

Rothamsted rainfall: monthly mean totals (mm) for 1853–1979, and, as a raingauge comparison, for decades 1960–69 and 1970–79

Period	Gauge	J	F	M	A	M	J	J	A	S	O	N	D	Year
1853–1979	1/1000 acre	65	50	49	50	54	56	62	65	61	73	71	67	723
1960–69	1/1000 acre	58	47	46	59	58	58	63	62	68	67	69	76	731
	5 inch, walled	56	46	45	57	56	57	61	58	65	64	67	74	706
	5 inch	55	44	44	56	56	56	61	58	65	64	66	72	697
1970–79	1/1000 acre	74	59	62	51	52	57	34	55	58	56	75	71	704
	5 inch, walled	74	57	62	50	50	55	33	53	56	53	72	69	684
	5 inch	70	55	60	49	49	54	32	53	55	53	72	68	670

Notes: (i) An analysis of mean and extreme values for annual rainfall was summarised in Penman's (1974) Figs 14 and 15.
(ii) Individual entries may be assumed accurate to ±3%.

decades 1960–69 and 1970–79. (The 1960–69 figures are from Penman (1974, Table 6), converted to metric units.) The difference between the mean annual totals recorded by the 5 inch (conventionally exposed) and the 1/1000 acre gauges was in both decades 34 mm. This loss of catch, equal to some 4·7% of the annual total, is in close agreement with findings at the Institute of Hydrology (1975) of a 4·6% loss by a Mark II gauge, conventionally

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exposed, as compared to the catch of a Mark II gauge mounted with its rim at ground level and set within an anti-splash surround. Concerning the turf wall surround, Penman (1974) had concluded from the 1960–69 data (reproduced in Table 8) that it improved only marginally the performance of a 5 inch gauge; this conclusion is confirmed by the 1970–79 results (Table 8).

During the decade 1970–79, July was on average much the driest month (Table 8); November was the wettest, as it had been during 1930–59 (Penman, 1974, Fig. 16), and December, the wettest month in 1960–69, received slightly less rain than both November and January. The two driest years of the decade were 1973 and 1976, with annual totals respectively of 540 and 583 mm, and the two wettest, with 895 and 909 mm, were 1974 and 1979. (The lowest recorded annual total was 409 mm, in 1921, and the highest 983 mm, in 1903; all as measured by the 1/1000 acre gauge.) The extremes, since 1852, in each calendar month are presented in Table 9 (a combined, updated and converted version of Penman's (1974) Table 7a and 7b). The 1970–79 decade included the wettest March on record, in 1977, but had no month that was the driest recorded, although totals as low as 9, 9 and 6 mm were measured respectively in August 1976, July 1977 and October 1978.

TABLE 9

Rothamsted: rainfall totals (mm) in wettest and driest months: 1852–1979: 1/1000 acre gauge

	J	F	M	A	M	J	J	A	S	O	N	D
Driest	14	2	2	3	12	3	5	2	4	3	10	1
	1880	1891 1950 1959	1929	1938	1896	1925	1921	1947	1865 1959	1947	1945	1864
Wettest	145	125	133	117	128	161	177	167	205	187	200	206
	1939	1900	*1977*	1920	1967	1936	1855	1879	1896	1865	1940	1914

Note: (i) Individual entries may be assumed accurate to ±2%.

There were, too, within the decade, periods longer than a month that were memorable for their excess or scarcity of rainfall, and for the fact that in two instances an extended period of unusual dryness was followed by several months with very high rainfall. Thus the dry autumn of 1978 (during which in southern England many fields sown to cereals were irrigated to promote germination) recorded an August–November rainfall of 97 mm —little more than one-third of the 270 mm August–November average—and the succeeding months December 1978 to May 1979, with 619 mm, were wetter by some 85% than their corresponding mean of 335 mm. Similarly, the period October 1975 to August 1976, which included the momentous drought of summer 1976, received a rainfall total of only 299 mm—less than half the October–August average of 662 mm; and the ensuing months September 1976 to March 1977 accumulated a total of 637 mm—some 201 mm higher than the corresponding mean. The drought of 1976 achieved, too, another noteworthy statistic: the period of 36 consecutive rainless days, from 21 July to 25 August, equalled in length the previous longest rainless period: 6 August–10 September 1947. The decade experienced two other notably rainless periods: of 24 days' and 29 days' duration, respectively occurring 31 August–23 September 1971 and 10 August–7 September 1972.

