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AN ANALYSIS OF MONTHLY POTENTIAL EVAPORATION TOTALS REPRESENTATIVE OF KEW FROM 1698 TO 1976

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SUMMARY

A very long series of monthly potential evaporation totals representative of grassland at Kew (estimated by Penman's formula from mid-1876 onwards, by an approximation to the formula from 1870 to mid-1876 and only from temperature data from 1698 to 1869) is analysed in terms of the frequency of annual, seasonal, and *n*-monthly totals. Attention is drawn to the very high decadal winter mean for 1960–69 and to the greater fluctuation of winter totals after 1870 than before. Two major 'troughs' occurred in summer and annual graphs of decadal means and the latter showed a remarkable, sustained and apparently genuine rise from the decade beginning in 1911 up to and including that beginning in 1961.

1. INTRODUCTION

This is the fourth of a series of papers, two dealing with the compilation and two with the analysis of very long place-representative sets of monthly rainfall and potential evaporation totals. It closely follows the writer's analysis of monthly rainfall totals (Wales-Smith, 1973a).

Monthly totals of Penman potential evaporation (Penman, 1948) using albedo 0·25 at pairs of stations several tens of kilometres apart have shown only minor differences. A comparison of monthly totals for an eight year period was made, by the writer, for Birmingham (Edgbaston) and Sutton Bonington as part of a nation-wide study of evaporimeter data. Edgbaston (163 metres above mean sea level) is some 60 km south-west of Sutton Bonington (48 metres above mean sea level). All pairs of monthly potential evaporation totals were within 19 mm of one another, 98 per cent of pairs were within 12·7 mm and 87 per cent were within 6 mm. Thus an analysis of the variability of monthly potential evaporation at a point may be regarded as representing other points within a sizeable area.

The parts of the series for 1698–1875 and 1876–1976 are considered reasonably homogeneous although they were obtained by different methods (Wales-Smith, 1973b). This view is supported by a comparison made over the period 1871–1970. The simple method which was employed to produce the first part of the series (before all the data required by Penman's formula became available at Kew) was used to make monthly estimates up to and including 1976. When annual totals of Penman estimates and 'synthetic' estimates of potential evaporation were compared 72 pairs lay within 25·4 mm of one another, 25 pairs were within 50·8 mm and the remaining 3 pairs were just over 50·8 mm apart. The decadal averages of the 'synthetic' estimates showed the rising trend which appears in Figure 11 on page 312.

2. Frequency distribution of annual and seasonal totals

Totals in 1-inch* ranges of amount for years and seasons from 1698 to 1970 are shown in Figure 1. Imperial units are used here for comparison with the rainfall analysis. The 4-month and 2-month 'seasons' used in the rainfall analysis were retained to facilitate comparison. It is interesting to note that whilst the summer rainfall diagram was convex (upwards) for low totals and concave (upwards) for high totals the corresponding diagram for potential evaporation has a concave profile for low totals and a convex one for high totals.

3. Probability analysis and listing of extreme values

The computer programs (written by J. D. Bacon and K. E. Bruley) for processing the Kew monthly rainfall series were also used on the potential evaporation series. The six greatest and six least totals in calendar months, *n*-month periods, seasons and whole years were identified (with year-dates); cumulative probabilities corresponding to given threshold values were also obtained. Both sets of data were plotted on probability paper, using the formula recommended by Jenkinson (1969). Lines of best fit for cumulative probabilities as rare as 0·005 (once in 200 years) were easily inserted by eye.

Relationships are shown in simple diagrams, the numbering corresponding, exactly, to that used in the rainfall analysis (Wales-Smith, 1973a). Totals of (Penman) potential evaporation expected to be (a) attained or exceeded and (b) not exceeded, for return periods up to 200 years are shown in Figures 2 to 6. In Figure 2 two sets of curves show, respectively, totals of potential evaporation expected, on average, to be reached or exceeded and not to be exceeded with the given return periods. Figure 3 displays the same information as Figure 2 but in a different form; five graphs are given for return periods of 5, 10, 20, 50, 100 and 200 years, the axes being potential evaporation and calendar month. Figures 4 and 5 are similar to Figure 2 but the curves are for potential evaporation accumulated through the summer and winter half-years as used by water engineers. Figure 6 is of the same type as Figures 2, 4 and 5 and presents relationships for the 4- and 2-month periods and for whole years.

4. Extrapolation to estimate probable extreme values

The probability analyses were examined to obtain rough estimates of probable maximum and minimum values. The results given in Table I may be compared with those given in the rainfall analysis (Wales-Smith, 1973a) where the return periods quoted should not, of course, be interpreted literally. The very small differences between potential evaporation totals with very large, nominal, return periods were taken to imply that those 'events' are not very far from probable maxima and minima.

5. Dates of extreme events

The six largest and six smallest calendar month, *n*-month, seasonal and annual totals of potential evaporation are set out in Tables II, III(a) and IV together with year-dates. The winter (Nov.–Feb.) and winter half-year (Oct.–Mar.) year-dates are those in which the winters started. As the estimates for 1698–1875 were produced from limited data the year-dates for this period are shown in brackets. Assuming no climatic change one might expect the 178 year period

* 1 inch = 25·4 mm.

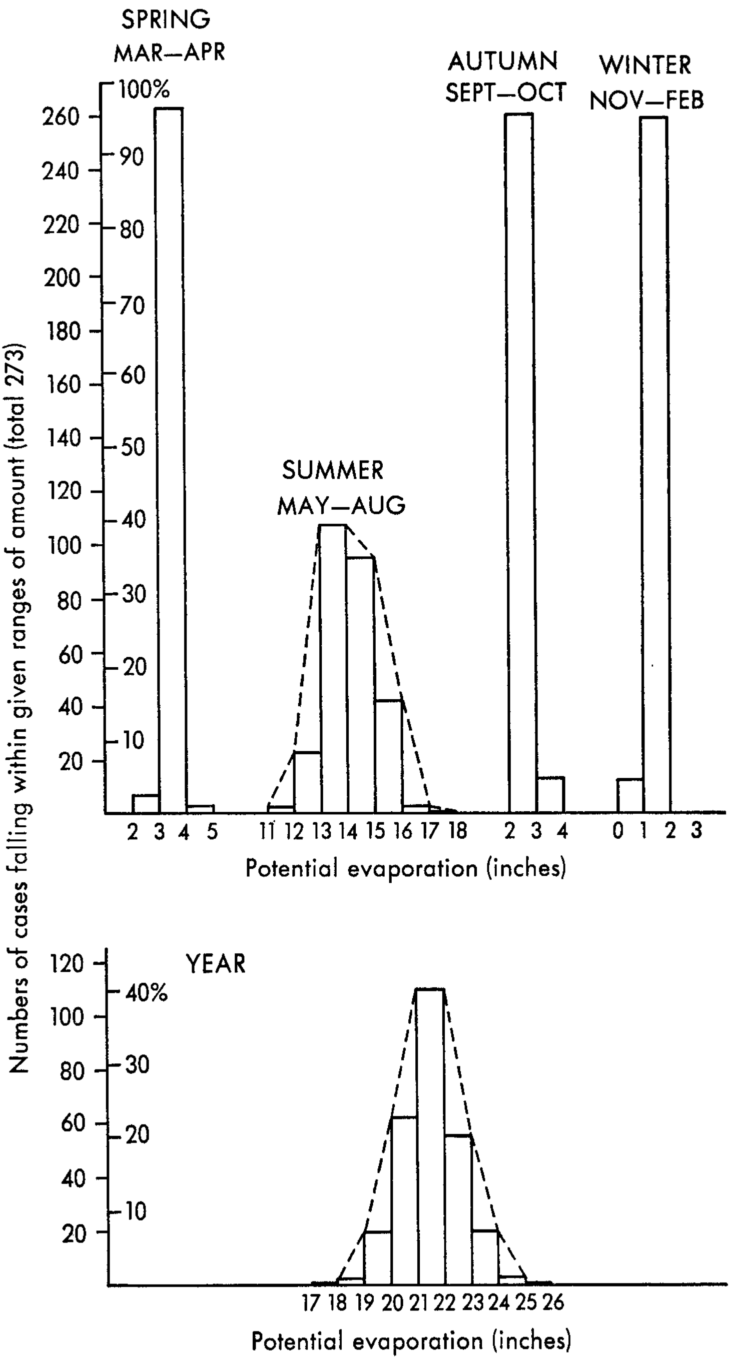

FIGURE 1—FREQUENCY DIAGRAMS OF SEASONAL AND ANNUAL TOTALS OF POTENTIAL EVAPORATION REPRESENTATIVE OF KEW, 1698–1970

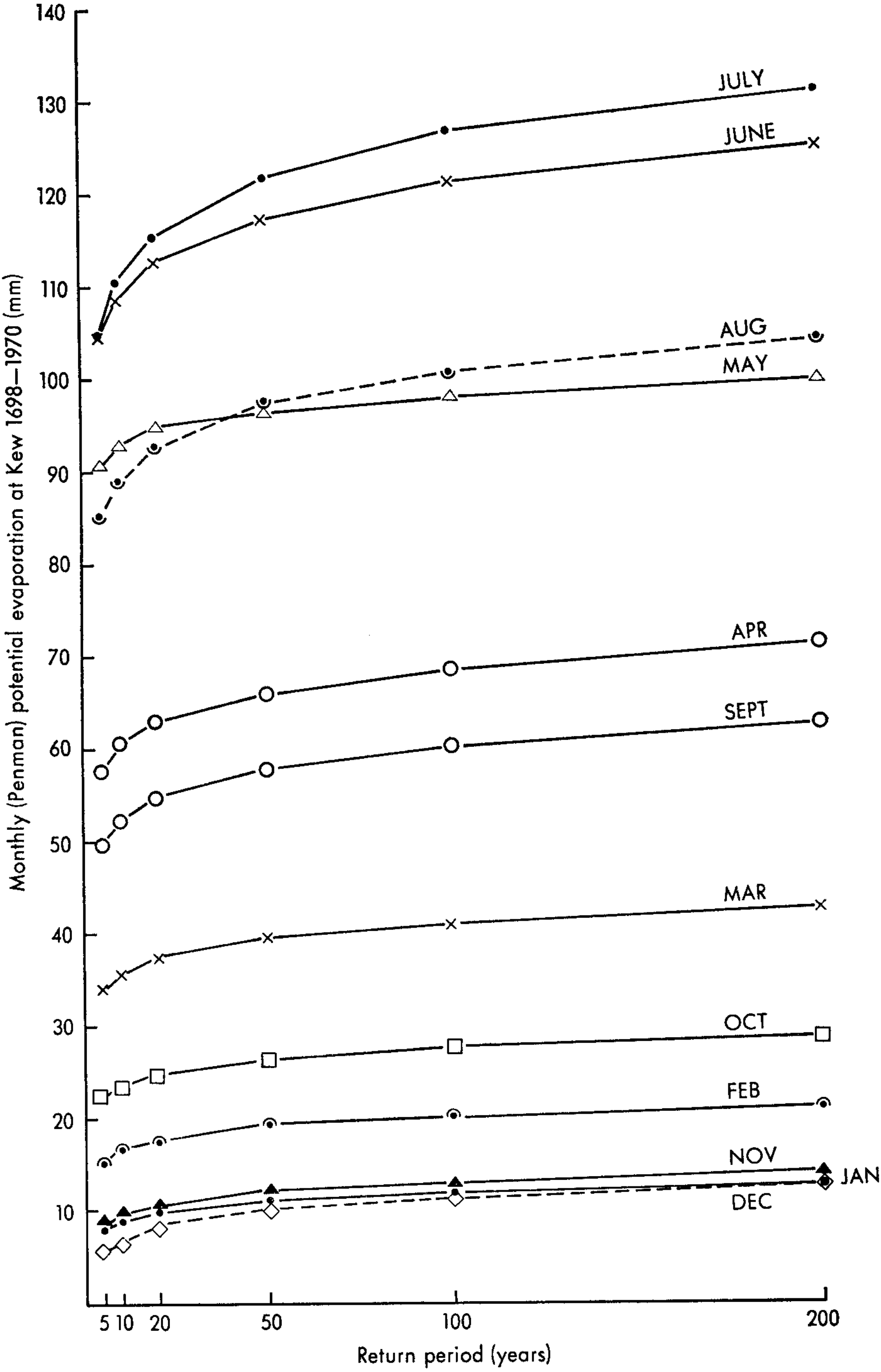

FIGURE 2(a)—HIGH POTENTIAL EVAPORATION—AMOUNTS LIKELY TO OCCUR OR BE EXCEEDED, IN GIVEN MONTHS, FOR RETURN PERIODS UP TO 200 YEARS, AT KEW

