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DROUGHT CLASSIFICATIONS AND A STUDY OF DROUGHTS AT KEW

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SUMMARY

Four objective methods of drought analysis are presented. Two are essentially based on meteorological parameters, one is based on hydrologically effective rainfall (defined in a simple manner) and the fourth is a very simple model for grassland drought. The various droughts (30 days' duration or longer) which occurred at Kew in the period 1871–1975 are ranked, using the four indices, and the more outstanding examples are briefly compared and described.

1. INTRODUCTION

There is no universally agreed definition of drought although the word is associated with rainfall deficiencies over more or less prolonged periods. Numerous indices of drought have been devised by meteorologists, hydrologists, agriculturists, geographers and others for specific purposes and to suit the climatology of particular parts of the world. Hounam *et alii* (1975) review the subject from a broad base, albeit with an agricultural bias, and give a comprehensive list of references.

In this paper emphasis is placed firstly on regarding drought as a relative phenomenon and secondly on relating it to a particular water use. Drought could be said to occur whenever the local water supplies of a district fall below the level associated with the more common fluctuations. Absolute values may be used to measure the severity of a drought, but these do not always enable comparisons with other areas to be readily made. Normally, however, such comparisons are required and relative measures must then be used. When a water deficiency is expressed in terms of an average no account is taken of difference in the variability of rainfall from place to place. Water usages may be expected to be geared to variability of supply. Management techniques in an area of high rainfall variability are generally more flexible than those in areas with more reliable rainfall. A practical way of including the effects of rainfall variability is to relate the severity of a drought to its return period, although simple ranking is used in the illustrative, single-station analysis for Kew.

Drought should also be related to water use. Agriculture is chiefly concerned with adequate summer rain to offset the evaporation and transpiration which occurs in that season. On the other hand, hydrological interests lie much more with winter rain which provides run-off for reservoirs and percolation to recharge aquifers. It seems sensible, therefore, to describe 'hydrological' drought and 'agricultural' drought separately. Various workers, notably Palmer (1961, 1965) have tried to combine these two types of water demand and hence to produce an overall measure of drought severity. In view of the great difference between hydrological and agricultural drought it is doubtful whether an assessment based on the mean of both has any special value. Physical considerations alone, unrelated to water usage, lead to a definition of 'meteorological' drought based only on meteorological parameters.

2. 'METEOROLOGICAL' DROUGHT

A simple measure of 'meteorological' drought (D_m) is the fractional deviation of rainfall (R) from the average ($\bar{R}$),

i.e. $$D_{m,1} = (R - \bar{R})/\bar{R}. \qquad (1)$$

In order to obtain a more accurate representation of the water balance, the effects of evaporation (taken to include transpiration) should be included. The potential evaporation (E_p) is the evaporation which takes place when the water supply is unrestricted. As such it is dependent only upon meteorological elements (radiation, temperature, wind and humidity), and hence is suitable for inclusion in a parameterization of 'meteorological' drought. Equation (1) can be modified to include the effects of E_p by writing

$$D_{m,2} = [(R - E_p) - (\bar{R} - \bar{E}_p)]/\bar{R}. \qquad (2)$$

In winter E_p does not depart significantly from mean values whereas in summer large deviations from average may occur. Hence the evaporation terms in equation (2) have much more effect in summer than in winter. For comparing 'meteorological' droughts which occur in the same seasons $D_{m,2}$ should be used. For comparing 'meteorological' droughts occurring in different seasons $D_{m,1}$ is to be preferred since $(E_p - \bar{E}_p)$ can be much larger in a summer month than in a winter month and for a given rainfall deficiency a summer-month $D_{m,2}$ value is likely to be more extreme than a winter-month value.

3. A SIMPLE MEASURE OF 'HYDROLOGICAL' DROUGHT

Hydrologists in the UK are interested in adequate winter rains to fill reservoirs and recharge aquifers. The hydrologically effective rainfall (R_e) for such purposes is the water surplus remaining after evaporation has taken place and any soil moisture deficit has been removed. R_e is therefore a possible measure of 'hydrological' drought

i.e. $$D_h = R_e. \qquad (3)$$

In order to calculate R_e it is necessary to model the departure of the actual rate of evaporation from the potential rate under conditions of soil moisture stress. In the present study, for simplicity, the root-constant concept of Penman (1949), as used by Grindley (1967) in the *Meteorological Office Soil Moisture Deficit Bulletin*, is employed. All the soil moisture lying within the rooting depth of a plant is transpired at the potential rate, and this amount of water, expressed as equivalent depth of rainfall, is the 'root constant'. In the model a further 0·8 inch (20·3 mm) of water are then allowed to be transpired at the potential rate before the ratio of actual to potential evaporation falls to a value of one-twelfth. In this paper a root constant of 3 inches, generally considered appropriate for grass, is used.

R_e is extremely seasonal in character, mostly occurring during winter, and water resources should be geared to withstand a long period of water depletion during the summer. To a first approximation, therefore, 'hydrological' drought may be regarded as a problem of deficiency of annual R_e. For this purpose the calendar year is unsuitable and the 12-month period from July to June is adopted here.

Hydrological interests are sensitive to R_e summed over more than one year; an excess or deficiency of R_e in any given year will be carried over to subsequent years. In Section 6 of this paper, in which comparisons of 'hydrological' drought at Kew are made, durations of up to 3 years are considered.

4. A SIMPLE MEASURE OF 'GRASSLAND' DROUGHT

Agricultural drought (D_a) is a general term covering a wide range of cases. Every crop has its own drought-sensitive periods, and a proper analysis should treat each crop separately. Grass, however, covers about 70 per cent of agricultural land in this country, and so in this paper attention is limited to grass.

The effects of agricultural drought in agriculture are felt mainly through the associated reduction in crop yield. For grass, crop yield may be related to plant growth, and this is reduced when the supply of either water or nutrients to the plant is restricted. The nutrients are mostly contained in the topmost layers of soil, where the most accessible soil water is also held. It follows that plant growth becomes restricted when the availability of water from the upper layers of soil becomes restricted. A possible measure of 'grassland' drought is therefore

$$D_a = E_p - E_g, \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

where E_g is defined as the evaporation (transpiration) effective for growth, and can be associated with water which has been mainly derived from the topmost layers of soil. In this paper, E_g has been obtained from E_p by using a 1 inch (25·4 mm) root constant. In Section 6, comparisons are made for $(E_p - E_g)$ summed over a whole year.

5. LIMITATIONS OF THE PRESENT ANALYSIS

It must be emphasized that the measure of 'hydrological' and 'grassland' drought proposed here are tentative and simple in character. In equations (3) and (4), D_h and D_a are expressed in absolute units and, for a drought of given return period, will take values which depend mainly upon the mean rainfall of the station under consideration. In order to obtain meaningful values of D_h and D_a meaned over an area, it would be necessary to derive expressions from which the dependence on mean rainfall has been removed. Such expressions would be rather complex, however, and as in Section 6, only results from a single station are considered, the simple equations using absolute units having been retained.

In the comparison of droughts made in Section 6, no attempt is made to calculate their return periods. The droughts in a given record are ranked in order of decreasing severity, and these rankings are then compared with one another.

6. Comparison of droughts at Kew over the period 1871–1975

Daily rainfalls have been recorded at Kew since 1871 but monthly averages of all the data required by the Penman formula for potential evaporation are only available from October 1876 onwards. Approximations to Penman potential evaporation prepared by Wales-Smith (1973) have been used for the period January 1871 to September 1876. Daily values of potential evaporation were estimated by apportioning monthly totals in accordance with the elevation of the sun. A complete analysis of 'meteorological', 'hydrological' and 'grassland' drought was made in the manner already described. The mean monthly values of rainfall and potential evaporation at Kew over the period 1871–1975 are given in Table I.

Table I—Mean monthly rainfall and potential evaporation (E_p) at Kew from 1871 to 1975

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean rainfall (mm)	50·0	38·9	39·3	42·2	44·9	50·5	59·3	57·7	52·8	60·2	61·1	53·8	610·7
Mean E_p (mm)	6·6	14·1	32·3	55·5	83·2	97·4	99·2	80·6	47·6	21·2	7·5	4·5	549·7

The ten most severe, independent (non-overlapping) 'meteorological' droughts ($D_{m,1}$ and $D_{m,2}$) corresponding to 12 chosen durations ranging from 30 days to 36 months, are presented in Tables II and III. For durations of 30 to 90 days daily rainfalls were analysed and droughts were allowed to start on any day of the month. For durations of four months or more only calendar-month data were analysed and the droughts were measured from the first day of the starting month. The 'non-overlapping' ranks were obtained from a list of droughts which were not allowed to overlap one another. The 'overlapping' rank was obtained from a list of droughts, each of which, to be counted, had to start within a different calendar month from the others. The averages from which the deviations are quoted are those for the period 1871–1975 (see Table I).

The ten most severe 'hydrological' and 'grassland' droughts (D_h and D_a respectively) are presented in Tables IV and V. The ranks were obtained from a list of droughts, each of which had to start in a different year. For 'hydrological' drought lasting over a winter, the year quoted corresponds to the first half of the season. Thus an entry for the year 1947 refers to the winter of 1947–48. For droughts assessed over more than a year the starting date is given. Thus for 'hydrological' drought measured over three years an entry of 1962 refers to the winters of 1962–63, 1963–64 and 1964–65.

Table VI lists the rankings of the more notable droughts of various types at Kew during the period 1871–1975. Each drought is identified loosely by the year in which the driest weather occurred. The Table enables the main characteristics of each drought to be readily identified and compared with others. A brief commentary on each of the listed droughts is given below.

1890

The winter of 1890–91 was one of considerable meteorological interest, and is described by Brodie (1891). The dry weather lasted from September 1890 to April 1891, and gave rise to a typical 'hydrological' drought. Over an eight-month period the rainfall deficiency ranks as the second most severe in the period under consideration, but as a result of the drought occurring during winter, when E_p seldom departs much from average, its position drops to sixth when $(R - E_p)$ is used as a basis for comparison. The summers of 1890 and 1891 being wet, there was no 'grassland' drought, but the winter of 1890–91 was one of four which failed to record any R_e.

1893

In contrast the summer of 1893, described by Brodie (1894), represents a typical 'grassland' drought. The dry weather encompassed the period March to September and the rainfall deficiency over 75 days starting in early March was the most severe ever recorded over that length of time. The March to September rainfall deficiency ranks seventh over a period of seven months, and when E_p is taken into account it rises to fourth. Since the dry weather spanned the summer half-year a 'grassland' drought ensued, and this stands as the third most severe on record.

1895–1902

The period from 1895 to 1902 was one of protracted dryness. The central portion, in 1897 and 1898, is described by Brodie (1899). For 'meteorological' drought based on $(R - E_p)$, the first six months of 1895 rank ninth, the 24 months starting in October 1897 rank fifth, and the 36 months starting in May 1899 rank second. The winters of 1897 and 1901 both enter the rankings for 'hydrological' drought, and the summer of 1899 stands as the ninth most severe 'grassland' drought. It is over a long period of time, however, that the drought becomes oustanding—for five years starting in May 1897 the rainfall was 20 per cent deficient, and R_e summed over the winters 1897–98 and 1902–03 was the second lowest recorded over a period of five years.

1921

The drought of 1921 is the most famous of all 'meteorological' droughts this century, and is described by Brooks and Glasspoole (1922). Maximum severity was attained over a period of about 12 months comprising the calendar year of 1921, but a glance at Table VI reveals how this drought dominates a wide range of time scales. The associated 'hydrological' and 'grassland' effects are, however, less outstanding. The 'grassland' drought of 1921 was surpassed by that of 1959, while the most severe 'hydrological' effects are obtained over a duration of three years, when the winters of 1919–20, 1920–21 and 1921–22 gave the third lowest total of R_e to be observed.

1933

The period of dry weather occurring around 1933, described by Glasspoole (1935), is remembered chiefly for its 'hydrological' effects. Maximum 'meteorological' severity occurred over a period of 24 months starting in November 1932. The rainfall deficiency stands as the worst on record over a period of 24 months, although when E_p is taken into account it ranks second. 'Grassland' effects were moderate, with the summer of 1933 ranking tenth, but the winter of 1933–34 was one of four when no R_e occurred, and R_e summed over the winters of 1933–34 and 1934–35 was the second lowest ever for a period of two years.

1938

The dry spell which occurred between February and July 1938 represents the most severe rainfall deficiency on record over a period of six months.

TABLE II—'METEOROLOGICAL' DROUGHT AT KEW FROM 1871 TO 1975: $D_{m,1} = (R - \bar{R})/\bar{R}$

Duration of drought

Non-o'lapping Rank	30 days Starting Date	30 days $D_{m,1}$	30 days O'lapping Rank	60 days Starting Date	60 days $D_{m,1}$	60 days O'lapping Rank	90 days Starting Rank	90 days $D_{m,1}$	90 days O'lapping Rank	4 months Starting Date	4 months $D_{m,1}$	4 months O'lapping Rank
1	10 Apr 1942	−1·000	1	27 Jun 1921	−0·951	1	1 Feb 1938	−0·861	1	May 1921	−0·723	1
2	20 Feb 1953	−1·000	2	6 Mar 1893	−0·943	2	30 May 1921	−0·856	2	Mar 1938	−0·713	2
3	14 Aug 1959	−1·000	3	31 Aug 1969	−0·937	3	6 Aug 1947	−0·765	6	Aug 1947	−0·694	4
4	23 Aug 1929	−0·998	4	3 Feb 1929	−0·906	7	1 Oct 1879	−0·753	7	Feb 1956	−0·670	6
5	14 Sep 1921	−0·995	5	1 Mar 1938	−0·897	8	1 Jan 1929	−0·748	9	Oct 1879	−0·668	7
6	20 May 1934	−0·992	6	14 Aug 1959	−0·884	10	5 Aug 1969	−0·748	10	Jul 1972	−0·667	8
7	4 Jun 1949	−0·991	7	21 Jan 1932	−0·865	11	10 Jun 1972	−0·747	11	Nov 1933	−0·666	9
8	18 Apr 1896	−0·986	8	16 Feb 1943	−0·861	12	17 Dec 1972	−0·747	12	Jan 1929	−0·651	11
9	1 Mar 1929	−0·984	9	19 Jul 1947	−0·855	13	2 Nov 1933	−0·732	15	Jun 1959	−0·608	17
10	11 Jun 1941	−0·983	11	9 Jul 1972	−0·850	14	9 Nov 1953	−0·730	16	Mar 1893	−0·601	18

Duration of drought

Non-o'lapping Rank	5 months Starting Date	5 months $D_{m,1}$	5 months O'lapping Rank	6 months Starting Date	6 months $D_{m,1}$	6 months O'lapping Rank	9 months Starting Date	9 months $D_{m,1}$	9 months O'lapping Rank	12 months Starting Date	12 months $D_{m,1}$	12 months O'lapping Rank
1	Feb 1938	−0·728	1	Feb 1938	−0·692	1	Feb 1921	−0·596	1	Jan 1921	−0·495	1
2	Jun 1921	−0·680	2	May 1921	−0·647	2	Jun 1972	−0·514	4	Apr 1972	−0·485	3
3	Jun 1972	−0·665	4	May 1972	−0·634	4	Oct 1933	−0·473	10	Oct 1897	−0·416	11
4	Jul 1947	−0·633	6	Jan 1929	−0·570	8	Aug 1890	−0·462	12	Jul 1933	−0·413	12
5	May 1959	−0·624	7	Sep 1890	−0·567	9	Feb 1959	−0·459	13	Jul 1955	−0·350	26
6	Oct 1933	−0·603	10	Dec 1873	−0·548	12	Jan 1929	−0·451	14	Oct 1948	−0·348	28
7	Jan 1929	−0·574	12	May 1959	−0·547	13	Feb 1938	−0·429	21	Jun 1933	−0·338	30
8	Feb 1895	−0·570	13	Jul 1947	−0·533	16	Dec 1873	−0·425	22	Nov 1928	−0·322	35
9	Oct 1890	−0·537	20	Jan 1895	−0·515	17	Nov 1943	−0·412	25	Nov 1958	−0·313	—
10	Feb 1956	−0·539	21	Oct 1879	−0·513	18	Oct 1879	−0·409	26	Jul 1964	−0·310	—

Duration of drought

Non-o'lapping Rank	18 months Starting Date	18 months $D_{m,1}$	18 months O'lapping Rank	24 months Starting Date	24 months $D_{m,1}$	24 months O'lapping Rank	30 months Starting Date	30 months $D_{m,1}$	30 months O'lapping Rank	36 months Starting Date	36 months $D_{m,1}$	36 months O'lapping Rank
1	Aug 1920	−0·376	1	Nov 1932	−0·308	1	Aug 1920	−0·272	1	Sep 1971	−0·237	1
2	Sep 1971	−0·350	4	Nov 1920	−0·304	2	Aug 1947	−0·265	2	Oct 1920	−0·228	3
3	Jun 1933	−0·336	7	Jun 1972	−0·285	7	Jul 1971	−0·260	3	Dec 1931	−0·223	5
4	Feb 1943	−0·327	10	Aug 1947	−0·277	12	Jun 1932	−0·249	5	Feb 1943	−0·221	6
5	Apr 1897	−0·319	17	Sep 1897	−0·267	16	Apr 1897	−0·236	15	Jul 1947	−0·202	13
6	Apr 1948	−0·278	39	Mar 1900	−0·251	27	Jun 1943	−0·224	24	May 1899	−0·198	18
7	Jan 1959	−0·262	—	Mar 1943	−0·239	36	Mar 1900	−0·180	—	Dec 1895	−0·156	—
8	Mar 1873	−0·257	—	Mar 1883	−0·166	—	Dec 1953	−0·175	—	Mar 1961	−0·131	—
9	Sep 1900	−0·253	—	Jul 1955	−0·165	—	Mar 1883	−0·137	—	Jun 1953	−0·129	—
10	Dec 1954	−0·251	—	Mar 1961	−0·149	—	Mar 1961	−0·128	—	Apr 1904	−0·109	—

A dash indicates that the overlapping rank exceeds 40.

TABLE III—'METEOROLOGICAL' DROUGHT AT KEW FROM 1871 TO 1975:

$$D_{m,2} = [(R - E_p) - (\bar{R} - \bar{E}_p)]/\bar{R}$$

Duration of drought

Non-o'lapping Rank	30 days Starting Date	30 days $D_{m,2}$	30 days O'lapping Rank	60 days Starting Date	60 days $D_{m,2}$	60 days O'lapping Rank	90 days Starting Date	90 days $D_{m,2}$	90 days O'lapping Rank	4 months Starting Date	4 months $D_{m,2}$	4 months O'lapping Rank
1	1 Jul 1921	−1·406	1	4 Jun 1921	−1·293	1	3 Jun 1975	−1·137	1	Jun 1959	−1·003	1
2	3 Jun 1975	−1·402	3	15 Mar 1893	−1·214	3	14 May 1921	−1·125	2	May 1921	−0·938	2
3	1 Sep 1959	−1·388	4	14 Aug 1959	−1·207	4	27 Apr 1959	−1·042	5	Aug 1947	−0·847	6
4	10 Apr 1942	−1·379	5	3 Jul 1899	−1·176	5	5 Aug 1947	−0·951	9	Mar 1957	−0·817	8
5	27 Jul 1899	−1·362	6	3 Jun 1975	−1·151	7	1 Jul 1899	−0·948	10	Mar 1893	−0·807	9
6	1 Apr 1893	−1·340	8	1 Jul 1911	−1·139	9	30 Jun 1911	−0·947	12	Jul 1972	−0·800	10
7	5 Aug 1947	−1·338	9	27 May 1959	−1·128	11	1 Feb 1938	−0·942	15	Mar 1938	−0·798	11
8	25 Jun 1911	−1·268	12	19 Jul 1947	−1·116	12	1 Apr 1957	−0·933	17	Jun 1949	−0·772	14
9	5 May 1919	−1·262	13	17 Jun 1887	−1·072	14	14 Mar 1893	−0·928	18	May 1975	−0·762	15
10	26 Jun 1959	−1·246	15	2 May 1895	−1·015	16	7 Aug 1972	−0·901	21	Feb 1956	−0·758	16

Duration of drought

Non-o'lapping Rank	5 months Starting Date	5 months $D_{m,2}$	5 months O'lapping Rank	6 months Starting Date	6 months $D_{m,2}$	6 months O'lapping Rank	9 months Starting Date	9 months $D_{m,2}$	9 months O'lapping Rank	12 months Starting Date	12 months $D_{m,2}$	12 months O'lapping Rank
1	May 1959	−0·995	1	May 1959	−0·877	1	Feb 1921	−0·717	1	Jan 1921	−0·599	1
2	Apr 1921	−0·849	3	Feb 1921	−0·810	3	Feb 1959	−0·700	2	Apr 1972	−0·557	5
3	Feb 1938	−0·819	5	Feb 1938	−0·736	8	Jul 1972	−0·595	10	May 1959	−0·506	9
4	Jun 1972	−0·738	8	May 1972	−0·711	9	Jun 1933	−0·534	18	Jul 1933	−0·490	13
5	Jul 1947	−0·734	9	Mar 1893	−0·644	13	Jan 1949	−0·510	21	Oct 1948	−0·409	38
6	Apr 1975	−0·676	14	Jul 1947	−0·628	15	Jan 1929	−0·496	23	Oct 1897	−0·406	39
7	Mar 1893	−0·669	15	Jul 1933	−0·575	20	Jan 1893	−0·476	27	Jul 1964	−0·393	—
8	Feb 1895	−0·643	20	Sep 1964	−0·568	21	Aug 1947	−0·464	29	Aug 1947	−0·379	—
9	May 1911	−0·625	21	Jan 1895	−0·566	22	Jul 1964	−0·446	32	Apr 1943	−0·374	—
10	May 1899	−0·615	23	Apr 1949	−0·565	23	Feb 1938	−0·444	34	Jul 1955	−0·373	—

Duration of drought

Non-o'lapping Rank	18 months Starting Date	18 months $D_{m,2}$	18 months O'lapping Rank	24 months Starting Date	24 months $D_{m,2}$	24 months O'lapping Rank	30 months Starting Date	30 months $D_{m,2}$	30 months O'lapping Rank	36 months Starting Date	36 months $D_{m,2}$	36 months O'lapping Rank
1	Jan 1921	−0·435	1	Jun 1972	−0·402	1	Dec 1971	−0·373	1	Sep 1971	−0·348	1
2	Jun 1933	−0·428	2	Nov 1932	−0·378	6	Apr 1947	−0·315	11	May 1899	−0·253	11
3	Jun 1972	−0·425	3	Dec 1920	−0·335	16	Jun 1932	−0·291	13	Nov 1932	−0·249	12
4	Jan 1959	−0·422	6	Aug 1947	−0·324	21	Aug 1920	−0·284	16	Jul 1947	−0·240	20
5	Mar 1943	−0·361	26	Oct 1897	−0·301	28	Apr 1897	−0·276	19	Oct 1920	−0·236	25
6	Apr 1897	−0·330	—	Mar 1900	−0·296	32	Mar 1943	−0·233	—	Feb 1943	−0·227	32
7	Apr 1948	−0·317	—	Mar 1943	−0·259	—	Feb 1959	−0·210	—	Mar 1961	−0·174	—
8	Jun 1900	−0·314	—	Oct 1958	−0·249	—	Jan 1963	−0·172	—	Dec 1895	−0·172	—
9	Dec 1954	−0·280	—	Jul 1955	−0·206	—	Jan 1955	−0·171	—	Nov 1956	−0·171	—
10	Apr 1928	−0·250	—	Mar 1961	−0·196	—	Mar 1883	−0·165	—	Apr 1904	−0·134	—

A dash indicates that the overlapping rank exceeds 40.

When E_p is taken into account it falls to third in the rankings. The period from February to April is described by Brooks (1938). If this period of dry weather had occured wholly in either the summer or the winter it would certainly have produced either a severe 'grassland' or 'hydrological' drought. In the event, however, there was no 'hydrological' drought and 'grassland' effects were only moderate, the early summer of 1938 giving the seventh worst 'grassland' drought.

1947

The dry weather of August 1947, described by Glasspoole and Rowsell (1950), marked the start of the third most severe rainfall deficiency to be recorded over a period of four months. Then, after a respite throughout much of 1948, the 12 months starting in October of that year were the sixth driest in over 100 years. The close proximity of these two dry spells meant that the 30 month period starting in April 1947 ranks as the second driest 30 month period to be recorded. The summer of 1949 gave the sixth worst 'grassland' drought while maximum 'hydrological' severity was attained over a period of two years, when the winters of 1947–48 and 1948–49 gave the fourth lowest total of R_e.

1959

The dry weather during the summer of 1959, described by Bleasdale and Grindley (1959), extended from May to September. The rainfall deficiency ranks fifth over a period of five months, but when the effects of E_p are included it rises to first place. The accompanying 'grassland' drought stands as the worst on record.

TABLE IV—'HYDROLOGICAL' DROUGHT AT KEW FROM 1871 TO 1975

	1 year		2 years		3 years	
Rank	Year	R_e(mm)	Year	R_e(mm)	Year	R_e(mm)
1	1890	0·0	1972	55·7	1971	147·7
2	1933	0·0	1933	73·5	1962	184·4
3	1964	0·0	1971	92·0	1919	202·8
4	1972	0·0	1947	98·8	1932	231·6
5	1897	7·8	1900	106·2	1943	233·0
6	1943	34·5	1889	112·5	1970	235·3
7	1901	38·4	1963	115·2	1920	248·0
8	1873	45·8	1920	138·0	1947	260·3
9	1908	45·8	1919	149·6	1931	267·5
10	1947	49·2	1897	150·1	1953	281·4
Mean		158·1		316·2		474·3

TABLE V—'GRASSLAND' DROUGHT AT KEW FROM 1871 TO 1975

Rank	Year	$E_p - E_g$
1	1959	344·5
2	1921	320·7
3	1893	290·9
4	1972	285·0
5	1975	277·8
6	1949	271·2
7	1911	264·2
8	1938	258·4
9	1899	258·2
10	1933	241·4
Mean		142·2

1964

Smith (1965) draws attention to an interesting example of 'hydrological' drought which took place between the years of 1962 and 1965. The overall rainfall deficiency at Kew during this period was quite unexceptional and the period barely enters the ranking for 'meteorological' drought. Such rainfall deficiency as there was, however, occurred mainly during the winter months and a surprisingly severe 'hydrological' drought ensued. No R_e occurred during the winter of 1964–65 and, taken with the two previous winters, this led to the second worst example of 'hydrological' drought over three years.

TABLE VI—RANKING OF SELECTED DROUGHTS AT KEW FROM 1871 TO 1975

	Duration	1890	1893	1898	1921	1933	1947	1959	1964	1972
	30 days	—	—	—	5	—	—	3	—	—
	60 days	—	2	—	1	—	9	6	—	10
	90 days	—	—	—	2	9	3	—	—	7
	4 months	—	10	—	1	7	3	9	—	6
	5 months	9	—	—	2	6	4	5	—	3
$D_{m,1}$	6 months	5	—	—	2	—	8	7	—	3
	9 months	4	—	—	1	3	—	5	—	2
	12 months	—	—	3	1	4	—	9	—	2
	18 months	—	—	5	1	3	—	7	—	2
	24 months	—	—	5	2	1	4	—	—	3
	30 months	—	—	5	1	4	2	—	10	3
	36 months	—	—	5	2	3	5	—	8	1
	30 days	—	6	—	1	—	7	3	—	—
	60 days	—	2	—	1	—	8	3	—	—
	90 days	—	9	—	2	—	4	3	—	10
	4 months	—	5	—	2	—	3	1	—	6
	5 months	—	7	—	2	—	5	1	—	4
$D_{m,2}$	6 months	—	5	—	2	7	6	1	8	4
	9 months	—	7	—	1	4	8	2	9	3
	12 months	—	—	6	1	4	8	3	7	2
	18 months	—	—	6	1	2	—	4	—	3
	24 months	—	—	5	3	2	4	8	10	1
	30 months	—	—	5	4	3	2	7	8	1
	36 months	—	—	2	5	3	4	—	7	1
	1 year	0	—	5	—	0	10	—	0	0
D_h	2 years	6	—	10	8	2	4	—	7	1
	3 years	—	—	—	3	4	8	—	2	1
D_a	1 year	—	3	—	2	10	—	1	—	4

$D_{m,1}$ represents 'meteorological' drought based on rainfall; $D_{m,2}$ represents 'meteorological' drought based on $(R - E_p)$; D_h represents 'hydrological drought' and D_a represents 'grassland' drought.
A dash indicates that the drought is not one of the ten most severe recorded in the period.
An entry of zero for D_h indicates one of several observations of zero R_e.

1972

The long period of dry weather centred on the years of 1972 and 1973 was recently pointed out by Jerome (1975). Over a period of 36 months the rainfall deficiency stands as the worst on record, and when E_p is taken into account its severity increases, first position then being occupied for durations of from 24 to 36 months. The 'grassland' drought of 1972 was the fourth most severe on record, but the 'hydrological' effects are outstanding. The winter of 1972–73 was one of four which failed to record any R_e, and the low totals of R_e observed during the preceding and succeeding winters ensured that the 'hydrological' drought over two and three years was the worst ever recorded.

1976

Since the above account was written an outstanding drought has taken place which it has not been possible to include in the full calculations, but a few comments are made here. The winter of 1975–76 was unranked in terms of 'hydrological' drought, but the rainfall deficiency for periods ending in August 1976 occupied first position for durations of from seven to eleven months, and again for fifteen months. Over the nine months starting in December 1975, rainfall was only 35·5 per cent of average. Calculations of 'grassland' drought have not been made, but the summer of 1976 is likely to compare with those of 1959 and 1921.

ACKNOWLEDGEMENTS

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SATELLITE INFRA-RED NEPHANALYSES

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SUMMARY

Although infra-red imagery has been available to the meteorological user community around the world for several years via direct read-out from American weather satellites, there is no accepted international scheme for nephanalyses based on such data. This paper explores the more obvious possibilities for formal schemes of infra-red nephanalysis, and presents examples of the application of four such schemes by the analyst to a selected infra-red image. The operational user is thereby offered a choice of method for incorporation into his particular program.

INTRODUCTION

The availability of visible imagery from meteorological satellites to the local user has long been appreciated by the weather-forecasting community. Detailed schemes for the identification of clouds in satellite pictures appeared soon after the first weather satellite was launched in 1960 (Conover, 1962, 1963), and comprehensive manuals for the interpretation of clouds and cloud organizations were available in the mid 1960s (e.g. WMO, 1966). From an early stage in the development of weather-satellite systems designed to give an adequate coverage of middle and high latitudes (following the pioneer satellites whose coverage was mainly tropical), forecasters wrote enthusiastically of the increased accuracy in short-term forecasting which was possible when the new data were consulted (e.g. Houghton, 1965). However, some means had to be devised whereby relevant information could be extracted from the satellite pictures for presentation to the duty forecaster for evaluation alongside the conventional weather observations. Thus the satellite nephanalysis was conceived. Until recently, this remained the only satellite-derived statement to be invoked during the operational forecasting procedure. Whilst new possibilities have opened up recently for the provision of numerical data from satellites to be used in computer-based forecasting procedures in principal meteorological offices (for example, vertical profile data from sounding spectrometers (Atkins and Jones, 1975)), hand-drawn cloud and weather-system analyses have by no means outlived their usefulness, especially for regions where upwind weather observations are sparse, or for some reason numerical forecasting is inadequate or inappropriate. It was for this reason that the present authors proposed recently an improved scheme for the nephanalysis of satellite visible images, updating and extending the scheme which has been in widespread use for more than a decade (Harris and Barrett, 1975).

We now consider satellite infra-red images, whose availability is as regular and easy as that of the visible images, but whose contents have been utilized less in forecasting operations, especially in developing countries. Although the physical implications of the infra-red cloud images are less complex than those of the visible images, the day-to-day use of infra-red imagery has often been of a decidedly *ad hoc* nature.

Regular usage of infra-red imagery is desirable on three operational grounds in particular, namely:

(a) as supplementary information on cloudiness for those situations for which visible imagery is also available,

(b) as additional information on cloudiness for those regions not served by geostationary satellites, doubling the opportunity for viewing cloud fields (by providing information on night-time as well as day-time conditions), and

(c) as the only available information on cloudiness for high-latitude regions when under the influence of winter darkness.

THE CHARACTERISTICS OF INFRA-RED IMAGERY

Although from an early stage in the development of operational infra-red radiometers efforts have been made to extract useful information therefrom (e.g. Boldirev, 1968; Koffler *et alli*, 1973) some potential users seem to have recognized only that visible and infra-red images often indicate different attributes of clouds without seeking to enquire seriously why and how they differ, or, conversely, to what extent their contents may be similar.

The most significant feature of infra-red cloud information is that the radiation temperature of the cloud is a function of the cloud-top altitude. Problems arise where radiation from below becomes compounded with radiation from the cloud itself, for example, in thin sheets of cirrus or cirrostratus (e.g. Fritz and Rao, 1967), and where cloud elements, or breaks in a cloud field, fall below the resolution of the imaging system, for example, where fair-weather cumuli or stratocumuliform sheets are found. However, the three-dimensional view which the infra-red approach affords is immediately striking and its advantages are clear when contemporaneous visible and infra-red images of equal resolution are compared, for example, in the correct identification of jet-stream cirrus (Valovcin, 1968).

Unfortunately, the resolution of early infra-red sensors—including the so-called High Resolution Infra-red Radiometer (HRIR) flown initially on NIMBUS 2 in 1964—was rather coarse for detailed differentiation of cloud types and cloud-field analysis (see Barrett, 1974). However, current sensors—notably the Very High Resolution Radiometer (VHRR) on NOAA satellites (0·9 km*), and the high-resolution scanning radiometers on DMSP (Defense Meteorological Satellite Program) satellites (0·6 km) (Air Weather Service, 1974), provide first-class data which have much reduced the problems related to cloud or cloud-break size versus the resolving power of the satellite system. Currently, there are few if any cloud varieties which may be positively identified on a visible image but not on a contemporaneous infra-red image of the same resolution.

Concerning similarities between the two image types, the existing literature is very sparse. However, it is worth noting that similarities do exist, particularly in the apparent areal extent of cloud. Although differences may be apparent in the internal structures of clouds and cloud fields, their outlines are almost always much the same in the two types of imagery. Of course, where thin cloud exists, whether high or low, slight variations may occur depending on the relationships between cloud and background brightness in the visible waveband, or cloud and Earth surface temperatures in the infra-red, but close outline correspondence is the rule rather than the exception.

Our studies further indicate that most of, if not all, the features of cloud structure apparent in visible images may be identified on infra-red images also. Since the infra-red systems provide data with more direct physical meaning and

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* All resolution statistics represent sub-satellite point performances.

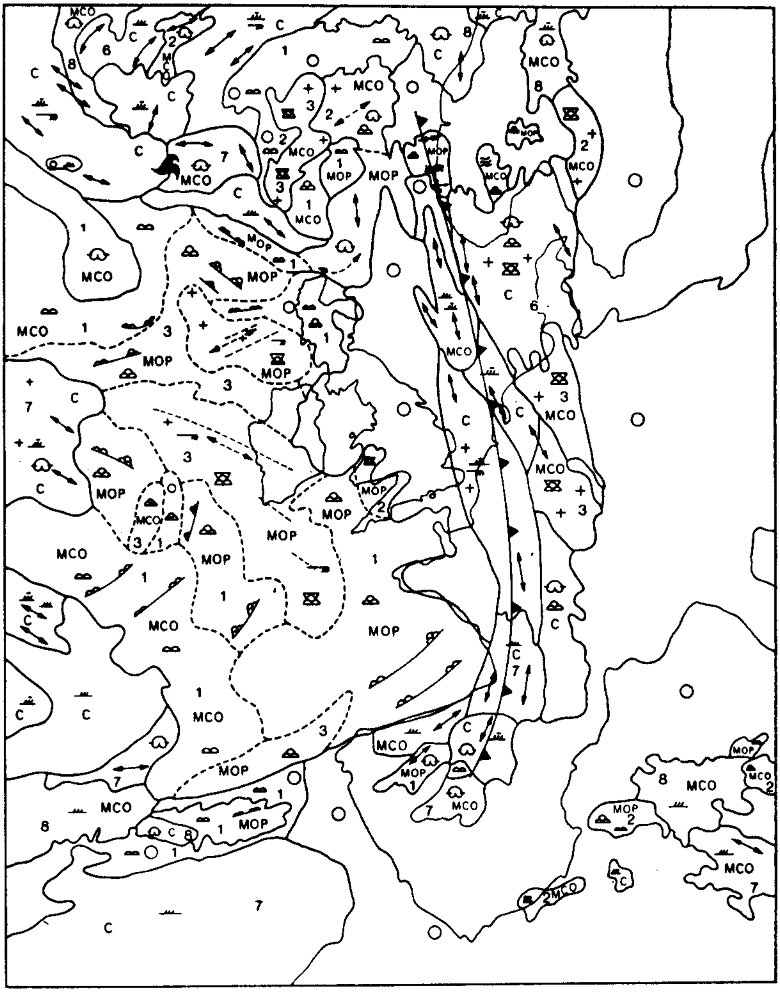

FIGURE 1—CONVENTIONAL NEPHANALYSIS OF THE DMSP INFRA-RED IMAGE SHOWN IN PLATE I

improve our view of the weather in various regions and different circumstances, as indicated on p. 11, we believe that proposals designed to formalize their analysis, and therefore to standardize the products prepared by different analysts to a greater extent, should lead to clear benefits for both operational and subsequent research users of infra-red data.

THE CHOICE OF AN INFRA-RED NEPHANALYSIS PROCEDURE

A number of possible schemes for infra-red nephanalysis may be readily envisaged. These include:

(a) A scheme employing the long-standing and internationally accepted (visible) nephanalysis code of symbols.

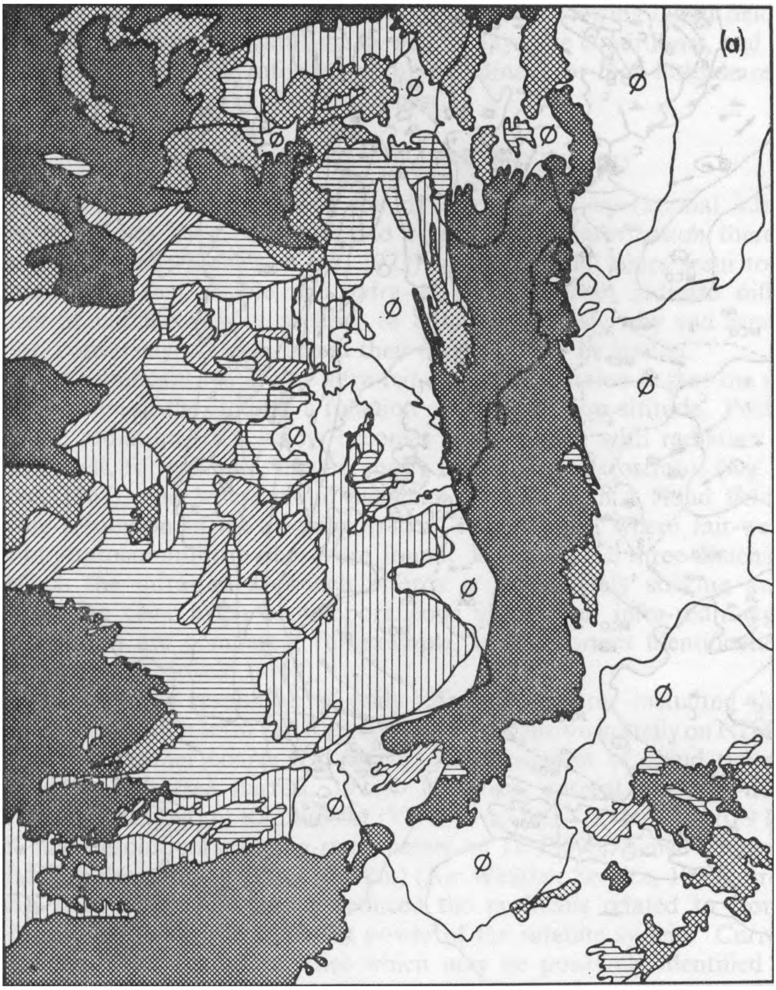

FIGURE 2—NEPHANALYSIS FOLLOWING THE IMPROVED (VISIBLE) SCHEME SUGGESTED BY HARRIS AND BARRETT (1975)

(a) cloud amount (b) cloud type and structure
(c) interpretation (d) key for Figures 2(a)–(c)

(b) A scheme following the procedure for improved operational nephanalysis of visible images, as outlined by Harris and Barrett (1975).

(c) A new scheme designed to recognize and, on a single map, to represent the special characteristics of infra-red images.

(d) A more detailed scheme for infra-red imagery analysis with the significant information displayed in a group of content-specific maps. This may be viewed as the infra-red counterpart to the improved (visible) nephanalysis (see (b) above). The sum of the parts would present considerably more information than the single-map infra-red nephanalysis.

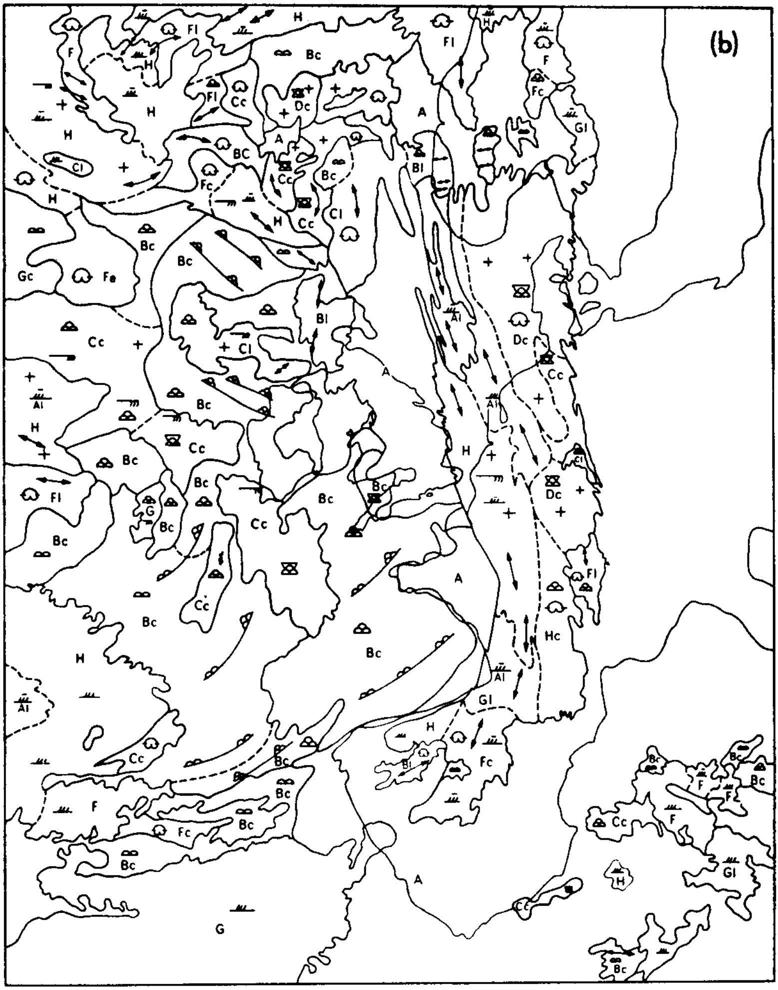

FIGURE 2—*continued*

The rationale behind this suggestion of a range of possibilities is two-fold. First, different users may have different needs, and, second, some users may wish to standardize their visible and infra-red nephanalyses on comparable bases, whilst others may have more opportunity for experiment. In every case, however, we feel that the objectives for satellite nephanalysis recognized and listed by Harris and Barrett (1975, p. 11) should be borne in mind, especially those necessitating an appropriate scale filter and standardization of the satellite image interpretation procedure.

THE PROPOSED ALTERNATIVES

We may profitably pass some further comments upon each of the procedures listed above in turn, with particular reference to the worked examples presented here as Figures 1–4, all of which are based on the same satellite image (Plate I).

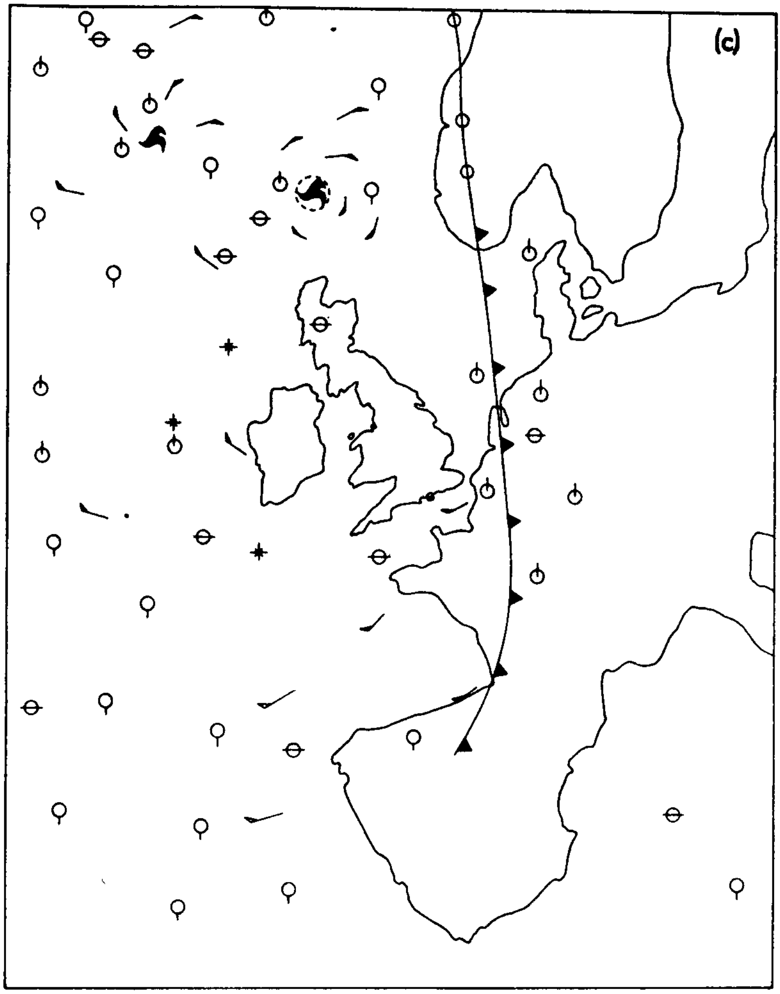

FIGURE 2—*continued*

(a) Figure 1 demonstrates that, when the differences in image characteristics are borne in mind, it is perfectly possible to produce infra-red nephanalyses directly comparable to the standard visible nephanalyses. No further comments are necessary in this case.

(b) The 'improved' nephanalysis portrayed by Figure 2 contains more detail than the standard, single-map format. It distinguishes between three basic aspects of cloudiness, namely cloud amount, cloud type and structure, and the interpretation of cloud features. Such maps may be best presented, side by side, the cloud-cover map serving as the central one of the three, with the other two as flanking overlays. In this way, any two, or all three, may be examined together as the need arises.

(c) More detailed comments are required in the case of this newly designed format. Here, special attention is paid to those aspects of infra-red imagery which are most characteristic and distinctive, namely 'cloud brightness' and

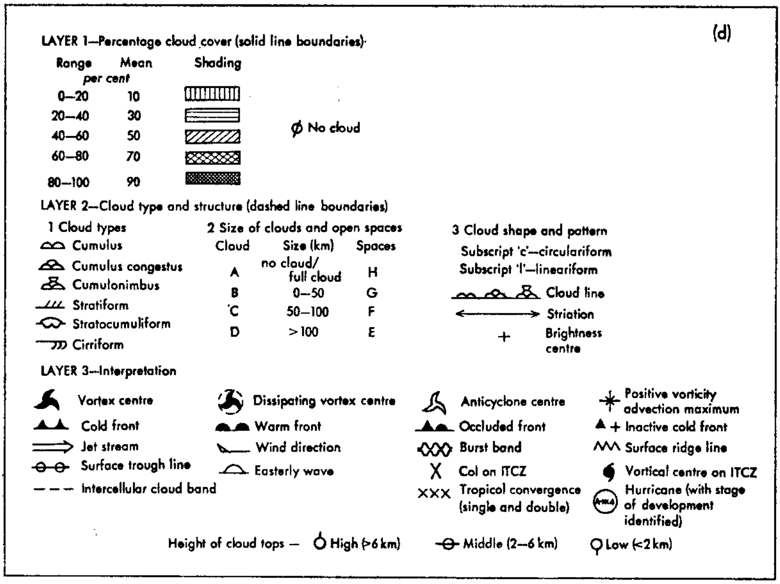

FIGURE 2—*continued*

'cloud texture'. We have already seen how infra-red picture brightness is generally well related to cloud-top height. Three brightness categories may be differentiated speedily by eye in the preparation of a single-panel nephanalysis, namely very bright, bright, and dim. The resulting map is interpretable in terms of high, middle-level and low cloud (see Bittner and Ruggles, 1970). Although synoptic, latitudinal and seasonal factors preclude the assignment of precise, constant values to the altitudes at which one brightness category gives way to the next, this fast 'eyeball' method of cloud-level identification involving so few categories is sufficiently accurate to be invoked in hand-drawn nephanalysis procedures, especially if the latitudinal spread of the area of interest is not excessive. For future uses of satellite-derived cloud-top information in computer-based forecasting programs, it will be necessary to take both local and zonal variations in temperature–height relationships into account.

Of course, it should not be forgotten that background (terrestrial) features are easily ignored by a human analyst: this is one of the most important ways in which 'eyeball' analyses score over machine-based (objective) methods of analysis currently under development. It should be noted further that, in our example, the brightness classes relate to the dominant brightness levels in each area: these would be much more difficult to assess by eye. The second most striking characteristic of the cloud contents of infra-red imagery is the 'texture' of the clouds. The key to Figure 3 illustrates the simple dendrogram on which its texture content is based.

Although Conover (1962) suggested that six criteria are necessary for successful cloud identification, namely cloud element size, shape, organization and shadow effects, in addition to brightness and texture, we feel that for most purposes the last two, considered carefully, are usually sufficient, especially in the case of infra-red studies where brightness indicates for most cloud types

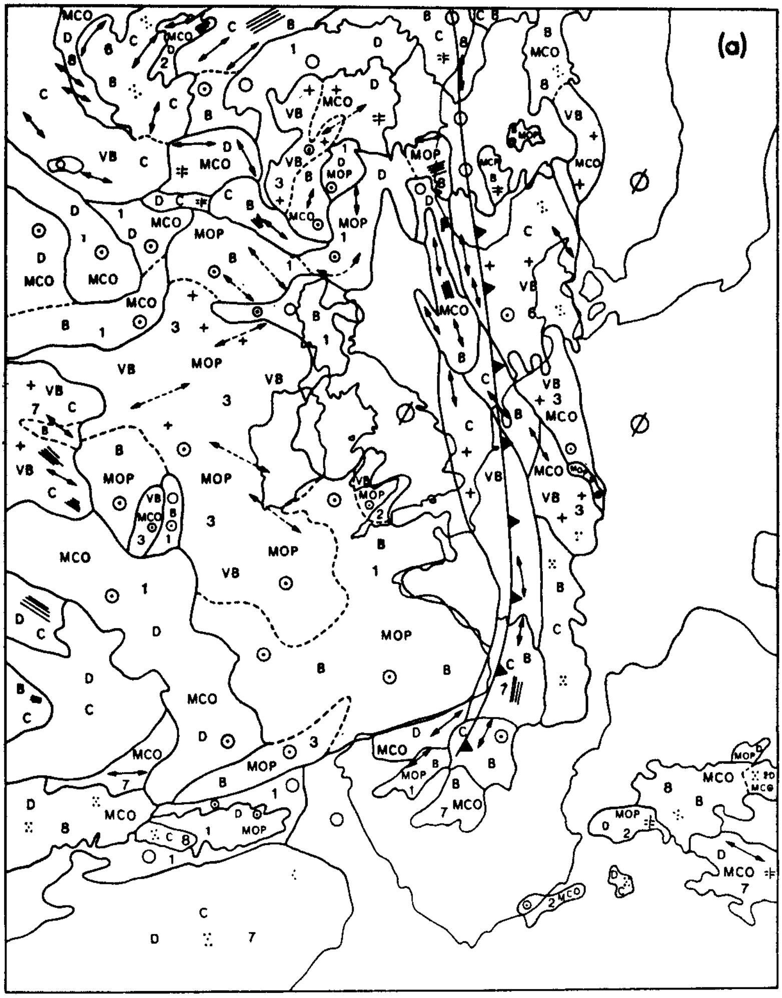

FIGURE 3(a)—SINGLE-PANEL INFRA-RED NEPHANALYSIS DISPLAYING CLOUD AMOUNT, BRIGHTNESS, TEXTURE AND INTERPRETATION FEATURES

the height of the cloud tops. The other types of information in Figure 3, the single-panel infra-red nephanalysis, are the familiar but invaluable categories of cloud amount (as in (a) in case the two might be used together), and feature interpretation. The whole has been designed to give about the same density of information content as (a), assuming the same minimum size thresholds of about 1° square for areal features and 2° long for linear features.

(d) The infra-red nephanalysis represented by Figure 4 is the most detailed that we feel might be required for either operational or research applications. The same minimum size thresholds are employed as in (c), but the various information categories are all enhanced to give more classes of subdivision. For example, the cloud-amount categories are now six instead of four, there are six cloud-brightness categories instead of three, and nine texture classes instead

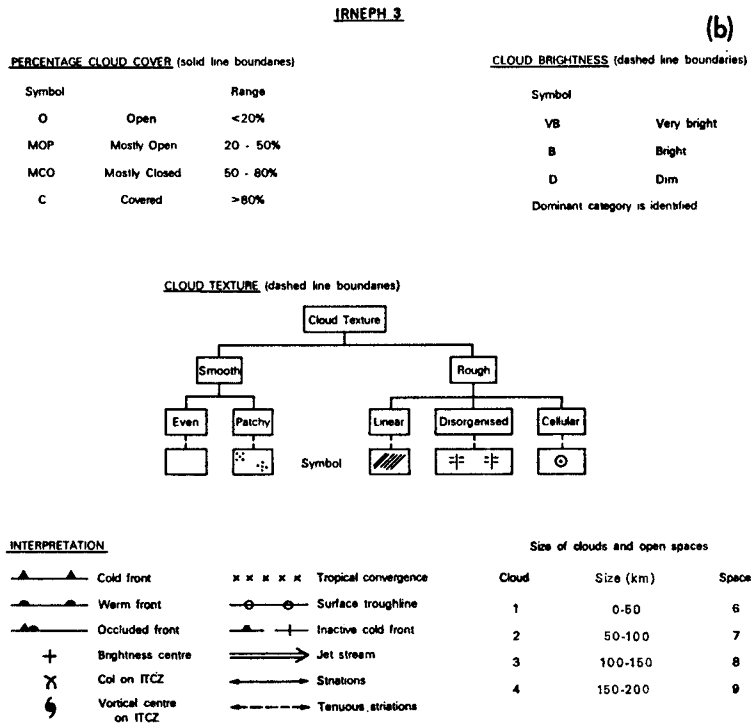

FIGURE 3(b)—KEY FOR FIGURE 3(a)

of five. The detailed additions may be identified by comparing the keys for Figures 2 and 4. Four panels or layers have been constructed for Figure 4, rather than the three in its visible counterpart (Figure 2) because we feel that the newness of the approach necessitates the extra flexibility for intercomparison between the types of information represented. It would be possible, with no loss of detail or any danger of overloading, to combine the cloud-amount and cloud-brightness panels should the saving in space be preferred. The brightness classes are based on the three utilized in the single-panel nephanalysis with three new classes added to indicate areas of roughly equal brightness mixtures. The shading relating to the nine texture classes is generally non-directional, though directional indications can be given where linear features are concerned.

CONCLUSIONS

There seem to be no irresistible reasons why infra-red images from weather satellites should not be invoked more widely as important contributors to the total information pool for short-term forecasting and allied research. One brake to progress hitherto seems to have been the lack of confidence of some people to analyse such images effectively. This paper has demonstrated that there are at least three broad choices available to would-be users of these valuable synoptic data, namely:

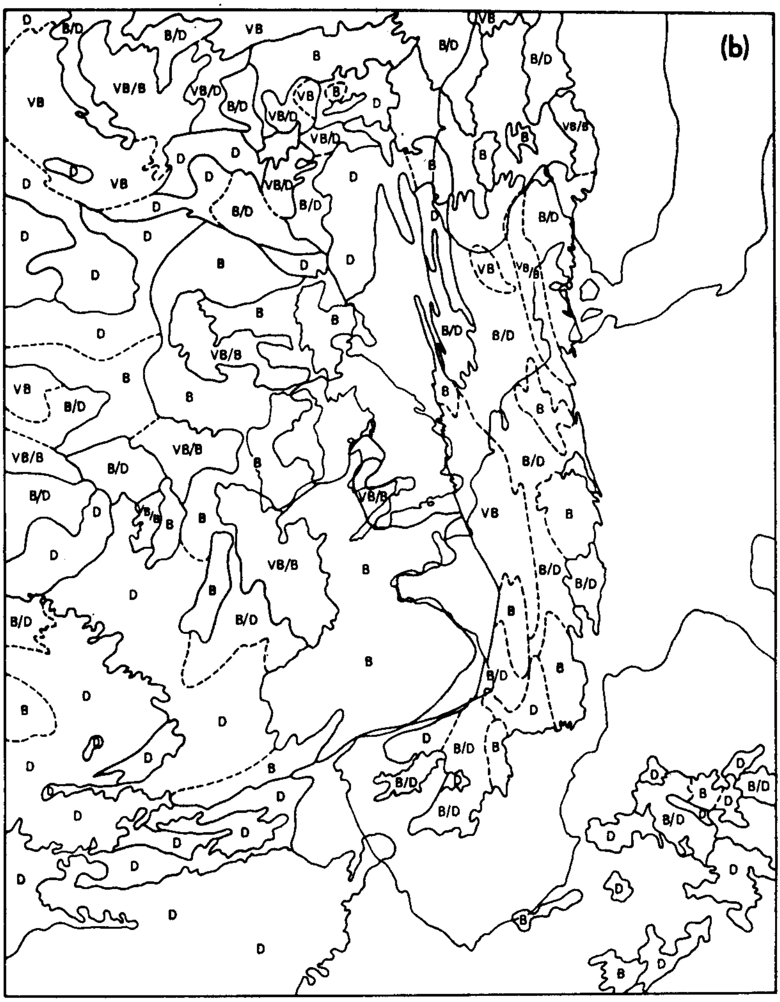

FIGURE 4—DETAILED FOUR-LEVEL NEPHANALYSIS

(a) cloud amount (see Figure 2(a)) (b) infra-red cloud brightness
(c) cloud texture (d) interpretation (e) key for Figures 4(a)–(d)

(a) Existing schemes of nephanalysis may be applied to the infra-red images in conjunction with the simultaneous visible images, to produce single nephanalyses from the combined evidences of the two different data types. For general purposes this might be the preferred course of action.

(b) Existing schemes of nephanalysis may be applied separately to infra-red data, perhaps for purposes of comparison with independently drawn visible nephanalyses. Perhaps such infra-red charts might be prepared most profitably for illustrating visible data-remote situations or for specialized applications or both, e.g. upper tropospheric forecasting for aviation.

(c) The analyst may apply purpose-built schemes to identify and represent

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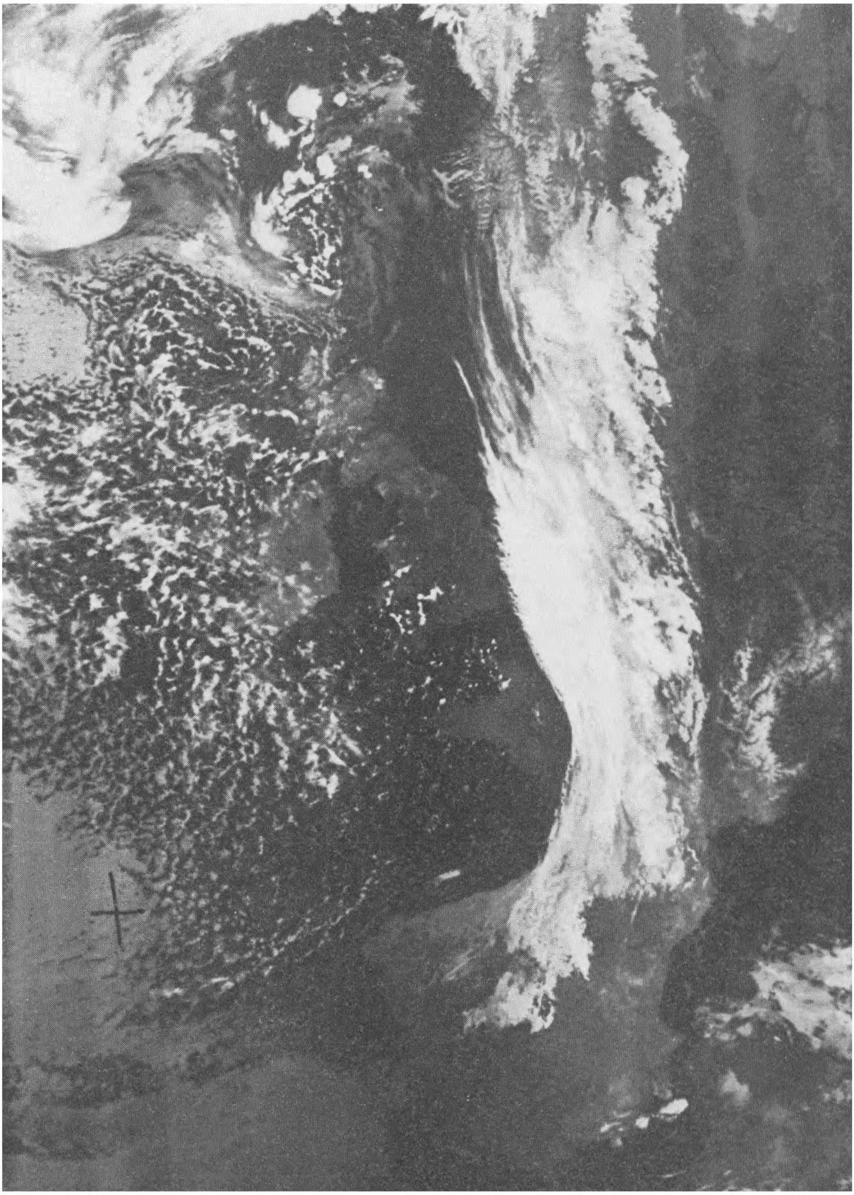

PLATE I—INFRA-RED IMAGE FROM AMERICAN DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) SATELLITE S, 0125 GMT, 30 APRIL 1975

The nominal best resolution of the scanning radiometer responsible for this image is about 0·6 km.
(See page 15.)

PLATE II—THE METEOROLOGICAL OFFICE TRANSMISSOMETER

This photograph was taken looking east along the main compound on the north side of the M4 motorway near Theale in Berkshire. The transmitter unit of the Transmissometer is in the foreground, with the meteorological sensors and other visibility instruments at the mid point of the compound. This experiment was part of a co-operative trial also involving the Home Office and the Transport and Road Research Laboratory.

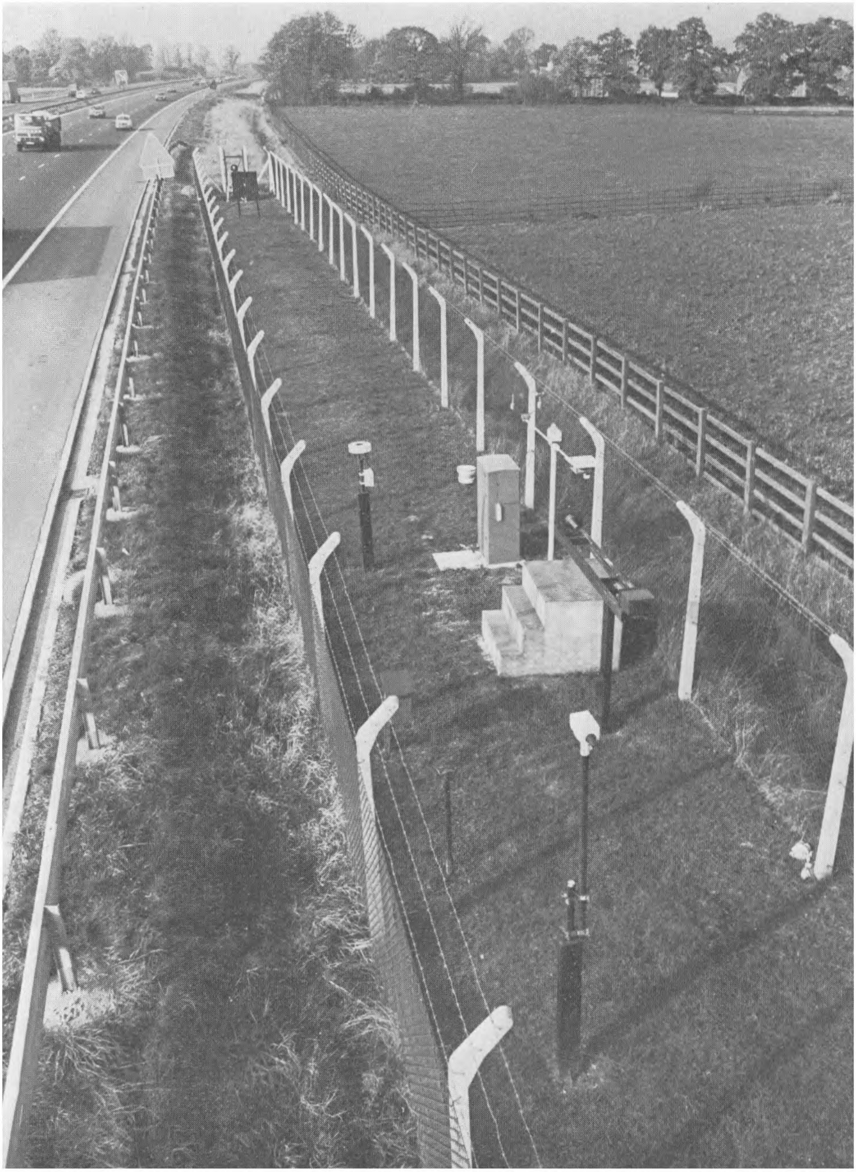

PLATE III—THE METEOROLOGICAL OFFICE TRANSMISSOMETER

This photograph was taken looking west along part of the main compound beside the M4 motorway near Theale. In the foreground are the visibility instruments undergoing comparison, and the meteorological sensors, with a background light meter in the near foreground. At the far end of the compound is the transmitter unit of the Transmissometer, which was the instrument standard during this co-operative trial involving the Transport and Road Research Laboratory and the Home Office.

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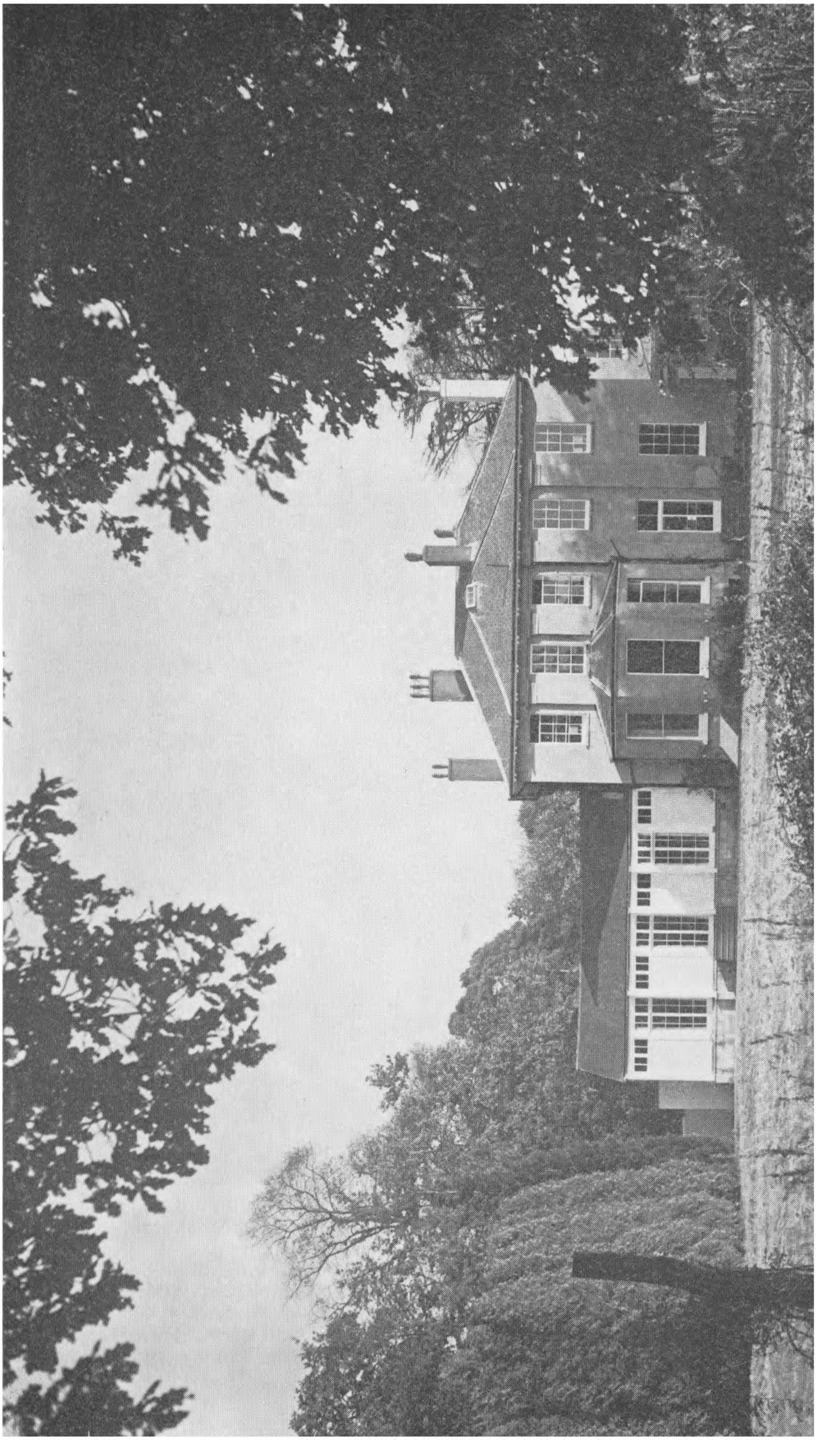

PLATE IV—THE METEOROLOGICAL OFFICE COLLEGE AT SHINFIELD PARK

Rear view of the Lodge

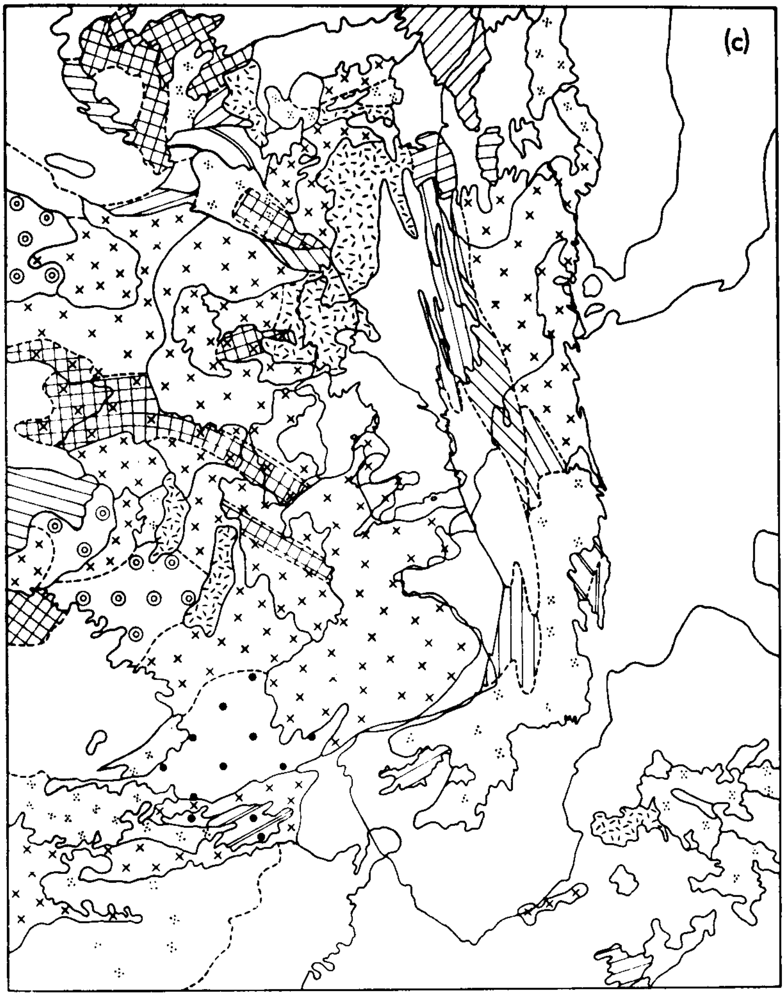

FIGURE 4—*continued*

not only the traditionally recognized features of satellite cloud images, but also certain other image variables (especially brightness and texture) whose implications have been rather neglected hitherto.