Woburn rainfall. Monthly and annual means of rainfall totals at Woburn are listed in Table 10 for the period 1930–79 and its component decades. Woburn rainfall is collected in a 5 inch Mark II raingauge that is *not* surrounded by a turf wall, and comparison of the Woburn totals with their Rothamsted counterparts (Table 8: 5 inch) shows that in the decades 1960–69 and 1970–79 the Woburn mean annual rainfalls were respectively

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TABLE 10

Woburn: rainfall (mm): average and extreme values: 1930–79

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Overall mean 1930–79	54	41	45	46	54	50	53	61	52	53	63	55	627
Decade means													
1930–39	55	37	37	51	60	46	63	62	54	57	62	50	634
1940–49	57	35	44	41	54	43	47	52	38	60	67	47	585
1950–59	53	49	46	38	58	55	61	71	53	46	64	56	650
1960–69	49	37	41	51	50	56	56	64	66	56	58	61	645
1970–79	57	45	55	47	51	51	36	59	49	48	62	60	620
Driest year (1933)	35	41	61	27	47	48	38	23	47	37	38	9	451
Recent dry years													
1972	59	38	43	49	40	27	67	15	36	22	52	46	494
1973	20	19	11	46	111	71	37	32	36	30	32	32	477
1976	24	17	19	16	28	14	24	7	93	108	50	98	498
Wettest year (1960)	73	57	44	10	30	95	80	81	89	114	76	93	842
Recent wet years													
1974	64	63	39	16	33	68	41	110	109	90	121	34	788
1979	60	51	127	87	103	43	14	70	15	81	46	131	828
Driest month													
	17	1	2	3	7	7	6	1	2	3	12	9	
	1950	1959	1931	1938	*1970*	1942	*1977*	1947	1959	*1978*	1945	1933	
Wettest month													
	108	106	127	90	125	135	163	155	119	127	182	131	
	1939	1937	*1979*	1931	1932	1958	1936	*1977*	1965	1949	1940	*1979*	
	1948												

Note: Individual entries may be assumed accurate to ±3%.

52 and 50 mm less than at Rothamsted. For both the long-term mean and the 1970–79 decade Woburn's wettest month is November, and its seasonal progression of monthly rainfall totals is similar to that at Rothamsted.

For annual totals (since 1930) the Woburn rainfall was least (at 451 mm) in 1933, and greatest (842 mm) in 1960. Each of these extremes was approached, but not reached, during the 1970–79 decade: 1973 recorded but 26 mm more than 1933; and 1972 and 1976 were little wetter (Table 10); and the 1979 total was less by only 14 mm than 1960. The tabulations for the extremes of monthly totals (also in Table 10) show that the decade included the driest recorded May, July and October and the wettest March, August and December. Moreover, in 1973—the decade's driest year—there was recorded the largest daily receipt of rainfall in the 1930–79 period: 52 mm on 21 May—exceeding slightly the previous record of 50 mm on 10 July 1968.

As at Rothamsted, the periods October 1975 to March 1977 and August 1978 to May 1979 each included a succession of very dry months followed by a sequence of very wet months. The August–November rainfall total for 1978 was 103 mm, less than half the 50-year mean for those months (229 mm), and the ensuing December–May recorded 535 mm, nearly twice the 295 mm average. The dry period October 1975–August 1976 received 235 mm, compared to a mean of 575 mm, and in the September–March that followed, 571 mm of rain fell—over 200 mm more than the 363 mm average. That dry summer of 1976 included, from 25 July to 27 August, a succession of 34 rainless days; and, as at Rothamsted, there were notable rainless periods in 1971—the 23 days 31 August–22 September, and in 1972: 25 days from 9 August to 2 September.