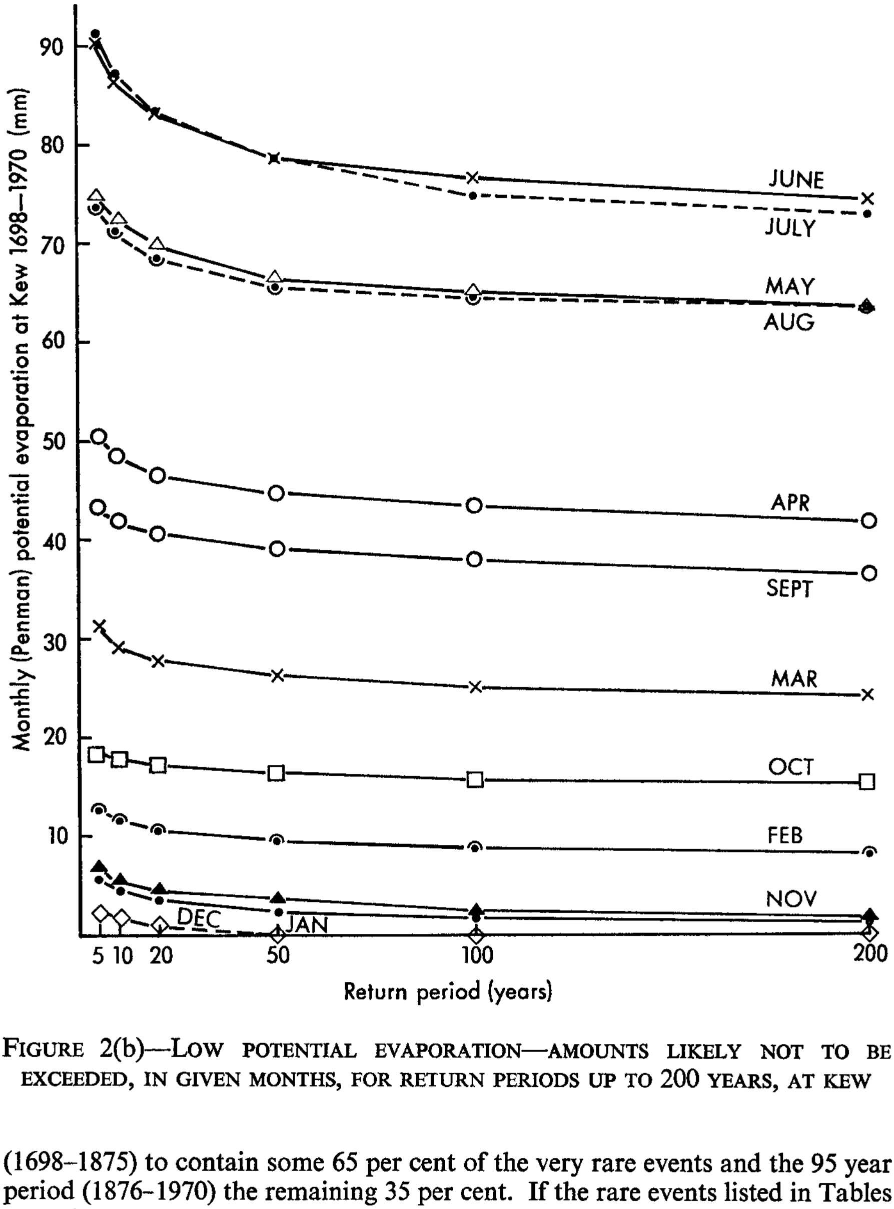

FIGURE 2(b)—LOW POTENTIAL EVAPORATION—AMOUNTS LIKELY NOT TO BE EXCEEDED, IN GIVEN MONTHS, FOR RETURN PERIODS UP TO 200 YEARS, AT KEW

(1698–1875) to contain some 65 per cent of the very rare events and the 95 year period (1876–1970) the remaining 35 per cent. If the rare events listed in Tables II, III(a) and IV falling in the two parts of the series are totalled and expressed as percentages the results are as set out in Table V.

There is a strong bias for extreme events to occur in the last 95 years of the series but although Figure 11 shows marked fluctuations there are no obvious signs of climatic change. The method used to produce the estimates for 1698–1875 has already been shown to be less sensitive than Penman's formula (Wales-Smith, 1973b). The lower sensitivity arises, of course, from the lack of all the required sunshine duration, wind speed and saturation deficit data during the first 178 years. Potential evaporation (as obtained by Penman's formula) is

TABLE I—EXTRAPOLATION OF PROBABILITY DIAGRAMS TO PROVIDE ESTIMATES OF EXTREMELY RARE (PENMAN) POTENTIAL EVAPORATION EVENTS AT KEW

	Probable extreme values	
Duration	High evaporation	Low evaporation
	mm	*mm*
Jan.	16	0
Feb.	25	5
Mar.	50	20
Apr.	80	35
May	110	55
June	140	65
July	150	65
Aug.	115	55
Sept.	70	30
Oct.	35	10
Nov.	20	0
Dec.	18	0
Year	690	410
Apr.–May	180	95
Apr.–June	300	180
Apr.–July	425	245
Apr.–Aug.	525	290
Apr.–Sept.	570	325
Oct.–Nov.	45	15
Oct.–Dec.	55	20
Oct.–Jan.	65	20
Oct.–Feb.	80	30
Oct.–Mar.	120	55
Mar.–Apr.	120	60
May–Aug.	465	255
Sept.–Oct.	95	30
Nov.–Feb.	60	10

TABLE II—POTENTIAL EVAPORATION TOTALS (mm) FOR THE 6 MOST AND LEAST POTENTIALLY EVAPORATIVE MONTHS AT KEW, 1698–1970

Jan.	Feb.	Mar	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					Most potentially evaporative						
13·5	23·6	46·0	75·2	101·9	127·0	133·3	107·9	68·6	30·2	14·7	13·7
1917	*1962*	*1967*	*1942*	*1909*	*1957*	*1911*	*1947*	*1959*	*1959*	*1888*	*1884*
11·9	20·8	43·9	72·4	99·3	124·7	130·8	103·6	59·2	28·7	13·5	12·7
1965	*1965*	*1968*	*1893*	*1922*	*1970*	*1959*	*1899*	*1898*	*1970*	*1911*	*(1870)*
11·2	19·8	39·1	67·1	98·3	124·2	126·7	100·8	58·7	27·4	13·5	11·9
1885	*1935*	*1966*	*1957*	*(1762)*	*(1846)*	*1921*	*1911*	*1964*	*1910*	*1966*	*(1874)*
10·9	19·8	38·6	66·3	97·5	120·9	124·5	98·8	58·2	26·9	12·5	10·9
1921	*1966*	*(1734)*	*1909*	*1943*	*(1858)*	*1900*	*1959*	*(1865)*	*1967*	*1893*	*1890*
10·9	18·8	38·6	65·8	96·8	117·6	123·7	98·0	57·4	25·9	12·5	10·9
1942	*1938*	*(1750)*	*1949*	*1956*	*1940*	*1934*	*1933*	*1911*	*(1735)*	*1912*	*1933*
10·7	18·5	38·3	64·8	96·3	114·8	119·9	96·8	56·9	25·9	12·5	10·9
(1872)	*1944*	*(1780)*	*1912*	*1919*	*1960*	*1887*	*1906*	*(1729)*	*(1798)*	*1961*	*1959*
					Least potentially evaporative						
1·0	8·4	23·6	41·7	62·5	72·4	71·6	62·7	34·8	14·7	1·0	0
1876	*1891*	*1947*	*1879*	*1932*	*1909*	*1888*	*1912*	*(1761)*	*(1740)*	*1948*	*1952*
1·0	8·6	24·9	42·2	63·3	75·4	73·1	64·0	37·3	15·2	2·0	0
(1870)	*1951*	*1942*	*1918*	*1879*	*1879*	*1879*	*(1817)*	*1931*	*(1817)*	*1925*	*1928*
1·5	9·4	25·4	42·4	65·0	76·5	74·4	64·0	38·9	16·0	3·1	0
1887	*1954*	*1916*	*(1837)*	*(1817)*	*1923*	*1913*	*(1816)*	*1881*	*1895*	*1916*	*1893*
2·0	9·4	25·7	43·9	65·5	78·0	75·2	64·5	39·1	16·0	3·3	0
1959	*1878*	*1923*	*(1701)*	*(1698)*	*1916*	*1919*	*(1833)*	*(1840)*	*1889*	*1949*	*1925*
2·0	9·7	25·9	45·0	66·0	79·0	80·3	65·0	39·1	16·3	3·3	0
1880	*1934*	*1915*	*(1713)*	*(1837)*	*1888*	*1910*	*(1725)*	*(1829)*	*(1840)*	*1937*	*(1875)*
2·3	9·9	26·4	45·0	68·8	79·0	81·0	65·5	39·4	16·8	3·3	0
1891	*1940**	*1917*	*(1702)*	*1887*	*(1821)*	*1927†*	*1922*	*1927‡*	*1888*	*1923*	*(1873)*

* also *1902* † also (*1816*) ‡ also *1877*

Year-dates to 1875 are shown in brackets (the estimates for 1698–1875 having been produced from limited data).

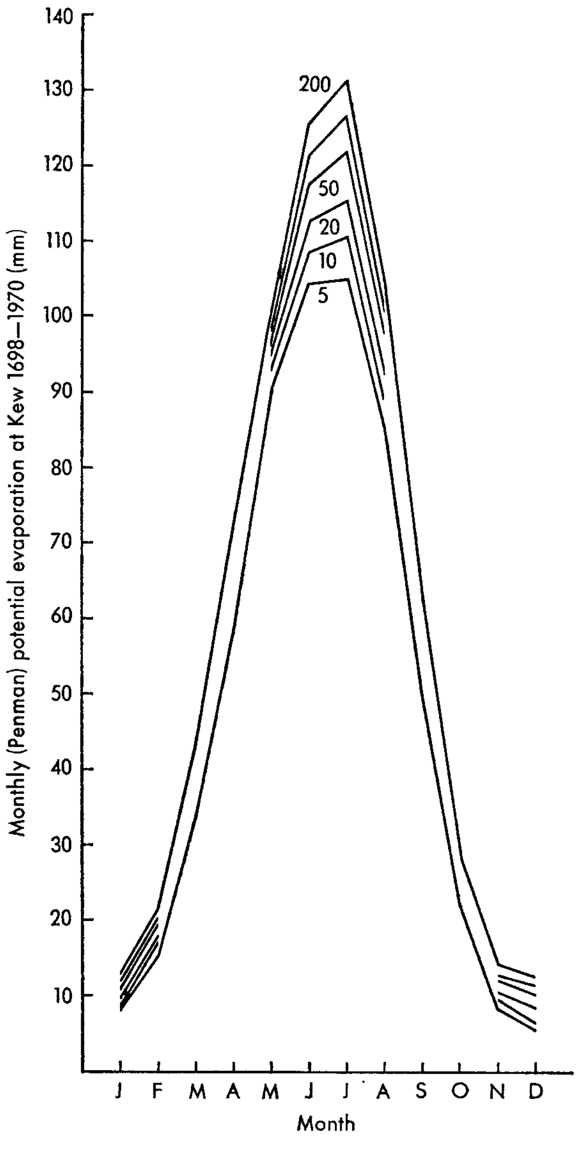

FIGURE 3(a)—HIGH POTENTIAL EVAPORATION—AMOUNTS LIKELY TO OCCUR OR BE EXCEEDED IN EACH MONTH OF THE YEAR FOR GIVEN RETURN PERIODS, AT KEW

underestimated by the indirect method in strongly evaporative conditions and overestimated under conditions of unusually low evaporation. Estimates of potential evaporation for the individual months listed in the upper half of Table II from the 'synthetic' 1876–1970 series already mentioned were compared with the Penman formula values in Table II. The 'synthetic' values for events of the first rank for March to October (the evaporative months of the year) were all close to 82 per cent of the corresponding Penman totals. Another comparison was made by obtaining the Table III(a) events from the period 1876–1970 only.