Looking further into the future, we would expect 'objective', machine-effected methods of picture analysis to become increasingly prevalent. TIROS N, the likely configuration for the polar-orbiting operational satellites of the early 1980s, will provide directly (through its on-board digitization of visible and infra-red images) the numerical data required as the input to such a program. For this, a new approach may be required to the description and classification of clouds; an appreciation of new aspects of cloudiness and its relations with other atmospheric parameters may be the prize for success.

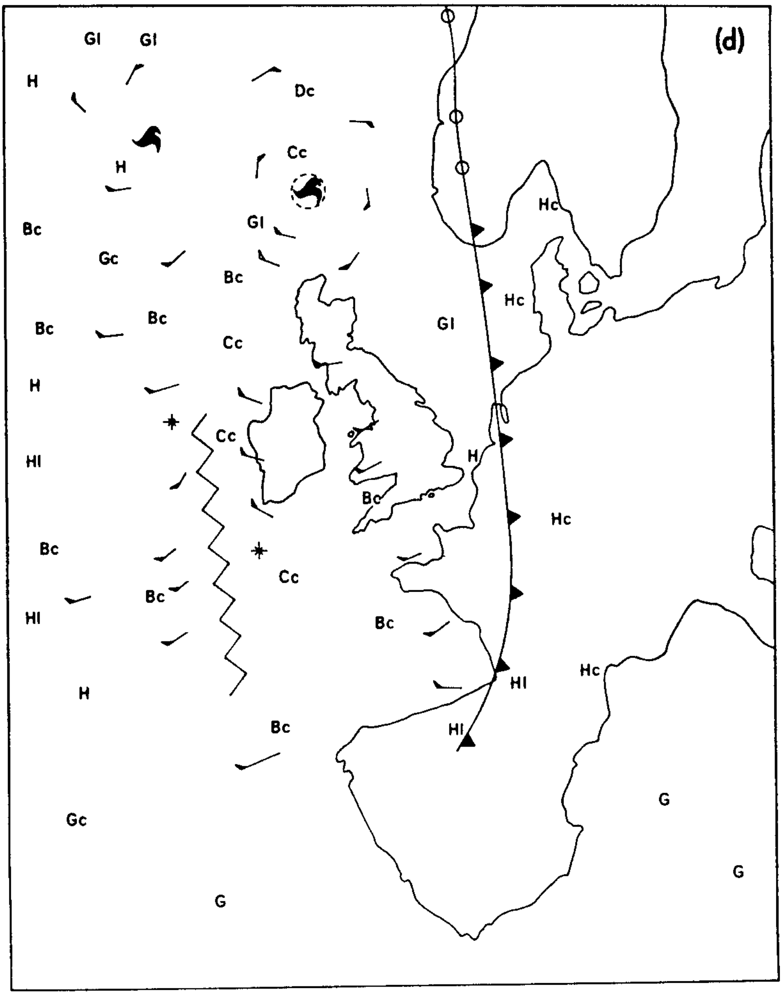

FIGURE 4—*continued*

In image science, it is generally accepted that objective analyses based on more characteristics are usually more successful than others based on fewer. Clearly the special characteristics of infra-red images are likely to be just as important in the search for objective schemes of nephanalysis as those with which we have become so familiar in visible cloud imagery.

For the immediate future it may be necessary for us to analyse infra-red images straightforwardly in terms of picture brightness and texture, as we have done here, rather than to attempt probably unsatisfactory interpretations of combinations of these qualities in terms of conventional cloud classes with little regard for detailed features. The greatest advantage of this scientific honesty might eventually emerge from the consequent opportunity to examine cloudiness in a new light, cut free from the constraints of the rather subjective and often clumsy standard scheme of cloud classification. For the immediate future, we foresee no insuperable problems for the meteorologist who might

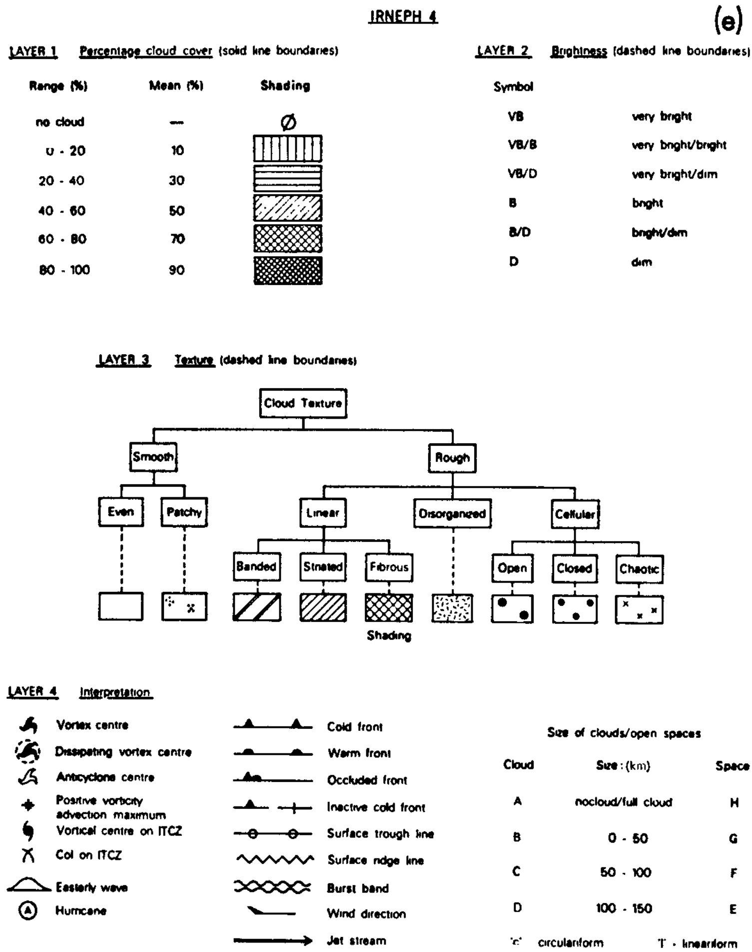

FIGURE 4—*continued*

choose to use our proposals for purpose-built infra-red nephanalyses alongside the rather different visible products: there are readily recognizable affinities between, for example, a cold front composed of a thick mixture of stratiform and cumulonimous cloud and a belt of very bright, rough-textured cloud in middle latitudes.

Finally, a word about the operational practicabilities of the schemes outlined in this paper. We have convinced ourselves that, after a suitable period of training, it would be possible for an analyst to prepare nephanalyses of any of the types introduced above within one hour, which we have taken to be the maximum acceptable time to elapse between receipt of the satellite signal and the transference of the analysed image to the prognostics section. Our research into cheap, efficient ways of undertaking comparable analyses as far as possible by objective means is continuing, and we hope to present some findings and suggestions soon.

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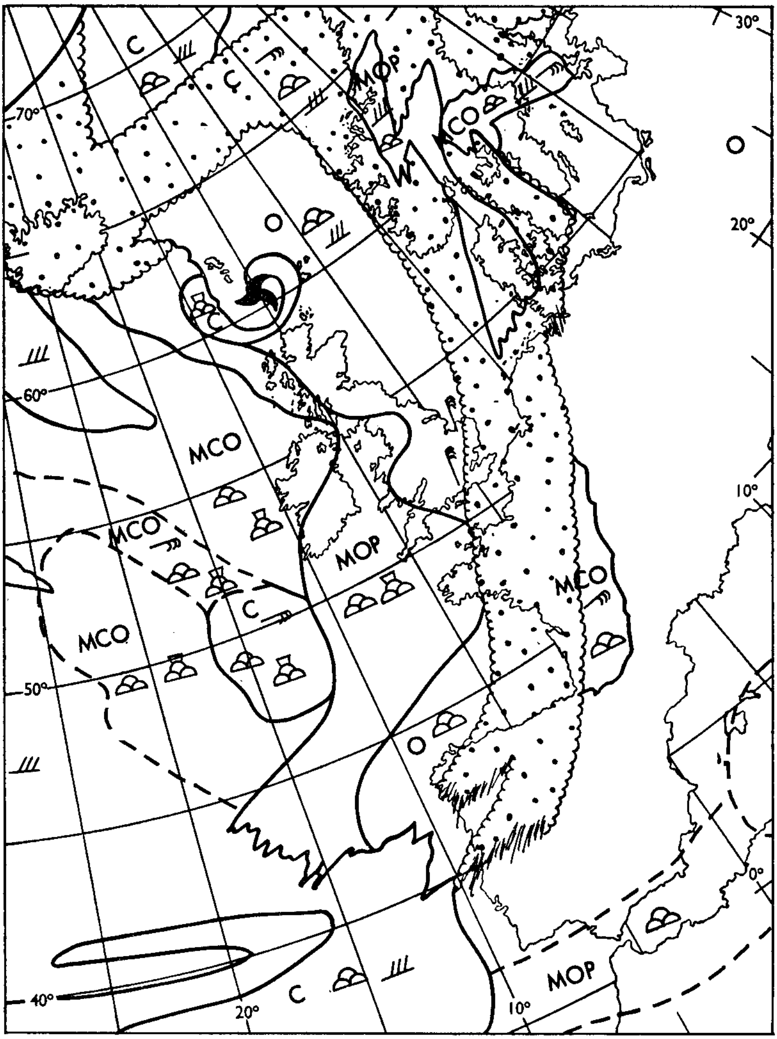
SOME ASPECTS OF SATELLITE ANALYSIS AT CFO

The paper by Barrett and Harris will, no doubt, interest and excite many readers of the *Meteorological Magazine* because it indicates the wealth of information that can be obtained from VHRR satellite imagery and, also, because it provides suggestions for methods of presentation of satellite pictures by a central office to those stations unable to receive the data directly.

Although CFO does not currently receive VHRR pictures these will be available in the near future. When such data are available the area received will be less than that on the DMSP picture used by Barrett and Harris because of the time taken firstly to process the VHRR signal at the receiving station and then to transmit the picture to Bracknell. The British Isles, North Sea and English Channel will normally be covered as routine with, in addition, one other similar-sized area available on request depending upon the weather situation. Routine satellite work in CFO will, in the immediate future, continue to be based upon the comparatively low-resolution imagery (2·5 km in the visual spectrum and 5 km in the infra-red) obtained from polar orbiting satellites (such as NOAA 4) and geostationary satellites (such as SMS 1 and the projected METEOSAT) enhanced by VHRR pictures in the vicinity of the British Isles.

My personal opinion regarding the analysis systems proposed by Barrett and Harris is that the techniques, although interesting and useful in investigation or research work, would be impracticable or, at best, of limited value in an operational environment. Reasons for this opinion are as follows:



OPERATIONAL IR NEPHANALYSIS PRODUCED AT CFO ON THE EVENING OF 29 APRIL 1975

(a) The size of some of the features portrayed is such that their life-times will only be an hour or so and, by the time analyses have been completed and broadcast, the features may well have ceased to exist.

(b) The complexity of the analyses in the paper by Barrett and Harris is such that, after dissemination by facsimile, much of the detail would be difficult to discern.

(c) Even if discernible, the quantity of detail on the analyses would not permit rapid assimilation and application by busy outstation forecasters.

(d) Some of the detail in the analysis is a matter of personal opinion. CFO analysts would, rightly or wrongly, take a different view of some of the features portrayed.

(e) The interpretation of cloud pictures in terms of synoptic features is the responsibility of the synoptic analyst using all available information. The decision on what constitutes a front, trough, ridge etc. should rest with the synoptician and not the satellite analyst.

It is my opinion that forecasters at CFO and certain other offices will benefit primarily from use of the original VHRR pictures with geographical grids superimposed instead of waiting for analyses, however ingenious or informative, to be produced.

As a comparison, in so far as the amount of detail is concerned, the operational satellite analysis produced in CFO from the NOAA 4 infra-red scanning radiometer about five hours previous to the DMSP picture used in their paper, is shown below.

The detail is limited by the coarse resolution (about 5 km as opposed to 0·5 km for the DMSP satellite). A reasonable compromise between these two extremes is provided by the day-time satellite analyses produced by CFO which are based upon visible and infra-red observations from NOAA 4. These provide a degree of detail somewhere between the VHRR pictures of the paper and the rather too simplistic analyses of cloud distribution obtainable within the limitations of the NOAA 4 infra-red scanning radiometer. My opinion is that the CFO analyses contain sufficient detail for most synoptic purposes. Some improvement will accrue from the use of VHRR but the principal benefits of VHRR imagery will be realized by those offices that receive the actual cloud pictures. These offices will gain partly by the forecasters being able to compare directly the satellite pictures with synoptic charts and partly by minimizing the time between the satellite observations and the pictures becoming available on the bench to the synoptician.

F. SINGLETON

551.578.42(41–4)

THE OCCURRENCE OF FALLING SNOW OVER THE UNITED KINGDOM

By M. C. JACKSON

SUMMARY

The paper presents a variety of statistics on falling snow, mostly appropriate to the 1941–70 snow climatology. The statistics are especially useful to civil and municipal engineers and others concerned with the frequencies of falling snow, and of general interest to meteorologists, climatologists and geographers.

Values of the average annual number of days with falling sleet or snow are reduced to a common altitude of 100 m by an altitude adjustment factor. From these values a fairly smooth, small-scale map is drawn. A simple model is developed so that an objective estimate can be made of the number of days per winter with snow that is exceeded on average once in *n* years.

A method is described of estimating the number of hours of moderate or heavy falling snow in a winter. Some statistics are presented of the frequencies of snow accumulation rates in specified durations. The paper concludes with some details of associated weather conditions, and the probability of falling snow with the time of year.

1. Introduction

It is difficult to determine precisely the average number of days with sleet or snow falling. One reason for this is the difficulty of keeping a fully alert watch for the isolated snowflake or the isolated melting snowflake in a fall of sleet, particularly during the night. However, Manley (1958) published values of the average annual number of days with snow falling for the period 1926–55, by making a thorough intercomparison of records from different places and assessing the quality of each station record. Manley (1969) also made estimates of the number of days with falling snow in London in each of the last 300 winters. This record contains large apparent variations in the number of days in different eras, with especially small numbers between 1901 and 1940, and generally larger numbers before 1820.

The average number of snow days (days with sleet or snow falling at some time in the 24 hours) at Kew for the years 1912–38 was 14 days (Manley, 1958), but for the period 1941–70 the value increased to 19 days. In the last century Greenwich had 22 days for the period 1871–1900, and 17 days for the period 1841–70, when Sunday observations seemed suspiciously low (Manley, 1969). An average of 18 days was estimated for Camden Square for the period 1875–1900.

The winters with notably large numbers of snow days in London in the period 1841–1970 are (for this century at Kew, and for the last century at Greenwich):

1963 (54 days), 1917 (41), 1947 (39), 1955 (38);

1879 (54), 1888 (53), 1876 (36), 1891 and 1865 (35), 1870 and 1886 (34) and 1895 (33).

Further details of the snowiness of individual winters in the United Kingdom during the past 100 years are given by Jackson (1977).

Examination of data in the Meterological Office (1923) for the period 1881–1915 shows that the average number of snow days reported was mostly lower than in the period 1941–70 (see Table I). Many of these increases may well be simply due to a more constant and vigilant watch now than in the last century, which would result in fewer cases of sleet or very slight snow being missed. Snow statistics presented in this report refer mostly to the period 1941–70, and mostly use data from this period. It is suggested that the use of figures from this more recent period is more realistic for planning purposes than those for the very un-snowy period 1901–40.

Table I—Average number of days with snow falling

Location	Period 1881–1915	Period 1941–70
Scilly Isles	3	4
Falmouth	5	6
Dungeness	12	17
Kew Observatory	13	19
Oxford	17	25
Great Yarmouth	17	23
Holyhead	7	4
Stonyhurst College	26	25
Glasgow	17	31
Stornoway	25	35
Aberdeen	34	37
Wick	25	47
Braemar	47	71
Buxton	38	38

Although most of the data available for analysis were the number of days with snow falling, civil and municipal engineers are usually more interested in the duration of falling snow, and the total number of hours of falling snow. Later sections show how the latter results were derived, despite the shortage of direct data.

2. Mapping the 1941–70 mean annual number of days with sleet or snow falling

Climatological Memorandum No. 74 (Meteorological Office, 1975a) presents a map of the distribution of the mean annual number of days with snow falling in the period 1941–70, with further maps for each of the months November to April. The isopleths on all the maps are highly smoothed, but nevertheless reveal the very important role of altitude in the occurrence of falling snow shown previously by Manley (1940). A more detailed annual map was drawn for the present work using, in addition, values from 25 high-quality stations manned 24 hours a day by staff of the Meteorological Office, but not covering the whole 30 year period.

Manley (1940) produced a map of the mean annual number of days with snow falling for the period 1912–38, and recognized the very important role played by altitude. He calculated an average rate of increase with altitude (1 day for every 50 feet of altitude), and used this altitude correction figure to reduce the values for all stations above 200 ft to an equivalent altitude of 200 ft. These common-altitude values he then mapped. The major variation in these common-altitude values is with distance from the extreme south-west of England, while particularly large values are found at places exposed to the north-east, and particularly small values at places sheltered from the north-east.

A similar exercise was carried out with the 1941–70 data, and the increase in the mean annual number of snow days with altitude was calculated for a variety of regions. Data were often scanty, but the increase in the number of snow days with altitude seemed to vary over England and Wales between about 5·1 days per 100 m over Cornwall and Devon to 7·3 days per 100 m over North Wales. The largest value obtained was 11·4 days per 100 m over the Grampian region of Scotland. Values given in Climatological Memorandum No. 74 are 5 days per 100 m over Wales and the Midlands, and 8 days per 100 m over northern England.

For simplicity in the mapping, it seemed reasonable to adopt the single average value of 6·5 days per 100 m (1 day per 50 ft), first used by Manley (1940). This altitude correction was applied to the mean annual number of snow days at all stations to bring them to a common altitude. The common altitude chosen was 100 m, and the resultant values are mapped in Figure 1.

A pattern similar to that in Manley's paper is revealed, with values increasing away from extreme south-west England, and being especially high in regions exposed to the north-east. The 1941–70 values are in general significantly larger, but partly because the altitude of 100 m is greater than the 200 ft chosen by Manley; the difference in altitude of the two maps is equivalent to about 3 days of falling snow. Figure 1 was used to check some suspect 1941–70 stations, and the map of actual mean annual number of snow days was drawn in detail using the isopleths of Figure 1, the contours of a topographic base map and the altitude factor 6·5 days per 100 m. Figure 2 shows a small-scale version of this final map. However, calculations of the mean number of snow

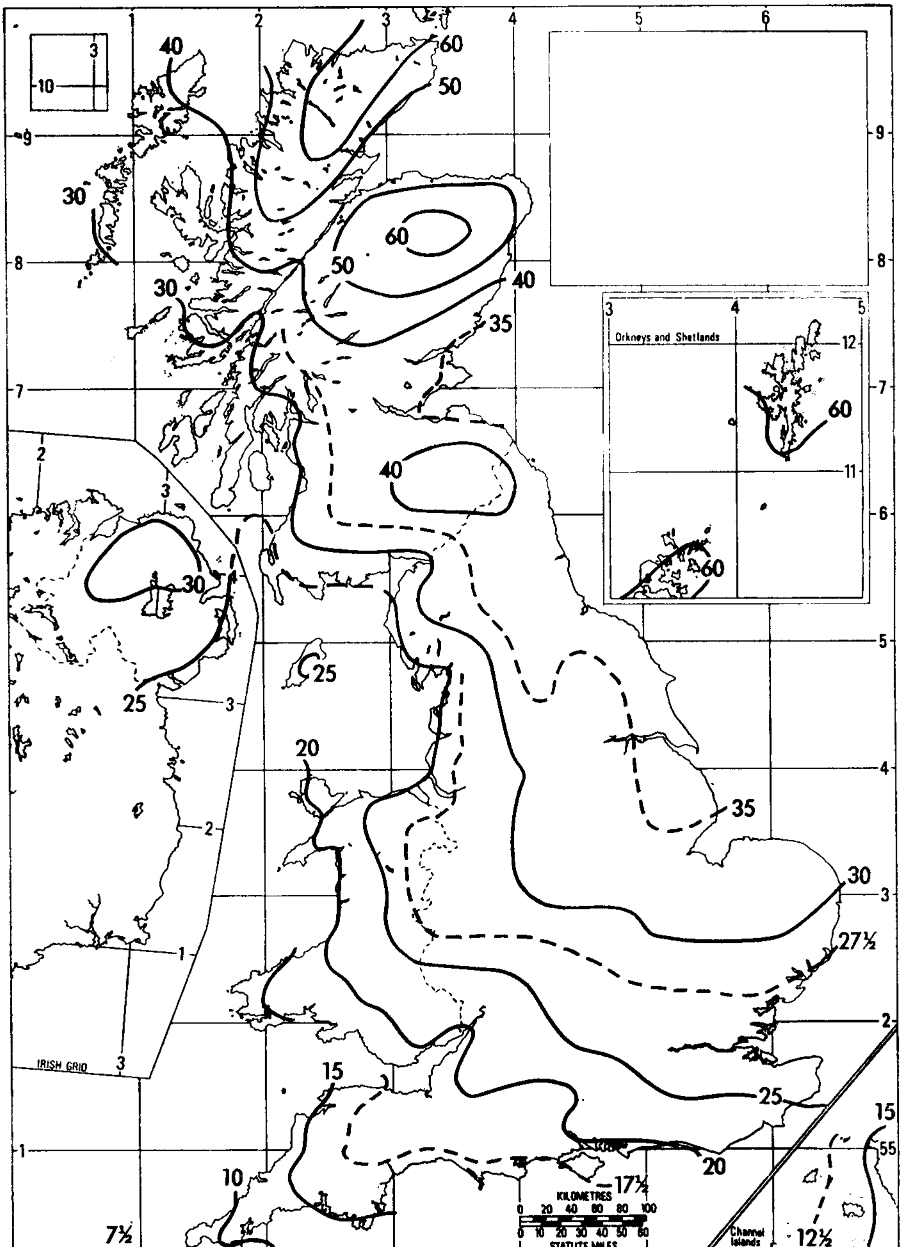


FIGURE 1—MEAN ANNUAL NUMBER OF DAYS WITH FALLING SLEET OR SNOW OBSERVED, 1941–70 ADJUSTED TO A COMMON ALTITUDE OF 100 m BY THE FACTOR 6·5 DAYS PER 100 m

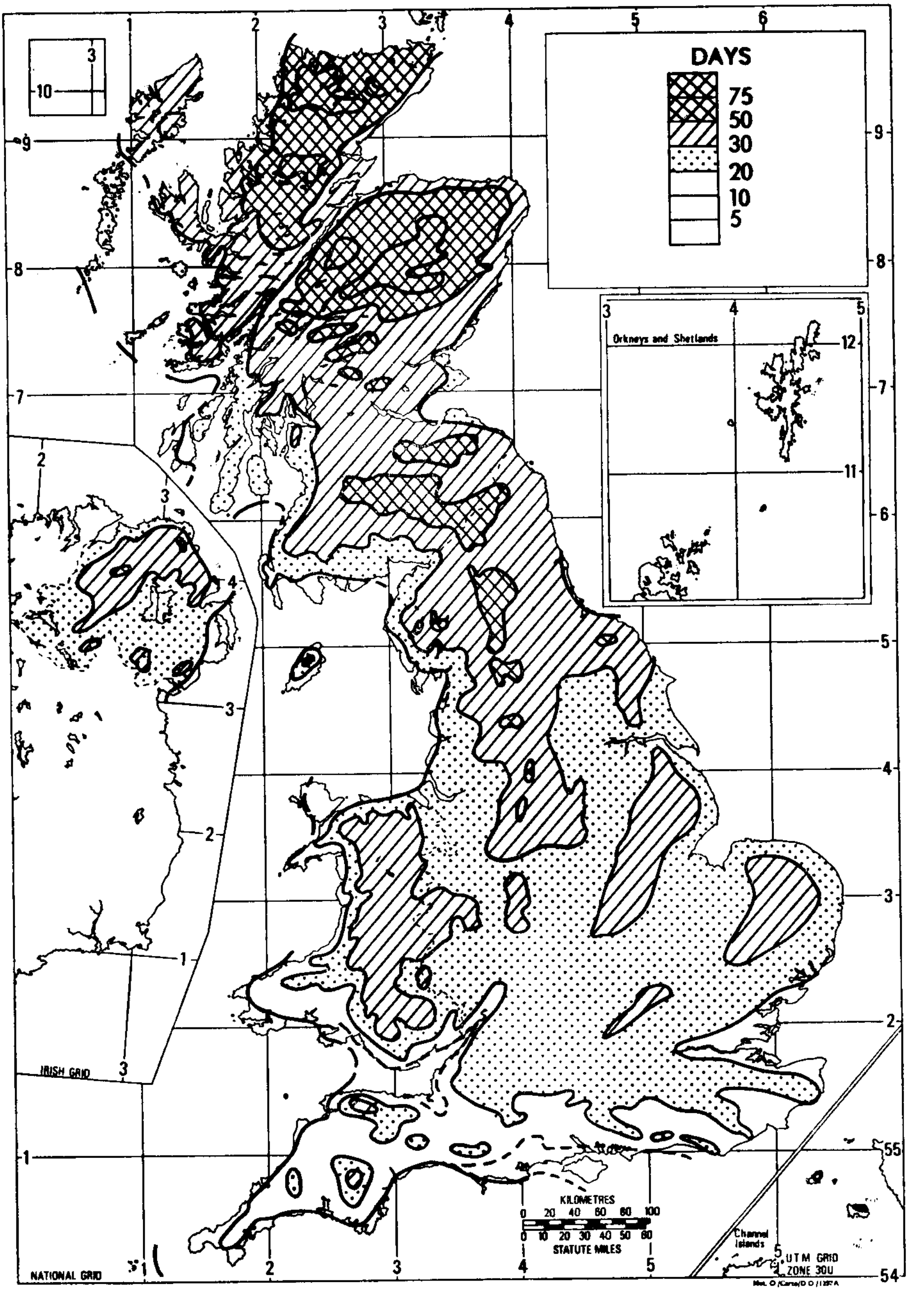


FIGURE 2—MEAN ANNUAL NUMBER OF DAYS WITH FALLING SLEET OR SNOW OBSERVED, 1941–70

(based on Figure 1)

days at any specific point for which the altitude is known should be calculated from Figure 1 and the altitude factor.

3. THE ANNUAL PROBABILITY DISTRIBUTION

Ordered annual values were plotted on normal probability paper for a wide range of lengths of record, mostly in the period 1941–70, and at most places form a curve rather than a straight line. When logarithms of the same values are plotted on normal probability paper (equivalent to using log–normal probability paper), some of the stations can be fitted by a straight line, e.g. Eskdalemuir 1941–74, but data from most places seem to fit a distribution between normal and log–normal. As a result, data have not been forced to fit any specific distribution, but are allowed to define their own distribution.

The number of snow days in each winter in the period 1941/42 to 1970/71 at 12 places in Great Britain was plotted on normal probability paper with plotting positions defined by Jenkinson (Meteorological Office, 1975b). Probability curves were drawn for each of these places. From the curve at each place, values of the number of snow days were read off for the median winter, the 5 year,* 10 year, 20 year and 50 year winter with more than the average number of snow days, and the 5 year, 10 year and 20 year winter with fewer than the average, values being estimated from the probability curve.

Each of these values was divided by the mean annual number of snow days at that place, and expressed as a ratio. Data for places with different periods of record were analysed in the same way (e.g. Derry Lodge, near Braemar, 1965/66 to 1973/74, which is 427 m above sea level). Some data from an earlier period, 1881–1915, were also used to confirm the basic shape of the probability distributions.

The ratios from all the places were plotted against the mean annual number of snow days (on a logarithmic scale). Straight lines could be drawn connecting the ratios for a fixed return period for the winters with more than the average number of snow days, while slightly curved lines were fitted for the winters with fewer than average snow days. These lines are assumed to be applicable to all parts of the United Kingdom, and to any period of time. For specified values of the mean annual number of snow days and return periods, ratios were read from the smooth lines on the graph, and are presented in Table II. They can be used as multiplying factors, so that for any place for which only the mean annual number of snow days is known, the number of snow days in a winter can be objectively estimated for a specified probability. In this way an estimate of the probability distribution can be made for any place in the United Kingdom, using estimates of the mean annual number of snow days from Figure 1, the altitude factor, and the ratios in Table II.

Values obtained in this way can be used to map the number of snow days in winters other than the mean. For example, the number of snow days in the 20 year snowy winter is mapped in Figure 3 (in practice it is recommended that the reader calculates the 20 year extreme winter at a point from Table II, not from Figure 3).

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* An *n*-year winter is a winter with a return period of *n* years, i.e. a probability of $1/n$ of being equalled or exceeded in a winter or a year.

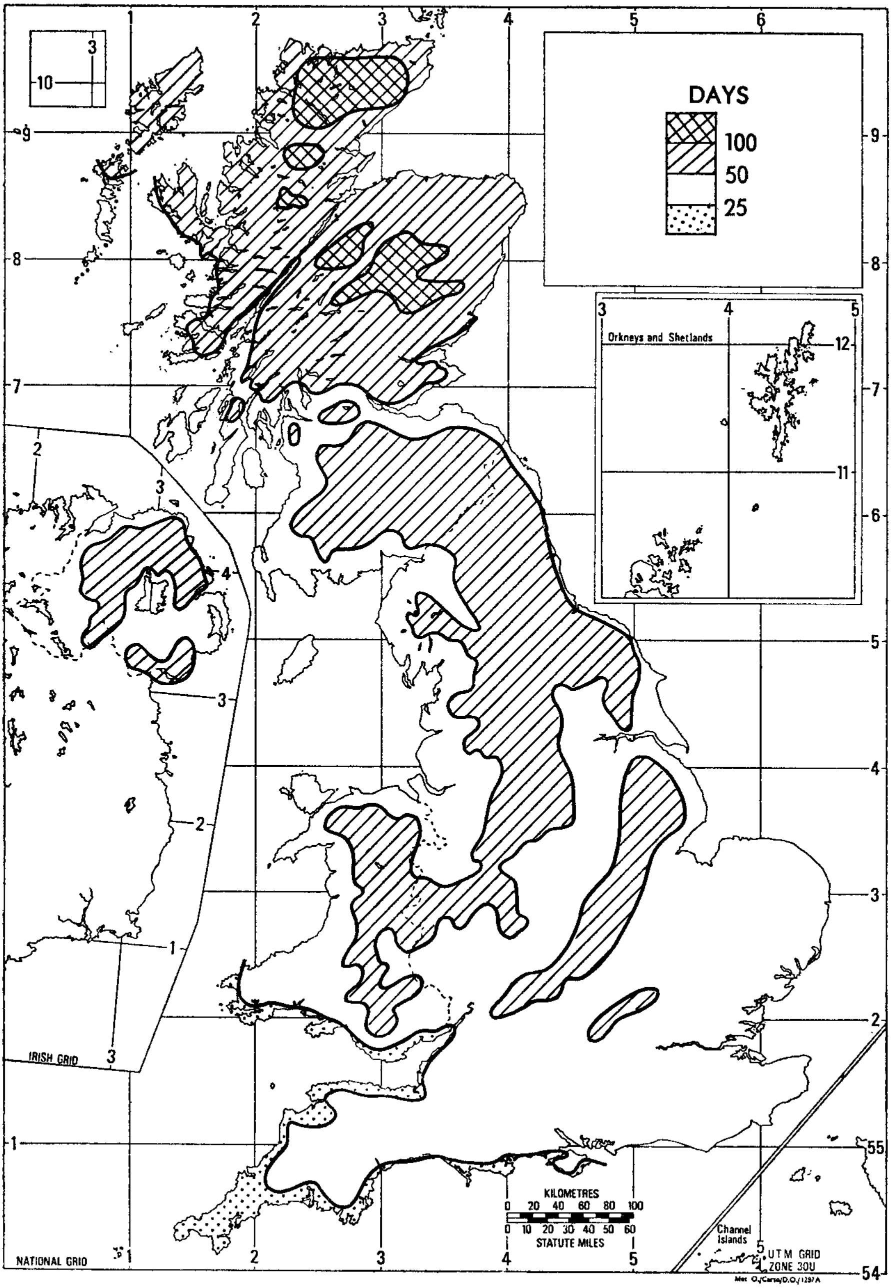

FIGURE 3—NUMBER OF DAYS WITH FALLING SLEET OR SNOW EXPECTED IN A 20-YEAR SNOWY WINTER

(1941–70 climatology)

TABLE II—MULTIPLYING FACTORS TO GIVE THE NUMBER OF SNOW DAYS IN A WINTER FOR ANY PLACE IN THE UNITED KINGDOM

Mean annual number of snow days	Un-snowy winters 20-yr	10-yr	5-yr	Median	Snowy winters 5-yr	10-yr	20-yr	50-yr
5	0·10	0·20	0·37	0·80	1·63	2·20	2·68	3·35
10	0·14	0·25	0·43	0·88	1·52	1·97	2·35	2·90
15	0·20	0·31	0·47	0·90	1·45	1·83	2·16	2·64
20	0·26	0·36	0·51	0·91	1·40	1·74	2·03	2·45
30	0·37	0·46	0·59	0·93	1·34	1·60	1·84	2·18
50	0·53	0·61	0·74	0·95	1·25	1·43	1·60	1·84
75	0·69	0·75	0·83	0·98	1·17	1·30	1·42	1·58
100	0·77	0·82	0·86	0·99	1·12	1·21	1·28	1·40
150	0·85	0·89	0·93	1·00	1·04	1·07	1·10	1·14

(Snowy winters are defined as ones with more than the average annual number of snow days, un-snowy winters as ones with fewer.)

4. THE DURATION OF FALLING SNOW AND SNOW ACCUMULATION

A day of falling snow might equally describe a day with a fierce blizzard or one with no more than a few snow grains. Of far more interest than the number of days with snow in a winter are estimates of the number of hours of falling snow, and of heavy falling snow. However, hourly snowfall data are very much more scanty than daily observations, and therefore only approximate conversions can be produced to estimate hourly data from daily data.

For the period 1949/50–1970/71 the number of days with falling sleet or snow was noted for each month at Birmingham (Elmdon) Airport. Also noted was the number of hours when falling snow of any intensity was reported, the number of hours when moderate or heavy snow was reported (water equivalent intensity $\geqslant 0{\cdot}5$ mm h^{-1}), and the number of hours when heavy snow only was reported (water equivalent $\geqslant 4{\cdot}0$ mm h^{-1}).

The number of snow days in each winter was plotted against the number of hours of falling snow in the same winter, and a straight line was fitted through the points by eye. It was assumed that this approximate conversion relationship which had been found by sampling a wide range of winters at one place could reasonably be applied to other parts of the country with different snow climates. It was also found that for every 1000 observations of snow flakes, crystals, grains or prisms (code figures 70–79), there were a further 137 observations of snow showers, and a further 33 of hail showers. These were included in the conversion relationship.

A map was drawn of the estimated mean annual number of hours of falling snow (and hail), by using the map of the mean annual number of snow days (Figure 2), and the conversion relationship from Birmingham, to re-label the isopleths.

Similarly a conversion relationship was found from a graph of the number of snow days in each winter against the number of hours with moderate or heavy snow in the same winter at Birmingham (Table III). For every 1000 observations of moderate or heavy snow (flakes), there are a further 79 observations of heavy or moderate snow shower, and a further 50 observations of moderate or heavy hail shower. The standard error of estimate for the number of hours of moderate or heavy snow at Birmingham by this method is between one and two hours for all values.

TABLE III—CONVERSION RELATIONSHIP FOR THE NUMBER OF HOURS OF MODERATE OR HEAVY FALLING SNOW, BASED ON AN ANALYSIS OF BIRMINGHAM DATA

Number of days in a winter with snow falling	5	10	20	30	50	75
Number of hours of moderate/ heavy snow	1·5	4·5	10·0	16·5	30	48

A map of the estimated mean annual number of hours with moderate or heavy falling snow may be drawn (Figure 4) using the map of Figure 2 and the conversion relationship for moderate or heavy snow given in Table III. Figure 4 gives an estimate of the number of hours in an average winter when snow is falling at a rate greater than a water equivalent of about 0·5 mm h^{-1}, which is on average an accumulation rate of lying snow of greater than 0·5 cm h^{-1}. It is not possible to give a quantitative measure of the accuracy of the estimates from Figure 4; the relationship derived for Birmingham has been assumed to apply anywhere in the UK.

Despite the approximations involved, the method was further extended to produce a tentative map of the number of hours with moderate or heavy falling snow in a 5 year and in a 20 year winter. The 5 year and 20 year values of the number of snow days are obtainable from Sections 2 and 3. These are then converted into hours of moderate or heavy snow by the conversion relationship of Table III.

The number of hours with moderate or heavy falling snow in each winter at Birmingham (but excluding showers and occurrences of hail) were ordered and plotted on normal probability paper. The probability estimates from the plot are given in Table IV.

TABLE IV—THE NUMBER OF HOURS WITH MODERATE OR HEAVY FALLING SNOW IN A WINTER AT BIRMINGHAM

Probability (per cent)	75	50	25	10	5	2
Number of hours exceeded in a winter	7·5	14	22·5	30	35	40

Snow depths reported at Birmingham (Elmdon) and Eskdalemuir every 3 hours in the 12 winters 1964–75 were examined, and the depths of snow which accumulated in 3 hour, 6 hour, 12 hour and 24 hour durations were noted. The frequencies of various depths were plotted against duration (on a logarithmic scale). Smooth curves were drawn connecting fixed return periods, and the depths were also smoothed between the return-period lines by using probability paper. Snow-depth accumulations read from the graph for several durations are given in Table V.

TABLE V—SNOWFALL ACCUMULATIONS (cm) IN SPECIFIED DURATIONS AND WITH SPECIFIED RETURN PERIODS AT BIRMINGHAM (ELMDON)

Duration (hours)	Frequency (per year)		Return period (years)		
	2	1	2	5	10
1	1·9(3·2)	3·4(4·3)	4·6(5·3)	6·6(6·6)	8·5(8·5)
3	3·2(5·1)	4·8(6·8)	6·5(8·3)	9·2(9·9)	12·7(12·8)
6	3·6(6·3)	5·7(8·3)	7·5(10·4)	10·5(12·5)	15·4(16·2)
24	3·9(8·5)	7·3(11·2)	9·5(14·7)	13·6(19·0)	20·8(23·8)

Values for Eskdalemuir are given in brackets.

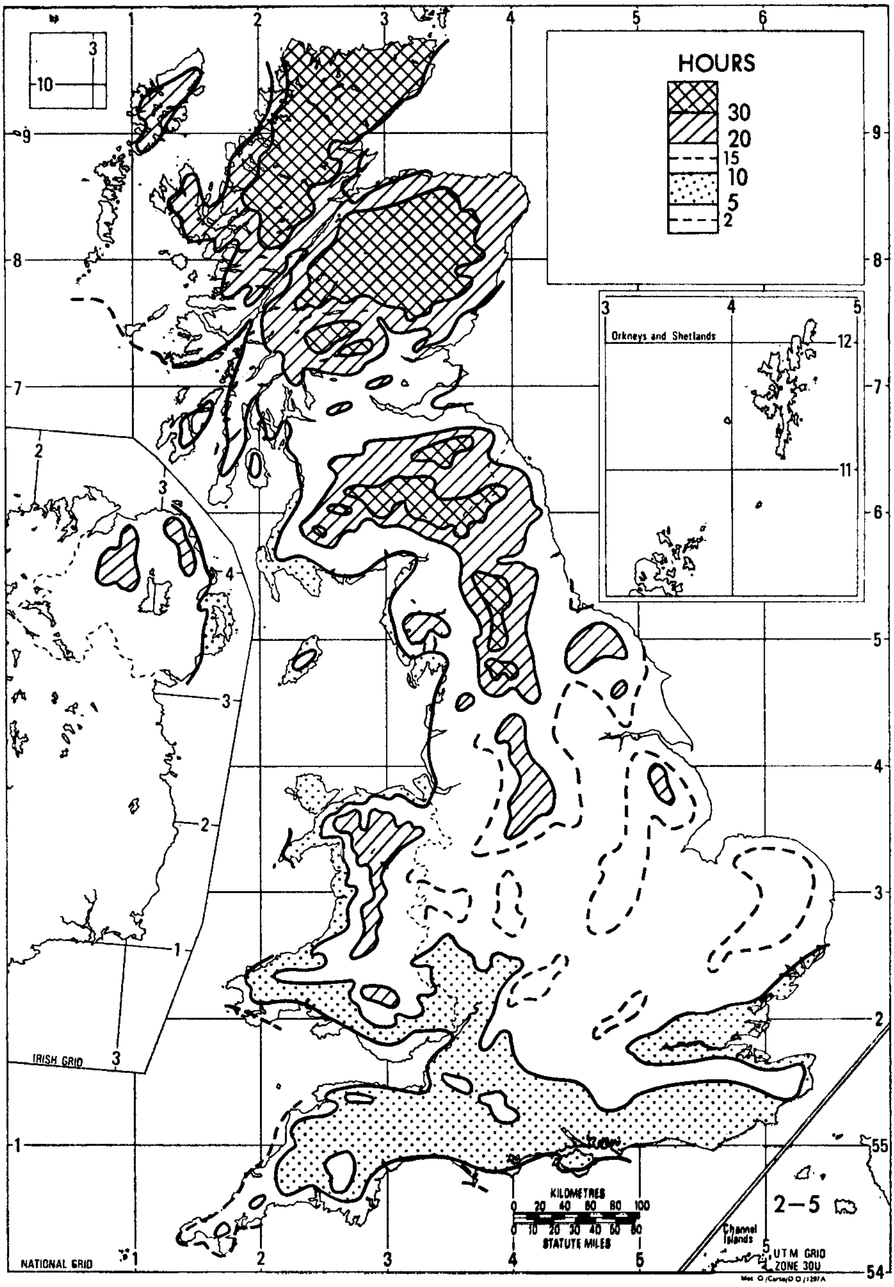

FIGURE 4—ESTIMATED MEAN ANNUAL NUMBER OF HOURS OF MODERATE OR HEAVY FALLING SNOW

(water equivalent intensities greater than 0·5 mm h^{-1})

It is interesting to note that the rare short-duration falls of only a few hours give very similar accumulations at both places. However, snowstorms at Eskdalemuir are more frequent and tend to last longer. White (1974) showed that in Michigan, USA, for depths of over 3 cm the one-day snow accumulation increases exponentially as the probability decreases.

5. Snow and other weather conditions

The average weather conditions in heavy falling snow at Birmingham Airport are:

visibility	700 m
air temperature	−0·1°C
wind direction/speed	030°, 10 kn.

The close relation between snowfall rate and visibility has often been noted, and has, for example, been calculated by Richards (1954) in the USA. In the present study the median values of visibility were found from the data for Birmingham (Elmdon) Airport:

	visibility
heavy non-showery snow	690 m
moderate non-showery snow	1080 m
slight non-showery snow	2650 m
moderate or heavy snow shower	1660 m
slight snow shower	4800 m.

The most important factor in the blocking of roads by snow in upland areas of the United Kingdom is the drifting of snow. Its occurrence depends on the combination of snow, air temperature below the melting-point of ice, and a strong wind. Temperature and wind-strength data were analysed at Birmingham (altitude 97 m) when moderate or heavy falling snow was reported. The wind data fit a normal probability distribution very closely, and the temperature data below and above 0°C each fit a normal distribution. Values for the two elements are given in Tables VIa and VIb.

Table VIa—Probability of air temperature being less than certain values when moderate or heavy snow is falling at Birmingham Airport

Probability (per cent)	90	75	50	25	10	5	2	1
Temperature (°C) less than	0·82	0·50	0·03	−0·89	−2·25	−3·10	−4·0	−4·6

Table VIb—Probability of wind speed exceeding certain values when moderate or heavy snow is falling and the temperature $\leqslant 0°C$

Probability (per cent)	75	50	25	10	5	2	1
Wind speed (kn) greater than	8·5	12·0	15·5	18·5	20·5	22·5	24·0

Table VI shows that on about 25 per cent of occasions when moderate or heavy snow is falling the temperature is below 0°C, and the wind speed greater than 12 kn, a speed near which snow starts to drift. Drifting usually becomes more serious with speeds over about 17 kn, as suggested by Richards (1954).

The occurrence of substantial falls of snow with various large-scale weather patterns has been discussed by Lowndes (1971). He found that most of the 562 substantial snowfalls (water equivalent greater than 7 mm in 24 hours) in the years 1954–69 were associated with either a warm front or warm occlusion approaching from between south and west (260 cases), or a polar low or trough in a northerly airstream (180 cases). Lowndes's data show that substantial falls of snow associated with a warm front or warm occlusion approaching from between south and west occurred in any part of the country with similar frequency, most places on low ground having had between 3 and 10 such falls in the 15 winters. However, near the east coast of England and over north Scotland polar lows or troughs in a northerly or easterly airstream gave more than 10 substantial snowfalls in any one place. The same weather situation over the rest of the country gave very many fewer substantial snowfalls. These facts give some insight into the distribution shown in Figure 1.

Clarke (1969) analysed the number of days with any snow or sleet falling over south-east England, 1954–69, and classified them according to the weather pattern. He found that the most common weather situations were (a) a warm front or warm occlusion approaching the station (113 cases), (b) snow showers with a north-easterly or easterly surface wind (90 cases), (c) a polar low or minor trough in a northerly type (64 cases) and (d) a polar low or minor trough in an easterly type (63 cases).

Many of the most severe blizzards experienced over southern England in the past 100 years have been associated with a depression moving slowly up the English Channel and giving very strong easterly or north-easterly winds. Notable examples are January 1881—central southern England, March 1891—south-west England, December 1927—south-east England and December/January 1962/63—southern England (Jackson 1977). Further north, however, the weather types associated with the heaviest snowstorms have been more varied.

6. Probability of snow with the time of year

Manley (1969) gives the mean dates of the first and last observations of falling snow in the London area:

1871–1900	23 November	12 April
1901–30	25 November	15 April
1931–60	8 December	1 April.

Summer snowstorms which are reported occasionally are almost invariably heavy hailstorms. The earliest authentic date for falling snow in London in the past 100 years (see Jackson 1977) is 25 September in 1885, and the latest date is 2 June in 1975. Some noteworthy snowstorms have been recorded on relatively low ground in different parts of the country in every month from October to May (e.g. 19–21 October 1880, snow 3 inches deep at Croydon, 5 inches deep at Exeter; 18 May 1891, snow 6 inches deep at Norwich and Daventry).

The occurrence of falling snow in London (Greenwich and Kew) from 1859 to 1958 has been analysed for each pentad (5 day period) of the year. The snowiest pentad was 20–25 February with 90 snow days. The number of snow days fell to 40 in the pentads 7–11 December and 27–31 March, and to 10 in the pentads 7–11 November and 26–30 April.

Analysis of the distribution of snow days between the various calendar months in the period 1941–70 is given in line 1 of Table VII.

TABLE VII—MONTHLY DISTRIBUTION OF SNOWFALLS IN THE UNITED KINGDOM (%)

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	Year
Distribution of snow days at an average station, 1941–70	<1	6	15	26	28	17	6	<1	100
Distribution of snow days in London	1	5	16	26	21	22	8	1	100
Distribution of hourly observations of snow at Birmingham	0	3	18	25	37	14	3	0	100
Distribution of heavy snowfalls over UK (after Lowndes)	0	6	20	25	29	16	4	0	100

The results varied slightly between places in the north and south of the country: both November and April ranged from 5 per cent in southern England to 9 per cent in northern Scotland, whilst January ranged from 29 per cent in southern England to 21 per cent in northern Scotland. The distribution of snow days in London, 1714–1896, was analysed by Mossman (1897), and is given in line 2 of Table VII.

Analysis of the hourly data at Birmingham Airport 1949/50 to 1970/71 (line 3 of Table VII) shows a similar distribution between the months, but with slightly larger percentages in midwinter and slightly smaller ones in autumn and spring. (It was interesting to note that the number of hours of falling snow in each individual month at Birmingham seemed to fit a normal probability distribution for values over 10 hours.)

Lowndes (1971) shows the number of occasions when over 7 mm water equivalent fell in 24 hours at any of 41 places in the United Kingdom in the period 1954–69. Percentage values from his analysis are given in Table VII (line 4), and are also very close to the other distributions in Table VII.

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APPOINTMENT

Dr B. J. Mason, C.B., F.R.S., the Director-General of the Meteorological Office, has been appointed senior Vice-President and Treasurer of the Royal Society for a five year period commencing 1 December 1976. He succeeds Sir James Menter. In this post he will be involved in policy-making over a wide field and responsible for administering all the Society's funds and grants.

NOTES AND NEWS

Retirement of Mr G. R. R. Benwell

Mr George Richard Raymond Benwell, who retired on 21 December 1976, joined the Office as a Technical Officer in September 1937 after graduating with a B.A. degree in Mathematics at Oxford University. After some initial practical experience at Kew Observatory and attendance at the Training School at Croydon Airport and South Kensington he joined the climatological branch for work connected with the British Rainfall Organization and the Inland Water Survey. He remained in that branch until the outbreak of the Second World War. Towards the end of 1939 he went to Linton-on-Ouse (Headquarters No. 4 Bomber Group) and received a commission as a Flight Lieutenant in the Royal Air Force Volunteer Reserve in April 1943. He stayed at Linton until 1944 and then had shorter spells of duty at CFO Dunstable, Headquarters Bomber Command, No. 5 Group and Tiger Force until he returned in September 1945 to Dunstable. He was demobilized from the RAFVR in April 1946 and promoted to Senior Scientific Officer in 1948 but he remained at Dunstable until early 1949 when he was posted to Habbaniyah for a tour of duty. He was promoted to Principal Scientific Officer whilst at Habbaniyah where he stayed until 1951 when he returned once again to Dunstable, and he stayed there until late 1961 when the units at Dunstable moved *en bloc* to the present Headquarters at Bracknell. During 1962 to 1964 he was engaged in synoptic research in Met 0 12 and when that branch was reorganized at the end of 1964 he transferred to Met 0 11 to continue work in forecasting research for a further eight years. In 1973 he was promoted to Senior Principal Scientific Officer, was appointed Assistant Director (Central Forecasting) and occupied that post until his retirement.

Dick Benwell has had a very long career which has been characterized by relatively few postings compared with the careers of many of his colleagues who also joined in 1937. A spell of over four years at one unit (Linton) during the war must be almost a record, and over his career as a whole he has spent a large part of his working life in the Central Forecasting Office and in research associated with synoptic meteorology. His very wide experience in these practical aspects has been of very great value to the Office and he drew substantially on this experience during his work in forecasting research.

Although Dick and I attended the same training courses in 1937 our official business and work were such that we did not work closely together as colleagues until the final year of our last postings. Dick's good humour, willingness to help, ability to co-operate with others, wide experience of practical forecasting, dedication and conscientiousness have been greatly appreciated by many of his colleagues for much of his long career and not least by me during this last year.

Their numerous friends will wish Dick and his wife Dorothy a long and happy retirement and hope that they enjoy good health to enable them to follow their interesting activities for many years to come.

N. BRADBURY

HALLEY LECTURE

The University of Oxford has invited Dr B. J. Mason, the Director-General of the Meteorological Office, to give the Halley Lecture on 17 May 1977. The subject of his lecture will be 'The Atmosphere of the Planets'.

OBITUARY

It is with regret that we have to record the death on 21 September 1976 of Mr H. E. Atkinson, Assistant Scientific Officer, of the Port Meteorological Office, Cardiff.

CORRECTIONS

Meterological Magazine, October 1976, page 296.
The sixth line below Table II should read

Mean: $\bar{x} = 234{\cdot}2$ mm.

The eighth line below Table II should read

Coefficient of variation CV: $= 100\ S_x/\bar{x} = 37{\cdot}9$.

Meteorological Magazine, November 1976, page 359. The title of the book reviewed should have read '*Climate and the environment—the atmospheric impact on man*' and not '. . . *of man*' as printed.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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THE METEOROLOGICAL MAGAZINE

Vol. 106, No. 1255, February 1977

RETIREMENT OF MR N. BRADBURY

Mr Neville Bradbury, Deputy Director (Forecasting), retired from the Meteorological Office on 20 January 1977 after a career of more than 39 years spent mostly on the Services side of the Office.

He graduated with high honours in both mathematics and physics from the University of London and joined the Office as a Technical Officer in 1937. Like many of his vintage he received his early training in synoptic meteorology and forecasting at Croydon. After a period of secondment to Iraq he was commissioned in the Royal Air Force in 1943 and saw service at a number of RAF headquarters, including a spell at HQ Transport Command, before demobilization with the rank of Squadron Leader in 1946. There followed a number of posts in both military and civil aviation including about four years at each of London (Heathrow) Airport and Uxbridge. In 1956 Mr Bradbury was assigned the formidable task of writing the Office's first Handbook of Weather Forecasting and it is a tribute to the excellence of his work that much of his original text remains in the revised edition at present being issued.

Another milestone in his career was his appointment in 1962 as CMetO, SHAPE with the rank of Group Captain. However, probably the greatest challenge to his versatility and tenacity came in 1965 when, with promotion to Senior Principal Scientific Officer, he was appointed Assistant Director (Data Processing) which involved the organization and management of the rapidly evolving branch concerned with large-scale computing in the Office. He rose to this challenge splendidly and when the time came to replace COMET (the English Electric KDF 9 computer) he took a major part in the acquisition and introduction into service in 1971 of the IBM 360/195 machine which is still the main work-horse for Office computing.

He was promoted to Deputy Chief Scientific Officer in 1973 and during his tenure of the post of Deputy Director (Observational Services) it fell to him to represent the UK Meteorological Office in the protracted negotiations leading up to the present Agreement for North Atlantic Ocean Stations. Even at this late stage in his career his versatility was again called on for a period as Deputy Director (Forecasting), the post from which he retired.

During his long career Mr Bradbury acquired wide experience in many different fields and became greatly respected for his sound, common-sense approach to problems and for his astute judgement. As a result, his advice was frequently sought and highly valued and he was especially a tower of strength during his later years in the Directorate. His sympathetic and wise handling of staff matters was also often in evidence and there must be many who will miss his congenial presence from our ranks.

We wish him and Mrs Bradbury a long and happy retirement in their new home in Kent.

G. A. CORBY

551.501.796:551.524.4

INFORMATION ON THE THERMAL STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER FROM ACOUSTIC SOUNDING

By B. A. CREASE, S. J. CAUGHEY and D. T. TRIBBLE
(Meteorological Research Unit, RAF Cardington, Beds.)

SUMMARY

Recent results from a vertically directed monostatic acoustic sounder installation at Cardington are discussed and compared with temperature profiles of the lower atmosphere. The facsimile charts of the sounder output illustrate the presence of thermal plumes, synoptic inversions, nocturnal inversions and internal waves. An example of the echo pattern typical of that in fog conditions is also described and discussed.

INTRODUCTION

The theory of the backscatter of sound in a turbulent medium has been developed by several authors in recent years, notably Kallistratova (1959), Tatarskiy (1961) and Monin (1962). It was shown that the strength of the scattered sound (i.e. echo) is determined by the high-frequency fluctuations of refractive index. Little (1969) pointed out that, in general, these fluctuations tend to be dominated by temperature and wind variations alone and that the echo strength is determined only by temperature fluctuations for the specific case of backscattered sound. Recently, however, Wesely (1975) has calculated that the contribution from humidity fluctuations cannot be considered negligible in certain conditions such as those present over very moist terrain and perhaps also within a synoptic inversion.

The development of acoustic sounding of the lower atmosphere proceeded rapidly following the early work of McAllister (1968). The principle of the technique is straightforward; a high intensity burst of sound (about 30 W at some 1500 Hz), in a well-collimated beam, is projected into the atmosphere using an array of loudspeakers (the inter-speaker distance being approximately equal to the half-wavelength of the transmitted sound). Alternatively a single loudspeaker and collimating dish may be used. The transmitting frequency is chosen to minimize the effects of the atmospheric absorption of sound (which increases at higher frequences) on the one hand and ambient noise (which has a greater effect at lower frequencies) on the other. The acoustic array is switched to the listening mode about 50 milliseconds (ms) after transmission when the loudspeakers have ceased ringing significantly. Any echoes received are amplified (by a factor of up to about 10^7) and displayed, for ease of appraisal, in height–time form on a facsimile chart recorder.

The particular design of acoustic array used in this study is similar to that developed by the Department of Electronic and Electrical Engineering, University College, London (Asimakopoulos and Cole, 1977). Other sounder features including the electronic circuitry were designed and built at the Meteorological Research Unit, Cardington (see the Appendix for a summary of the operating characteristics). The sounder was sometimes operated with a pulse length of 5 ms, corresponding to a resolution of around 2 metres. This value is an order of magnitude less than that normally chosen (50–200 ms) and permits, for example, the detection of small-scale turbulent regions associated with breaking waves. The pulse repetition rate was 0·5 Hz with an operating frequency of 1732 Hz. Contamination of the echoes by environmental and wind-generated noise is reduced to a minimum by housing the array in a pit 2 metres deep and 3·6 metres in diameter. Two-inch thick polyurethane foam (which has good sound absorbing characteristics) lines the interior wall of this pit. A smooth airflow over the installation is encouraged by means of a sloping earth bank.

Acoustic sounding offers a method for remotely estimating important turbulence quantities such as the structure parameters for wind and temperature (C_V^2 and C_T^2 respectively (Tatarskiy, 1961)), at any chosen height, since the eddies producing the scattered sound are of a length scale found within the inertial subrange (Lumley and Panofsky, 1964). Detailed quantitative comparisons between sounder-derived and direct estimates have been the subject of much recent experimental work (Asimakopoulos *et alii*, 1975 and 1976; Neff, 1975). Additionally the echoes provide information on the wind structure in the boundary layer through the magnitude of the Doppler shift (Beran *et alii*, 1973). Recent comparisons have shown that the vertical velocities obtained from sounder returns compare well with direct estimates (Caughey *et alii*, 1976). The technique thereby offers an attractive method of remotely assessing the mixing quality of the lower atmosphere. Further careful comparisons between sounder-derived quantities and direct measurements (preferably at several heights simultaneously), in a wide variety of atmospheric conditions, are required to establish the accuracy limits and percentage of time that useful information can be obtained.

The object of this paper is to show that useful qualitative information can be obtained just by looking at a sounder facsimile chart. In general terms the sounder will 'see' any atmospheric structure having associated fine-scale turbulence producing significant temperature and humidity fluctuations on a length scale approximately equal to that of the transmitted sound half-wavelength (i.e. about 10 cm). Thus it will readily indicate the presence of ground-based thermal activity, synoptic and nocturnal inversions, breaking waves and the turbulent thermal structure associated with a fog. Examples of these features are given in the following section.

DESCRIPTIVE DETAILS

Certain factors must be borne in mind when one attempts to relate the structure present on a monostatic* sounder facsimile chart to turbulent activity in the atmospheric boundary layer. Firstly, the chart illustrates only that part of the atmosphere being advected over the vertically directed transmitter–receiver system. As a consequence the sounder provides only a 'height–time' section through any structure and so any inference about the three-dimensional shape cannot be attempted nor can the Lagrangian evolution of any features of interest be usefully discussed. The correspondence between the chart-implied and the actual structure will depend closely on the applied gain and dynamic range of the system. Therefore the location of, for example, thermal plume edges may be ill-defined. Furthermore, examination of the charts reveals an apparent 'fading' of turbulent thermal activity with height. To understand this it must be remembered that the sounder 'sees' only part of the turbulent spectrum corresponding to a length scale of about the transmitted half-wavelength (in our present case 10 cm). Recent experimental work has revealed that the intensity of temperature fluctuations on this particular scale falls off rapidly with height (Kaimal *et alii*, 1976). This means, for example, that a monostatic sounder typical of those in general use will significantly underestimate the upper limit of convection in deep boundary layers.

The following factors must be recalled to mind when qualitative interpretation of facsimile charts is attempted:

(a) *Inversion-capped convective boundary layer*

The synoptic situation over the British Isles at 1800 GMT on 28 October 1975 is shown in Figure 1(a). Eastern England was under the influence of an anticyclone centred over Poland which produced a light southerly airflow. The midday Balthum (Painter, 1970) ascent at Cardington is shown in Figure 1(b) and indicates a near adiabatic boundary layer capped by a strong (10°C) inversion with a stable region aloft. The acoustic sounder was in operation with a pulse length of 50 ms and the facsimile chart for the period 1335–1445 GMT is given in Plate I. A good correspondence is apparent between the strong echo near 200 m and the inversion recorded by the Balthum. It is felt that this echo is produced by temperature and humidity fluctuations generated by breaking waves or convection-induced hummocks at the inversion base. A similar echo is not apparent at the upper boundary of the inversion near 300 m and direct measurements showed that only a small fraction (about 0·5°C) of the total inversion strength occurred across the intense echo region. Further, more comprehensive measurements of the mean and fluctuating temperature and humidity fields in the neighbourhood of inversions will be required to obtain a fuller understanding of the source of such echo layers.

A closer study of the intense echo near 200 m reveals that it is distorted by a series of perturbations of similar scale but markedly differing frequency. The larger-scale undulations (with a period of some 30 minutes) may originate from mesoscale variations of the inversion base associated with slightly deeper convection or perhaps the outcome of very low-frequency waves propagating in the stable air above. The smaller-scale irregularities, with durations of some

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* i.e. with transmitter and receiver either sharing the same antenna or placed so close to each other that their separation may be ignored.

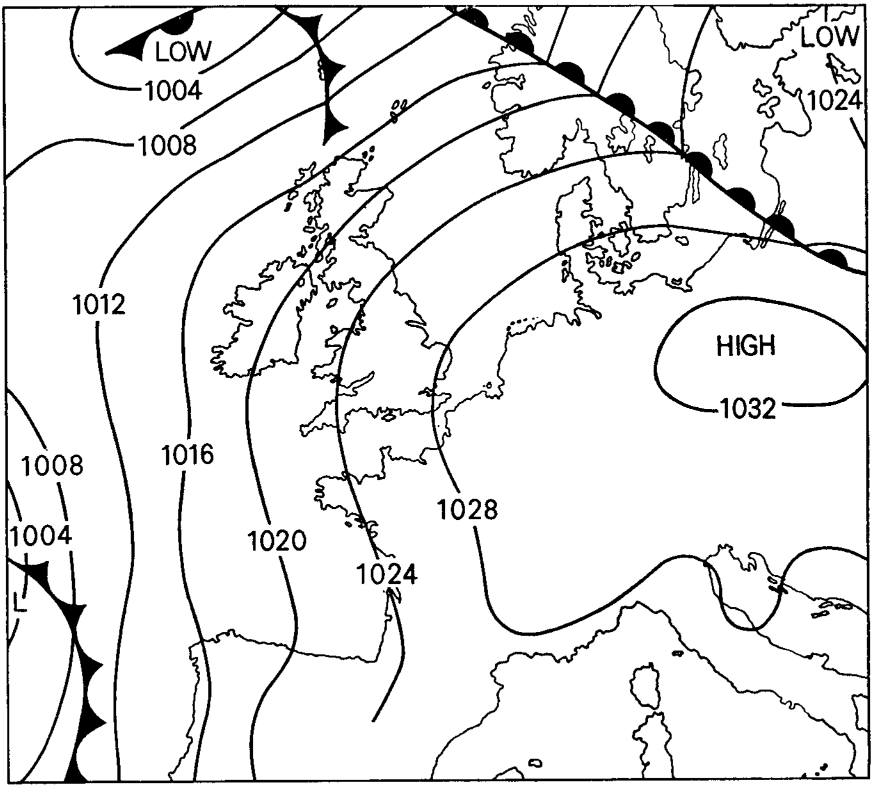

FIGURE 1(a)—SYNOPTIC SITUATION AT 1800 GMT ON 28 OCTOBER 1975

30 seconds to several minutes, have sharply defined boundaries and characteristics similar to the 'hummocks' described by Rayment and Readings (1974). These authors observed 'hummocks', some 50 m in depth and 500 m in length, propagating with approximately the mean wind speed within the mixed layer. In accordance with their findings (i.e. that these were induced by convective activity) the sounder chart indicates some correlation between thermal activity and upward movement of the echo layer. Below the inversion lower interface the 'plumes' (i.e. the column-shaped areas of more intense return on the facsimile chart) have durations comparable with these smaller-scale irregularities and those that extend towards the 200-m level can often be associated with 'hummocks' of greater vertical displacement. It is of interest to note that within the larger 'plumes', regions of enhanced return are evident and may imply a plume 'substructure' within which more intense temperature fluctuations occur (see Hall *et alii*, 1968). There is also some evidence (for example near 1426 GMT) of thermal activity extending from the inversion well down into the boundary layer. However, the energy within the mixed layer was not sufficient to effect a general lifting of the synoptic inversion on this day.

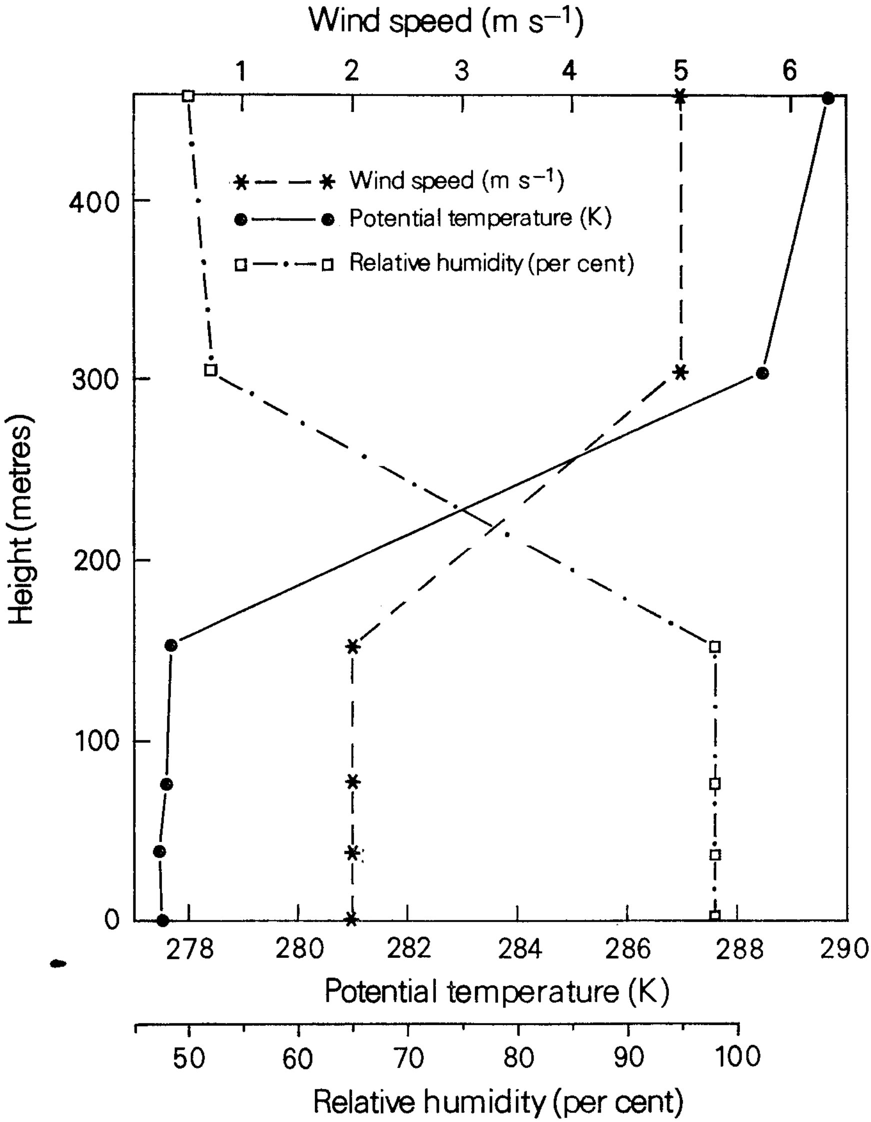

FIGURE 1(b)—CARDINGTON BALTHUM PROFILE FOR THE PERIOD 1048–1158 GMT ON 28 OCTOBER 1975

(b) *Rising inversion*

By 29 October 1975 the anticyclone present over Europe had receded eastwards and a frontal system was approaching the British Isles from the south-west. As the ridge over the North Sea declined convective activity was, on this occasion, successful in driving the inversion aloft. The acoustic sounder was used to monitor this rise (again using a 50 ms pulse duration) and a section of the facsimile chart (covering the period 1000–1100 GMT) is shown in Plate II.

