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A spectral and filter analysis of long-period rainfall records in England and Wales

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Summary

Four long-period rainfall records in England and Wales have been subjected to maximum entropy spectral analysis in order to identify any regular periodicities which may be present. Unitary filters were used as a coarse form of spectral analysis in support of the maximum entropy technique, and the series were filtered to examine the temporal variations in the amplitudes of some of the periodicities. A wide range of seasons and epochs was examined, and although some regular periodicities were evident, random fluctuations were dominant. Cycles that could be regarded as permanent were located at 2·1 and 2·4 years, of which the latter, associated with the summer half-year, was the most important. Cycles that were less prominent, but which attained 5 per cent significance over the complete length of all the series examined, were found at periods of 3·9, 5, and 6 years.

1. Introduction

Major searches for periodicities in meteororological data were carried out in the 1920s and 1930s, a notable investigation being due to Brunt (1927). Later the search for cyclic behaviour fell from favour, but the advent of computer techniques renewed interest, and Ward and Shapiro (1961) made power spectral analyses of a wide variety of meteorological parameters on a world-wide basis. A general review of investigations into cyclic behaviour in the atmosphere is provided by Lamb (1972), but the majority of studies have dealt with temperature or pressure. Recently, the well-known rainfall record for England and Wales has been augmented by three homogeneous series representative of particular sites in England. In addition, the last 20 years or so have seen rapid developments in the field of power spectral analysis, with the latest techniques providing much finer resolution than the earlier methods. In the search for periodicities in rainfall in this paper, therefore, the latest techniques of spectral analysis are combined with the long-period rainfall series which have only recently been published.

In this paper the complete lengths of the four rainfall series are spectrally analysed and the significant spectral peaks are tabulated for a number of seasons. The analysis was repeated on component 80 year epochs of the series to determine the degree of permanence of the spectral peaks. A quasi-orthogonal unitary filter analysis applied to the complete records was used as a coarse form of spectral analysis in support of the maximum entropy technique, while filtered time series were used to examine in more detail the amplitude of some of the periodicities found.

2. Data

The four series of monthly rainfall totals analysed were

(i) England and Wales from 1727, first compiled by Nicholas and Glasspoole (1932) and since maintained by the Meteorological Office.

(ii) Kew from 1697, first prepared by Wales-Smith (1971) and revised in 1978.

(iii) Pode Hole, Lincolnshire, from 1726, assembled by Craddock and Wales-Smith (1977).

(iv) Manchester from 1786, published by Manley (1973) and revised in 1976.

Decadal means of annual rainfall for the four series are presented in Figure 1. The two main features of interest are the rise in the totals for England and Wales, most of which occurred before 1820, and the convex nature of the graph for Pode Hole, with low values in the early eighteenth century and high totals in the first half of the nineteenth century. These features contrast with the relative absence of long-period trends at Manchester and Kew. However, the relatively large changes in rainfall indicated by the series for Pode Hole and England and Wales may not be real. The first 40 years of the England and Wales series are based mostly on data from only two or three stations with unorthodox sites by modern standards. During the next 60 years the number of stations used was only about 10, and they are not evenly distributed over the country. From 1820 onwards, the number of stations was sufficient to enable a mapping technique to be used to derive the areal rainfall, and thus it is only from this date that the England and Wales series can be regarded as reliable. The compilation of the series for Pode Hole, a rural site, was inevitably based on less evidence than the series for Kew and Manchester, yet both the latter have been subject to revision. It may well be that the Pode Hole series will require revision in future, with the probability that the large fluctuation in decadal rainfall in the present record will be diminished.

The uncertainty attached to the values accorded to the earlier portions of the records casts doubt on the reality of trends or long-period cycles in the data. Fluctuations of shorter periods will be less affected, however, and cycles of wavelengths less than about 25 years may be regarded as being relatively undistorted.

3. Spectral techniques used

3.1 *Brief survey of methods of spectral analysis.* When a series of observations is transformed from the time to the frequency domain, and the square of the amplitude (i.e. power) is plotted against frequency, the result is known as a power spectrum. The area under the curve in a power spectrum is proportional to the variance. A good account of spectral analysis in general is provided by Bath (1974). The transformation from the time to the frequency domain may be made by taking the Fourier transform of the time series (direct method) or of the autocorrelation function of the series (indirect method).

In the pre-computer era, harmonic analysis (the direct approach) was used, and the results were usually displayed as a plot of amplitude against frequency (the periodogram). Later, Blackman and Tukey (1959) developed a method for computers based on the indirect approach, but Cooley and Tukey (1965) then derived the Fast Fourier Transform (FFT). This is essentially the direct method, but the ordinary 'direct' formulae are replaced by more computationally efficient ones. These methods are efficient when operating only on M^n data points where M can equal 2, 3, 4, ... In practice, therefore, the series is often truncated or extended at both ends with mean values until the number of points equals a multiple of M.

Jenkinson (1977) has described a direct method which produces a quasi-continuous form of the periodogram. The increase in resolution obtained is especially pronounced at long wavelengths because the frequency elements are chosen to be logarithmically spaced.

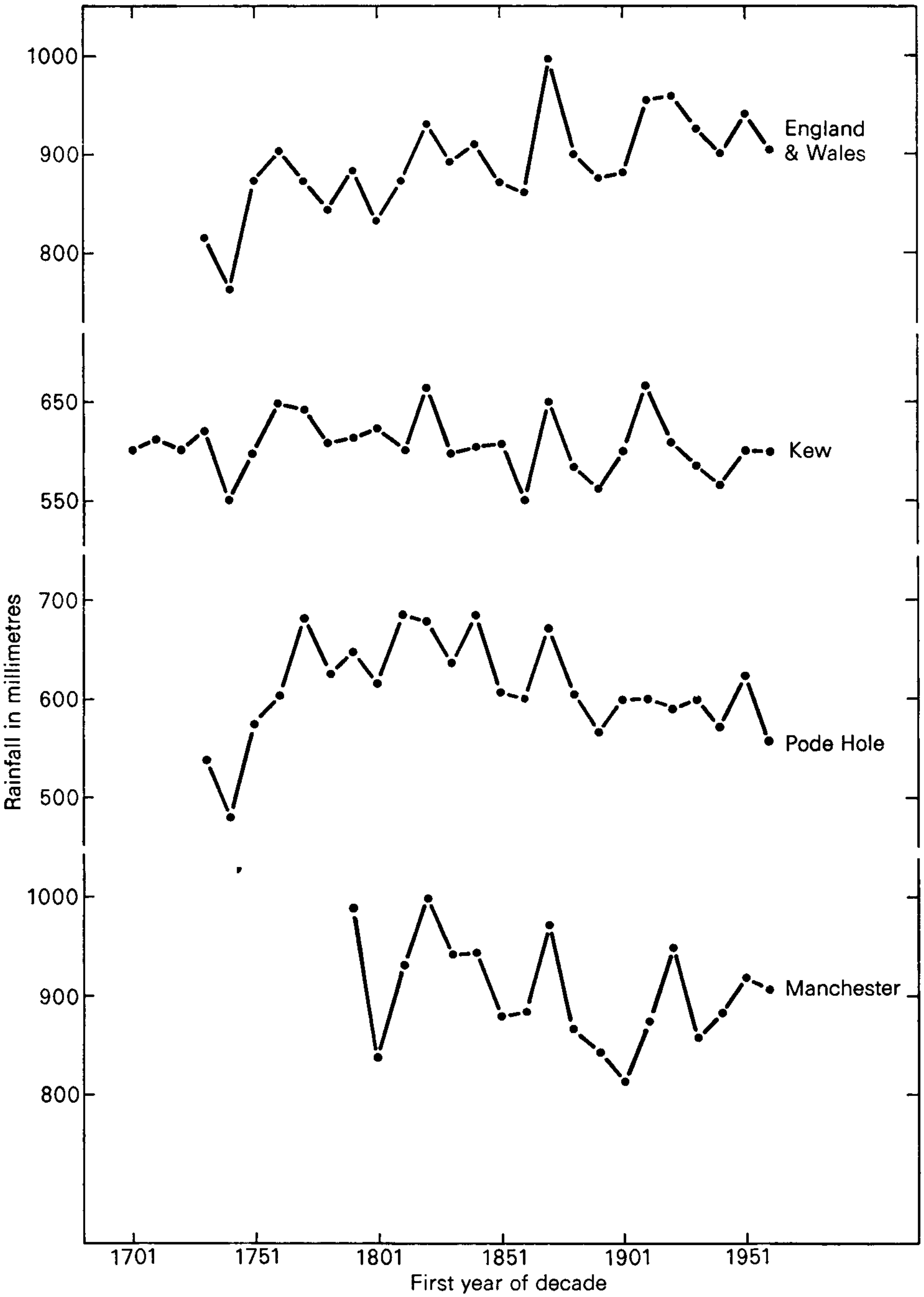

Figure 1. Decadal means of annual rainfall.

The maximum entropy method, first suggested by Burg (1967), is described by Lacoss (1971) and Ulrych and Bishop (1975). It is an indirect method, based on the transformation of an autoregressive process which neither adds information to nor subtracts information from the data (the concept of maximum entropy). The resulting extension of the original data series means that the method is capable of much higher resolution than the earlier methods.

In this paper a maximum entropy package due to Ross (1975) has been used.

3.2 *Calculation of variance and significance of spectral peaks.* Spectral peaks have arbitrarily been taken to lie between those frequencies where the power is one-third of its peak value. The variance attributed to a given peak has therefore been limited to the area contained between the one-third power points, as illustrated in Figure 2.

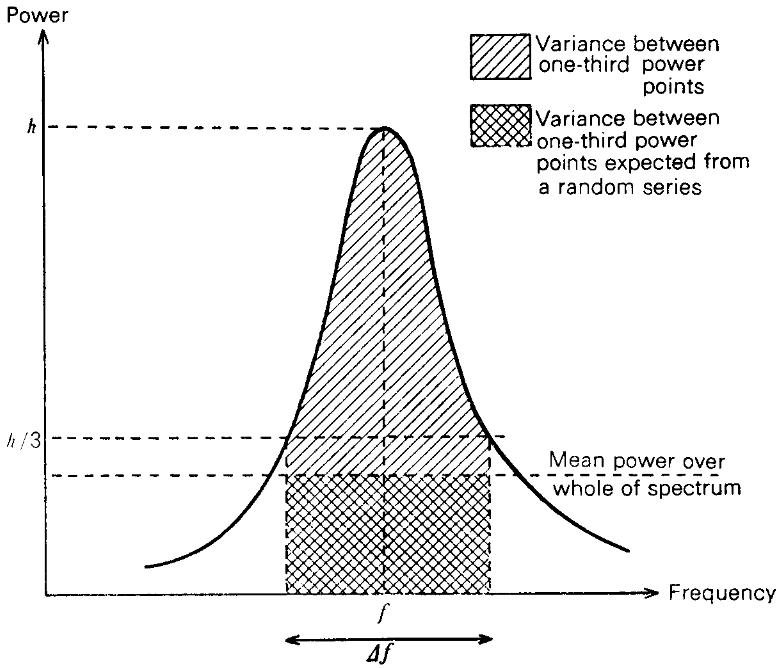

Figure 2. Definition of spectral peak by one-third power points.

The estimation of the statistical significance of a peak is based on the variance ratio, that is to say the ratio of the variance observed to that expected from a random series. If the width of the peak defined by the one-third power points is Δf, the mean power over the frequency range Δf is h_p, and the mean power over the whole of the spectrum is h_A, then the variance ratio R is given by h_p/h_A. As serial correlation was absent in the rainfall data examined, the number of degrees of freedom associated with the frequency range 0 to 0.5 was set at N, the number of data points in the original series. The degrees of freedom were assumed to be uniformly distributed in frequency space, so the number attributed to the frequency range Δf was taken as $n = N \times \Delta f/0.5$. The significance of a peak was estimated from statistical tables of Snedecor's F distribution using the variance ratio R and the number of degrees of freedom N and n.