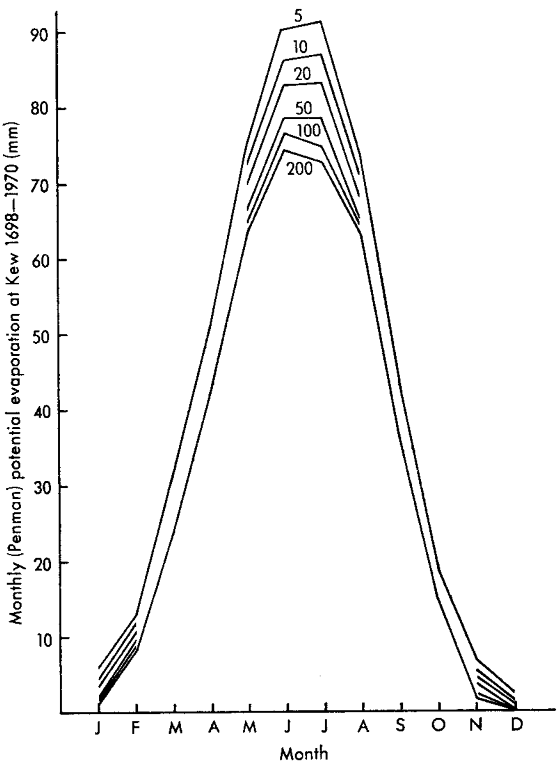

FIGURE 3(b)—LOW POTENTIAL EVAPORATION—AMOUNTS LIKELY NOT TO BE EXCEEDED IN EACH MONTH OF THE YEAR FOR GIVEN RETURN PERIODS, AT KEW

The resulting variations from Table III(a) are shown in Table III(b). If the 'new' (III(b)) 6th rank totals are compared with those obtained from the whole 273 year series it can be seen that the changes are small. The implications of these comparisons are that if all the data required by Penman's formula had been available at Kew from 1698 the distribution of extreme events would probably have been fairly even throughout the whole period. Tables II, III(a) and IV thus show the extreme events from the period 1876–1970 and *some* of the extreme events which occurred during the period 1698–1875. Although less sensitive than Penman estimates the 'synthetic' estimates are of surprisingly good quality.

6. THE PERIOD 1971–76

The analysis so far has been confined almost entirely to the period ending in 1970. This has been done for two reasons, firstly to make the analysis directly comparable with that for rainfall and secondly to highlight extreme evaporative demand during the 1975–76 drought. Table VI shows the points at which the potential evaporation totals in the period 1971–76 enter the highest 6 ranks in Tables II, III(a) and IV. (None entered the lowest ranks.) The summer half-year of 1976 and the winter half-year beginning in 1974 stand out, both attaining first rank.

TABLE III(a)—SIX MOST AND LEAST POTENTIALLY EVAPORATIVE OF SETS OF 1 TO 6 CONSECUTIVE MONTHS STARTING IN OCTOBER AND APRIL, AT KEW 1698–1970, WITH POTENTIAL EVAPORATION AMOUNTS (mm)

Oct.	Oct.–Nov.	Oct.–Dec.	Oct.–Jan.	Oct.–Feb.	Oct.–Mar.	Apr.	Apr.–May	Apr.–June	Apr.–July	Apr.–Aug.	Apr.–Sept.
					Most potentially evaporative						
30·2 *1959*	39·1 *1970*	47·2 *1959*	54·9 *1959*	73·4 *1964*	109·2 *1966*	75·2 *1942*	168·1 *1909*	286·5 *1957*	397·8 *1959*	496·6 *1959*	565·1 *1959*
28·7 *1970*	38·1 *1961*	44·7 *1910*	54·1 *1884*	70·6 *1884*	107·2 *1964*	72·4 *1893*	164·9 *1893*	271·5 *(1762)*	387·3 *1957*	475·2 *1911*	532·6 *1911*
27·4 *1910*	36·6 *1911*	43·2 *1911*	52·6 *1964*	69·9 *1961*	104·4 *1959*	67·1 *1957*	163·3 *1942*	270·0 *1893*	382·3 *(1762)*	470·9 *1957*	519·2 *1957*
26·9 *1967*	36·3 *1959*	42·9 *1884*	52·3 *1911*	69·6 *1911*	104·1 *1965*	66·3 *1909*	162·1 *1943*	269·5 *1970*	379·2 *1921*	465·8 *1893*	517·4 *(1846)*
25·9 *(1735)*	34·5 *1910*	42·9 *1970*	51·1 *1910*	69·1 *1959*	102·9 *1884*	65·8 *1949*	159·5 *1957*	269·0 *1942*	377·2 *(1846)*	464·1 *(1846)*	516·9 *1893*
25·9 *(1798)*	34·5 *1946*	41·9 *1966*	47·5 *(1874)*	65·0 *1965*	102·4 *1911*	64·8 *1912*	157·2 *(1762)*	268·7 *(1846)*	374·4 *1911*	463·3 *1921*	516·1 *1899*
					Least potentially evaporative						
14·7 *(1740)*	19·6 *1948*	21·1 *1925*	25·4 *1925*	36·8 *1925*	65·5 *1951*	41·7 *1879*	104·9 *1879*	180·3 *1879*	253·5 *1879*	324·4 *1879*	364·7 *1879*
15·2 *(1817)*	21·1 *1925*	22·6 *1953*	27·9 *1879*	38·6 *1953*	67·3 *1952*	42·2 *1918*	108·5 *(1837)*	199·6 *(1816)*	280·7 *(1816)*	344·7 *(1816)*	385·3 *(1816)*
16·0 *1895*	21·3 *(1740)*	23·1 *1889*	27·9 *(1875)*	38·9 *1951*	67·3 *1953*	42·4 *(1837)*	111·3 *(1817)*	200·4 *1923*	285·2 *1888*	354·1 *1888*	394·2 *1888*
16·0 *1889*	21·6 *1949*	23·4 *(1873)*	28·2 *1951*	39·6 *1879*	70·9 *1950*	43·9 *(1701)*	114·3 *1932*	204·0 *(1740)*	291·6 *(1821)*	356·6 *(1817)*	402·1 *(1817)*
16·3 *(1840)*	21·8 *1953*	23·9 *1948*	28·7 *1952*	40·1 *1948*	71·1 *1918*	45·0 *(1713)*	116·6 *(1782)*	204·7 *(1837)*	292·6 *(1817)*	364·7 *(1812)*	406·9 *(1812)*
16·8 *1888*	22·6 *1918**	23·9 *(1740)*	29·2 *1953*	40·6 *1952*	73·4 *1948*	45·0 *(1702)*	116·6 *(1698)*	207·3 *(1821)*	297·2 *1932†*	365·5 *1954*	412·7 *(1725)*

* also *1892* † also *(1812)*

Year-dates to 1875 are shown in brackets (the estimates for 1698–1875 having been produced from limited data).

TABLE III(b)—VARIATIONS FROM TABLE III(a) IF ALL EXTREMES ARE DRAWN FROM THE PERIOD 1876–1970

Oct.	Oct.–Nov.	Oct.–Dec.	Oct.–Jan.	Oct.–Feb.	Oct.–Mar.	Apr.	Apr.–May	Apr.–June	Apr.–July	Apr.–Aug.	Apr.–Sept.
					Most potentially evaporative						
—	—	—	—	—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—	270·0 *1893*	—	—	—
—	—	—	—	—	—	—	—	269·5 *1970*	379·2 *1921*	—	—
—	—	—	—	—	—	—	—	269·0 *1942*	374·4 *1911*	—	516·9 *1893*
25·7 *1961*	—	—	—	—	—	—	—	266·9 *1959*	371·3 *1970*	463·3 *1921*	516·1 *1899*
24·4 *1903**	—	—	47·0 *1902*	—	—	—	155·2 *1882*	264·2 *1960*	371·1 *1893*	461·0 *1899*	515·6 *1921*
					Least potentially evaporative						
16·0 *1895*	—	—	—	—	—	—	—	—	—	—	—
16·0 *1889*	—	—	—	—	—	—	114·3 *1932*	200·4 *1923*	285·2 *1888*	354·1 *1888*	394·2 *1888*
16·8 *1888*	21·6 *1949*	—	28·2 *1951*	—	—	45·7 *1889*	119·1 *1877*	208·8 *1926*	297·2 *1932*	365·5 *1954*	413·8 *1954*
17·0 *1919*	21·8 *1953*	23·9 *1948*	28·7 *1952*	—	—	45·7 *1884*	119·6 *1930*	211·1 *1898*	297·9 *1916*	371·3 *1889*	415·5 *1889*
17·0 *1953*	22·6 *1918*	25·4 *1904*	29·2 *1953*	—	—	46·5 *1919*	120·7 *1926*	212·3 *1932*	298·5 *1889*	375·4 *1890*	416·7 *1916*
17·3 *1951†*	22·6 *1892*	25·9 *1879*	29·7 *1904‡*	—	—	46·5 *1926*	123·4 *1941*	212·9 *1878§*	299·7 *1954*	375·7 *1920*	418·3 *1931*