Over this period the intense echo region rose about 6 mb. If it is assumed that this corresponds to an inversion-rise rate of about 6 mb per hour it is within reasonable limits of values found by other experimenters (e.g. Rayment and Readings, 1974 and Chorley *et alii*, 1975). The 'hummocks' are still clearly resolved although the intense echo is more diffuse in comparison with the previous day. (Note that the dark bands running vertically on the chart are the result of noise generated by passing aircraft.)

(c) *Fog situation*

The Cardington area was fogbound from 2000 GMT on 13 November 1975 and throughout the following day, the mean visibility being less than 100 m. On the second day the temperature only rose above 0°C during the period 1300–1600 GMT and surface winds were very light (about 1–1½ m s^{-1}). The sounder facsimile chart for the period 0856–0926 GMT for 14 November 1975 is shown in Plate III. This indicates an intense echo at about 100 m which correlates well with the inversion layer as recorded by the midday Balthum ascent (see Figure 2) and is probably associated with the fog top. (The humidity profile from the Balthum ascent shows much drier air above 100 m and saturated air below.) Although saturated air in no way implies the presence of fog this profile supports the notion that the layer of intense echo provides an upper limit to the depth of the fog. Within the body of the fog weak 'convective' activity is observed with features remarkably similar to thermal plumes being resolved. This agrees with the Balthum's slightly unstable profile of potential temperature extending up to near 100 m. Undulations of the echo layer, on time-scales of a few minutes, may illustrate the interaction of the weak thermals with the inversion layer present as well as the existence of waves in the stable air aloft. Regions of activity apparently extending 'downwards' from the base of the intense echo between the thermal 'plumes' could be due to the overturning of these convective elements and their interaction with tight gradients present in the inversion regions. This would strengthen the evidence for the model of downward entrainment of air through an inversion interface put forward by Readings *et alii* (1973).

During the period between Balthum ascents (i.e. 1201–1656 GMT) the fog continued to persist at the surface; however, some interesting phenomena were detected by the sounder at higher levels. Between about 1250 and 1340 GMT, when the surface visibility averaged 50 m, the echo layer (i.e. the probable vertical extent of the fog) descended substantially to be less than 50 m from the surface while the stable layer above showed the presence of a succession of waves (see Plate IV). (It was during this period that the screen temperature first rose above 0°C; having been —0·1°C at 1251, it rose to 1·4°C by 1350). The majority of waves present in the first 70 m have the same amplitude and appear to be in phase, with periods of some few minutes. Those at higher levels are of higher frequency but of similar amplitude. By 1435 GMT the oscillatory patterns have dispersed and another intense echo layer has formed but this time much closer to ground level (about 40 m). Horizontal visibility continued to decrease, being 40 m at 1450, when a surface temperature of 1·3°C was recorded. The sounder chart for the period 1435–1600 GMT is shown in Plate V and indicates that during this interval the intense echo descends by about 15 m to be at its lowest level (i.e. about 25 m) at 1555. Below the strong echo layer weak convective activity can still be just discerned. However, in the

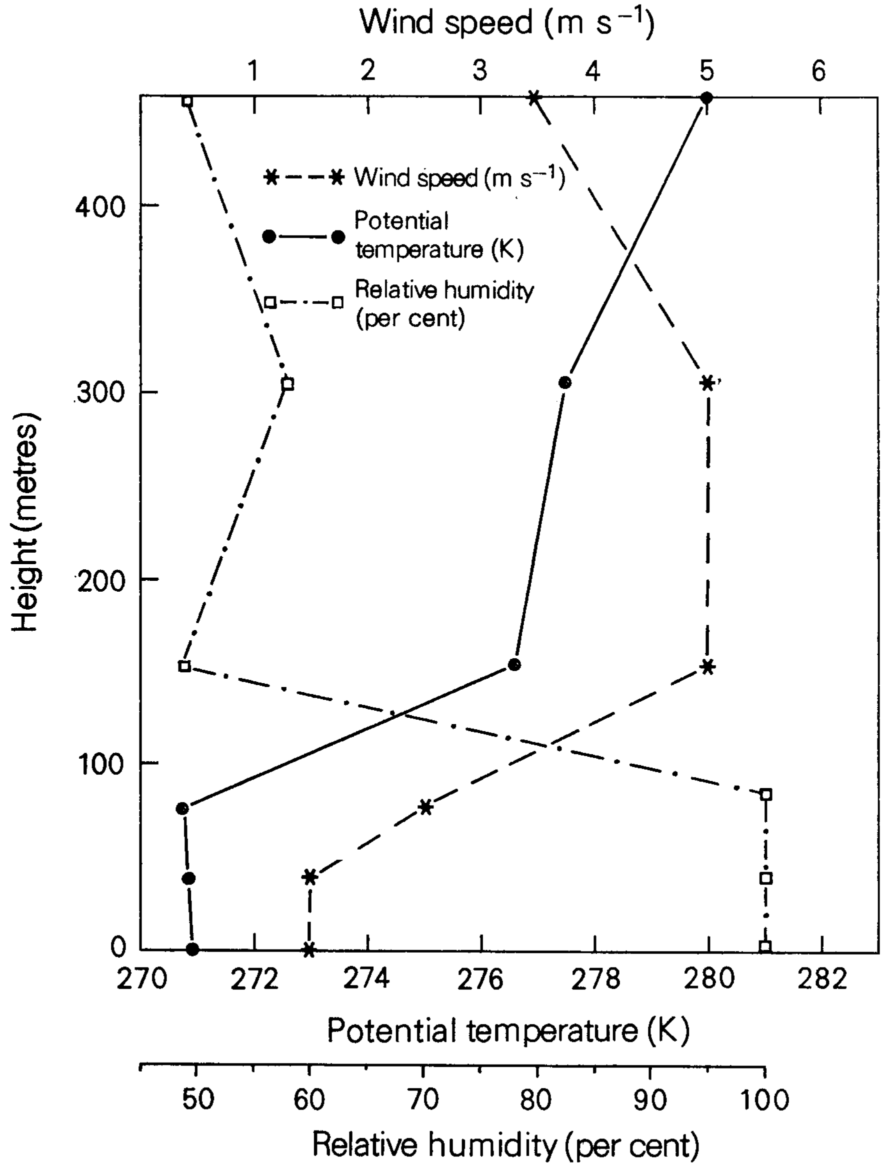

FIGURE 2—CARDINGTON BALTHUM PROFILE FOR THE PERIOD 1048–1201 GMT ON 14 NOVEMBER 1975

stable air above, the chart reveals the appearance of bursts of activity between 1455 and 1555 GMT which are probably associated with the presence of breaking gravity waves. The sounder in this instance was operating with a 5 ms pulse duration enabling structures to be resolved down to about 2 m. Therefore these oscillatory patterns must represent fluctuations occurring within a depth of only a few metres. Their structure, from the chart, resembles closely that observed by Caughey and Readings (1975) and Hooke *et alii* (1973). The temperature fell below 0°C at 1700 GMT when the lowest visibility (about 25 m) was observed and the fog persisted until 0200 GMT on 15 November when, with the approach of a warm front from the south-west and the advection of stratocumulus, it cleared within an hour. If the reasonable assumption is made that the intense echo recorded by the sounder represents the upper limit for the fog depth then it seems that the simple monostatic sounder could form a useful aid in the prediction of radiation fog clearance.

(d) *Nocturnal inversion*

The Balthum profile for the night of 6/7 November 1975 (Figure 3) shows that a strong nocturnal inversion, extending up to approximately 350 m, was present in the Cardington area. Plate VI shows the sounder facsimile chart for the period 0208–0253 GMT on this night. It reveals a 'filamentary' form of turbulence fluctuations below about 150 m, which, from the Balthum profile,

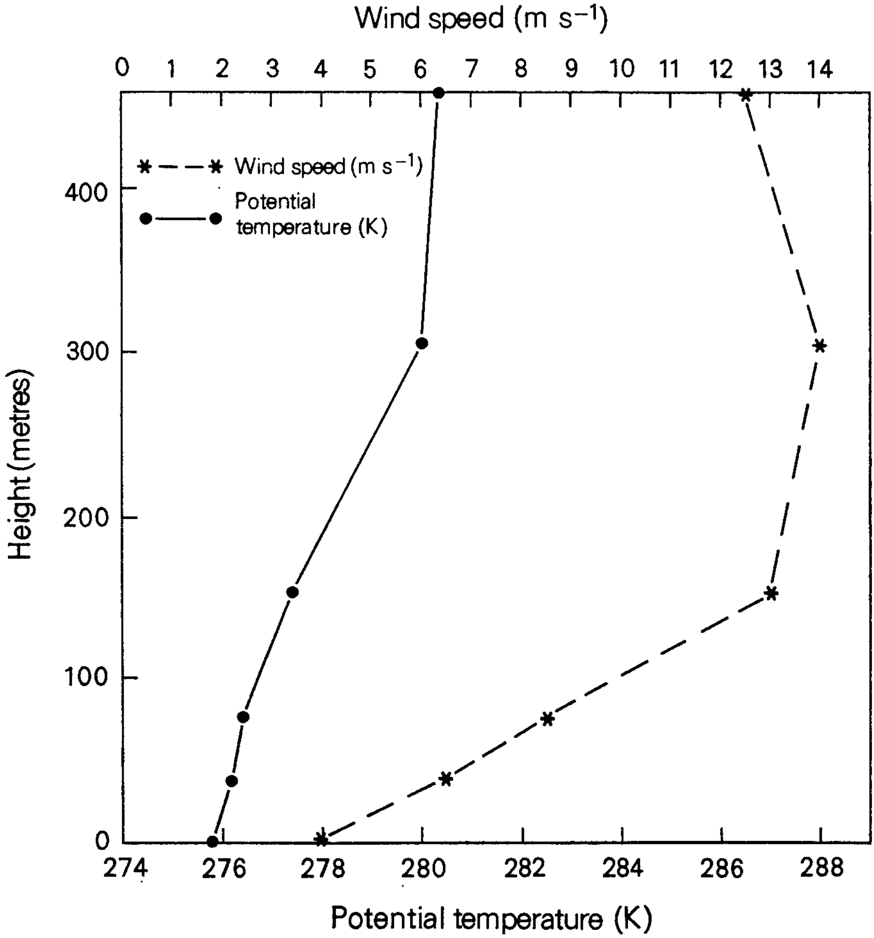

FIGURE 3—CARDINGTON BALTHUM PROFILE FOR THE PERIOD 0635–0723 GMT ON 7 NOVEMBER 1975

was a region of marked wind shear. It therefore seems plausible that the echoes on this occasion were from temperature fluctuations generated by mechanical turbulence acting on the steep temperature gradient. The 'filaments' of activity probably reflect the presence of regions of stronger mixing. In the region of small wind shear, between 150 and 300 m, no echo is evident although the temperature gradient is still quite appreciable.

Concluding remarks

A simple vertically directed monostatic acoustic sounder has been shown to be a valuable asset in the investigation of the structure of turbulence in the planetary boundary layer. The visual display of atmospheric features provided by the sounder facsimile chart forms a very useful supplement to direct measurements of the turbulent flow. In particular it greatly aids the positioning of balloon-borne instrumental packages in regions of interest and gives a physical insight into the structures generating the average statistics. The monostatic sounder may also provide a useful aid in the prediction of radiation fog clearance and this will be investigated in field studies of fog formation and dissipation to be carried out in the near future. A bistatic sounder (i.e. recording off-axis as well as backscattered sound) should also provide useful information on the fluctuation wind field and this topic is at present under study at Cardington (Caughey *et alii*, 1976). Acoustic sounding also appears promising as a remote sensing method for quantitatively estimating important turbulence statistics and in this respect long-term evaluation studies still seem necessary.

Acknowledgements

The authors wish to thank their colleagues at the Meteorological Research Unit, Cardington for assistance in all stages of the acoustic sounder evaluation program.

Appendix

Operating parameters for the Cardington acoustic sounder installation

A. *Transmitter*

1. Repetition rate: Nine settings from 0·05 to 1·0 Hz.
2. Height marks: Always in operation marking the facsimile chart every 100 m.
3. Pulse length: Continuously variable between 5 and 500 milliseconds.
4. Transmission frequency: Choice of 4 frequencies; these may be pre-set anywhere in audio-spectrum (present values 580, 820, 1300 and 1732 Hz).
5. Power output: Variable from 0 to 500 watts (r.m.s.) electrical power.

B. *Receiver*

1. Head amplifier: Has a fixed gain of 10^3 for a frequency of 1732 Hz.
2. Ramp gain: (a) Height of ramp (where ramp is initiated by transmit pulse) is variable from 10^{-2} to 1.
   (b) Length of ramp is variable from 0·3 to 20 seconds (equivalent to 50–3300 m in height).
3. Band pass filter: For each of the 4 transmit frequencies a choice of bandwidth exists at ± 5, ± 10 and ± 20 per cent of that particular transmit frequency.

4. Overall gain: Continuously variable up to maximum value of 10^7.

C. *Outputs*

1. Data signals: Received signal converted to d.c. voltage for logging on analogue tape recorder and fast sampling by a computer-controlled analogue–digital system (voltage range 0–5·5 V); a.c. signal available for Doppler shift work.
2. Facsimile chart signals: Mufax equipment has a gain control (independent from the rest of the system) with logarithmic response as well as noise clip level. Can be varied continuously by operator to produce optimum picture quality.

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THE ANNUAL COURSE OF SOME INDICES OF THE ZONAL AND MERIDIONAL CIRCULATION IN MIDDLE LATITUDES OF THE NORTHERN HEMISPHERE

By M. K. MILES

SUMMARY

The annual course of indices of the zonal and meridional surface circulation together with meridional thickness gradients is presented for several areas and for the whole hemisphere. It appears that if for convenience a single latitude band is desired for all areas and all seasons the 20° latitude band from 35°N to 55°N best encompasses the surface westerlies.

Some notable differences are apparent between the course of the westerlies in the Pacific and Atlantic Oceans and between the time of the winter peak of the zonal circulation and that of the meridional circulation.

1. INTRODUCTION

Although the climatology of the middle-latitude westerlies is well known in many respects, a study of some simple indices of the zonal circulation reveals some remarkably clear-cut differences between the rate of development of the westerlies over the Pacific and Atlantic Oceans in the late autumn. It may be important to recognize these clearly because their explanation could increase our understanding of the fluctuations of the winter westerlies which are such an important feature of our climate. These indices are presented along with appropriate mean values of the tropospheric temperature gradient, because these two features have often been linked in a kind of causal relationship, often without any quantitative study.

Some indices of the meridional circulation are also presented because of their possible relation to the meridional flux of heat and the meridional temperature gradients.

2. Preparation of the indices

(a) *General*

All the indices were prepared from grid-point values in the magnetic tape library of the Synoptic Climatology Branch of the Meteorological Office. These grid points are spaced 5° of latitude apart and at 10° longitude intervals up to 65°N and thereafter at 20° longitude intervals to 80°N. Most of the indices are based on means for the period 1951–70 but in a few cases values based on the period 1900–70 are shown in the diagrams.

(b) *Zonal indices—surface*

The basic units for the zonal indices are values of mean geostrophic west wind worked out from meridional surface pressure differences across 5° latitude bands. The basic time of averaging is a half month. Indices for the following longitude areas are formed by summing the values for the appropriate meridians and taking the means:

Atlantic area	60°W to 10°W (inclusive)
western Pacific	140°E to 180°E (inclusive)
eastern Pacific	170°W to 130°W (inclusive)
northern hemisphere	mean of 36 meridians.

Values of the mean indices in metres per second are then available for six 5° latitude bands.

A band about 20° latitude wide seems to be the optimum width to represent the surface westerlies on a hemispheric basis. Values of the mean indices for half months and the seasons are shown in Table I for three 20° bands. The bands 35–55°N and 40–60°N display the westerlies about equally well, but values for 35–55°N have been used in most of the diagrams because they display the winter maximum over the oceans better, and indeed in winter the 30–50°N band is even more appropriate for the Pacific. When comparing the development of the westerlies from the autumn to the winter in the two oceans modified band widths have sometimes been used.

(c) *The meridional thickness gradient*

This has been expressed as the difference in the mean monthly thickness (1000/500 mb) between 35°N and 55°N along each meridian, each averaged over a month.

Mean values for the following longitude areas have been obtained:

Atlantic area	60°W to 10°W
western Pacific	140°E to 180°E
eastern Pacific	170°W to 130°W
Europe and Asia	0 to 130°E
America	120°W to 70°W
hemisphere	mean of 36 meridians.

(d) *The meridional gradient of geopotential at 500 millibars*

This has been treated exactly like the thickness gradient.

(e) *Meridional indices—surface*

The basic unit here is the monthly mean northerly geostrophic wind determined over a 30° longitude band. These have been determined at 18 meridians

TABLE I—ANNUAL COURSE OF THE ZONAL INDEX FOR THE NORTHERN HEMISPHERE FOR VARIOUS LATITUDE BANDS—MEANS FOR PERIOD 1900–70

Half months	30–50°N	35–55°N	40–60°N
		$m\ s^{-1}$	
Jan. (1)	1·5	2·4	2·5
Jan. (2)	1·2	1·7	1·7
Feb. (1)	1·1	1·4	1·2
Feb. (2)	1·3	1·6	1·2
Mar. (1)	1·1	1·3	1·0
Mar. (2)	1·1	1·4	1·2
Apr. (1)	0·9	1·4	1·3
Apr. (2)	0·9	1·3	1·0
May (1)	0·9	1·3	0·9
May (2)	0·7	1·1	0·9
June (1)	0·5	0·9	0·9
June (2)	0·5	1·1	1·3
July (1)	0·4	1·3	1·7
July (2)	0·1	1·2	1·7
Aug. (1)	−0·2	1·1	1·7
Aug. (2)	−0·4	0·9	1·6
Sept. (1)	−0·5	0·9	1·8
Sept. (2)	−0·4	1·3	2·2
Oct. (1)	0·1	1·9	2·9
Oct. (2)	0·5	2·2	3·0
Nov. (1)	1·0	2·5	2·9
Nov. (2)	1·3	2·6	2·9
Dec. (1)	1·8	2·9	2·9
Dec. (2)	2·1	2·9	2·7
Seasons			
Winter	1·5	2·2	1·9
Spring	0·9	1·3	1·0
Summer	0·2	1·1	1·5
Autumn	0·3	1·9	2·6

spaced 20° apart round the hemisphere, and are summed without regard to sign to give an index of the meridional circulation for various zones and for the whole hemisphere.

Values are available for the latitude bands 35–55°N and 55–75°N.

3. ANNUAL COURSE OF THE INDICES

The annual course of the surface zonal index and the meridional thickness gradient for the whole hemisphere and for the oceanic regions is shown in Figure 1. It brings out how much stronger the surface westerlies are over the oceans than over the hemisphere as a whole. In fact the land areas have a net easterly at most times of the year. The meridional thickness gradients are not, however, markedly different over the land and ocean areas. There are some interesting differences brought out in Figure 2. The rate of increase of the meridional thickness gradient from August to November is surprisingly rather greater over the oceans than over the land areas. This seems to be connected with the increase in the oceanic westerlies, especially in the Pacific, during this time. The gradient reaches its peak over the oceans in December whereas the peak over the land is not reached until February.

Figure 3 shows the zonal indices and meridional thickness gradients for the western and eastern Pacific separately. They both show peaks in November

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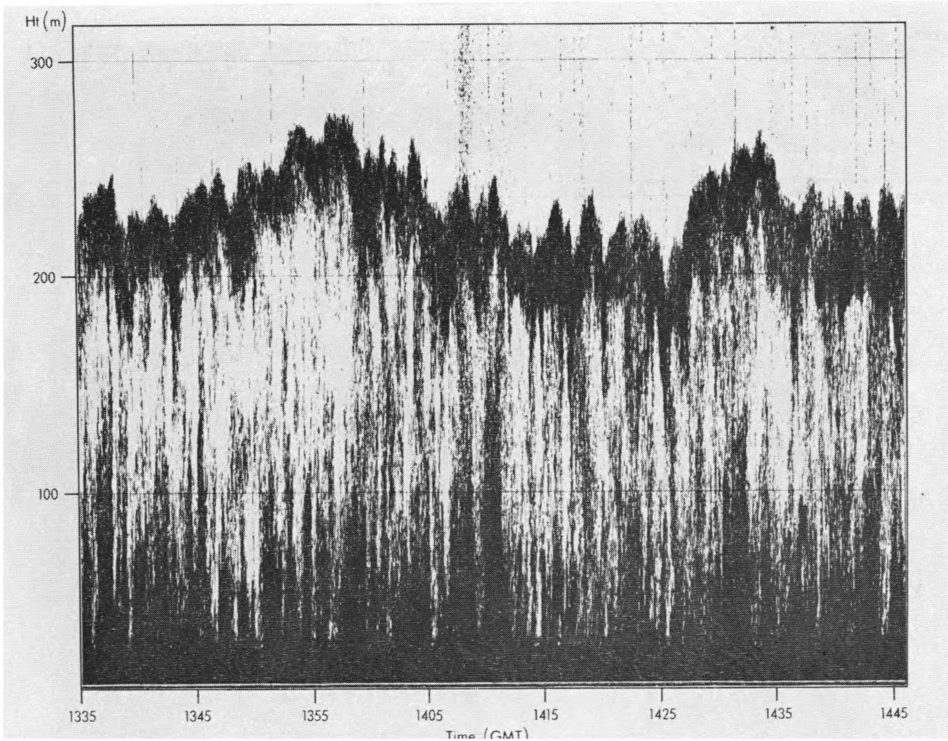

PLATE I—SOUNDER FACSIMILE CHART FOR THE PERIOD 1335–1445 GMT ON 28 OCTOBER 1975

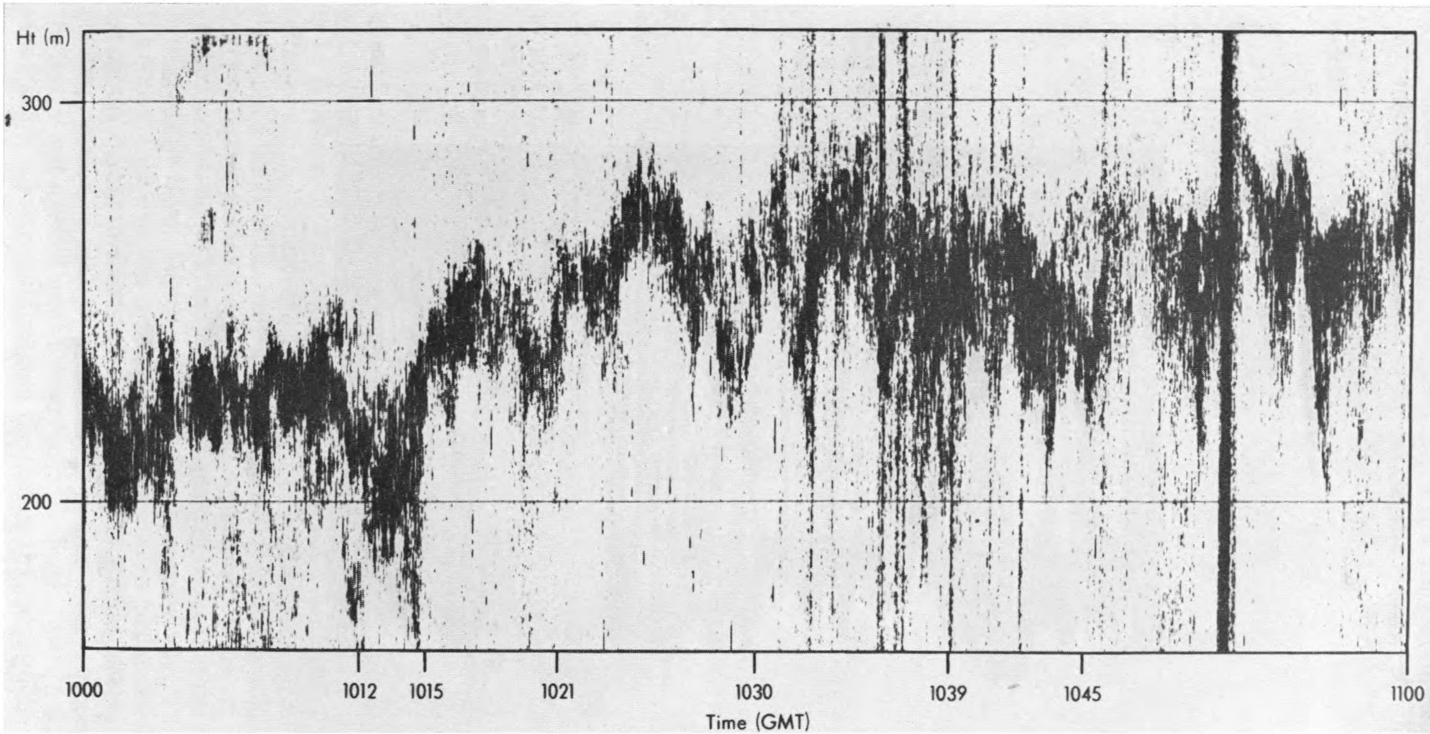

PLATE II—SOUNDER FACSIMILE CHART FOR THE PERIOD 1000–1100 GMT ON 29 OCTOBER 1975

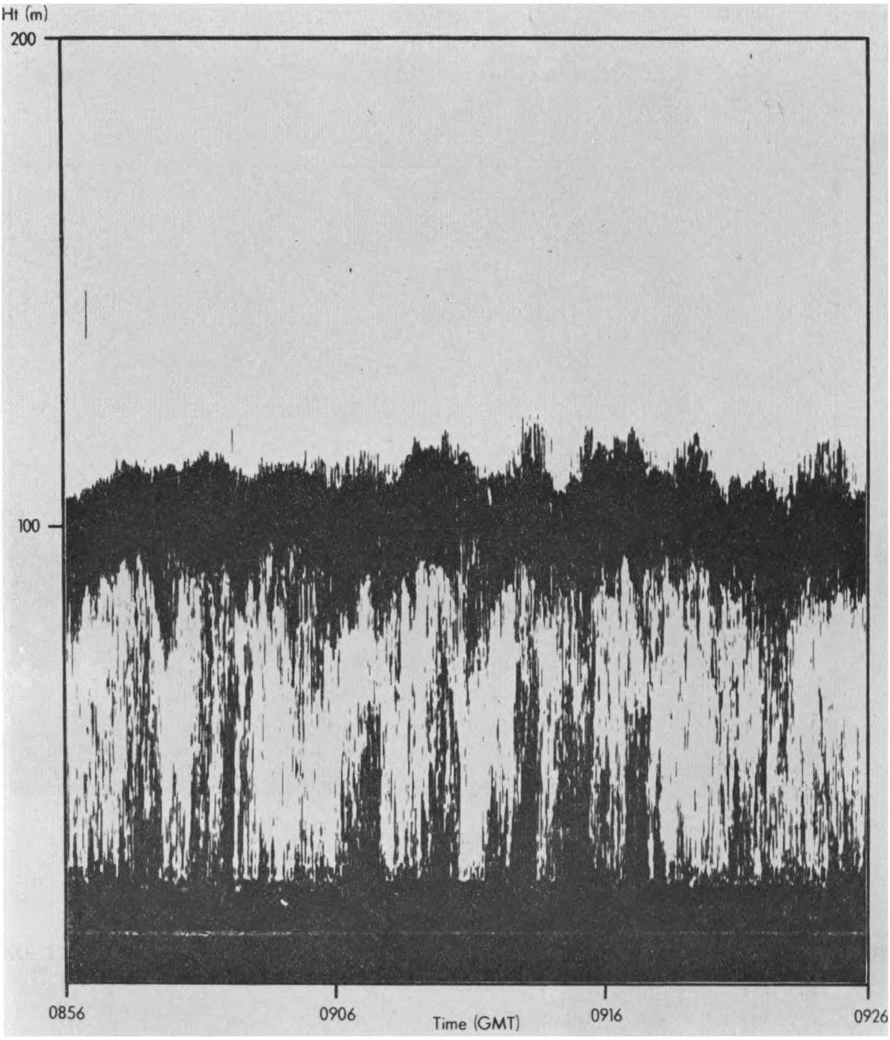

PLATE III—SOUNDER FACSIMILE CHART FOR THE PERIOD 0856–0926 GMT ON 14 NOVEMBER 1975

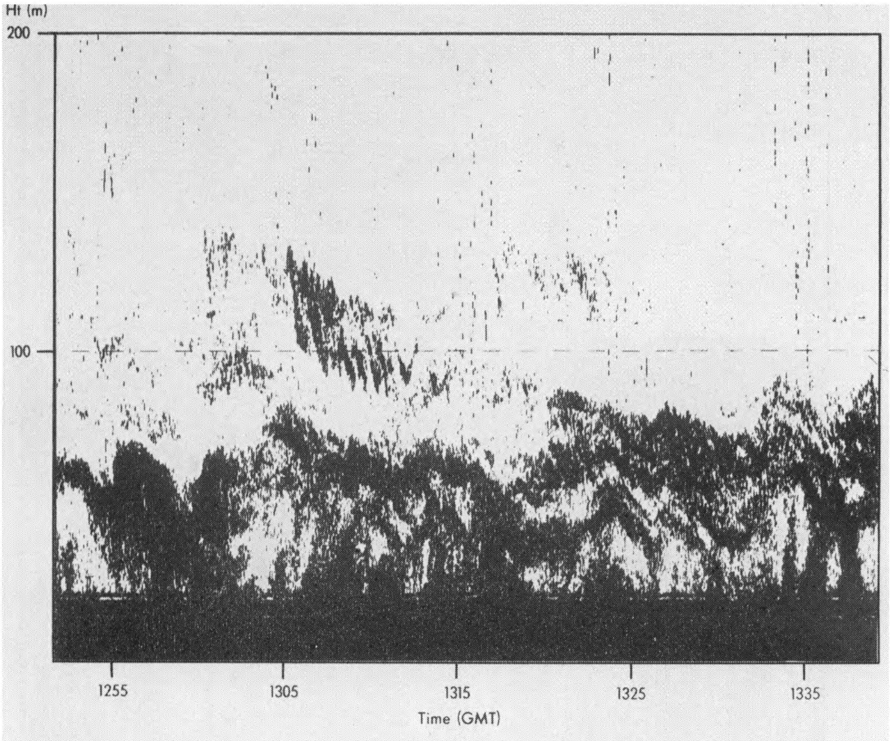

Figure 2

PLATE IV—SOUNDER FACSIMILE CHART FOR THE PERIOD 1250–1340 GMT ON 14 NOVEMBER 1975

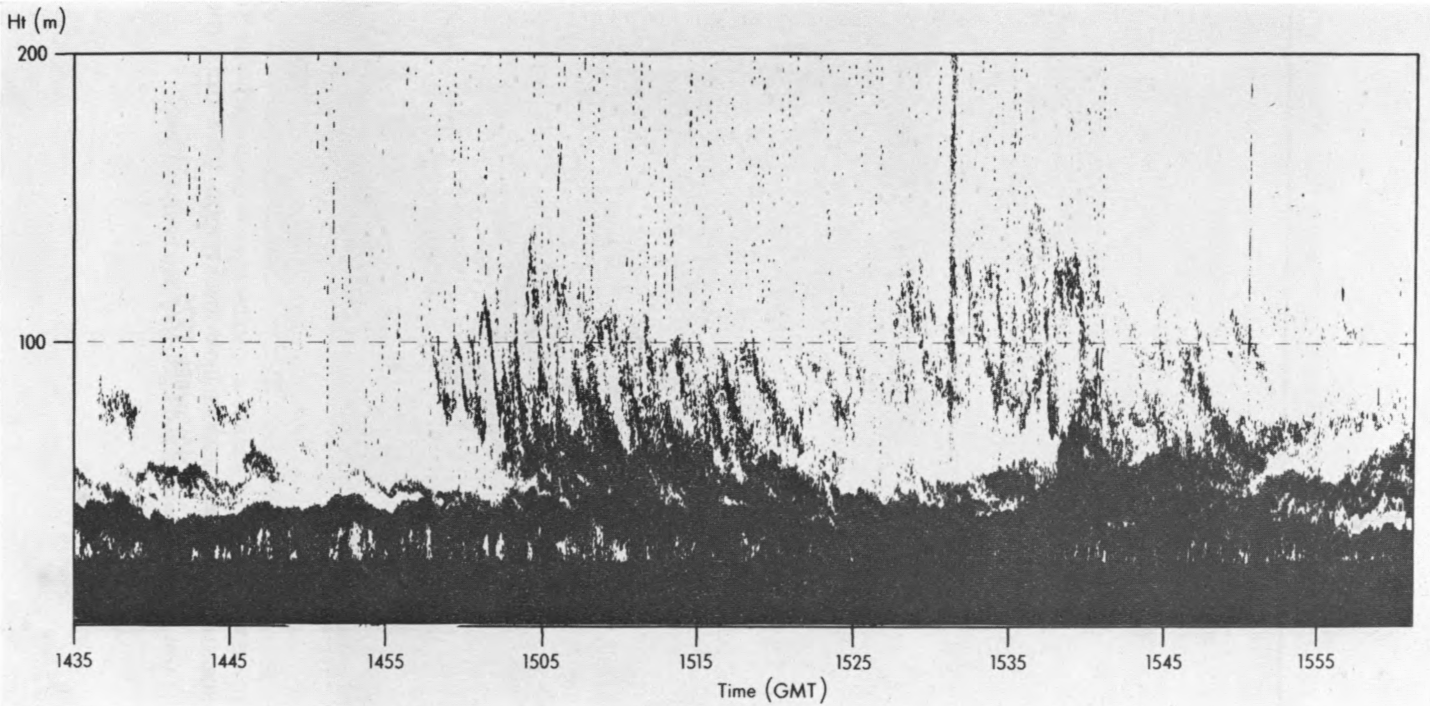

PLATE V—SOUNDER FACSIMILE CHART FOR THE PERIOD 1435–1600 GMT ON 14 NOVEMBER 1975

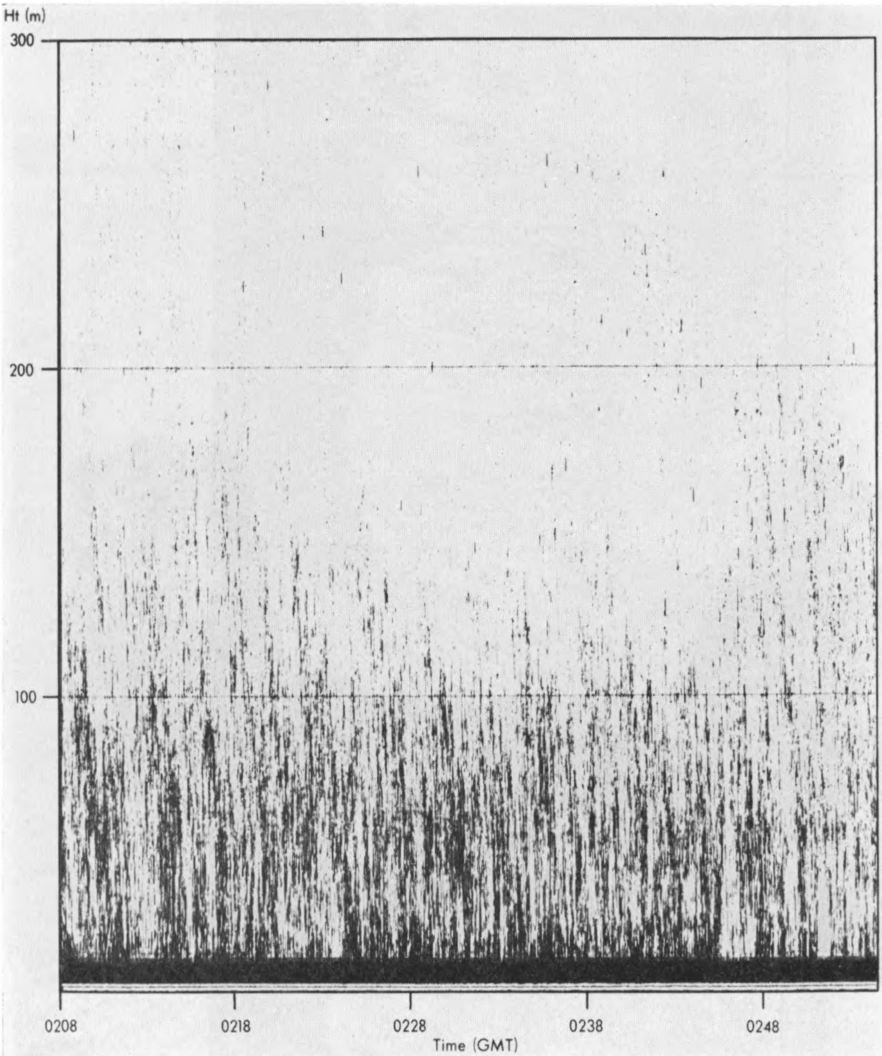

PLATE VI—SOUNDER FACSIMILE CHART FOR THE PERIOD 0208–0253 GMT ON 7 NOVEMBER 1975

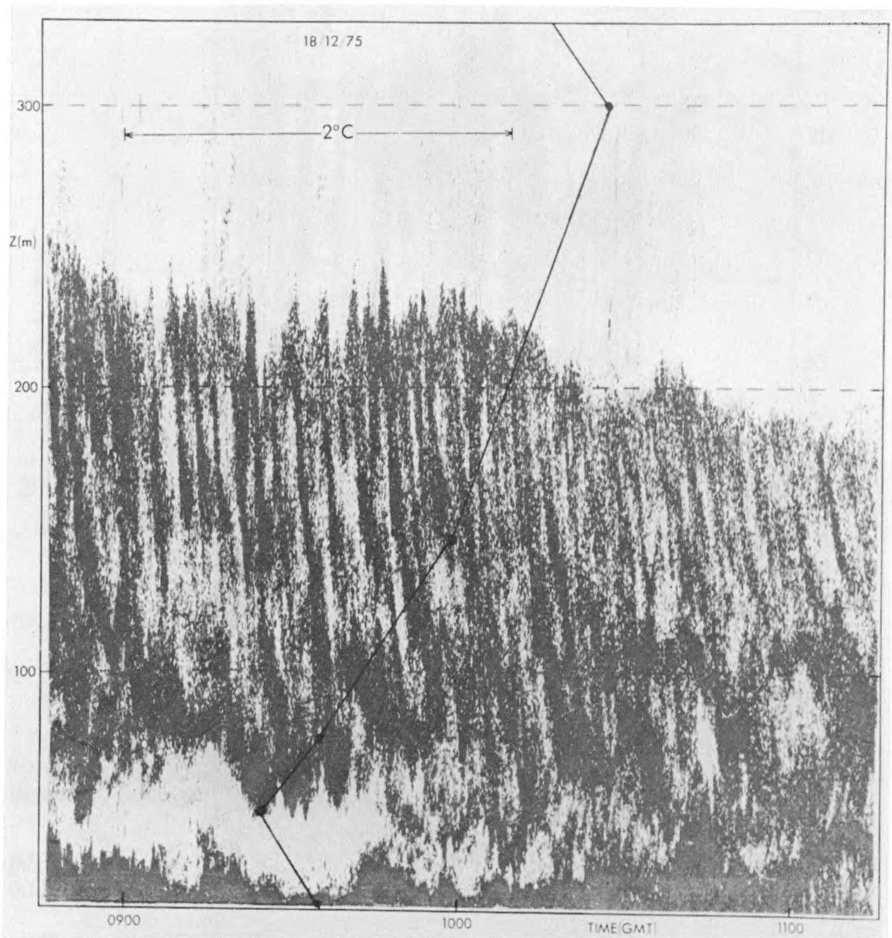

PLATE VII—BREAKING WAVES WITHIN A STABLE LAYER. A CARDINGTON BALTHUM IS SHOWN FOR REFERENCE

(See Crease *et alii*, page 42; Plate not referred to in text.)

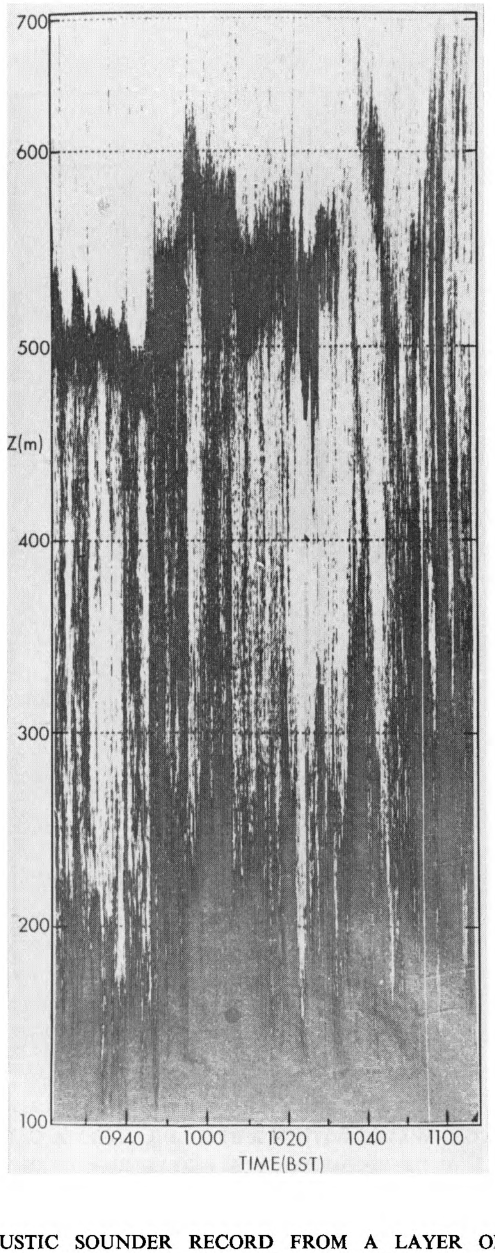

PLATE VIII—ACOUSTIC SOUNDER RECORD FROM A LAYER OF STRATUS CLOUD WHICH EXTENDED FROM NEAR THE SURFACE TO ABOUT 500 m. THE CLOUD BEGAN TO DISSIPATE (WEAKENING LAYER ECHO) AT AROUND 1030 GMT OWING TO INCREASING CONVECTION

(See Crease *et alii*, page 42; Plate not referred to in text.)

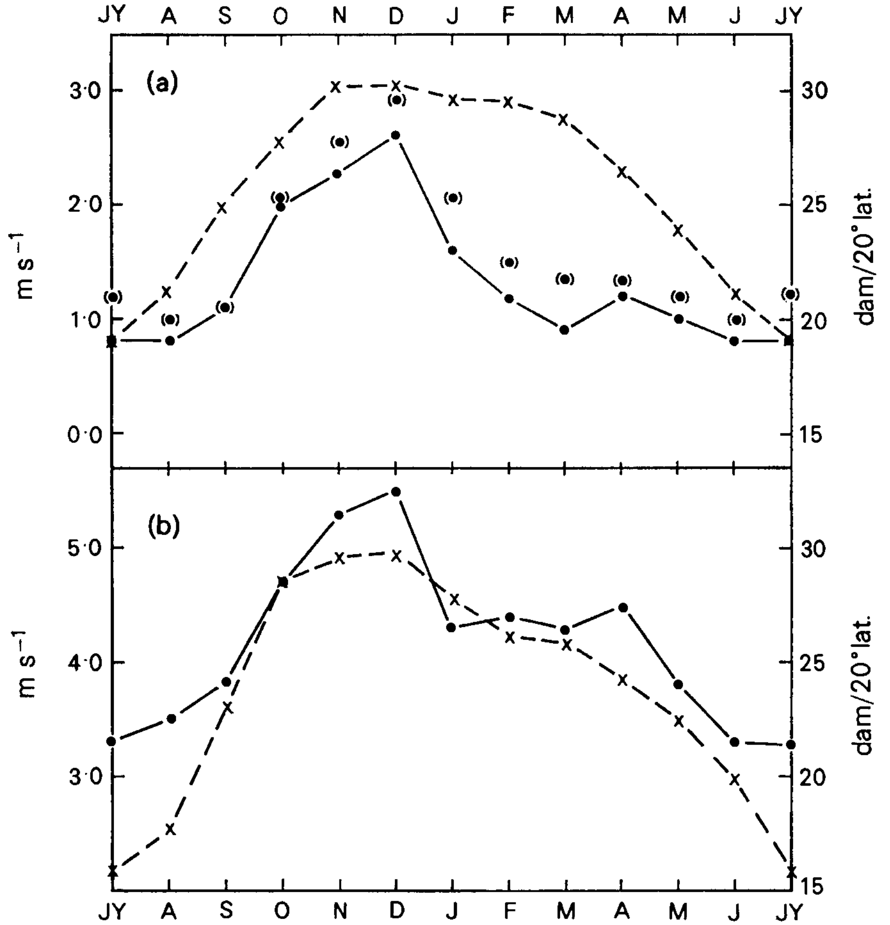

FIGURE 1—MONTHLY AVERAGES OF ZONAL INDEX (•——•) AND MERIDIONAL THICKNESS GRADIENT (1000/500 mb) (×---×) FOR LATITUDE BAND 35–55°N FOR PERIOD 1951–70

(Values plotted (·) are averages for 1900–70.)
(a) Hemisphere (b) Oceanic areas

but this is exaggerated because the flow moves mainly south of 50°N after November. The thickness gradient is much stronger in the western Pacific owing to the intense gradient present, just off the east Asian coast, but is not accompanied by such strong surface westerlies as in the eastern Pacific where the thickness gradient is much smaller. This is true for the 30–50° latitude band as well.

In comparing the Pacific and Atlantic it is necessary to measure the westerlies over different latitude bands, 35–55°N for the Atlantic and 30–50°N for the Pacific. The longitude band chosen for the Pacific is 150°E to 150°W which avoids the disturbing effects of the land areas on either side of the Ocean.

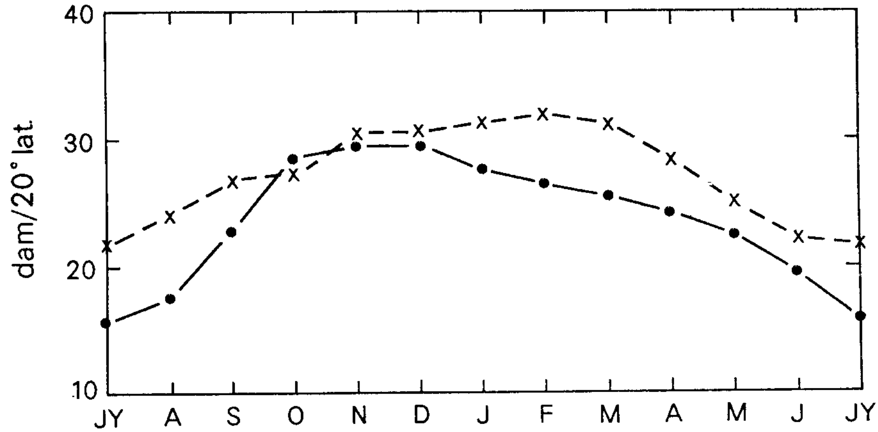

FIGURE 2—AVERAGE MONTHLY MERIDIONAL THICKNESS GRADIENT (1000/500 mb) FOR LATITUDE BAND 35–55°N FOR PERIOD 1951–70. OCEANIC AREAS (•——•) LAND AREAS (×– – –×)

Figure 4 shows the annual course of the zonal indices and meridional thickness gradients for the two oceans. The following points are worth noting:

(1) The larger seasonal range in the Pacific of both westerly wind and thickness gradient—due mainly to the intense monsoonal effect over Asia.

(2) The rapid growth in the westerlies in the Pacific between October and November in contrast to the stagnation in the Atlantic at this time.

(3) The November peak in the thickness gradient in the Pacific—one or two months earlier than in the Atlantic.

(4) The relation of the zonal index to the thickness gradient is similar in one respect: the peak of the zonal index is not accompanied by a peak of thickness gradients.

(5) Although peak values of the zonal index in the Atlantic are slightly less than in the Pacific the ratio of zonal index to thickness gradient is notably higher in the Atlantic.

Figure 5 shows that for the band 35–55°N the maximum meridional zonal gradient at 500 mb is reached over the oceans in November and December. Although the strongest flow moves southwards through the winter the 30–50° band still shows a substantial fall in gradient from December to January. Despite weaker thickness gradients in almost all months the 500 mb flow is stronger over the oceans than over the land areas—a result of the baroclinic conversion of the potential energy to zonal kinetic energy in the western parts of the oceans.

Figure 6 shows the annual course of the hemispheric meridional indices for the two latitude bands. The main features are a maximum in January in both bands, and a secondary maximum in July in the 35–55° band due largely to the monsoonal developments over Eurasia and America.

Meridional indices for the band 35–55°N chosen to represent the Pacific and Atlantic Oceans are shown in Figure 7. The maximum is reached in January or February in contrast to the earlier peaking of the zonal circulation (Figures 3 and 4). Again there is a secondary maximum in July indicating the relative accentuation of the high-pressure area over the central parts of the two oceans at this time of year.

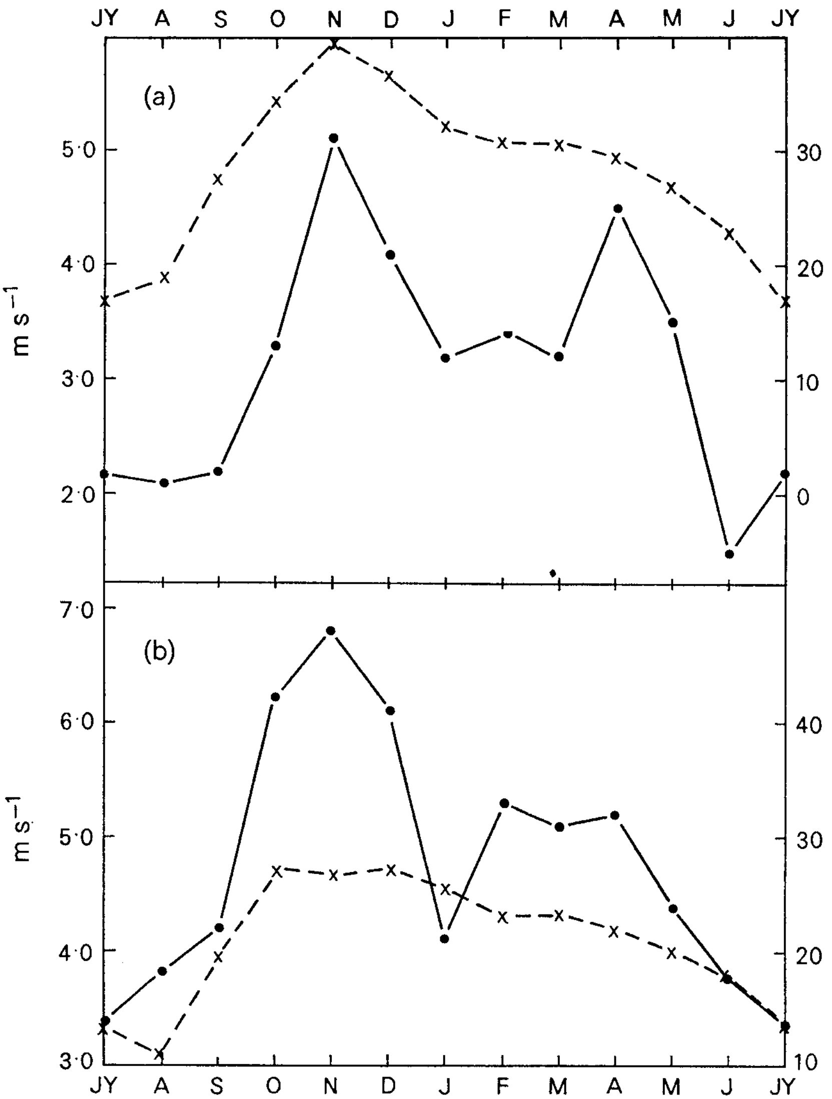

FIGURE 3—MONTHLY AVERAGES OF ZONAL INDEX (•——•) AND MERIDIONAL THICKNESS GRADIENT (1000/500 mb) (×- - -×)

(a) Western Pacific 140°E–180°E
(b) Eastern Pacific 170°W–130°W

4. THE VARYING RATES OF GROWTH OF THE WINTER WESTERLIES

The zonal indices show quite clearly that the autumnal increase in the westerly circulation does not occur at the same time in the three oceanic regions. It occurs earliest in the eastern Pacific Ocean where the rate of growth reaches a maximum around the end of September. Figure 8 shows the rates of growth obtained by differencing the adjacent half-month means of the zonal index.

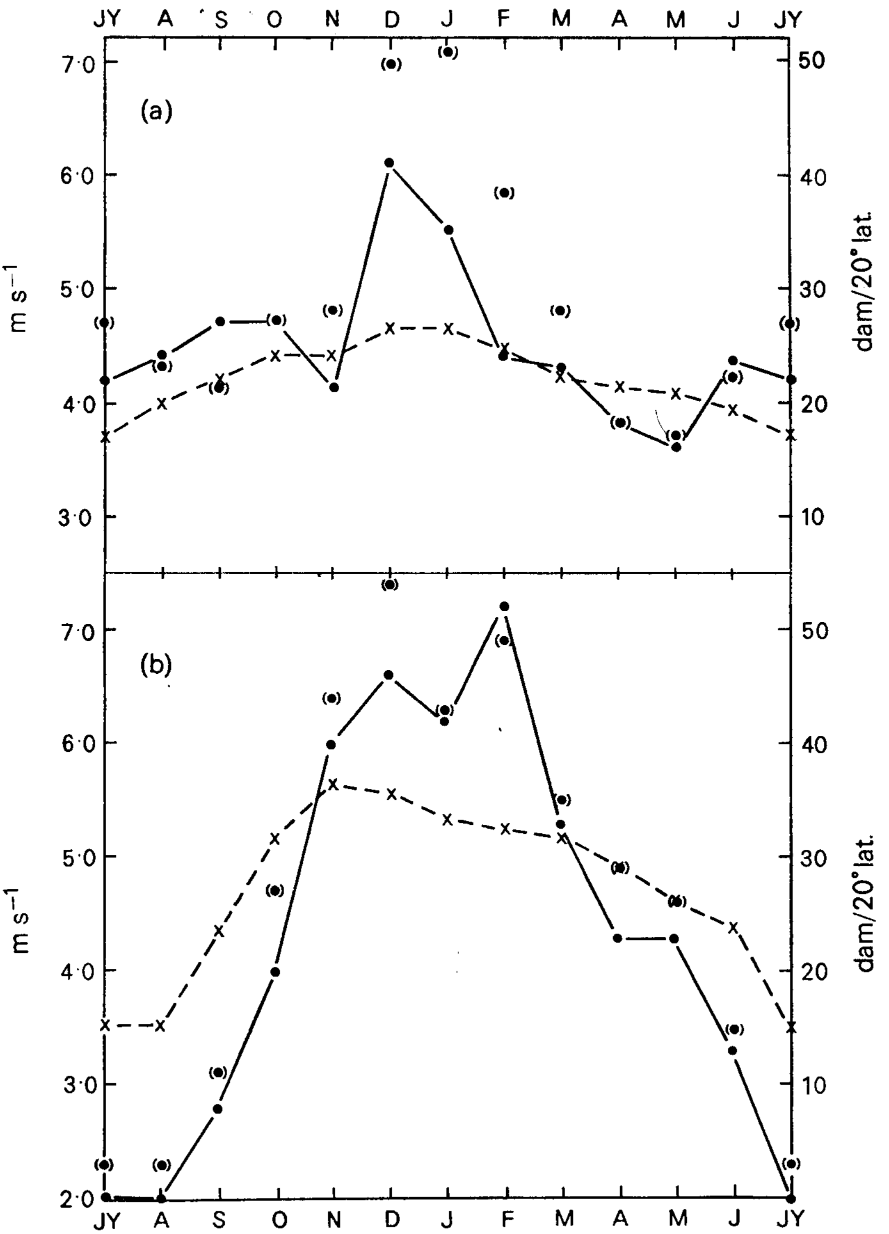

FIGURE 4—MONTHLY AVERAGES OF ZONAL INDEX (•——•) AND MERIDIONAL THICKNESS GRADIENT (1000/500 mb) (×- - - ×)

(Values plotted (·) are averages for 1900–70.)
(a) Atlantic Ocean 35–55°N
(b) Pacific Ocean 30–50°N and 150°E to 150°W

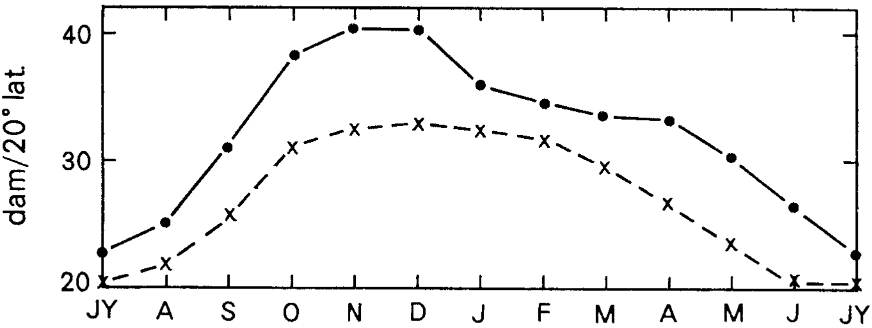

FIGURE 5—AVERAGE MONTHLY MERIDIONAL CONTOUR GRADIENT AT 500 mb FOR 35–55°N

Oceanic areas (•——•) Land areas (×- - -×)

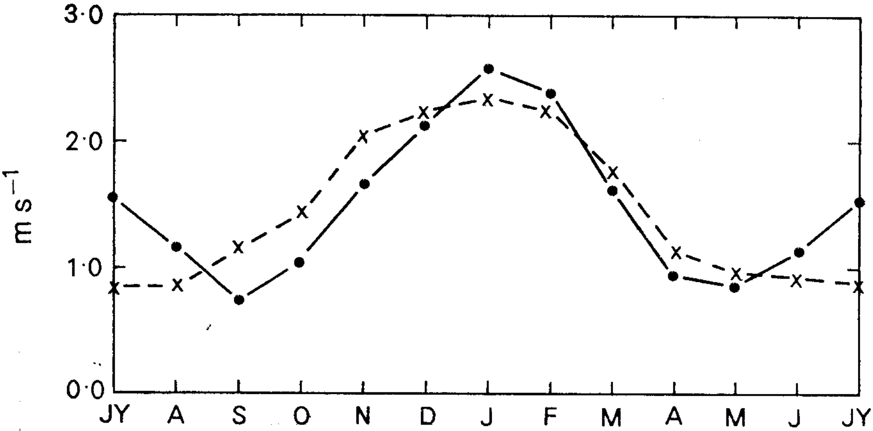

FIGURE 6—MONTHLY AVERAGES OF HEMISPHERIC MERIDIONAL INDICES FOR 35–55°N (•——•) AND 55–75°N (×- - -×) FOR PERIOD 1951–70

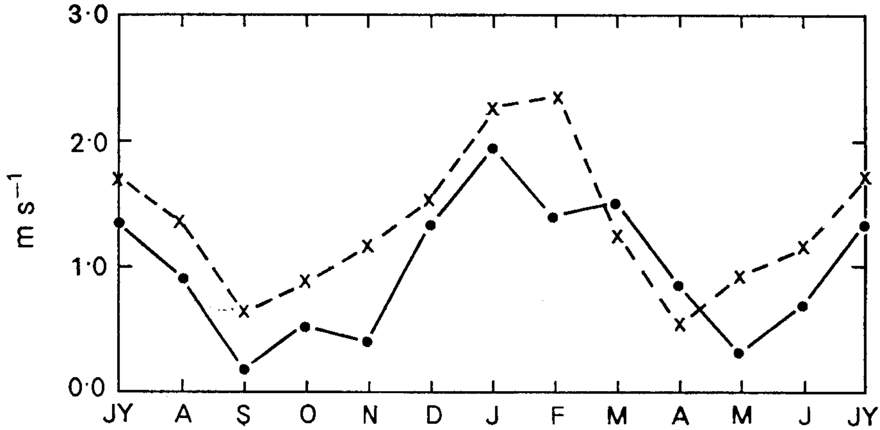

FIGURE 7—MONTHLY AVERAGES OF A MERIDIONAL INDEX FOR 35–55°N FOR THE ATLANTIC (•——•) AND THE PACIFIC (×- - -×) FOR PERIOD 1951–70

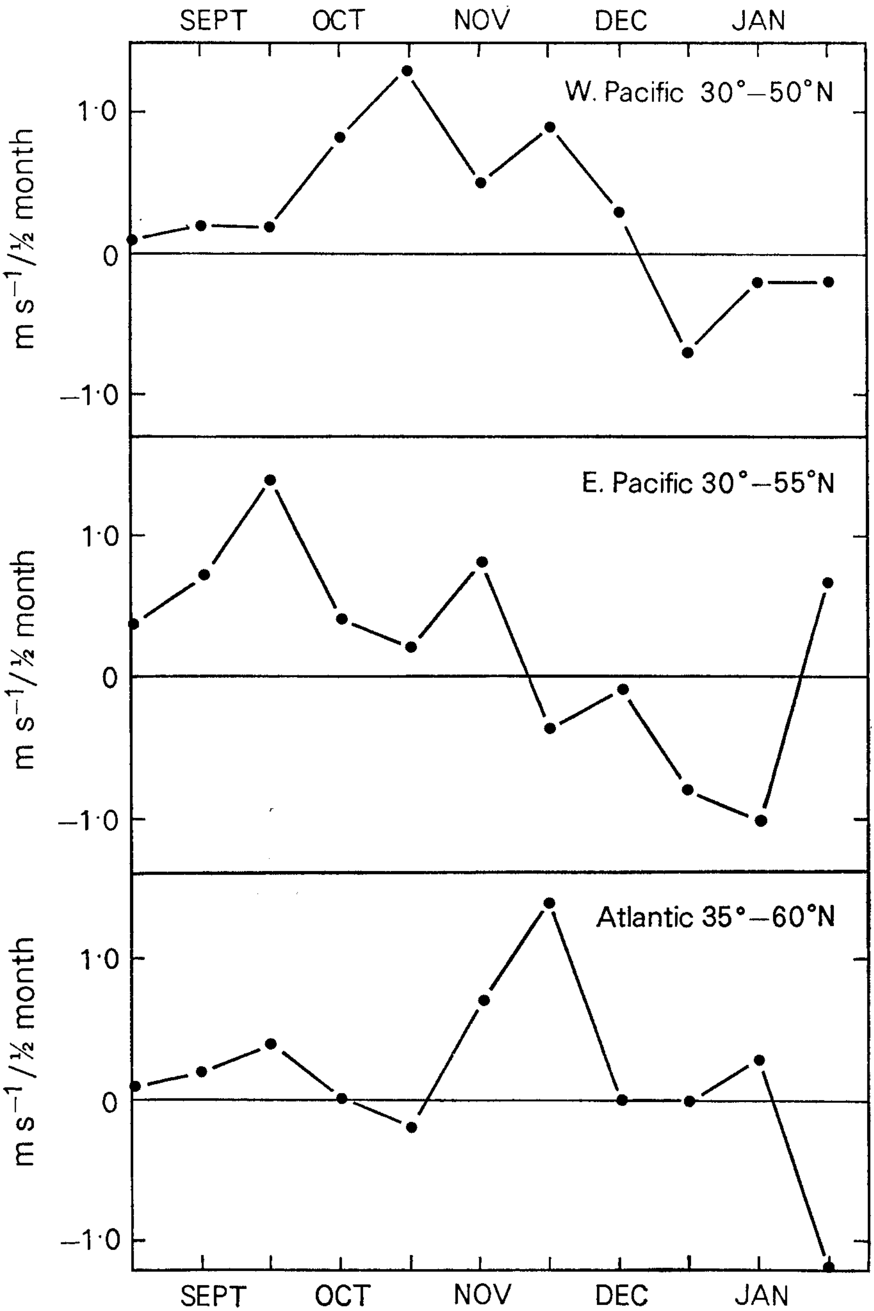

FIGURE 8—RATE OF CHANGE OF THE ZONAL INDEX FOR THREE OCEANIC AREAS IN THE WINTER HALF YEAR FROM 1900–70 AVERAGES

(The mid plot for each month is the change in the half-monthly mean index between the first and second halves of that month.)

To avoid disturbing effects arising from changes in latitude of the strongest westerlies over the period August to February, 25° latitude bands have been used—30–55°N for the eastern Pacific and 35–60°N for the Atlantic. The western Pacific westerlies show little increase until October and maximum rate of growth occurs around the end of October. The growth curve is a full month later again in the Atlantic after a minor phase of activity in October.

The same behaviour is evident in the cumulative increase from the second half of August shown in Figure 9.This flattens off after November in the eastern Pacific, after about mid December in the western Pacific and not until January in the Atlantic. This earlier and more vigorous growth of the westerlies in the Pacific compared with the Atlantic is a notable feature which deserves closer consideration. It might be said that from September to the end of October the Pacific is recovering from very low summer values and reaching the strength prevailing in the Atlantic. The growth, however, continues through November while the Atlantic index stays about the same. The thickness gradient also rises very rapidly from the very low values of July and August to an October value substantially higher than that in the Atlantic.

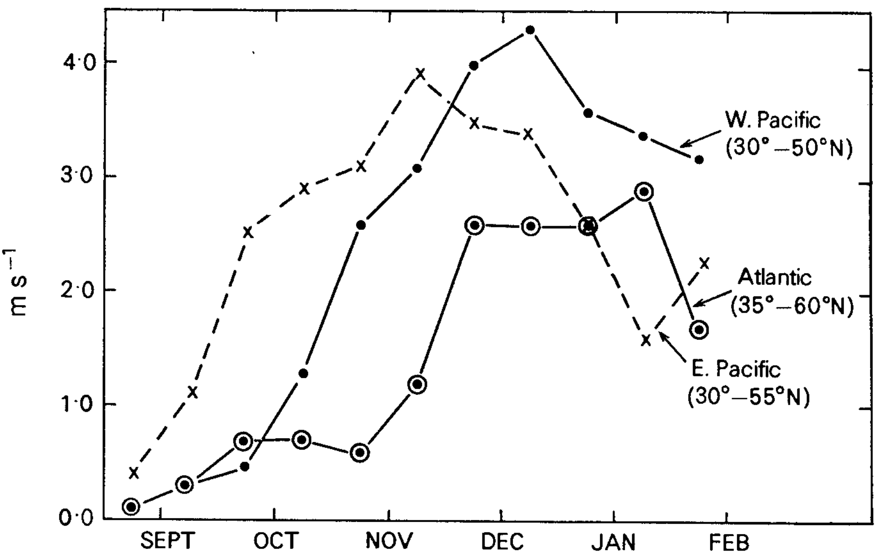

FIGURE 9—CUMULATIVE CHANGE IN THE ZONAL INDICES FOR THREE OCEANIC AREAS FROM THE SECOND HALF OF AUGUST

These differences in behaviour are reflected in the changes that occur in the zone of the upwind troughs during this period. Figures 10 and 11 show the course of the meridional thickness gradient in the regions of the American and Asian winter troughs. The values are similar in September but by November those in the Asian trough are considerably greater, paralleling the more rapid growth of the Pacific westerlies. In this association what is cause and what is effect is not easy to determine. Miles (1975) has shown that the zonal index over the Atlantic in winter has a correlation of about 0·5 with the contemporaneous thickness gradient 35–55°N in the area of the American trough. Correlations with a half-month lag and lead are lower than this and so afford no indication of which is the cause. From the data given in Table II there is little indication of a close relationship between the westerlies and the changes of thickness gradient in the upwind trough. There is a general higher ratio of zonal index to thickness gradient in the Atlantic in the autumn and early winter, with November appearing as an anomalous month in the Atlantic and February as an anomalous month in the Pacific.