There are two important criticisms of the procedure described above. The first is that the use of the F test to assess the significance of the variance ratio R applies only when the frequency range Δf is arbitrarily defined as, for example, when the frequency range 0 to 0.5 is divided into M equal parts. By choosing the width and central frequency of Δf to suit the peak under examination, a systematic over-estimation of significance results. In this paper, however, the significance of a given peak relative to another is just as important as its absolute value, and the procedure described above leads to more accurate values of this than if the spectral peaks had been assessed over arbitrarily pre-defined frequency ranges.

The second criticism relates to the uncertainty in the number of degrees of freedom when $N \times \Delta f/0.5$ is close to unity. This uncertainty only applies to narrow peaks for which Δf is small, however, and in most cases dealt with in this paper the estimate of $N \times \Delta f/0.5$ will be reasonable.

3.3 *Comparison between maximum entropy and other methods of spectral analysis.* The maximum entropy method of spectral analysis is not universally accepted, and so it is pertinent to make comparisons with other methods, such as the FFT and Jenkinson periodogram. In the maximum entropy method the number of autoregressive coefficients used to extend the data has to be chosen by the user, and this is perhaps the most frequent criticism of the technique. The number of coefficients determines the resolution or 'spikiness' of the spectrum. A small number of coefficients produces a highly smoothed estimate but the resolution becomes finer as the number of coefficients is increased, as illustrated in Figure 3. With other methods the resolution of a spectrum increases with the number of data points N, and is fixed for a given length of input data. Akaike (1970) suggested that the number of coefficients to be used in the maximum entropy method should be such that any further increase would produce a reduction in variance that is not statistically significant. This is of little value, as it determines the length of the auto-regressive series from a measure of its predictive power. A much greater length may be needed to display periodicities of scientific interest which may not have much predictive power. A practical solution is to use $N/3$ coefficients for N less than 100, and then to use a decreasing fraction of N as N increases beyond 100.

The significant spectral peaks obtained from an analysis of annual rainfall at Kew from 1697 to 1975 are presented in Table I. The results are obtained from the FFT, Jenkinson periodogram, and the maximum entropy method using 25, 40, 60 and 100 coefficients. The variances and significances were obtained using the procedures described in section 3.2, and only peaks which were significant at 5 per cent or better have been entered in the table.

Considering first the results of the maximum entropy method, the number of peaks produced in each spectrum was about 40 per cent of the number of coefficients used (see Figure 3). Thus, as the number of coefficients and the number of peaks increases, the proportion of the variance accounted for by each peak decreases. In contrast, the estimated significance of a given peak increases with the number of coefficients. This fact, combined with the greater number of peaks produced for the larger number of coefficients, means that the number of significant peaks produced increases rapidly with the number of coefficients. Thus a tabulation of the significant spectral peaks derived from a maximum entropy spectral analysis is highly dependent on the number of coefficients used. A large number of coefficients produces a relatively large number of significant peaks each of which accounts for only a small proportion of the variance, while a small number of coefficients produces a relatively small number of significant peaks each of which accounts for a more substantial portion of the variance. Despite this variation in the absolute values of the variances and significances associated with a given fluctuation, the relative importance of the peaks is independent of the number of coefficients. In the analysis of long-period records which follows, the maximum entropy method has been used with 26 coefficients for 80 year epochs, 60 coefficients over the complete length of record (about 250 points) and 100 coefficients for the complete records divided into three month seasons (about 1000 points). In all cases, the linear trend was removed from the data before the power spectra were produced.

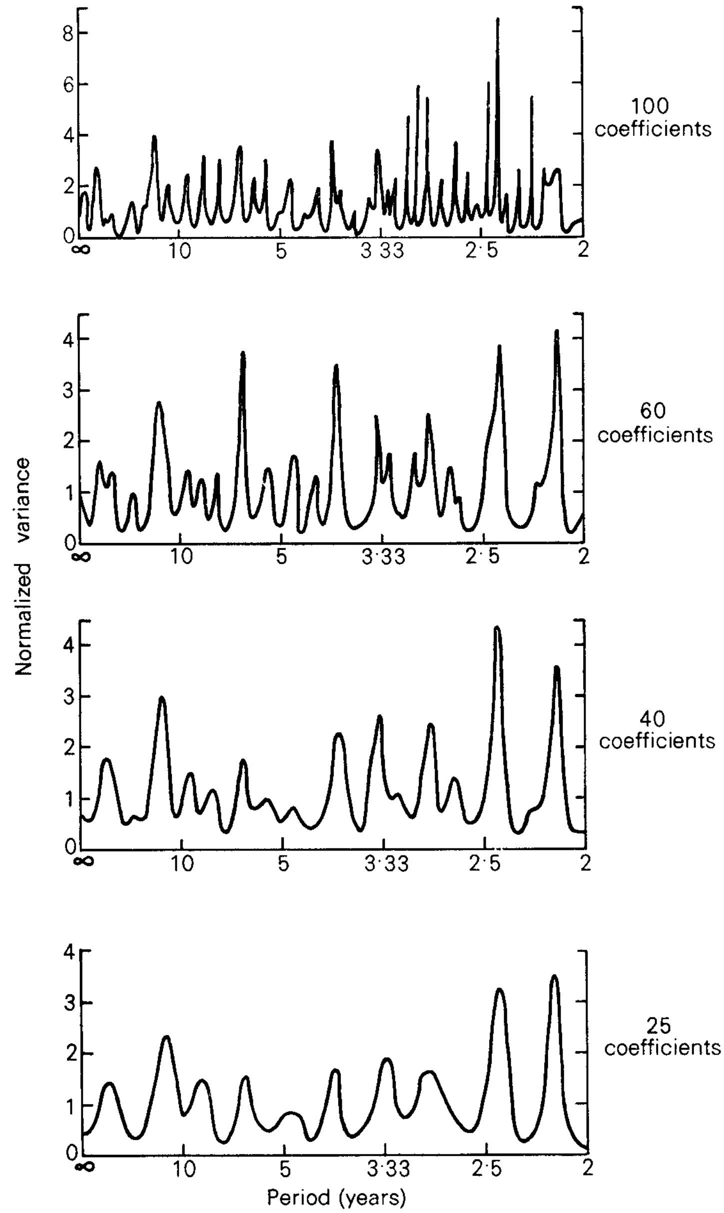

Figure 3. Maximum entropy power spectra of annual (calendar year) rainfall at Kew from 1697 to 1975 using 100, 60, 40, and 25 coefficients.

Table I. *Significant spectral peaks of annual rainfall at Kew from 1697 to 1975. Comparison of FFT, Jenkinson and maximum entropy methods of spectral analysis*

	FAST FOURIER TRANSFORM								
T	11·9	6·02	3·91	2·93		2·45	2·40		2·12
V	9·3	4·8	5·2	3·1		3·6	4·2		8·2
S	5	5	5	3		0·9	0·3		0·9
	JENKINSON PERIODOGRAM								
T	12·3		3·90	2·95		2·46	2·40		2·12
V	4·2		4·7	2·3		2·7	5·5		7·4
S	4		5	4		4	0·9		2
	MAXIMUM ENTROPY (100 COEFFICIENTS)								
T	12·3	6·00	3·89	2·94	2·85	2·46	2·40	2·21	2·13
V	3·8	2·6	4·5	2·2	2·2	2·5	3·9	1·5	7·4
S	3	4	4	4	5	3	0·3	5	3
	MAXIMUM ENTROPY (60 COEFFICIENTS)								
T	12·6	6·11	3·90				2·40		2·11
V	7·8	3·4	4·1				9·4		6·9
S	1	5	5				0·8		2
	MAXIMUM ENTROPY (40 COEFFICIENTS)								
T	12·3						2·41		2·12
V	6·0						8·1		6·6
S	5						0·8		4
	MAXIMUM ENTROPY (25 COEFFICIENTS)								
T							2·41		2·13
V							9·6		7·8
S							2		2

T = period (years); *V* = proportion of variance (%); *S* = level of significance (%). Peaks are listed only if significant at 5% level or better (similar remarks apply to Tables V–XIII). The horizontal displacement from the left-hand margin of a column in this and similar tables is roughly proportional to the associated frequency, i.e. inversely proportional to the period.

The results of the FFT and the Jenkinson periodogram agree well with one another and also with the maximum entropy analysis for 60 coefficients. Table I shows that an analysis made by any of these methods will enable the variance associated with a given fluctuation to be estimated to within a factor of about 2, and its statistical significance assessed to within a factor of about 5. The degree of absolute accuracy is therefore poor, but the assessment of the relative importance of peaks is much better. The main aim of this paper is to analyse rainfall data to see if any periodicities of a permanent nature are present and if so, whether they account for a useful proportion of the variance. The results presented in Table I show that if any major periodicities are present, then all three methods of spectral analysis examined here will detect them, and they will also agree as to their relative importance.

4. Quasi-orthogonal filter analysis

Sixth-order unitary filters due to Craddock (1968) are used in this section, and the combinations chosen are described in Table II (using the notation of Craddock). In a random series, the band pass filters labelled 1 to 5 pass approximately 1/6th of the total variance around the peak periods indicated in Table II, while the low and high pass filters labelled 0 and 6 pass approximately 1/12th of the variance around wavelengths of ∞ and 2 respectively. The variance obtained from a given series can be compared with the variance expected to be obtained from a random series, and the ratio between the two is known as the normalized variance. The significance of a departure of the ratio from unity is assessed using

Table II. *Description of quasi-orthogonal filters used*

Number of filter	Composition	Peak period	Half-power points	
		Number of data points		
0	$1{\cdot}0\,F_{0,6} + 0{\cdot}2\,F_{1,6}$	∞		23·5
1	$0{\cdot}2\,F_{0,6} + 1{\cdot}0\,F_{1,6} + 0{\cdot}2\,F_{2,6}$	10·7	18·6	7·50
2	$0{\cdot}2\,F_{1,6} + 1{\cdot}0\,F_{2,6} + 0{\cdot}2\,F_{3,6}$	5·91	7·88	4·74
3	$0{\cdot}2\,F_{2,6} + 1{\cdot}0\,F_{3,6} + 0{\cdot}2\,F_{4,6}$	4·00	4·81	3·42
4	$0{\cdot}2\,F_{3,6} + 1{\cdot}0\,F_{4,6} + 0{\cdot}2\,F_{5,6}$	3·02	3·49	2·68
5	$0{\cdot}2\,F_{4,6} + 1{\cdot}0\,F_{5,6} + 0{\cdot}2\,F_{6,6}$	2·46	2·72	2·24
6	$0{\cdot}2\,F_{5,6} + 1{\cdot}0\,F_{6,6}$	2·00	2·19	

Snedecor's F test, as first suggested by Craddock (1957). The results of an analysis of rainfall for England and Wales, Kew, Pode Hole, and Manchester for a variety of seasons are presented in Table III. In this paper, the word 'season' is used to describe a period of consecutive months starting in a specified month. The summer half-year refers to the period April–September and the winter half-year to October–March. The rainfall totals were not serially correlated, and so the number of degrees of freedom allocated to each series was equal to the number of data points involved. Only significances of 5 per cent or better have been entered in the table.