* also *1886* † also *1931* ‡ also *1948* § also *1889*

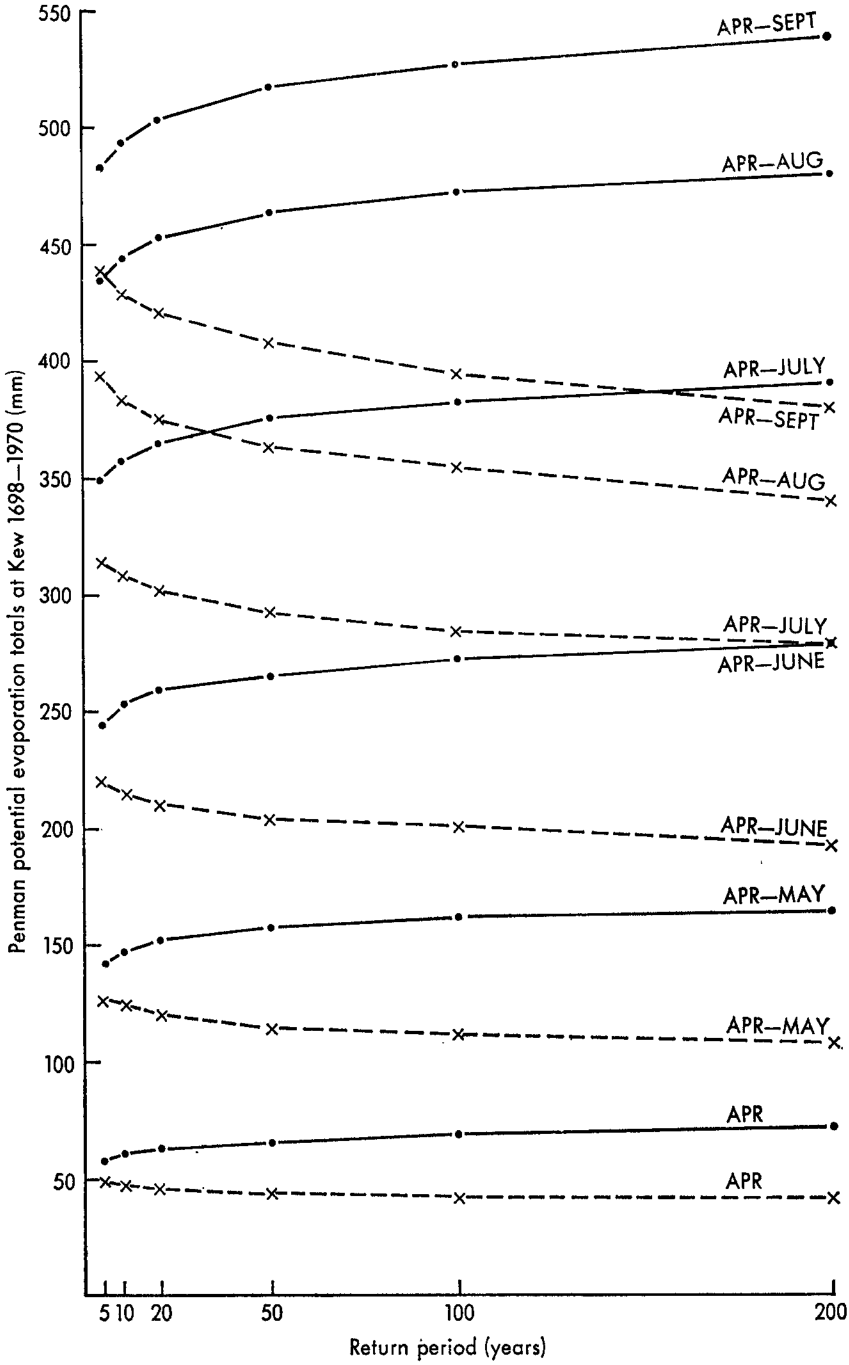

FIGURE 4—AMOUNTS OF POTENTIAL EVAPORATION AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

• —— • likely to occur or be exceeded × – – × likely not to be exceeded

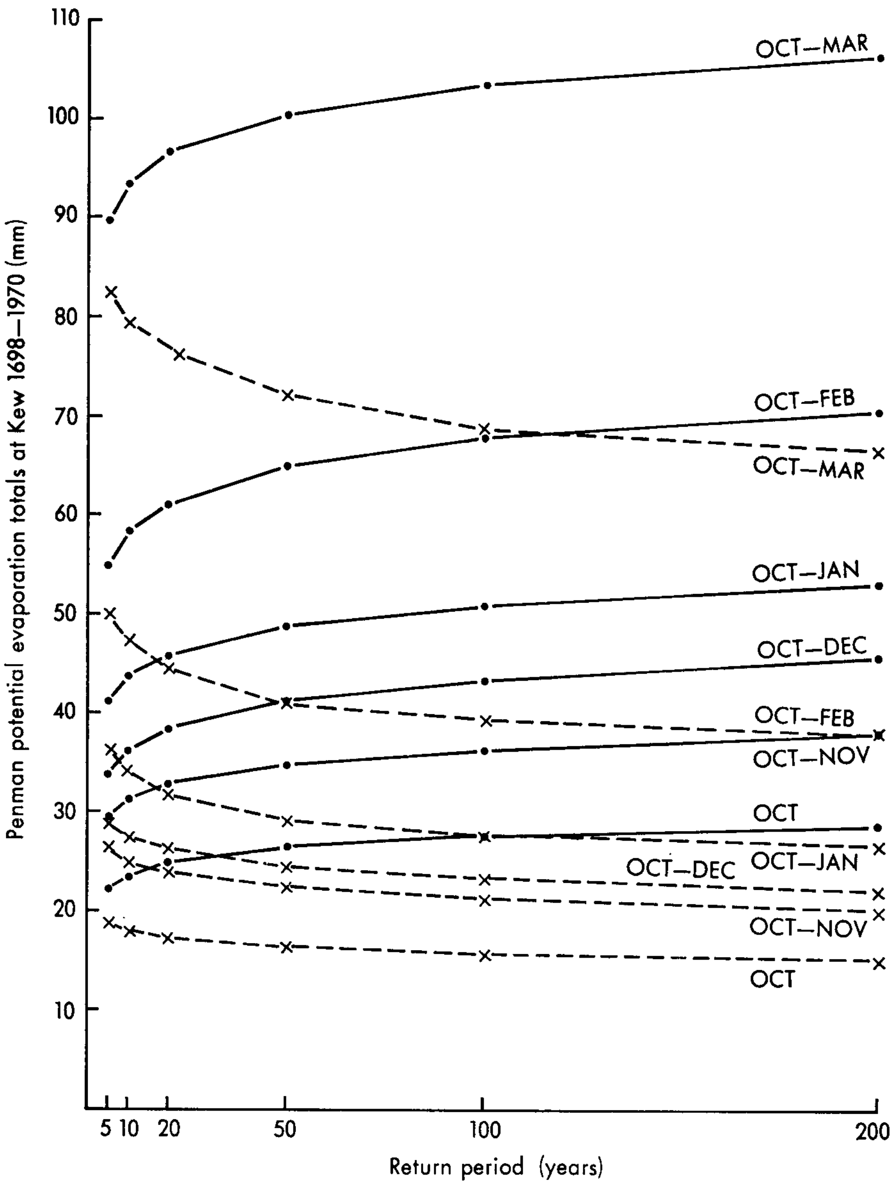

FIGURE 5—AMOUNTS OF POTENTIAL EVAPORATION AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

• —— • likely to occur or be exceeded × – – × likely not to be exceeded

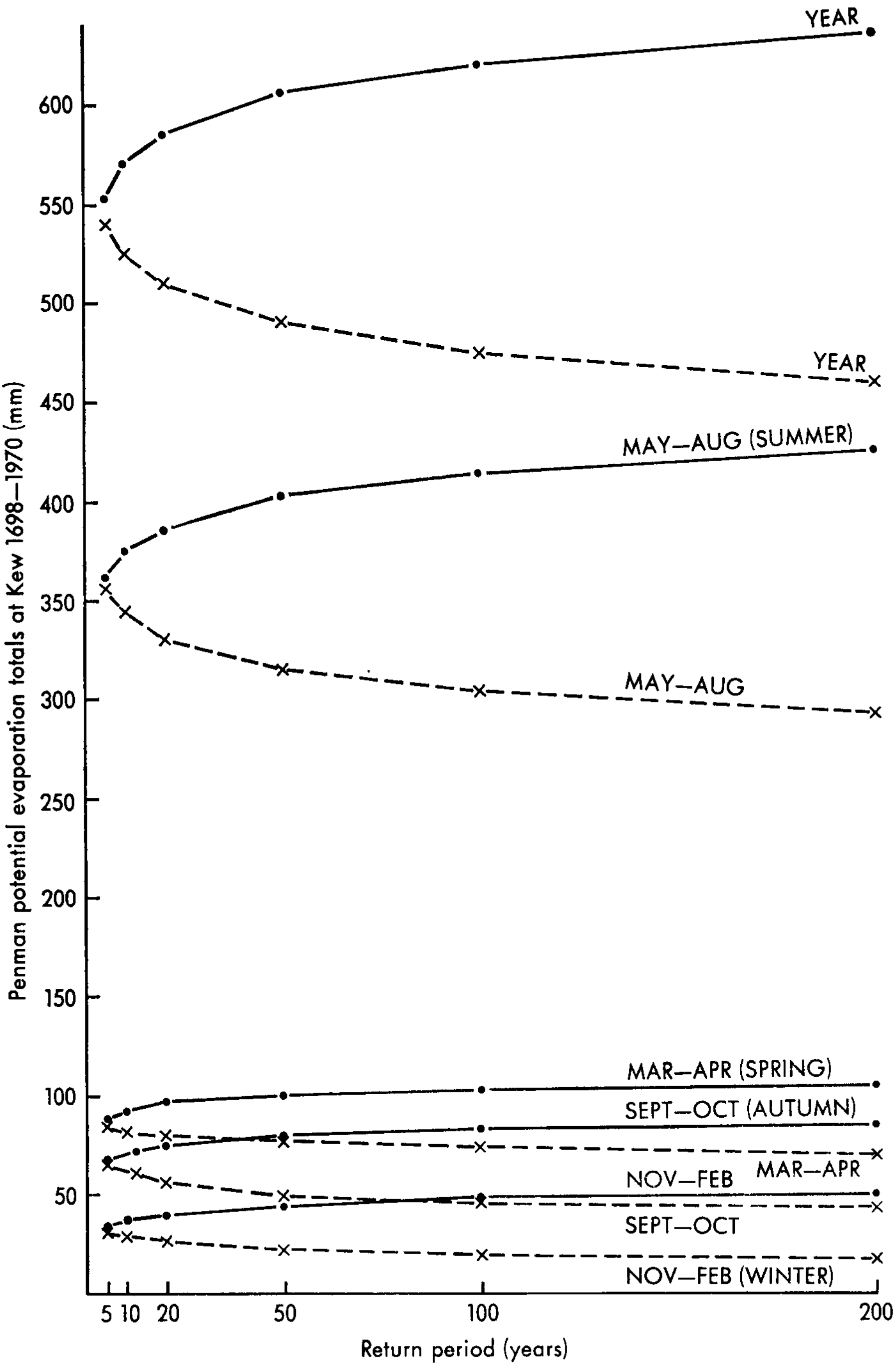

FIGURE 6—AMOUNTS OF POTENTIAL EVAPORATION AT KEW IN A YEAR AND IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

• —— • likely to occur or be exceeded × – – × likely not to be exceeded

TABLE IV—SIX MOST AND LEAST POTENTIALLY EVAPORATIVE SEASONS AND YEARS AT KEW, 1698–1970, WITH POTENTIAL EVAPORATION AMOUNTS (mm)

Spring (Mar.–Apr.)	Summer (May–Aug.)	Winter (Sept.–Oct.)	Autumn (Nov.–Feb.)	Year
		Most potentially evaporative		
107·2	437·9	98·8	53·9	657·9
1893	*1959*	*1959*	*1964*	*1959*
102·6	417·1	82·0	50·0	624·1
1967	*1911*	*1898*	*1884*	*1911*
102·4	409·5	81·3	46·5	614·4
1957	*1899*	*1970*	*1911*	*1957*
100·1	408·9	80·5	45·5	613·4
1942	*(1846)*	*1911*	*1912*	*1921*
99·1	406·1	79·5	44·5	605·8
1949	*1921*	*(1865)*	*1966*	*(1846)*
98·8	405·1	79·3	44·2	605·5
1948	*(1868)*	*1932*	*1961*	*1893*
		Least potentially evaporative		
70·6	282·7	54·4	18·0	438·9
1879	*1879*	*(1761)*	*1925*	*1879*
72·9	296·7	54·6	19·1	468·6
(1837)	*(1816)*	*1931*	*1952*	*(1816)*
73·9	306·3	55·4	19·8	479·0
1917	*1888*	*(1840)*	*1877*	*1888*
73·9	309·6	56·9	20·3	483·4
1919	*1954*	*1888*	*(1875)*	*(1817)*
75·2	310·4	57·1	20·3	486·2
1889	*(1817)*	*(1829)*	*1958*	*1889*
75·9	312·9	57·4	21·6	490·0
1918	*(1725)*	*(1836)*	*1948**	*(1812)*

* also *1951*
Year-dates to 1875 are shown in brackets (the estimates for 1698–1875 having been produced from limited data).