TABLE II—THE RELATION BETWEEN ZONAL INDEX OVER THE OCEANS AND THE THICKNESS IN THE UPWIND THERMAL TROUGH (35–55°N FOR ATLANTIC, 30–50°N FOR PACIFIC)

Month	Thickness gradient 60–90°W *dam/20° lat.*	Zonal index Atlantic *m s*$^{-1}$	Ratio zonal index/ thickness gradient
Sept.	30·1	4·7	0·16
Oct.	30·2	4·7	0·16
Nov.	34·3	4·1	0·12
Dec.	38·5	6·1	0·16
Jan.	41·4	5·5	0·13
Feb.	40·0	4·4	0·11
Mar.	35·2	4·3	0·12

Month	Thickness gradient 120–150°E *dam/20° lat.*	Zonal index Pacific *m s*$^{-1}$	Ratio zonal index/ thickness gradient
Sept.	28·4	2·8	0·10
Oct.	35·5	4·0	0·11
Nov.	46·5	6·0	0·13
Dec.	49·2	6·6	0·13
Jan.	47·7	6·2	0·13
Feb.	46·6	7·2	0·15
Mar.	42·4	5·3	0·12

In Figures 10 and 11 surface temperature differences are shown as well as thickness gradients. The aim was to find some indicator of the strength of these thermal troughs which would be available before the era of radiosondes, for use in climatic change studies. The two stations chosen to represent the American trough are Moosonee (51°16′N, 80°39′W) and Cape Hatteras (35°15′N, 75°40′W) and for the east Asian trough Nikolayevsk-na-Amure (53°09′N, 140°42′E) and Tokyo (35°41′N, 139°46′E). They cover the greater part of the 20° latitude band used for the thickness gradient and lie near the longitude of the average thermal trough in the two regions. The Moosonee–Cape Hatteras surface temperature difference follows the thickness gradient throughout the year very closely but there is a considerable lack of fit for the Nikolayevsk–Tokyo difference. The greater rate of increase in the thickness gradient of the east Asia trough between October and November is however, reproduced. The decline in the thickness gradient in January is due to a substantial part moving south of 35°N. The course of thickness gradient for the band 30–50°N resembles the surface temperature difference more closely, though it has a flat maximum in December. The maximum of surface temperature difference in January is probably due to a more stable lapse rate setting in at the latitude of

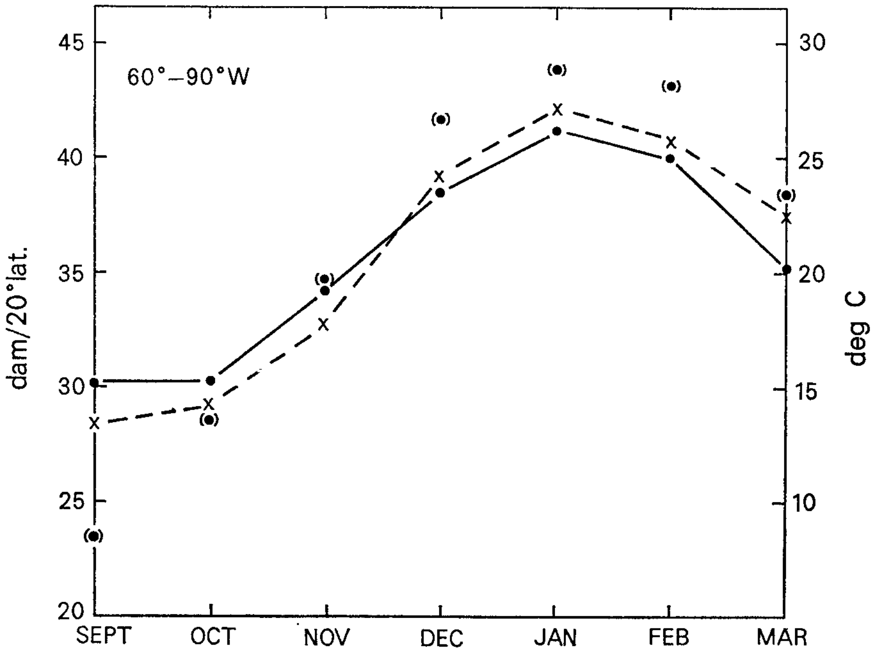

FIGURE 10—MERIDIONAL THICKNESS GRADIENT (1000/500 mb) BETWEEN 35°N AND 55°N (•——•) AND SURFACE TEMPERATURE DIFFERENCES (×– – –×) BETWEEN TWO STATIONS IN THE AREA OF THE WINTER AMERICAN TROUGH

(The scale for the temperature difference is on the right of the diagram.) Values of the thickness gradient for the band 30–50°N are plotted (•).

Nikolayevsk than at that of Tokyo. This feature come out quite clearly in Table III where zonally averaged surface temperature gradients for January are compared with 500 mb temperature gradients based on data by Oort and Rasmusson (1971).

TABLE III—TEMPERATURE GRADIENTS NEAR THE SURFACE (1000 mb) AND AT 500 mb FOR VARIOUS LATITUDE REGIONS IN JANUARY—OORT AND RASMUSSON (1971)

Latitude region	Temperature gradients °C/20° lat.	
	500 mb	*1000 mb*
15–35°N	13·6	13·8
35–55°N	11·9	17·6
55–75°N	6·5	17·8

The earlier and more rapid growth of thickness gradient in the east Asian trough is also associated with an earlier and stronger growth in the northerly flow in the region of the Asian trough. Figures 12 and 13 show the differences in northerly flow for two latitude bands. In particular the great increase in the northerlies 55–75°N between October and November in the Asian area is noteworthy. This mainly reflects the development of the winter north-east monsoon but in part it is due to the deepening of the Pacific low-pressure system to the east of Kamchatka, which must accompany the growth of the zonal index for the west Pacific at this time. Again cause and effect are hard to disentangle.

In the light of these various considerations it seems that the different behaviour of the westerlies in the two oceanic regions is not to be readily explained by reference to the thermal troughs over the upwind continents.

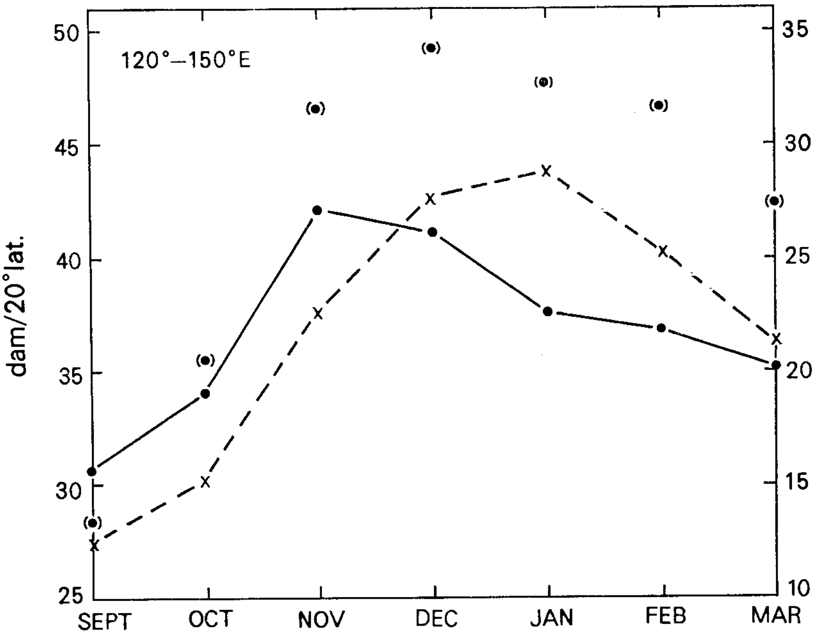

FIGURE 11—MERIDIONAL THICKNESS GRADIENT (1000/500 mb) BETWEEN 35°N AND 55°N (·——·) AND SURFACE TEMPERATURE DIFFERENCES (×– – –×) BETWEEN TWO STATIONS IN THE AREA OF THE WINTER EAST ASIAN TROUGH

(The scale for the temperature difference is on the right of the diagram.) Values of the thickness gradient for the band 30–50°N are plotted (·).

5. CONCLUSIONS

The following points emerge from this study:

1. The annual course of the zonal and meridional indices of the surface circulation in the northern hemisphere shows a maximum circulation in the winter half year. The peak of zonal flow occurs in December while the peak of the meridional flow is in January.

2. In the Pacific the westerlies fall to a very low value in July and August but increase more rapidly than the Atlantic westerlies in the autumn and early winter to reach a peak somewhat earlier. The difference in the two oceans is not easily to be explained by reference to the upwind thermal troughs.

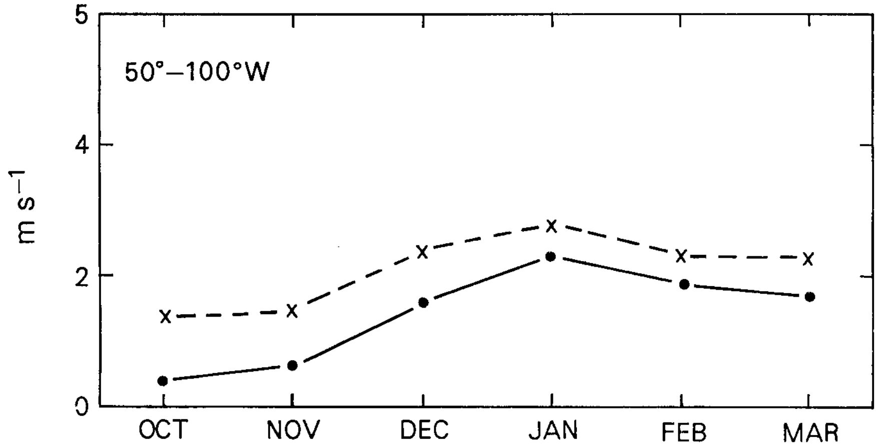

FIGURE 12—AVERAGE NORTHERLY GEOSTROPHIC WIND OVER TWO LATITUDE BANDS IN THE AREA OF THE WINTER AMERICAN TROUGH 50–100°W

(·——·) is for the latitude band 35–55°N.
(×– – –×) is for the latitude band 55–75°N.

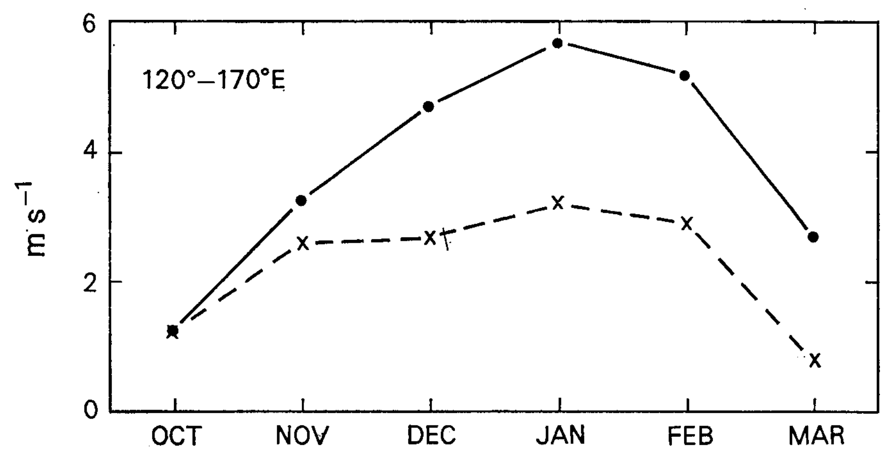

FIGURE 13—AVERAGE NORTHERLY GEOSTROPHIC WIND OVER TWO LATITUDE BANDS IN THE AREA OF THE WINTER EAST ASIAN TROUGH

(·——·) is for the latitude band 35–55°N.
(×– – –×) is for the latitude band 55–75°N.

3. The meridional thickness gradient over the oceans after being slightly less in summer than over the land areas increases more rapidly in the autumn. It reaches a peak in December whereas that over the land area has its maximum in February.

ACKNOWLEDGEMENT

The help of Mr P. R. Benwell, Mr P. Collison and Mr S. Lawson in writing the programs to obtain these indices is gratefully acknowledged.

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OORT, A. M. and RASMUSSON, E. M. 1971 Atmospheric circulation statistics. NOAA Prof. Paper, No. 5. US Department of Commerce.

REVIEWS

Radioisotopes and global transport in the atmosphere, by I. L. Karol'. 245 mm × 175 mm, pp. xiii + 323, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Susssex, 1975. Price £13·25.

This book is a presentation of Russian work on the use of both natural and artificial isotopes to study global transport mechanisms. As is natural in view of the stabilization altitude of the debris clouds from nuclear weapon tests, there is considerable emphasis on the lower stratosphere, and exchange processes across the tropopause.

The first chapter reviews in considerable detail observed fields and their fluctuations in time and space. The second chapter constructs, in spherical co-ordinates, a two-dimensional, meridional model of global transport between the planetary surface and 25 km. Chapter 3 deals with vertical transport, and removal processes for aerosols. Chapter 4 deals with the global distribution of zonal mean transport parameters appropriate to the model derived in Chapter 2. In Chapter 5 numerical models for solving the model equations are discussed, in Chapter 6 the model is used to examine the planetary distribution of radon and its decay products, and in Chapter 7 it is further used to examine the spread of debris from nuclear weapon tests, with particular reference to W^{185} and Mn^{54}. Chapter 8 deploys the model upon the natural isotopes resulting from cosmic ray impact, such as C^{14} and Be^{7}. The book ends with a three-page Conclusion, in which the major results are stated in a concise manner.

The subject is treated throughout in a quite detailed mathematical manner, equations being liberally interlarded with data tables. While making a valuable reference book for the specialist who needs a convenient compendium of the Russian work, this approach has the disadvantage of discouraging those looking for a readable, explanatory review of meridional transport processes. Such readers would be well advised to read the Introduction and skip to the Conclusion, wherein a clear concise statement of the book's results is given.

The date of the original Russian text is February 1972; in the four and a half years that have elapsed since then there has been considerable impetus given to the subject of meridional global transport, by the concern that aircraft flying in the stratosphere might cause chemical damage to the ozone there. This has rather badly dated the author's observation that three-dimensional models should be constructed. On the other hand, his conclusion that the mean climatic intensity of large-scale turbulent diffusion proved to be only a fraction of the values given in well-known estimates by western workers should provide food for thought in two-dimensional modelling circles. A point occurring to your reviewer in passing is that if the time taken to remove half the material of a nuclear blast from the lower stratosphere is that quoted of just barely less than a year, it is not easy to reconcile with lower estimates for the values of large-scale turbulent diffusion.

The book suffers from what has become an endemic fault of translations; in addition to being over four years old, it has no index. One assumes that the statement on page 47 'Thus, energywise, the lower troposphere is a refrigerating machine, . . .' includes an infelicitous translation of the Russian for stratosphere; pedants may also deduce with dismay the existence of a Russian equivalent of 'energywise'.

In conclusion, this should prove a useful book for the specialist, with some interesting results which warrant further study.

A. F. TUCK

CORRECTION

Meteorological Magazine, November 1976, p. 343. The Jenkins (1969) reference should be

JENKINS, I. 1969 Increase in averages of sunshine in Greater London. *Weather*, **24**, pp. 52–54.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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THE CONTRIBUTION OF A WEATHER RADAR NETWORK TO FORECASTING FRONTAL PRECIPITATION: A CASE STUDY

By F. F. HILL, K. W. WHYTE and K. A. BROWNING

(Meterological Office Research Unit, Royal Signals and Radar Establishment*, Malvern, Worcestershire)

SUMMARY

The recent development at Malvern of techniques for the processing and transmission of composite radar data from several sites to remote centres brings nearer the possibility of providing meteorological offices with a real-time, semi-quantitative display of precipitation distribution. A case study of frontal precipitation is presented illustrating the value of such a system for mesoscale and synoptic-scale forecasting. The case is analysed using both a subjective and an objective approach. The indications are that improvements in the forecasts can be achieved for periods of three to six hours ahead.

1. INTRODUCTION

The purpose of this paper is to investigate by means of a case study the potential value of a network of quantitative radars for providing improved forecasts of frontal precipitation. The approach we have adopted is to concentrate on the mesoscale aspects of the precipitation patterns which have reasonable persistence, rather than on individual small-scale features.

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* Formerly the Royal Radar Establishment.

It is a long time since Ligda (1957) suggested the usefulness of a radar network by producing his montage. However, it is only recently that the technology has become available to provide the automatic compositing facilities that are required if the data are to be exploited for forecasting purposes (Taylor and Browning, 1974). The techniques for processing, transmitting and displaying the radar data are being developed by the joint team from the Meteorological Office and the Royal Signals and Radar Establishment at Malvern. The intensity of the echoes from precipitation is averaged over 5 km squares and displayed almost in real time on a colour television set at a remote site. Such data, obtained from a number of radars at intervals of approximately 15 minutes, can be replayed to reveal the movement and development of the precipitation. This obviously helps in making short-period forecasts by subjective extrapolation of existing trends. Additionally the information is available in a computer-compatible format which is suitable as an input to objective forecasting schemes. Hence the technique is capable of being exploited to the benefit of both subjective and objective methods of prediction. However, these are very recent developments and, in the absence of an ample network of quantitative weather radars in Britain for this synoptic-scale study, it has been necessary to simulate one using photographs from radars providing qualitative information only and to quantify much of the data by the analysis of autographic rain-gauge records.

The particular situation considered here is the occlusion of 14 February 1975. Although this case was straightforward in the sense that it lacked major orographic effects, it nevertheless provided a good example of other difficulties with which the forecaster is frequently confronted. One was the intensification of the precipitation, caused by a small-scale perturbation of the medium-level flow, as it crossed an area devoid of regular observations. A second difficulty was that the persistence of a narrow band of convergence near to the occlusion led to an accumulation of moderate falls of rain within restricted regions which were hard to locate by routine reports alone.

2. Evolution of rainfall in relation to the surface analysis and upper-air structure

Figure 1 shows the surface analysis and principal cloud areas at 2100 GMT on 13 February 1975. The northward progress of frontal systems had become slow owing to the intensification of a ridge of high pressure from Greenland to southern Norway. The depression shown in the Atlantic had been moving north-eastwards but it was expected to turn eastwards towards the English Channel, with the occlusion bringing rain to most parts of England and Wales on the following day.

Figure 2(a) shows the total rainfall for the complete system of precipitation associated with the occlusion, from the evening of the 13th when rain reached south-west Ireland until the afternoon of the 15th when it cleared from south-east England. It can be seen that falls of from 15 mm to over 30 mm occurred in a fairly narrow band from south-west Wales to Kent, whereas comparatively little rain affected Ireland and south-west England. The movement of the precipitation is depicted by the set of hourly rainfall maps (Figures 2(b–k)). For these, radar evidence has been used to supplement data from autographic rain-gauges, particularly with regard to the existence of the bands over Ireland, the location and movement of the rain over the Irish Sea, and the intensity over

Wales and the Midlands at times when the precipitation was partly composed of snow.

Before 0200 on the 14th, none of the twenty autographic gauges over southern Ireland recorded more than 0·5 mm in any hour, with most falls being only a trace. By 0400, however, Figure 2(b) shows that small areas of moderate rain had appeared. The radar evidence is that they were organized into west-north-westerly to east-south-easterly bands which were moving slowly eastwards. Meanwhile broader bands of mainly slight rain were moving north-eastwards across the Celtic Sea. The rainfall intensified during the next three hours, both

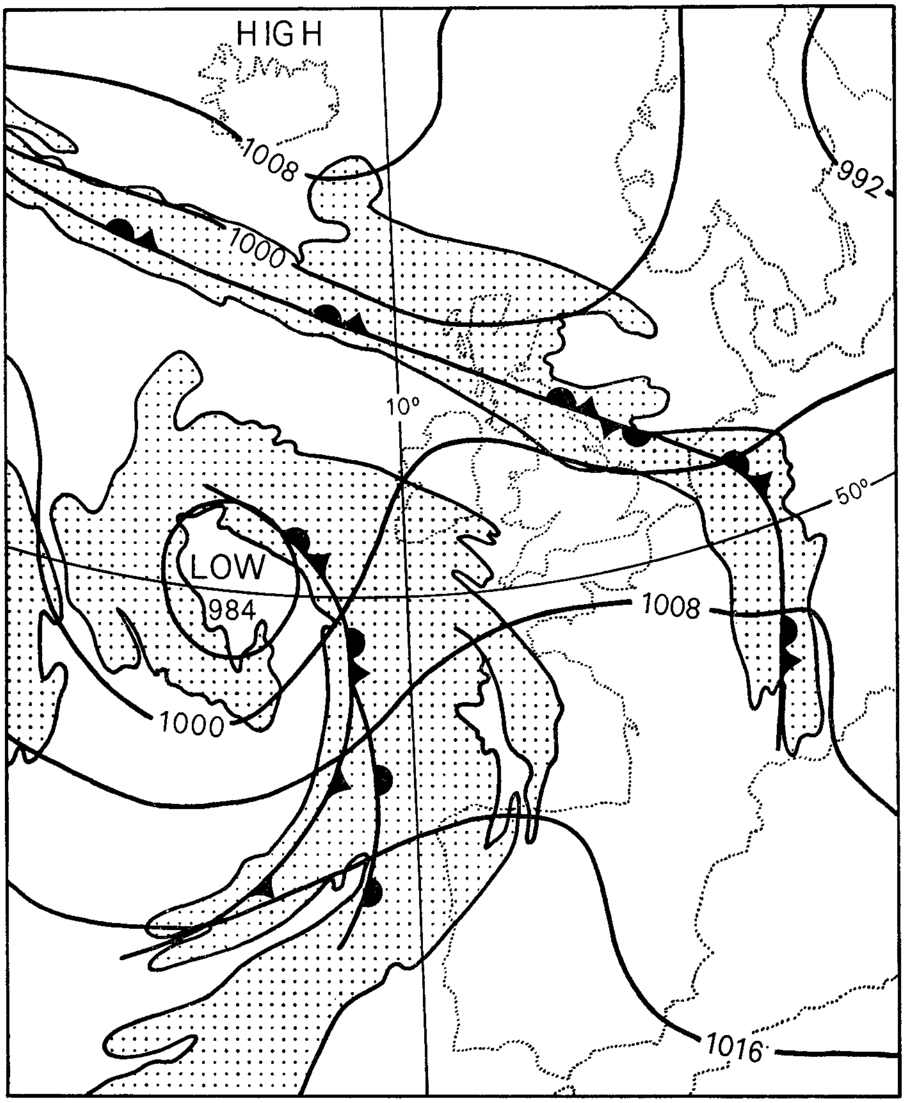


FIGURE 1—SURFACE ANALYSIS FOR 2100 GMT, 13 FEBRUARY 1975, WITH SATELLITE NEPHANALYSIS OF PRINCIPAL CLOUD AREAS

in the bands over central Ireland and near the coast of south-east Ireland. By 0700 moderate rain covered most of the Irish Sea to the south of a line from Dublin to Anglesey (Figure 2(c)). This intensification was associated with increased vertical velocity below approximately 500 mb on the southern flank of an upper trough which had moved east-south-eastwards across northern Ireland during the night. Calculations of the convergence using Bellamy triangles* show that the maximum vertical velocity was over Cardigan Bay by

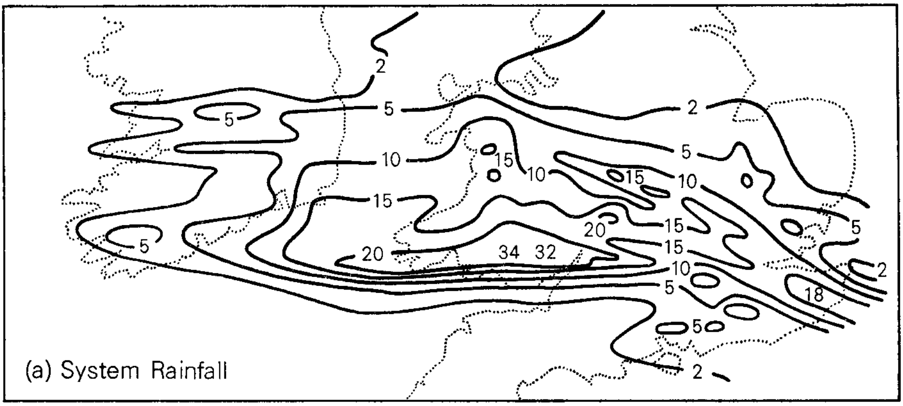


FIGURE 2(a)—SYSTEM RAINFALL (mm) COMPILED FROM DAILY TOTALS AND AUTOGRAPHIC GAUGES

the late morning and that this convergence zone extended east-south-eastwards across Wales and central England during the day (Figure 3).

From 0600 it is possible to divide the area of rain over the Irish Sea into two broad regions and to consider their history in relation to the midday upper-air analyses (Figures 3 and 4). This account is supported by a series of ascents launched by the Malvern Research Unit from a site near Pembroke and by some non-routine ascents launched by the Meteorological Offices at Aberporth, Camborne and Liverpool (Aughton). Although the intensification of the whole rain area appears to have been due to the proximity of the upper trough, the southern part was also in the region of weaker convergence associated with the occlusion. The precipitation in this region was generated by the ascent of a narrow band of warm moist air at low levels. The winds veered with height within this band from south-easterly near the surface to westerly at 700 mb, so that the eastward component through the band was small. Around the southern flank of the upper trough, slight veering of the wind above 700 mb brought cooler but still quite moist air across the top of this warm tongue, thus enhancing the potential instability which in the heavy rain extended from 750 to 600 mb. The warm air near the surface did not penetrate much further north than St George's Channel and the air at low levels over Cardigan Bay and central Wales remained cold and comparatively dry (Figure 4 (b)). The precipitation over North Wales was generated mostly between 700 and 500 mb, which levels were

* Divergence is calculated from the rate of change of area of a triangle assumed advected with the winds measured at its apexes. (J. C. Bellamy; Objective calculations of divergence, vertical velocity and vorticity. *Bull Amer Met Soc*, **30**, 1949, pp. 45–50.)

close to the axis of the stronger west-north-westerly winds which lay across central Wales. Further, the air was considerably drier to the north-west of the trough axis. Hence, as the trough continued to move across central England, the precipitation in the northern part of the rain area was carried east-south-eastwards fairly quickly and clearer weather reached North Wales by the early afternoon. In effect, the northern half of the rain area became detached from the southern half which continued to move slowly eastwards. This differential motion is evident in Figures 2(e–g), where the distinct areas have been labelled **A** and **B**.

During the evening, the air up to middle levels from southern Ireland to South Wales remained comparatively moist and unstable, and with weak convergence persisting in this region further outbreaks of moderate rain moved eastwards to the rear of area **B**, resulting in rainfall totals of over 20 mm in a narrow band across South Wales. The occlusion became quasi-stationary across southern England during the night and area **B** moved slowly along it. The rainfall analyses suggested that some new development occurred in the northern part of **B** and moved south-eastwards, but in general the area of appreciable rain remained compact as it approached south-east England (Figures 2(i–k)). Those parts of London and Kent which came under the converging paths of the cells received a total rainfall of over 15 mm.

3. The contribution of a radar network to subjective analysis and forecasting

In this case study there were a number of problems which confronted the analyst for which the existence of a radar network could have provided valuable information. They are described here in chronological order.

(a) *To establish the extent and intensity of the developing rain area before it reached Wales.*

During the night of 13/14 February, all the synoptic reports indicated that the occlusion was a weak feature. The Shannon radar at first confirmed this, revealing at 0115 only thin bands of echo moving eastwards. However, by 0515 the echoes had intensified and the bands had become broader as they moved across central Ireland (Figure 5). It is likely that a radar covering south-east Ireland would have shown the development of the rain associated with areas **A** and **B** as early as 0500 but, with only routine reports available, the passage of **A** to the south of Dublin (which remained dry throughout) prevented adequate warning of the moderate precipitation which was shortly to reach North Wales. Only Rosslare reported moderate rain as area **B** intensified. Figures 6(a–b) show the 0750 surface chart and the composite radar display for 0900, presented together for comparison of the two sets of data which would have been available at approximately the same time. Apart from clarifying the extent of the precipitation affecting Wales, the radar showed that another area of heavy rain (i.e. area **B**) was already close to the coast of south-west Wales. However, this reached Brawdy and Aberporth too late for the 0850 observations, so that it was not until 1030 by teleprinter and 1110 by facsimile that the existence of this heavy rain was established on the basis of routine observations.

(b) *To predict the northern limit of appreciable rain over England*

During the late morning, rain occurred at most of the observing stations in Lancashire. As late as 1250, Blackpool reported moderate rain (Figure 7(a)).

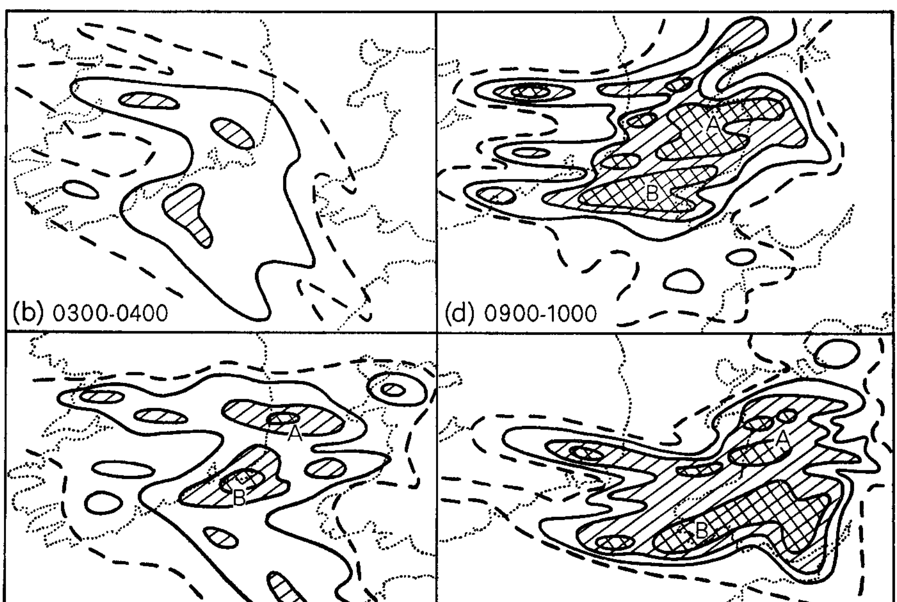
The impression given was that north-west England might still have a significant rainfall as the occlusion edged north-eastwards. However, the radar evidence was that Lancashire was being affected by a relatively small area of mainly slight rain which was moving east-south-east and that this would soon be followed by dry weather (Figure 7(b)).

(c) *To anticipate the movement of precipitation across the Midlands*

Referring again to Figure 7(a), the synoptic chart leaves much to the imagination as regards the location and movement of the heavier precipitation areas, given that the surface pressure was continuing to rise slowly over most of England. Apart from identifying these areas, the radar showed that over North Wales the rain was moving steadily east-south-east ahead of a clearance, while the rain nearer to the occlusion was moving only slowly eastwards. Thus the elongation of the rain area due to this differential motion would have been observable quite early in the afternoon by a radar network but was not apparent at any time in the routine observations, even in retrospect, owing to such factors as the large gaps which exist between reporting stations in some regions and the wide range of precipitation intensities which are possible between routine observations.

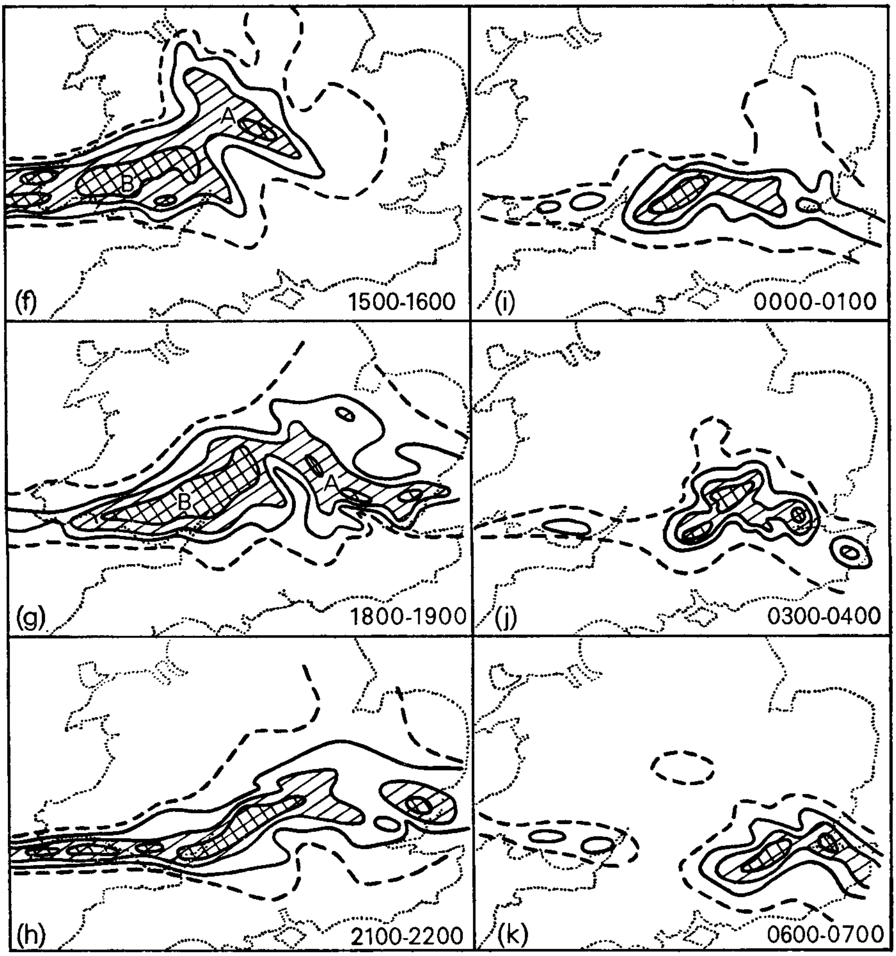
(d) *To identify small areas of rainfall of rather high intensity over south-east England*

The occlusion became slow moving across southern England during the



FIGURES 2(b–k)—HOURLY RAINFALL TOTALS AT 3 HOUR INTERVALS COMPILED FROM RADAR DATA AND OVER 100 AUTOGRAPHIC GAUGES

Contours at 0.1 mm (broken lines), 0.5 mm (full lines), 1.0 mm (hatched), 2.0 (cross-hatched). Letters A and B refer to centres of general rain areas discussed in text rather than specific cells.



FIGURES 2(b–k)—*continued*

evening. Despite the superior surface network of observations in this region, the boundaries of the main concentrations of rain became obscure as area **B** moved across the south Midlands (Figure 8). No radar evidence can be presented here, but it seems from the detailed rain-gauge analyses that cells in the northern part of area **B** may have intensified and then moved south-eastwards across the Chilterns towards Kent. At the same time the rainfall maxima in the southern part of area **B** continued to move on a more easterly course. Thus the constriction of the higher rainfall totals into a narrow band across London and Kent could probably have been anticipated, by the persistence of current trends, as early as 0300 if radar data had been available.

4. THE USE OF A RADAR NETWORK FOR OBJECTIVE RAINFALL FORECASTING

In this section we assess the potential of objective forecasting methods, using information obtained in the 14 February 1975 case study. The basic data for the forecasts were the hourly rainfall accumulations of which examples are shown in Figures 2(b–k). As already noted, these results were inferred from the available radar data, supplemented by autographic rain-gauge measurements.

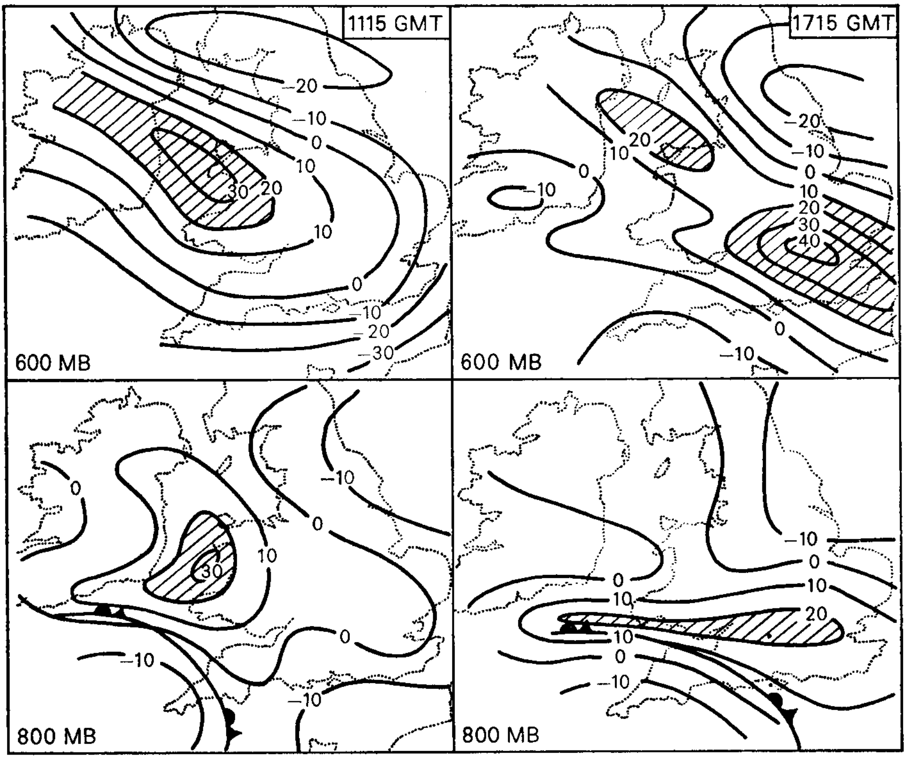


FIGURE 3—VERTICAL VELOCITY (mb h^{-1}) AT 800 AND 600 mb, AT 1115 AND 1715 GMT, 14 FEBRUARY 1975

Main areas of ascent are hatched.

We consider that these rainfall fields are of comparable accuracy to what might be obtained by a network of weather radars whose spacing was dense enough to ensure reliable quantitative coverage for the region being considered. In an actual forecasting situation the accuracy could be impaired if too much reliance was placed on radar information from beyond the effective quantitative range (about 100 km with the present generation of weather radars). For this study digitized rainfall data were available from one radar (Llandegla) for 5 km squares, but the other data sources did not always justify a resolution finer than 10 km and so the hourly rainfall fields were digitized manually on an 82 × 45 10 km grid. A logarithmic scale for rainfall intensity was used so that in the subsequent computation not too much weight was given to the heavier rain cells compared with the size and shape of the rain area as a whole. An example, for 1100–1200 GMT, is shown in Figure 9. Hourly data of this kind formed the input to a computer program which used the pattern-matching technique described by Austin and Bellon (1974) (and previously used by Leese *et alii* (1971) for obtaining cloud motions) to determine the mean pattern velocity from hour to hour. This translation velocity was found by calculating the correlation between successive rainfall fields for various spatial displacements and selecting the displacement corresponding to the maximum correlation. Forecast rainfall accumulations for up to six hours ahead were then produced by a simple extrapolation of the existing pattern with the translation velocity. About three minutes central processing time was required for each forecast on an ICL 1907F computer.

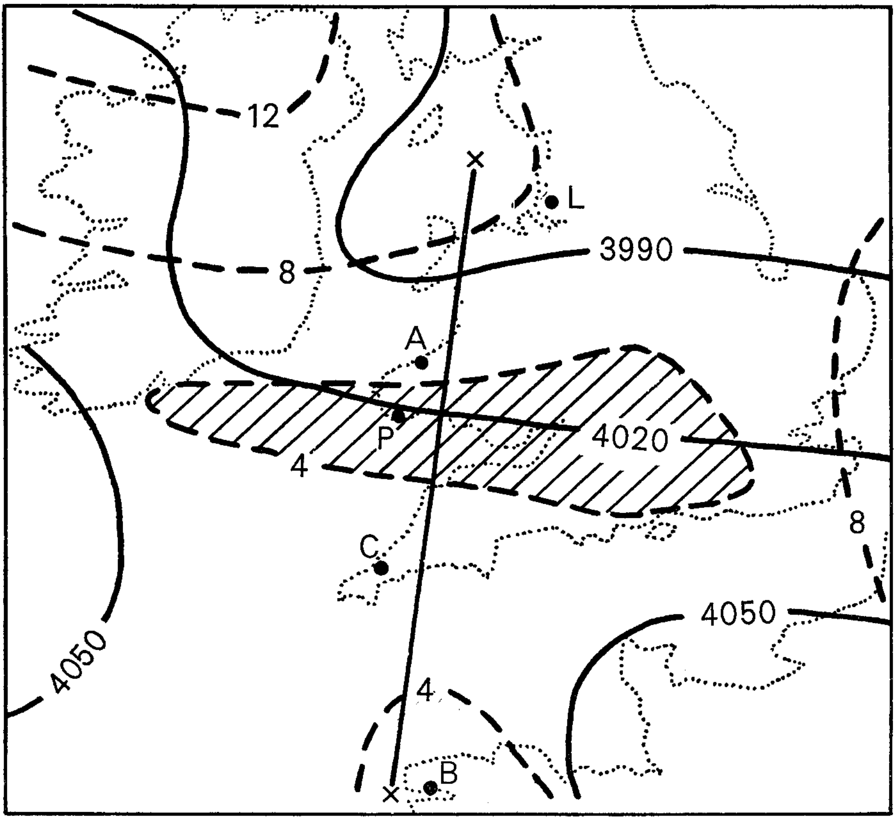


FIGURE 4(a)—600 mb ANALYSIS FOR 1115 GMT, 14 FEBRUARY 1975

——— geopotentials (gpm) - - - - dew-point depression (°C)
X ——— X location of cross section shown in Figure 4 (b)
L — Liverpool, A — Aberporth, P — Pembroke, C — Camborne and B — Brest
Main area of moist air is hatched. (Correction on p. 96).

The main results from this experiment are displayed in Table I which summarizes the outcome of six forecasts made at three-hourly intervals, using an advecting velocity determined from (a) the previous hour, and (b) the average of the previous three hours. In each case the forecasts are of the rainfall accumulated during the succeeding six-hour period and averaged over 20 km squares. The further reduction in the spatial resolution from 10 to 20 km for the purpose of forecast assessment represents a balance between smoothing out errors on the 10 km scale and retaining forecastable detail. Examples of two of the forecasts compared with the actual six-hour accumulations are shown in Figures 10 and 11. These show good general agreement in the size and shape of the rain area and in the total accumulations. However, in each case the positioning of the heavier rainfall is too far south, the reason for which will be discussed later.

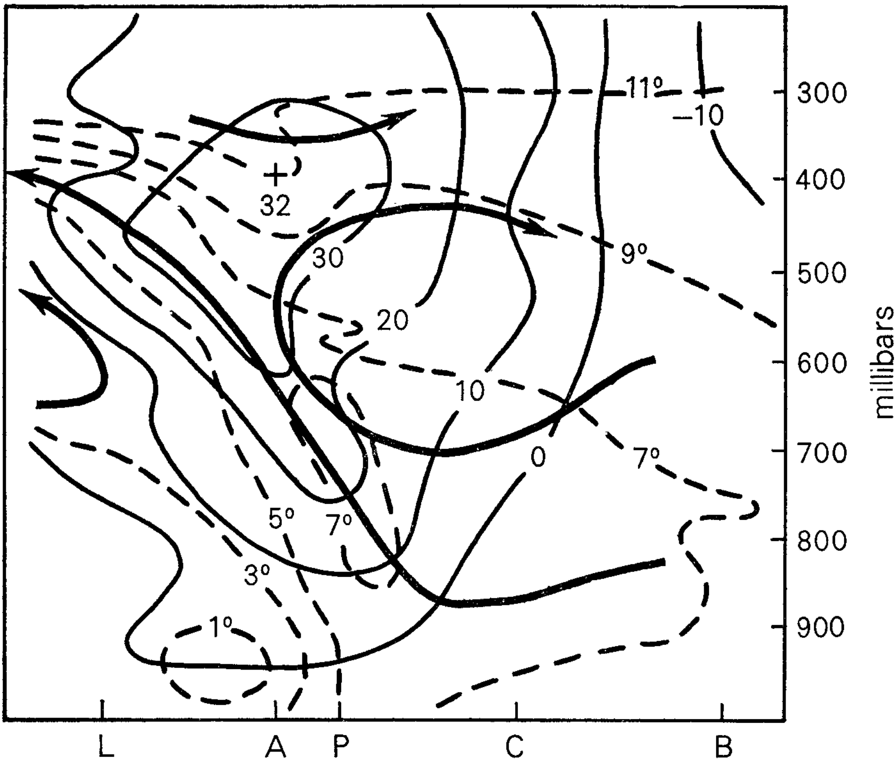


FIGURE 4(b)—1115 GMT, 14 FEBRUARY 1975: CROSS SECTION USING ASCENTS AT LIVERPOOL (L), ABERPORTH (A), PEMBROKE (P), CAMBORNE (C) AND BREST (B)

——— wind component (kn) normal to cross section, i.e. along mean direction of movement of precipitation area

– – – – wet-bulb potential temperature (°C)

Arrows represent the transverse circulation inferred assuming two-dimensional continuity in the plane of the Figure.

Listed in Table I are the absolute error averaged over all the 20 km grid squares and also the root mean square (r.m.s.) error and correlation coefficient evaluated over the same grid (unbracketed values). Since for much of the area a successful forecast of no rainfall needs little skill, the errors and correlations have also been calculated after eliminating correct forecasts of zero, and these values are bracketed in Table I. A comparison of the results in Tables I(a) and I(b) shows that averaging the objectively determined motion over three hours produced only a slight improvement compared with using the movement over the previous hour. The main improvement is in the forecast from

0600, and this is probably because early in the period the results of individual cross correlations were adversely affected by unavoidable inaccuracies in the rainfall analyses over the sea.

TABLE I—ERRORS AND CORRELATIONS FOR SIX HOUR FORECASTS OF ACCUMULATED RAINFALL MADE AT THE SPECIFIED TIMES FOR 14 FEBRUARY 1975

	Start time for six-hour forecast (GMT)	Predicted translation velocity (10 km grid lengths per hour) East	North	Mean absolute error *mm*	r.m.s. error *mm*	Correlation coefficient
(a)	0600	0	1	1·0 (1·9)	2·1 (2·9)	0·58 (0·45)
	0900	2	0	0·9 (1·7)	2·1 (3·0)	0·70 (0·61)
	1200	3	−1	1·0 (2·0)	2·4 (3·4)	0·69 (0·60)
	1500	3	0	0·5 (1·0)	1·1 (1·7)	0·91 (0·88)
	1800	2	−1	0·5 (1·9)	1·5 (2·9)	0·74 (0·59)
	2100	1	0	0·5 (2·1)	1·5 (3·1)	0·85 (0·77)
(b)	0600	$1\frac{1}{3}$	0	0·8 (1·7)	1·7 (2·5)	0·75 (0·65)
	0900	2	0	0·9 (1·7)	2·1 (3·0)	0·70 (0·61)
	1200	2	$-\frac{2}{3}$	0·9 (1·9)	2·3 (3·4)	0·76 (0·69)
	1500	$2\frac{2}{3}$	0	0·5 (1·1)	1·1 (1·7)	0·90 (0·88)
	1800	$2\frac{2}{3}$	$-\frac{2}{3}$	0·4 (1·5)	1·3 (2·4)	0·82 (0·72)
	2100	$1\frac{1}{3}$	0	0·4 (2·0)	1·4 (3·0)	0·86 (0·78)

(a) Translation velocity determined from displacement over previous hour.
(b) Translation velocity determined from average displacement for previous three hours
Bracketed values calculated after eliminating matchings of zero rainfall.

Table I shows that the average r.m.s. error in the forecast accumulation over six hours is about 2·7 mm when grid squares with correct zero forecasts have been eliminated. This is rather smaller than the actual rainfall accumulation (3 mm) averaged over all the non-zero squares and is much smaller than the peak rainfall (20 mm) accumulated in the wettest grid square. In fact, after

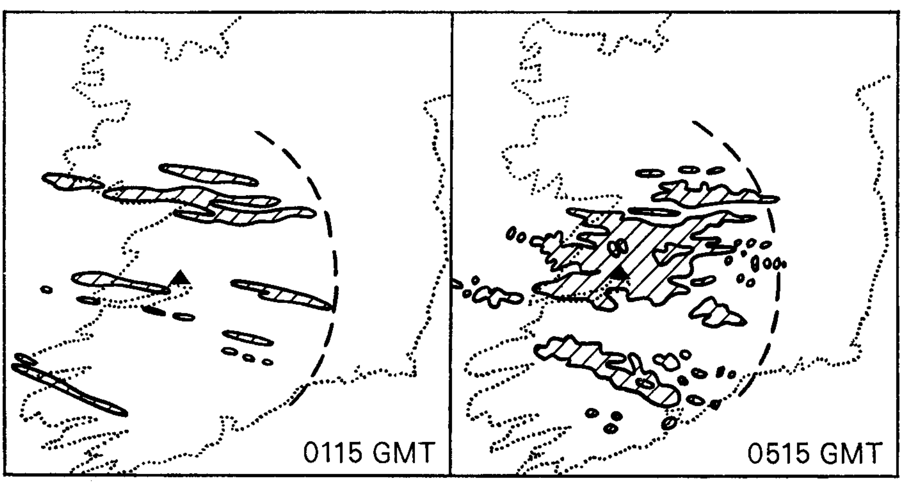


FIGURE 5—RADAR ECHOES OBSERVED AT SHANNON, 0115 AND 0515 GMT, 14 FEBRUARY 1975

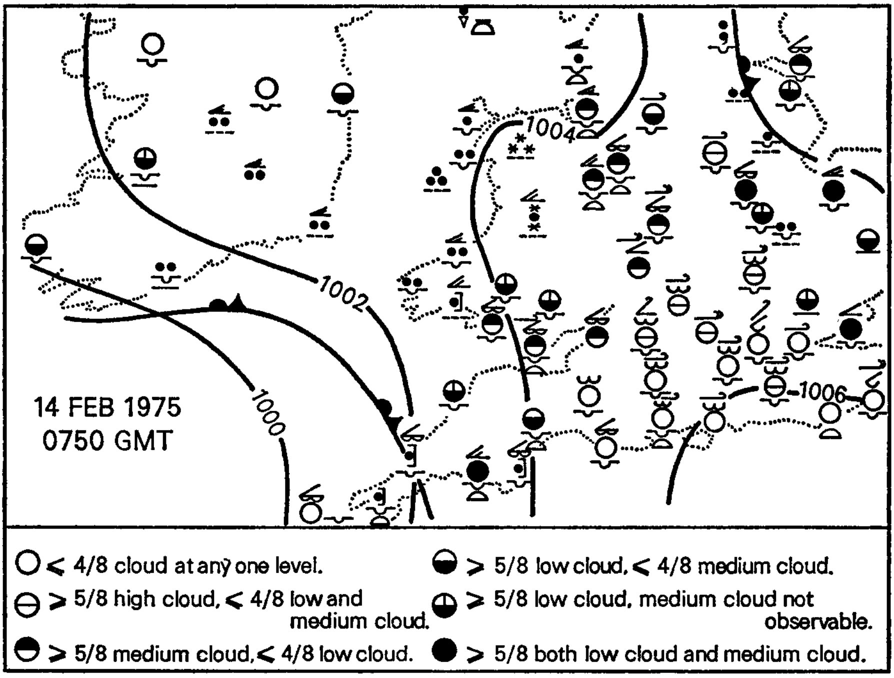


FIGURE 6(a)—SURFACE CHART FOR 0750 GMT, 14 FEBRUARY 1975

Conventional symbols for precipitation and cloud types are used.

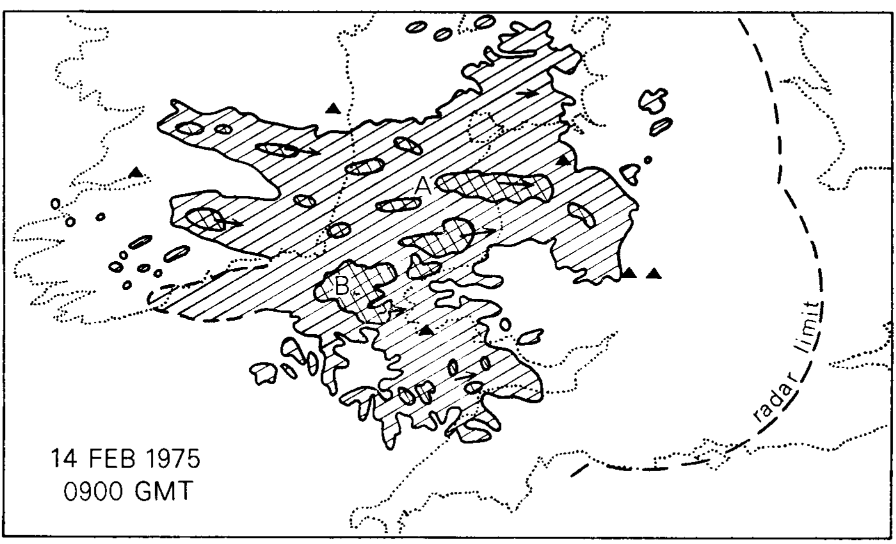


FIGURE 6(b)—COMPOSITE RADAR DISPLAY FOR 0900 GMT, 14 FEBRUARY 1975

Sites used (shown by triangles) at Shannon, Dublin, Llandegla (North Wales), Pembroke (south-west Wales), Malvern and Defford (Worcestershire). Areas of moderate and strong echoes are cross-hatched. Approximate hourly movement is indicated by arrows. A and B indicate centres of general areas referred to in text rather than specific cells.

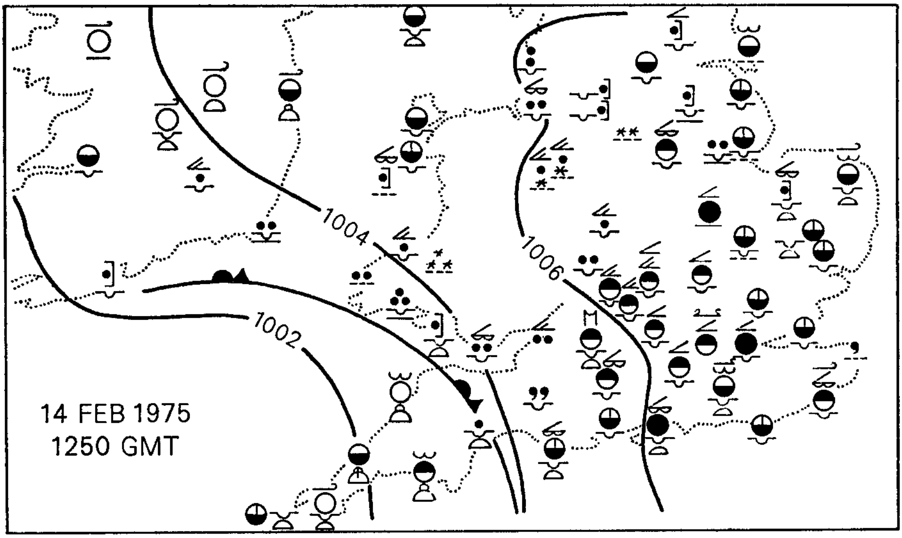


FIGURE 7(a)—SURFACE CHART FOR 1250 GMT, 14 FEBRUARY 1975
Legend in Figure 6(a) applies. (Correction on p. 96).

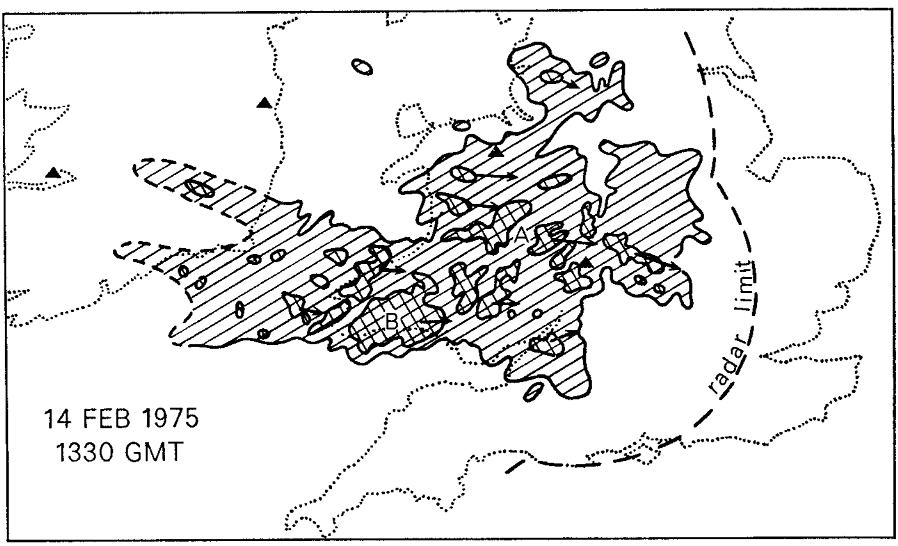


FIGURE 7(b)—COMPOSITE RADAR DISPLAY FOR 1330 GMT, 14 FEBRUARY 1975
Legend in Figure 6(b) applies.

ignoring correct forecasts of zero rain, values for 81 per cent of the remaining 2200 grid squares in the six forecasts are within 3 mm of the actual six-hour accumulation. It is therefore considered that these six-hour forecasts do give a useful, albeit crude, indication of the magnitude and distribution of the rainfall on a 20 km scale. Part of the inaccuracy is due to errors in the predicted translation velocity but, as will be shown later, most of it is caused by the neglect of development and changes in the shape of the rain area.

So far we have given no indication of the quality of the forecasts regarding the detailed trend of rainfall intensity within each six-hour period. To examine this aspect we have considered forecasts for two specific grid squares. These forecasts are illustrated in Figure 12 which compares, for the 20 km squares containing Birmingham and Oxford, the actual rainfall rate with overlapping zero-to-six-hour predictions made at three-hour intervals. The better forecasts are those for the Birmingham square, where the increase and decrease in the forecast precipitation rate correspond quite well with the actual rainfall profile although the forecast times of commencement and cessation of the rain are in error by two hours or so. Predictions for the Oxford square suffer from being on the edge of the heavier rain area for much of the period. As a consequence the rain is forecast to be slightly heavier than it actually was and to intensify earlier than in fact it did.

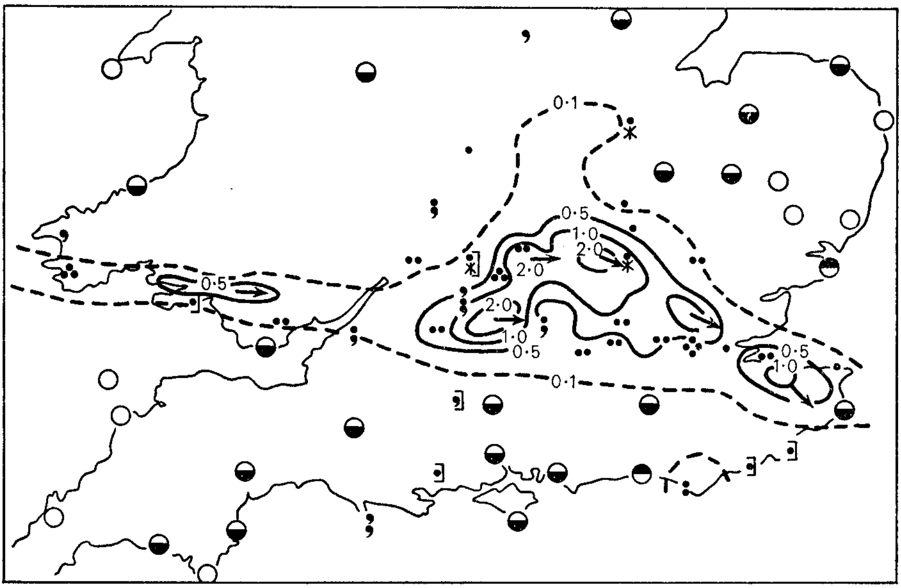


FIGURE 8—SURFACE OBSERVATIONS FOR 0250 GMT, 15 FEBRUARY 1975, COMPARED WITH TOTAL RAINFALL FOR 0200–0300

Cloud symbols are as Figure 6(a).

The objective forecasts discussed above have been obtained very simply by neglecting any development in the pattern and any distortions in the shape of the rainfall area caused by the differential motion of its different parts. We know that this will have introduced errors because, as discussed in Section 2, not only was there an overall long-term trend in the vigour of the system but also the rain areas **A** and **B** travelled with different velocities. Although this did not invalidate the overall coarse prediction, it did account for the forecasts of the peak rainfall accumulations in Figures 10(a) and 11(a) occurring about 40 km further south than the actual peak values as shown in Figures 10(b) and 11(b). These peak accumulations were associated with rain area **B** (see

PLATE I—AWARDS TO CIVIL AIRLINE CAPTAINS

From left to right: Captain W. J. Jackson and Miss Jackson, Director-General of the Meteorological Office, Mrs Jones and Captain R. A. E. Jones (see p. 93).

To face page 82

PLATE II—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES, AIR MARSHAL D. G. EVANS AND AIR COMMODORE D. F. M. BROWNE (DIRECTOR OF FLIGHT SAFETY ROYAL AIR FORCE)

Left to right: Mrs Groves, Mr C. L. Hawson, Major K. G. Groves, Chief Technician T. C. Maine, Air Marshal D. G. Evans, Mr D. J. George and Air Commodore D. F. M. Browne (see page 91).

PLATE III—MRS K. G. GROVES PRESENTING MR D. J. GEORGE WITH THE METEOROLOGICAL OBSERVER'S AWARD

(See page 91)

To face page 83

PLATE IV—MAJOR K. G. GROVES PRESENTING THE 1976 METEOROLOGY PRIZE TO MR C. L. HAWSON

(See page 91.)

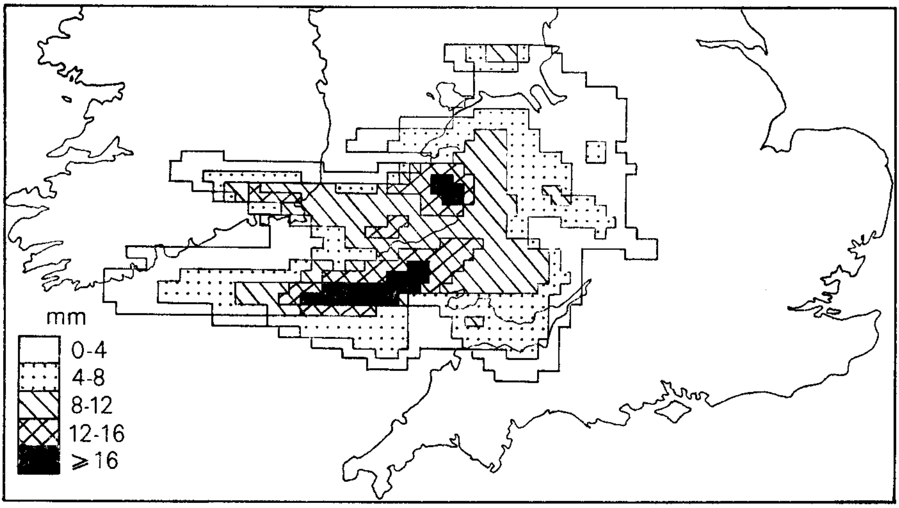


FIGURE 9—DIGITIZED RAINFALL FIELDS ON A 10 km GRID FOR 1100–1200 GMT, 14 FEBRUARY 1975

Section 2) which radar showed to have had less of a southerly component than the average for the entire rain area.

In order to isolate the errors due to distortion and development from those due simply to a non-optimal translation of the whole rain system, the results were recalculated using a number of different translation velocities at intervals of half a grid length per hour in each component. The velocities which gave the most accurate six-hour accumulations, using the criterion of lowest r.m.s. error, for each of the six forecast periods, are listed in Table II together with the corresponding errors and correlations. After eliminating correct matches of zero, the average lowest r.m.s. error for the remaining grid squares over the six periods is 2·3 mm. This value is not very much less than the average r.m.s. error of 2·7 mm from Table I(b) thereby confirming that the errors listed in Table I, although due in part to non-optimal forecast motions for the overall system, are mainly caused by effects such as development and differential movement of the various rain areas.

TABLE II—THE MOTION TO THE NEAREST HALF GRID LENGTH GIVING THE LOWEST r.m.s. ERROR, WITH CORRESPONDING ERRORS AND CORRELATIONS FOR THE SAME AS TABLE I

Start time for six-hour period (GMT)	Translation velocity (10 km grid lengths per hour)		Lowest mean absolute error (*mm*)	Lowest r.m.s. error (*mm*)	Correlation coefficient
	East	North			
0600	$2\frac{1}{2}$	0	0·7 (1·5)	1·6 (2·3)	0·80 (0·72)
0900	2	−1	0·8 (1·5)	1·7 (2·4)	0·84 (0·79)
1200	3	0	0·7 (1·6)	1·7 (2·6)	0·89 (0·86)
1500	3	0	0·5 (1·0)	1·1 (1·7)	0·91 (0·88)
1800	$2\frac{1}{2}$	$-\frac{1}{2}$	0·3 (1·3)	1·0 (2·0)	0·90 (0·83)
2100	3	0	0·4 (1·7)	1·3 (2·7)	0·81 (0·71)

Bracketed values as in Table I

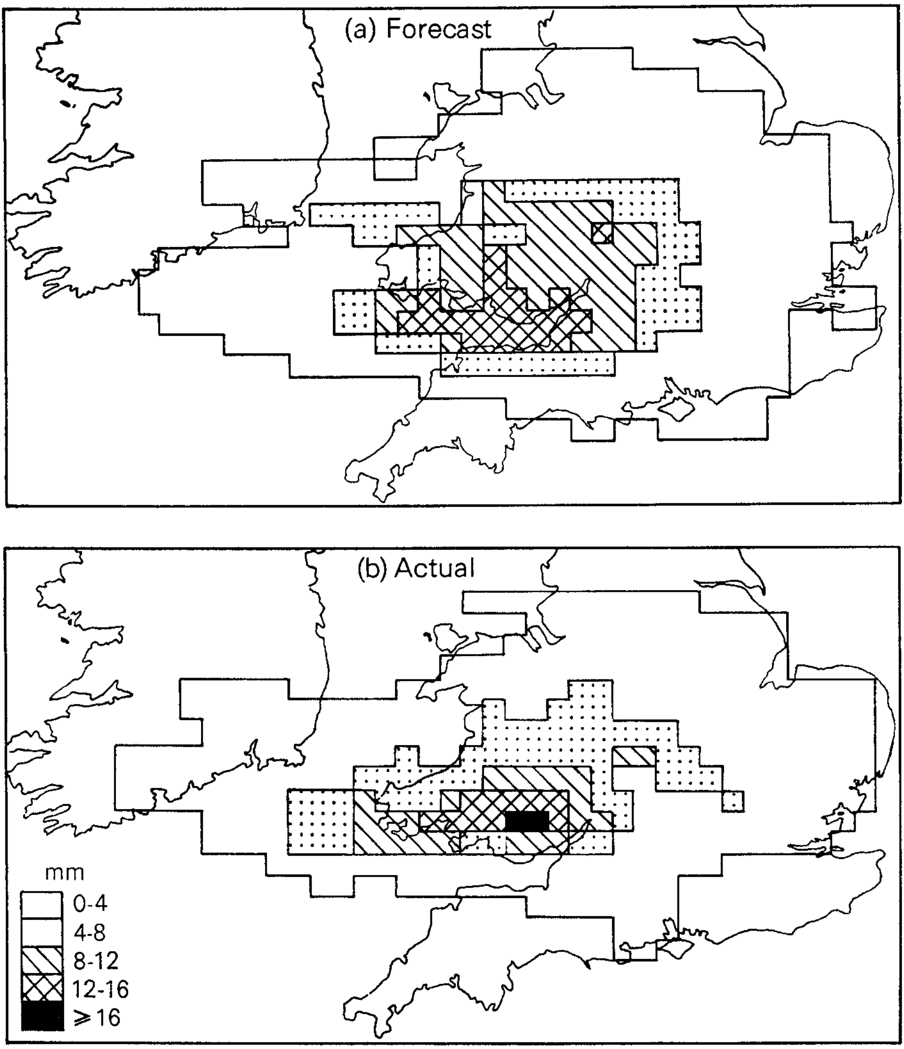


FIGURE 10—FORECAST AND ACTUAL RAINFALL ACCUMULATIONS ON A 20 km GRID FOR 1200–1800 GMT, 14 FEBRUARY 1975

Attempts to forecast the motion of separate rain areas or of different identifiable parts of large areas have been made by various workers (notably Blackmer *et alii* (1973)) who have objectively tracked such cells between successive radar pictures. An objective tracking procedure has also been developed by Ostlund (1974). There are problems with this approach in selecting an arbitrary threshold to define the cell boundaries and in dealing with splits and mergers of echoes, and we have not attempted such a procedure in this instance. Instead we have experimented with an alternative technique, dividing the total area into a number of sub-areas (which may either be fixed or move with the system

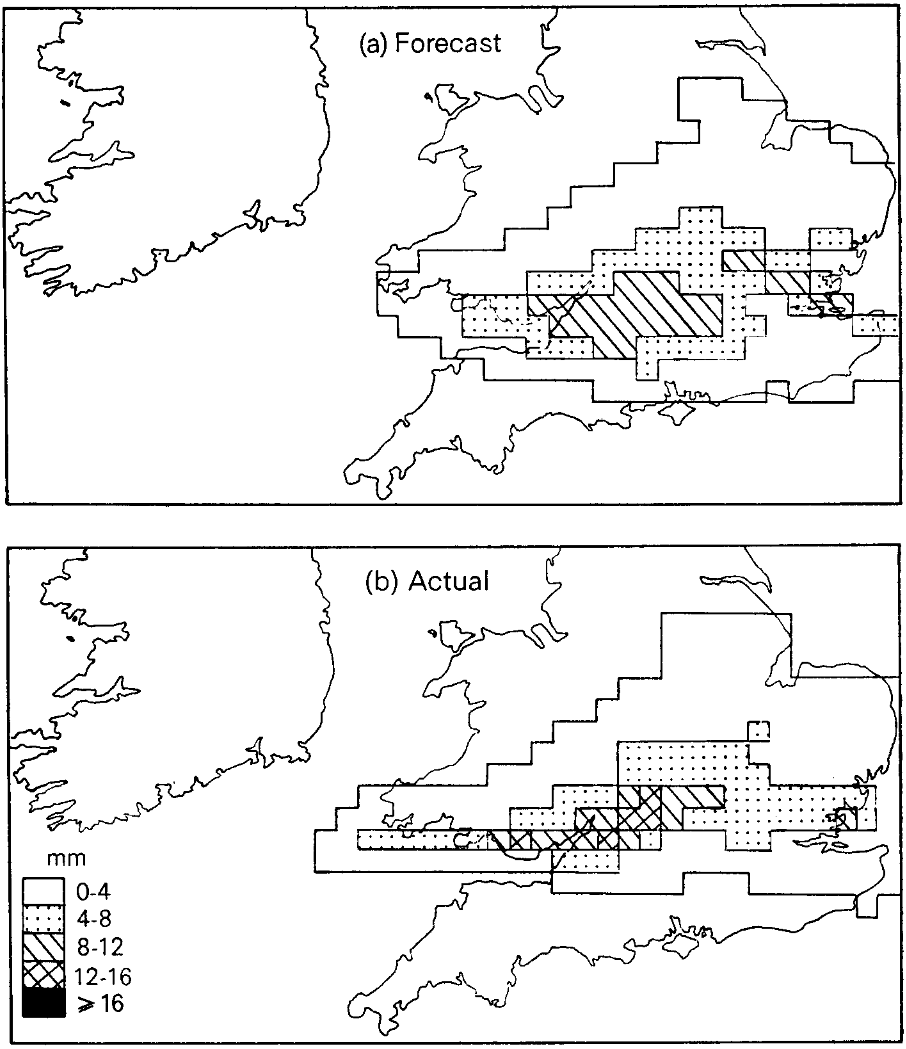


FIGURE 11—FORECAST AND ACTUAL RAINFALL ACCUMULATIONS ON A 20 km GRID FOR 1800–2400 GMT, 14 FEBRUARY 1975

velocity) and then using the basic cross-correlation method to determine a separate translation velocity for each sub-area. However, some smoothing of the forecast fields is necessary where discontinuities develop at the sub-area boundaries. In attempting to deal with the problem of development and decay we have adopted a simplified version of Schaffner's (1975) proposed forecast equation in which straightforward advection of the rain area has been supplemented by extra terms representing its linear intensification and its expansion or contraction. In the present case this method of handling development, used in conjunction with moving sub-areas, produced some slight improvements in the first two hours of the forecasts. The differing motions determined by the sub-area method confirmed the south-eastward movement in the north and the eastward translation of the southern section of the rain area discussed earlier; however, attempts to extrapolate development and differential motion beyond two hours have led to rapidly increasing errors.