In Table II most of the normalized variances are close to unity, showing that the variances of the filtered series are not significantly different from those which would be expected from a random series. The exception is for filter 0, which measures the variance associated with long-term fluctuations. It can be seen that large departures from a random series have occurred at Pode Hole, especially in the autumn, and also over England and Wales during the winter half-year. These findings quantify the magnitude of the long-period variations in the data illustrated in Figure 1 and discussed in section 2. Apart from those with long periods, the only other filtered series to attain significance at the 5 per cent level is that for periods of around 2.5 years in the spring at Kew. No great importance is attached to this, as 1 in 20 random filtered series could be expected to reach the 5 per cent significance level by chance.

It is interesting to compare the results for 12 months starting in January with 12 months starting in July. For longer periods, the behaviour of rainfall totals summed over 12 months will be independent of the starting month, but for shorter wavelengths this is not necessarily the case. The biggest differences between starting months are found at Kew, where the variance for filters 5 and 6 is less for 12 months starting in July than for 12 months starting in January.

So far only the rainfall occurring in individual seasons has been examined. A chronologically ordered data set comprising all seasons mixed together, i.e. spring followed by summer, autumn, winter, spring, and so on, would not necessarily give the same results. Accordingly, data sets were formed of rainfall summed over the conventional three month seasons with departures from average being expressed in terms of the standard deviation for each season. The number of data points was four times as many as for the previous series examined, and the shortest period that could be examined fell from 2 years to 0.5 year. The results of the filter analysis are presented in Table IV, but they show only a continuation of normalized variances close to unity. As a result of the half-power points of filter 0 dropping from 23.5 years to 5.9 years, the normalized variances associated with filter 0 are less than those displayed in Table III, and only the series for Pode Hole achieves significance at better than 5 per cent.

5. Maximum entropy spectral analysis

5.1 *Analysis of individual seasons.* A maximum entropy spectral analysis of the complete series for England and Wales, Kew, Pode Hole, and Manchester was made for a wide range of seasons—the winter and summer half-years and the conventional three month seasons are supplemented by 12

Table III. *Normalized* variance (V_N) and corresponding level of significance (S per cent)† associated with quasi-orthogonal filter analysis of seasonal rainfall*

England and Wales 1727–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	22·0	1·62	5	1·59	5	2·12	0·1	1·25		1·80	1	1·14		1·09		1·60	5
1	10·7	42·1	0·73		0·75		1·04		1·00		1·12		1·01		1·07		0·88	
2	5·9	43·4	0·82		1·05		0·88		1·18		0·86		1·00		1·12		0·87	
3	4·0	43·4	1·04		1·10		0·95		0·96		0·80		1·04		0·79		0·70	
4	3·0	43·4	1·08		0·98		0·83		0·78		0·86		0·84		0·88		1·09	
5	2·5	42·1	1·10		0·80		0·76		1·22		0·91		1·08		1·30		1·07	
6	2·0	22·0	0·82		0·97		1·08		0·83		1·11		0·80		0·87		0·80	

Kew 1697–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	24·8	0·81		0·88		0·79		0·98		1·19		0·86		0·72		1·02	
1	10·7	47·4	1·04		1·06		1·26		1·06		1·25		1·01		1·10		0·92	
2	5·9	48·8	0·92		1·13		0·90		1·22		0·81		1·23		1·03		0·91	
3	4·0	48·8	0·89		1·01		1·03		0·87		0·98		0·68		0·82		0·88	
4	3·0	48·8	1·13		1·07		0·88		0·86		0·78		0·87		0·84		1·24	
5	2·5	47·4	1·13		0·87		0·89		1·02		1·05		1·35	5	1·24		1·12	
6	2·0	24·8	0·97		0·77		1·29		0·97		1·21		0·92		1·19		0·70	

Pode Hole 1726–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	22·2	2·07	0·2	2·01	0·2	1·85	1	1·66	4	1·47		0·84		1·15		2·16	0·1
1	10·7	42·5	0·92		0·82		0·85		1·19		1·14		1·17		1·11		0·74	
2	5·9	43·7	0·86		0·89		0·86		1·03		0·95		1·01		1·07		0·79	
3	4·0	43·7	0·98		0·94		1·10		0·96		0·93		0·95		1·07		0·71	
4	3·0	43·7	1·01		1·10		0·99		0·80		0·67		0·91		0·91		0·97	
5	2·5	42·5	0·87		0·90		0·89		0·99		0·98		0·92		1·17		1·09	
6	2·0	22·2	0·83		0·60		0·79		0·76		0·97		1·07		0·63		0·99	

Manchester 1786–1975

Number of filter	Peak period (years)	Degrees of freedom	12 months from Jan V_N	S	12 months from July V_N	S	Winter half-year V_N	S	Summer half-year V_N	S	Winter V_N	S	Spring V_N	S	Summer V_N	S	Autumn V_N	S
0	∞	16·9	1·65	5	1·72	5	1·11		1·59		0·84		1·57		1·35		1·73	5
1	10·7	32·3	0·84		0·75		0·94		0·92		1·05		0·96		0·87		0·84	
2	5·9	33·2	0·81		1·05		0·98		0·98		1·11		0·76		0·99		1·03	
3	4·0	33·2	0·95		1·16		0·82		0·82		0·94		1·06		0·72		0·81	
4	3·0	33·2	0·93		1·03		1·14		0·69		0·94		0·76		1·09		1·26	
5	2·5	32·3	0·91		0·68		1·04		1·14		0·94		1·34		1·29		0·72	
6	2·0	16·9	0·98		0·72		1·17		1·00		1·09		0·69		0·97		0·88	

* See section 4 of text. † Listed only if 5% or better.

months starting in January, April, July and October. The number of coefficients used was 60 and the significant spectral peaks are presented in Tables V–VIII. Only peaks significant at 5 per cent or better have been entered in the tables.

Of the features common to all four series, the most impressive are the quasi-biennial peaks at periods of around 2.1 and 2.4 years. The most important of these is the 2.4 year cycle which is essentially a phenomenon of the summer half-year. This is illustrated in Figure 4, where the large quasi-biennial peaks for rainfall at Kew summed over 12 months starting in January (which preserves the summer half-year) are seen to disappear when the rainfall is summed over 12 months starting in July (which

Table IV. *Normalized* variance (V_N) and corresponding level of significance (S per cent)† associated with quasi-orthogonal filter analysis of rainfall summed over consecutive three-month periods*

		England & Wales 1727–1975			Kew 1697–1975			Pode Hole 1726–1975			Manchester 1786–1975		
Number of filter	Peak period (years)	Degrees of freedom	V_N	S	Degrees of freedom	V_N	S	Degrees of freedom	V_N	S	Degrees of freedom	V_N	S
0	∞	88	1·06		99	0·97		89	1·44	0·6	67	1·19	
1	2·7	169	1·03		190	1·15		170	1·11		129	0·93	
2	1·6	174	0·83		195	1·04		175	0·86		133	0·87	
3	1·0	174	1·17		195	1·06		175	1·01		133	1·04	
4	0·75	174	0·86		195	0·85		175	0·90		133	0·96	
5	0·6	169	1·05		190	1·01		170	0·87		129	1·11	
6	0·5	88	0·96		99	0·84		89	0·92		67	1·03	

* See section 4 of text. † Listed only if 5% or better.

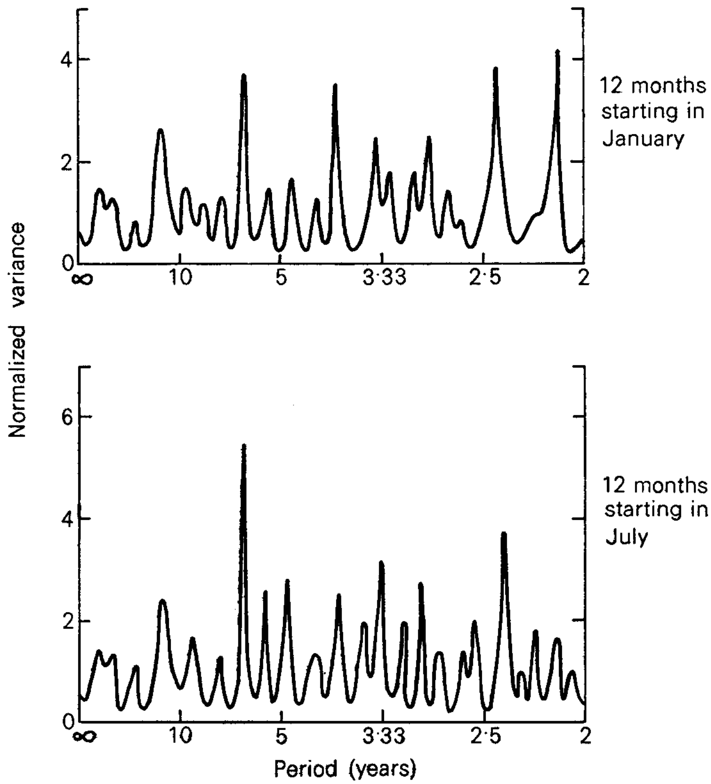

Figure 4. Maximum entropy power spectra (60 coefficients) of rainfall at Kew summed over (a) 12 months starting in January, and (b) 12 months starting in July, during the epoch 1697–1975.

Table V. *Significant spectral peaks of England and Wales rainfall from 1727 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend												
						12 months starting in January							
T	—	51·2				3·90					2·39	2·11	2 00
V	5·5	4·6				4·2					7·5	3·1	3·1
S	—	1				5					0·3	2	5
						12 months starting in April							
T	—	52·6				3·89				2·75	2·41	2·20	
V	5·5	4·1				4·3				3·6	4·2	4·0	
S	—	1				3				2	0·8	5	
						12 months starting in July							
T	—	52·5		6·03	4·92	3·87			2·96		2·42		
V	5·5	4·2		3·5	4·6	4·3			2·8		2·2		
S	—	2		4	5	0·9			5		5		
						12 months starting in October							
T	—	52·6		6·07	4·95			3·38		2·54			2·06
V	5·5	4·6		4·4	6·0			3·8		4·7			3·3
S	—	1		4	2			0·4		2			5
						Winter half-year							
T	—				4·97					2·75			2·07
V	9·6				5·7					3·5			3·9
S	—				2					5			1
						Summer half-year							
T	—		10·3	6·05			3·78				2·40	2·13	
V	0·0		4·4	5·5			5·1				6·4	2·8	
S	—		5	5			2				0·1	3	
						Winter							
T	—					3·88							2·07
V	7·4					2·8							4·8
S	—					5							2
						Spring							
T	—		9·25	5·47				3·47			2·38		
V	1·3		4·7	3·9				4·1			6·1		
S	—		1	5				0·9			2		
						Summer							
T	—		10·2				3·79		2·98	2·44	2·37		
V	0·3		3·9				4·7		4·6	6·9	6·2		
S	—		5				5		4	1	1		
						Autumn							
T	—	58·8						3·39		2·76			
V	1·6	5·1						3·3		9·4			
S	—	0·9						2		0·8			

divides the summer half-year). The 2.4 year periodicity has previously been identified by Alter (1927) in northern Europe and the Pacific coast of the U.S.A., and by Jenkinson (1975) in East Africa. The relationship of the 2.1 and 2.4 year cycles to the quasi-biennial oscillation in tropical stratospheric winds is uncertain, as there are insufficient data available for the latter phenomenon to enable proper comparisons to be made. Since observations became available in 1954, the tropical stratospheric winds have displayed a mean periodicity of around 2.2 years.