TABLE V—PERCENTAGES OF RARE POTENTIAL EVAPORATION EVENTS (LISTED IN TABLES II, III(a) AND IV) FALLING IN THE PERIODS 1698–1875 AND 1876–1970

		High values		Low values	
Duration of event		Percentage in 1698–1875	Percentage in 1876–1970	Percentage in 1698–1875	Percentage in 1876–1970
Calendar month	(Table II)	18	82	29	71
n-month periods (Oct. to Oct.–Mar., Apr. to Apr.–Sept.)	(Table III(a))	14	86	40	60
2- and 4-month 'seasons' and whole years	(Table IV)	13	87	40	60

7. FEATURES IN THE SERIES

Seasonal totals for 4- and 2-month periods and annual totals from 1701 to 1970 are combined into 10-year means in Figures 7 to 11. In Figures 7, 9 and 10 the highest and least totals in each decade, only, are also shown as unconnected points. In Figures 8 and 11 (summer and whole year) all ten totals are shown in each decade. Figure 7 (spring) contains little of interest and is included mainly for completeness. Figures 9 and 10 (autumn and winter) show little variation in decadal means except for the 1960–69 jump in winter mean. Extreme departures

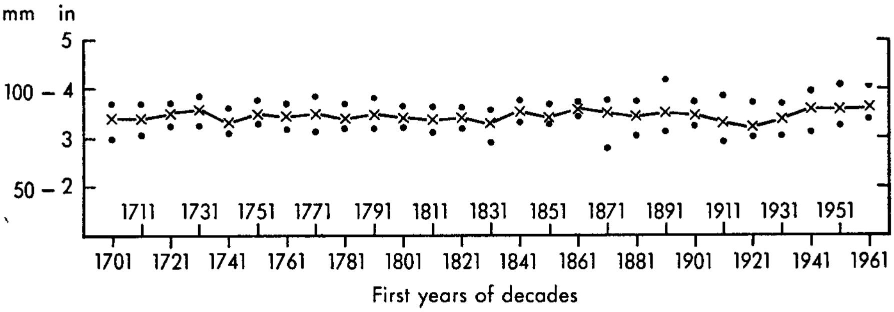

FIGURE 7—SPRING POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages : decadal extremes

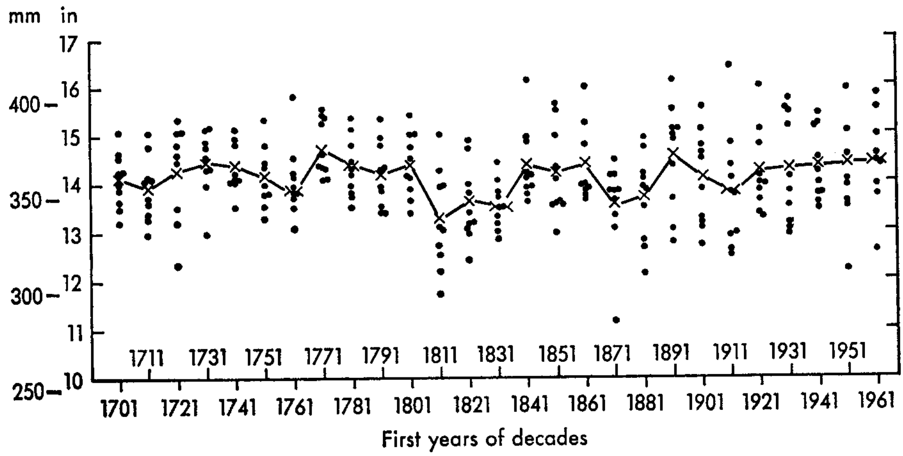

FIGURE 8—SUMMER POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages · summer totals

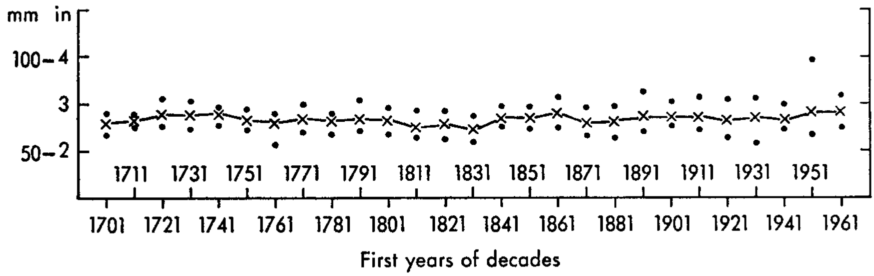

FIGURE 9—AUTUMN POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages : decadal extremes

TABLE VI—VARIATIONS FROM TABLES II, III(a) AND IV, RESULTING FROM THE ADDITION OF MONTHLY EVAPORATION ESTIMATES FOR THE YEARS 1971–76

The monthly, *n*-monthly and seasonal totals of potential evaporation for the period 1971–76 enter the top rankings as follows:

Monthly totals—most potentially evaporative—Table II

Month	Event Amount *mm*	Year	Rank
Jan.	14·7	1976	1
	12·2	1975	3
	10·7	1974	8
May	100·3	1976	2
June	120·4	1975	5
	118·9	1976	6
July	138·2	1976	1
Aug.	98·3	1975	5
	98·0	1976	6
Oct.	26·2	1972	5
Dec.	14·0	1974	1

n-monthly totals—most potentially evaporative—Table III(a)

Duration	Event Amount *mm*	Year	Rank	Duration	Event Amount *mm*	Year	Rank
Apr.–May	162·8	1976	4	Oct.	26·2	1972	5
Apr.–June	281·7	1976	2	Oct.–Nov.	34·5	1974	5
Apr.–July	419·9	1976	1	Oct.–Dec.	48·5	1974	11
Apr.–Aug.	517·9	1976	1	Oct.–Jan.	60·7	1974	1
	472·4	1975	4		48·5	1970	7
Apr.–Sept.	563·1	1976	2	Oct.–Feb.	73·7	1974	1
				Oct.–Mar.	102·9	1974	5

Seasonal totals—most potentially evaporative—Table IV

Duration	Event Amount *mm*	Year	Rank
Mar.–Apr.	100·3	1976	4
May–Aug.	455·4	1976	1
	416·3	1975	4
Nov.–Feb.	49·0	1975	3

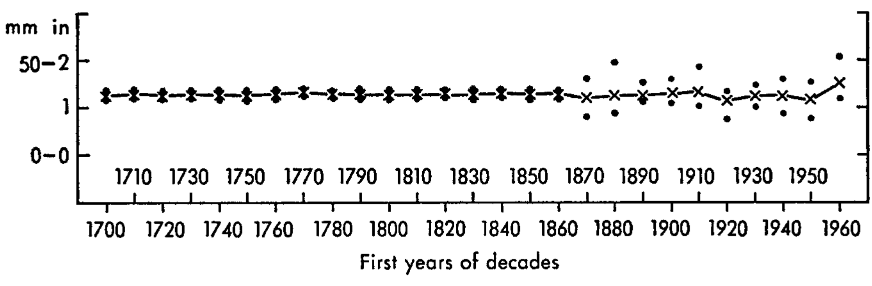

FIGURE 10—WINTER POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages : decadal extremes

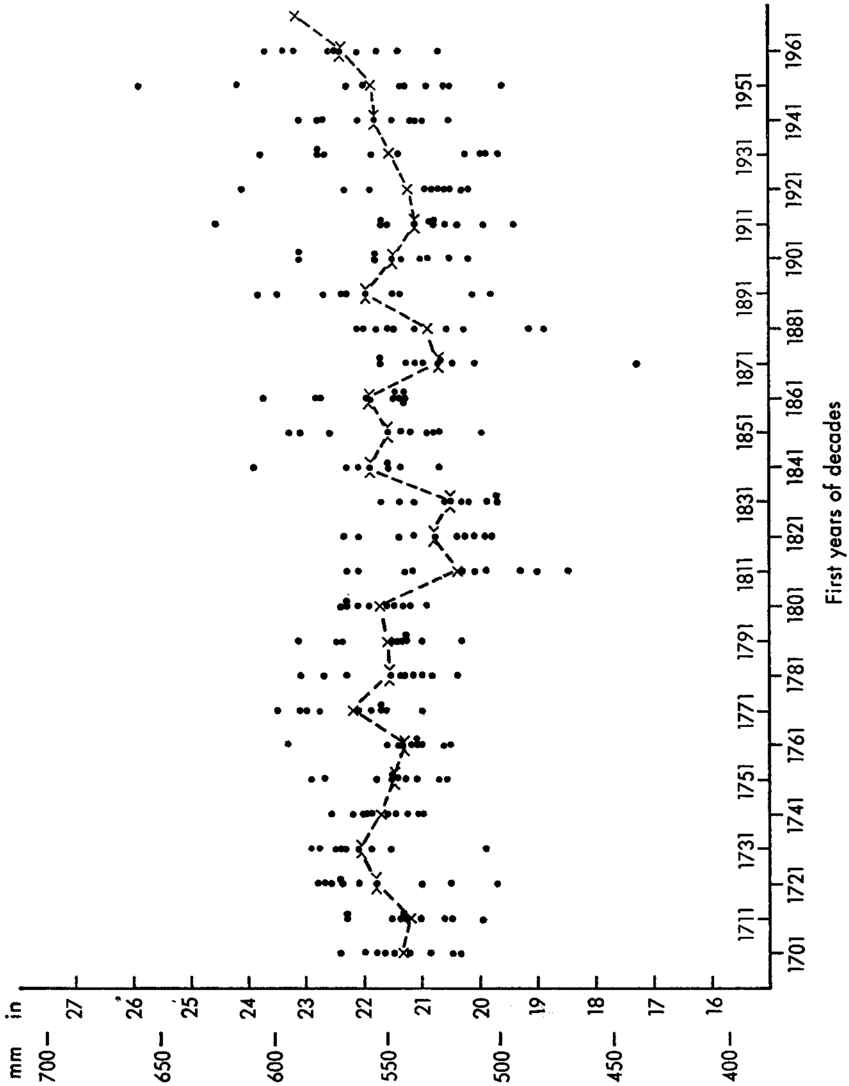

FIGURE 11—ANNUAL POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages · annual totals

from mean values are generally greater from the 1870/71 decade onwards, especially in winter. It is assumed that the decadal averages before and after 1871 are a reasonably homogeneous series. There have been two major 'troughs' in annual means (Figure 11) early and late in the 19th century and several gentle undulations. It is interesting to compare Figure 8 (summer potential evaporation) with Figure 8 of Wales-Smith (1973a) (summer rainfall). In most cases peaks of summer potential evaporation coincide with rainfall troughs and vice versa. The same general anti-phase relationship is also shown by the annual graphs (Figure 11). This result is in accordance with expectation on physical grounds, rain and cloudiness being associated with low potential evaporation and clear, dry weather with high potential evaporation. The sustained rise from the decade beginning in 1911 to that beginning in 1961 is interesting, especially the last decadal mean, the highest in the whole series. The latter part of this rise has been carefully examined as part of a separate study and found to be genuine. All the data used in the Penman calculations were carefully rechecked. Upward trends in average daily duration of bright sunshine and in average air temperature were found in several months and these accounted for the upward trend in Penman potential evaporation. As would be expected, mean potential evaporation in the period from May to August is the dominant component in the mean annual potential evaporation, and Figure 8 is, in effect, a damped version of Figure 11 having all the major features of the graph of decadal annual averages.

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A STATISTICAL STUDY OF THE LIKELY CAUSATIVE FACTORS IN THE CLIMATIC FLUCTUATIONS OF THE LAST 100 YEARS

By M. K. MILES and P. B. GILDERSLEEVES

SUMMARY

Time-series of carbon dioxide concentration, volcanic dust veil index, Wolf relative sunspot number, polar ice extent and zonal circulation index have been assembled for the period from 1870 to 1969. Multiple regression equations have been solved for the relation of various combinations of these series to hemispheric mean temperature.

Carbon dioxide and volcanic dust can together account for about 65 per cent of the variance of the hemispheric temperature. The inclusion of an ice index raises the total variance accounted for to over 80 per cent but leads to difficulties in interpretation. The development of a second approximation to the ice index enables some of these difficulties to be overcome. There is an indication that the varying strength of the circulation is also a significant factor.

INTRODUCTION

It is possible to find in the literature on climatic change claims that one or other factor has been primarily responsible for the climatic warming culminating in the early 1940s or for the cooling thereafter. Sometimes it is solar activity, sometimes volcanic dust, sometimes carbon dioxide, and, for the recent cooling, man-made dust.

These claims are usually based on a statistical relationship between the factor and temperature. The time-series of the various factors are, however, correlated among themselves and this complicates the issue of determining the 'causal' factor or factors.

We have therefore assembled time-series since 1870 of some possible causative factors and calculated multiple regression equations with northern hemisphere temperature for various combinations of the factors.