Finally, it is worth while mentioning alternative ways of deriving the pattern velocity. Clearly, more weight could have been given to the motion of the heavier rain cells by correlating the actual rainfall fields (rather than their logarithmic transformation) or by ignoring values below a particular threshold. Both these methods were tried but neither resulted in improved predictions in this instance, nor was any benefit gained from interpolating within the field of correlation coefficients to obtain non-integral grid-length displacements. Another approach is that adopted by Tatehira and Makina (1974), who have produced four-hour forecasts using the 700 mb wind as the steering velocity, together with a field of development tendency. However, in the present study the height of the wind field that corresponded best with the rainfall translation varied from 800 to 600 mb and, of course, in general the optimum mid tropospheric level to use would be difficult to determine in advance.

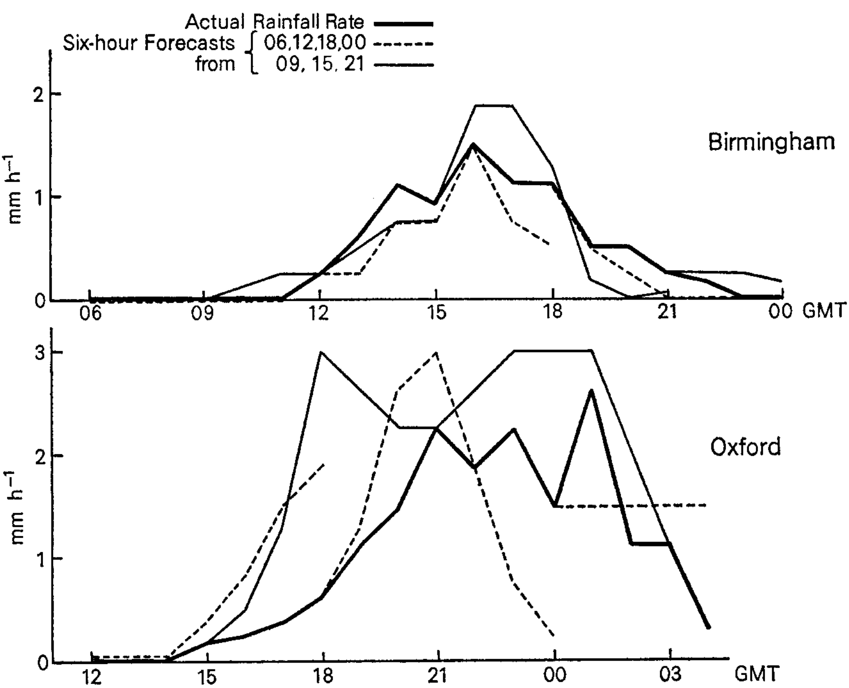


FIGURE 12—ACTUAL RAINFALL COMPARED WITH SIX-HOUR FORECASTS MADE EVERY THREE HOURS FOR THE 20 km SQUARES CONTAINING BIRMINGHAM AND OXFORD, FOR 14–15 FEBRUARY 1975

5. Conclusions

It is suggested in this case study that significant improvements in subjective analysis would have been possible given the prompt availability of data from an adequate radar network. Developing areas of moderate frontal precipitation would have been observed up to four hours before their existence was established on the basis of routine observations. Differential movement of the rain areas could have been detected while they were over the data-sparse regions of Wales and the west Midlands, and valuable information on the location of small areas of rather high intensity rainfall could have been obtained as they crossed south-east England. A simple pattern-matching technique has been used to simulate objective forecasts and these successfully reproduced the major features of the rainfall pattern for periods of up to six hours ahead.

Two of the four forecasting problems discussed in Section 3 could have been tackled by observations of echoes from isolated radars, as indeed can be the development of slow-moving storms in summer. Of course, facilities for prompt transmission of radar data are still required if meteorological offices remote from the radar are to supply forecasts for that region. However, for most mesoscale and synoptic-scale forecasts, isolated radar evidence is not sufficient. As an instance of this from the case discussed here, it is clear that the movement of the precipitation seen from Llandegla was appreciably different to that observed from Pembroke, and it required both radars to give a true impression.

We are enthusiastic about the immediate benefits that a radar network would bring to subjective forecasting. Subjective analysis is still the main tool for short-period forecasting; it depends on there being adequate surface and upper-air reports for the essential characteristics of a system to be diagnosed. Unfortunately the analyst is continually working with information which is to some extent out of date by the time it has been received, plotted and analysed, so that even the commencement of a forecast represents a projection of data acquired at least a couple of hours earlier. Further, the distribution of reports is uneven. Not only with localized showers and troughs but also in frontal systems, the areas of precipitation are often little more than a few mesoscale features which contribute the bulk of the total rainfall but cannot be resolved with the present inadequate network of observations. Hence there is all too often a failure to describe adequately the 'present' state of the weather in a given region—frequently a cause of greater irritation than later errors in the forecast itself. In addition, to the forecaster looking for confirmation of some anticipated development, the delay between its actual occurrence and the receipt of a report confirming it may so undermine his confidence as to lead to a rainfall forecast which lacks reference to what should be its chief ingredients: intensity, location and timing. A continuous display of current patterns of precipitation, even if only of a semi-quantitative nature, could become a powerful tool for the analyst, when supported by his knowledge of the dynamical influences involved and extended by conventional synoptic data.

The objective predictions in this case study gave a good indication of six-hour rainfall accumulations on a 20 km scale, but their accuracy was affected by development and differential motion of the precipitation areas. These are aspects which arise in all weather situations and are predominant in many, so that they impose limitations on the period to which the greater detail which would be possible in the analysis could be retained in the forecast. We have referred to several objective methods which endeavour to cope with these problems, but more work is required to devise adequate techniques of handling the wide variety of weather types that occur from day to day. It is likely that the availability of more continuous satellite data (e.g. METEOSAT) could be helpful in locating areas of imminent development. Further, the problem of rainfall enhancement due to topography was small in this case study, owing to light winds. This would not often be so, and for objective forecasts of orographic rain we may have to look to the development of empirical climatological rules, such as those formulated by Nicholass and Harrold (1975) for North Wales. Additionally, advected rainfall patterns could be used as input to a fine-scale numerical model such as that proposed by Collier (1975). If methods are devised of tackling these problems with a reasonable degree of success, we foresee the possibility of issuing useful objective forecasts to meteorological offices at regular intervals on the same television set as would be used to display the real-time radar data. The time taken to derive such a forecast and to display it would be as little as five minutes after the time of acquisition of the data on which the forecast was based.

Therefore we are confident that, at first as a result of more accurate and detailed subjective analysis and later perhaps by the routine dissemination of objective quantitative rainfall predictions, the establishment of a weather radar network would often lead to marked improvements in short-term forecasting. The length of the useful forecast period will depend on the characteristics of the weather system, the location of the region of interest with respect to it, and the limits imposed by the size of the radar network, but some improvement should frequently be possible for periods of three to six hours ahead.

6. Acknowledgements

The authors are grateful to the following organizations and individuals for their contributions as listed: the Irish Meteorological Service for data from the weather radars at Shannon and Dublin and for autographic rain-gauge charts; the Dee Weather Radar Project for data from the Llandegla radar; the staff from the Royal Signals and Radar Establishment for data from radars at Malvern and Defford; the Commanding Officer and staff at the Castlemartin RAC Range for use of the site; the radiosonde teams at Aberporth, Aughton and Camborne for launching non-routine ascents; the technical staff of the Meteorological Research Unit at Malvern led by S. R. Smith and the radiosonde team under D. Sumner; the voluntary observers who maintain autographic rain-gauges for the Malvern Meteorological Research Unit; the observers and authorities who provided additional rain-gauge data, including numerous meteorological offices; the Observational Requirements and Practices branch and the Agriculture and Hydrometeorology branch at Meteorological Office Headquarters Bracknell; all divisions of the Welsh National Water Development Authority; Rhondda Borough Council; the Anglian, Severn–Trent, Sussex, and Thames Water Authorities.

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THE METEOROLOGICAL MAGAZINE 1866–1977

The *Meteorological Magazine* has, in one form or another, been published for more than 111 years and we thought that our readers, particularly the new ones, would be interested in a brief history of how the Magazine came into being and of its subsequent management and organization, including an account of the various editors. The Magazine, as the official journal of the Meteorological Office, dates only from February 1920 and is really an amalgamation of *Symons's Meteorological Magazine* (published by the old voluntary British Rainfall Organization) and the official *Meteorological Office Circular.*

Symons's Meteorological Magazine

This magazine began its life in February 1866 as *Symons's Monthly Meteorological Magazine,* the monthly publication of the British Rainfall Organization, and hence owes its existence to that remarkable man George James Symons. F.R.S. Mill (1938) has given a succinct account of Symons's life, of how he resigned in 1863 from the Meteorological Department of the Board of Trade (later to become the Meteorological Office) in exasperation at the attitude of his official superiors, and of his immense achievement in creating the British Rainfall Organization virtually single-handed. Although the Magazine was started primarily to inform and unify Symons's army of co-operating voluntary rainfall observers, and was an improvement on his 'Rainfall Circulars' of the previous few years, almost from the first it carried short articles and notes on a wide variety of climatological and meteorological phenomena very much as the monthly magazine *Weather* (published by the Royal Meteorological Society) does today.

For a number of years before the end of the century Symons was helped in the task of running the British Rainfall Organization—which included editing the annual *British Rainfall* as well as the monthly Magazine—by H. Sowerby Wallis. Symons died in 1900 and on 1 January 1901 Hugh Robert Mill, D.Sc., LL.D., was appointed joint-director of the Organization with Wallis. Mill edited the Magazine until his early retirement—due to ill-health—in 1919; his life and work are well described by Glasspoole (1950) and Carter (1951). Following Mill's appointment the word 'monthly' was dropped from the title of the Magazine.

Mill's eyesight had given him trouble since 1913, and an increasing share of the responsibility for the Organization and its publications was taken by Martyn de Carle Sowerby Salter who became joint-director and joint-editor. Mill's retirement in 1919 coincided with the taking over of the British Rainfall Organization by the Meteorological Office, of which it became a Division with Carle Salter—as he was generally known—as its Superintendent. The last issue of *Symons's Meteorological Magazine* was for January 1920.

The Meteorological Office Circular

On 20 June 1916 the Meteorological Office began the publication of a leaflet called the 'Meteorological Office Circular' principally for distribution among observers. This provided a convenient means for the publication of official notices, changes in observing staff, brief reviews of recent publications and other matters of general meteorological interest. The first four numbers were edited by R. Corless, and the remainder by F. J. W. Whipple. The last issue was dated 2 February 1920.

The Meteorological Magazine

The *Meteorological Magazine* was first published in February 1920 with a cover which in addition to line-portraits of FitzRoy, Symons, Sabine and Strachey bore the words: THE METEOROLOGICAL MAGAZINE, *Symons's Meteorological Magazine Incorporating the Meteorological Office Circular.* (This design of cover was used until January 1937, the last issue of Volume 72.)

The Magazine was edited jointly by Carle Salter and F. J. W. Whipple who was Superintendent of the Climatological Division. An editorial in the last issue of the old Symons's Magazine stated 'Whilst becoming, as a matter of course, the organ of the combined meteorological services, the Magazine will, it is hoped, fully maintain its traditional character as a channel of communication between amateur meteorologists'; it is probably true to say that this hope was largely realized during the following twenty years.

In 1923 Carle Salter died at the tragically early age of 43 (see Mill (1923)), and Whipple was transferred to the British Rainfall Organization Division, becoming sole editor. In 1925 a reorganization of Meteorological Office structure took place, involving the setting up of Divisions of General Climatology and British Climatology with the British Rainfall Organization being attached to the latter. The Division of General Climatology was put under the charge of C. E. P. Brooks who was promoted to the grade of Superintendent;

his job included supervision of the Meteorological Office Library, the study of world climatology, and the Editorship of the *Meteorological Magazine*.

Brooks continued to edit the Magazine for 22 years including the period of the Second World War, although after June 1940 the need to conserve manpower led to the suspension of general publication in printed form and it was only a typescript edition—albeit with diagrams and photographs—that maintained a limited internal circulation. Proper publication was resumed with the issue for January 1947, the wartime break having given the editor an opportunity to begin his next volume with that month and not February, a mildly irritating practice that had continued ever since February 1866. In the late summer of 1947 Brooks was succeeded as Editor by G. A. Bull who was later to become Assistant Director (Support Services).

After the war, a change of policy in the editing became apparent. Before 1940, the Magazine contained short general articles on meteorology and climatology, with accounts of remarkable weather events, Meteorological Office news, accounts of personalities including retirements, obituaries, promotions and special appointments, and correspondence from members of the Office and amateurs; there was little or no mathematics and nothing that could really be described as a scientific paper suitable for a learned journal. After 1947 an increasing number of papers appeared describing the results of original investigations carried out in official time.

By the time that Bull was succeeded as Editor by R. F. Zobel in November 1960, the Magazine had largely assumed its present appearance and character, although minor changes of content and cover design still occurred from time to time. Zobel was replaced in April 1962 by A. H. Gordon who was in his turn succeeded in March 1963 by W. S. Garriock.

Garriock proved to be another long-standing editor who spent nine years maintaining the high standards of accuracy and sub-editing which had rightly become characteristic of a Magazine that acted as the official organ of an old-established Government scientific department; he retired in June 1972.

Between June 1972 and September 1974 the post of editor was filled successively by F. E. Lumb, J. G. Cottis, and J. B. Andrews; the present editor is R. P. W. Lewis.

AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 26 November 1976 at the Ministry of Defence, Whitehall. The Vice-Chief of Air Staff, Air Marshal D. G. Evans, C.B.E. presided and the awards were presented by Major K. G. Groves and Mrs Groves. The ceremony was attended by the Director of Services of the Meteorological Office, Mr G. A. Corby, and the Director of Research, Dr K. H. Stewart.

The 1976 Aircraft Safety Prize was awarded to Chief Technician T. C. Maine of Royal Air Force, Laarbruch, with the following citation:

'The problems associated with aircraft blocking runways as a result of a tyre-burst or brake seizure are well known in the Royal Air Force.

Speed is essential in removing the aircraft and clearing the runway to enable other aircraft to land safely, but the time taken to carry out the repair *in situ* is often considerable. Moreover, during rectification, engineering evidence of the cause can be destroyed inadvertently.

With this problem in mind, Chief Technician Maine has designed a skate, a platform on rollers, capable of being inserted under the affected wheel of the aircraft by the aircraft-towing tractor and, by a series of simple functions using the two sections of the skate, the aircraft can be quickly towed off the runway thus clearing it for use by other aircraft. The skate, which has been primarily designed for the Buccaneer aircraft, is currently in use at Royal Air Force Laarbruch. The device can be made locally and can be adapted for use with many other types of aircraft. It is in recognition of his initiative and for this practical contribution to the safety of aircraft about to land that Chief Technician Maine has been awarded the 1976 L. G. Groves Aircraft Safety Prize.'

The 1976 Meteorology Prize was awarded to Mr C. L. Hawson of the Meteorological Office with the following citation:

'For many years Mr Hawson has contributed to a wide range of research in the Meteorological Office and in particular has been responsible for encouraging research into local weather phenomena at outstations. He has given lectures on investigational techniques at the Meteorological Office College, has helped students with their training projects and on their return to outstations has continued to give active assistance in the selection and development of research work. As a result of his efforts, many excellent papers have been produced and many significant improvements made in local forecasting techniques particularly, in the last year or two, for snow and frost.

Mr Hawson is also the acknowledged expert in the Meteorological Office on winds and temperatures in the lower and middle stratosphere and on the accuracy of measurement of wind and temperature at high levels. His advice on these subjects is frequently sought by scientists from both inside and outside the Office, and is never asked for in vain.'

The Meteorological Observer's Award for 1976 was awarded to Mr D. J. George of the Meteorological Office with the following citation:

'Since 1968 members of the Meteorological Office have served aboard the Trawler Support Vessels off Iceland. These vessels are now maintained by the Ministry of Agriculture, Fisheries and Food, and provide British trawlers in the area with weather forecasts and warnings.

The meteorologists work on their own in a most difficult environment. Their duties include making regular weather observations, the frequency of which increases in hazardous weather conditions. As well as experiencing conditions of sustained severe gales and worse, the meteorologists face the special problems to be overcome in arctic seas, carrying through their programmes when the superstructure is laden with frozen spray and the meteorological screen has to be chipped free of ice so that correct readings may be taken. Mr D. J. George has completed five voyages in Trawler Support Vessels during the past four winters. He has displayed particular keenness and dedication, both in his work on station and in preparing papers for the *Polar Record* and the *Marine Obseruer* based on the observations made.'

A happy feature of the occasion was that Mr George's award was presented to him by Mrs Groves, Major Groves explaining that with the increasing part now played by women in all aspects of public life he had at last managed to persuade his wife to take a more active part in the ceremony.

Air Marshal Evans concluded the proceedings with his own congratulations to the winners of the prizes and awards, including a graceful tribute to their wives whom he was very pleased to see present. (See Plates II–IV.)

Meteorological Office awards to captains and navigators of civil airlines

Since 1954 the awards have been made annually to encourage civil airline captains and navigators to provide air weather reports. Suitably inscribed books are awarded to aircrew members who have provided the best series of reports during the year under review. Captains who have given long and meritorious service in the provision of air reports are considered for the award of brief-cases.

Last year the awards were presented by the Director-General at a ceremony in the Lodge of the Meteorological Office College at Shinfield Park, near Reading, on 19 October.

Captain W. J. Jackson of British Airways (European Division) was presented with a brief-case and Captain R. A. E. Jones of British Airways (Overseas Division), at his own request, received a selection of books. (See Plate I.)

REVIEWS

Topics in applied physics, Volume 12—Turbulence, edited by P. Bradshaw. 235 mm × 180 mm, p.p. xi + 335, *illus.* Springer-Verlag, D-1 Berlin 33, Heidelberger Platz 3, Berlin-West, 1976. Price DM 97.

There is a shortage of specialist review papers and books in the field of turbulence and it is refreshing that this book by eight authors has the stated objective of emphasizing the breadth of the subject rather than its depth. In spite of the alarming number of authors the material is carefully cross-referenced and each author appears to have paid some heed to the words of the others. As claimed by Bradshaw in the preface it has been freed as far as possible from discipline-orientated details and the approach is 'applied' rather than 'pure' with the aim of helping people who need to understand or predict turbulence in real life. Although the text assumes some familiarity with the elementary ideas of fluid mechanics and turbulence, it is sufficiently self-contained to meet the needs of research workers not experienced in the field. Much of the material is of review type and as might be hoped, the book is an extensive well-catalogued source of references.

The introduction by P. Bradshaw is a characteristically clear summary of the basic equations, quantities and ideas of turbulence which, though not unique to this book, serves to help unify the subsequent sections. The sections on External

Flows by H. H. Fernholz and Internal Flows by J. P. Johnston are built around examples in aeronautics and engineering but workers in other fields should not let themselves be put off. The material is presented in a manner which puts emphasis upon the basic processes many of which are fundamental to other disciplines.

In consequence of the material in these chapters the section on Geophysical Turbulence and Buoyant Flows by P. Bradshaw and J. D. Woods deals mainly with the effects of stable or unstable stratification. It reviews the Atmospheric and Oceanic boundary layers with clarity but brevity.

The section on the calculation of Turbulent Flows by W. C. Reynolds and T. Cebece will be of practical value to workers in all disciplines since it not only discusses the frontiers of research but also gives details of the older simpler methods. The section on Heat and Mass Transport by B. E. Launder supplements the preceding two sections by giving further discussion of Buoyant Flows and the extension of calculation methods to include these factors.

The final section on Two-Phase and Non-Newtonian Flows is a brief introduction to the complexities of these effects with emphasis on the drag reduction properties of long-chain polymer solutions.

In conclusion, this book contains a broad but unified collection of authoritative articles on 'applied turbulence'. To the meteorologist the subjects of Aeronautics and Engineering can present a bewildering wealth of references so I feel this book will be of great value in bringing within easy grasp the expertise of these fields.

P. J. MASON

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LETTER TO THE EDITOR

Satellite infra-red analyses

We refer to the discussion initiated by our recent paper, and continued by Singleton*.

We are glad that he sees some merit in our suggestions, which have arisen during the course of a broader enquiry aimed ultimately at establishing the types of satellite image contents which might be extracted automatically in formalized, operational programs for a wide range of possible applications in both meteorology and climatology.

We would like, however, to comment briefly in turn on Singleton's five reasons why our schemes for hand-drawn infra-red nephanalyses seem to him to be 'impracticable, or at best, of limited value in an operational environment'.

(a) The size filter we suggest is more important as a procedural concept than an inflexible law. Different base data and different applications might require a different threshold from the one we chose for the DMSP imagery.

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* *Meterological Magazine*, **106**, pp. 11–26.

(b) The use of a low size threshold might be expected to lead to the production of nephanalyses of special interest to local regional forecasters, since some mesoscale features would be included. Our choice of a 1° square mesh permits the mapping of features down to some 90 km across. Though the lives of a few such features might be quite short, their number and distribution would, even then, be indicative of the weather-producing processes at work. Perhaps the problem of deterioration of chart contents through facsimile transmission could be side-stepped by the transmission of enlarged sections of the national nephanalyses to regional centres as appropriate.

(c) Were satellite data considered of sufficient value, outstation procedures might be modified to permit assimilation of the contents and implications of the cloud images and cloud maps. Weather services have evolved in the past; it might be a brake to progress were present procedures to be considered sacrosanct.

(d) and (e) If satellite data were to be interpreted only in terms of conventional synoptic data—especially in regions like the North Atlantic whence conventional data are sparse, irregularly distributed and of inconsistent quality—it would seem that their usefulness might be unnecessarily curtailed. From our academic viewpoint, we would prefer satellite images to be considered as independent statements of reality, through which conventional charts might be enhanced and improved, especially where *in situ* observations are sparse. Perhaps the man best equipped to interpret a satellite image is the trained photo-analyst, not the synoptician who might tend to interpret the cloud patterns in terms of an analysis already substantially completed on the basis of possibly inadequate conventional observations. Were this thought to be the case, the satellite and synoptic analyses might be compared after their independent preparation, and the synoptic charts corrected accordingly.

Regarding Singleton's final paragraph, it seems worth pointing out that the spatial resolutions of the NOAA–SR and DMSP–HR infra-red imagery are approximately 7·5 km and 0·6 km respectively, according to official figures accepted by the Meteorological Office, not about 5 km and 0·5 km. Although a reasonable compromise between the information contents of the two types of imagery might indeed be provided by day-time analyses in CFO based on both visible (3·7 km resolution) and infra-red observations from NOAA, it is clear that any night-time charts (if drawn) and day-time charts for areas of polar night or twilight could be based only on the low-resolution infra-red data, resulting in 12-hourly charts with alternately higher and lower degrees of detail being compiled. This would seem to be distinctly unsatisfactory. With geostationary satellites (e.g. METEOSAT) soon to provide much more frequent imagery, we believe that steps should be taken to standardize the analysis and interpretation of satellite imagery so that the valuable meteorological statements this system will provide might make their own contribution to further improvements in short-term weather forecasting, especially at the meso scale. In many countries the use of satellite data has developed along decidedly *ad hoc* lines. Is this the best that can be done?

E. C. BARRETT
for E. C. BARRETT and R. HARRIS

Department of Geography
University of Bristol
Bristol

Mr Singleton comments as follows: I certainly do not regard current procedures as sacrosanct—in fact I hope that Meteorological Office outstations will regard the Barrett and Harris paper together with my note as an opportunity to consider present practices in nephanalysis and to discuss what they would like in future (Editor).

OBITUARY

It is with regret that we have to record the death on 3 November 1976 of Mr D. W. Leeson, Scientific Officer, Honington.

CORRECTIONS

The following corrections apply to the first article in this issue:

Figure 4(a): area enclosed by dotted line around Brest (B) should be hatched.

Figure 7(a): hook is missing from one of the four cirrus symbols over Ireland.

THE METEOROLOGICAL MAGAZINE

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CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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MONTHLY RAINFALL TOTALS REPRESENTING THE EAST MIDLANDS FOR THE YEARS 1726 TO 1975

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SUMMARY

The problems of producing a homogeneous record of monthly rainfall totals for a limited geographical region, extending from the earliest years of observations up to the present time, are discussed with reference to an area in the East Midlands centred at Pode Hole, near Spalding. Estimates are made of the standard of reliability to be expected from the early data, and monthly totals are given for each of the years 1726 to 1975.

1. INTRODUCTION

This paper sets out to extend the time base of observations suitable for use in the study of regional rainfall. It is intended to be one of several following the same pattern, each of which suggests monthly rainfall totals for a particular region of the British Isles for as long a period of years as the data will support. The East Midlands is the region first considered because four stations in this region, namely Southwick (Oundle), Lyndon, South Kyme and Pode Hole, provide actual observations for all except two of the years 1726 until now. The figures are the best which can be offered at present without embodying corrections which are speculative at this stage, or which depend much on data from stations at a considerable distance. If improvements in statistical method make it clear from observations at distant stations or otherwise that revision is necessary, then the present values can readily be adjusted to include the new evidence.

2. THE 10 YEAR BOOKS AND OTHER SOURCES OF EARLY RAINFALL RECORDS

Ever since G. J. Symons began to collect rainfall records in the 1860s the '10 year books', now kept by the Meteorological Office, have formed the most comprehensive source of information on monthly rainfall in the British Isles. However, as they comprise about 16 000 separate records of which some 6000 are still continuing and total perhaps 250 000 station-years of observations, it is not always easy to find an individual record when wanted or to estimate the coverage in space and time for a particular area. Hence our first step in seeking to extend recent records back into past centuries was to go through the early volumes of the 10 year books, and to catalogue all records with data for years before 1820. There are about 260 of these for stations in Great Britain, and Table I lists all those for which at least 10 years' annual totals are given or which are important for other reasons. This attempt to provide comprehensive and easy reference to the earliest rainfall records seems to be the first of its kind since one was published by G. J. Symons in 1866 and Table I points to much the most important part of the instrumental evidence on British rainfall in the 1700s which will ever be known. It is included firstly to draw attention to the gaps which exist in the records for particular regions, and secondly to invite any reader who knows of other considerable records for the same period to inform either one of the authors or the Meteorological Office. For the years after 1820 the problem changes from one of finding records of any kind to that of making the best possible use of records known to exist.

Most of the records in the 10 year books before 1820 were known to G. J. Symons and, indeed, appear to have been copied by him, or on his behalf, from the original sources. These are manuscript copies, in copperplate handwriting, on paper of the type used in ledgers. The entries, which include both monthly and annual totals, have been checked for internal consistency. The entries made in Symons's time have been added to at intervals ever since, but there is rarely anything to show the date of any addition or correction, or the name of the person who made it. There is some duplication, since sometimes the same record has been copied twice, by different people working from different source documents, and occasionally it is doubtful which version is to be preferred. Most entries contain some references back to the original sources, and brief notes, also dating back to Symons, on the exposures and construction of the rain-gauges. However, comparisons between these notes and the source documents, in the *Philosophical Transactions of the Royal Society* (1740) for example, show that the figures have been copied with more care than the descriptive notes. The user who works from the 10 year books alone, without reference to the original sources, is liable to lose information recorded in the sources which has never found its way into the Meteorological Office archives.

3. ERRORS IN RAINFALL MEASUREMENTS WHICH MAY BE FOUND IN ANCIENT RECORDS

Table I contains, for each station listed, a comparison between the annual rainfall as reported, averaged over all the years given before 1820, and the estimated 1916–50 average rainfall for the same position, based on the best official maps. It is clear that about half the pre-1820 averages fall below the modern estimates by amounts which cannot possibly be due to climatic change but must be due to defects in the construction or exposures of the ancient instruments. It is therefore useful at this stage to consider the probable nature of these errors.

An extensive bibliography on the measurement of rainfall has been given by Kurtyka (1953). A modern hydrometeorologist inspecting a rainfall station should look for any of nearly 20 sources of error each of which is known to have occurred at least once and which may make the catch as recorded either larger or smaller than it should be. However, most are irrelevant in the present context because of the impossibility of checking the presence of minor faults in ancient instruments which have long since disappeared. Nevertheless some broad generalizations are justified and useful.

(i) The early observers were mostly scientists, doctors, parsons and country gentlemen who took their scientific activities seriously and who appear to have had the time to treat rain-gauging as a matter of considerable importance. There are no good reasons for believing that they were more prone to making clerical or measuring errors than are the best modern observers. Their letters, preserved for example in the Library of the Royal Society, provide ample evidence of the care they gave to overcoming the instrumental problems of which they knew.

(ii) Of faults leading to an excessive catch, the most important are obvious matters, such as a gauge with a broad brim from which raindrops slide or bounce into the funnel, or a tree overhanging the gauge and dripping into it. It is reasonable to suppose that observers of the calibre of the early pioneers in rain-gauging would not overlook such faults for long.

(iii) Faults leading to a deficiency of catch are the most numerous, and while some are obvious and were avoided from very early years, others are not obvious, or may develop gradually over the years. The modern attitude towards rainfall measurement did not exist in the early 1700s and it is worth while considering the guidance which a prospective observer in those days would have obtained from his predecessors.

The first observer whose records are known is Richard Townley (1694) who gives a graphic description of his rain-gauge. It consisted of a funnel 12 inches in diameter raised above the roof of his country house in Lancashire, with a pipe leading down from it 27 feet vertically before turning in through a window into a container. William Derham (1697) used something similar, since he refers the reader to Townley's article for a description of his apparatus, while Dr James Jurin (1722), although he does not say so at the time, in fact refers to the Royal Society rain-gauge which was on a flat leaded roof. Jurin, as Secretary to the Royal Society, issued an invitation to collaborators to make weather observations according to a common pattern which inspired the pre-1800 observations used here, and most other observers of the early 18th century. He describes the recommended apparatus in detail, and the account of the rain-gauge, translated from his Latin by Miss V. Craddock, is worth quoting:

'Sixth and last, was measured the depth of rainfall, (or snow melted to water) which had fallen since the time before, both in London inches and their decimal parts. Thus I estimated easily that with the help of funnels two or three feet across, water flowing down the funnels could be caught in a container and a cylindrical measure with a scale in inches and decimals. The funnel was so sited that, from wherever the wind blew, no part of the rain might be intercepted either by an intervening building or any other shelter anywhere. Thus there would be a bottle containing water properly closed in from all sides, lest it should disperse into the air, with one narrow opening left to collect the water from above, through the funnel. The diameter of the cylindrical measure should be allotted smaller than that of the funnel by ten parts; thus it is that water is an inch high in the measure to the height of 1/100 inch in the funnel, and thus the fall on the rest of the earth can be calculated, and similarly for the tenth part of inches.'

This, then, is the advice that prospective rainfall observers would have received in the 1720s if they had consulted the main scientific journal of the

TABLE I—IMPORTANT RAINFALL RECORDS FOR YEARS BEFORE 1820

(taken from the Meteorological Office 10 year books in July 1974)

Ref.	Name and Author	Period	Est.	Obs.
			*inches**	
Y2	Tottenham, London (Luke Howard)	1797–1810	25·30	24·36
Y3	Somerset House, London (Royal Society)	1787–1809 1812–1819	23·70	16·22
Y6	Temple Bar, London (William Bent)	1795–1808	23·65	18·62
Y7	Crane Court, London (Royal Society)	1725–1735	23·60	21·73
Y8	Lambeth, London (Symons's MS)	1765–1782	23·40	24·90
Y9	South Lambeth, London	1782–1791	23·74	22·94
Y12	Camden Town, nr London (James Joyce)	1802–1808	25·00	30·73
Y13	Highgate Hill, London (James Joyce)	1809–1815	26·50	32·79
Y18	Falkham, North Fleet } Kent (John Hooker)	1729–1734	(3)	21·57
Y18a	Tonbridge, Kent (John Hooker)	1735–1764	28·80	26·91
Y23	Selborne, Hants (Gilbert White)	1780–1792	38·00	36·41
Y31	Southwick, nr Oundle (George Lynn)	1726–1739	23·80	22·83
Y45	Longleat, Wilts. (Jeremiah Cruse)	1789–1799	35·50	24·75
Y47	Upminster, Essex (Dr W. Derham)	1697–1716	22·00	19·90
Y48	Norwich, Norfolk (W. Anderson)	1750–1762	26·80	25·41
Y49	Plymouth, Devon (Dr J. Huxham)	1725–1752	39·00	30·32
Y59	Stroud, Gloucester (Dr Hughes)	1771–1773 1775–1813	34·00	30·90
Y60	Radcliffe Observatory, Oxford	1795–1804 1815–1819	25·10	21·15
Y64	Lyndon, Rutland (Thomas Barker)	1737–1798 1800	24·56	22·97
Y65	Ferriby, Hull (Editor, Monthly Mag.)	1800–1812	25·00	27·53
Y71	Chatsworth, Derbys. (Lord George Cavendish)	1761–1813	34·00	30·90
Y73	Derby (Mr Swanwick)	1809–1819	28·00	25·06
Y77	Liverpool Docks (Mr Hutchinson)	1775–1792	33·50	34·36
Y78	Liverpool, Walton (Mr J. Holt)	1792–1804	35·00	33·15
Y80	Manchester (Thomas Hanson)	1807–1813 1816–1819	(4)	35·09
Y81	Manchester (Dr Dalton)	1794–1819	(5)	32·63
Y87	Townley, nr Burnley, Lancs. (R. Townley)	1677–1703 with gaps	47·50	41·87
Y88	Lancaster (Dr Campbell)	1784–1796	39·50	44·29
Y91	Kendal (J. Gough) (6)	1788–1799	57·50	59·77
Y96	Barrowby, Leeds (George Lloyd)	1772–1781	27·90	27·14
Y118	Carlisle, Abbey St (Dr J. Carlyle)	1757–1783	32·30	24·33
Y120	Carlisle, Shaddongate (Mr Pitt)	1801–1819	32·30	29·52
Y126	Wigton, Aikbank (Rev. J. Golding)	1790–1810	34·00	34·64
Y131	Dumfries (Dr Copland)	1775–1783 1790, 1793	43·00	38·06
Y133	Branxholm, Roxburgh	1773–1783	34·50	32·07
Y136	London	1798–1809	23·78	22·86
Y147	South Kyme, Lincs. (Rev. H. S. Neucatre)	1800–1819	23·62	25·34
Y151	Welbeck Abbey, Notts. (Duke of Portland's estates)	1807–1819	23·20	25·48
Y157	Kendal (a brother of J. Dalton) (6)	1798–1809	57·50	49·67
Y186	Lancaster, Ellel (Ford)	1798–1817	49·00	38·14
Y194	Kendal (Harrison and Gough) (6)	1810–1819	57·50	50·19

Notes

(1) The estimates are based on the fullest information for 1916–50.
(2) The Obs. column gives the average of annual totals observed and reported for all years before 1819.
(3) Falkham 1728–30 26·70. North Fleet 1731–33 23·00.
(4) 1807–11 35·50. 1812–19 35·00.
(5) 1794–1803 34·00. 1803–1819 34·50.
(6) Sites unknown—taken as modern town of Kendal.

* Non-metric units are used throughout this paper to maintain uniformity with those units used with historical references and quotations.

times. Following Jurin's advice, they would have had rain-gauges which were not sheltered in any direction by obstacles, and which preserved the catch from evaporation, but the funnel might have been so flat that raindrops were scoured out by the wind, and there was then no suggestion that the elevation of the funnel above the ground surface could have had any effect on the catch. Dr Heberden (1767) was the first to demonstrate, by placing similar rain-gauges on the square tower of Westminster Abbey and at his house in Westminster, the general principle that 'the higher the rim of the collecting funnel above the ground surface, the smaller the catch'. This has often been confirmed since, for example, by comparative measurements at Oxford and Paris but the processes involved were not understood till the time of Symons (1881) and Mill (1901). Mill's work in particular shows that the loss of catch with an elevated gauge depends mainly on eddies produced by the horizontal component of the wind, with the result that the loss of catch tends to be greater in the winter months when the winds are on average stronger. Painter (1975) compared measurements from ground level to 45 cm. Nash (1918) analysed the monthly totals from 1871 to 1910 of rainfall measured at Greenwich with gauges at ground level, and 10, 22, 38 and 50 feet above and showed that the average catch of the 38 foot gauge varied from 87 per cent of the ground-level value in August to only 71 per cent in March. Two points should be made to conclude this discussion:

(i) with a sharp-rimmed gauge, reasonably well exposed, it is almost impossible to catch too much rain, so that the general rule can be 'when in doubt, accept the larger reading' and

(ii) when an old record was set up by a gentleman with scientific interests, under what seemed to him to be satisfactory conditions, any changes which took place with time were liable to have produced a gradual diminution of catch. These changes may have included the growth of trees near the gauge, leaks, the slow blockage of the pipe leading to the receiving vessel, or the internal surface becoming porous. Such changes may not have been noticed unless the observer compared his records with a neighbour, but then, if he was not too old to take action, he may have put things right.

4. Stations in the East Midlands

Coming from the general to the particular, the stations considered in this paper are listed in Table II. The names underlined provide nearly all the data in the homogeneous series produced here; on 12 and 13 May 1976, one of us (J. M. Craddock) visited these sites in search of further evidence. The findings form the basis of paragraph 10. Pode Hole was chosen as key-site, because it has a very good continuing record which started as early as 1829, and is about equidistant from South Kyme and Boston in one direction, and Southwick and Lyndon in the other. Although the distances to the supporting stations ranging from 18 to 22 miles are not negligible, they are across flat country, and are a good deal less than the distances which have to be considered when data for other parts of the country are homogenized, or which must be accepted when a user of such data treats the record for a key-site as referring to his own area.

5. Estimating the conversion factors to be applied to early data

The method of homogenization consists in using the monthly totals given in an early record to estimate totals for the same months at Pode Hole by multiplying

TABLE II—STATIONS USED IN ESTIMATING RAINFALL TOTALS TO REPRESENT THE EAST MIDLANDS FOR THE YEARS 1726 TO 1975

Station	Nat. Grid. Ref.	Altitude	Observer	Period	Distance from Pode Hole	1916–50 estimate
Pode Hole	214219	22′	Various	1829–1975	0	23·65 in
Southwick (Oundle)	920020	110′	George Lynn	1726–1740	22 miles	23·80 in
Lyndon (Rutland)	044907	300′	Thomas Barker	1737–1798, 1800	22 miles	24·56 in
South Kyme (nr Sleaford)	170498	11′	Rev. H. S. Neucatre	1800–1868 except 1826	18 miles	23·62 in
Boston, Grand Sluice	440327	40′	W. Veall *et alii*	1824–1869 1865–1970+	16 miles	24·30 in
Empingham	950086	175′	W. Fancourt	1836–1861	18 miles	24·20 in
Witham-on-the-Hill	165050	170′	General A. C. Johnson	1831–1869	11 miles	23·40 in
Wellingborough	894675	187′	Various	1860–1975	38 miles	24·50 in

by a conversion factor which is itself the product of an exposure factor and a distance factor. The exposure factor converts the observed totals into estimates for a standard rain-gauge well sited at the same place with rim 1 ft above ground. These are based on the consideration of the sites given below. The distance factors convert the estimates for the 1 ft level gauges at different places into estimates for Pode Hole, by taking account of the ratio of the annual catches in the 1916–50 period, as estimated from the latest official maps and given in Table II. These factors and their products are given in Table III.

TABLE III—CONVERSION FACTORS USED FOR THE HOMOGENEOUS PODE HOLE SERIES FOR 1726 TO 1975

Years used	Station	Exposure factor	Distance factor	Product
1726–1736	Southwick	1·030	0·994	1·024
1737–1798	Lyndon	1·080	0·963	1·040
1799	West Bridgford	—	—	1·000
1800–1825	South Kyme	1·030	1·000	1·030
1826	Witham	1·000	1·011	1·011
1827, 1828	South Kyme	1·030	1·000	1·030
1829–1975	Pode Hole	—	—	1·000

6. THE INDIVIDUAL RECORDS

The records for West Bridgford and Witham, each used to estimate for only one year, do not warrant individual discussion, but those for Southwick, Lyndon and South Kyme are more important. The records at Southwick and Lyndon provide the best evidence which still exists for British rainfall regimes before 1800, and deserve further study which may, of course, modify the present conclusions.

(i) Southwick Hall, Oundle has been a gentleman's residence since the Middle Ages, and when the rainfall measurements were made by George Lynn the elder (1740), from 1726 to 1740, the main structure was much the same as it is today. The house is surrounded by lawns, gardens and trees, with the church and village of Southwick at no great distance, and the probability is that these also have only changed in detail during the last 250 years. George Lynn, in a letter to Dr Jurin, describes the situation of his thermometer and barometer in considerable detail, but says nothing whatever about the exposure of his rain-gauge, an omission which suggests that he considered it too obvious a matter to deserve mention. A modern hydrometeorologist looking for a site for a rain-gauge would indeed have an obvious first choice, namely, the middle of the lawn to the west of the house, in clear view from the windows of the main drawing room (improved by George Lynn). He might also feel that this site, although the best available, is somewhat oversheltered. It lies between the manor house and the church, and there are and probably always have been big isolated trees (although not the same ones) and woods around. Any other site likely to be chosen would be more sheltered, and of course George Lynn had to make his choice without the experience available to modern observers. The impression left by a visit to the site is that an upward revision of the figures by three per cent to allow for exposure is unlikely to be excessive.

(ii) As regards the even more important Lyndon record, Thomas Barker (1771) describes his rain-gauge as follows:

'I have, on the other side, sent, as you desired, the height of my rain measurer above the ground, which, if you think proper, may be added to my former letter. Mr Edward Lawrence, who observed the rain at Stamford part of the time I have done here, generally found more water in his measurer which stood on the ground, than I did in mine; but I cannot depend on his observations, because I have been told the servants at the house used to play him tricks, and pour into his cistern more water than fell in, to which a thing on the ground is very liable . . . My rain cistern has all along stood on the top of a wall, where another meets it at right angles. The top of the cistern on the North side is 7 ft. 3 ins.; on the southwest side 8 ft. 6 ins.; and on the south-east side 10 ft. above the ground; it is all open southward for 25 yards, the north side is an orchard, but no tree hangs over it.'

The immediate response to this account is that a rain-gauge exposed in this way would catch less than one on the ground without any assistance from the pranks of mischievous servants. However, arriving at the right correction is less easy, since none of the experimenters seem to have considered a rain-gauge situated above the junction of two walls. The terrain at Lyndon is more similar to that at Stratfield Turgis than it is to the moors at Rotherham, or the urban terrain around Greenwich, and an exposure factor of 1·080 (which gives a product with the distance factor of 1·040), seems as good as any which can be suggested.

(iii) Information about the record at South Kyme can be pieced together from notes in the 10 year books, where the rainfall totals were copied by G. J. Symons, and an extensive extract from the observation book. During the 1930s a Flt Lt Lowe, stationed at Cranfield, lent the book to the Meteorological Office, stating his intention of depositing it in 'the local museum'. This book contained the observations of pressure, temperature and rainfall made by the Reverend H. S. Neucatre, vicar of Kyme Manor, from his appointment in 1826 until the summer of 1869, but it also contains similar observations for the years 1800 to 1825, which Neucatre must have copied from an at present unknown source. The site of the rain-gauge is stated to be 'near the old tower'. The book was returned to Flt Lt Lowe, and has not been seen since. A visit to South Kyme showed that the old tower is not the remains of a previous church, but a most impressive relic from a former castle, standing in open parkland not far from the church and manor house, which was built of stone from the castle. A water-colour of the old tower in the Museum of Local Antiquities at Lincoln shows that the surroundings of the old tower when the picture was painted (between 1850 and 1870) were the same as they are now, and it is hard to see how a rain-gauge could be sited near the old tower and avoid overexposure, without placing it in the actual shelter of the tower. Here again, an upward revision of the observations of three per cent to allow for exposure seems reasonable.

(iv) As regards Pode Hole itself, the facts are summarized in the official records as in Table IV.

These changes in gauge height etc. should not result in serious inaccuracies, and it appears, too, that some of them may be matters of description rather than fact, since it seems that for many years a Glaisher gauge, with rim 2 ft 6 in above the ground surface, was surrounded by a low hedge of 1 ft 3 in height. These observations have therefore been accepted as correct.

TABLE IV—INFORMATION ABOUT PODE HOLE

Spalding (Pode Hole) NGR TF(53)214219 12 ft a.s.l. Gauge No. 32-154720

Brief history of rain-gauging

Year	Observer/Authority	Gauge dia.	Height of rim	Site a.s.l.	Information	Notes
1829	A. Harrison		0′ 00″	19′ ?	10 yr	
1869	A. Harrison		0′ 00″	19′	10 yr	
1870	A. Harrison	12″	0′ 00″	20′ ?	BR	
1872	A. Harrison	12″	0′ 03″	20′	BR	
1890	A. Harrison	12″	0′ 03″	20′	BR	
1891	W. Grigg	12″	1′ 00″	20′	BR	
1905	W. Grigg	12″	1′ 00″	20′	BR	1905 may have been Rly Stn record (10 yr)
1906	W. Grigg	N & Z Glaisher	1′ 00″	20′	10 yr	
1910	W. Grigg	N & Z Glaisher	1′ 00″	20′	10 yr	1906–10 data rec'd 23.5.1912
1911	H. Bain	8″	1′ 03″	13′	BR	
1938	H. Bain	8″	1′ 03″	13′	BR	
1939	Deeping Fen Drainage Trust	8″	1′ 03″	12′	BR	
1946	Deeping Fen Drainage Trust	8″	1′ 03″	12′	BR	
1947	South Holland Drainage Board	8″	1′ 03″	12′	BR	
1958	South Holland Drainage Board	8″	1′ 03″	12′	BR	10 yr gives gauge as Glaisher 1951–60
1961	Deeping Fen, Spalding and Pinchbeck Internal Drainage Board	8″ Glaisher	1′ 03″	12′	10 yr	
1965	Deeping Fen, Spalding and Pinchbeck Internal Drainage Board	8″ Glaisher	1′ 03″	12′	10 yr	

(1962) (Two 5″ gauges installed—Pode Hole 2 and 3) 10 yr

N & Z = Negretti and Zambra BR = British Rainfall 10 yr = 10 year book

7. DISCUSSION AND CONCLUSION

The annual totals which result from this homogenization are given as percentages of the 1916–50 annual average in Table V which follows, and the monthly totals

TABLE V—ESTIMATED ANNUAL RAINFALL TOTALS FOR 1726–1828 AND MEASURED TOTALS FOR 1829–1975 FOR PODE HOLE EXPRESSED AS PERCENTAGES OF THE 1916–50 AVERAGE 23·65 in (600·7 mm)

1726	115·1	1754	87·3	1782	141·1	1810	123·9	1838	89·2	1866	113·1	1894	94·7	1922	111·2	1950	101·9
1727	108·0	1755	93·4	1783	100·2	1811	109·0	1839	133·8	1867	98·8	1895	92·5	1923	96·8	1951	116·1
1728	116·0	1756	110·8	1784	119·7	1812	116·3	1840	90·1	1868	104·7	1896	96·2	1924	111·9	1952	96·1
1729	101·8	1757	104·1	1785	88·9	1813	104·2	1841	124·5	1869	117·8	1897	99·9	1925	97·3	1953	98·3
1730	92·9	1758	94·9	1786	120·0	1814	114·6	1842	135·7	1870	71·3	1898	85·6	1926	99·2	1954	124·3
1731	76·9	1759	92·1	1787	100·2	1815	105·9	1843	124·5	1871	107·9	1899	88·2	1927	124·7	1955	86·8
1732	88·3	1760	80·4	1788	75·6	1816	165·1	1844	93·9	1872	137·4	1900	120·5	1928	106·9	1956	97·5
1733	76·3	1761	94·1	1789	123·1	1817	118·6	1845	115·2	1873	83·0	1901	99·7	1929	88·4	1957	101·3
1734	119·1	1762	78·7	1790	95·1	1818	114·0	1846	110·3	1874	68·7	1902	95·7	1930	105·7	1958	132·7
1735	107·4	1763	126·4	1791	108·7	1819	108·7	1847	108·3	1875	136·4	1903	130·0	1931	109·0	1959	76·0
1736	105·7	1764	103·3	1792	129·3	1820	104·0	1848	145·0	1876	131·0	1904	93·9	1932	107·2	1960	126·7
1737	92·1	1765	87·9	1793	100·8	1821	137·2	1849	116·0	1877	102·5	1905	104·1	1933	80·8	1961	90·8
1738	75·5	1766	83·4	1794	116·9	1822	101·4	1850	88·5	1878	108·4	1906	110·0	1934	78·9	1962	77·5
1739	94·8	1767	93·7	1795	94·1	1823	93·8	1851	94·1	1879	103·1	1907	94·9	1935	100·9	1963	85·1
1740	76·1	1768	135·9	1796	97·1	1824	136·2	1852	131·1	1880	157·0	1908	72·8	1936	109·1	1964	70·9
1741	70·3	1769	94·5	1797	122·5	1825	94·4	1853	112·5	1881	110·4	1909	101·5	1937	126·3	1965	109·8
1742	76·0	1770	125·6	1798	96·4	1826	75·7	1854	75·1	1882	129·0	1910	110·4	1938	83·4	1966	112·1
1743	70·6	1771	77·3	1799	120·3	1827	99·9	1855	93·1	1883	130·6	1911	80·3	1939	119·0	1967	86·3
1744	99·9	1772	126·0	1800	108·0	1828	125·1	1856	95·7	1884	70·9	1912	124·2	1940	94·6	1968	111·3
1745	90·3	1773	129·2	1801	107·0	1829	127·9	1857	117·8	1885	101·0	1913	89·3	1941	130·2	1969	106·1
1746	81·1	1774	155·0	1802	77·5	1830	145·0	1858	74·0	1886	127·9	1914	92·1	1942	93·9	1970	87·8
1747	105·9	1775	139·4	1803	96·2	1831	145·1	1859	106·8	1887	64·0	1915	108·8	1943	79·3	1971	84·7
1748	75·7	1776	122·4	1804	114·7	1832	122·1	1860	128·4	1888	90·9	1916	117·9	1944	101·0	1972	77·0
1749	70·1	1777	103·8	1805	107·4	1833	105·5	1861	108·9	1889	112·1	1917	84·3	1945	85·3	1973	85·5
1750	72·2	1778	115·5	1806	107·6	1834	76·5	1862	105·3	1890	85·3	1918	111·9	1946	115·0	1974	94·1
1751	119·5	1779	96·2	1807	86·1	1835	102·3	1863	96·7	1891	106·3	1919	112·0	1947	79·8	1975	83·5
1752	93·0	1780	88·4	1808	113·8	1836	112·7	1864	74·6	1892	96·2	1920	101·8	1948	97·9		
1753	97·6	1781	91·5	1809	108·5	1837	101·1	1865	123·2	1893	76·7	1921	53·5	1949	84·8		

from 1726 to 1828 are in Table VI (the monthly totals for 1829 to the present are the published figures for Pode Hole). These figures are offered as the best advice now available on the rainfall regimes of the East Midlands during the last 250 years. It would be difficult at present to suggest better data for relation to agricultural statistics in Lincolnshire, for example, but their suitability for use with data for places further afield is less clear. The question of the manner

TABLE VI—MONTHLY AND ANNUAL RAINFALL TOTALS AND DECADAL AVERAGES FOR PODE HOLE 1726–1828 (ESTIMATED) AND 1829–1975 (MEASURED)

	J	F	M	A	M	J	Jy	A	S	O	N	D	Year	Dec.
1726	430	103	154	101	41	409	378	29	528	151	142	255	2721	
1727	322	204	142	129	438	330	202	30	213	156	41	288	2555	
1728	471	95	335	202	147	289	329	98	88	286	156	249	2745	
1729	16	49	134	113	159	85	231	250	545	225	428	172	2407	
1730	41	154	266	82	256	348	205	87	164	307	205	82	2197	
1731	82	102	15	215	31	348	174	164	154	143	154	236	1818	
1732	92	123	143	123	348	61	184	174	72	379	123	266	2088	
1733	102	143	225	102	2	205	225	369	143	61	51	174	1802	
1734	51	266	184	61	522	133	184	410	174	287	92	451	2815	
1735	215	72	225	174	154	246	236	328	328	174	174	215	2541	
1736	236	297	215	61	82	143	614	174	143	266	61	205	2497	
1737	63	173	184	71	104	75	32	655	361	210	59	190	2177	
1738	186	59	124	128	225	252	64	148	219	171	72	137	1785	
1739	253	260	84	269	193	160	204	244	198	54	162	160	2241	
1740	26	6	66	90	108	149	382	291	168	109	155	251	1801	2157
1741	113	64	59	28	46	142	90	170	513	152	204	51	1632	
1742	149	89	5	199	161	149	327	17	185	249	252	17	1799	
1743	43	37	124	130	90	40	544	116	1	321	75	149	1670	
1744	125	98	149	287	131	362	85	100	343	327	236	122	2365	
1745	86	59	264	178	119	359	75	409	94	152	215	128	2138	
1746	183	178	196	79	57	302	150	48	170	236	186	133	1918	
1747	297	126	129	106	294	162	234	7	200	60	512	378	2505	
1748	98	38	203	142	123	316	362	135	57	110	45	161	1790	
1749	258	106	194	57	115	316	109	79	64	113	72	174	1657	
1750	115	93	106	244	103	215	157	67	104	92	220	190	1706	1918
1751	322	96	213	320	276	192	519	164	271	189	139	122	2823	
1752	262	144	125	86	222	320	383	138	50	31	113	326	2202	
1753	176	191	122	146	102	105	269	352	74	152	219	401	2309	
1754	96	93	130	151	146	300	400	110	11	194	204	231	2066	
1755	106	86	173	204	145	188	165	235	265	170	327	147	2211	
1756	210	72	142	406	131	309	333	443	216	159	101	98	2620	
1757	223	61	199	217	142	38	312	630	54	203	156	227	2462	
1758	194	214	186	96	132	225	522	178	152	107	95	145	2246	
1759	92	40	194	315	285	309	97	388	88	156	102	112	2178	
1760	110	194	47	41	93	257	94	171	242	263	223	167	1900	2302
1761	20	153	55	51	211	363	59	375	244	384	150	160	2225	
1762	180	101	159	61	77	79	116	376	159	432	96	24	1860	
1763	62	300	96	72	239	253	589	305	344	167	197	366	2990	
1764	414	118	86	158	114	227	480	184	86	141	184	250	2442	
1765	149	129	288	219	43	82	60	291	73	503	133	109	2079	
1766	17	218	81	204	342	237	245	43	112	86	202	186	1972	
1767	320	208	109	88	220	225	383	158	72	293	97	42	2215	
1768	294	318	41	210	168	470	250	179	315	324	420	224	3213	
1769	125	162	72	87	151	496	207	245	268	125	128	167	2233	
1770	88	77	201	198	161	288	186	236	127	324	813	271	2970	2420

All totals and averages are expressed in hundredths of an inch. 1 inch=25·4 mm.

TABLE VI—*continued*

	J	F	M	A	M	J	Jy	A	S	O	N	D	Year	Dec.
1771	147	97	95	101	69	165	108	222	121	423	82	201	1831	
1772	223	362	244	92	194	405	93	175	469	340	256	128	2981	
1773	118	152	58	62	711	249	112	352	292	272	375	302	3055	
1774	344	203	284	158	327	258	336	407	832	121	159	237	3666	
1775	205	262	180	108	94	93	424	495	590	362	371	113	3297	
1776	261	332	158	93	170	259	192	541	255	214	293	128	2896	
1777	112	251	131	165	206	309	333	134	53	417	164	179	2454	
1778	206	99	125	108	137	282	426	41	173	441	400	294	2732	
1779	22	233	14	197	132	251	420	157	128	184	213	326	2277	
1780	105	163	123	284	125	200	163	45	357	320	152	55	2092	2728
1781	235	173	17	202	101	308	175	114	417	8	329	177	2166	
1782	242	67	200	638	595	135	281	323	536	156	111	54	3338	
1783	188	240	167	58	439	315	277	114	150	69	185	166	2368	
1784	196	128	114	181	301	396	528	292	181	23	248	242	2830	
1785	155	38	22	19	70	163	341	448	344	172	118	212	2102	
1786	361	70	86	130	248	164	187	274	295	495	306	223	2839	
1787	43	89	185	179	163	187	330	205	128	388	152	321	2370	
1788	101	278	111	61	158	63	186	289	253	147	47	93	1787	
1789	270	192	120	105	175	463	443	34	295	513	125	177	2912	
1790	194	25	27	71	303	248	234	180	163	103	327	375	2250	2496
1791	251	132	84	201	119	96	419	303	62	345	440	120	2572	
1792	218	74	114	420	173	420	382	297	414	183	79	283	3057	
1793	199	111	288	312	47	44	81	271	400	132	357	140	2382	
1794	44	146	173	207	108	74	437	300	371	367	412	127	2766	
1795	171	208	218	163	42	291	175	144	6	472	192	144	2226	
1796	203	171	40	68	295	97	587	116	197	137	213	174	2298	
1797	137	8	95	300	263	439	319	252	498	119	168	298	2896	
1798	107	160	55	137	197	99	306	202	292	315	265	146	2281	
1799	169	285	130	292	175	76	259	506	490	221	162	80	2845	
1800	368	49	44	384	145	102	58	146	323	162	508	265	2554	2588
1801	203	65	149	60	202	97	373	193	174	158	503	355	2532	
1802	38	213	65	117	127	204	305	75	100	228	172	190	1834	
1803	244	113	56	239	369	158	64	69	151	75	310	428	2276	
1804	270	228	219	200	141	70	359	300	44	265	528	89	2713	
1805	223	176	138	215	119	344	246	408	170	162	130	208	2539	
1806	295	96	145	64	149	65	510	217	203	89	351	361	2545	
1807	96	127	80	43	264	181	90	138	173	125	399	320	2036	
1808	146	138	51	268	203	150	356	249	346	417	277	89	2690	
1809	507	203	72	379	131	94	261	239	207	44	227	204	2568	
1810	28	137	279	93	147	85	357	321	64	307	612	501	2931	2466
1811	137	161	90	146	243	203	373	267	193	266	250	249	2576	
1812	202	331	262	162	216	259	356	192	48	365	270	90	2753	
1813	59	259	78	216	261	286	357	64	168	511	130	75	2464	
1814	380	65	224	152	149	265	135	271	152	267	291	358	2709	
1815	141	150	272	236	130	206	165	254	187	302	167	295	2505	
1816	242	226	244	212	260	506	476	385	418	359	276	301	3905	
1817	399	173	178	90	352	273	291	270	67	150	169	393	2805	
1818	208	277	374	399	267	98	44	33	348	202	300	147	2697	
1819	236	271	141	268	262	176	161	69	280	188	249	269	2570	
1820	179	135	69	153	272	291	356	182	249	216	161	195	2458	2744

TABLE VI—*continued*

	J	F	M	A	M	J	Jy	A	S	O	N	D	Year	Dec.
1821	284	64	242	169	207	254	302	253	258	272	473	467	3245	
1822	61	75	131	276	165	137	322	162	164	384	398	125	2400	
1823	228	262	125	171	131	205	265	229	188	296	202	228	2220	
1824	65	228	219	213	375	370	183	250	373	267	355	323	3221	
1825	119	90	65	174	337	94	34	260	243	262	296	260	2234	
1826	26	164	137	113	71	47	162	101	524	152	182	113	1792	
1827	149	131	220	111	114	108	182	113	303	470	170	289	2360	
1828	393	108	117	218	176	427	588	322	201	99	109	199	2957	
1829	221	213	28	487	20	412	378	437	345	162	210	112	3025	
1830	325	460	44	275	470	463	320	213	279	63	187	130	3429	2688
1831	200	300	162	230	125	310	499	410	425	290	250	240	3432	
1832	125	10	280	250	310	310	230	425	37	310	350	250	2887	
1833	126	515	206	300	82	312	30	350	120	210	75	170	2496	
1834	225	50	50	100	50	90	625	210	125	100	125	60	1810	
1835	200	175	250	150	220	160	140	120	340	425	180	60	2420	
1836	125	260	325	200	15	270	125	130	230	275	400	310	2665	
1837	360	175	50	170	125	175	210	220	225	220	210	250	2390	
1838	180	175	110	140	170	325	210	200	210	150	140	100	2110	
1839	150	140	370	100	80	500	450	300	225	240	420	190	3165	
1840	200	100	75	75	225	150	330	225	180	190	290	90	2130	2550
1841	375	150	120	120	150	300	300	375	280	300	300	175	2945	
1842	480	150	160	60	275	360	230	290	565	90	450	100	3210	
1843	170	250	125	230	560	180	300	450	25	410	220	25	2945	
1844	150	230	200	25	25	150	370	250	200	250	320	50	2220	
1845	175	75	350	150	270	225	240	480	175	140	120	325	2725	
1846	240	30	40	475	140	60	175	290	310	475	150	225	2610	
1847	140	120	72	75	500	250	50	340	160	380	125	350	2562	
1848	140	325	330	275	50	400	290	380	450	550	60	180	3430	
1849	175	120	75	250	287	237	350	87	387	300	100	375	2743	
1850	163	87	50	137	137	63	475	163	237	237	169	175	2093	2748
1851	187	50	300	150	50	225	525	187	125	213	150	63	2225	
1852	313	63	63	37	87	363	225	537	437	275	525	175	3100	
1853	175	300	163	150	100	300	337	275	137	363	225	137	2662	
1854	265	50	63	75	150	125	163	137	150	187	213	200	1778	
1855	100	225	100	25	213	137	513	113	25	425	225	100	2201	
1856	300	125	37	125	163	125	113	487	150	300	175	163	2263	
1857	413	37	175	225	75	137	187	600	287	413	213	25	2787	
1858	25	63	113	150	137	75	213	250	137	325	113	150	1751	
1859	75	125	113	250	200	200	175	287	325	375	176	225	2526	
1860	265	113	187	75	337	537	125	400	300	187	287	225	3038	2433
1861	100	200	200	87	150	563	450	25	187	137	313	163	2575	
1862	163	63	363	163	237	225	237	213	363	200	113	150	2490	
1863	225	37	100	87	187	387	63	313	265	250	300	75	2289	
1864	75	175	263	113	175	163	63	87	175	137	213	125	1764	
1865	263	213	163	63	225	237	363	487	37	575	187	100	2913	
1866	163	237	113	137	137	400	300	337	363	175	163	150	2675	
1867	400	125	175	175	350	87	175	225	137	200	63	225	2337	
1868	213	137	163	175	50	50	37	375	225	287	113	650	2475	
1869	213	237	287	287	463	163	50	175	287	75	175	375	2787	
1870	137	175	113	75	75	137	87	125	50	287	125	300	1686	2399

TABLE VI—*continued*

	J	F	M	A	M	J	Jy	A	S	O	N	D	Year	Dec.
1871	113	163	113	275	87	350	413	225	475	113	125	100	2552	
1872	275	175	213	300	175	275	350	300	150	400	350	287	3250	
1873	150	137	125	63	225	263	275	225	175	163	125	37	1963	
1874	100	175	63	75	100	63	106	150	237	206	163	187	1625	
1875	213	150	50	87	125	400	900	113	225	387	450	125	3225	
1876	250	213	200	637	75	250	100	137	450	113	237	437	3099	
1877	287	150	137	337	200	87	263	300	175	125	213	150	2424	
1878	150	113	63	150	375	150	37	675	113	187	400	150	2563	
1879	125	187	50	225	313	300	387	263	300	75	113	100	2438	
1880	25	175	87	250	150	550	675	263	587	575	163	213	3713	2685
1881	75	300	163	100	50	175	300	500	187	300	225	237	2612	
1882	150	75	187	250	187	263	275	313	263	500	250	337	3050	
1883	175	287	125	187	225	263	475	75	625	213	325	113	3088	
1884	150	75	87	125	113	63	275	113	225	137	113	200	1676	
1885	125	175	63	137	213	225	25	225	313	463	350	75	2389	
1886	275	13	250	137	413	125	400	250	75	425	275	387	3025	
1887	225	87	63	125	175	63	100	87	175	163	163	87	1513	
1888	69	206	200	225	75	200	450	200	113	13	237	163	2151	
1889	150	150	200	263	550	37	275	275	225	300	63	163	2651	
1890	187	113	267	87	225	225	225	163	25	87	363	50	2017	2417
1891	150	0	125	125	263	137	250	350	113	463	250	287	2513	
1892	125	225	113	113	213	237	237	200	225	400	100	87	2275	
1893	175	225	37	13	100	125	300	100	125	213	250	150	1813	
1894	163	137	50	125	150	225	400	163	125	263	275	163	2239	
1895	263	63	200	175	75	213	250	200	63	237	300	150	2189	
1896	100	75	200	87	75	200	113	137	475	363	125	325	2275	
1897	137	313	213	137	87	225	213	350	313	125	125	125	2363	
1898	100	50	150	225	275	113	87	337	37	275	200	175	2024	
1899	237	125	50	200	250	87	150	150	300	213	137	187	2086	
1900	337	525	63	100	175	225	87	487	37	213	213	387	2849	2263
1901	100	125	150	175	100	125	475	200	100	175	175	437	2337	
1902	87	150	125	150	313	313	137	287	175	200	163	163	2263	
1903	187	75	275	200	275	150	250	450	312	625	175	100	3074	
1904	200	275	225	83	263	50	237	325	200	87	100	175	2220	
1905	125	75	187	200	87	375	275	313	275	137	313	100	2462	
1906	313	200	225	75	163	263	75	275	125	375	313	200	2602	
1907	100	125	125	200	275	150	174	269	77	283	208	259	2245	
1908	59	104	196	214	131	114	229	195	172	100	82	126	1722	
1909	55	18	305	114	105	345	338	189	180	339	42	370	2400	
1910	166	238	72	222	280	107	250	304	122	142	212	497	2612	2394
1911	124	77	148	88	51	210	24	140	170	202	237	421	1898	
1912	280	115	198	16	223	302	498	555	108	175	219	249	2938	
1913	240	57	291	209	182	156	82	153	152	300	238	51	2111	
1914	145	82	258	99	120	302	125	153	62	194	219	419	2178	
1915	202	207	144	51	175	77	492	345	87	128	260	406	2574	
1916	86	354	397	91	191	256	200	342	135	169	294	274	2789	
1917	215	71	112	137	113	179	120	429	105	322	105	86	1994	
1918	224	125	60	167	301	55	296	277	453	184	259	245	2646	
1919	312	258	304	239	51	104	287	243	168	145	204	334	2649	
1920	176	78	223	373	198	237	314	107	231	176	69	226	2408	2415

TABLE VI—*continued*

	J	F	M	A	M	J	Jy	A	S	O	N	D	Year	Dec.
1921	185	53	73	113	116	45	44	197	67	132	115	126	1266	
1922	275	264	183	257	114	84	547	196	199	134	117	261	2631	
1923	142	328	193	116	113	57	215	213	211	266	159	276	2289	
1924	222	93	60	152	374	204	295	198	190	465	234	210	2647	
1925	104	195	118	182	311	12	177	244	270	261	209	217	2300	
1926	315	154	36	209	259	288	132	89	249	220	315	81	2347	
1927	161	211	229	171	110	342	221	296	412	217	304	275	2949	
1928	285	106	175	103	151	408	224	206	47	341	261	222	2529	
1929	166	97	19	90	106	122	194	138	81	259	391	427	2090	
1930	213	62	164	233	265	54	295	233	389	104	284	205	2501	2355
1931	217	269	40	227	236	157	408	263	406	71	199	84	2577	
1932	81	88	174	264	377	57	409	284	320	279	139	63	2535	
1933	125	233	226	114	143	162	70	56	243	281	194	63	1910	
1934	134	76	141	206	54	104	191	204	117	93	206	341	1867	
1935	216	171	47	255	59	244	60	158	264	250	400	263	2387	
1936	303	222	96	204	151	355	507	84	150	144	210	155	2581	
1937	320	291	315	260	475	154	330	41	159	217	157	267	2986	
1938	236	130	27	17	210	99	215	132	189	154	161	403	1973	
1939	458	64	181	230	78	169	314	249	135	425	300	211	2814	
1940	207	251	165	101	90	79	361	49	62	266	457	150	2238	2387
1941	378	252	358	93	294	73	563	394	94	218	307	55	3079	
1942	238	143	135	75	252	93	223	252	148	228	285	150	2222	
1943	383	28	57	107	205	229	99	237	193	108	155	74	1875	
1944	164	181	19	183	99	275	224	270	380	226	254	113	2388	
1945	220	164	58	84	149	246	173	321	140	199	63	200	2017	
1946	110	246	107	116	156	223	214	354	219	242	514	218	2719	
1947	186	183	423	192	47	230	208	5	118	21	88	187	1888	
1948	375	91	49	115	267	304	106	228	214	220	144	203	2316	
1949	126	69	85	198	224	52	237	117	130	371	266	131	2006	
1950	85	302	62	218	285	172	268	240	217	67	370	123	2409	2292
1951	250	309	335	223	317	74	123	365	124	102	398	127	2747	
1952	163	44	277	142	307	95	25	265	261	256	249	190	2274	
1953	100	188	87	165	271	343	196	356	110	219	213	77	2325	
1954	169	229	166	27	386	278	261	334	224	235	417	215	2941	
1955	244	304	199	105	302	232	34	88	99	150	136	160	2053	
1956	489	105	87	133	107	245	229	379	147	108	91	187	2307	
1957	110	265	195	29	157	218	264	242	390	106	194	224	2395	
1958	243	331	171	87	240	379	373	427	206	265	145	272	3139	
1959	294	17	266	127	71	58	227	95	34	103	162	344	1798	
1960	366	265	140	46	78	109	273	294	268	458	349	351	2997	2498
1961	253	129	35	277	62	86	194	179	198	228	205	301	2147	
1962	126	54	124	232	116	12	156	282	274	81	238	138	1833	
1963	113	75	267	196	122	158	162	341	131	81	320	48	2014	
1964	79	102	296	192	60	268	88	176	75	96	111	134	1677	
1965	204	77	210	164	119	155	284	205	451	24	298	405	2596	
1966	117	298	39	314	177	326	198	311	185	269	197	219	2650	
1967	66	126	86	219	391	142	123	107	135	303	199	145	2042	
1968	146	75	67	255	194	221	428	325	346	197	247	131	2632	
1969	287	183	256	132	470	172	242	157	26	30	299	255	2509	
1970	213	176	134	277	27	101	160	211	86	73	479	140	2077	2218
1971	268	32	167	143	202	198	114	297	80	146	217	140	2004	
1972	192	111	248	129	157	123	147	50	182	28	234	220	1821	
1973	60	66	61	156	384	352	298	53	233	143	72	143	2021	
1974	150	159	98	29	67	222	213	343	218	362	274	91	2226	
1975	202	76	354	286	235	45	195	84	179	59	132	129	1976	

in which the value of rainfall evidence decreases with distance, both annually and seasonally, is still under investigation. There are other homogeneous series published or in course of preparation, including series from Kew (Wales-Smith 1971)*, Manchester (Manley 1971)* and other places in Great Britain and also several from adjacent continental countries. Comparisons may suggest revision of a series which seems to be getting unreasonably out of line with the rest, or which is at variance with other evidence on the prevailing rainfall regimes; several years may elapse before climatologists can be assured that the homogenized records are as near the truth as the nature of the evidence will allow.