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Wind

Rothamsted: wind speed at heights of 2·0 and 10·0 m. Monthly and annual values for daily wind speed at 2·0 m above a grass surface, as recorded by a cup counter anemometer, are listed in Table 11. The decade 1970–79 is seen to have been slightly more windy

TABLE 11

Rothamsted: average wind speed (km day^{-1}) at 2·0 m above grass: decade means for monthly and annual values

	J	F	M	A	M	J	J	A	S	O	N	D	Year
1960–69	211	229	241	225	194	165	146	155	152	158	203	209	191
1970–79	249	229	252	260	229	185	172	163	176	190	227	237	214

Notes: (i) Estimates for the ranges in monthly and annual averages of daily wind speed are given (for the period 1968–72) in Penman's (1974) Table 9.
(ii) Individual entries may be assumed accurate to ±10 km day^{-1}.

than 1960–69, and in both decades average wind speeds were highest in March/April. Wind speed at 10·0 m above ground was continuously recorded, from 1954 to April 1976, using a Dines anemometer, and since November 1977 has been measured, again continuously, by a Monro instrument. The highest wind gust yet recorded by these instruments, of 78 m.p.h. (35 m s^{-1}), occurred within the 1970–79 decade, on 2 January 1976; prior to that decade the maximum recorded gust was 73 m.p.h. (33 m s^{-1}), on 4 November 1957.

Woburn: wind speed at 2·0 m. Table 12 shows wind speeds at Woburn, recorded 2·0 m above a grass surface by a cup counter anemometer, for the decade 1970–79. The values are slightly less than the corresponding Rothamsted ones (Table 11), and are highest in

TABLE 12

Woburn: wind speed (km day^{-1}) at 2·0 m above grass: means and extremes for monthly and annual values in the decade 1970–79

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Decade means 1970–79	232	205	229	212	195	177	177	155	184	173	231	234	198
Lowest monthly average	177	137	166	164	134	145	127	133	114	137	164	153	179
Highest monthly average	330	264	314	266	243	206	241	190	254	248	297	391	225

Note: Individual entries may be assumed accurate to ±10 km day^{-1}.

November/December/January. The ranges, within the decade, of monthly and annual averages are also shown in Table 12; they are consistent with those listed for Rothamsted by Penman (1974, Table 9), but are expectedly larger because they relate to a 10-year, rather than with Penman, a 5-year, period.

Evaporation and drainage

Rothamsted: open water evaporation. Average rates of monthly and annual evaporation from a standard Meteorological Office (Symons) evaporation tank are listed in Table 13 for the decades 1960–69 and 1970–79 and for the period 1948–79. Evaporation rates were slightly lower than average in 1960–69, and rather more than average in the decade 1970–79, in which the years 1975 and 1976 registered 663 and 740 mm of evaporation, respectively 5 mm below and 72 mm above the previous highest total of 668 mm in 1949.

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TABLE 13

Rothamsted: open water evaporation (mm month^{-1}) from a Symons tank: decade means and extreme years

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Overall mean 1948–79	5	9	30	52	79	94	95	80	59	32	14	6	555
Decade means													
1960–69	4	8	32	51	77	93	88	76	56	31	14	4	534
1970–79	8	10	27	49	83	99	103	91	69	34	16	8	597
Year of least evaporation													
1954	7	4	23	57	62	70	72	53	51	25	13	10	447
Recent year of low evaporation													
1977	7	15	23	49	89	54	97	63	72	31	21	7	528
Year of most evaporation													
1976	11	9	40	64	90	140	152	124	59	25	15	11	740
Extreme evaporation totals: summer months (1970–79 only)													
Least					71 1972	54 1977	84 1978	64 1977					
Most					95 1970	140 1976	152 1976	124 1976					

Note: Individual entries may be assumed accurate to ±1 mm or ±4%, whichever is greater.

The year of least evaporation in 1970–79 was 1977, for which the evaporation total exceeded by some 80 mm the lowest recorded annual total of 447 mm in 1954. In 1977, as Table 13 shows, there were recorded the decade's *lowest* June and August evaporation totals, and in 1976 its *highest* June, July and August totals—but in that latter drought year, tank evaporation will have given a poor representation of the rate of transpiration from a natural surface.

Rothamsted: drainage through bare soil. A summary of 99 years' of measurements with the Rothamsted draingauges, and of the 20 inch (0·51 m) gauge records in particular, was included in Penman's 1974 survey of Rothamsted weather. In that survey Penman included (as Table 12) a month-by-month comparison of rainfall (1/1000 acre gauge) and drainage (20 inch gauge) for the decade 1960–69; a corresponding analysis for 1970–79 is presented in Table 14. Although the averaged annual totals of drainage were the same in each decade, at about 380 mm, the seasonal distributions were rather different: in 1970–79 there was less drainage in the summer 6 months (91 mm as against 115 mm in 1960–69). Such a difference would be expected (Penman & Schofield, 1941) if the distributions of summer rainfall were different—as indeed they were: 368 mm from 87 raindays in the summers of 1960–69, and 307 mm from 72 in 1970–79.