Other periodicities of note include a 3.9 year cycle in annual and winter rainfall, most evident in the record for England and Wales, but also visible in the other series. Rainfall summed over the winter

Table VI. *Significant spectral peaks of Kew rainfall from 1697 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend												
						12 months starting in January							
T	—		12·6		6·11		3·90				2·40		2·11
V	0·1		7·8		3·4		4·1				9·4		6·9
S	—		1		5		5				0·8		2
						12 months starting in April							
T	—				6·07		3·92	3·27			2·41	2·20	
V	0·1				3·9		3·5	8·6			4·2	3·6	
S	—				5		5	5			4	4	
						12 months starting in July							
T	—				6·04			3·36					
V	0·2				4·8			5·0					
S	—				0·8			4					
						12 months starting in October							
T	—		12·6		6·03			3·37					2·13
V	0·1		5·2		4·2			3·6					6·0
S	—		3		1			2					0·3
						Winter half-year							
T	—			8·84		4·92						2·19	
V	0·0			3·6		4·0						9·3	
S	—			2		5						5	
						Summer half-year							
T	—	48·7			6·09						2·42		2·12
V	0·3	3·4			5·9						5·2		2·7
S	—	4			3						1		4
						Winter							
T	—									2·56		2·23	
V	0·0									4·7		6·7	
S	—									2		5	
						Spring							
T	—			8·88	5·95						2·39		
V	0·3			4·3	5·6						6·5		
S	—			2	4						1		
						Summer							
T	—		12·7		6·10						2·45		2·13
V	0·2		5·7		4·1						9·1		5·3
S	—		0·3		2						<0·1		0·2
						Autumn							
T	—	∞						3·45	2·78	2·59		2·34	
V	0·0	2·9						10·7	6·7	2·1		7·4	
S	—	5						3	0·5	4		5	

half-year displays a periodicity of 5 years in all the series, but is least well developed at Kew. A periodicity around 6 years in annual and summer half-year rainfall is evident at Kew, and although absent at Pode Hole is also present for England and Wales and Manchester.

Peaks important only in individual series include a 50 year cycle in annual rainfall over England and Wales (using data from 1727), but this feature is probably detected as a periodicity of 40 years at Manchester (using data from 1786). A 2.9 year cycle is also prominent at Manchester for annual and winter rainfall, while the Kew data indicate a 12 year periodicity in annual and summer rainfall. At Pode Hole peaks at 3.3 years and very long periods are present, the latter being the attempt by the

Table VII. *Significant spectral peaks of Pode Hole rainfall from 1726 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend														
	12 months starting in January														
T	—	∞		9·61							2·93				2·11
V	0·2	14·2		3·6							4·6				3·4
S	—	<0·1		5							4				2
	12 months starting in April														
T	—	∞		9·65				3·92		3·33					
V	0·1	13·7		4·1				3·5		4·4					
S	—	<0·1		5				5		5					
	12 months starting in July														
T	—	∞				6·05				3·35			2·56		
V	0·1	14·1				3·9				6·0			3·6		
S	—	<0·1				5				2			5		
	12 months starting in October														
T	—	∞								3·37					
V	0·1	15·2								4·6					
S	—	<0·1								4					
	Winter half-year														
T	—	133·2	21·5				4·95	3·93	3·57	3·35					
V	0·7	7·4	3·3				4·5	3·3	2·8	4·0					
S	--	0·6	3				0·8	3	5	3					
	Summer half-year														
T	—	∞			7·96		4·64	3·74							2·12
V	1·4	3·7			3·9		3·7	3·2							2·7
S	—	4			2		3	4							4
	Winter														
T	—	99·9		10·1			4·96							2·33	2·07
V	0·7	4·8		7·8			3·7							3·1	3·2
S	—	5		5			1							5	3
	Spring														
T	—		15·5			5·40		4·31		3·46					2·10
V	0·4		4·5			3·4		3·1		5·0					4·7
S	—		4			3		5		5					3
	Summer														
T	—						4·62	4·00			2·92			2·45	
V	1·7						5·3	3·2			4·4			6·0	
S	—						3	4			3			0·5	
	Autumn														
T	—	400·0				5·47						2·75	2·57	2·38	2·12
V	0·3	15·1				3·2						7·9	4·4	3·4	3·3
S	—	0·1				5						5	4	2	5

maximum entropy method to resolve into a sine wave the convex curve displayed by the (Pode Hole) data in Figure 1. Peaks at periodicities of 11 and 22 years, which could possibly be associated with the sunspot cycle, are generally absent, the closest approach being the 12 year cycle at Kew.

5.2 *Analysis of 'mixed' seasons.* The spectral analysis over the complete length of records was repeated when the data were arranged chronologically into mixed seasons as described in section 4. The larger number of data points than were available for the single season analysis permitted greater resolution to be obtained, and the power spectra were produced using 100 coefficients. As a result, more peaks were obtained than for the single season analysis (see section 3.3) and the larger number of data points available also reduced the threshold of the various levels of significance. These facts would lead one to

Table VIII. *Significant spectral peaks of Manchester rainfall from 1786 to 1975*

Results were obtained from the Maximum Entropy Method using 60 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend												
12 months starting in January													
T	—	41·6					3·85		2·90	2·56	2·41		2·00
V	3·6	8·0					4·1		5·4	2·8	3·9		3·3
S	—	0·7					5		4	4	0·5		1
12 months starting in April													
T	—	42·5			6·15		3·87				2·42		
V	3·3	7·3			4·0		3·9				3·9		
S	—	0·7			3		4				0·9		
12 months starting in July													
T	—	41·2					3·79					2·30	
V	3·6	7·8					6·7					2·8	
S	—	0·3					4					5	
12 months starting in October													
T	—	41·6			6·11	4·93			2·93	2·54			2·08
V	3·2	8·3			3·6	3·7			3·1	5·0			4·3
S	—	0·7			2	5			5	2			5
Winter half-year													
T	—			8·36		4·97			2·93				2·07
V	1·2			4·3		4·4			4·7				4·6
S	—			3		1			1				0·8
Summer half-year													
T	—	39·2			6·18					2·55	2·41		2·00
V	0·3	7·3			4·8					6·2	3·9		2·1
S	—	0·3			2					0·8	3		5
Winter													
T	—		14·9	8·50	7·35				2·93	2·54			
V	0·0		5·2	5·1	3·6				5·3	5·2			
S	—		0·4	5	5				0·9	5			
Spring													
T	—	45·4	23·0			4·28	3·88	3·49		2·54	2·43		
V	0·5	5·3	7·5			3·1	4·3	3·7		4·4	5.1		
S	—	4	0·1			5	4	2		1	1		
Summer													
T	—		16·2	8·39	6·16					2·54			
V	1·4		4·0	2·9	5·0					6·7			
S	—		5	4	0·2					1			
Autumn													
T	—	76·8	12·6		6·94				2·87				2·06
V	4·0	10·0	2·9		5·5				11·0				3·4
S	—	2	5		4				2				5

expect more significant peaks than were obtained with the single season analysis. The results, presented in Table IX show only about the same number of significant peaks as before. This indicates that fewer features of interest are present when the data are formed into mixed seasons than when they are arranged into individual seasons. The major peaks found in section 5.1 are in general absent, but another common peak emerges at a period of around 1.14 years. This had been observed by Brunt (1927) in London rainfall, but only a small proportion of the variance is accounted for.

5.3 *Analysis of 80 year epochs.* The single season form of spectral analysis was repeated when the complete records were divided into 80 year epochs. This enabled one to examine the stability of the significant spectral peaks found in section 5.1 and, more generally, to see how the structure of the variance

Table IX. *Significant spectral peaks in rainfall summed over consecutive three month periods*

Results were obtained from the Maximum Entropy Method using 100 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

	Trend									
				England & Wales 1727–1975						
T	—					1·15	1·00			0·60
V	1·2					2·7	4·0			2·7
S	—					5	0·1			3
				Kew 1697–1975						
T	—		3·35	2·40	1·88	1·14	1·08			
V	0·0		2·4	4·5	3·0	3·2	2·8			
S	—		5	5	1	4	3			
				Pode Hole 1726–1975						
T	—	∞	3·37							
V	0·0	3·6	2·7							
S	—	<0·1	5							
				Manchester 1786–1975						
T	—	35·7				1·13		0·75	0·71	0·55
V	0·0	3·5				2·3		2·5	2·4	4·1
S	—	0·3				3		5	2	5

evolved with time. The seasons examined were spring, summer, autumn and winter, together with the calendar year and the winter half-year, and the number of coefficients used was 26 (i.e. $N/3$). The reduced number of coefficients led to a smaller number of peaks being produced than for the analysis of the complete records, and the smaller number of data points involved also increased the thresholds of the various significance levels. As a result, the number of significant peaks obtained was less than in section 5.1. The results, presented in Tables X–XIII, show that no spectral peak achieved 5 per cent significance in all the epochs examined. There were also large differences in the power spectra between one epoch and another. This is illustrated in Figure 5 for the winter half-year rainfall over England and Wales.

The differences in the structure of the variance between one epoch and another are not surprising. Consider a model of rainfall variance in which random fluctuations predominate, but in which regular oscillations are also present. Over any given frequency range, the power or variance may be regarded as being composed of random and regular components. The regular cyclic component may be assumed (in the model) to be constant with time, but the random component will vary with respect to epoch. In 19 epochs out of 20, the random component of the variance will be contained by the lower and upper 5 per cent levels of significance, but over a narrow frequency band, these limits will be wide. In a series of 250 data points, variations in the mean noise level of a power spectrum, i.e. the variance over the complete frequency range 0 to 0.5, will be determined by the standard error of the variance derived from 250 points. The standard error of the variance over 1/10th of the frequency range will be equivalent to the standard error over the whole frequency range based on only 1/10th of the data, i.e. 25 points. The regular fluctuations found in section 5.1 generally occupied even narrower frequency bands. Thus the power over a narrow frequency band which contains a regular cyclic fluctuation is still subject to large random variations. When the random component of power is large, the spectral peak due to the regular periodicity is boosted, while when the random component is small, it is depressed. It is therefore not surprising that the spectral peaks found in section 5.1 did not maintain a regular level of significance over epochs as short as 80 years.

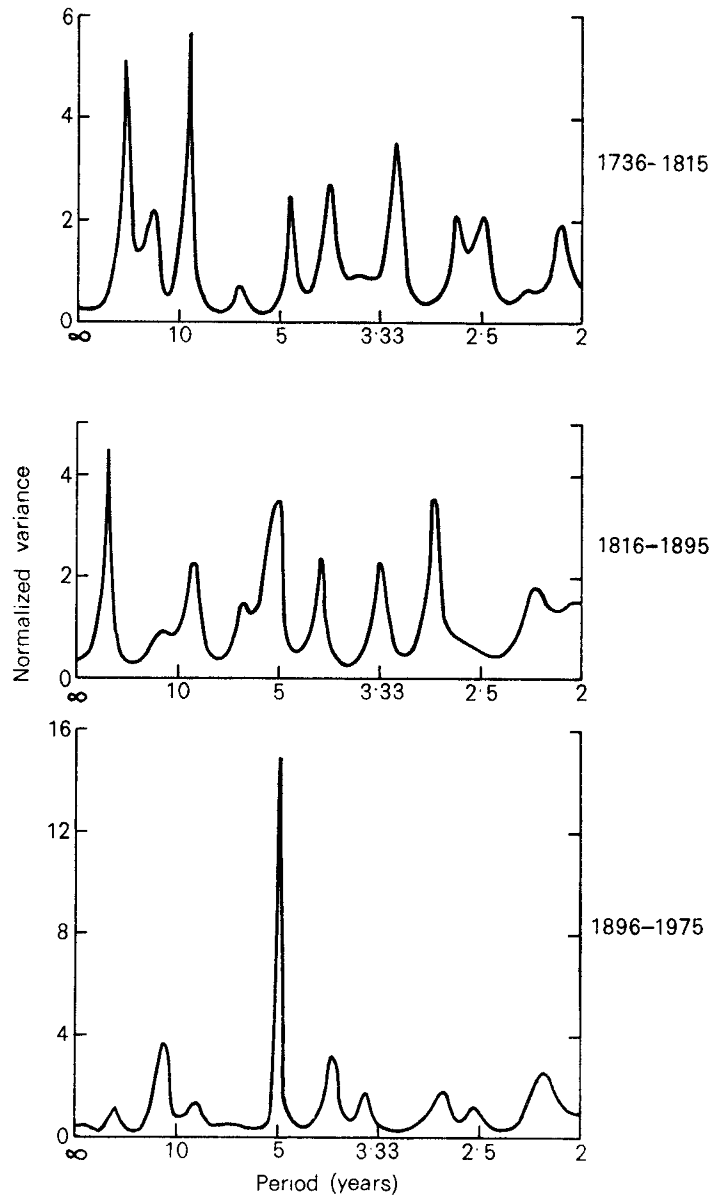

Figure 5. Maximum entropy power spectra (26 coefficients) of winter half-year rainfall over England and Wales during the epochs 1736–1815, 1816–95, and 1896–1975.