When evaluating and using a carefully constructed 'key-site' assemblage of monthly rainfall estimates made from recorded or intelligently adjusted totals at other places the following points should be borne in mind:

(i) The distribution of severe thunderstorms over a given area in a summer month can easily result in totals differing by as much as 2 inches at places only a few miles apart. Similarly, the distribution of intense rainfall in a major, synoptic-scale rainfall event lasting, say, two or three days can easily result in a 20 per cent difference between annual totals at two places with fairly low average annual rainfalls and only some 50 miles or even less apart.

(ii) At the worst an estimated monthly total for a 'key-site' is a good estimate of the rainfall not far from the site even if not at the site itself. At best the estimate is a close approximation to the true total fall at the site. Summer-month estimates are generally less reliable than those for other seasons. In the authors' view, the figures, with all their uncertainties, present a fairer view of the rainfall regimes of the East Midlands than has been available hitherto, and the references given enable any reader to judge the evidence for himself.

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AGROMETEOROLOGICAL USE OF THE SYNOPTIC DATA BANK IN PLANT DISEASE WARNING SERVICES

By R. J. ADAMS and JUDITH M. SEAGER

SUMMARY

The agricultural section of the Meteorological Office has for some years offered a plant disease data service to the Ministry of Agriculture, Fisheries and Food. Information has been provided on the occurrence of weather conditions conducive to the spread of various plant diseases. In the past this service has been based on the manual extraction of meteorological data from incoming weather reports. An account is given of the conversion of these schemes to automatic extraction from the synoptic data bank of the Meteorological Office COSMOS computer. The form of the disease criteria and the advantages gained from a computerized scheme are described.

INTRODUCTION

The rate at which biological processes take place is affected by the weather and this applies not only to the growth and development of a particular plant but also to the diseases affecting it. Diseases which affect agricultural and horticultural crops can cause a reduction in yield which may be considerable in certain years. This means a financial loss both to the individual farmer and to the country as a whole. Sprays can be applied to combat some of the diseases, but applications need to be kept to a minimum because of their high cost, possible mechanical damage to the crop and long-term environmental effects.

Work has been carried out in the past by plant pathologists of the Ministry of Agriculture, Fisheries and Food (MAFF) and agricultural meteorologists to identify weather conditions which are favourable for the development and spread of certain crop diseases. In some cases it has been possible to define criteria for potential infection periods in terms of meteorological variables, quantities which are observed as routine. Other factors will affect the development of disease and these include the growth stage of the crop, existing disease levels and carry-over from previous years.

Plant pathologists, given information about potential infection periods together with a knowledge of these other factors, can advise on the need for spraying and the best timing to achieve optimum effect. It is usually necessary for the spray to be applied within a few days of the occurrence of an infection period, thus the information has to be passed to the plant pathologists with the minimum of delay. Schemes have been in operation (some for several years) whereby weather data for the past 24 hours have been examined, infection periods identified and plant pathologists informed by telephone, telex or letter. The number and efficiency of warning schemes which could be operated using traditional 'manual' methods were limited, thus an automated method was initiated to extend and improve the service. Computer programs have been written (the first became operational in 1975) which extract the required data from the synoptic data bank of the computer at Meterological Office Headquarters. The data are automatically processed to check whether certain criteria have been satisfied. Finally a paper tape containing the required information is produced. This allows telex transmission of the data to MAFF Headquarters and thence to regional plant pathologists.

Diseases for which infection periods have been defined

Apple scab

Apple scab is a fungal disease which causes lesions on the leaves and developing fruit which can become misshapen if heavily infected. The fungus overwinters on fallen leaves and infects the apple trees in the spring when the buds are bursting. The impact of raindrops causes spores to be released from the fallen leaves and then a period of leaf wetness allows the spores to infect the new growth on the tree. The length of the period of leaf wetness required for infection depends on the average temperature throughout the period. A 'Mills period' (Mills and La Plante, 1954) was defined, based on leaf wetness which is not an observed meteorological quantity. Following the development of an instrument for continuously recording the wetness of a polystyrene element (Hirst, 1957), it was found that hours of surface wetness correspond very nearly to hours when the relative humidity is not less than 90 per cent (Hearn, 1961). Although it is recorded, relative humidity is not reported hourly to Bracknell by observing stations. Since dry-bulb and dew-point temperatures are reported rounded to the nearest whole degree Celsius, calculations of relative humidity from these temperatures cannot be precise. A difference between reported dry-bulb and dew-point temperatures of 0°C or 1°C corresponds in most cases to a relative humidity of 90 per cent or more, but occasionally relative humidities in the range 88–90 per cent will be included and some greater than 90 per cent will be missed. Thus the depression of the dew-point may be used as an indicator of leaf wetness and it has been possible to redefine the criteria using only readily available meteorological data from hourly observations. 'Smith periods' have been defined as follows (Preece and Smith, 1961):

A possible infection period starts when precipitation is reported, and continues as long as there is precipitation, or a dew-point depression of 1°C or less is reported. Breaks in these conditions of one hour are allowed. A 'Smith period' occurs when this period satisfies the temperature/time condition as for the 'Mills period'.

In practice this requires that the relative humidity criteria are satisfied for at least nine hours. A 'near miss' condition can also occur, defined as a period which is either one hour too short, or 0·5°C too cool to satisfy the temperature/time criteria.

Barley mildew

Barley mildew is a disease which, if unchecked, can spread very rapidly. It is a fungal disease in which the mildew affects the leaves, reducing their photosynthetic efficiency, producing a loss in grain yield which can be very severe, with annual losses estimated to be about £30–£40 million. These losses can be reduced dramatically by the timely application of suitable sprays.

Spores of barley mildew tend to be released under dry conditions and their spread assisted by strong winds. Two sets of criteria have been defined and are in current use. Polley and Smith (1973) suggested that the following conditions are favourable for spore release:

daily maximum temperature above 15·6°C
daily sunshine more than 5 hours
daily rainfall less than 1 mm
wind speed at 00, 06, 12 or 18 GMT greater than 15 knots.

The number of these conditions occurring determines the 'Polley count' for the day. A high-risk day is a day on which one of the following is satisfied:

a Polley count of 4
the 2nd consecutive day with a count of 3
the 3rd consecutive day with a count of 2 provided that at least one of these days had a count of 3.

An alternative method of identifying high-risk days is by means of the 'Smith index', I, defined as:

$$I = 3T + \tfrac{1}{2}W + H$$

where T = maximum temperature (°C), W = wind speed at 1200 GMT (knots) and H = hours of sunshine for the day in question (Polley and Smith, 1973). A high-risk day is one on which this index exceeds 64.

Plant pathologists can advise on the best time to spray from a knowledge of high-risk periods, current levels of mildew in the crop and growth stage of the crop.

METHODS OF DERIVING PLANT DISEASE DATA

The criteria outlined in the previous sections were all designed (or subsequently modified) to incorporate data which are reported to the Meteorological Office Headquarters primarily for use in synoptic forecasts in the Central Forecasting Office. These data are automatically stored in the synoptic data bank of the Meteorological Office COSMOS computer complex to be immediately available for forecasting programs.

The barley mildew warning scheme was the first of the agrometeorological services to be automated, the new system being introduced in 1975. In previous years during the period 15 April–31 July relevant data were extracted by hand from copies of the teleprinter messages received from the collecting centres; 35 stations in England and Wales were used and these had to be identified from among all those reporting, as had the individual figures specifying the required elements in the messages. All the data required to calculate the Smith index and Polley count were then tabulated and passed to the Telecommunications Branch for manual punching and transmission to the appropriate recipients. An analyst familiar with meteorological codes and the day-to-day running of the scheme could expect to produce this final table within two to three hours of the last observation. The analyst also had to compute the Smith indices and Polley counts for stations in the south-east region, and inform plant pathologists by telephone if they reached critical values. For other regions, the meteorologists at MAFF Bristol, Cambridge and Harrogate were responsible for these calculations and the information service.

The computer program followed essentially the same series of operations as those involved in the manual operation, but in addition indices and counts for all stations were evaluated and included in the final table. The main problems in programming arose from the different ways in which the same meteorological information is reported by different classes of observing stations. For example, some stations report maximum temperature and a 12 hour rainfall total at 2100 GMT; others report at 0900 GMT on the following day, with a 24 hour rainfall figure. Some stations report sunshine hours in precisely defined positions within the message while others include this information within one of a varying number of '9-groups'. The program thus has to identify the appropriate group of figures if present and recognize that it refers to sunshine hours and not, for example, to optical phenomena such as rainbows or haloes. A small section of the program deals with the computation of daily rainfall totals involving trace amounts, which are stored as −0·1 mm in the synoptic data bank. The program also has to cope with occasions of missing and, to some extent, misreported data. For example, the absence of sunshine hours from the calculation of the Smith index would give an erroneous result, but the failure to include an observation of a 1200 GMT wind would not matter in the calculation of a Polley count if (and only if) a report at one of the other observing times exceeded 15 knots.

The program produces a table of meteorological data, indices and counts in a computer printout format. To eliminate the need for manual punching of the table by telecommunications staff a further section was written to provide a simultaneous output of the table on paper tape, in the particular form required for teleprinter transmission. This message is then passed by telex to MAFF Headquarters for insertion in their telecommunications network for transmission to the regional meteorologists and plant pathologists. The total computing time to extract and process the data and to prepare the tape for transmission is of the order of eight seconds (Central Processing Unit time). The scheme now covers over 50 stations, including for the first time some in Scotland. The program is run daily throughout the year, but results are communicated to plant pathologists only during the part of the year when mildew is likely (mid April to end of July). However, the meteorological data are of relevance to agriculturists throughout the year so distribution to the regional meteorologists is continued. Because of this more general application, a section to extract daily minimum temperatures has been included in the program.

An automated 'apple scab' service was introduced in 1976. For several years before its introduction a manual scheme had been in operation in which infection periods were identified from hourly observations plotted on charts. Ten stations in the southern half of England were used. The Plant Pathology Laboratory at Harpenden was notified by telephone of infection periods as they occurred and these were confirmed by post. Plant pathologists at the Reading Regional Office of MAFF were informed by telephone of infection periods in their region.

The new scheme has enabled the number of observing stations used to be increased to 29. The distribution to the recipients has been improved, following the same method as that used in the barley mildew service. The computer program developed for the scheme uses several of the techniques in the barley mildew program. The principal difference lies in the cumulative aspect of the apple scab criteria in that the treatment of each observation depends on previous observations. The program is run each day throughout the critical time of year (1 March to 15 June). Data for each of the previous 24 hours are extracted, rainfall and relative humidity criteria examined and, when a high humidity period has ended, the time/temperature criteria are checked against a mathematical representation of the Mills time/temperature criteria. At the end of each day's run details of any continuing high humidity periods need to be stored for use on the following day.

INCLUSION OF OTHER DISEASES

Schemes for two further diseases were introduced in 1976 and are on a trial basis. *Rhynchosporium* of barley and *septoria* of wheat are diseases for which experimental criteria have been suggested. Information on infection periods using these criteria is useful to plant pathologists currently conducting trials and may allow the criteria to be confirmed so that new routine services can be introduced. The criteria at present used for *rhynchosporium* require the same hourly data as those for apple scab. For *septoria*, rainfall totals are also needed and these are provided in the data output by the barley mildew program.

CONCLUSION

The automatic warning schemes have several advantages over the old methods. The repetitive process of data extraction is accomplished in seconds and the man-hours spent on the task are considerably reduced. Difficulties arising over backlogs of work after weekends and public holidays have been removed, and the load upon the limited staff of regional meteorologists has been reduced. The greater speed of the computerized scheme makes possible the incorporation of more observing stations thus giving a better service over the country. The resulting data are distributed earlier and to a greater number of interested recipients. Finally, the basic agrometeorological programs for extracting information from the synoptic data bank may apply to any agrometeorological situation where relationships with current meteorological data have been developed. Thus a continually improving service can be offered to the agricultural community.

The agrometeorological programs provide data on meteorological conditions consistent with the spread of plant diseases only if other conditions are satisfied in the field. The plant pathologists have to apply their own expertise and knowledge to the information which the Meteorological Office provides and to find appropriate ways of speedily conveying their warnings and advice to the farming and horticultural community.

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RAINFALL CRITERIA FOR URBAN DRAINAGE DESIGN

By J. F. KEERS

SUMMARY

An appraisal is made of those aspects of rainfall which are important for the economic design of urban storm water drainage systems. These include the mean rainfall intensity for specified durations, the average frequency of occurrence and regional variability of heavy local falls, the relationships between rainfall intensity and time (storm profiles) and between rainfall at a point and over an area. Also discussed are other aspects of rainfall which may be important as input to models of more advanced design including statistics describing the movement of extreme rainstorms, for example once-in-two-year storms, across the catchment.

INTRODUCTION

Urban drainage is concerned with the disposal of storm water, the removal of all waste water and the control of flood waters. Storm water, often referred to as surface water, is defined as the run-off of rainfall from both natural and artificial surfaces such as roads, roofs, etc. In many urban areas storm water and domestic sewage are discharged into the same pipe system, referred to as a combined system. There are also many examples of partially combined systems in the United Kingdom. In general, however, new sewerage schemes use separate systems for storm water and domestic sewage and then only the storm water sewers present a design problem because of the great variability of storm rainfall. In the United Kingdom the design of urban drainage schemes is commonly based on rainfall events (design rainfalls) with a frequency of between once a year and once in ten years but which may be up to once in 100 years in special circumstances.

The designer of storm water sewers is concerned with two types of rainfall: average rainfalls over long periods and heavy rainfalls of short duration, usually less than two hours. The former are required for estimating annual pumping costs, and the latter for determining the size of sewers, pumps, etc. The good daily rain-gauge network in the United Kingdom, approximately 3000 stations in the year 1900 and 7000 stations today, has enabled meteorologists to determine for any location or catchment area (i) monthly, seasonal and annual rainfall averages, and (ii) the geographical variation of daily or longer-period rainfall totals with any specified frequency of occurrence.

The network of continuously recording rain-gauges is much less dense than the daily rain-gauge network and until recently the best statistics of short-duration rainfall, i.e. less than a few hours, were those derived by Bilham (1936) and modified by Holland (1964). Bilham used 10 years of data (1925 to 1934) from only 12 recording rain-gauge stations widely distributed throughout England and Wales to derive a formula for estimating an average frequency of intense short-duration rainfall (up to two hours duration). Holland (1964) modified Bilham's formula for rainfalls with intensity above 32 mm/h. Holland (1967) also investigated plots of rainfall intensity against time, hereinafter referred to as storm profiles, and the relationship between point and areal rainfall for areas up to 20 km^2 in size using data from a close network, with an inter-gauge spacing of approximately 1 kilometre, of recording rain-gauges near Cardington in Bedfordshire.

In the mid 1960s the Road Research Laboratory (RRL)—now the Transport and Road Research Laboratory (TRRL)—developed a computer package based on *Road Note* No. 35 (1963) for assisting with the design of drainage systems, including sewer systems. The RRL method used the results of Bilham and Holland for determining design rainfalls. Neither Bilham nor Holland considered the geographical variation of frequencies of short-duration rainfall. Moreover, neither author overcame the restrictions imposed by the shortage of long-period records from recording rain-gauges or the problem of the great variability in time of extreme rainfall in a two-hour storm.

In order to overcome the limitations of the results of Bilham and Holland, an intensive investigation of rainfalls of all durations has been made using all available rainfall records, reports of thunder, observations of precipitable water, etc., for stations in the British Isles. This work was carried out under the direction of A. F. Jenkinson of the Meteorological Office during the years 1971 to 1974 and culminated in the publication of the *Flood Studies Report* (Vol. 2—Meteorological Studies) in March 1975. Vol. 2 of the *Report* quantifies the significant geographical variation in the rainfalls of any specified return period and duration up to one month. Also the availability of relatively long-period rainfall records from a selection of stations means that estimates of the rainfall of longer return periods derived using the *Flood Studies Report* are more reliable than previous methods of estimation. The *Flood Studies Report* also enables the storm profile to be specified for design purposes and this will be discussed in a later section.

Mean rainfall intensity for design purposes

One of the most common storm sewer design methods is known as the Rational or Lloyd-Davies (1906) Method. This method relates the peak flow in the sewer, Q, to the size of drainage area, A, a surface impermeability factor, p, and the mean rainfall intensity, $\bar{R}$ (the latter for a specified duration and average frequency of occurrence) as follows:

$$Q = C_1 A p \bar{R}, \qquad \text{(1)}$$

where the constant C_1 depends on the units employed.

For a particular urban catchment the drainage area may be taken as constant and if the impermeability factor is also fixed, i.e. its variability is neglected, Equation (1) reduces to

$$Q = C_2 \bar{R}, \qquad \text{(2)}$$

where C_2 is a known constant.

Before the Road Research Laboratory introduced their computer package for drainage design in the mid 1960s it was common practice to use an equation of type (1) or (2), and even today *Road Note* No. 35 (1963) (1976 revision in the press) recommends that such an equation should be used when the largest sewer does not exceed 2 ft ($\approx$0·6 m) in diameter, since the simplifications involved are not significant in terms of selected pipe diameter. From Equation (2) the fundamental importance of the mean rainfall intensity over short durations is obvious and many researchers have devised equations for determining the rainfall in the United Kingdom for a range of durations and return periods (Bilham, 1936; Maclean, 1945; Holland, 1964). However, the *Flood Studies Report* (1975) undoubtedly presents the most reliable method so far devised for determining the design rainfall for any location in the United Kingdom; an example of the sort of rainfall data which can be derived is given in Table I. In Table I an event with an average frequency of occurrence of once-in-N-years is referred to as an event with a return period of N years.

TABLE I—RATES OF RAINFALL AT BALA IN NORTH WALES FOR SPECIFIED DURATIONS AND RETURN PERIODS

	Return period (years)						
	1	2	5	10	20	50	100
Duration (minutes)				*mm/h*			
2	50	61	78	89	102	120	136
5	38	47	61	71	81	96	109
10	29	35	47	54	63	75	87
15	24	29	39	45	53	64	74
30	17	21	27	32	38	46	54
60	11·8	14	19	22	26	32	37
90	9·5	11·4	15	17	21	25	30
120	8·2	9·7	12·4	15	17	21	25
(hours)							
4	5·6	6·6	8·2	10·3	11·3	13·8	16·0
6	4·5	5·3	6·4	7·5	8·7	10·6	12·2
12	3·1	3·6	4·2	4·9	5·6	6·7	7·6

TIME OF CONCENTRATION

It has been common practice to design a storm sewer by assuming that the N-year peak flow in the sewer is directly attributed to the N-year rainfall. The mean rainfall of any specified return period decreases markedly with increasing duration and so it is very important to specify the optimum duration of rainfall for design. When Equation (1) or (2) is used the optimum duration is the time taken for the maximum flow in a sewer to reach the design point* from the remotest part of the drainage area. This duration is called the time of concentration and is made up of the time of entry, i.e. the time for rain water to run over roof and road surfaces etc. before reaching the sewer, plus the time of flow through the sewers to the point at which the discharge is to be calculated. In general the larger the drainage area the longer the time of concentration, but other contributory factors include the size and gradient (slope) of the sewers and the type of land and its use. The time for rain water to run off an unpaved surface, such as school playing fields, is greater than the time required to run off a steeply sloping roof and through a short length of drain before arriving at a sewer. Formulae for computing the time of peak run-off and time of flow in the sewers were developed more than 50 years ago but as with rainfall the variability with time presents problems. Typically the time of concentration varies between a few minutes for a small residential estate to a few hours for a medium-sized town.

STORM PROFILES

Storm rainfall rarely falls at a uniform rate. The profile of rainfall intensity versus time, as in Figure 1, is commonly referred to as a storm profile. For drainage design purposes the storm profile is important because for a specified duration and total rainfall the storm with the greatest peak intensity, i.e. the sharpest profile, will often result in the greatest peak flow in the sewer. Also the

* Design point: point of outfall of all upstream sewers for the particular piece of pipe being designed.

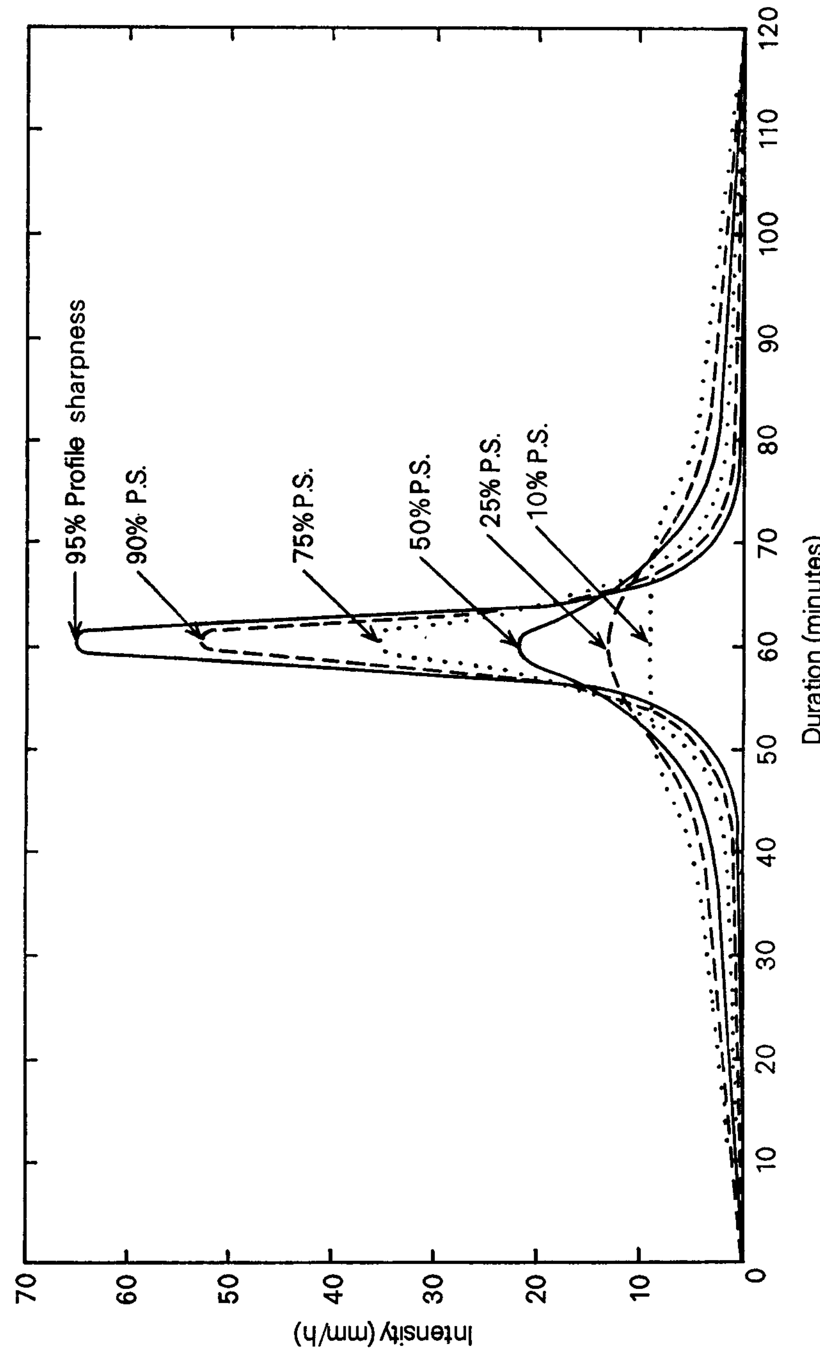

FIGURE 1—RANGE OF STORM PROFILES
(return period of one year)

variation of flow with time, i.e. the hydrograph, can only be investigated if the rainfall input is also allowed to vary in time as occurs in nature.

For a given storm duration and total rainfall there is an infinite variety of storm profiles. The variation is caused by the different rainfall types; for example, very sharp storm profiles of short duration (less than two hours) are usually associated with convective storm rainfall and flatter profiles with more continuous and less intense rainfall processes such as warm-front rain. The speed of movement of the rainfall system across the point or area and the local development and decay of rainfall intensity contribute to the shape of the storm profile. The research carried out in the Meteorological Office on the subject of storm profiles (*Flood Studies Report* (1975)) included a percentile analysis of profile sharpness. The results of this analysis apply to design storm profiles of any specified duration. The technique used by the Flood Studies research team ensures that all the storm profiles derived for design purposes are symmetrical about the mid point of the specified storm duration. A 90 per cent profile is one which is not exceeded in terms of sharpness of the storm profile shape on 90 per cent of occasions, where a numerical measure of sharpness is given by the ratio of maximum rainfall rate to mean rate over the whole duration of the storm. The 50 per cent profile is the median profile. Figure 1 shows some storm profiles at a given location for a fixed duration and return period. Figure 2 presents a range of 50 per cent profiles for the same location, and illustrates the fact that the shape of the profile is a function of the duration.

A design engineer is faced with some difficult problems if he wishes to use the results referring to the various shapes of the storm profile, for example how sharp should the storm profile be and what storm duration should be used. In practice an engineer generally opts for a simplified design technique. For example the RRL *Road Note* No. 35 (1963) storm sewer design technique uses the same storm profile for all locations, and although the rainfall changes with return period the shape and duration of the profile does not change. However, this approach assumes that variation of storm profile sharpness and storm duration are not important, which may not always be true.

A weakness of the storm profiles described in *Road Note* No. 35 (1963) is that the total rainfall in the two-hour period is varied according to the return period required, but no consideration is given to the probability of such a sharp storm profile occurring. Also there may be occasions when the optimum storm duration may be greater or less than two hours. These storm profiles simplify rainfall input since their construction assumes that one storm profile of specified return period is adequate for all pipe systems with a time of concentration of approximately two hours or less. This assumption stems from the *N*-year 10 minute rainfall being 'nested' in the *N*-year 15 minute rainfall and this in turn being nested in the *N*-year 30 minute rainfall, and so on up to 120 minutes.

The *Flood Studies Report* (1975) permits a design storm profile to be constructed to any predetermined specification and if the specification is not certain a variety of design storms can be constructed, all for a given return period. The best storm for a particular design purpose can then be determined by experiment.

The Meteorological Office and the Transport and Road Research Laboratory carried out a series of experiments with differently shaped storm profiles and concluded that there is a relationship between storm duration and the sharpness of the storm profile. In effect if the required once-in-*N*-year rainfall is distributed in time according to the median summer storm profile (50 per cent) then

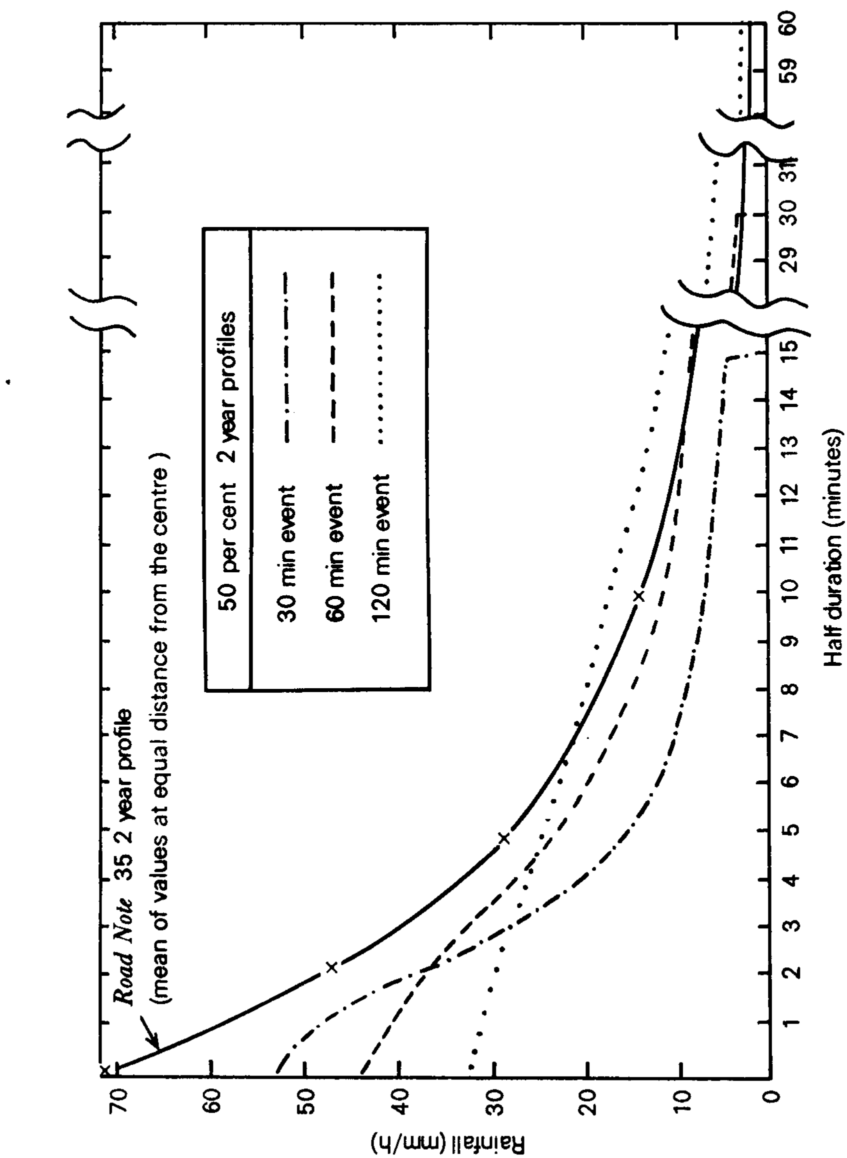

FIGURE 2—COMPARISON OF STORM PROFILES
(return period of two years)

the optimum (resulting in greatest peak flow) storm duration is between two and three times the time of concentration; for example the 60 minute storm should be used for a drainage scheme with time of concentration 20 to 30 minutes but the pipes lying far upstream should be designed using a shorter-duration storm or mean rainfall intensities applied by using the Rational Method. Figure 3 illustrates the application of this technique to a large urban surface water sewer system. The Institute of Hydrology (*Flood Studies Report*, Vol. 1 (1975)) also recommends a particular shape of storm profile (75 per cent winter profile) for river catchment studies with the storm duration determined from catchment characteristics and the total depth of rainfall determined by the specified return period.

Point to area rainfall relationships

The depth–duration frequency relationships for extreme rainfalls (twice-a-year and over) discussed earlier in this paper all refer to point rainfalls, i.e. to rainfall at a specific location, since they all derive from rain-gauge measurements. Invariably the design engineer requires information on areal rainfall rather than on point rainfall where typically the area may be an electricity generating station, an urban area, or a large river catchment.

Consider a particular river catchment with several rain-gauges suitably located to obtain a good estimate of the mean catchment rainfall. Some rainfall events will give little or no rain at a particular rain-gauge location even though the mean catchment rainfall is very large. Other rainfall occasions may result in an extremely high rainfall at the same rain-gauge location when the mean catchment rainfall is relatively low. However, for extreme rainfall events, for example once-a-year or rarer events, the N-year point rainfalls meaned over all rain-gauge locations will always be greater than or equal to the N-year catchment rainfall. This is because extreme rainfall events often affect only a limited part of a catchment and during the course of a year there are enough extreme rainfall events affecting different parts of the catchment to result in each point location's experiencing at least one rainfall that is greater than the greatest single rainfall event averaged over the whole catchment. This simplified explanation may not apply to a catchment with very varied rainfall characteristics, however, because in this case the N-year mean catchment rainfall may be greater than the N-year rainfall for some point locations in the generally drier part of the catchment; the practical application of the areal reduction factor (ARF) takes this into consideration.

The factor to be applied to the mean of the N-year point rainfalls to reduce it to the N-year catchment rainfall is commonly called an areal reduction factor (ARF). The spatial variability of rainfall is such that the ARF approaches unity as the size of area decreases. Also the spatial scale of storm rainfall generally increases with increasing duration, therefore for design storms the ARF approaches unity as the rainfall duration increases. Table II presents the relationship between the ARF, size of area and rainfall duration, as given in the *Flood Studies Report* (1975).

Every rainfall event affects an area rather than a point and the area–depth relationship is different in every case. The values of ARF in Table II present a statistical relationship between N-year point rainfalls and N-year areal rainfall events, where the geographical differences are accounted for by the differences in point rainfall values. Thus depth–duration-frequency statistics for areal rain-

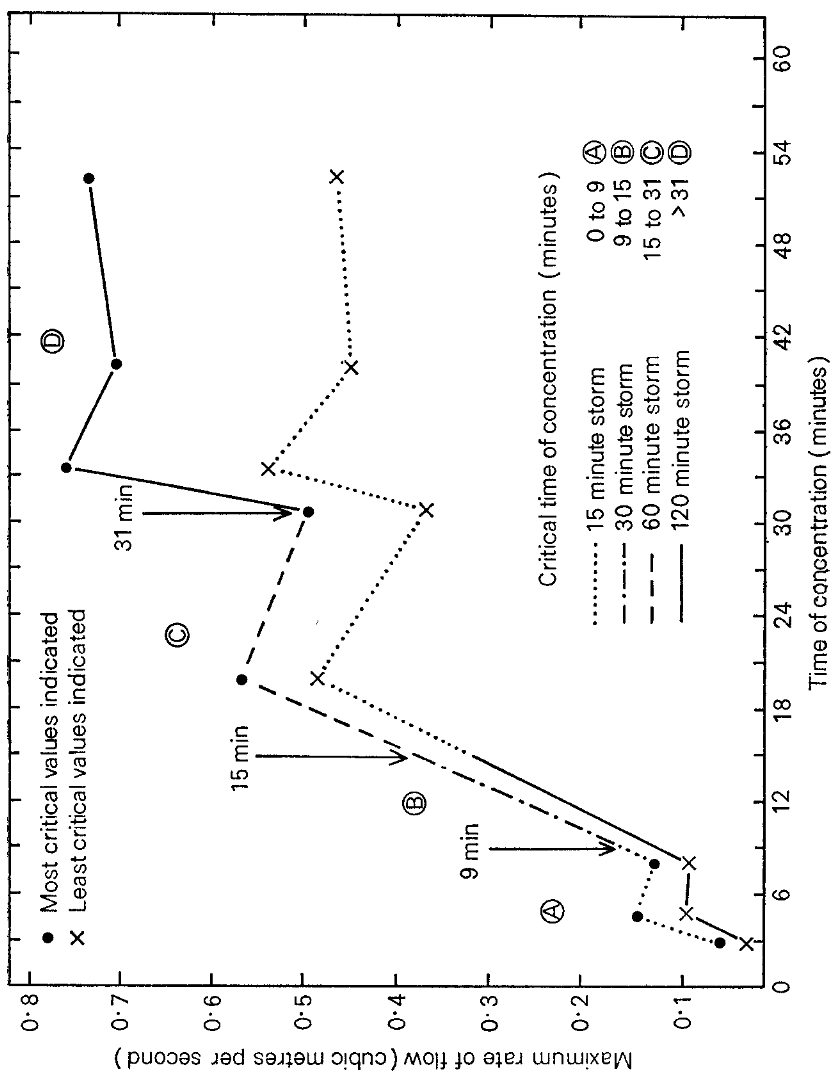

FIGURE 3—VARIATION OF FLOW RATES WITH TIME OF CONCENTRATION AND DURATION OF STORM EVENT

fall can be derived from the comprehensive statistics of point rainfall. An alternative approach using only areal rainfall factors to investigate areal rainfall statistics is not justified in view of the relatively limited data on extreme areal rainfall events compared with point rainfall measurements in many parts of the United Kingdom. Also the spatial variability of rainfall is such that in many instances areal rainfall cannot be adequately measured from the existing network of rain-gauges.

TABLE II—AREA REDUCTION FACTOR

	Area (km²)						
	1	5	10	30	100	300	1000
Duration (minutes)							
5	0·90	0·82	0·76	0·65	0·51	0·38	0·28
10	0·93	0·87	0·83	0·73	0·59	0·47	0·32
15	0·94	0·89	0·85	0·77	0·64	0·53	0·39
30	0·95	0·91	0·89	0·82	0·72	0·62	0·51
60	0·96	0·93	0·91	0·86	0·79	0·71	0·62
(hours)							
2	0·97	0·95	0·93	0·90	0·84	0·79	0·73
3	0·97	0·96	0·94	0·91	0·87	0·83	0·78
6	0·98	0·97	0·96	0·93	0·90	0·87	0·83
24	0·99	0·98	0·97	0·96	0·94	0·92	0·89

STORM MOVEMENT AND OTHER RAINFALL FACTORS

The models used for designing urban storm water sewer systems in the United Kingdom do not specifically take account of the dynamic effects associated with storms moving across the drainage catchment. The effect of storm movement is to complicate the sequence, and therefore the magnitude, of the peak flows in the various branches of the sewer system. The peak flows may be significantly increased if the storm rainfall movement is of comparable speed and direction to the flow in the sewer system. Speed of storm rainfall movement often exceeds 10 m/s, which reduces the possibility of movement significantly affecting the peak flow in the sewer, since the latter is generally less than 3 m/s. However, if there are preferred directions of storm rainfall movement then this may be important for some drainage purposes. Other rainfall factors such as shape and orientation of the rainfall area are relatively unimportant factors for urban drainage design criteria.

Many towns and cities in the United Kingdom have large recreational areas, and many have flood plains adjoining rivers and streams, wherein antecedent rainfall may be important for drainage design purposes through its effect on soil moisture and hence on rainfall run-off characteristics. The latter is a subject which is now being investigated at several establishments including the Institute of Hydrology, Bristol University and Imperial College, using statistical-empirical models, analytical models and physical models. Given a design rainfall, the surface run-off must be determined and then the actual flows in the sewer must be estimated. The latter is a problem of hydraulics and is being studied at the Hydraulics Research Station, Wallingford.

CONCLUSION

The rainfall depth, for a specified frequency and duration (approximately the time of concentration of the sewer system) is the most important single rainfall factor for design purposes. The location with respect to preferred areas of heavy short-duration rainfall is also important. Storm profiles represent the variation of rainfall in time and obviously this variability is significant since storm water sewers are designed to cope with peak flows rather than mean flows. The spatial variation of rainfall over a drainage area is dealt with statistically by applying an areal reduction factor.

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REVIEWS

The weather almanac (first edition), edited by J. A. Ruffner and F. E. Blair. 225 mm × 150 mm, pp. viii + 578, Gale Research Company, Book Tower, Detroit, Michigan, 1974. Price $17·50.

The major part of this Almanac describes the weather and climate of the United States of America. The averages and extremes of temperature and the averages of precipitation and sunshine are presented in a series of charts for the country as a whole and these are followed by sections describing the types of severe weather affecting various regions, hurricanes, tornadoes, winter storms, heat waves etc. Over one-half of the volume is devoted to detailed statistics for over 100 cities throughout the 50 States. Accompanying texts successfully highlight the principal features of the topographical situation and local climate of each city. The Almanac should appeal to the weather-conscious citizen who wishes to know the average conditions to be expected during a business journey or when on vacation. A comparatively short section entitled Round-the-World Weather contains basic temperature and rainfall statistics for some 500 locations outside the USA.

P. G. F. CATON

British weather disasters, by Ingrid Holford. 250 mm × 170 mm, pp. 127, *illus.*, David and Charles, Brunel House, Newton Abbot, Devon, 1976. Price £4·75.

This book is an attempt to gather together non-technical descriptions of some of the disasters resulting from weather action which have occurred in Britain over the last three centuries. The criteria for the selection of the events described are not stated or even implied, since although loss of life occurred in most of the cases discussed, one or two resulted merely in damage, albeit severe, to property or structures. Of the 39 events described, 30 are from the present century and 23 occurred after 1950, but this apparent bias towards more recent events is perhaps understandable in a book intended for the popular market. Press reports have been used extensively as the basis for the descriptions of the events from recent decades and many spectacular photographs of devastation accompany the text.

The earliest case described is one of lightning damage to the church at Widecombe-in-the-Moor, Devon, on 21 October 1638, and the latest one of local flooding at Surbiton in July 1973. Other notable rainfall flooding events described include the two events in southern England in 1968, the Lynmouth catastrophe of 1952 and the Norwich flood of 1912. The storm surge floods of 1928 and 1953 are discussed, as are the effects of the 1947 snowmelt floods. Occasions of severe wind damage in urban areas include the Sheffield gales of 1962 and the central Scotland gales of 1968. In most cases, the author presents a simple description of the synoptic development prior to the event, and then describes the damage caused and the effects on the unfortunate people involved.

A few errors were noted in the book. The date of the Tay Bridge collapse is consistently given as 1897, instead of 1879, and the diagram purporting to show calculated streamlines over the Pennines at the time of the Sheffield gales of 16 February 1962 relates, in fact, to 12 February.

The scientific content of this book will satisfy neither the professional meteorologist, concerned with understanding and possibly predicting extremes of weather, nor the professional engineer, concerned with establishing a rational and economic design standard. However, the human implications of weather disasters should be borne constantly in mind by both. Unless one has been personally involved with events of the kind described, the memory of such events soon fades, and so perhaps an important function of a book such as this is to act as a reminder to meteorologists, hydrologists and structural engineers that disasters continue to occur in Britain despite improvements in their technical skills.

J. S. HOPKINS

Note. That the wrong streamline diagram for the Sheffield gale was printed in *British Weather Disasters* was to a considerable extent the fault of the Meteorological Office who supplied the wrong original drawing of the diagram from *Geophysical Memoirs* Mo. 108. This drawing had been incorrectly annotated and the mistake was not discovered until the book was ready for publication.

(Editor)

The physics of atmospheric ozone, A. Kh. Khrgian, 245 mm × 175 mm, pp. v + 262, *illus.*, (translated from Russian by Israel Program for Scientific Translations, Jerusalem), John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1975. Price £13·25.

The book is a translation of a Russian original published in 1973. It sets out to give an historical review of all branches of research on ozone in the atmosphere, with the exception of its role in the ionosphere and in polluted urban atmospheres. The translation reads easily, though at least in one place transliteration into Cyrillic script and back again has transformed Århus into Orkhus. The technical description of instruments clearly presents problems for a translator, and it is not clear whether it was during translation into Russian or back into English that 'phosphor' became 'phosphorus' (p. 48) and 'sputtering' became 'spraying'.

There is little doubt that the Russian original provided a useful background for workers entering the sphere of ozone research after the upsurge of interest which followed the assertion in 1971 that oxides of nitrogen in the exhaust of stratospheric aircraft could damage the ozone layer. There is, however, no mention of this in the text and the only extension of the Chapman oxygen-only photochemical model to find a place is the inclusion of odd hydrogen species OH and HO_3. The latest of the 436 references is dated 1970.

While the book is an historical review, it has a typically eastern lack of historical perspective. All authors are equally in the foreground of the picture. Thus one is left at the end of Chapter V with the impression that the only significant measurements of ozone in the troposphere are those of Kay in 1952–53 and Britaev in 1960–61, quite ignoring the wealth of data available from the lower portions of stratospheric ozonesonde ascents. This particular instance is due in part to the author's distrust of ozonesondes in the troposphere, which he states without justification in Chapter VIII (p. 147). Elsewhere the tendency is to accept all authors and data uncritically.

The units used in ozone research have varied over the years, depending on the starting point of the authors' interests, and the inclusion of a section on units in Chapter III is very useful. The author points out that the reduced thickness of ozone per kilometre of atmosphere (expressed in 10^{-3} cm/km) is in fact a measure of ozone (partial) density, and gives the equivalent in μg m^{-3}. He then, astonishingly, says it is a volume mixing ratio of 10^{-8}, and is abbreviated pp h m.

Notwithstanding the probable usefulness of the Russian original, this translation is now little more than a comprehensive review of ozone literature prior to 1971, and as such is of only limited use to anyone engaged in ozone studies in the late 1970s.

E. L. SIMMONS

CORRECTION

Meteorological Magazine, March 1977, p. 91. After end of 'The Meteorological Magazine 1866–1977' article, add

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	1938	*Met Mag*, **73**, pp. 165–168.

OBITUARIES

It is with regret that we have to record the death on 9 December 1976 of Mr R. R. Webb, Assistant Scientific Officer, Port Meteorological Office, Southampton, and on 27 January 1977 of Miss J. C. Perfect, Higher Scientific Officer, Met O 11.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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THE 1975/76 DROUGHT OVER THE UNITED KINGDOM—HYDROMETEOROLOGICAL ASPECTS

By R. MURRAY

SUMMARY

Some outstanding features of the rainfall deficiency over the United Kingdom from May 1975 to August 1976, notably the 16 month period of rainfall deficiency which was unprecedented over England and Wales as a whole since records began in 1727, are discussed. The patterns of change of evaporation, including transpiration, and soil moisture deficit during the summer half-years of 1975 and 1976 are compared.

The abnormal dryness, which led to severe difficulties in water supply in many parts of England and Wales and to agricultural droughts in the summers of 1975 and 1976, came to an end with heavy rain in some areas, mainly in southern Britain, in the last few days of August and nearly everywhere else around 10 September 1976.

1. INTRODUCTION

Miles (1977) has described various features of the atmospheric circulation over the northern hemisphere, particularly over the Atlantic–European sector, over many months. He has pointed out that abnormally high surface pressure occurred over and near southern Britain during much of 1975 and 1976. As part of the abnormal atmospheric circulation much more dry anticyclonic weather than usual occurred over a wide area centred on southern Britain during the period from May 1975 to August 1976. As a consequence of the anomalous meteorological patterns, a prolonged and marked rainfall deficiency developed in most parts of Britain. The deficiency of rainfall, combined with the loss of water by considerable evaporation and transpiration during the two very warm, sunny summers of 1975 and 1976 led to shortages of water for general use, that is, to drought conditions.

Drought can be defined objectively in numerous ways to suit particular purposes and different climates. A WMO *Technical Note* (1975) discussed, *inter alia*, the classification of droughts. More recently Tabony (1977) presented arguments for the use of indices which differentiate between meteorological drought, agricultural drought and hydrological drought, and he employed these indices to rank the different types of drought at Kew. Whatever objective indices might be used to classify droughts, it has long been recognized that the root cause of drought is a rainfall deficiency of considerable duration and that there is a difference between hydrological drought and agricultural drought. Over the United Kingdom, reservoirs, lakes and aquifers are normally replenished by rainfall in the winter half-year when evaporation is low; if rainfall is sufficiently below average, surface water and ground water reserves may be inadequate for all requirements during the summer half-year and the drought may be termed a hydrological drought. On the other hand a drought in the growing season, i.e. in the summer half-year, when the loss of water to the atmosphere by evaporation and transpiration is generally greater than the total rainfall, may be called an agricultural drought.

The demand for water is such that water managers become very concerned when rainfall is substantially deficient over the winter half-year especially if the preceding seasons have been drier than usual. On the other hand most farmers want dry weather in the winter half-year, since many farming operations are difficult or even impossible in wet winter months when the ground may be waterlogged. This article presents a description of the rainfall patterns over the United Kingdom and draws attention to some features of evaporation (transpiration) and soil moisture deficits during the drought period. These hydrometeorological aspects, which result from essentially meteorological causes, are only part of the hydrological cycle. However, they are important parts of the drought story for the water industry, as well as to the scientist.

2. Some rainfall features

Figure 1 shows the sequence of monthly rainfall as percentages of average for England and for Wales from December 1974 to October 1976. A wet autumn in 1974 was followed by mainly wet months (apart from February 1975) to April 1975. In the subsequent period, up to August 1976, the monthly rainfall in each country was markedly below average for 13 months out of 16 months—rainfall was above average in July 1975, well above average in September 1975 and near average in May 1976. The dramatic change from the exceptionally dry summer month of 1976 to the remarkably wet autumn months stands out. The England and Wales rainfall for the two month period September and October 1976 was 313 mm, a figure never previously reached in the 250 years of the England and Wales rainfall series; the next highest rainfall for the same two month period was 310 mm in 1903. From a hydrological point of view the drought can be said to have started in May 1975 and ended in September 1976. From an agricultural point of view there was a drought in the summer of 1975 and an even more notable one in summer 1976.

The monthly rainfall sequence for Scotland and for Northern Ireland, shown in Figure 2, is broadly similar to those for England and for Wales throughout 1975; however, much more rainfall variability on a monthly time-scale is in evidence in Figure 2 than in Figure 1 during the winter and spring of 1976 when January, March and May were wet months over Scotland and Northern Ireland. The dry summer and wet autumn sequence in 1976 was broadly similar over England, Wales, Scotland and Northern Ireland.

The spatial distribution of the rainfall pattern over the United Kingdom for the 16 months from May 1975 to August 1976 is depicted in Figure 3, where it is seen that the main rainfall deficiency (50 to 60 per cent of average) extends from southern parts of England to Yorkshire, but all regions except north-west Scotland experienced rainfall less than or equal to 90 per cent of average. The most intense period of the drought was from June to August 1976 and Figure 4 shows the rainfall patterns for summer 1976. Most of the United Kingdom experienced less than 60 per cent of average rainfall, with some localities in England and Wales having less than 20 per cent.

In Table I is shown the rainfall (as percentages of average) for the UK and for individual countries of the UK for various periods from 3 to 18 months ending in August 1976. Rainfall was clearly deficient in all countries for each of the specified periods, with the lowest percentages of rainfall for England and Wales. Over England and Wales combined the rainfall was slightly less in the 3 month period June to August in 1800 than in 1976, and in the 6 month period March to August in 1741 than in 1976, but for the other periods shown in Table I the rainfall over England and Wales was the lowest on record for the 9, 12, 15, 16 and 18 month periods with return periods of at least 250 years. On the other hand, over Scotland the rainfall was very much less remarkable in each of the periods from 6 to 18 months, although the summer (June to August) 1976 was the second driest since 1869.

TABLE I(a)—RAINFALL, AS PERCENTAGE OF AVERAGE (1916–50), FOR VARIOUS PERIODS FROM 3 TO 18 MONTHS ENDING IN AUGUST 1976 OVER PARTS OF AND THE WHOLE OF THE UNITED KINGDOM

	3 months June 76 –Aug. 76	6 months Mar. 76 –Aug. 76	9 months Dec. 75 –Aug. 76	12 months Sept. 75 –Aug. 76	15 months June 75 –Aug. 76	16 months May 75 –Aug. 76	18 months Mar. 75 –Aug. 76
United Kingdom	41	64	68	74	73	73	76
England and Wales	35	52	55	63	63	64	70
England	37	52	55	63	63	64	70
Wales	27	50	57	64	64	64	68
Scotland	48	79	83	86	85	83	84
Northern Ireland	48	74	74	80	76	73	75

TABLE I(b)—ESTIMATED AVERAGE FREQUENCY OF OCCURRENCE (ONCE IN *N* YEARS) OF RAINFALL PERCENTAGES FOR ENGLAND AND WALES AND FOR SCOTLAND SPECIFIED IN TABLE I(a)

Number of years = 250 for England and Wales and 108 for Scotland.

	3 months June 76 –Aug. 76	6 months Mar. 76 –Aug. 76	9 months Dec. 75 –Aug. 76	12 months Sept. 75 –Aug. 76	15 months June 75 –Aug. 76	16 months May 75 –Aug. 76	18 months Mar. 75 –Aug. 76
				N years			
England and Wales	125	125	$\geqslant 250$	$\geqslant 250$	$\geqslant 250$	$\geqslant 250$	$\geqslant 250$
Scotland	54	8	8	4	4	6	6

Table II lists the 10 driest spells over England and Wales since 1820 for various periods from 3 to 24 months. In this table the spells of the same duration are non-overlapping, but they are not restricted to beginning with a particular month. The recent drought was unprecedented for periods of 12, 16 and 18 months irrespective of starting month. For 3 and 24 months the rainfall totals during the recent drought were not the minima which have been recorded for comparable periods since 1820, except when comparisons are made with other 3 month periods starting in June, and with other 24 month periods starting in September. It is interesting to note in Table II that two separate or non-overlapping 24 month periods, one beginning in July 1972 and the other in September 1974, are in the top 10, thus emphasizing the dryness of the past 5 years.

TABLE II—ENGLAND AND WALES RAINFALL: 10 DRIEST PERIODS OF DURATION FROM 3 TO 24 MONTHS SINCE 1820

(starting date and rainfall totals given)

	3 months		*mm*	6 months		*mm*	12 months		*mm*
1	1938	Feb.	56	1921	Feb.	179	1975	Sept.	570
2	1929	Feb.	71	1976	Mar.	204	1854	Feb.	618
3	1893	Mar.	71	1887	Feb.	221	1920	Nov.	618
4	1868	May	74	1929	Jan.	230	1887	Feb.	624
5	1854	Feb.	74	1870	Apr.	241	1963	Dec.	637
6	1976	June	76	1826	Mar.	249	1933	Apr.	651
7	1844	Apr.	77	1893	Mar.	256	1857	Dec.	661
8	1947	Aug.	82	1959	Apr.	261	1904	Mar.	667
9	1963	Dec.	83	1896	Jan.	263	1955	July	670
10	1921	May	88	1939	Feb.	264	1863	Nov.	673
	16 months		*mm*	18 months		*mm*	24 months		*mm*
1	1975	May	756	1975	Mar.	908	1853	Oct.	1439
2	1854	Feb.	811	1853	Dec.	933	1932	Nov.	1439
3	1933	Apr.	855	1887	Jan.	997	1862	Nov.	1461
4	1887	Feb.	857	1933	Apr.	1003	1887	Feb.	1493
5	1920	Aug.	880	1873	Feb.	1031	1974	Sept.	1496
6	1873	Apr.	899	1857	Dec.	1032	1972	July	1497
7	1857	Nov.	907	1863	Feb.	1043	1904	Oct.	1507
8	1943	Feb.	909	1943	Feb.	1044	1857	Feb.	1512
9	1963	Dec.	920	1963	Dec.	1047	1920	Aug.	1513
10	1869	June	928	1921	Jan.	1061	1947	Aug.	1520

3. EVAPORATION AND SOIL MOISTURE ASPECTS

Drought is naturally linked to excessive evaporation from water surfaces and transpiration from grass, plants and forests as well as to prolonged rainfall deficiency. Evaporation and transpiration are generally almost negligible in midwinter and reach a maximum in the summer months in the United Kingdom. In the 16 month period of rainfall deficiency from May 1975 to August 1976 there were two summers (June to August) which were predominantly dry, warm and sunny over most of England and Wales. The summer of 1976 was the drier, warmer and sunnier of the two fine summers. The exceptional warmth of summer 1976 may be seen from the anomalies of mean daily maximum temperature for the 3 month period June to August in Figure 5: particularly noteworthy are the remarkably large anomalies of +4°C or more from Devon to Cambridgeshire. The exceptional sunshine of summer 1976 is shown in Figure 6.

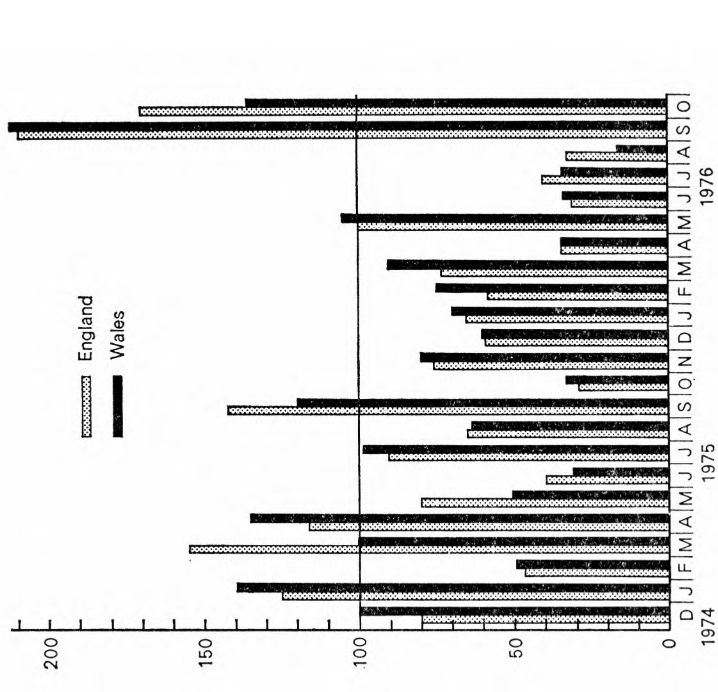

FIGURE 1—MONTHLY RAINFALL, AS PERCENTAGE OF AVERAGE (1916–50), FROM DECEMBER 1974 TO OCTOBER 1976 OVER ENGLAND AND WALES

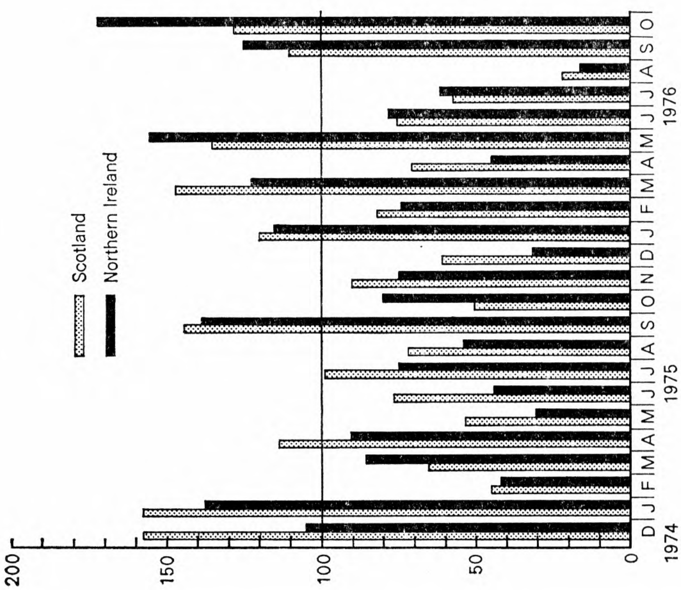

FIGURE 2—MONTHLY RAINFALL, AS PERCENTAGE OF AVERAGE (1916–50), FROM DECEMBER 1974 TO OCTOBER 1976 OVER SCOTLAND AND NORTHERN IRELAND

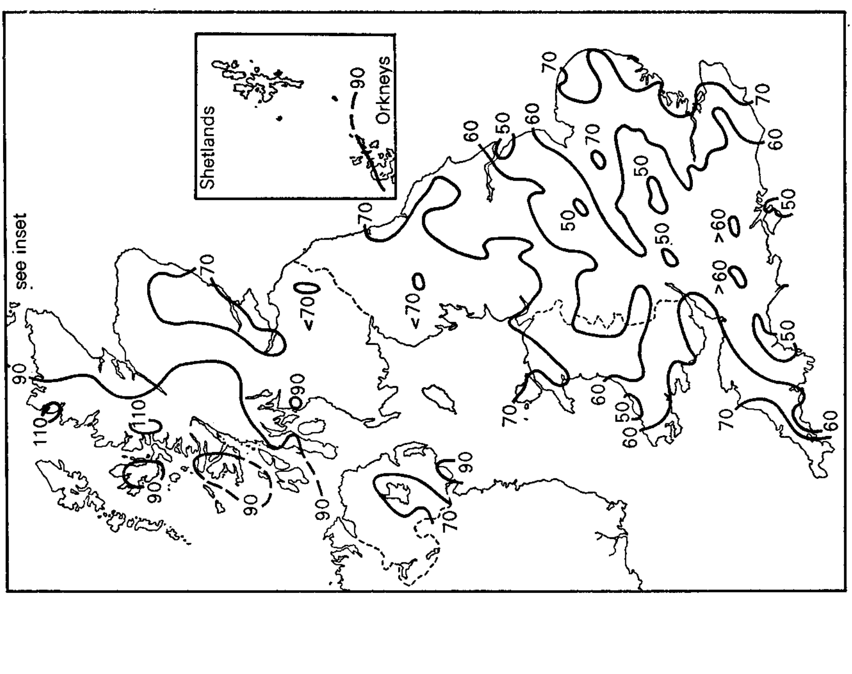

FIGURE 3—RAINFALL, AS PERCENTAGE OF AVERAGE (1916–50), FOR THE 16 MONTH PERIOD FROM MAY 1975 TO AUGUST 1976 OVER THE UNITED KINGDOM

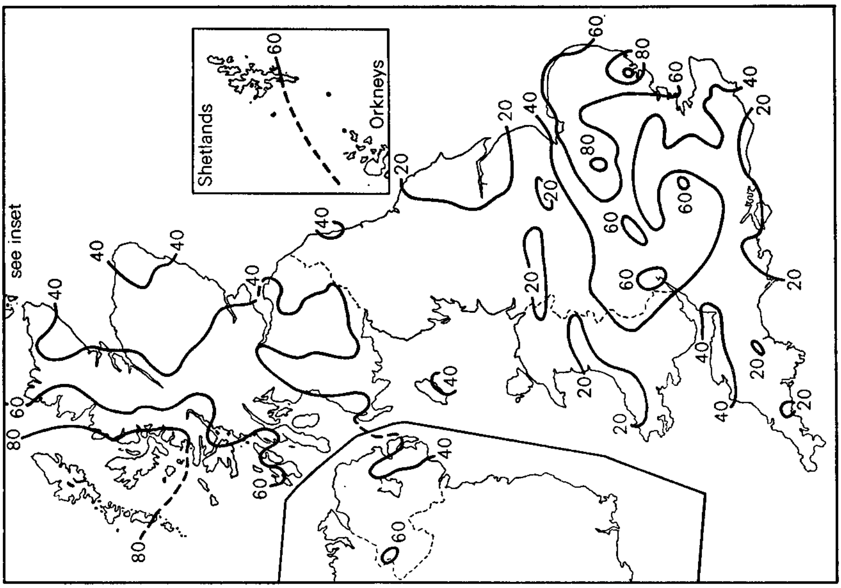

FIGURE 4—RAINFALL, AS PERCENTAGE OF AVERAGE (1916–50), FOR SUMMER (JUNE TO AUGUST) 1976 OVER THE UNITED KINGDOM

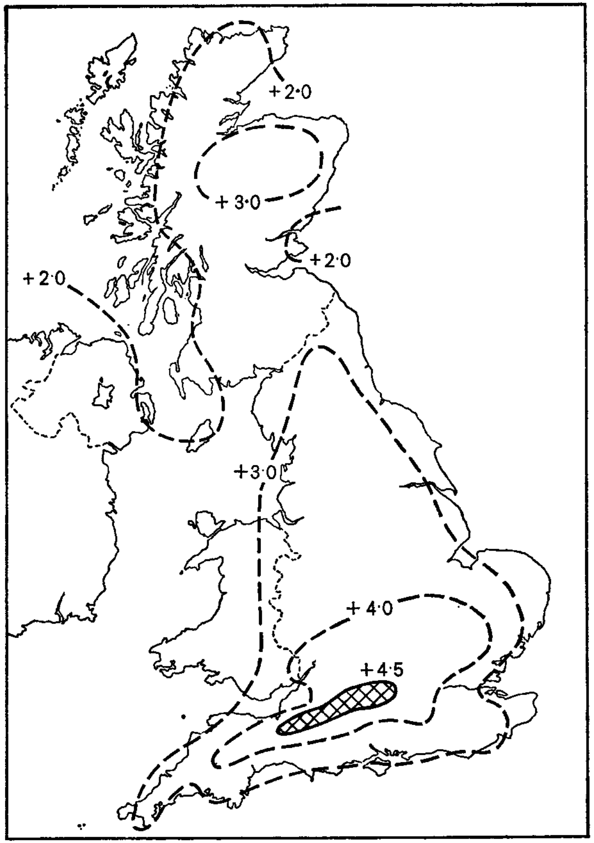

FIGURE 5—DEPARTURE FROM AVERAGE (1941–70) OF MEAN DAILY MAXIMUM TEMPERATURE FOR SUMMER (JUNE TO AUGUST) 1976 OVER THE UNITED KINGDOM

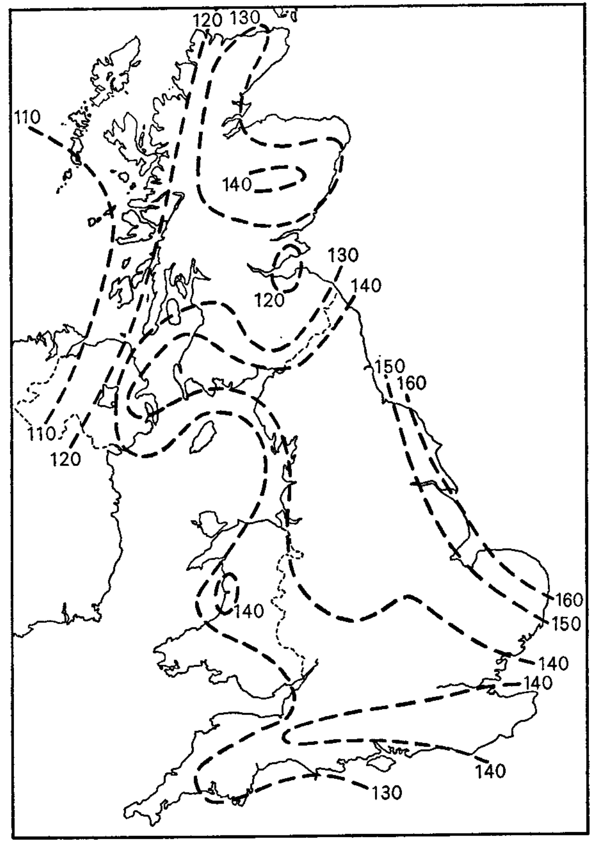

FIGURE 6—SUNSHINE DURATION AS PERCENTAGE OF AVERAGE (1941–70) FOR SUMMER (JUNE TO AUGUST) 1976 OVER THE UNITED KINGDOM

There were notable differences in the way in which soil moisture deficits* developed during the spring and summer months in 1975 and 1976. For instance, in the routine issue of the Meteorological Office SMD Bulletin for 23 April 1975 (not shown) the SMD estimates, using the grassland model as described by Grindley (1967), were small (0 to 12 mm) everywhere, largely because the preceding six months were somewhat wetter than usual. The warm dry weather which set in during May 1975 over much of England Wales, followed by a preponderance of warm dry and sunny weather in the summer, led to the development of large soil moisture deficits in England by the end of August, as may be seen in Figure 7, although deficits were mostly unremarkable in Scotland. In most years deficits generally disappear at some time during the autumn or early winter months, but following the fine summer of 1975, the autumn and winter were drier than usual and soil moisture deficits were slow to disappear, so that even by mid-February 1976 there were still small areas which were not yet at field capacity in eastern England (Figure 8). Largely as a result of the dry March and April, deficits soon began to increase again, much earlier than usual over England, so that deficits on 21 April 1976 (see Figure 9) were already larger than usual for the time of the year in much of the south, east and central parts of England, where they were mostly 25–50 mm in marked contrast with the very small deficits about the same time in April 1975. Even larger deficits built up in summer 1976 than in the previous summer; the deficits on 25 August 1976 (see Figure 10) were large everywhere in Britain, and they were near the extreme values possible in most of England. Despite the large and extensive deficits which were in existence late in August 1976, the exceptionally wet September and October brought the soil to capacity over most of Britain before the end of October 1976, much earlier than usual.

The pattern of change in evaporation (including transpiration) and soil moisture deficit during the two summers will now be described in more detail for a few representative places, using a grassland model. Figure 11 shows the end-of-month estimates of actual and potential evaporation (including transpiration)—AE and PE—at Exeter in 1975 and 1976. PE estimates, based essentially on the theory of Penman (1948), assume that moisture is non-limiting. AE is frequently and typically less than PE in the summer, when soil moisture deficits have increased sufficiently. Figure 11 shows that by the end of June 1975 there was a large difference between PE and AE and this difference remained until September. In 1976 there was already a difference between PE and AE at the end of May, and in June, July and August the difference was near the maximum possible for the grassland model, and, moreover, AE was very small. Grass and other short-rooted vegetation became essentially desiccated during this period since there was virtually no moisture in the topsoil, and little or no transpiration was possible. The position changed abruptly by the end of September 1976. A similar diagram (Figure 12) for Wyton in Cambridgeshire shows essentially the same patterns in the time-sequence of PE and AE as at Exeter.

* The soil is at field capacity when it holds the maximum amount of water by surface tension and capillary action against gravity. The maximum amount of water retained at field capacity and also the part of this water which can be extracted from the soil by vegetation is a function of both soil and crop type. A soil moisture deficit (SMD) develops where any extraction of water from the soil by evaporation or transpiration is not compensated by rainfall or irrigation. The soil moisture deficit is in effect the amount of water needed to restore the soil to field capacity (i.e. to zero deficit).