TIME-SERIES USED

Non-overlapping five year means for the time-series that we have used in this study are listed in Table I and some of them are shown in Figure 1.

The five year means of northern hemisphere temperatures are the mean of values read from the graphs published by Willett (1950), Budyko (1969) and Mitchell (1961). The carbon dioxide values are based on data published by Callendar (1958). The second series is a mean of these and the values given by Broecker (1975). The five year means of the dust veil index (DVI) were formed from the annual values given in Table 7(a) of Appendix II to Lamb (1970). The Wolf relative sunspot numbers up to 1960 are from Waldmeier (1961) and after 1960 they are taken from the monthly bulletins of the Swiss Federal Observatory, Zürich. The zonal index is based on grid-point surface pressure data as described by Miles (1977) and is for the latitude band 35–55°N. There are some gaps in the hemispheric data before 1900 and for the periods 1915–19, 1940–44 and 1945–49. These were filled by using values based on regression lines of hemispheric zonal index on (a) the pressure difference between Ponta Delgada and Stykkisholmur and (b) the zonal index for the Atlantic. The correlations on which these regression lines are based are +0·7 and +0·9 respectively.

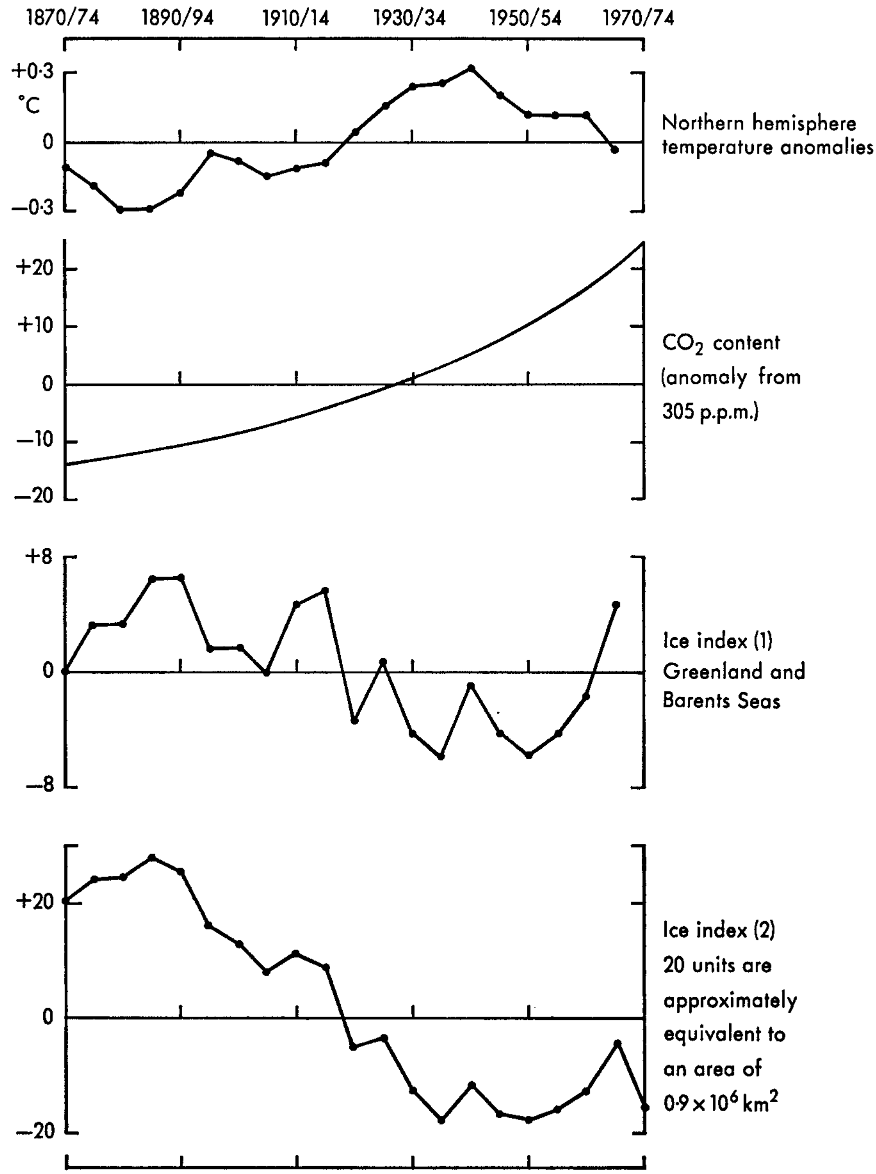

FIGURE 1(a)—FIVE YEAR MEANS OF QUANTITIES USED IN THE STUDY
Units are more fully explained in Table I.

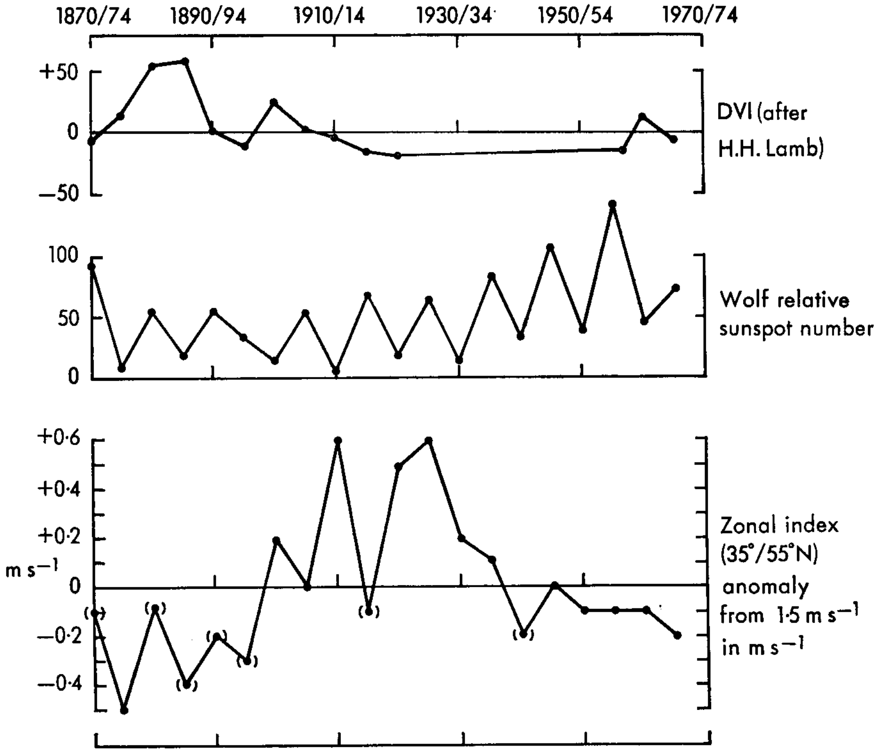

FIGURE 1(b)—FIVE YEAR MEANS OF QUANTITIES USED IN THE STUDY
Units are more fully explained in Table I.

The ice index is an attempt to represent the extent of Arctic Sea ice. It is based on work by Davis (1972) in which the ice coverage near the Iceland coast (as given by Koch (1945)) was placed in three categories—light, medium and severe. Additional data for the index were derived from a similar classification for the Barents Sea produced by Davis from data received from the Hydrometeorological Service of the USSR. The present index was formed by adding the values from these two classifications, calling light −1, medium 0 and severe +1. A year in which both were classified as severe would count +2 and a five year period made up of such years would have an index of +10. The five year means of such an index have a correlation of 0·75 with five year means of planimetric determinations of areal extent of ice in the summer half-year for the Greenland Sea between 1924 and 1968 made by Kirillov and Khromtsova (1972). The index thus appears to describe in a general way the variations in the Greenland Sea. From Sanderson (1975) it is apparent that the variations in the Greenland and Barents Seas mirror the total amount of ice in the north polar regions quite well. The index probably does not measure the full extent in the years at the end of the nineteenth century because 'severe' then probably implied more ice than it did in say 1915–19 or 1940–44 when there were a number of

TABLE I—FIVE YEAR MEAN VALUES OF THE TIME-SERIES USED

Time	Temperature °C	Carbon Dioxide (1)	Carbon Dioxide (2)	DVI	Wolf No.	Zonal index	Ice index (1)	Ice index (2)
1870–74	−0·10	−14	−14	−8	93	−0·1	0	+20
75–79	−0·18	−14	−13	+28	10	−0·5	+4	+24
80–84	−0·28	−13	−12	+108	55	−0·1	+4	+24
85–89	−0·28	−12	−11	+118	21	−0·4	+8	+28
90–94	−0·21	−11	−10	+2	56	−0·2	+8	+25
95–99	−0·05	−9	−9	−20	34	−0·3	+2	+16
1900–04	−0·08	−8	−8	+52	17	+0·2	+2	+13
05–09	−0·15	−6	−7	+4	55	0	0	+8
10–14	−0·11	−4	−6	−2	8	+0·6	+6	+11
15–19	−0·08	−2	−4	−28	70	−0·1	+7	+9
20–24	+0·05	0	−3	−32	20	+0·5	−4	−5
25–29	+0·15	+2	−1	−32	64	+0·6	+1	−3
30–34	+0·24	+5	+1	−32	17	+0·2	−5	−12
1935–39	+0·24	+8	+3	−32	86	+0·1	−7	−17
40–44	+0·32	+11	+6	−32	35	−0·2	−1	−11
45–49	+0·20	+13	+8	−32	110	0	−5	−15
50–54	+0·12	+16	+11	−32	42	−0·1	−7	−17
55–59	+0·12	+19	+14	−32	143	−0·1	−5	−15
60–64	+0·12	+23	+17	+24	49	−0·1	−2	−12
65–69	−0·03	+27	+21	−8	74	−0·2	+6	−4

Units of the various quantities are as follows:
Temperature: anomalies in °C.
Carbon Dioxide: anomalies in parts per million by volume from 305.
D(ust) V(eil) I(ndex): units as given by Lamb (1970)—anomalies from 32 units.
Wolf relative sunspot number: as defined by Waldmeier (1961).
Zonal index: anomalies in m s^{-1} from the 100 year average of 1·5 m s^{-1}.
Ice index: (1) arbitrary units—anomalies from 100 year average. In (2) 10 units ≈ 0·45 × 10^6 km^2.

years classified as severe. To overcome this defect the index was scaled in the following way to give the second index referred to as Ice index (2) in Table I. From satellite estimates of the ice edge in the Greenland and Barents Seas values for the change of area between the two five year periods 1966–70 and 1971–75 were obtained. They amounted to decreases of 0·2 × 10^6 km^2 for the Barents Sea and 0·25 × 10^6 km^2 for the Greenland Sea. By comparing this with the simple index Iceland/Barents Sea which was +4 for 1966–70 and −6 for 1971–75 we have an approximate equivalence of 10 units of index (1) to 0·45 × 10^6 km^2 for the combined area. With the lower value of Flohn's (1973) estimate of the change of Arctic ice between the 1880s and 1935–39 i.e. 2 × 10^6 km^2 the index for 1885–89 would need to be 45 units greater than that for 1935–39, compared with the difference of 15 in the simple index. To achieve this a cumulative addition of 3 units per five years was made to each five year value before 1935–39 back to 1885–89 and a constant value of 30 was added to the earliest three values. Values in Table I are anomalies from 100 year average.

MULTIPLE REGRESSION PROCEDURES USED

The multiple regression equations were evaluated by a biomedical data processing computer program for stepwise regression developed by the Health Sciences Computing Facility at the University of California, Los Angeles sponsored by N.I.H. Special Resources Grant RR-3.

The program (with revision date February 1976) enters the independent variables into the regression equation in a stepwise manner starting with the most significant. Significance at this stage is judged by the absolute value of the partial correlation coefficients of the variables to be entered.

At each step an analysis of variance is carried out and an '*F* value' or modified form of the variance ratio is calculated for each of those variables not entered in the regression equation. The variable whose *F* value is (a) greatest and (b) above a predetermined significance level—which can be set by the programmer, is entered into the equation in the next step. The value of *F* is designed so that only those variables enter the next step of the calculation that significantly increase the subsequent multiple correlation coefficient.