Tables X–XIII show that the most regular of the spectral peaks are those at 2.1 and 2.4 years. The 2.4 year cycle is the most important, and is most developed in the first and last epochs. The 3.9, 5 and 6 year cycles do not receive regular support, but the 5 year periodicity in winter half-year rainfall is very pronounced in the most recent epoch (see Figure 4). An 11th-order filtered series of the 5-year cycle for

Table X. *Significant spectral peaks in England and Wales rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

		12 months starting in January								Spring						
	T						2·39	2·11	*T*							
1736–1815	*V*						12·6	5·2	*V*							
	S						0·1	5	*S*							
	T	34·4			4·04	3·35			*T*							
1816–1895	*V*	8·3			7·7	10·3			*V*							
	S	5			5	3			*S*							
	T				3·92				*T*		16·8		5·43			
1896–1975	*V*				9·0				*V*		9·0		11·1			
	S				4				*S*		2		2			
		Summer								Autumn						
	T	29·4			3·88	2·98			*T*	40·0						2·13
1736–1815	*V*	12·7			6·2	5·5			*V*	13·1						6·5
	S	3			5	5			*S*	5						4
	T						2·39		*T*					3·34	2·81	
1816–1895	*V*						9·3		*V*					7·0	14·5	
	S						5		*S*					4	0·1	
	T	18·9							*T*						2·97	
1896–1975	*V*	16·1							*V*						12·2	
	S	5							*S*						1	
		Winter								Winter half-year						
	T	15·1				2·62			*T*	22·0		9·00				
1736–1815	*V*	21·5				19·0			*V*	9·6		6·9				
	S	2				2			*S*	5		5				
	T	40·0		8·39		2·88			*T*							
1816–1895	*V*	8·3		6·7		9·1			*V*							
	S	5		5		3			*S*							
	T		11·2		3·97				*T*				5·02			
1896–1975	*V*		9·3		9·4				*V*				11·7			
	S		4		4				*S*				0·3			

England and Wales rainfall summed over 12 months starting in October is displayed in Figure 6. The fluctuation is seen to have been well developed between 1860 and 1885, and after 1925, since when the filter has passed 25 per cent of the variance. Over the complete length of the England and Wales record, the filter has passed 15 per cent of the variance, which is significant at the 5 per cent level.

Another feature of the winter half-year rainfall which is unlikely to be permanent, but which has been well developed this century, is an 11 year periodicity. This is illustrated in Figure 7 by means of a sixth-order filtered series which has accounted for one-third of the total variance since 1908. The fluctuations have not, however, maintained a constant phase relationship with the sunspot cycle.

6. Conclusions

Four long-period rainfall records for England and Wales have been subjected to a maximum entropy spectral analysis. The data used, the spectral techniques employed and the method of calculation of variance and significance attributed to each fluctuation, are all imperfect and open to many criticisms. Unitary filters, however, were used to support the main findings of the maximum entropy analysis, while the effect of imperfections in the data were lessened by the fact that four independent series were used.

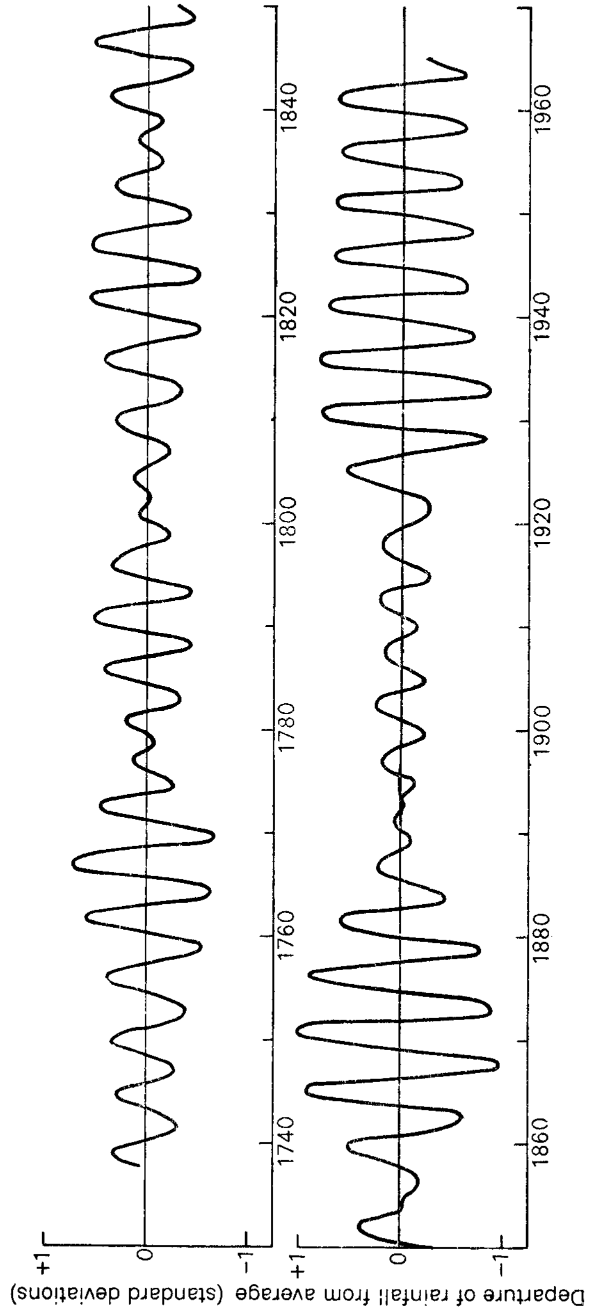

Figure 6. Eleventh-order filtered series illustrating five-year periodicity in England and Wales rainfall summed over 12 months starting in October.

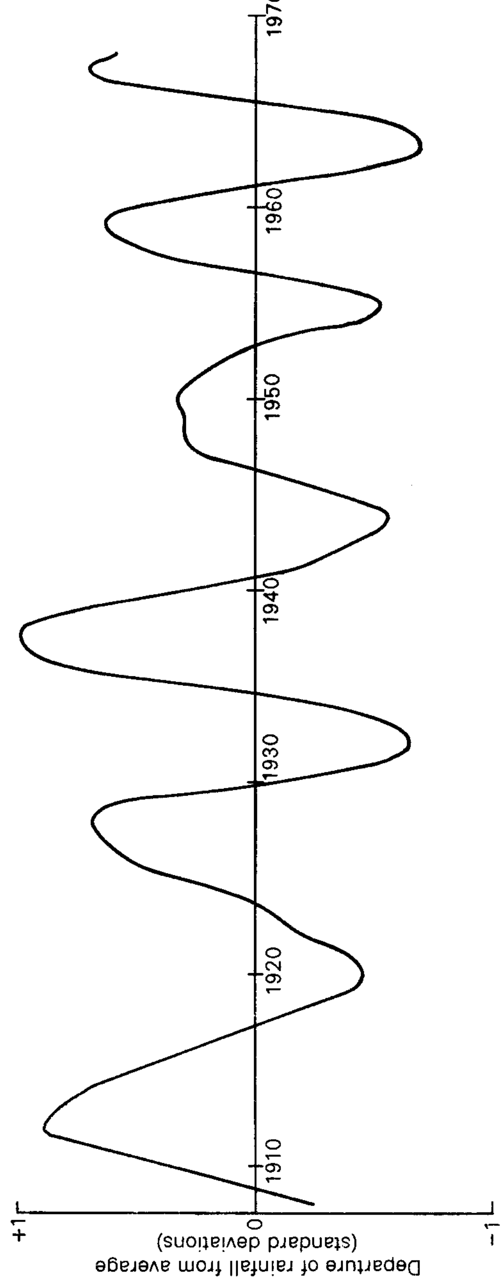

Figure 7. Sixth-order filtered series illustrating 11-year periodicity in winter half-year rainfall over England and Wales.

Table XI. *Significant spectral peaks in Kew rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); V = proportion of variance (%); S = level of significance (%).

		12 months starting in January										Spring		
	T					2.40		*T*		5·53			2·42	
1736–1815	*V*					9·2		*V*		8·6			28·7	
	S					3		*S*		1			0·7	
	T				3·33			*T*			3·33			
1816–1895	*V*				15·2			*V*			11·9			
	S				0·9			*S*			5			
	T		11·8			2·40		*T*		5·55				
1896–1975	*V*		15·1			6·6		*V*		14·3				
	S		0·9			5		*S*		2				
				Summer								Autumn		
	T	51·2		7·16		2·63		*T*	6·05	4·77	3·44	2·62		
1736–1815	*V*	8·5		10·1		8·8		*V*	10·7	8·4	8·8	7·2		
	S	5		0·5		2		*S*	0·7	4	4	5		
	T			6·18				*T*		5·40	3·34	2·82		2·15
1816–1895	*V*			10·9				*V*		7·3	8·8	10·9		7·2
	S			4				*S*		4	4	2		3
	T		12·6			2·43	2·10	*T*				2·77	2·38	
1896–1975	*V*		9·5			14·4	9·4	*V*				11·1	10·5	
	S		0·8			0·8	0·9	*S*				3	5	
				Winter							Winter half-year			
	T		17·4			2·65		*T*	8·84					
1736–1815	*V*		16·7			13·3		*V*	11·5					
	S		5			2		*S*	2					
	T	38·4				2·89	2·08	*T*						2·14
1816–1895	*V*	10·7				7·4	23·7	*V*						20·0
	S	4				5	0·9	*S*						0·1
	T		11·2			2·55		*T*	12·2		3·54			
1896–1975	*V*		11·2			7·7		*V*	13·3		10·3			
	S		4			2		*S*	0·5		4			

It was found that rainfall fluctuations were largely random, and although some regular periodicities were evident, their use for forecasting was limited because they accounted for only a few per cent of the total variance. Cycles that could be regarded as permanent were located at periods of 2.1 and 2.4 years, of which the latter, associated with the summer half-year, was most important. Cycles that were less prominent, but which attained 5 per cent significance over the complete length of all the series examined, were found at periods of 3.9, 5, and 6 years. The 6 year cycle related mainly to the summer half-year, while the 5 year cycle, which has been well developed this century, is associated with the winter half-year.

Acknowledgements

The author is grateful for useful discussions with Messrs A. F. Jenkinson and G. H. Ross. The work was funded by the Department of the Environment under contract DGR 480/87.

Table XII. *Significant spectral peaks in Pode Hole rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); *V* = proportion of variance (%); *S* = level of significance (%).