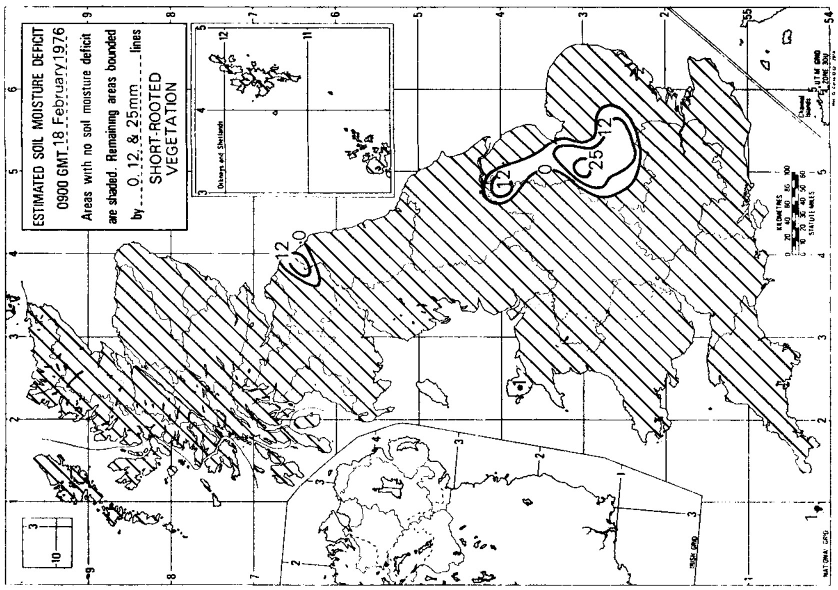

FIGURE 8—ESTIMATED SOIL MOISTURE DEFICIT (mm) (SHORT-ROOTED VEGETATION MODEL) ON 18 FEBRUARY 1976 IN BRITAIN

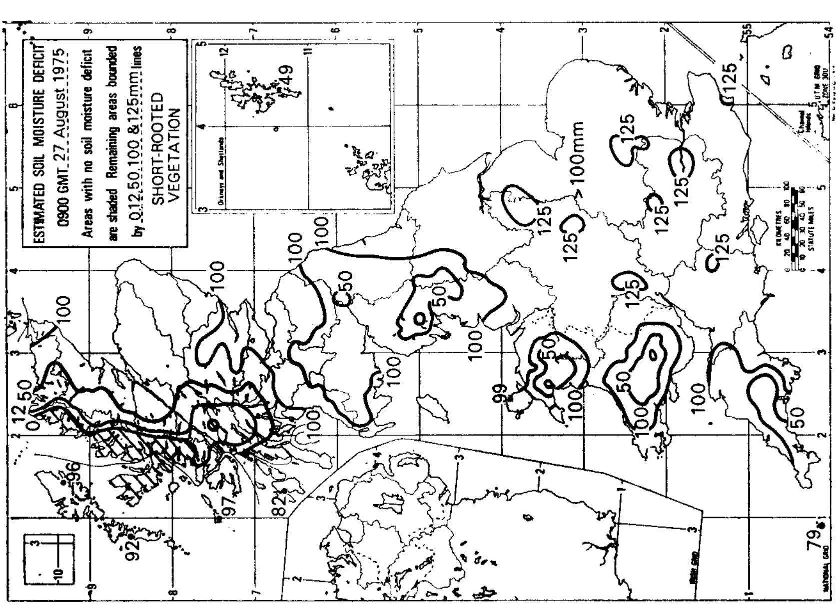

FIGURE 7—ESTIMATED SOIL MOISTURE DEFICIT (mm) (SHORT-ROOTED VEGETATION MODEL) ON 27 AUGUST 1975 IN BRITAIN

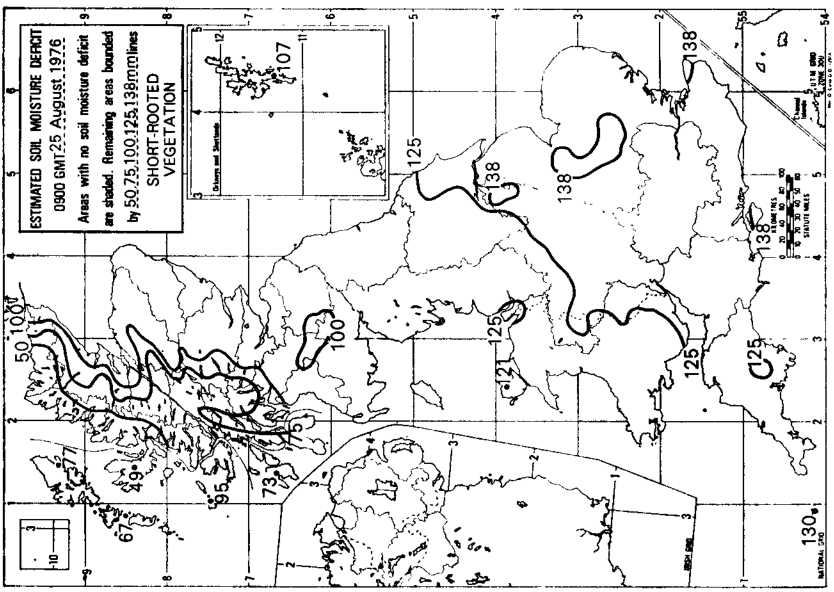

FIGURE 10—ESTIMATED SOIL MOISTURE DEFICIT (mm) (SHORT-ROOTED VEGETATION MODEL) ON 25 AUGUST 1976 IN BRITAIN

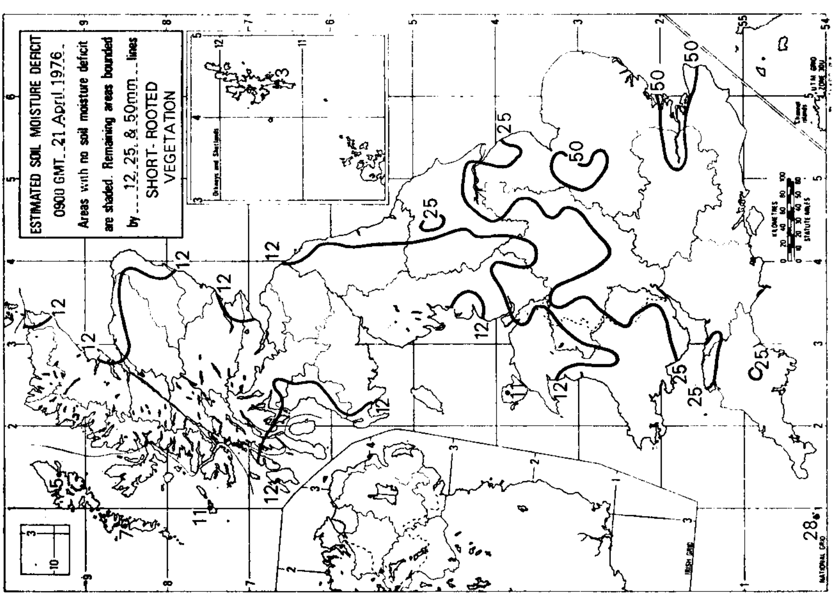

FIGURE 9—ESTIMATED SOIL MOISTURE DEFICIT (mm) (SHORT-ROOTED VEGETATION MODEL) ON 21 APRIL 1976 IN BRITAIN

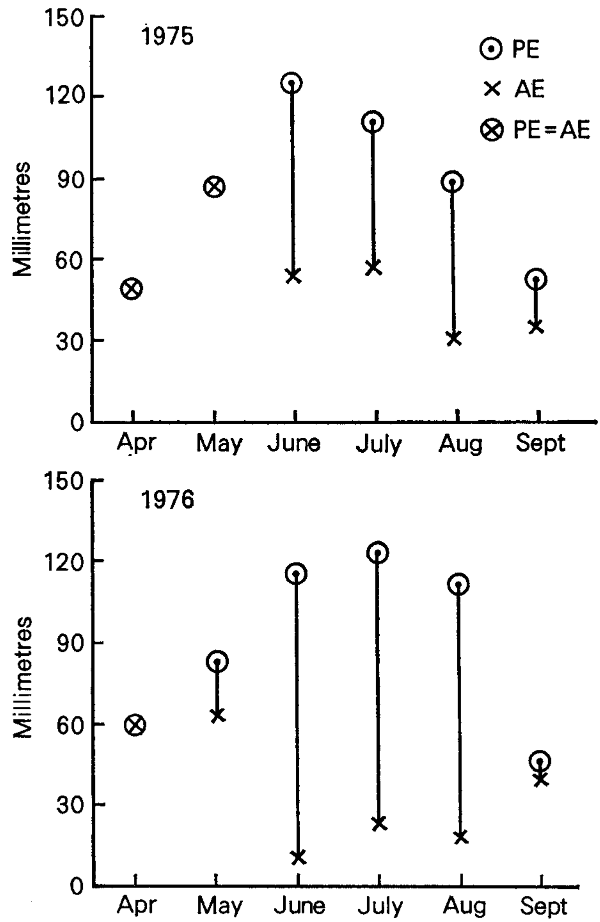

FIGURE 11—MONTHLY TOTALS (mm) OF POTENTIAL AND ACTUAL EVAPORATION (PE AND AE) (SHORT-ROOTED VEGETATION MODEL) AT EXETER FROM APRIL TO SEPTEMBER IN 1975 AND 1976

The contrast between the behaviour pattern of evaporation (including transpiration) at Plymouth and Carlisle may be seen readily in Figures 13 and 14 for 1975 and 1976 respectively. The histograms show weekly totals of PE and AE from April to September. The picture in 1976 (Figure 14) shows a very striking contrast between the two places. At Carlisle AE was clearly not seriously restricted until late July and August. On the other hand at Plymouth AE was already noticeably less than PE in May and the difference between them was pronounced from May to August. AE from short-rooted vegetation is estimated to have been almost negligible for five weeks from late July to near the end of August.

For the same stations (Plymouth and Carlisle) the soil moisture deficits, both actual SMD and potential SMD, varied throughout 1975 as shown in Figure 15. At Plymouth both types of SMD were greater than at Carlisle. This was also true in 1976, but there were other notable features (see Figure 16). At Plymouth

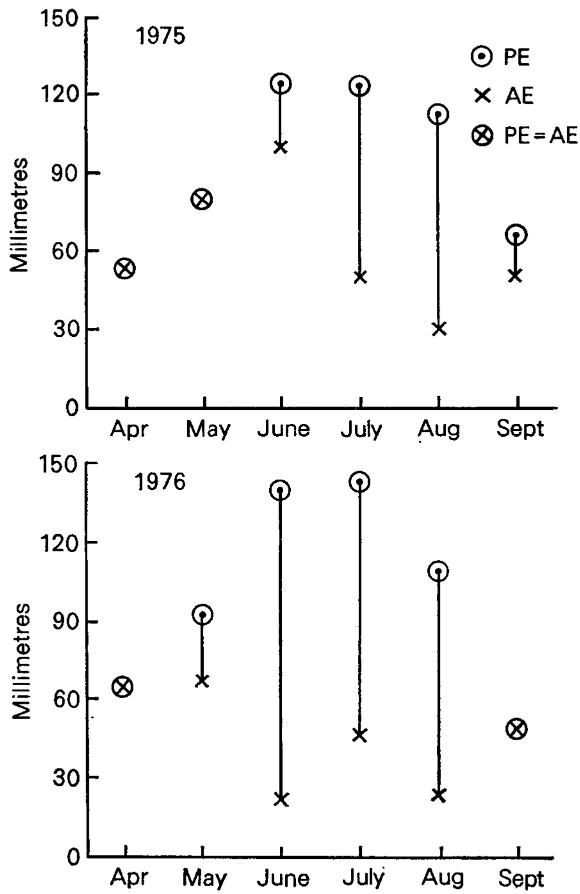

FIGURE 12—MONTHLY TOTALS (mm) OF POTENTIAL AND ACTUAL EVAPORATION (PE AND AE) (SHORT-ROOTED VEGETATION MODEL) AT WYTON FROM APRIL TO SEPTEMBER IN 1975 AND 1976

in 1976 actual SMD was between 100 mm and 130 mm from the beginning of June to mid-September and potential SMD increased to a maximum of nearly 400 mm at the end of August. At Carlisle actual and potential SMD did not markedly diverge until late July. The agricultural drought in 1976 was clearly neither as intense nor as prolonged at Carlisle as at Plymouth.

4. GENERAL

The beginning and ending of a drought are not often clear-cut and depend on the definitions used. In this article it is not possible, and probably not profitable, to attempt to pin-point the beginning, temporary interruption and the ending of the meteorological, agricultural and hydrological droughts in great detail in different parts of the United Kingdom. It is sufficient to give some broad indications. In this instance it is evident that the various types of drought were

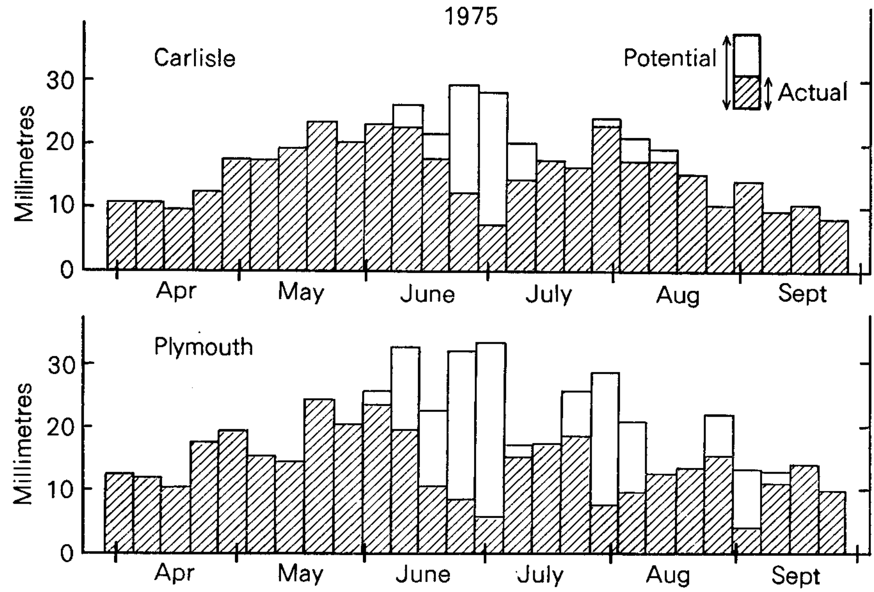

FIGURE 13—WEEKLY TOTALS (mm) OF POTENTIAL AND ACTUAL EVAPORATION (GRASSLAND MODEL) AT PLYMOUTH AND AT CARLISLE FROM APRIL TO SEPTEMBER 1975

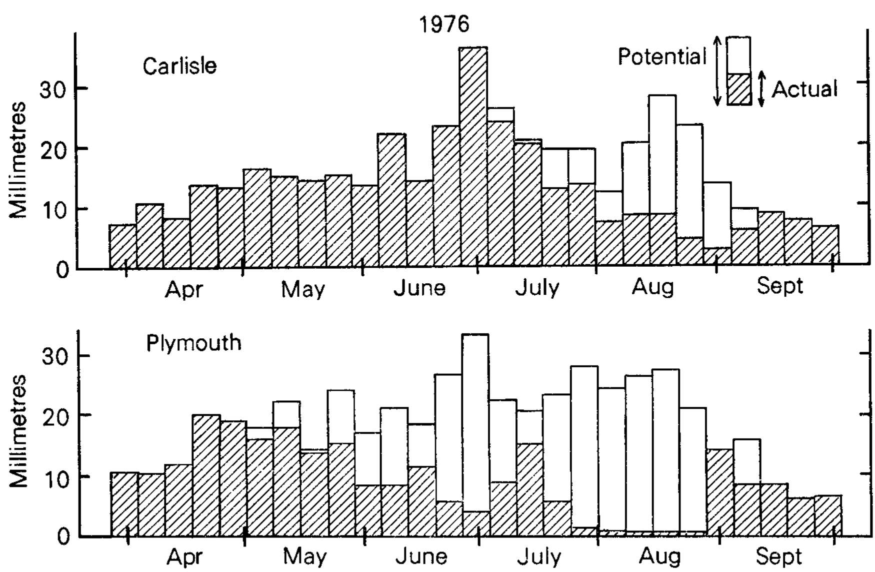

FIGURE 14—WEEKLY TOTALS (mm) OF POTENTIAL AND ACTUAL EVAPORATION (GRASSLAND MODEL) AT PLYMOUTH AND AT CARLISLE FROM APRIL TO SEPTEMBER 1976

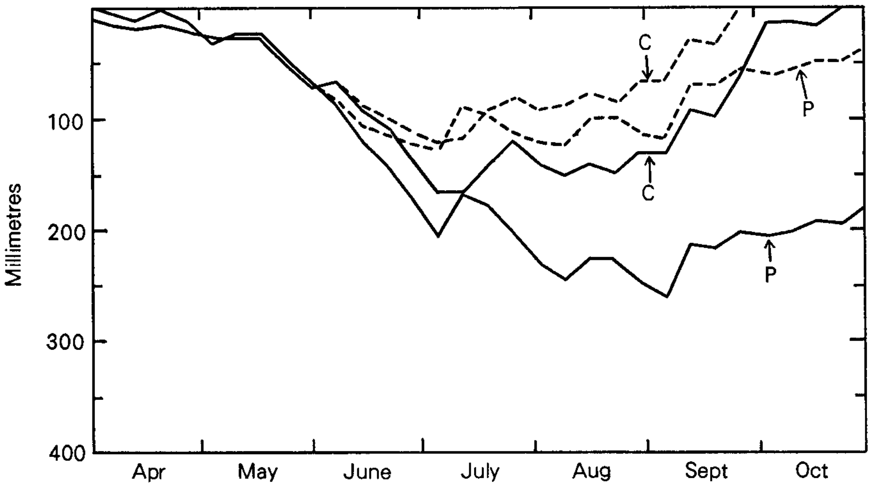

FIGURE 15—ACCUMULATED POTENTIAL AND ACTUAL SOIL MOISTURE DEFICITS (GRASSLAND MODEL) AT PLYMOUTH AND AT CARLISLE FROM APRIL TO OCTOBER 1975

P ——— Plymouth potential
P - - - - Plymouth actual
C ——— Carlisle potential
C - - - - Carlisle actual

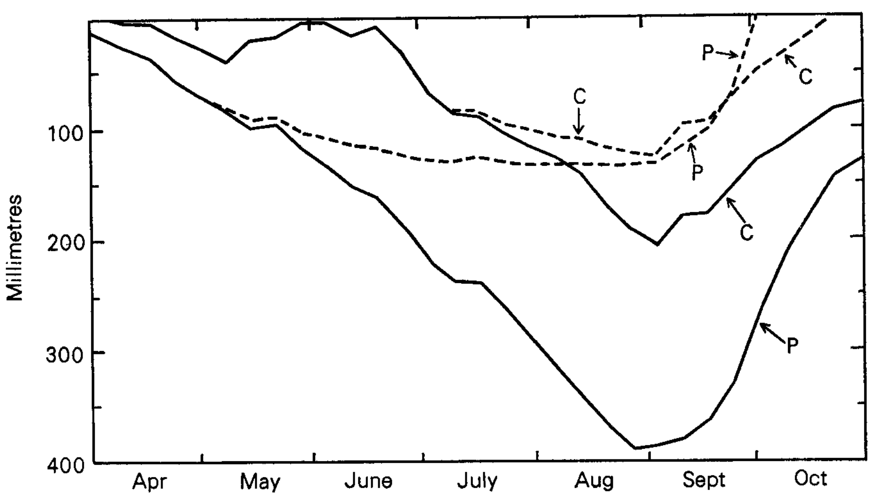

FIGURE 16—ACCUMULATED POTENTIAL AND ACTUAL SOIL MOISTURE DEFICITS (GRASSLAND MODEL) AT PLYMOUTH AND AT CARLISLE FROM APRIL TO OCTOBER 1976

P ——— Plymouth potential
P - - - - Plymouth actual
C ——— Carlisle potential
C - - - - Carlisle actual

certainly over, on the monthly time-scale and nation-wide, in September 1976, as clearly indicated by the rainfall patterns shown in Figures 1 and 2.

The ending of the main meteorological drought of the summer of 1976 occurred in the last few days of August in most parts of the United Kingdom. It was in fact rainless over much of England and Wales for several weeks in the latter part of July and most of August. In particular it was dry in many parts of South Wales, south-west and southern England for 35 to 42 days until rain was recorded on 27, 28 or 29 August. For instance, a remakable run of 42 dry days at Thorney Island (Hampshire) and Newhaven (East Sussex) ended with rain on the 27th, although the rainless spells were broken at most other places one or two days later. It again became dry nearly everywhere for about a week from 2 September, but the main meteorological drought can, with hindsight, be said to have ended in most parts in the last five days of August.

For hydrological purposes the Meteorological Office prepares soil moisture deficit maps on the basis of composite land-use in which it is assumed that any unit area consists of 50 per cent short-rooted vegetation, 30 per cent long-rooted vegetation and 20 per cent riparian. This over-simplified land-use assumption is expected to be superseded by more realistic land-use information in the near future. However, using the composite model currently in operational use, estimates of the first dates on which significant rainfall became effective for hydrological purposes were made by taking the difference between rainfall and estimated evaporation, after soil moisture deficit had been eliminated. The end of the hydrological drought is here taken arbitrarily as the dates when 5 mm of hydrologically effective rainfall (as defined) were computed to have occurred. Figure 17 shows the estimated dates of the ending of hydrological drought. The heavy rains near the end of August may be said to have broken the hydrological drought on 28–29 August over a band from south-east Wales to Norfolk, but most other places did not have significant hydrologically effective rainfall until around 10 September and a few places lasted out until early October.

The estimated accumulations of hydrologically effective rainfall (on the basis of the composite 3 tier land-use model) are shown in Figure 18. It is evident that there were large accumulations of hydrologically effective rainfall at the end of October 1976 over northern England, Wales and south-west England, with estimates of over 300 mm in some hilly areas. Meteorologists are well aware of the complexity of the hydrological problem in relation to the crudity of the existing operational soil moisture deficit model and the paucity of data, so that the details in Figure 18 have considerable uncertainty, although the broad picture is unlikely to be far from the truth. It is not surprising, in the light of the estimates in Figure 18, that the very low water levels in reservoirs in most drought-stricken areas late in August 1976 rose rapidly, particularly in Wales, south-west and north England, and also that flooding followed so closely on the heels of the drought in many places.

The effect of drought on agriculture depends in a complex way on many factors, including plant-type, state of crop, root-depth, soil-type, etc: the effectiveness of rainfall in ending agricultural drought also depends on many factors. Breaks in a long agricultural drought can occur fairly easily, especially with some short-rooted vegetation which may benefit almost immediately after the onset of significant rainfall. However, late in the growing season, when transpired moisture normally decreases, drought can be considered to have come

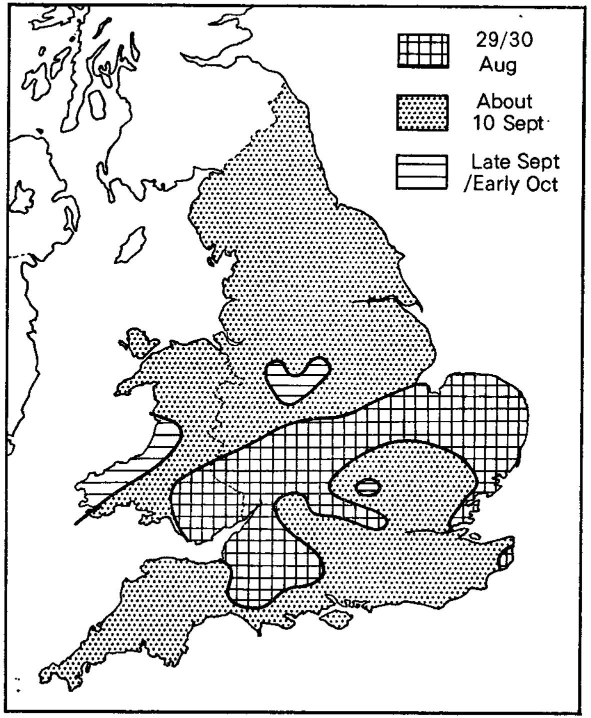

FIGURE 17—ESTIMATED DATE OF END OF 1975/76 DROUGHT IN ENGLAND AND WALES: DATE BY WHICH EFFECTIVE RAINFALL ACCUMULATED TO 5 mm (COMPOSITE LAND-USE MODEL)

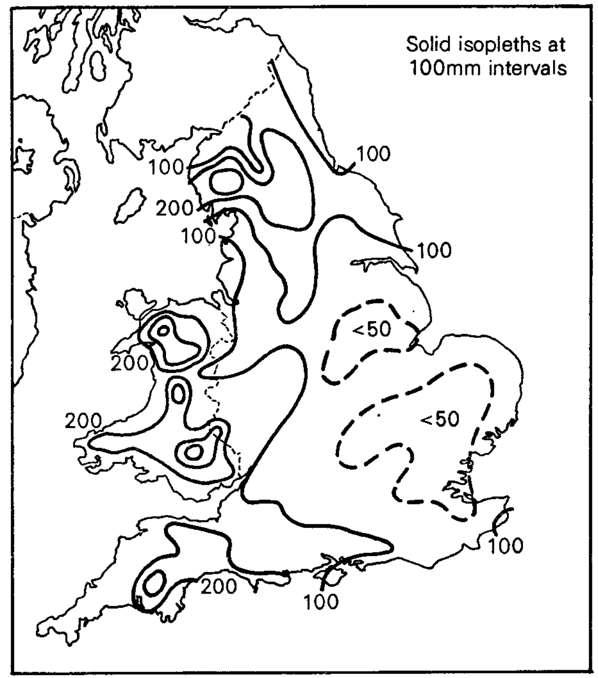

FIGURE 18—ACCUMULATED EFFECTIVE RAINFALL (mm) FROM AUGUST TO OCTOBER 1976 OVER ENGLAND AND WALES (COMPOSITE LAND-USE MODEL): ISOPLETHS AT 100 mm INTERVALS

to an end on the date following which accumulated rainfall becomes and remains greater than accumulated transpiration. The dates of ending of the agricultural drought of 1976 in different parts of the country were not later than the dates for the ending of the hydrological drought which are estimated in Figure 17; the dates were probably about 28 August in the areas from south-east Wales to Norfolk shown in Figure 17 and probably a few days before 10 September in most other parts of England and Wales. A complicated pattern of estimated dates for the ending of the agricultural drought in different places could be derived on the basis of various assumptions, but it would scarcely be justified in view of the great variability of rainfall in space and time, as well as other factors with large uncertainties.

ACKNOWLEDGEMENTS

I would like to thank colleagues who prepared the material and also Miss M. G. Roy and Mr J. Grindley for helpful discussions.

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A SYNOPTIC CLIMATOLOGIST'S VIEWPOINT OF THE 1975/76 DROUGHT

By R. A. S. RATCLIFFE

SUMMARY

The drought is shown to be related to a variety of factors including unusual coldness in the North Pacific Ocean and over Canada in the winter half-year, stronger than usual upper winds in the central Pacific and the quasi-biennial oscillation. Feedback reactions involving Atlantic sea temperatures and the drought itself helped to maintain the atmospheric mode which appeared to show considerable inertia. The final breakdown was initiated by strong arctic cooling in early autumn which precipitated a southward jump in the latitude of the main jet stream.

All meteorologists will be aware that it is not possible to indicate a definite cause for an event such as the 1975/76 drought. It arose as a result of many interrelated factors and the most that one can do is to draw attention to some important anomalies and perhaps suggest how they may have come together to produce the drought situation.

The first point to note is that the four winters 1971–74 were all mild, not only in Britain, but over most of Europe as far east as about Moscow. As a result the coldest air was displaced to the western side of the hemisphere and there were negative anomalies of 1000/500 mb thickness over Canada and the North Pacific during those winters compared to the 1951–70 averages (Painting, 1976).

The second interesting fact is that the jet stream in the east Atlantic/European sector was displaced between 5 and 10 degrees of latitude northwards over the 16 months' drought period compared to the same 1951–70 averaging period—see Figure 1. This northward movement occurred in the late autumn of 1974 and, on a monthly mean basis, was persistent with only short-period variations until September 1976, suggesting a good deal of inertia in the atmosphere over this 16 month period (Morris and Ratcliffe, 1976).

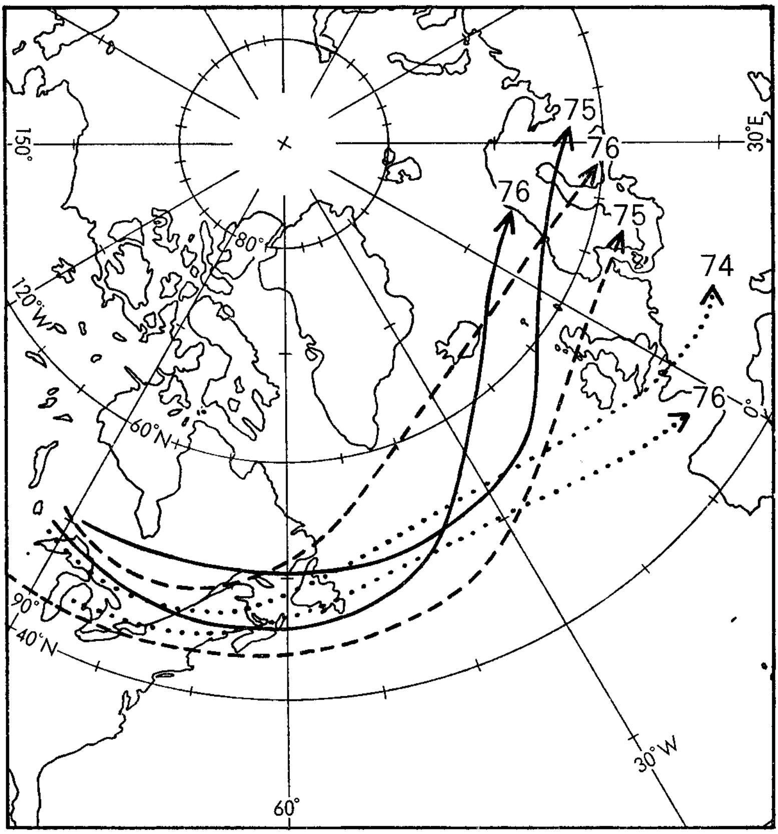

FIGURE 1—JET STREAM POSITIONS FOR SUMMER (1975 AND 1976), WINTER (1975 AND 1976) AND AUTUMN (1974 AND 1976)

Summer ——— Winter - - - - Autumn . . . . . .

Thirdly it is noticeable that the Pacific Ocean north of 40°N was continuously colder than usual, especially from spring 1975 to summer 1976 inclusive. Figure 2 shows the mean anomaly of sea temperature per 5° × 5° latitude/longitude quadrangle over the whole North Pacific north of 40°N since the summer of 1974. It is probable that the coldness of the ocean was partly due to the coldness of the winters of the early 1970s in that sector of the hemisphere: in particular ice was excessive in the North Pacific in late winter 1975 and 1976 and its melting may well have been partly responsible for the sharp increase of negative sea temperature anomalies in the springs and summers of those years.

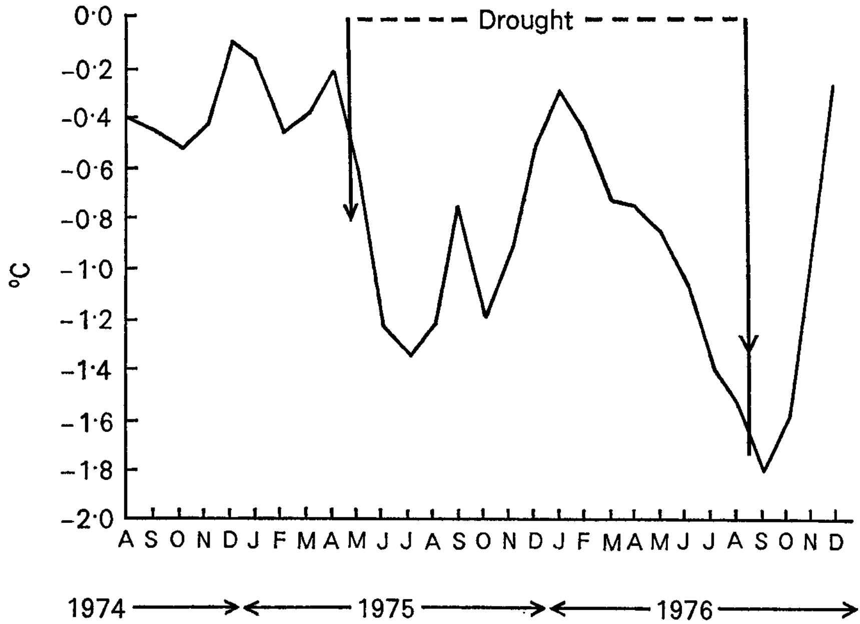

FIGURE 2—NORTH PACIFIC SEA TEMPERATURE ANOMALIES—MEAN ANOMALY NORTH OF 40°N AND FROM 150°E TO AMERICAN COAST, RELATIVE TO LONG-PERIOD NORMAL

Normal values from US Oceanographic Office (1969)

The 500 mb flow was computed for the drought period over the hemisphere north of 15°N and compared with the average at each grid point on the standard grid. There were three areas where the flow was significantly different (at the 5 per cent level using 'Student's' *t*-test) from average. Two of these were, as one would expect, in regions to the north and south of the British Isles where the flow was significantly stronger and weaker respectively, reflecting the northward displacement of the jet stream. The third area was at 45°N in the east central Pacific between 150 and 180°W: here the mean flow was 4 m s^{-1} stronger than the average of 17 m s^{-1}, an enhancement of the flow by more than 20 per cent over the 16 months as a whole. The time series of the anomalous flow at the mid point of the area is shown in Figure 3. Since there was also considerable enhancement of the 1000/500 mb thickness gradient from north to south in the Pacific during the drought, it seems highly probable that the cold water north of 40°N was a factor contributing strongly to the enhanced flow especially as sea temperatures south of 40°N were not in general colder than usual. The relationship between strong flow in the central Pacific near 45°N and weather over Britain was examined more closely by selecting the 14 summers since 1873 when surface flow between 35 and 55°N and 150/180°W was noticeably enhanced, and comparing with the 8 summers when flow was noticeably decreased in the same area. The mean summer rainfall over England and Wales for the 'enhanced' sample was 196 mm while that for the 'decreased' sample was 265 mm, a difference significant at the 5 per cent level. The 'enhanced' sample mean was significantly more anticyclonic than the 'decreased' sample while 12 of the 14 'enhanced' sample years had good summers over Britain compared with only one good summer in the 'decreased' sample, as measured by the index of cyclonicity (see Murray and Lewis, 1966).

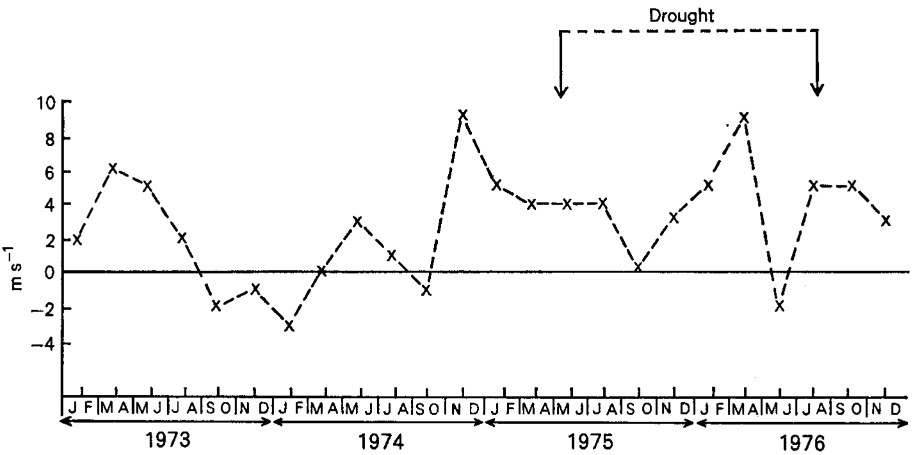

FIGURE 3—ANOMALIES OF THE 500 mb ZONAL COMPONENT OF GEOSTROPHIC WIND AT 45°N 170°W RELATIVE TO 1951–70 NORMAL (17 m s^{-1})

Two-month seasonal values

The enhanced Pacific flow and the winter coldness over Canada appear to have been important factors in the drought situation. The hemispheric 500 mb flow pattern can be resolved into its major orthogonal component patterns by eigenvector methods. One can then select the component patterns which represent enhanced Pacific flow and enhanced flow around the east Canadian trough and compound them to see what are the normal downstream consequences. For the two month season January–February the resulting 500 mb anomaly pattern is shown in Figure 4 which may be compared with the actual anomaly pattern for January–February 1976 (Figure 5). There is clearly a good deal of similarity indicating a connection between the enhanced Pacific and Canadian flow and the anomalous ridge over western Europe. In fact the technique is able to show that what happened over Europe in the winter half-year 1975/76 was the normal concomitant of stronger than usual flow in the Pacific and over eastern Canada. In summer, when wave lengths are shorter, a 500 mb ridge developed over east Canada in both 1975 and 1976 so that the east Canadian flow was decreased. Figure 6 shows the 500 mb anomaly pattern which results from adding together those flow patterns which represent this state of affairs, which compares closely with the actual anomaly pattern for summer 1976 (Figure 7). The anomaly pattern for summer 1975 was also very similar.

In addition to the factors already mentioned, there were almost certainly feedback reactions acting on the atmosphere through the Atlantic sea temperature anomaly patterns during the drought. In the summers of both 1975 and 1976, ocean temperatures to the east and south-east of Newfoundland were in general colder than usual. Ratcliffe and Murray (1970) showed that such patterns of sea temperature are normally followed by rather blocked anticyclonic situations over Britain. The cold ocean itself may well have owed its origin to the unusual winter and spring coldness over east Canada which, with the normal prevailing westerly circulation, would be likely to cool the adjacent ocean gradually. In the winter half-year 1975/76 the Atlantic was colder than usual north of about 55°N owing perhaps to the excessive cyclonic activity south of Iceland. Such a sea temperature anomaly pattern has been shown to favour an anomalous ridge extending towards Britain from the Azores anticyclone much as actually happened in the winter of 1975/76.

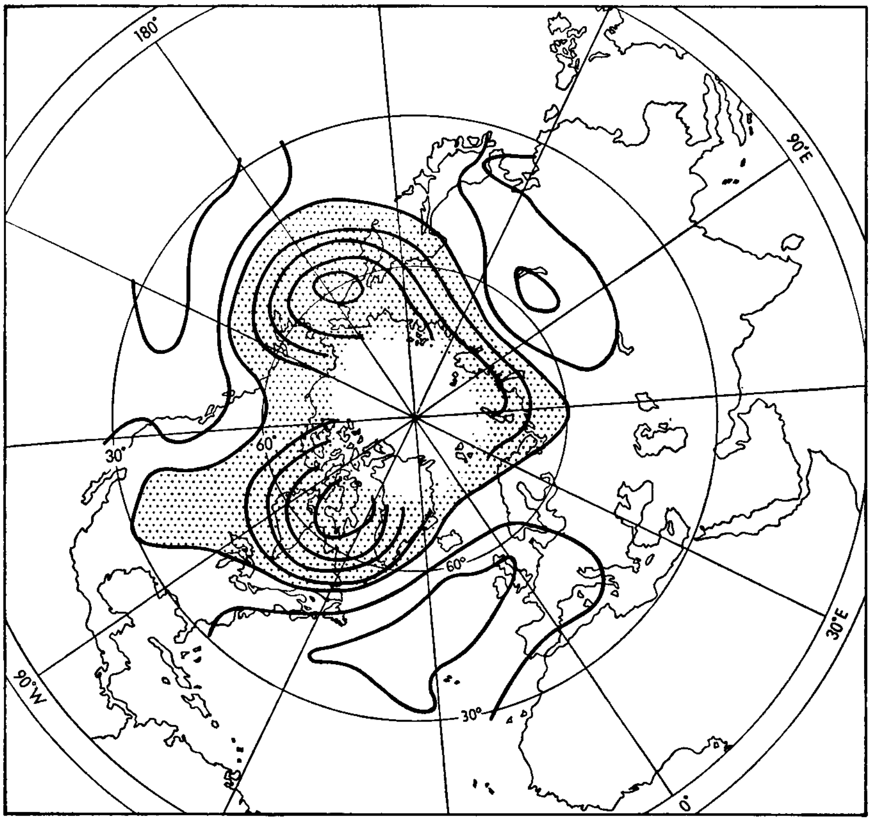

FIGURE 4—COMPOUND OF 500 mb EIGENVECTOR PATTERNS SHOWING ENHANCED PACIFIC AND ENHANCED CANADIAN TROUGH: TWO-MONTH SEASON, JANUARY–FEBRUARY

(arbitrary units) (negative values shaded)

Yet another interesting fact is that most of the drought period was associated with the westerly phase of tropical stratospheric winds (QBO). This phase started in spring 1975 and continued until early summer 1976. Ebdon (1975) has shown that the Atlantic jet stream is usually further north (see Figure 1) in westerly compared to easterly QBO phases.

About late spring 1976 the broad-scale meteorological situation, which had shown considerable inertia and persistence for over a year, was showing signs of a change. Extra baroclinicity became apparent in the upper flow in mid Atlantic near 50°N and the main jet stream had reached an extremely far north

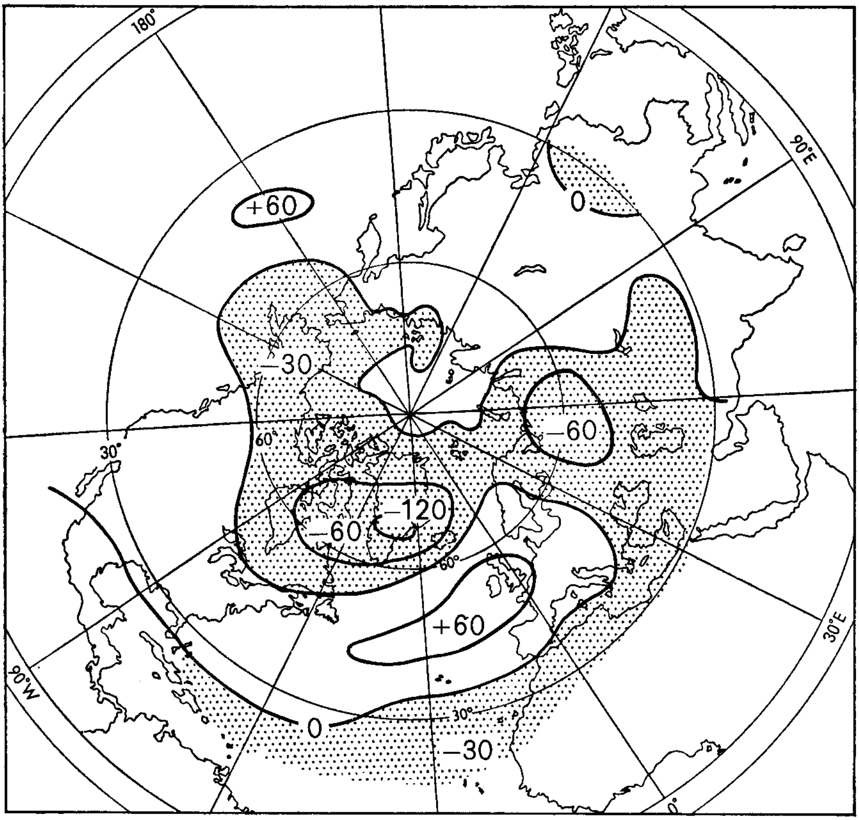

FIGURE 5—ANOMALIES OF 500 mb GEOPOTENTIAL SURFACE (gpm) RELATIVE TO 1951–70 NORMAL: TWO-MONTH SEASON JANUARY–FEBRUARY 1976

(negative values shaded)

position near Iceland. The westerly phase of the QBO was also about to end and indeed all seemed set for a breakdown of the long-standing regime and a transfer of the jet stream to near 50°N. The upper flow in the Pacific at 45°N had also weakened (see Figure 3). All the statistical evidence, on which the experimental summer forecast for 1976 prepared in the Synoptic Climatology Branch of the Meteorological Office was based, suggested a breakdown to a normal unsettled summer pattern. Why did this not happen?

It is my view that the weather did not break at this stage primarily because of the drought itself (perhaps aided by the resurgence of Pacific flow—see Figure 3). It has been demonstrated (Ratcliffe, 1976) that the excessive dryness of the ground in the late spring and early summer resulted in something like 80–90 per cent of incoming solar radiation being available for heating the ground and hence the air, compared with about 50 per cent in the normal year (the other 50 per cent is used in evaporation and transpiration). The favourable anticyclonic

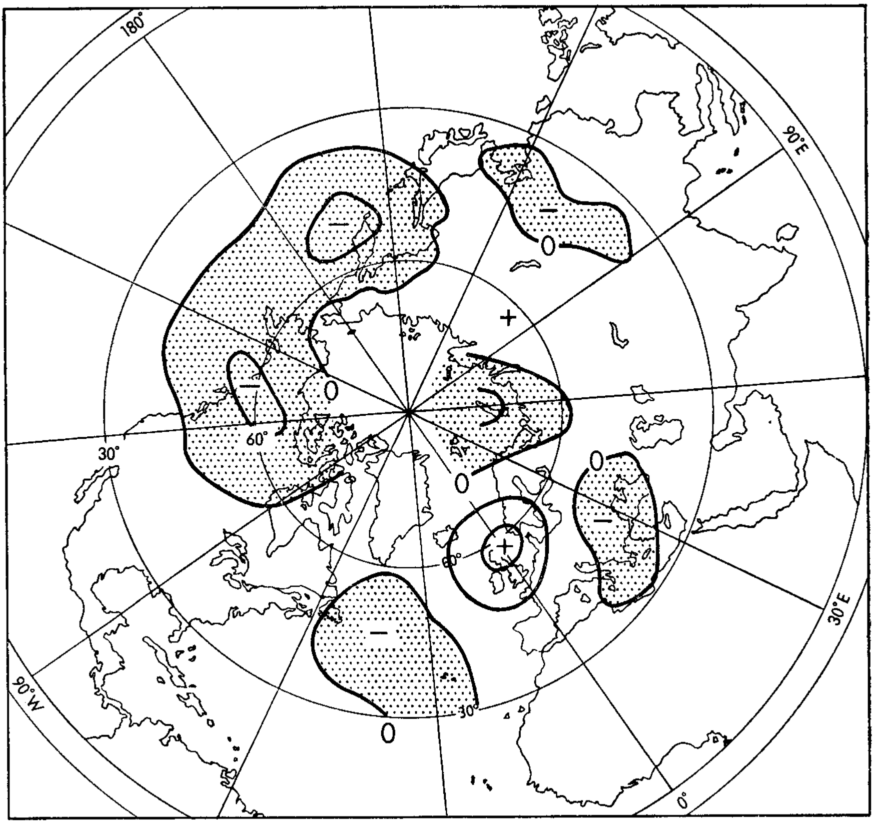

FIGURE 6—COMPOUND OF 500 mb EIGENVECTOR PATTERNS SHOWING ENHANCED PACIFIC AND WEAK CANADIAN TROUGH: TWO-MONTH SEASON, JULY–AUGUST

(arbitrary units) (negative values shaded)

situation which developed around 20 June thus resulted in very high temperatures and also exceptionally high 1000/500 mb thicknesses being built up over Britain and western Europe. The thickness anomaly over Britain for mid-June to mid-July was in fact about twice that in any other comparable period since the war. This factor may have played a part in keeping Britain on the warm side of the main baroclinic zone and this caused frontal systems to slide away northwards just to the west of Ireland, effectively maintaining the fine weather and drought until the end of August.

With the imminent onset of arctic cooling, the extreme northern position of the jet stream near Iceland could not be maintained much longer. The intensification of thermal gradient noted in the early summer in mid Atlantic around

50°N had, if anything, increased and the most likely event appeared to be a discontinuous evolution so that the main flow would be transferred from the latitude of Iceland to about 50°N across the Atlantic. This change was initiated

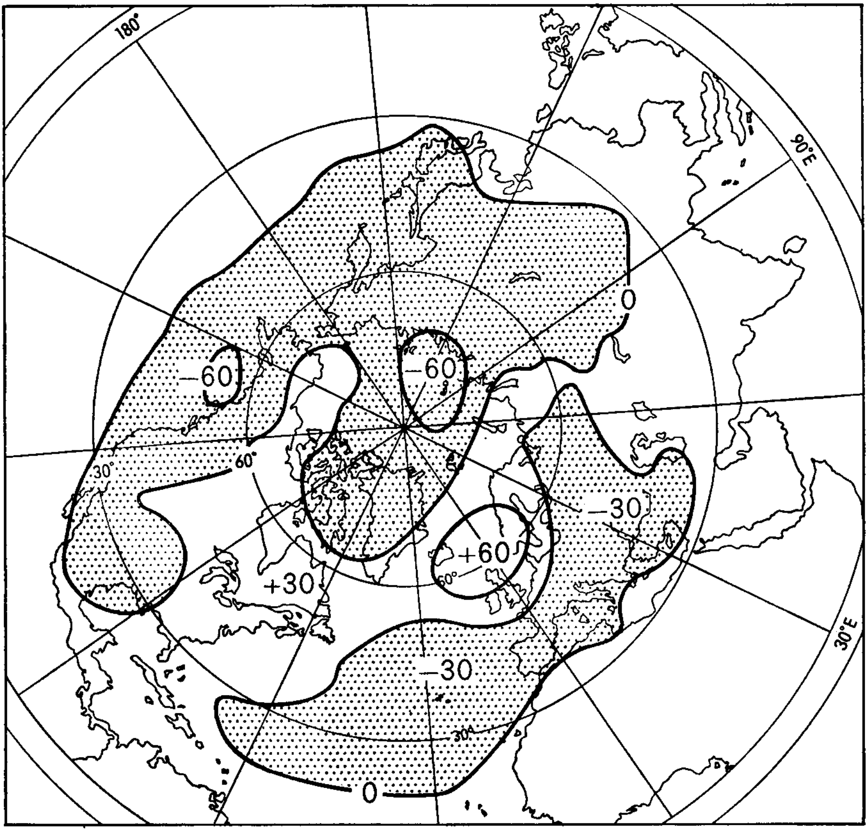

FIGURE 7—ANOMALIES OF 500 mb GEOPOTENTIAL SURFACE (gpm) RELATIVE TO 1951–70 NORMAL: TWO-MONTH SEASON, JULY–AUGUST 1976

(negatives values shaded)

by an outbreak of cold air from the Arctic into northern Canada in late August which started a major retrogression of the arctic flow pattern and precipitated a cold plunge down the North Sea which eventually formed a cold trough west of Biscay and resulted in the main upper flow becoming established across the Atlantic near 50°N (Ratcliffe, 1977). This development was unusual and against the normal climatology since there is often strong persistence of weather in Britain from August to September: in fact an increase of wave length is normal as the general circulation begins its seasonal strengthening. The change of regime resulted in a shortening of wave length and hence was unusual for the season. Once this major change in the circulation had taken place, the excessive rains of September and October followed. One reason for their exceptional nature was undoubtedly the high sea temperature (up to 2°C above average) which existed to the south-west of the British Isles owing to the long hot summer (Figure 8). Such high ocean temperatures enabled more moisture and more sensible heat to be transferred to the atmosphere than is usual and, given the favourable synoptic situation provided by the upper trough, greatly enhanced the rain-producing process. The abnormal gradient of sea temperature existing between about 40°N 30°W and 35°N 20°W (see Figure 8) is also believed to be a factor aiding cyclonic development to the south-west of Britain. To some extent at least, therefore, it would appear that the exceptional autumn rains of 1976 had their origin in the exceptional summer.

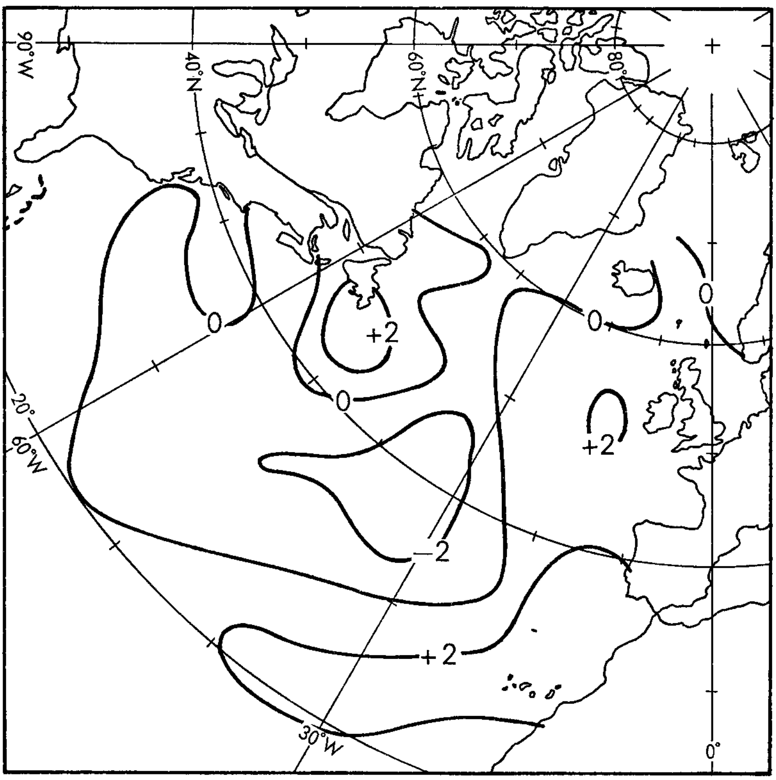

FIGURE 8—NORTH ATLANTIC SEA TEMPERATURE ANOMALY (°C) 3–7 SEPTEMBER 1976 RELATIVE TO LONG-PERIOD NORMAL

(US Hydrographic Office (1967))

CONCLUSION

The drought is seen as part of a continuous evolution of the hemispheric circulation over a period of at least the two years from autumn 1974 to autumn 1976. After the succession of mild European winters of the early 1970s with the main hemispheric coldness transferred to Canada and the North Pacific, the east Atlantic jet stream moved north and its apparent inertia aided by feedbacks from the Atlantic sea temperature and perhaps also the excess ice cover in the North Pacific, maintained the situation. Another exceptional feedback may have arisen because of the extra sensible heating available to the atmosphere in the summer due to the greatly decreased evaporation and transpiration. The eventual break came with strong seasonal cooling in the Arctic initiating a discontinuous southward jump of the jet stream.

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ATMOSPHERIC CIRCULATION DURING THE SEVERE DROUGHT OF 1975/76

By M. K. MILES

SUMMARY

The anomalies of the northern hemisphere circulation at the surface and 500 mb for the 16 months of the drought (i.e. May 1975 to August 1976) are shown and discussed. It appears that the marked absence of rain was due primarily to a deficiency of cyclonic types over the British Isles. The association of the anomalous circulation over the British Isles with conditions over the North Pacific Ocean is discussed.

1. INTRODUCTION

The 5 years 1971–75 are the driest over England and Wales since 1898–1902 but the 16 months from May 1975 are the driest in the record of England and Wales rainfall back to 1727. Table I shows the nearest approaches to this for 12 month and 16 month periods back to 1820.

TABLE I—RAINFALL TOTALS FOR ENGLAND AND WALES FOR THE 12 MONTH PERIOD BEGINNING SEPTEMBER 1975 AND FOR THE 16 MONTH PERIOD BEGINNING MAY 1975 WITH SOME EARLIER DRY 12 AND 16 MONTH PERIODS

	12 months			16 months	
Year	1st month	Rainfall	Year	1st month	Rainfall
		mm			*mm*
1975/76	Sept.	571	1975/76	May	757
1854/55	Feb.	618	1933/34	Feb.	811
1920/21	Nov.	618	1933/34	Apr.	855
1887/88	Feb.	624	1887/88	Feb.	857
1963/64	Dec.	637	1920/21	Aug.	880

The 16 month drought included two summers, which perhaps makes it of unusual interest to agriculturists.

This article examines the atmospheric circulation over most of the northern hemisphere for the 16 month period from May 1975 to August 1976 during which there was only 64 per cent of the 1916–50 average rainfall over England and Wales.

2. THE HEMISPHERIC GEOSTROPHIC CIRCULATION

Figure 1 shows the surface pressure distribution and the anomalies from the 1951–70 average and Figure 2 shows the geopotential of the 500 mb surface and anomalies from the 1951–70 average. In each case the largest anomaly is over the British Isles. Even for a 12 month period these anomalies are greater than three standard deviations from the mean so for a 16 month period they represent an occurrence with an expectation of something less than about 1 in 500.

Departures of three standard deviations occur somewhere on annual maps about once each year but at any given grid point this means once in 300 years. The negative anomalies over Greenland are also just about over three standard deviations from the mean. They are probably a dynamical consequence of the circulation pattern which led to the positive anomalies over the British Isles.

The mean strength of the 500 mb zonal flow for the hemisphere in the latitude band 35–55°N where it is on average strongest was very little different from average. It was above average over the Pacific and below average in all other sectors. The zonal speed in the latitude band 55–75°N was about 15 per cent above the average. It was near average in the Pacific sector and above average in all other sectors. This means that the cyclonic shear of the 500 mb circumpolar circulation was generally below average north of the belt of maximum flow.

The meridional index of the surface flow as described by Miles (1976) was below average for the latitude band 35–55°N and about the same amount above average for the band 55–75°N. For annual means these anomalies would represent quite small deviations.

The latitude of the circumpolar flow at 500 mb was very near the average for all sectors except that between 30°W and 30°E. Here it was north of the average position reaching a maximum displacement of over 10° latitude near the Greenwich meridian. The mean meridional profile of the west–east component of the flow is shown in Figure 3 for longitudes 20°W to 10°E inclusive. Instead of a maximum near 50°N there is a rather broad one near 60°N leading to a reversal of the usual cyclonic shear over the British Isles.

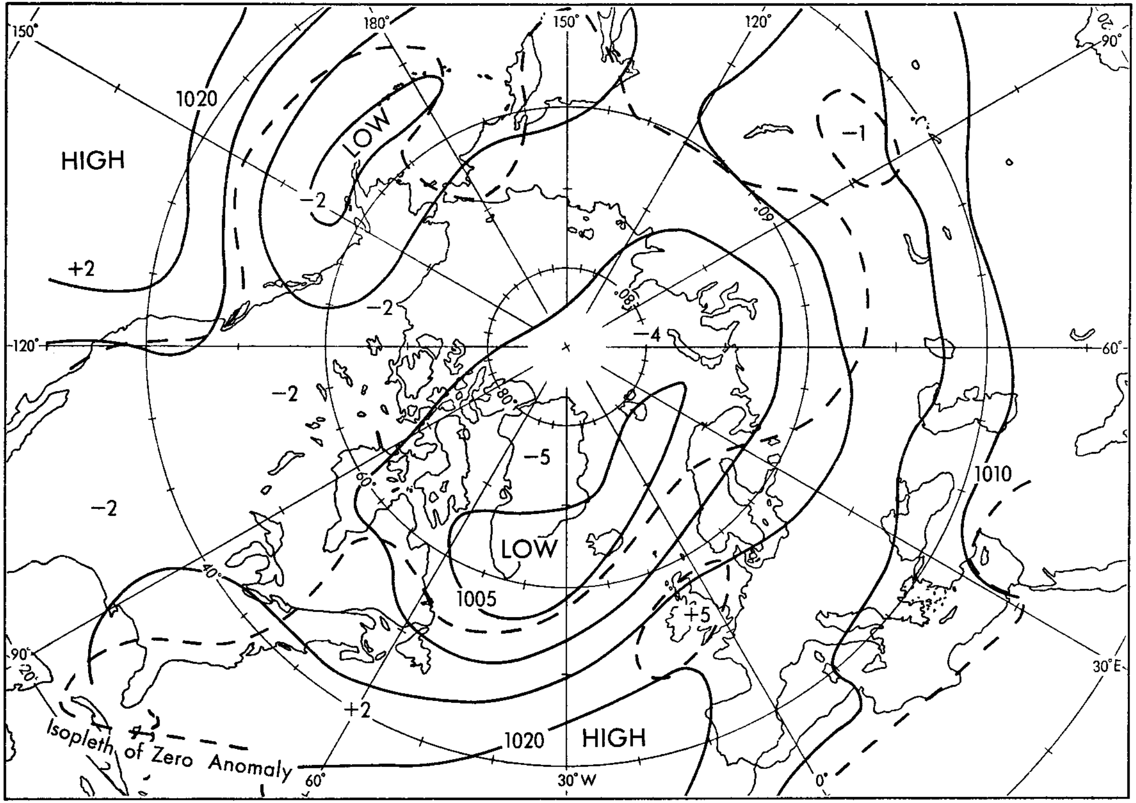

FIGURE 1—ISOPLETHS OF SURFACE PRESSURE AND ANOMALIES FROM THE 1951–70 AVERAGE IN MILLIBARS DURING THE PERIOD MAY 1975 TO AUGUST 1976 INCLUSIVE

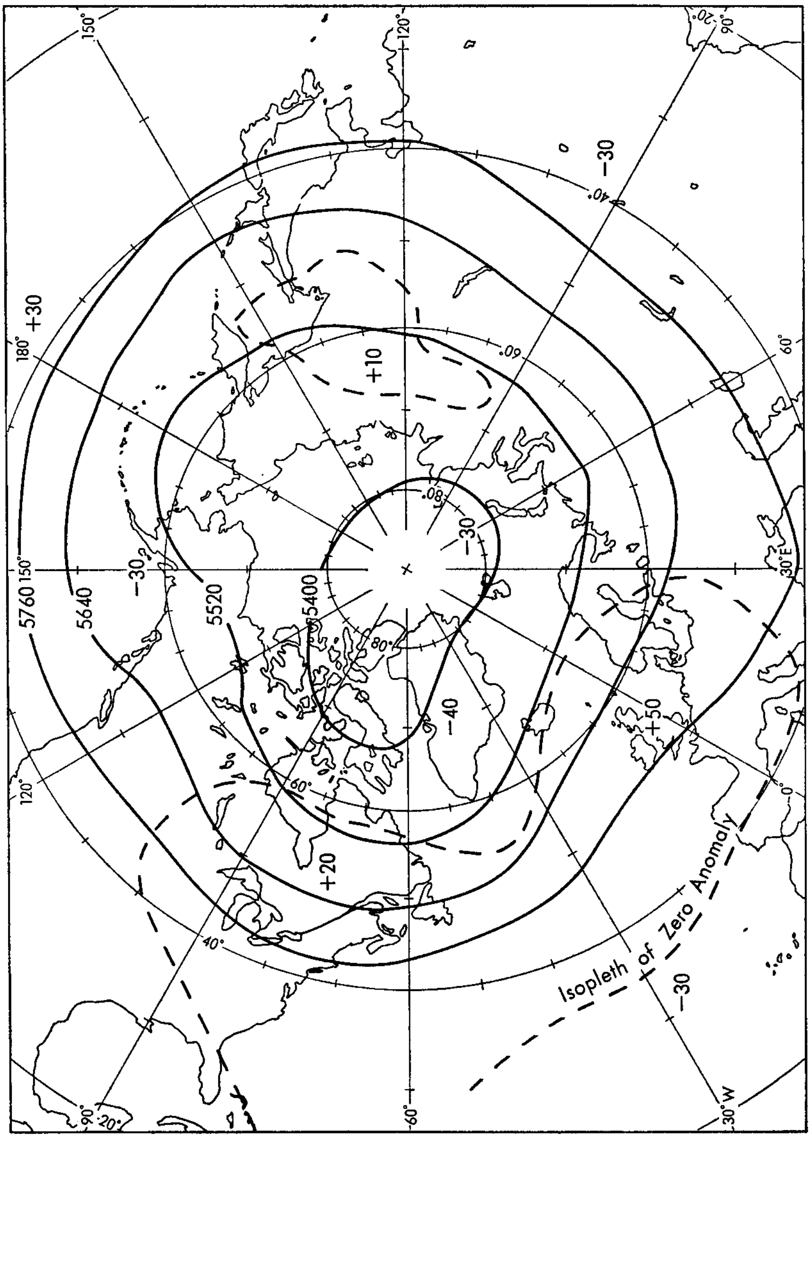

FIGURE 2—GEOPOTENTIAL OF THE 500 mb SURFACE AND ANOMALIES FROM THE 1951–70 AVERAGE DURING THE PERIOD MAY 1975 TO AUGUST 1976 INCLUSIVE (gpm)

This northward displacement of the maximum flow at 500 mb is an indicator that Atlantic cyclonic systems, of which there was no shortage during this period were turning left more markedly than usual as they approached the British Isles. The cyclonicity index described by Murray and Lewis (1966)

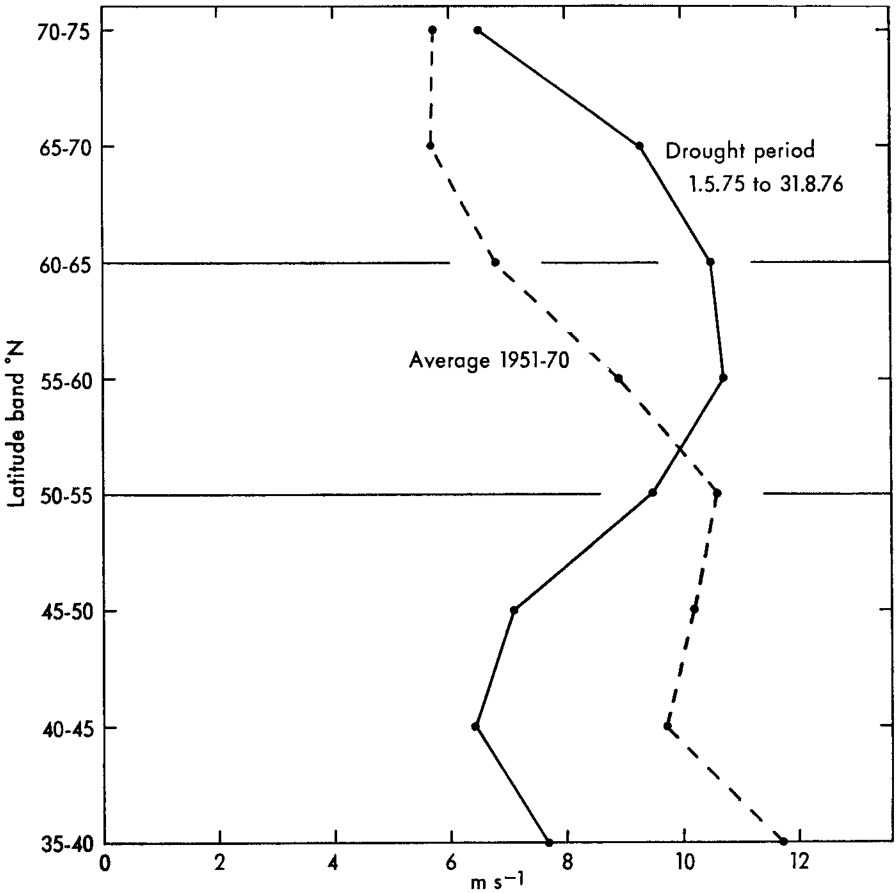

FIGURE 3—MERIDIONAL PROFILE OF WEST–EAST COMPONENT OF GEOSTROPHIC WIND AT 500 mb BETWEEN 20°W AND 10°E FOR THE PERIOD MAY 1975 TO AUGUST 1976 INCLUSIVE

shows that cyclonic types were much below average frequency over the British Isles. The index was, as Figure 4 shows, below the long-period average in 13 of the 16 months which is an event which should not occur by chance more often than once every few hundred years. This index is strongly correlated with England and Wales rainfall and its low value suggests that the large rainfall deficit during the drought is mainly to be ascribed to the lack of cyclonic types over the British Isles. Whether the increasing dryness of the ground as the drought continued was a further factor is a matter perhaps deserving of special study.

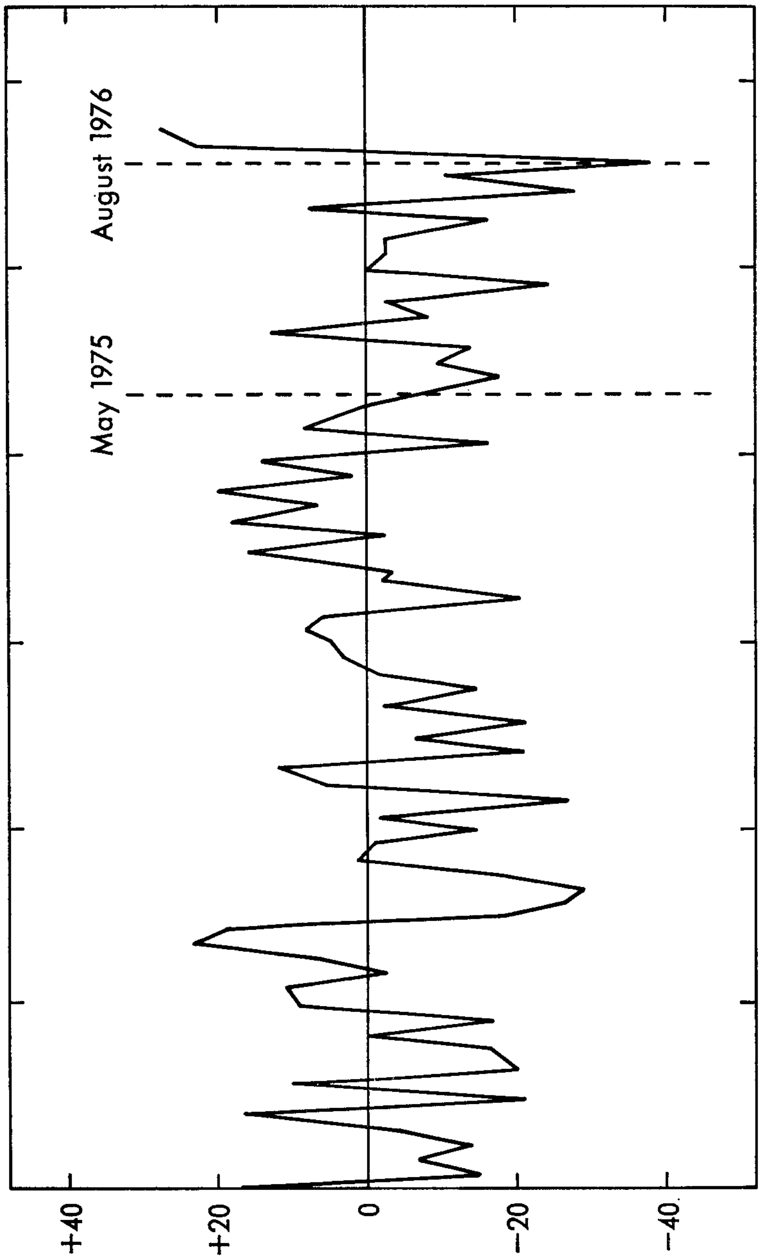

FIGURE 4—MONTHLY ANOMALIES OF THE CYCLONICITY INDEX FOR THE BRITISH ISLES

During the last three months of the drought when this effect would have been at its strongest the rainfall over England and Wales was about 20 mm less than that indicated by the regression line of rainfall on cyclonicity index. This is well within the statistical expectation and does not require or preclude the invocation of additional or unusual factors.