When all significant variables have been entered the program halts and a summary table is printed.

Analysis of results

The partial correlation coefficients of the individual series are shown in Table II.

TABLE II—PARTIAL CORRELATION COEFFICIENTS BETWEEN THE VARIOUS TIME-SERIES USED

	Temperature	CO_2 (1)	CO_2 (2)	DVI	Wolf No.
CO_2 (1)	0·70				
CO_2 (2)	0·66				
DVI	−0·72	−0·48	−0·44		
Wolf No.	0·26	0·41	0·41	−0·33	
Zonal index (no lead)	0·30	—	0·03	−0·33	−0·11
Zonal index (lead)	0·72	—	0·38	−0·45	0·09
Ice index (1)	−0·78	—	−0·47	0·53	−0·31
(2)	−0·91	—	−0·84	0·67	−0·37

We see that the factors most strongly correlated with hemispheric temperature (*T*) are also fairly strongly correlated with one another. So in the multiple regression equation they explain only a fraction of the variance that they would appear to be explaining when they are taken singly. The zonal index was used with a lead of 20 years because of the similarity of the profiles of temperature and zonal index when this displacement is made and because of an intuitive feeling that the strength of the westerlies is an important factor in determining the hemispheric temperature.

We will discuss the results for six combinations of the factors as set out in Table III.

TABLE III—COMBINATION OF FACTORS IN THE SIX RUNS

	CO_2 (1)	CO_2 (2)	DVI	Wolf No.	Zonal index No lead	Zonal index 20 year lead	Ice index (1)	Ice index (2)	Multiple correlation
1	✓		✓	✓					0·83
2		✓	✓	✓					0·82
3		✓	✓	✓			✓		0·90
4		✓	✓	✓	✓				0·82
5		✓	✓	✓		✓			0·80
6		✓	✓	✓				✓	0·94

The multiple regression equations obtained from each of the six runs are shown in Table IV.

TABLE IV—MULTIPLE REGRESSION EQUATIONS FOR THE SIX RUNS

1 $T = 0{\cdot}0064\ CO_2\ (1) - 0{\cdot}0020\ DVI - 0{\cdot}0081$ } Wolf No. coefficient is −0·0006 but
2 $T = 0{\cdot}0073\ CO_2\ (2) - 0{\cdot}0021\ DVI + 0{\cdot}0082$ } not significant in both runs 1 and 2
3 $T = 0{\cdot}0058\ CO_2\ (2) - 0{\cdot}0015\ DVI - 0{\cdot}0008$ Wolf No. −0·168 Ice index (1) +0·0564
4 $T = 0{\cdot}0073\ CO_2\ (2) - 0{\cdot}0021\ DVI + 0{\cdot}0080$ (Wolf No. and Zonal index not significant)
5 $T = 0{\cdot}0045\ CO_2\ (2) - 0{\cdot}0017\ DVI + 0{\cdot}0231$ Zonal index +0·0142 (Wolf No. coefficient is −0·0004 but not significant)
6 $T = 0{\cdot}0049\ CO_2\ (2) - 0{\cdot}0005\ DVI - 0{\cdot}0120$ Ice index (2) +0·0361

In runs 1 and 2 the Wolf number was not able to make a significant contribution after the other two factors had reduced the variance by over 65 per cent. In the third run it came in with a small negative coefficient though its partial correlation indicates a positive coefficient of 0·0013.

From equations (1) and (2) we deduce (a) that a doubling of CO_2 from 305 to 610 p.p.m. would give an increase in T of 1·95 and 2·23 K respectively, and (b) that the complete clearing of volcanic dust from the atmosphere between its peak value in 1885–89 and 1920–24 would give a warming of 0·30 and 0·32 K respectively.

However, in run 3 with the first approximation to an ice index included, the contributions of the other two principal factors are reduced to 1·77 K for a doubling of carbon dioxide and to 0·23 K for the warming due to the clearing of the dust. The ice contribution is +0·20 K to 1920–24 and +0·25 K to 1940. The first ice index is certainly incorrect in not having a sufficient downward trend from the 1880s to 1940 but it probably describes the fluctuations about a trend line fairly well. The increased multiple correlation coefficient in run 3 with ice index included probably arises because it explains some of the temperature fluctuations about the upward temperature trend not explained by the other two factors. Since the contributions of the other two factors have been reduced it would appear to be explaining some of the variance explained by them in runs 1 and 2. The conclusion which might be drawn is that if the effect of ice is not included explicitly the contributions attributed to the other factors are enhanced by the ice-albedo feedback effect.

The multiple regression equation from run 4 is practically identical to that from run 2 because the zonal index does not contribute significantly.

When the zonal index is entered with a lead of 20 years, i.e. in run 5, the contributions of the dust veil and the carbon dioxide are reduced—the latter by rather more than the former. The coefficient of the zonal index term indicates a rise of temperature of nearly 0·2 K between the low-index values of the nineteenth century and the peak values of the twentieth century.

When the second ice index is introduced in run 6 it explains the bulk of the variance on its own, depressing the contribution of dust to a quarter of the earlier values and actually changing the sign of the carbon dioxide contribution. The probable interpretation of this is that if, as Sellers (1969) suggests, the ice extent is proportional to the change in hemispheric temperature (produced by primary effects) then the ice extent could explain all the variance in the temperature distribution. Thus the contribution attributed to the ice index in a multiple regression equation could represent the sum of the primary effects plus the ice-albedo feedback effect. From equation (6) the contribution of the ice index between 1885–89 and 1935–39 comes to 0·54 K, which is just about the total warming in this period. This suggests that the second approximation to the ice index is quite a relevant one and represents the main primary effects magnified by the feedback effect. What estimates can be made of the size of this magnification? Using Budyko's (1969) expression for the change in planetary albedo due to a reduction in ice extent of 2×10^6 km^2 between latitudes 70 and 75°N we obtain a reduction in albedo of 0·5 per cent. This leads to a gain in absorbed radiation equivalent to an increase in solar constant of 0·21 per cent, and assuming the temperature response to an increase of 1 per cent in solar constant to lie between 0·8 and 1·2 K this indicates a warming of between 0·17 and 0·25 K, say 0·2 K due to the ice-albedo feedback. This implies that the primary effects up to 1940 amounted to 0·34 K which indicates a magnification of about 1·6 by the ice feedback. This estimate is admittedly rather rough but is near enough to the figure of 1·65 which can be deduced from Manabe and Wetherald's (1975) results for a general circulation model simulating an increase in solar constant to justify a tentative use of it. The results from runs 1, 2, 4 and 5 (i.e. those without ice index) will therefore be divided by 1·6 to give an estimate for the size of the various primary contributions. A summary of these results is given in Table V for various periods and chosen changes in the magnitudes of the chosen factors; the values in the last column are the estimates of the primary contributions.

TABLE V—TEMPERATURE CHANGES ASSOCIATED WITH VARIOUS FACTORS IN THE MULTIPLE REGRESSION EQUATIONS WITHOUT ICE INDEX

Factor	Change of factor	Temperature effect in kelvins including ice feedback	Temperature effect in kelvins without ice feedback
Carbon dioxide	(a) 305 p.p.m. i.e. 100% increase	+1·4 to 2·2	+0·9 to 1·4
	(b) 35 p.p.m. i.e. change in 100 years	+0·16 to 0·26	+0·10 to 0·16
	(c) 8 p.p.m. from 1885–89 to 1920–24	+0·04 to 0·06	+0·03 to 0·04
	(d) 14 p.p.m. from 1885–89 to 1935–39	+0·06 to 0·10	+0·04 to 0·06
DVI	Reduction of 150 units i.e. from 1885–89 to 1920–24	+0·26 to 0·32	+0·16 to 0·20
Wolf No.	Increase of 65 i.e. from 1885–89 to 1920–24	−0·05	−0·03
Zonal index with 20 year lead	Increase of 1 m s^{-1} i.e. from the end of 19th century to 1940	+0·23	+0·14

Thus the contribution to the warming of about 0·6 K up to 1940 could be 0·06 K due to carbon dioxide and 0·20 K due to clearance of the dust veil amplified to a total of nearly 0·4 K by the ice feedback, or 0·04 K from carbon dioxide, 0·16 K from dust veil and 0·14 K due to the effect of increasing circulation amplified by ice feedback to a total of 0·54 K. Any effect due to sunspot changes appears to be smaller than those due to the other factors. Without invoking some effect related to the circulation the peak of the warming and the subsequent cooling are underestimated. Figure 2 shows the predicted temperatures from equation (4) plotted against the actual temperatures. Only in run number 5 was any persistent cooling predicted after 1945—owing to the declining zonal circulation when introduced with a 20 year lag. It is of course possible that the dust veil index is not adequately representing the volcanic eruptions after 1950 but no alternative estimates have yet been published.

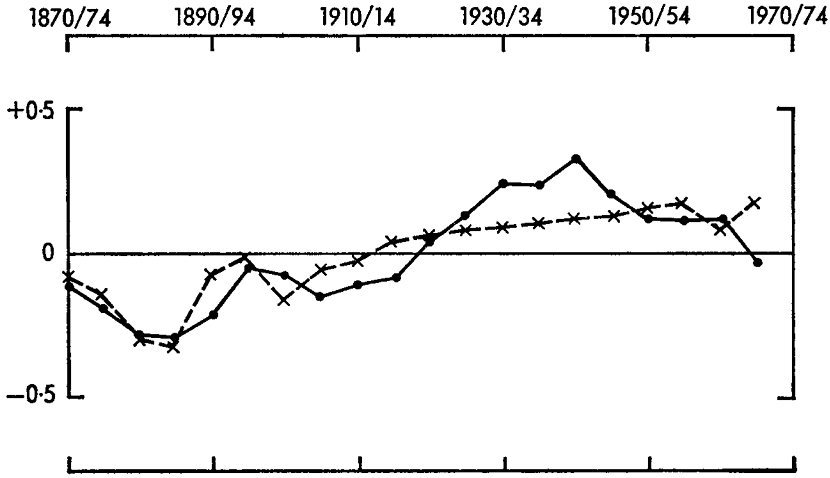

FIGURE 2—ACTUAL TEMPERATURE ANOMALIES AND VALUES PREDICTED FROM MULTIPLE REGRESSION EQUATIONS WITH ICE INDEX EXCLUDED

· —— · Actual northern hemisphere temperature anomaly
× – – × Predicted from multiple regression equation in run 4

Temperature anomalies are in °C.

It must of course be remembered that the correlations do not prove a causal connection of any of the factors with hemispheric temperature. They do, however, set some limits to speculation and their interpretation may indicate some fruitful lines of attack in this difficult subject.

CONCLUSIONS

About 65 per cent of the variance of the hemispheric temperature over the last 100 years can be explained by a multiple regression equation including only carbon dioxide concentration and volcanic dust veil index. The primary contributions to the warming up to 1940 are 0·06 K and 0·20 K respectively, magnified by the ice feedback effect to give a total of about 0·4 K.

It is possible that the enhanced westerly circulation in the first 30 years of the 20th century made a further contribution to the reduction of ice extent, thereby increasing the ice feedback effect from the 0·15 K suggested above to a figure nearer to, or even above, 0·2 K.

The sunspot changes typified by the Wolf number appear not to make a significant contribution despite a partial correlation coefficient with temperature of 0·26. The reason for this probably lies in the higher partial correlations that the Wolf number has with carbon dioxide and dust veil index.

As a by-product of the experiment an index for the polar pack ice extent was arrived at (entirely without reference to temperature) which appears to have a high degree of relevance to the hemispheric temperature changes.

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REVIEWS

Optics of the atmosphere—scattering by molecules and particles, by Earl J. McCartney. 225 mm × 150 mm, pp. xv + 408, *illus*. John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1976. Price: £19·20.