12 months starting in January

1736–1815	*T*	2·38	
	V	8·5	
	S	4	
1816–1895	*T*	3·37	2·89
	V	9·3	10·2
	S	3	2
1896–1975	*T*	2·40	
	V	10·5	
	S	2	

Spring

1736–1815	*T*	8·47	2·09	
	V	20·9	6·7	
	S	4	4	
1816–1895	*T*			
1896–1975	*T*	16·5	5·46	3·48
	V	9·7	14·8	7·8
	S	2	3	3

Summer

1736–1815	*T*	7·01	5·44	2·58
	V	11·1	9·5	10·3
	S	2	4	4
1816–1895	*T*	4·61		
	V	10·4		
	S	4		
1896–1975	*T*	2·44		
	V	15·5		
	S	0·3		

Autumn

1736–1815	*T*	37·8	2·38		
	V	17·9	7·2		
	S	4	4		
1816–1895	*T*	5·50	3·34	2·83	2·15
	V	11·4	6·4	9·3	8·4
	S	5	5	2	3
1896–1975	*T*	7·24	2·74		
	V	7·2	11·6		
	S	3	0·5		

Winter

1736–1815	*T*	15·5	2·65	
	V	11·6	17·7	
	S	4	4	
1816–1895	*T*	3·95		
	V	5·9		
	S	5		
1896–1975	*T*	21·3	10·1	5·00
	V	7·6	16·2	9·4
	S	5	5	2

Winter half-year

1736–1815	*T*	3·27	
	V	8·8	
	S	2	
1816–1895	*T*	5·08	
	V	15·0	
	S	3	
1896–1975	*T*	11·4	4·96
	V	10·5	10·4
	S	5	3

Table XIII. *Significant spectral peaks in Manchester rainfall during 80 year epochs*

Results were obtained from the Maximum Entropy Method using 26 coefficients.
T = period (years); *V* = proportion of variance (%); *S* = level of significance (%).

Season	Epoch				
12 months starting in January	1816–1895	*T*	6·20	4·88	2·84
		V	6·0	9·3	12·4
		S	5	0·9	4
	1896–1975	*T*	3·81	2·00	
		V	12·6	11·3	
		S	0·9	0·1	
Spring	1816–1895	*T*			
		V			
		S			
	1896–1975	*T*	3·52	2·46	
		V	10·8	11·6	
		S	2	3	
Summer	1816–1895	*T*	8·50	6·03	
		V	8·1	12·0	
		S	5	3	
	1896–1975	*T*	2·56	2·42	2·00
		V	12·1	13·7	7·3
		S	4	3	4
Autumn	1816–1895	*T*	35·0		
		V	9·4		
		S	4		
	1896–1975	*T*			
		V			
		S			
Winter	1816–1895	*T*	15·1	8·39	2·92
		V	11·1	8·6	10·6
		S	3	5	3
	1896–1975	*T*	2·53		
		V	9·3		
		S	1		
Winter half-year	1816–1895	*T*	8·47		
		V	9·0		
		S	5		
	1896–1975	*T*	5·10	3·07	
		V	10·1	15·0	
		S	3	5	

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551.578.45(423+429)

The blizzard of 18–19 February 1978 in south-west England and South Wales

By Joyce Laing
(Meteorological Office, Bracknell)

Summary

Heavy falls of snow accompanied by strong to gale force winds affected the south-west of England and South Wales on 15–16 February 1978 and again on 18–19 February 1978. The sudden onset and the severe drifting of the snow caused considerable disruption to communications and damage to property and livestock. Although some hill tops and open fields were scoured of snow cover, drifts of 6 metres were reported in valleys and deep-set roads. A comparison with past snowstorms indicates that not since 1891 has there been so much snow in conjunction with high winds over such a wide area of south-west Britain.

1. Introduction

During the third week of February 1978 snowfalls were considerable in south-west Britain and culminated in the blizzard of 18–19 February when the combination of strong to gale force easterly winds and heavy snowfall practically brought life to a standstill from Hampshire to East Cornwall and north to Avon and Glamorgan. A quick thaw on the 20th and 21st produced some flooding on the south coast but in some areas drifts remained until May.

2. Synoptic situation

The broad pattern remained virtually unchanged over the British Isles from 15 to 21 February 1978. A large depression, centred at about 50°N, dominated the North Atlantic, and a ridge of high pressure extended south from the polar regions into central Europe, which resulted in a south-easterly airstream over much of the United Kingdom.

On the 15th an occluding frontal system approached south-west England, bringing the warm, moist air from the Atlantic into juxtaposition with the established cold air. A small low-pressure centre formed on this front between the Isles of Scilly and Brest by midnight on the 15th and moved into northern France. A further low-pressure centre developed off south-west Ireland late on the 16th and also moved into northern France. Late on the 18th another occlusion moved in from the west with a small wave developing into a centre near Scilly by midnight. This low became stationary in the mouth of the English Channel on the 19th and gradually filled. Figure 1 shows the synoptic situation at 06 GMT on 19 February 1978.

Strong to gale force east to south-easterly winds over the south and west of the country were produced between the ridge which remained over northern and eastern Britain and the succession of lows near south-west England. On the 20th this ridge moved eastwards allowing the weakening fronts to move north-eastwards and the winds to moderate.

3. Data used

The climatological returns received in the Meteorological Office from the network of observing stations were the main source of information for this survey. These returns are from both official meteorological offices and from auxiliary and climatological co-operating stations. Use has also been made of the reports from the contributors to the *Snow Survey of Great Britain* (Meteorological Office, 1978). Figure 2 shows the locations of all the stations in southern England and South Wales

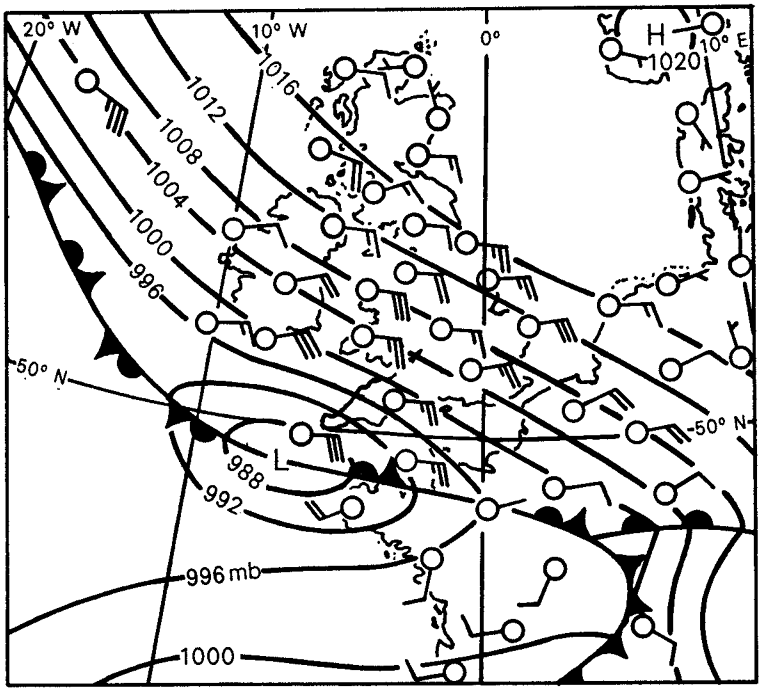

Figure 1. Synoptic situation at 06 GMT on 19 February 1978.

which were used in this report. Supplementary accounts have also been received from the meteorological offices at Mount Batten, Rhoose (Cardiff/Wales Airport) and Upavon, and reports in the national and local newspapers have been consulted.

References to accounts of past snowstorms are given at the end of this paper.

4. Weather

The weather at the beginning of February 1978 was changeable with periods of mild, stormy weather in the south-west. From the 7th it turned gradually colder and during the three days from the 8th to the 10th slight snow showers fell over many parts of the south-west. After a fine, sunny day on 11 February the next few days saw some moderate falls of snow, mainly over the higher ground. More general snow fell on the nights of 15/16 and 16/17 February, giving an appreciable cover over most of southern England, from Surrey and Sussex westward, and South Wales; more than 25 cm were recorded on Exmoor and Dartmoor, and drifts of up to 10 ft (3 metres) quickly formed in the strong easterly winds, blocking many roads.

The winds moderated on 17 February and the weather that day was fine and sunny. As a result of valiant efforts by council workers all main roads in the west were clear of snow by that night. However, after a cold night, Saturday 18 February became cloudy, and rain and sleet in Cornwall turned to snow as it spread further east and north. In the transitional state between rain and snow, generally in south-east Cornwall and south-east Devon, some unusual forms of precipitation were noted, variously described as ice pellets, ice needles, wet icicles or hail. The snow spread into south-west England and by evening had extended to South Wales and central England. The winds increased again to strong to near gale force from an easterly direction, causing severe drifting of the snow especially over the higher

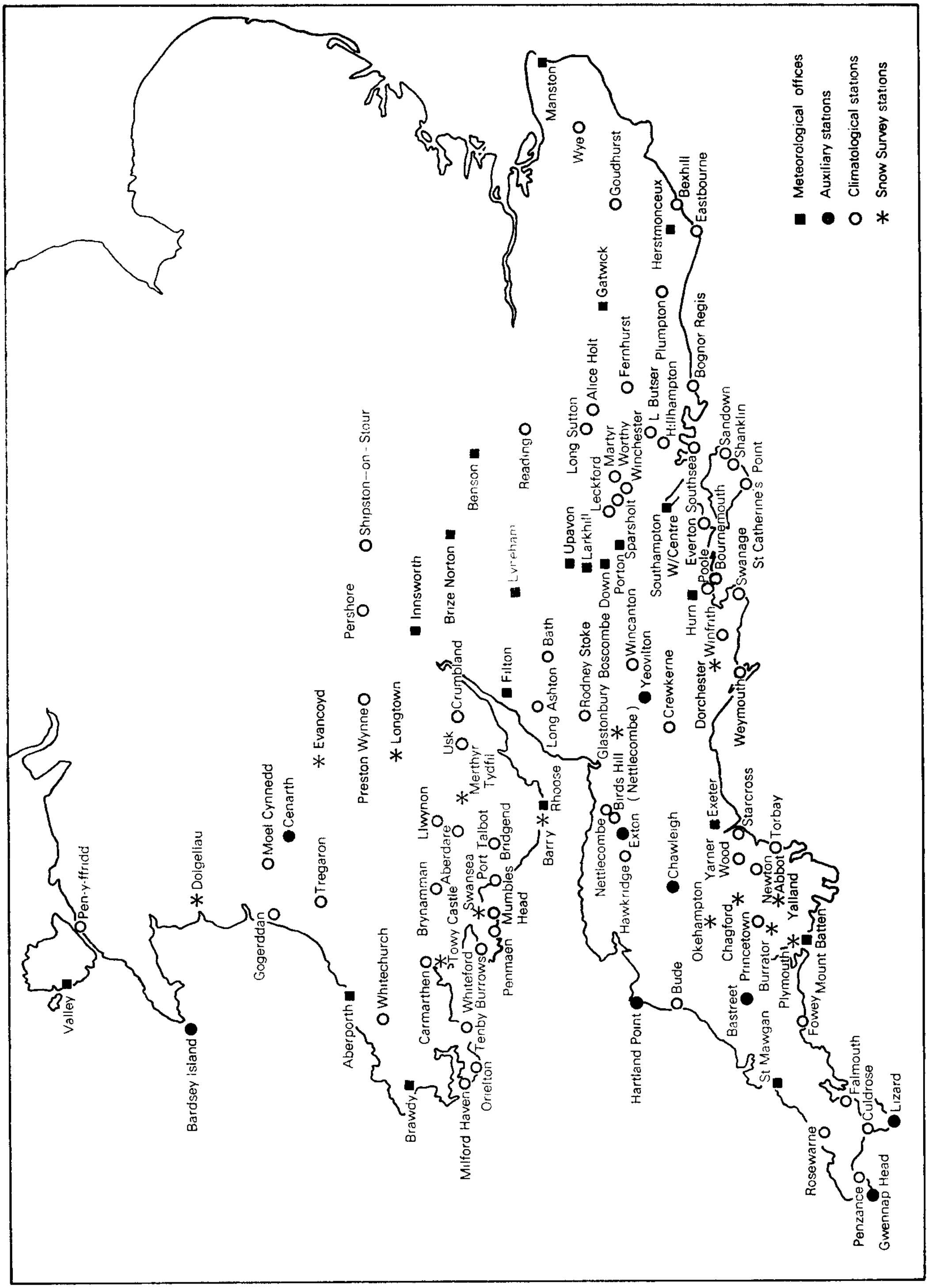

Figure 2. Location of stations reporting to the Meteorological Office during the period 16–20 February 1978 and used in this report.