The difference in the numbers of summer raindays can also be invoked to explain the

TABLE 14

Rothamsted: drainage: average response (mm) in 1970–79 of 20 inch draingauge

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Rainfall, R	74	59	62	51	52	57	34	55	58	56	75	71	704
Drainage, d	64	48	38	20	18	16	3	14	20	31	53	58	383
$R - d$	10	11	24	31	34	41	31	41	38	25	22	13	321
Tank evaporation	8	10	27	49	83	99	103	91	69	34	16	8	597

Notes: (i) Rainfall as measured by 1/1000 acre gauge.
(ii) Drainage estimates accurate to ±1 mm or ±3%, whichever is greater.

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difference, as between the decades, in the estimates that the draingauge affords for the rates of summer evaporation. These estimates are derived as the difference between rainfall and drainage: $R - d$ in Table 14 and in Penman's Table 12. Consider first the values for *tank* evaporation that are included in the tables as rough approximations for the atmosphere's *potential* evaporating power; these values (of decade means) exceed the corresponding rainfall averages in almost all the summer months in both 1960–69 and 1970–79. Thus, if water was evaporated from the draingauge at the *potential* rate, one would expect little or no drainage through the gauge in these summer months—whereas the observed drainage totals were 100 mm or so. The contradiction is explained by recalling that the draingauge surface is of bare soil, which, when dry, permits of rather little evaporation. The actual evaporations (ignoring effects of month-to-month carry-over) are more realistically represented by $R - d$, and they depend strongly on the number of days for which the soil surface is wet and therefore able to evaporate, and this number is in part determined by the number of raindays. The data of Table 14 are consistent with this thesis (and Penman (1974) showed that so too were his Table 12 data): the totals of $R - d$ in the months April–September in 1960–69 and 1970–79 were respectively 254 and 216 mm, and the corresponding numbers of raindays were 87 and 72.

Annual values for R, d and $R - d$ for various portions of the 109-year drainage record are presented in Table 15. The data for 1970–79 agree well (and those for 1940–59 less well) with earlier findings (Penman and Schofield, 1941) that annual values of $R - d$ are almost constant, but are less in years of lower annual rainfall.

TABLE 15

Rothamsted: drainage: averages (since 1871) of annual responses (mm) of 20 inch draingauge

Period	Rainfall, R	Drainage, d	$R - d$
1871–1939	743	378	365
1940–1959	702	352	350
1960–1969	730	380	350
1970–1979	704	383	321

Notes: (i) Rainfall as measured by 1/1000 acre gauge.
(ii) Drainage estimates accurate to ±3%.

Future analyses

In the fore-going survey, means and extremes have in the main been reported for the largest numbers of years that the records allowed. These periods of years have necessarily differed between the two meteorological stations and between the different weather variables. Since the extremes observed for some particular variable depend on the duration of the record for that variable, the comparisons of the extreme weathers at Rothamsted and Woburn in terms of these various-length records were thus not entirely valid. Furthermore, there is evidence of trends in some of the variables (e.g. temperature, Table 5, and seasonal distribution of rainfall, Table 8) that may invalidate the inter-station comparison of long-term means also—if they be derived for different periods. There are thus good reasons for comparing the various data for one standard period, and for assessing the weather's variability in terms of the data's variance, rather than their range, within that period. (These variances are themselves useful statistics, both for agriculture and for other endeavours such as building and energy resource management.)

Two considerations determined that the calculation of variances and the standardisation of periods should not be undertaken for this present survey. The calculation of variances for the many weather variables is an arithmetic task of some magnitude—one that will best await the computer archiving within the next two years of the bulk of the

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ARS' weather station records—including those for Rothamsted and Woburn. The consideration of standardised periods is an international one: the World Meteorological Organization (and the United Kingdom Meteorological Office) refer their collated climatological statistics to standard 30-year periods, the next of which will be that for 1951 to 1980. A computer-aided analysis, to be undertaken in 1981 or thereabouts, of the Rothamsted and Woburn data and their variances will thus have the benefit of the ARS' data archiving and the merit of being referred to an internationally standardised period.

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