The science of atmospheric optics plays an important role in atmospheric physics through the support it provides to other fields such as meteorology and remote sensing of planetary atmospheres. Many scientists' knowledge of the subject does not extend beyond the empirical formulae that they occasionally use in simple calculations. At the other extreme atmospheric physicists perform repeated mathematical gyrations with the complex equations that are generated when providing a complete description of the physical processes. Dr McCartney has tried to provide a fresh description of the problem, removing the over-sophistication and personalized treatments that have pervaded the literature in recent years. This book is written in a clear style that will make it a valuable text for both the specialist and the non-specialist.

The book is divided into six comprehensive chapters supplemented by several appendices. Chapter 1 gives an adequate review of atmospheric scattering and the common nomenclature and definitions. The chapter concludes with an interesting section on the literature of atmospheric optics which includes a table listing the topics covered in about 25 books devoted to this subject.

Chapter 2 is concerned with the structure and composition of the gaseous atmosphere and includes a brief discussion of the kinetic theory of gases. The third chapter describes the physical nature, size distribution and vertical distribution of particles in the atmosphere. An entire chapter is devoted to Rayleigh scattering and includes a historical account of molecular scattering theory. The discussion also includes a simple physical model for the phenomenon and a derivation from first principles of the relevant formulae. All these chapters are both elementary and reasonably complete in their content.

The final two chapters are concerned with Mie scattering by monodispersions (single particles) and polydispersions respectively. One deficiency is the absence of physical explanations of the features appearing in the computed results for scattering of light by spheres. Furthermore, some of the interesting aspects of atmospheric optics, such as haloes, rainbows and glories are not discussed. In addition to their aesthetic appeal these features are important in the remote sensing of planetary cloud layers, such as in the atmosphere of Venus.

I found the book very readable, and the subject matter presented in a style that will be valuable for both the specialist and non-specialist. I certainly recommend it as a useful addition to an atmospheric physics library.

G. E. HUNT

Climates of the Soviet Union, World Survey of Climatology, Volume 7, by Paul E. Lydolph. 300 mm × 210 mm, pp. xii + 443, *illus*. Elsevier Scientific Publishing Co., PO Box 330, Amsterdam, The Netherlands, 1977. Price: $81·75.

This book by Professor Lydolph is a major work in English on the climates of the Soviet Union. While a large amount of Soviet climatological research is published, modern works on the general climatology of the USSR are rare. Up to now, students of the climatology of the Soviet Union have had to make use of *Climates of the USSR*, by Borisov (1965), a translation of a work in Russian. This particular book by Lydolph is interesting from a number of points of view. The author is an American and is Professor of Geography at the University of Wisconsin in Milwaukee, so the primary language of the book is English; it is not a translation from Russian. This is an advantage, since Russian climatological works often lose clarity in translation, especially when the translator is not a meteorologist. The book represents the results of nine years of research by Professor Lydolph and his students, during which time the author made extensive use of material supplied by Soviet meteorologists. The author is a trained meteorologist and also an expert on Russian area studies, which makes him extremely well qualified to write this book. Indeed, the publishers claim that this is the first compendium on the climate of the Soviet Union ever to be written outside that country.

The book starts with a general analysis of climatic controls over the USSR. The author comments that Soviet climatologists contend that the only primary controls of climate are solar radiation and the nature of the surface underlying the atmosphere. Lydolph takes the view that since during winter over much of the Soviet Union the net radiation is negative, the air is losing heat to the ground and therefore the influences of the surface upon the air are minimal and do not differ significantly from one place to another. Similarly, in summer he considers that day-to-day weather occurrences in the Soviet Union are probably more the result of atmospheric circulation than anything else. Therefore, Lydolph's discussion of the causes of climate centre largely on atmospheric circulation patterns and synoptic situations. Discussions of radiation distributions and energy exchanges do not form part of his introduction to the climatology of the USSR.

The major part of the book is concerned with descriptions of the climates of various regions of the USSR. The division into regions is based on common circulation features and atmospheric dynamics. Thus the broad plain of European USSR and western Siberia is taken as one region because the same circulation features generally affect the entire area. A substantial use is made of synoptic situations and weather types in the climatic descriptions of the regional chapters. This approach to regional climatology is a stimulating one, and is far removed from the dry statistics of the climatology books of 50 years ago.

Lydolph comments that the USSR in general lacks heat and, where heat becomes adequate, it lacks moisture. Thus Soviet meteorologists have carried out extensive investigations on heat and water balances, and these are reflected in the book. Chapter 8 on the Thermal Factors produces detailed maps of global radiation, albedo, radiation balance etc. during the various seasons. These are followed by maps on latent and turbulent heat exchange and advection, and various maps of temperature characteristics. Chapter 9 on the Moisture Factor includes maps showing moisture flux, vapour pressure, cloud, rainfall, snowfall etc. The book ends with 120 tables of climatic data for the USSR. Extensive references are given, mostly in Russian.

A volume of this type must be judged by the picture it gives of the climate of the USSR. The picture is on the whole good, though there are some large gaps. Drought is hardly mentioned, though it must be of great importance in the agricultural regions of the country. Another important field that is neglected is that of climatic change. It would be interesting to know if the steppe and semi-arid regions are becoming drier, or the arctic warmer. The book is strongly recommended for students of the climatology and geography of the USSR. It forms an excellent addition to the Elsevier series 'World Survey of Climatology'.

J. G. LOCKWOOD

Light scattering in planetary atmospheres, by V. V. Sobolev (translated from the Russian by W. M. Irvine). 260 mm × 180 mm, pp. xvii + 256, *illus.* Pergamon Press Ltd, Headington Hill Hall, Oxford OX3 0BW, 1975. Price: $25·00.

The problem of interpreting the radiation scattered by a planetary atmosphere to derive the composition and structure of the atmosphere and clouds forms one of the fundamental problems in planetary physics. Professor Sobolev and his collaborators at the University of Leningrad, USSR, have studied this type of problem for many years and have developed their own classical mathematical approach. The Russian school are disciples of the school of analytical mathematical representation which, for the special conditions of multiple scattering of radiation according to simple anisotropic scattering laws in homogeneous atmospheres, enables the problems to be reduced to a generalized set of functions. This approach was originally developed by Ambartsunyan, Sobolev and Chandrasekhar, while in recent years Sobolev's group have contributed to the extension of this method for more general anisotropic scattering laws. The test therefore serves as a useful reference for the analytical methods of radiative transfer, and the procedures adopted by the Sobolev school in particular. The book is further enhanced by the excellent translation by Professor Irvine, who has also provided useful additional explanatory information and illustrative material to augment the content of the original Russian publication.

The book is divided into 11 chapters supplemented by some useful appendices. Chapter 1 provides an adequate discussion of the basic definitions and equations, while Chapters 2, 3, 4 and 7 are concerned principally with methods of deriving the diffuse reflection and transmission of a plane-parallel atmosphere. In Chapters 5 and 6 the more general problem of determining the internal radiation field is discussed.

To my mind Chapter 8, in principle, should be the most important section of the book since it is concerned with approximate methods for multiple-scattering theory. Regrettably, the problem is dismissed in a mere 20 pages, with no reference to the results that may be obtained by the more flexible, and consequently more time-consuming numerical techniques. Without this comparison we have no evidence to determine the value of these simplistic methods.

Chapter 9 provides an adequate discussion of the transformation of the predicted intensity to a distribution of brightness over a planetary disc at a given phase angle. The application of these methods to remote sensing of planetary atmospheres is disappointingly brief and sketchy. There has been a considerable amount of work performed with these analytical techniques by the group led by Professor Teifel' at Alma Ata, USSR, whose work receives little discussion beyond a polite reference. Surely there is adequate room to discuss this important work and thereby broaden the text from being mainly a description of the personal research activities of the Sobolev group. The final chapter is concerned with the effects of atmospheric curvature and provides an introduction to problems of multiple scattering in spherical atmospheres.

There is no doubt that this book contains a great deal of valuable information for students of radiative transfer theory. However, I firmly believe that texts devoted to analytical methods would be more valuable if they provided a detailed discussion of, and comparison with, numerical methods, which in my opinion are far more suitable for studying multiple-scattering problems. In spite of these personal reservations, I am sure this book will be useful to the radiative transfer specialist.

G. E. HUNT

Tree rings and climate, by H. C. Fritts. 240 mm × 150 mm, pp. xii + 567, *illus*. Academic Press Inc. (London) Ltd, 24–28 Oval Road, London NW1 7DX, 1977. Price: £16.

The first impression left by this book is that is should be compulsory reading for anyone intending to work on, or to express an opinion on, the relationships between tree rings and climate. It is so thorough and raises so many points that are usually overlooked. After a historical and descriptive first chapter, the author gives three chapters on the growth and structure of trees, and their biological response to variations in temperature and rainfall and to non-climatic influences such as fires, or competition for light within a wood. The next chapter deals with observation and measurement, and the simpler statistical techniques. The remaining chapters cover more advanced statistical methods for estimating from tree ring data the climatic conditions either at a point, or over a large part of the earth's surface. The latter rely largely on principal component analysis or related techniques applied either to climatic data or to tree ring measurements made at widely separated sites.

Trees which are subject to climatic stress provide the most information, and scientists in North America have both the range of climates capable of producing such stress, and the resources to send expeditions to collect evidence from remote and inhospitable sites. The question arises whether techniques developed under these conditions can be applied so readily in Europe, and in any case there is a limit to the information which can be extracted from indirect measurements. Indeed, the author remarks at one point 'The tree ring chronologies which are integrated records of climate over an entire year simply did not have sufficient information in their differences to reconstruct the monthly climatic data'. Nevertheless, tree ring data may suffice to reconstruct broader climatic features, if not monthly data, and if this account reveals the extent of the painstaking research carried out by the author, his colleagues and predecessors, it offers the promise that similar work carried out elsewhere will not be in vain.

The book is well produced, a little verbose perhaps, but nevertheless strongly recommended. How long must we wait for a companion column of equal authority on tree rings and climate in the European area?

J. M. CRADDOCK

FRANK HENRY LUDLAM, D.Sc., D.I.C.

It is with great regret that we record the death on 3 June 1977 of Professor F. H. Ludlam of the Atmospheric Physics Group, Imperial College of Science and Technology, London. Although most of Professor Ludlam's working life had been spent at Imperial College, his professional career began in 1938 when he joined the Meteorological Office at the age of 18 as an Assistant III. He served throughout the war, becoming a forecaster and rising to the rank of Temporary Flight Lieutenant in the Royal Air Force Volunteer Reserve. On demobilization in 1947 he was assimilated as an Experimental Officer and was posted to the Forecasting Division at Dunstable. His great enthusiasm and feel for atmospheric science soon became apparent and in 1948 he was regraded as a Scientific Officer.

For several years he had been making detailed observations of ice clouds and thinking deeply about the physics of their formation. On the basis of his paper 'The forms of ice-clouds' published in the *Quarterly Journal of the Royal Meteorological Society* in 1948, he was awarded a Leverhulme research grant and given a two-year leave of absence from the Office to study in the Department of Meteorology, Imperial College, under the late Sir David Brunt. In 1951 he resigned from the Office to become a lecturer at Imperial College. There followed several highly productive years in which he collaborated closely with B. J. Mason and R. S. Scorer and supervised such outstanding students as K. A. Browning and W. C. Macklin. His researches on the structure of cumulus, cumulonimbus and hail storms and the initiation of showers by both the coalescence and ice-crystal mechanisms gained him a high international reputation. This was recognized by the University of London in the award of a D.Sc. degree in 1960 and a personal professorship in 1966.

Frank Ludlam was essentially a naturalist and an artist with a deep insight and intuitive understanding of what he observed and recorded. He had little sympathy with big research teams and facilities—'the scientific juggernaut', as he would say. He felt intimidated by the advent of modern technology with its computers, satellites etc. and modern methods of data acquisition and processing. He also had little use for computer models; his best work was done with slide rule and graph paper with an intuitive feel for the magnitude of the forces at work. Nevertheless scientists who did not share his views would come to seek his opinions and be stimulated and refreshed by his iconoclastic views.

Despite a long and progressive illness he retained his interest in and love for meteorology until the end. Frank Ludlam was a rare spirit who will be greatly missed by all who knew him. We may not see his like again.

B. J. MASON

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