ground. This blizzard with mean winds of 25–30 knots and blowing snow continued on to 19 February, causing havoc to communications, power supplies and livestock, mainly in Devon, Dorset, Somerset and Glamorgan. Temperatures were low away from the south coast; at Cardiff/Wales Airport, the temperature did not rise above —0.7 °C and on Exmoor the maximum recorded was —1.6 °C. South and west Cornwall, however, had comparatively little snow. The gale force winds continued throughout the 19th and the blown snow prevented accurate assessment of the amounts of snow actually falling. Wind speeds in gusts of 50–60 knots were recorded at a number of places and a maximum gust of 73 knots was recorded at Gwennap Head (Cornwall). Exposed areas such as North Hessary Tor, Dartmoor, were scoured of lying snow while some adjacent areas had drifts of 20 feet (6 metres) or more. Accumulations of level snow to a depth of about 60 cm were recorded in places on Dartmoor and Exmoor and in Glamorgan. The greatest depth recorded was 85 cm at Nettlecombe (Bird Hill) in north-west Somerset.

The area affected by the blizzard stretched from the South Downs west of Beachy Head and including the Isle of Wight, across Dorset, Devon, Somerset and Avon and into Gwent, Glamorgan and parts of Dyfed. Table I gives the snow depths recorded at a selection of places throughout the area between 13

Table I. *Depths of level undrifted snow in centimetres at 09 GMT, 13–23 February 1978*

Place	Altitude *metres*	Date 13	14	15	16	17	18	19	20	21	22	23
South Wales												
Aberporth	134	6	5	4	4	3	3	5	3			
Brawdy	111	7	8	4	4	9	5	18	14	11		
Brynamman	183	2			3	4	3	17	6	3		
Merthyr Tydfil	235			tr	tr	3	2	46	56	48	30	5
Rhoose	67	tr			4	8	7	30	39	30	22	10
Somerset & Avon												
Filton	59					3		12	5	4		
Nettlecombe (Bird Hill)	96	tr			20	29	27	(50)	85	(60)	40	
Hawkridge	314	1	2		23	31	31	62	50	20	10	
Crewkerne	101				13	21	14	25	38	38	8	
Yeovilton	18				6	2	7	29	16	12	7	tr
Devon												
Mount Batten	27	tr						tr				
Exeter	32		tr		3	7	4	21	32	15	9	
Starcross	9					2		14	14	9	2	
Chawleigh	168				15	18	18	40	45	40	28	20
Princetown	414	tr	3	3	29	26	26	45	60	32	8	
Burrator	230	2	8	5	16	10	10	25	30	—	—	—
Dorset												
Dorchester	69	tr			4	13	12	30	30	25	15	5
Winfrith	26				5	9	6	35	40	30	20	
Poole	5					6		25	30	10		
Hurn	10				3	6	6	17	22	14	5	
Wiltshire												
Boscombe Down	126				5	7	4	11	10	9	4	
Hampshire												
Southampton	3				5	2		6	8			
St Catherines I.O.W.	16							15	8			

Figures in brackets are estimated values; tr = trace, i.e. less than 0·5 cm;—indicates no observation; see Figure 2 for location of stations.

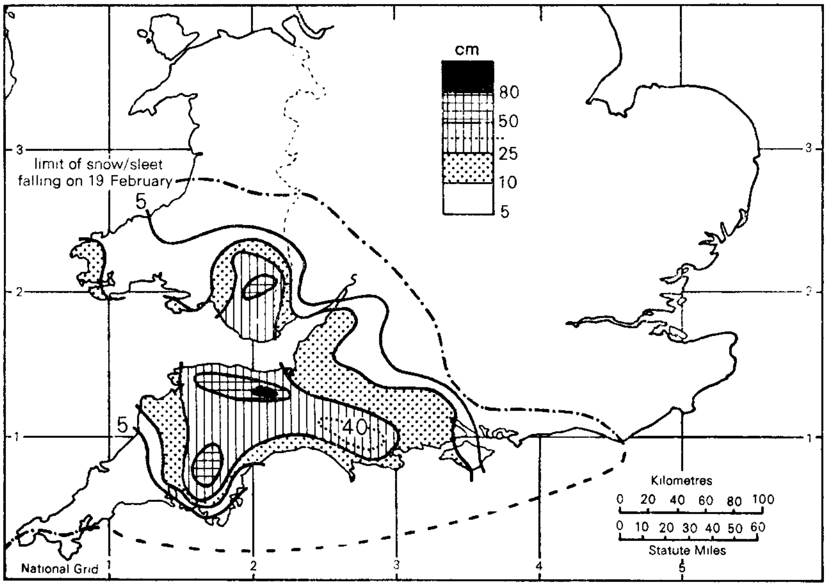

Figure 3. Maximum snow depths (level undrifted snow) measured at 09 GMT on 19 or 20 February 1978.

and 22 February 1978 and Figure 3 shows the greatest depths recorded on the mornings of 19 and 20 February, together with the extent of snowfall on 19 February.

On the 20th the winds slowly moderated and further snowfall in the west turned first to freezing rain and then, as temperatures rose, to rain, which, together with the melting snow, brought further problems with flooding in some areas. Although much of the snow thawed quickly, drifts remained for some time in places in the Glamorgan valleys and on Exmoor and Dartmoor; even as late as 1 May a drift two feet deep still remained on Dartmoor.

The sequence of events as they occurred at Rhoose between 12 and 20 February is given in Figure 4. This shows the rise in wind speeds coinciding with the snow on 15–16 and 18–19 February and also the combination of below-freezing temperatures and strong winds on 18–19 February. In fact at Rhoose there were 15 hours on 18–19 February 1978 when the temperature was below freezing and the associated hourly mean wind speed was 29 knots or more. This is no common occurrence and there have been only 30 such hours during the past 18 years; only one of these occasions was in February (February 1969, also in conjunction with snow.)

5. Some problems caused by the blizzard

Eyewitnesses in some of the worst affected areas spoke of the suddenness with which vehicles became buried in the snow; the drifts were forming much more quickly than they could be cleared. At one stage all inessential transport was prohibited from entering Devon to ease the work of the snow ploughs and rescue workers.

Farmers in Devon and Somerset reported drifts up to the eaves of their houses and on Dartmoor some drifts reached the top of the walls of Princetown Prison. Sheep, which tend to seek shelter in the lee of banks or hedges, were buried in the drifts, though many were rescued after several days. Unfortunately the floods which followed the blizzard drowned some of the sheep before they could be dug

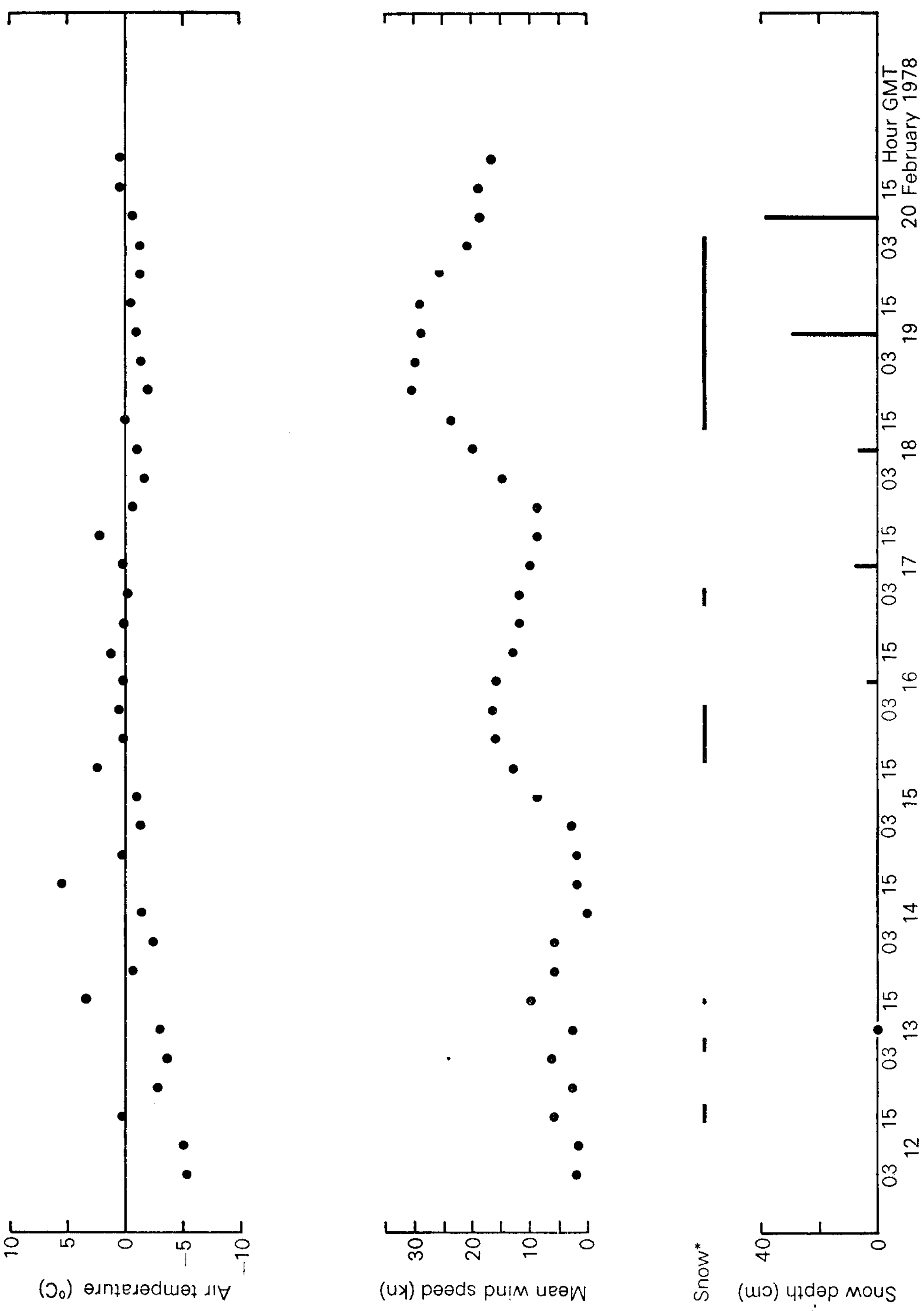

Figure 4. Temperature, wind speed and snow recorded at Cardiff/Wales Airport. Wind speeds are 10-minute means; * indicates duration of snow falling.

out. A farmer near Lynton had so much snow in his yard that he could not find his horses. Later he managed to dig down to them where they were lying on their backs and get them into the barn where they thawed out and revived. In a number of places milk could not be transported from the farms and had to be poured away.

Considerable damage was done to trees and property. Glasshouses suffered greatly as they collapsed under the weight of snow. On the west side of Dartmoor hundreds of trees were brought down by the snow and wind. The Royal Mint, Llantrisant, had to close and the staff were sent home. Electricity lines were damaged and this caused pump failure and lack of water supplies to some areas. In the Cardiff area many people attending the Wales–Scotland rugby match found themselves stranded for several days.

The thaw brought its attendant problems. Dense fog curtailed helicopter flights that were engaged in rescue work and in flying in supplies to stranded communities and fodder for cattle and other livestock. Heavy rain combined with the melting snow coinciding with the high tides brought flooding to Kingsbridge (Devon) where the water rose to seven feet in the town. Fields were flooded in many areas, especially in the Taw and Torridge valleys and around Taunton. Huge slabs of snow drifted down the swollen streams, and lakes formed behind snowdrifts.

The weather observers, both professional and amateur, had an arduous task during these days as instruments became buried in snow and the difficulties of reaching the site became almost insurmountable. At Rhoose the enclosure was inaccessible because of deep snow from the 18th to the 20th. At Hartland Point on the 18th observers were unable to open the screen because of icing and remarks for the 19th–20th state 'station closed down—snowed under'. The climatological observer at Sidmouth turned out although suffering from bronchitis but found the journey to the site too strenuous and had to seek shelter in a nearby house. The following account by the observer at Chawleigh (Devon) gives some idea of the appalling conditions.

'Doing the 2100 ob at Chawleigh on Saturday 18th was very difficult as it was next to impossible to see; however the 40 metre journey to the enclosure was made successfully. The 0900 [observation] on Sunday morning however was done in impossible conditions—great drifts of snow 15 ft high or more had to be climbed with visibility almost non-existent, the temperature was −2.0 °C and the wind near 50 kt—indeed conditions were almost beyond the limit of human endurance and the observation was a nightmare, as was the 2100 the same day.'

6. Past snowstorms in the south-west

The following are some of the more severe snowstorms to which the south-west of England and South Wales have been subjected.

1962/63. Although the total amount of precipitation during this winter was not great there were some heavy falls of snow in the south-west. Tredegar (Gwent) recorded 65 inches (156 cm) of level snow on 8 and 9 February. This weather was caused by troughs of low pressure moving into southern England from France (Shellard, 1968; Meteorological Office, 1963).

1947. A trough moving west from the continent covered virtually all Britain with snow on 27/28 January, and a depression which formed on this trough became centred in the western Channel and prolonged the snow in south-west England, including the Isles of Scilly, where 7 inches (18 cm) were measured (Douglas, 1947; Meteorological Office, 1947).

1945. A complex situation of small secondary lows off the south-west coasts moved east and brought snow to the Bristol Channel areas during the period 22–25 January. Cardiff recorded 30 inches (76 cm) of level snow; Okehampton (Devon) reported a greater depth than at any time since 1895 but remarked that there was little drifting (Bonacina, 1950; Jackson, 1977).

1933. Snowfall, associated with a polar low which developed in St George's Channel and moved southwards, affected a wide area of England and Wales on 23–26 February. In South Wales the general depth of level snow was 1–2 feet (30–60 cm) with deep drifts (Bonacina, 1937).

1929. On 16 February heavy snowstorms occurred in west England and Wales. Cardiff had great difficulty in keeping the streets clear of snow. On Dartmoor it was estimated that up to six feet (180 cm) of snow fell in 15 hours. This is thought to be the deepest fall of snow in a single storm anywhere in the British Isles at so low an elevation as 1000 ft (300 m), but it cannot be classed as a blizzard as there was little wind at the time (Bonacina, 1937).

1927. Heavy snow over the Christmas period was accompanied by gale force north-easterly winds engendered by a depression in the western Channel. Drifts of 20 ft (6 m) were reported on Salisbury Plain and on Dartmoor the prison was unapproachable for days. On the south coast the effects of drifting were most striking; there were reports of snow being blown off the Isle of Wight over the sea. In terms of drifting this storm was comparable with those of 1881 and 1891 (Bonacina, 1937; Jackson, 1977; Douglas, 1928).

1891. From 9 to 13 March the 'great west country blizzard' affected the whole of the south of England and South Wales with areas of great intensity in Kent and in Devon and Cornwall. The average depth of snow in the south-west was reported as about 2 ft (60 cm) with immense drifts, and locally on Dartmoor this amount was doubled by a secondary outbreak of snow on 12 March. Great disruption to transport was caused, with many trains marooned and many ships sunk in the Channel. In those days drifts had to be cleared by manual labour, the railway gangers vying with each other to keep their own lines open. This blizzard was the result of waves developing on a cold front: one such low-pressure centre, on 9–10 March, deepened at Ushant and moved up the Channel, depositing snow in drifts with the strong east to north-east winds (Bonacina, 1928; Jackson, 1977; Symons, 1891; Shellard, 1968).

1881. The great blizzard of 18–21 January mainly affected the Wessex area, that is to say east Devon, Somerset, Dorset, Wiltshire and Hampshire. The Isle of Wight was particularly badly hit: 'the depth of snow which was doubled on 20th was about 3 feet with gigantic drifts'. A depression was centred near the Channel Islands on the 18th and moved steadily up Channel. The blizzard was described at the time as the worst since 1836 (Bonacina, 1928; Symons, 1891).

Figures 5 and 6 show the distribution of the maximum snowfall in 1881 and 1891 (Jackson, 1976).

7. Conclusion

The main features of the blizzard of February 1978 were the comparative shortness of the cold spell, the persistence of the snowfall in one area for two days, the severity of the drifting and the quickness of onset of both the snow and the thaw.

The snowfall was the heaviest to occur in the south-west for many years. The combination of so much snow with gales had not been experienced in Devon since 1927 and in south-west England and South Wales as a whole since 1891.

Of the eight outstanding storms in the south-west since 1850 the visitations of March 1891 and January 1881 seem to have been very similar in extent and severity to those of 1978. All three were the result of low-pressure centres in the western Channel.

Bonacina (1928) remarks that in the storms of 1881, 1891 and 1927 there were two phases to the snowfall with a gap of one or two days between, and although in each phase the depths were substantial it was the combination of the two falls which produced such outstanding conditions. This feature was present also in 1978; the snow on 15 and 16 February was followed by the main blizzard of 18–19 February which more than doubled the depths of snow and drifts in some areas.

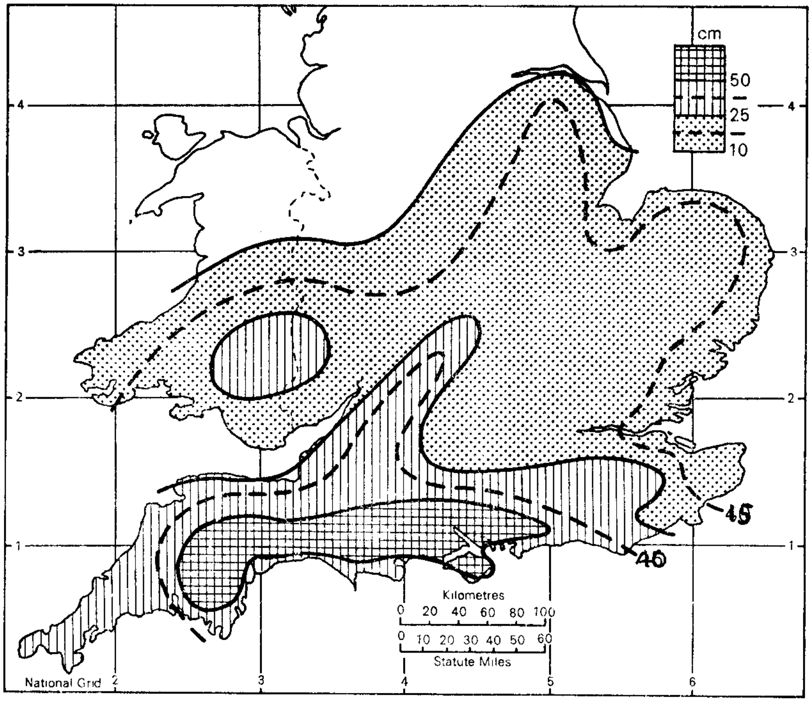

Figure 5. Maximum snow depths 17–21 January 1881.
(N.B. Correction: the '15' and '40' labels should be interchanged.)

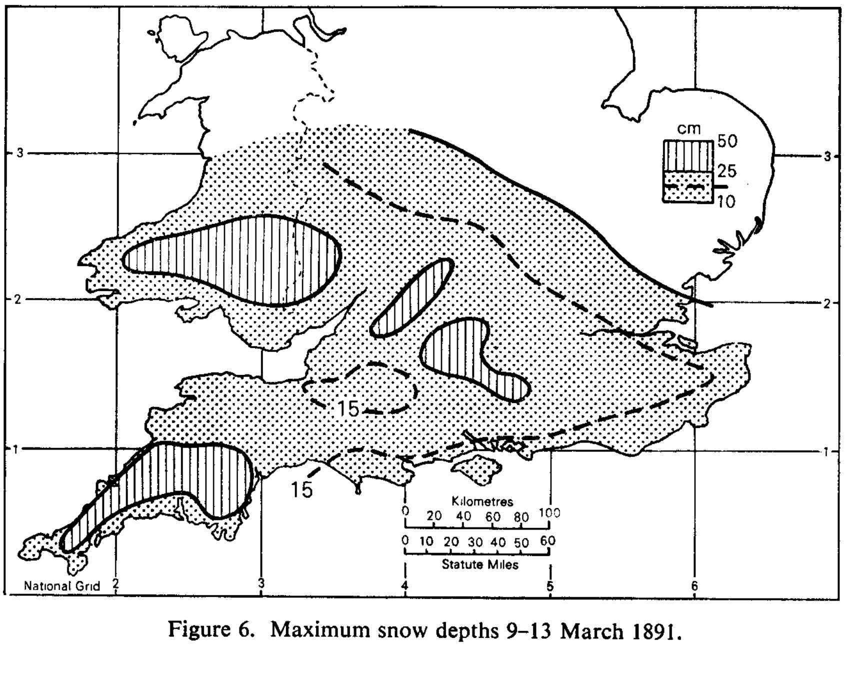

Figure 6. Maximum snow depths 9–13 March 1891.

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Notes and news

Dr P. M. A. Bourke

Dr P. M. Austin Bourke, Director of the Irish Meteorological Service since 1964, retired in May of last year. Apart from a few years as a university lecturer in mathematics, his career was spent entirely in the Irish Meteorological Service. He became well known for his work on agricultural meteorology and had regular close contact with Mr L. P. Smith and the Agricultural Meteorology section of the Meteorological Office; he preceded Mr Smith as president of the WMO Commission for Agricultural Meteorology, serving from 1958 to 1962.

Dr Bourke is highly regarded, not only for his intellectual ability, but also for his humour and charm which have enlivened many international meetings. We wish him well in his doubtless active retirement.

Obituary

We record with regret the death on 12 January 1979 of Miss C. A. Parkhouse, Assistant Scientific Officer, HQ Strike Command, after a brief illness. Miss Parkhouse joined the Office in August 1978.

Corrections

Meteorological Magazine, Volume 107, December 1978; article by J. P. Cowley. The unit used for Figure 5, pp. 366–372, is MJ m^{-2}.

Meteorological Magazine, Volume 108, January 1979; article by C. J. Richards. In the penultimate line of the caption to Figure 2, p. 14, 1970 should read 1976. In equation (10), p. 22, a fraction bar and a figure 2 have been omitted after the second square-root sign.

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NOTICES

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