Figure 5 shows the distribution of the 1000/500 mb thickness and the anomalies from the 1951–70 average. The distribution is quite near average over the British Isles. The most unusual zone is in the west Pacific where the occurrence of anomaly centres of +30 gpm and −30 gpm on almost the same meridian indicates a 20 per cent increase in thermal wind. The Pacific was the only sector where the thermal wind in the latitude band 35–55°N was above average: the hemispheric mean was about 0·1 m s^{-1} below average. The surface westerly component in this band was about 0·1 m s^{-1} above the average—hence the near-average 500 mb westerly component in this band.

3. The location and intensity of the mean troughs and ridges at 500 mb

Figure 6 allows us to see how the mean location of the main troughs and ridges during the 16 month period differs from the 1951–70 average at two latitudes. At 60°N the broad trough usually located over north-east Asia was displaced into the eastern Pacific. The ridge usually near the Rockies was less intense and displaced a little east. The trough over eastern Canada was slightly more intense and geopotentials were lower than usual east of the axis. The most marked intensification was of the ridge normally over southern Norway. It was also located nearly 10° longitude west of the average position. There was thus a small reduction in the usual spacing between the Rockies ridge and that near the British Isles. This is apparently inconsistent with the enhanced zonal flow (about 20 per cent above average) at this latitude in this sector and indicates that there was probably a considerable departure from the implied assumption of constant absolute vorticity.

At 45°N the east Asian trough was a little more intense but in about the average position. The Rockies ridge and Canadian trough are also not far from their average location, but again the east Atlantic ridge is more intense and so also is the east European trough.

Generally one could summarize the wave pattern at 500 mb during the period in the statement that most features tended to be a little east of their average location (determined for the 20 years 1951–70) and there was exceptional intensification of the ridge near the British Isles.

4. Other persistent features during the drought

The average sea surface temperature of the North Pacific for the past two or three years has been below the long-term average. Figure 7 shows the distribution of sea surface temperature in both North Atlantic and North Pacific for the 16 months of the drought. It may not be coincidence that the thermal wind over the Pacific has been above average during most seasons since 1973 as can be seen from Figure 8. An examination of the association of these features with the drought is contained in an article by Ratcliffe (1977).

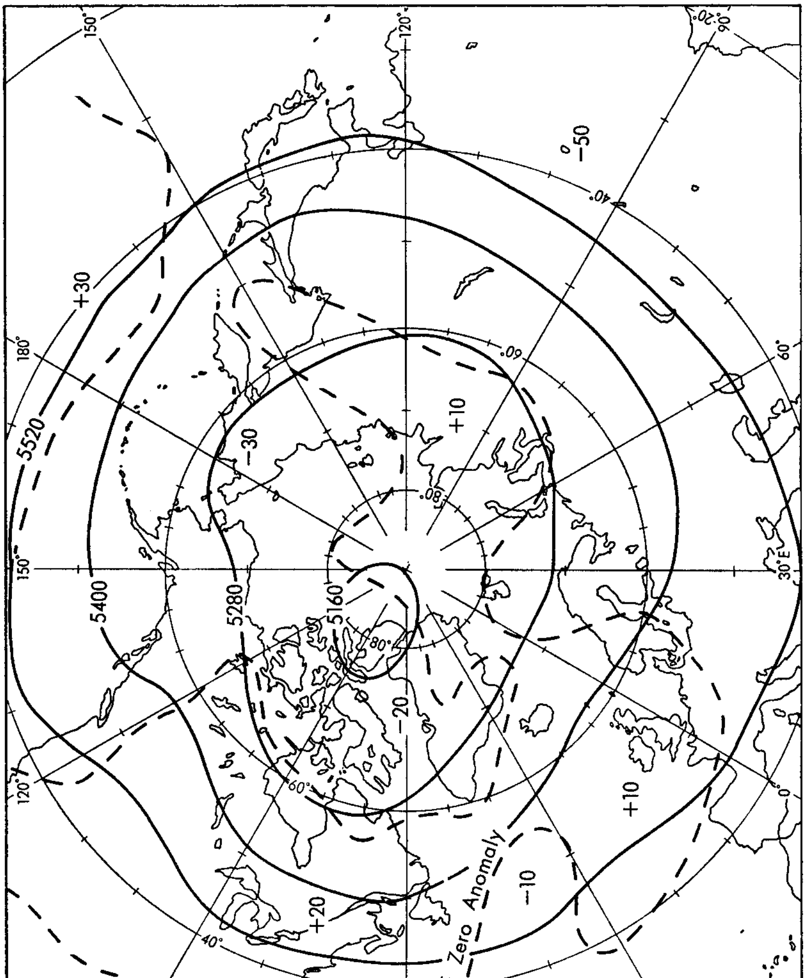

FIGURE 5—THE 1000–500 mb THICKNESS AND ANOMALIES FROM THE 1951–70 AVERAGE DURING THE PERIOD MAY 1975 TO AUGUST 1976 INCLUSIVE (gpm)

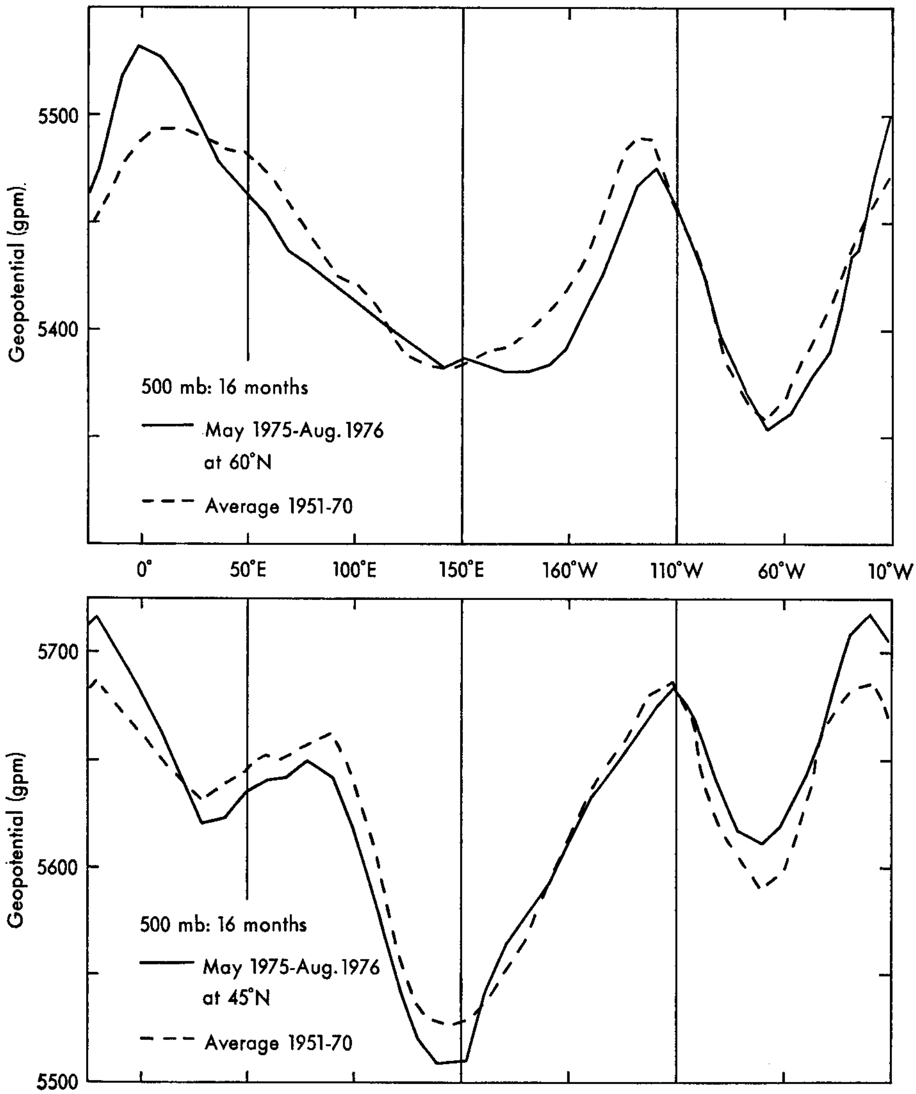

FIGURE 6—PROFILE OF THE 500 mb GEOPOTENTIAL AROUND TWO LATITUDE CIRCLES FOR THE PERIOD MAY 1975 TO AUGUST 1976 INCLUSIVE

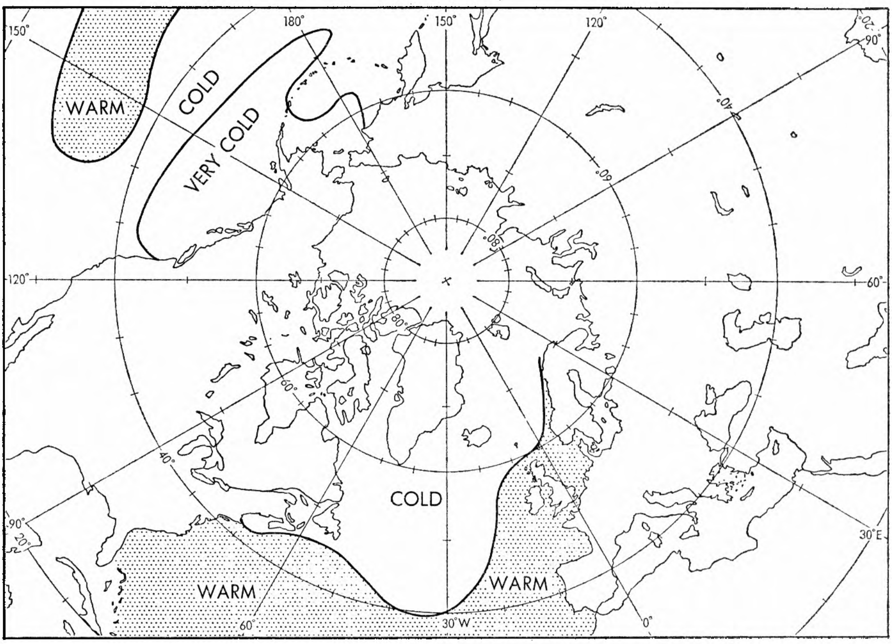

FIGURE 7—ANOMALIES OF SEA SURFACE TEMPERATURE FOR THE PERIOD MAY 1975 TO AUGUST 1976 INCLUSIVE

Isopleths are at intervals of 1·0°C. Stippling denotes areas warmer than average.

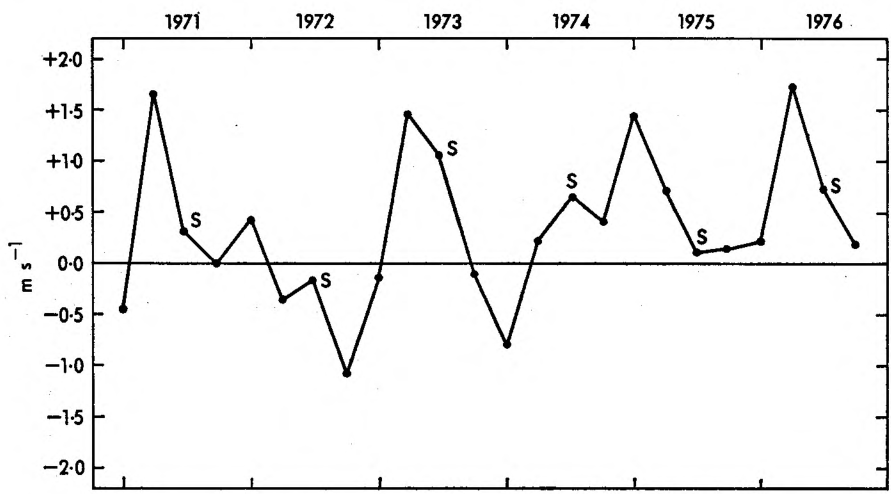

FIGURE 8—ANOMALIES OF THE THERMAL WIND 35–55°N BY SEASONS OVER THE NORTH PACIFIC

Period of average is 1966–76. The summer seasons are denoted by S.

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HONOUR

We note with pleasure that Dr F. Pasquill was elected a Fellow of the Royal Society on 17 March for studies of turbulence and diffusion processes in the atmospheric boundary layer and their application to the transport of pollutants. Dr Pasquill retired from the Meteorological Office on 7 September 1974 as a Special Merit Deputy Chief Scientific Officer. An account of his career and his outstanding research work is given in the *Meteorological Magazine* Vol. 103, pp. 274–275.

NOTES AND NEWS

Upper-air observations at St Helena

The last of the series of new upper-air stations established overseas by the United Kingdom for the global network of the World Weather Watch was opened at Bottom Woods, St Helena on 27 October 1976 by the Governor of St Helena, Sir Thomas Oates, C.M.G., O.B.E.

During January 1977 Mr J. H. Convery of the High Atmosphere Branch visited the station and brought the Dobson Ozone Spectrophotometer into operation; routine daily observations of total ozone, made by staff of the upper-air station, began on 20 January. This station fills a major gap in the global ozone observational network.

North Atlantic Ocean Stations

The WMO agreement for Joint Financing of North Atlantic Ocean Stations, negotiated in November 1974 (*Met Mag*, **104**, 1975, pp. 90–91 and 311) entered into force on 1 December 1976. The First Session of the Board to administer the NAOS agreement was convened at WMO Headquarters, Geneva on 13–16 December 1976. Delegations from 14 contracting parties attended, including the United Kingdom, and seven other states were represented by observers. The estimated cost of the network for 1977 is just over £7 million.

Dr R. Berggren of Sweden was elected President of the Board and M. R. du Chaxel of France was elected Vice-President and both will serve in these capacities until the end of 1977.

Two UK weather ships being refurbished to maintain Station 'L' will be renamed *Admiral FitzRoy* and *Admiral Beaufort*.

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NOTICES

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A FURTHER COMPARISON OF 50-MILLIBAR GEOPOTENTIALS OBTAINED FROM SATELLITE INFRA-RED SPECTROMETER SOUNDINGS AND ANALYSED CHARTS

By V. BAILEY

SUMMARY

In March 1975 the National Oceanic and Atmospheric Administration (NOAA) introduced a 'regression' method of retrieving Satellite Infra-red Spectrometer (SIRS) temperature profiles from Vertical Temperature Profile Radiometer (VTPR) data. Comparisons of 50 mb SIRS geopotentials with those derived from a series of 50 mb charts, based upon radiosonde data, have been carried out for the period 25 August 1975 to 12 April 1976. Although the quality of the SIRS data is still rather variable, there has been a marked reduction in bias errors and some decrease in the standard deviation of the SIRS minus analysed differences since the new retrieval method became operational in August 1975, especially over the Atlantic and southern North Pacific Oceans. However, north of 50°N in the Pacific, a bias error persists.

In a previous comparison of 50 mb geopotentials from Satellite Infra-red Spectrometer (SIRS) soundings and analysed charts, which covered the period June 1974 to May 1975 (Watson and Bailey, 1976), the quality of the SIRS data was found to be very variable. The mean SIRS minus analysed differences displayed a marked latitude dependence, the SIRS geopotentials being comparable to the analysed geopotentials at 60°N and about 10 geopotential decametres too high between 20° and 30°N. The mean difference varied with time, with discontinuities whenever the instrument or spacecraft, or both, changed. It was noted in that paper that a new technique to produce the SIRS thicknesses from observed Vertical Temperature Profile Radiometer (VTPR) radiances was introduced by the National Oceanic and Atmospheric Administration (NOAA) on 13 March 1975. In this technique (Hayden, 1976) each thickness is derived from a regression equation involving the deduced clear-column radiances for several VTPR channels.

The regression coefficients were derived from an analysis of co-located radiosonde and SIRS observations. These coefficients were initially calculated from comparisons made during January and February 1975 and subsequently updated on 21 August 1975 with collocations made in June and August. It is understood that, since this date, there has been no change of coefficients or methods. Instrument No. 2 on NOAA 4 was in use throughout the period of this study. Indeed, it has been learnt that, contrary to Figure 1 of Watson and Bailey (1976), instrument No. 2 on NOAA 4 was brought into use from December 1974. Thus the abrupt decrease in mean differences in March 1975 was solely the consequence of introducing the regression method for deducing SIRS thicknesses.

For this present investigation, comparisons have been made on 34 occasions, seven days apart, during the period 25 August 1975 to 12 April 1976. The method of comparison was similar to that used in the previous investigation; values were taken from a daily (00 GMT) series of northern hemisphere 50 mb charts, drawn up using radiosonde data only. Comparisons were made for SIRS observations made within ± 3 hours of 00 GMT and therefore were confined to the Atlantic and western Pacific Oceans. The average number of SIRS minus analysed differences on each occasion was 33, with a maximum of 47 and a minimum of 15. It was found that the two populations of differences for the Atlantic and Pacific respectively were significantly different at the 1 per cent level. Figure 1 shows the mean differences, together with the standard errors of the means, at intervals of seven days for both areas. The average of the mean differences for the Atlantic was $+1{\cdot}0$ geopotential decametres and for the Pacific

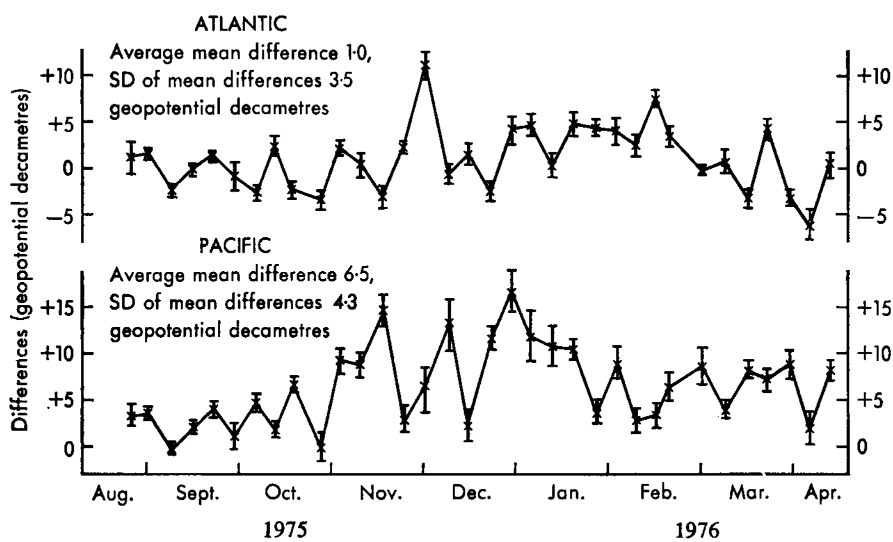

FIGURE 1—MEAN (SIRS MINUS ANALYSED) GEOPOTENTIAL DIFFERENCES AT 50 MILLIBARS FOR 25 AUGUST 1975 TO 12 APRIL 1976 AT INTERVALS OF SEVEN DAYS FOR ALL AVAILABLE COMPARISONS BETWEEN 20° AND 70°N

Vertical bars indicate standard errors of means.

+6·5 geopotential decametres. The increased variability of the mean differences for the winter months when compared with autumn is particularly noticeable.

For the Atlantic area, an examination of the data for the period August 1975 to April 1976 in 10° latitude bands showed (bottom plot of Figure 2) the variation of the mean difference with latitude to be small. It varied from 1·8 geopotential decametres between 20° and 30°N to −0·6 between 40° and 50°N and 2·8 between 60° and 70°N. In order to assess the impact of the change of retrieval method directly, data for part of the previous study period (15 December 1974 to 13 March 1975) have been reanalysed. During the latter period, the same instrument (No. 2) on NOAA 4 was being used but SIRS values were being derived by the 'minimum information method'. These results are included in Figure 2. The current regression method of retrieval has considerably suppressed the variation with latitude and eliminated the systematic error at the 50 mb level.

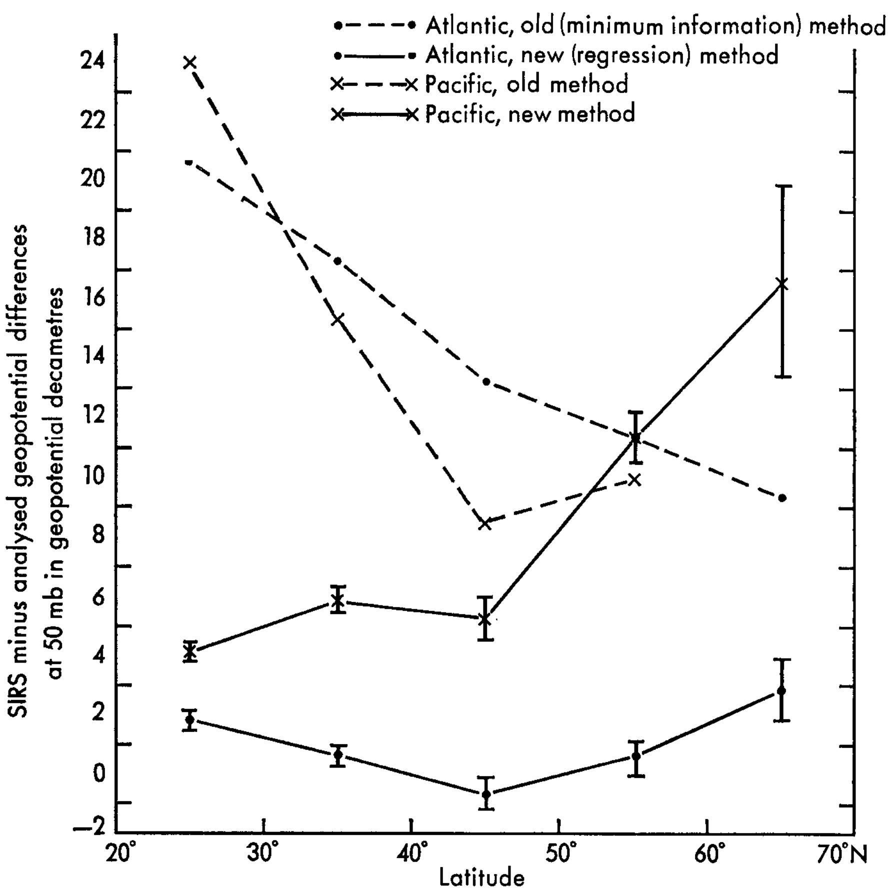

FIGURE 2—VARIATION WITH LATITUDE OF THE MEAN DIFFERENCES OF GEOPOTENTIAL BETWEEN SIRS AND ANALYSED DATA

Vertical bars indicate standard errors of means.

The data for these two periods are summarized in Table I. *N* is the number of observations.

TABLE I—50-MILLIBAR SIRS MINUS ANALYSED GEOPOTENTIAL DIFFERENCES OVER THE ATLANTIC (IN GEOPOTENTIAL DECAMETRES)

	Minimum information method 15/12/74–13/3/75			Regression method 25/8/75–12/4/76		
	N	Mean	SD	*N*	Mean	SD
60–70°N	56	9·4	9·4	104	2·8	9·8
50–60°N	83	11·4	10·0	203	0·6	8·6
40–50°N	80	13·3	10·9	239	−0·6	7·3
30–40°N	104	17·3	13·9	339	0·7	6·3
20–30°N	61	20·6	11·3	260	1·8	4·3

Using the standard deviation (SD) as a measure of variability of the differences, the Table suggests that there has been a considerable improvement in the quality of the SIRS data at 50 mb over the Atlantic at lower latitudes.

For the Pacific (Table II) there is still a mean systematic error. The variation with latitude is also more marked, the SIRS minus analysed difference increasing from 4·1 geopotential decametres between 20° and 30°N to 11·3 geopotential decametres between 50° and 60°N. (Only 14 observations were available north of 60°N.) However, the latitude dependence (Figure 2) shows a considerable improvement south of 50°N. The standard deviations are also improved in this region and are only slightly larger than for the Atlantic.

TABLE II—50-MILLIBAR SIRS MINUS ANALYSED GEOPOTENTIAL DIFFERENCES OVER THE PACIFIC (IN GEOPOTENTIAL DECAMETRES)

	Minimum information method 15/12/74–13/3/75			Regression method 25/8/75–12/4/76		
	N	Mean	SD	*N*	Mean	SD
60–70°N	—	—	—	14	16·6	11·9
50–60°N	76	9·9	11·9	166	11·3	11·4
40–50°N	78	8·5	8·9	193	5·3	9·6
30–40°N	90	15·4	8·9	227	5·8	7·4
20–30°N	87	23·9	7·7	267	4·1	5·2

The bias in the north of the Pacific area still persists, but it may be asked whether this reflects an error in the SIRS values or in the analysis. The method of analysis requires that corrections be applied to the various types of sonde observations to make them compatible with each other, using the Kew Mk 2b radiosonde as a standard. These corrections, obtained by the comparisons of sondes with the objective analysis, are small (up to −4 geopotential decametres) over the Pacific in low latitudes but fairly large (up to −11) in high latitudes for 00 GMT (when this area is in sunlight). Campbell and May (1976) have carried out an investigation using co-located SIRS/sondes, analysing their results by types of sonde. In relation to the Kew sonde, they found differences which, while having the same sign as the corrections that we apply in our chart analysis, were smaller. For instance, they found that the mean difference (in geopotential decametres) between the Kew sonde and the Russian sonde was approximately 3 for the 1000–100 mb thickness, which would correspond to about 4 for the 1000–50 mb thickness, compared with the correction of 11 applied during chart analysis. Use of the Campbell and May figures would greatly reduce the latitude dependence in the north of the Pacific area. This, of course, assumes that SIRS values are in some way more consistent than radiosonde values in judging the difference between sondes at night over the Atlantic and in daylight over the Pacific. The only sonde for which Campbell and May were able to investigate differences between day and night was the Japanese sonde. Their findings were that the SIRS minus analysed values were 3·9 geopotential decametres greater by night than by day, in close agreement with 4·7 obtained from the objective analysis scheme. This result suggests that SIRS soundings for a given location do not show any significant day-to-night difference. However, other possibilities exist in the SIRS analysis for the introduction of bias between the Atlantic and the Pacific. NOAA uses several sets of regression coefficients, selected by values of observed clear-column radiances in the window channel and a channel (No. 2) with a weighting function in the stratosphere. The climatic difference between the North Pacific and North Atlantic temperatures at low stratospheric levels (Labitzke *et alii*, 1972) presumably causes a bias towards different sets of coefficients for the production of SIRS values for the North Pacific and North Atlantic. This is something that the ordinary user of SIRS soundings cannot check without also accessing the clear-column radiance data.

In conclusion, it is clear that there has been a marked improvement in quality of SIRS geopotential estimates at 50 mb since the regression method of retrieval was introduced, mainly because of the reduction in bias error for the Atlantic and southern North Pacific. For the northern part of the Pacific area our analysis suggests either that there is a bias error in some of NOAA's sets of regression coefficients or that our present estimates of sonde corrections over the north of the Pacific in daylight are misleading. Continuation of the present form of comparison of SIRS values with the analysed charts is now no longer valid. This is because the 50 mb charts are constructed from a 100 mb chart, produced in the Central Forecasting Office, which now contains an element of SIRS observations. Hooper (1975) has suggested that satellite radiances calculated from upper-air soundings may provide a useful basis for comparison of sondes. Studies of SIRS minus analysed differences will be continued in order to improve the understanding of both SIRS and sonde behaviour.

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A NUMERICAL INDEX TO MONITOR THE AFRO-ASIAN MONSOON DURING THE NORTHERN SUMMERS

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SUMMARY

The identification of the core of the major low-level air current of the Afro-Asian summer monsoon at a topographically fixed position over eastern Africa has allowed an attempt to be made to monitor the low-level flow and relate it to rainfall downstream over western India. An index of the southerly flow over eastern Africa at a station a few degrees south of the Equator for the month of July, for a period of 24 years, is compared with the July rainfall of ten stations in the western part of the State of Maharashtra, India.

It is found that months with an index of high or low wind correspond well with months of high or low rainfall respectively, especially when two-year overlapping averages are used. An interesting feature of the analysis is that there is a one-year lag between maxima and minima of the wind index over eastern Africa and the corresponding features of the rainfall of western India. A tentative calculation is made to illustrate how the lag might be used for long-range rainfall prediction.

1. INTRODUCTION

It has been reported earlier (Findlater, 1969a, 1969b and 1971) that the low-level airflow of the Afro-Asian summer monsoon is organized into a narrow high-speed current circulating at about 1·5 km above mean sea level in the western periphery of the monsoon system. A simplified map of the mean flow at 1 km for the month of July is shown in Figure 1, and it is noticeable that the core of the current, though primarily an oceanic phenomenon, passes over the flat arid lands of eastern Kenya, eastern Ethiopia and Somalia.

It was over these land areas that low-level jet streams, with speeds reaching 25–50 m/s, were first noticed some years ago (Findlater, 1966 and 1967). These low-level jet streams, or surges in the major current, have been located over the ocean as well as over land—usually in the vicinity of the axis of maximum flow shown in Figure 1 and orientated along it.

The fact that the axis of the major current passes over land was used in an earlier analysis to monitor the flow at an equatorial station in eastern Africa and, when five-day overlapping means were used, a close relationship between pulsations of the flow over eastern Africa and fluctuations in the rainfall of western India was noticeable (Findlater, 1969a). Similar but unpublished analyses for some other years have confirmed this relationship. It should be noted, however, that the correspondence between cross-equatorial flow over eastern Africa and the rainfall of western India can only be located if the upper-wind stations which are used lie under or very close to the core of the current shown in Figure 1. Attempts to use radar-wind data from Nairobi (01°18′S, 36°45′E, 1798 m above mean sea level) or Dar es Salaam (06°53′S, 39°12′E, 55 m) have proved fruitless because Nairobi is not affected by the current and Dar es Salaam lies on the fringe of it and is distant from the core. Recourse must be had to pilot-balloon data, and the earlier analysis used data from Garissa (00°29′S, 39°38′E, 128 m), a station almost on the Equator and close to the core of the current.

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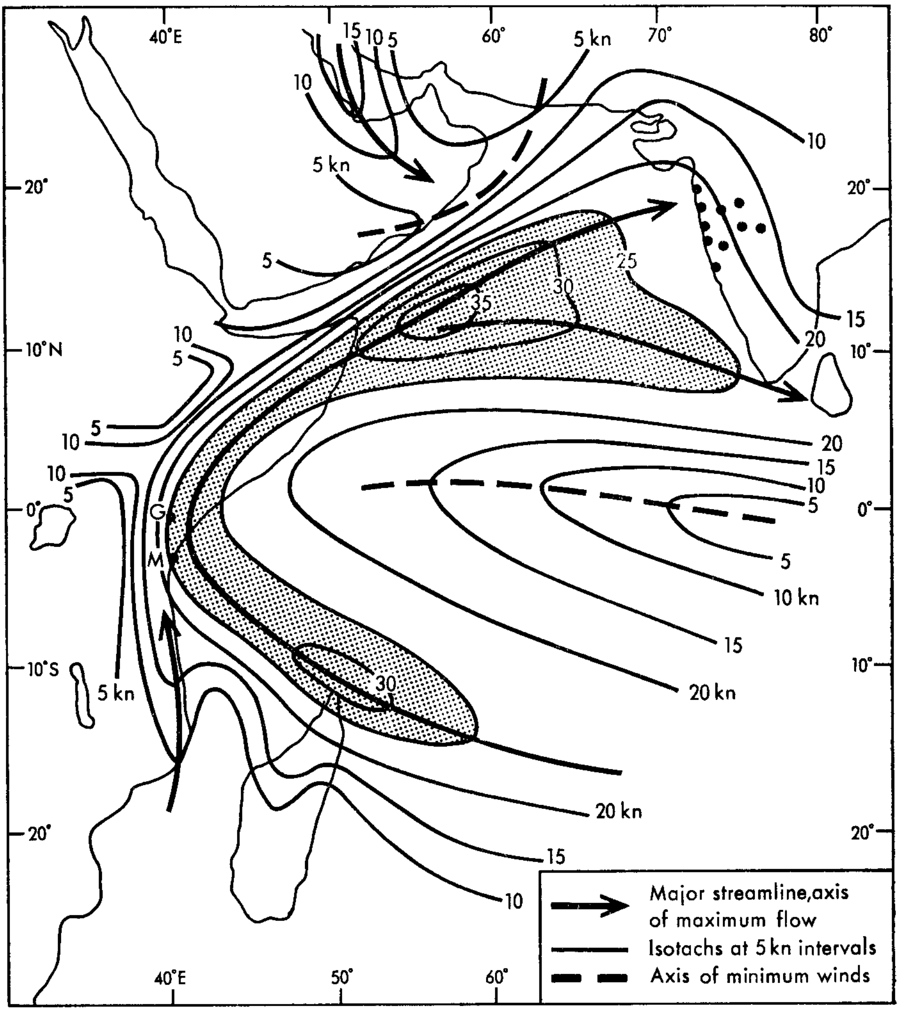

FIGURE 1—MEAN MONTHLY AIRFLOW AT 3000 ft (1 km) IN JULY
M—Mombasa G—Garissa
(The dots over India represent the ten selected rainfall stations.)

The aim of this present study is to monitor the flow over eastern Africa, using mean values for the month of July from as many years as possible, to compare the vigour of the monsoon from year to year and to relate it to the mean July rainfall downstream over western India.

2. SELECTION OF A MONITORING PARAMETER

Although the pilot-balloon station at Garissa is ideally situated for monitoring the flow at the core of the major current where it crosses the Equator, upper-wind soundings commenced there only in 1962. However, another station—Mombasa (04°02′S, 39°37′E, 57 m)—lies close to the position where the core of the current first comes inland from the Indian Ocean, and the length of record of upper winds is much greater. Also, the sounding program at Mombasa has been much more regular than at Garissa. For these reasons Mombasa was selected as the monitor station for this study. The mean characteristics of the low-level flow at these two stations is shown in Figure 2 where the mean southerly and easterly components of the July winds, up to the 3 km level, illustrate the jet-like profile of the southerly wind. The peak value at Garissa is higher because that station lies a little nearer to the core than Mombasa.

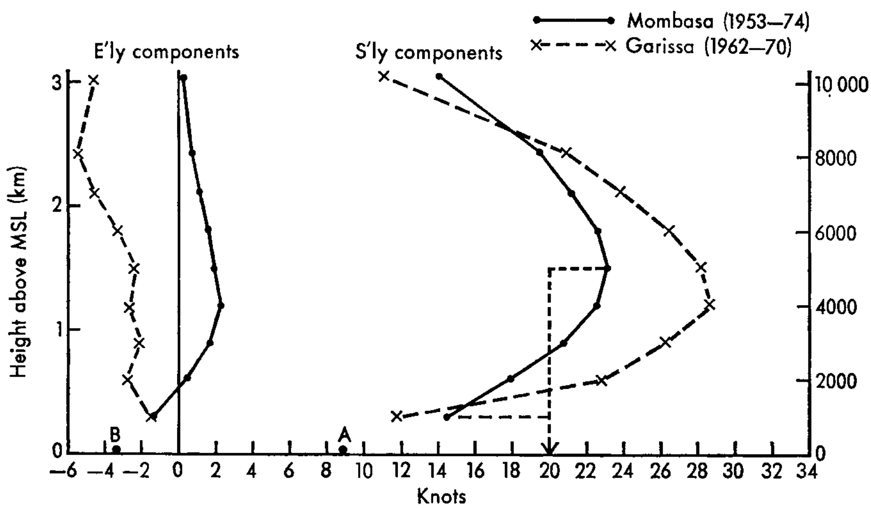

FIGURE 2—MEAN COMPONENTS OF THE LOW-LEVEL CURRENT IN JULY AT MOMBASA AND GARISSA

The index of cross-equatorial flow is the mean of the monthly values of the southerly component at 1000, 2000, 3000, 4000 and 5000 ft above MSL.

For Mombasa the 22-year mean of the index is 20·0 kn.

Points A and B represent the components of the mean daily surface wind in July at Mombasa, as calculated from data given by Ramsey (1971).

When monitoring the flow each July only the lower half of the profile shown in Figure 2 is used because many more pilot balloons reach the 1·5 km level than the 3 km level. The monitor value is calculated for each July as the mean of the southerly components of the wind at the levels of 0·3, 0·6, 0·9, 1·2 and 1·5 km above MSL (corresponding to winds measured at 1000, 2000, 3000, 4000 and 5000 ft above MSL). The 22-year mean of the monitor value for Mombasa for the years 1953 to 1974 is 20·0 kn (=10·3 m/s) and it is shown graphically in Figure 2. The monitor values for July in each of the years 1953–76 are listed in Appendix I*. Extreme values of 16·9 and 22·6 kn have been recorded. The monitor value for each year, hereinafter referred to as the wind index, is also shown in (a) of Figure 3.

*Pilot-balloon winds have been measured at Mombasa since 1937 but all daily records prior to 1953 have been destroyed. Only an incomplete set of monthly frequency tables for a few upper levels remains.

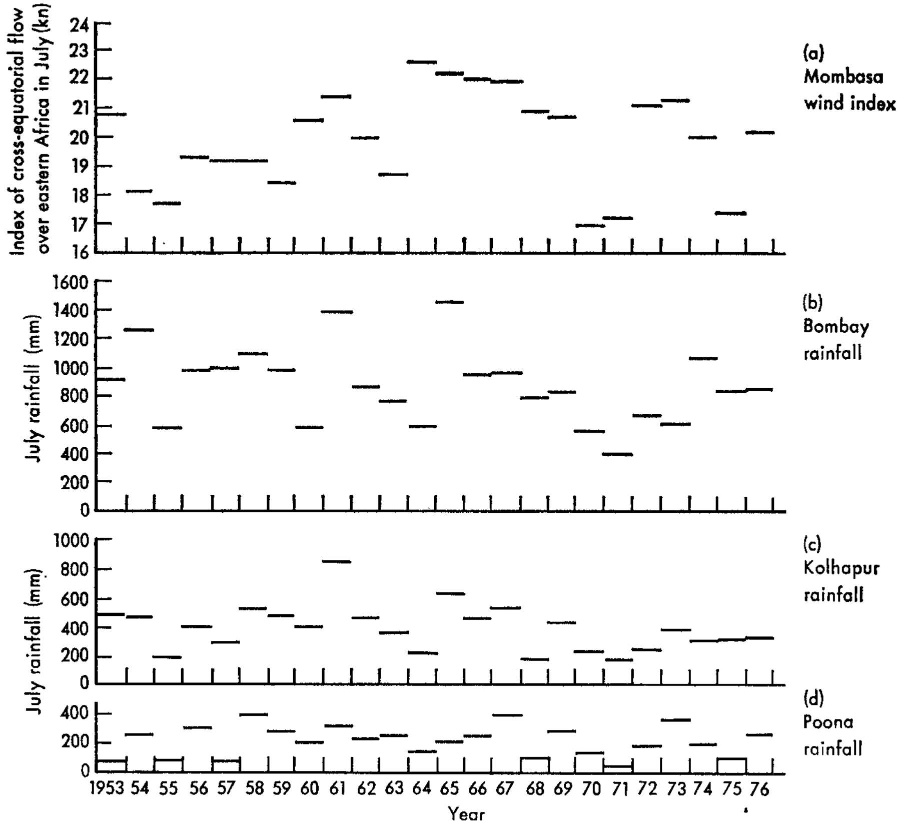

FIGURE 3—CROSS-EQUATORIAL FLOW AT MOMBASA IN JULY (a), AND TOTAL JULY RAINFALL AT THREE STATIONS IN WESTERN MAHARASHTRA (b), (c) AND (d)

(b) represents a high-rainfall station, (c) a medium-rainfall station, and (d) a low-rainfall station.

3. COMPARISON OF LOW-LEVEL FLOW OVER EASTERN KENYA AND THE RAINFALL OF WESTERN INDIA

The July rainfall of western India varies considerably from year to year and (b), (c) and (d) of Figure 3 show the total July rainfall at three stations in the western part of the State of Maharashtra, India for the years 1953–76. The three stations represent a high-rainfall station (Bombay), a medium-rainfall station (Kolhapur) and a low-rainfall station (Poona). The 1953–76 mean July rainfall values at these stations are 873·0, 390·0 and 208·2 mm respectively. Although these stations are at different altitudes and have different exposures, it is clear that all lie in the same rainfall regime. Wet and dry years are generally reflected at all three stations.

Data from these three stations can be combined for comparison with the Mombasa wind index. This comparison is shown in Figure 4. The profiles of

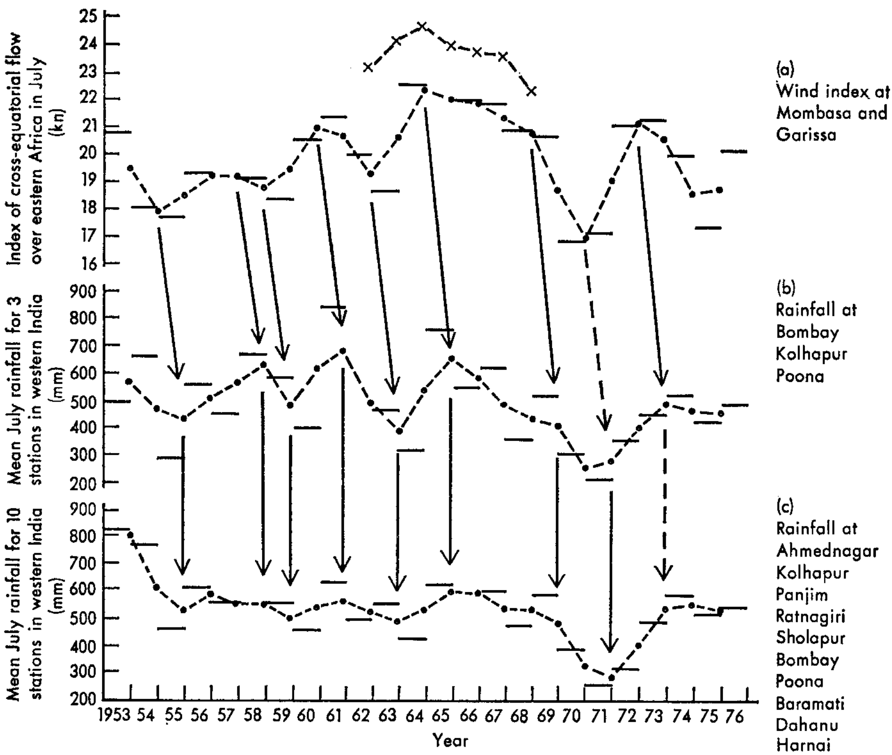

FIGURE 4—COMPARISON OF THE INDEX OF CROSS-EQUATORIAL FLOW OVER EASTERN AFRICA IN JULY (a), THE MEAN JULY RAINFALL AT THREE STATIONS IN WESTERN INDIA (b), AND THE MEAN JULY RAINFALL AT TEN STATIONS IN WESTERN INDIA (c)

The dots represent the mean July value for two consecutive years. The crosses in (a) represent the two-year mean July values at Garissa, for comparison with those of Mombasa.

the wind index, (a) of Figure 4, and of the mean rainfall at the three stations in India, (b) of Figure 4, show some similarities and also some differences. To assist interpretation, two-year overlapping mean values have been calculated. These values, plotted as dots joined by broken lines, illustrate a close association between the two derived parameters. Generally, peaks and troughs are nearly coincident but the striking feature is the lag between the two curves of overlapped mean values. Peaks and troughs in the rainfall lag behind, by one year, the corresponding features of the wind-index curve.

The physical causes of the lag are not yet known but it is hypothesized that the strength of the wind index influences the ocean currents and surface temperatures of the Arabian Sea in such a way that sea-surface temperature anomalies persist for one year, thus affecting the stability of the air, evaporation from the sea surface, and hence the rain-bearing potential of the Indian summer monsoon air. This hypothesis requires verification.

In (a) of Figure 4 crosses have been inserted to represent the two-year overlapping means of the wind index at Garissa in order to illustrate the correspondence between upper-wind stations near the core of the low-level current. The averages for Garissa have not been calculated for the years after 1968–69 because of paucity of data. For example, in 1970 upper-wind measurements at Garissa were made on only nine days in July. Nevertheless the Garissa wind index for earlier years shows the generally higher speeds recorded at that station, and the curve of the two-year averages shows the same trends as at Mombasa.

The comparison of the Mombasa wind index and the Indian rainfall is extended by using a total of ten rainfall stations in western Maharashtra instead of only three; these data are shown in (c) of Figure 4. Again the same general correspondence of curves is evident, though less pronounced, and the one-year lag is seen in both smoothed and unsmoothed values.

All wind and rainfall data used in these analyses are tabulated in Appendix I. Station details are listed in Appendix IV.

The correspondence between the rainfall curves of (b) and (c) of Figure 4 is not solely due to the three rainfall stations of (b) being included in the ten stations used to construct (c), since all stations used in this study show similar features in their rainfall regimes. For example, if another three stations, Dahanu, Harnai and Ratnagiri, are analysed in similar fashion, the pattern is the same and the lag of one year between troughs and ridges in the wind index and rainfall curves is repeated. It should be noted, however, that the relationships reported in this paper do not necessarily apply to rainfall stations which lie outside the area selected for study, or to other months.

4. Rainfall prediction

The lag of one year between significant features of the wind and rainfall, shown in Figure 4, suggests that the curve of Indian rainfall may be extrapolated one year ahead for the month of July only. The trend or change of the two-year mean values of the wind index may be determined and related to the trend of the two-year mean rainfall of western India one year later; for example, the change in the two-year mean wind index between 1953–54 and 1954–55 is −1·6 kn, and is related to the change in the two-year mean rainfall for the ten stations in western India for 1954–55 and 1955–56, −79·2 mm. These comparative values, listed in Appendix III and plotted in Figure 5, are calculated from data given in Appendix I. The line of best fit in Figure 5 is inserted by the method of least squares, whilst parallel and equidistant lines contain the range of observations. The correlation coefficient between the two-year wind-index change and the two-year mean rainfall change one year later is +0·82. Values for the correlation coefficient (r) for a lag varying from −2 to +2 years are:

Lag (years)	−2	−1	0	+1	+2
r	−0·43	−0·54	+0·41	+0·82	+0·04.

Provided that the trends of wind and rainfall over the last 24 years are preserved in future years, and provided that the pilot-balloon data at Mombasa remain sufficiently regular to furnish an accurate measure of the vigour of the cross-equatorial current (and bearing in mind the inherent uncertainty of extrapolating time-series into the future), then the type of diagram shown in Figure 5 might be used for experimental predictions of the July rainfall of western Maharashtra for one year ahead.

For example, the 1974–75 and 1975–76 mean values of the Mombasa wind index are 18·7 and 18·8 kn respectively, a change of +0·1 kn. From Figure 5 a change of +0·1 kn corresponds to a change of +2·0 mm (±80 mm) between the 1975–76 and 1976–77 mean July rainfall for the ten selected stations in western India. Because the 1975–76 mean rainfall is known to be 535·4 mm, the 1976–77 mean value may be predicted to be 535·4 + 2·0 = 537·4 mm (±80 mm).

Furthermore, the 1976 measured value of the rainfall is 551·1 mm and the predicted mean for 1976–77 is 537·4 mm, therefore the predicted mean for July 1977 is:

$$537{\cdot}4-(551{\cdot}1-537{\cdot}4) = 523{\cdot}7 \text{ mm } (\pm 160 \text{ mm}).$$

This predicted amount represents 97 per cent (±29·6 per cent) of the 24-year average July rainfall (540·1 mm) for the ten stations in western Maharashtra. The calculation of the forecast value may also be made graphically by using Figure 5 and (c) of Figure 4.

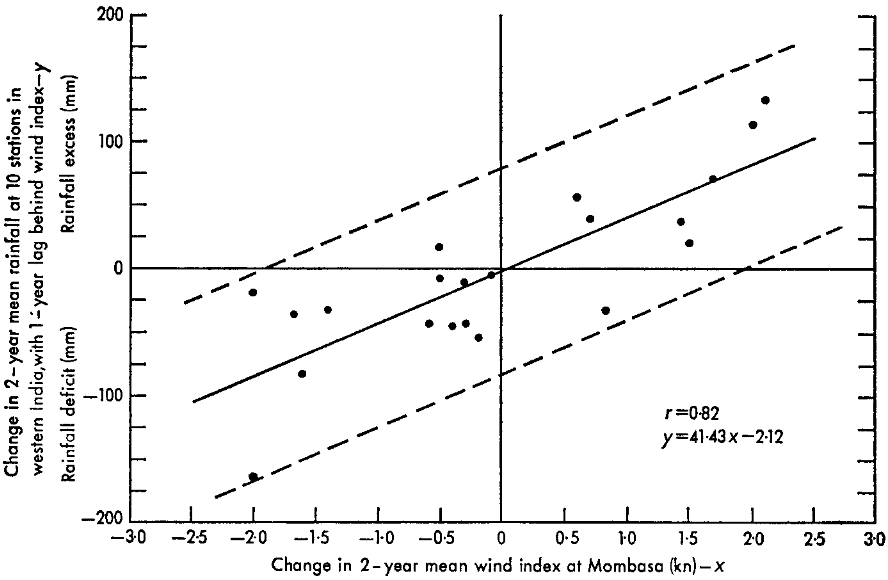

FIGURE 5—CHANGE IN TWO-YEAR MEAN CROSS-EQUATORIAL FLOW OVER EASTERN AFRICA RELATED TO THE CHANGE IN TWO-YEAR MEAN RAINFALL AT TEN STATIONS IN WESTERN INDIA ONE YEAR LATER

If similar calculations are made for all years for which data are available, as in Appendix II, it is evident that the mean July rainfall of the ten selected stations might have been forecast one year ahead with an average error of only 11·3 per cent, had the relationships between the Kenya wind index and the Indian rainfall then been known. The maximum error in the forecasts would have been 29·6 per cent. All details are listed in Appendix II.

Experimental forecasts using this method were made in August of 1972, 1973, 1974 and 1975 for the July rainfall of 1973, 1974, 1975 and 1976 respectively, but data from these years have now been incorporated into the dependent data set and the correlation coefficient and line of best fit have been recalculated to the values now shown. However, it will be many years before the forecasting potential of this method can be adequately tested against an independent data set.

It is not the intention here to propose an operational forecasting technique as such, but rather to demonstrate that careful monitoring of the flow near the core of the cross-equatorial current over eastern Africa and the rainfall downstream over India may yield, after much further study, some relationships which might be useful in forecasting the rainfall of the Indian summer monsoon. This paper is only a short step in that direction.

5. Conclusions

Earlier work relating cross-equatorial flow at low levels over Kenya to the rainfall of western India, using five-day overlapping mean values during the northern summer, indicated that surges and lulls in the cross-equatorial flow were reflected in the rainfall of western India a few days later. This present study attempts to ascribe an index to the core of the cross-equatorial current in July for as many years as possible, so that the vigour of the monsoon current may be compared between years.

This index has been found to vary as the mean July rainfall of western Maharashtra, especially when two-year averages are used.

A feature of considerable interest is that there is a lag of one year in maxima and minima of rainfall behind those of the wind index. This lag may have some long-range predictive value.

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Appendix I—Mean wind index at Mombasa, Kenya, and mean rainfall at stations in Western India: July only

	Wind index		Rainfall														
	Mombasa	Overlapped mean	Ahmednagar	Baramati	Dahanu	Harnai	Kolhapur	Panjim	Ratnagiri	Sholapur	Bombay (Santa Cruz)	Poona	Mean of Bombay, Kolhapur, Poona	Overlapped mean	Mean of all stations	Overlapped mean
	knots		millimetres													
1953	20·8	19·5	136·9	*	837·9	1502·1	484·3	1720·8	1545·3	278·8	922·0	68·6	491·6	576·7	832·9	800·9
1954	18·1	17·9	129·2	117·6	1070·3	1294·6	474·2	1404·8	1501·1	185·9	1264·9	246·4	661·8	472·6	768·9	613·0
1955	17·7	18·5	59·4	62·9	352·2	958·5	192·5	1077·9	1067·0	144·2	586·7	71·1	283·4	422·1	457·2	533·8
1956	19·3	19·3	149·8	89·9	1397·0	571·7	399·7	1064·2	842·7	306·5	983·0	299·7	560·8	506·1	610·4	587·4
1957	19·2	19·2	77·7	27·9	966·7	1117·0	284·9	922·0	1046·9	133·0	993·1	76·2	451·4	561·3	564·5	557·5
1958	19·2	18·8	137·4	65·2	995·2	740·8	519·4	780·4	689·7	83·6	1097·1	397·3	671·3	628·1	550·6	552·8
1959	18·4	19·5	58·3	38·0	1365·6	535·4	484·6	1086·4	590·6	122·0	987·5	282·6	584·9	490·9	555·1	505·3
1960	20·6	21·0	73·4	15·1	629·3	882·9	402·3	825·8	850·0	88·4	589·8	198·2	396·8	622·9	455·5	543·4
1961	21·4	20·7	72·4	35·4	1240·7	797·3	844·3	*	856·2	133·8	1385·5	316·9	848·9	683·5	631·3	564·6
1962	20·0	19·3	33·7	40·6	1031·6	833·6	472·0	*	820·0	168·5	858·3	224·1	518·1	488·7	498·0	524·5
1963	18·7	20·7	110·1	51·5	1177·1	1094·7	365·4	*	1052·2	97·2	760·0	252·1	459·2	387·7	551·1	493·7
1964	22·6	22·4	112·0	54·5	728·1	690·2	225·2	841·4	778·0	210·2	588·3	137·1	316·2	538·8	436·3	530·2
1965	22·2	22·1	126·9	39·0	979·3	758·9	624·9	997·5	907·7	148·1	1455·5	203·8	761·4	654·9	624·2	600·7
1966	22·0	21·9	82·0	84·2	746·7	932·0	458·9	979·4	1137·1	166·6	944·0	241·9	548·3	586·8	577·3	591·4
1967	21·9	21·4	164·5	77·2	714·1	814·8	534·5	1104·0	1029·1	276·8	962·2	379·2	625·3	490·3	605·6	539·9
1968	20·9	20·8	120·9	79·6	533·8	804·5	182·7	1334·7	710·6	91·8	793·9	89·2	355·3	433·9	474·2	533·6
1969	20·7	18·8	180·7	132·8	416·8	1204·3	432·3	843·5	1417·7	197·3	828·8	276·2	512·4	408·1	593·0	492·1
1970	16·9	17·1	45·0	6·9	567·8	549·9	229·5	830·7	850·8	149·8	549·0	132·9	303·8	252·3	391·2	327·1
1971	17·2	19·1	4·3	0·0	358·6	432·4	174·6	760·7	447·7	24·4	384·9	42·6	200·7	277·5	263·0	291·7
1972	21·1	21·2	12·8	2·3	345·8	672·6	241·6	594·0	489·8	24·6	651·2	169·7	354·2	401·1	320·4	403·7

1973	21·3	20·7	80·5	117·3	766·4	731·9	385·5	814·7	887·0	128·4	608·4	350·2	448·0	482·8	487·0	536·0
1974	20·0	18·7	55·9	32·8	989·2	956·2	306·6	1018·7	1160·8	84·3	1066·3	180·0	517·6	466·9	585·0	552·3
1975	17·4	18·8	202·4	43·4	382·4	845·5	317·6	1206·2	1045·3	223·2	835·5	95·9	416·3	448·9	519·7	535·4
1976	20·2		45·8	39·4	826·1	915·5	323·5	1065·0	1081·2	93·7	855·7	265·5	481·6		551·1	
Mean	19·9		94·7	54·5	809·1	859·9	390·0	1013·0	950·2	148·4	873·0	208·2			540·1	

* Data not available

APPENDIX II—TEST OF THE FORECASTING TECHNIQUE USING DEPENDENT DATA AND THE DERIVED RELATIONSHIP,

$$y = 41{\cdot}43x - 2{\cdot}12\text{: JULY ONLY}$$

Change in 2-year mean wind index x Years	knots	Forecast change in 2-year mean rainfall y Years	mm	Actual mean 2-year rainfall a Years	mm	Forecast mean 2-year rainfall $b = a + y$ Years	mm	Actual rainfall c Year	mm	Forecast rainfall $c + 2(b-c)$ Year	mm	Actual rainfall Year	mm	Error mm	Rainfall, percent. of normal F'cast %	Actual %	Error %
53/54—54/55	−1·6	54/55—55/56	−67·9	54/55	613·0	55/56	545·1	55	457·2	56	633·0	56	610·4	+22·6	117·2	113·0	+4·2
54/55—55/56	+0·6	55/56—56/57	+22·7	55/56	533·8	56/57	556·5	56	610·4	57	502·6	57	564·5	−61·9	93·1	104·5	−11·4
55/56—56/57	+0·8	56/57—57/58	+31·0	56/57	587·4	57/58	618·4	57	564·5	58	672·3	58	550·6	+121·7	124·5	101·9	+22·6
56/57—57/58	−0·1	57/58—58/59	−6·3	57/58	557·5	58/59	551·2	58	550·6	59	551·8	59	555·1	−3·3	102·2	102·8	−0·6
57/58—58/59	−0·4	58/59—59/60	−18·7	58/59	552·8	59/60	534·1	59	555·1	60	513·1	60	455·5	+57·6	95·0	84·3	+10·7
58/59—59/60	+0·7	59/60—60/61	+26·9	59/60	505·3	60/61	532·2	60	455·5	61	608·9	61	631·3	−22·4	112·7	116·9	−4·2
59/60—60/61	+1·5	60/61—61/62	+60·0	60/61	543·4	61/62	603·4	61	631·3	62	575·5	62	498·0	+77·5	106·5	92·2	+14·3
60/61—61/62	−0·3	61/62—62/63	−14·5	61/62	564·6	62/63	550·1	62	498·0	63	602·2	63	551·1	+51·1	111·5	102·0	+9·5
61/62—62/63	−1·4	62/63—63/64	−60·1	62/63	524·5	63/64	464·4	63	551·1	64	377·7	64	436·3	−58·6	69·9	80·8	−10·9
62/63—63/64	+1·4	63/64—64/65	+55·9	63/64	493·7	64/65	549·6	64	436·3	65	662·9	65	624·2	+38·7	122·7	115·6	+7·1
63/64—64/65	+1·7	64/65—65/66	+68·3	64/65	530·2	65/66	598·5	65	624·2	66	572·8	66	577·3	−4·5	106·1	106·9	−0·8
64/65—65/66	−0·3	65/66 66/67	−14·5	65/66	600·7	66/67	586·2	66	577·3	67	595·1	67	605·6	−10·5	110·2	112·1	−1·9
65/66 66/67	−0·2	66/67—67/68	−10·4	66/67	591·4	67/68	581·0	67	605·6	68	556·4	68	474·2	+82·2	103·0	87·8	+15·2
66/67—67/68	−0·5	67/68—68/69	−22·8	67/68	539·9	68/69	517·1	68	474·2	69	560·0	69	593·0	−33·0	103·7	109·8	−6·1
67/68—68/69	−0·6	68/69—69/70	−27·0	68/69	533·6	69/70	506·6	69	593·0	70	420·2	70	391·2	+29·0	77·8	72·4	+5·4
68/69—69/70	−2·0	69/70—70/71	−85·0	69/70	492·1	70/71	407·1	70	391·2	71	423·0	71	263·0	+160·0	78·3	48·7	+29·6
69/70—70/71	−1·7	70/71—71/72	−72·5	70/71	327·1	71/72	254·6	71	263·0	72	246·2	72	320·4	−74·2	45·6	59·3	−13·7
70/71—71/72	+2·0	71/72—72/73	+80·7	71/72	291·7	72/73	372·4	72	320·4	73	424·4	73	487·0	−62·6	78·6	90·2	−11·6
71/72—72/73	+2·1	72/73—73/74	+84·9	72/73	403·7	73/74	488·6	73	487·0	74	490·2	74	585·0	−94·8	90·8	108·3	−17·5
72/73—73/74	−0·5	73/74—74/75	−22·8	73/74	536·0	74/75	513·2	74	585·0	75	441·4	75	519·7	−78·3	81·7	96·2	−14·5
73/74—74/75	−2·0	74/75—75/76	−85·0	74/75	552·3	75/76	467·3	75	519·7	76	414·9	76	551·1	−136·2	76·8	102·0	−25·2
74/75—75/76	+0·1	75/76—76/77	+2·0	75/76	535·4	76/77	537·4	76	551·1	77	523·7	77	—	—	97·0	—	—

Average error = 61·0 mm 11·3 %

= 11·3 per cent of the 24-year average July rainfall for the 10 stations in western India (540·1 mm).

APPENDIX III—CHANGE IN 2-YEAR MEAN WIND INDEX RELATED TO CHANGE IN 2-YEAR MEAN RAINFALL ONE YEAR LATER

Change in 2-year mean wind index at Mombasa, Kenya		Change in 2-year mean rainfall at ten selected stations in western India, one year later	
	knots		*mm*
1953/54—1954/55	−1·6	1954/55—1955/56	−79·2
1954/55—1955/56	+0·6	1955/56—1956/57	+53·6
1955/56—1956/57	+0·8	1956/57—1957/58	−29·9
1956/57—1957/58	−0·1	1957/58—1958/59	−4·7
1957/58—1958/59	−0·4	1958/59—1959/60	−47·5
1958/59—1959/60	+0·7	1959/60—1960/61	+38·1
1959/60—1960/61	+1·5	1960/61—1961/62	+21·2
1960/61—1961/62	−0·3	1961/62—1962/63	−40·1
1961/62—1962/63	−1·4	1962/63—1963/64	−30·8
1962/63—1963/64	+1·4	1963/64—1964/65	+36·5
1963/64—1964/65	+1·7	1964/65—1965/66	+70·5
1964/65—1965/66	−0·3	1965/66—1966/67	−9·3
1965/66—1966/67	−0·2	1966/67—1967/68	−51·5
1966/67—1967/68	−0·5	1967/68—1968/69	−6·3
1967/68—1968/69	−0·6	1968/69—1969/70	−41·5
1968/69—1969/70	−2·0	1969/70—1970/71	−165·0
1969/70—1970/71	−1·7	1970/71—1971/72	−35·4
1970/71—1971/72	+2·0	1971/72—1972/73	+112·0
1971/72—1972/73	+2·1	1972/73—1973/74	+132·3
1972/73—1973/74	−0·5	1973/74—1974/75	+16·3
1973/74—1974/75	−2·0	1974/75—1975/76	−16·9
1974/75—1975/76	+0·1	1975/76—1976/77	?

Correlation coefficient (r) = +0·82 (significant at the 1 per cent level of probability).

APPENDIX IV—LIST OF STATIONS USED IN THE ANALYSIS

For wind analysis

Station No.	Station	Position	Height above MSL *metres*
63723	Garissa	00°29′S 39°38′E	128
63820	Mombasa	04°02′S 39°37′E	57

For rainfall analysis

Station No.	Station	Position	Height above MSL *metres*
43009	Ahmednagar	19°05′N 74°48′E	657
43069	Baramati	18°09′N 74°35′E	551
43001	Dahanu	19°58′N 72°43′E	5
43109	Harnai	17°49′N 73°06′E	20
43157	Kolhapur	16°42′N 74°14′E	570
43192	Panjim	15°29′N 73°49′E	57
43110	Ratnagiri	16°59′N 73°20′E	35
43117	Sholapur	17°40′N 75°54′E	479
43003	Bombay (Santa Cruz)	19°07′N 72°51′E	14
43063	Poona	18°32′N 73°51′E	559

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NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1976

By D. H. McINTOSH and MARY HALLISSEY
(Department of Meteorology, University of Edinburgh)

Table I summarizes the observations of noctilucent clouds (NLC) made over western Europe and the Atlantic during 1976 and reported to the Department of Meteorology, Edinburgh University.

Observers' reports, positive or otherwise, were requested for the months May to August. As in previous years, sightings were confined to the period from late May to early August. The periods of time during which the clouds were observed appear in the second column of the Table. These should not be taken as being necessarily the total duration of the display; this is stated where possible, but it is obviously difficult, particularly for voluntary observers, to record a display to the point of disappearance. Brief notes on the displays appear in the third column. In the remaining columns, details of the relevant station co-ordinates are listed to the nearest half degree, and the maximum elevation and limiting azimuths of the observed cloud, where known.

Positive reports were received from some 30 stations of the Meteorological Office station network of Great Britain and of the Meteorological Service of Ireland, ranging from Lerwick to Mount Batten, Plymouth, and from Birr to Wattisham; also from a Fair Isle lighthouse-keeper and from 10 voluntary observers scattered throughout the UK, Denmark and Norway. We are grateful to Drs Gadsden and Jenkins of Aberdeen University for observations recorded in their log in connection with their work for the International Magnetospheric Study on the polarization of NLC.

Records of tropospheric cloud amounts were also received from Meteorological Office stations, including nights on which no positive observations of NLC were made. The confirmed absence of NLC, especially during what is statistically their peak incidence time (mid-June to mid-July) is now regarded as significant 'negative' information. Unfortunately, the incidence of tropospheric cloud and haze was rather high during this four week period and no negative finding can be regarded as definitely confirmed.

Time-lapse photography of the clouds was carried out on most nights from Edinburgh and revealed one occasion, in particular, on which there was a dramatic invasion of the sky, by movement of the clouds from the north, late in the night.

A special study of the display of 18–19 June was made by an observer, Dr D. A. R. Simmons of Milngavie, near Glasgow, whose paper on the event has been accepted for publication in *Weather*.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE AND THE ATLANTIC DURING 1976

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. *degrees*	Limiting azimuths *degrees*
27/28 May	0130	Patch of NLC seen from train when observer travelling NE England	54·5N 01·5°W	0130	5	

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position*	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
2/3 June	2210–0200	Some doubt by observers in Aberdeen as to authenticity of NLC to high elevation before 2300 but NLC seen clearly from more southerly stations one of which later reported veil and billow formation. From northerly station NLC faint and diffuse without marked regular structure. At 0020 as seen from Aberdeen northern edge of cloud field clear of N horizon.	57°N 02°W	2220	50	045
				2315	5	340–045
				0020	10	045
			55·5°N 01·5°W	2330	7½	330–010
				0050	9	350–010
			55°N 04·5°W	2230	15	020
			54°N 04·5°W	2400	5	345–015
				0200	10	340–040
5/6	0115–0150	NLC already at max. when first seen at 0115: compact herring-bone-pattern patch with N edge 11° NNE–NE. Intensity, never high, faded progressively until dawn, around 0200.	56°N 04·5°W	0115	27	014–043
6/7	0001–0030	Fairly bright but featureless bands seen from southern position; later seen in breaks in tropospheric cloud from Edinburgh.	56°N 03°W	0030		
			51°N 02°W	0001	7	340–015
7/8	2110–0215	Bright NLC with fine herring-bone structure seen from Denmark (photographs available): marked longitudinal extension to east; from Liverpool seen as veil background to brighter bands, fading into haze.	56°N 03°W	2240	10	310–360
			55·5°N 12°E	2200		
			55°N 14·5°E	2110	40	270–020
				2245	18	315–070
				2328	11	315–070
			53·5°N 03°W	0110	5	020–040
				0200	3	020–040
8/9	2200, 2230	NLC visible through breaks in tropospheric clouds in Denmark; herring-bone pattern discernible Edinburgh.	56°N 03°W	2230	30	
			55·5°N 12°E			
9/10	2400, 0200	Details obscured by cloud from Ronaldsway; banded structure discernible from Watnall.	54°N 04·5°W			340–020
			53°N 01·5°W	0200	10	340
10/11	2330	Moderately bright NLC above cloud bank to 5°. Fairly extensive cloud field, but E limit hidden by tropospheric clouds.	56°N 03°W	2330	12	
17/18 June	0045–0200+	Very bright bands and billows with veil background became visible after midnight from Newcastle. Earlier in Denmark, NLC recognized in tropospheric cloud breaks.	55°N 14·5°E	2150	5	360
			55°N 01·5°W	0045	10	340–020
				0145	15	350–030
18/19	2340–0300	Earliest sighting of bright bands from Ronaldsway, I.O.M. Max. extension southwards around 0200 when southern edge of cloud field, though obscured by tropospheric clouds at many stations, was overhead at Boulmer, Northumbria, and to elevation of 160° from Aberdeen. NLC structure described variously as 'tangled', 'feathery'. Measurements made from series of photographs taken near Glasgow.	57·5°N 03·5°W	2400	21	340–020
			57°N 02°W	2345	22	340–020
				0030	28	315–020
				0200	160	135
			56·5°N 03°W	2400	20	340–010
			56°N 04·5°W	0030	25	340–040
				0130	25	330–040
			56°N 03°W	2345	15	340
			55·5°N 01·5°W	0100	15	330–030
				0200	85	330–070
			54·5°N 06°W	0115		340–080
				0200		330–110
			54°N 04·5°W	2340	10	320–023
				0040	12	320–040
				0200	20+	320–090+
19/20	2330–2350	Short-lived period of visibility before NLC obscured by tropospheric cloud.	55·5°N 05°W	2330	10	315
21/22	2300	In UK brief recognition through tropospheric cloud break—no identification of form. Bright display seen Denmark above tropospheric cloud to 10°.	57°N 02°W	2300	45	045
			56°N 03°W	2308		
			55·5°N 12°E	2200	25	340–045
			53°N 01·5°W	2300		360
22/23	0030	In Edinburgh NLC glow visible through tropospheric cloud covering N sky to zenith.	56°N 03°W	0030		
	0518–0553	NLC visible from aircraft over Newfoundland.	48°N 55°W	0530		
23/24	2315	NLC visible through breaks in tropospheric cloud.	56°N 03°W			

* To nearest 0·5 degree.

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
24/25	2310	Faint NLC above cloud bank to 10°.	56°N 03°W	2310	20	360
26/27	2400–0200	Veil with band formation visible from all reporting stations (including the top of Ben Lomond). Extensive sighting and detailed report from Aldergrove; there, as earlier in Denmark, bands, billows and whirl formations identified, the tenuous structure thickening into broad bands at southern edge before fading in brightening sky. 4° elevation of northern edge as seen from Aldergrove.	56°N 04·5°W	2400	15	345–015
			56°N 03°W	2315	15+	
			55·5°N 07·5°W	2400	11	360–040
				0200	21	355–060
			55·5°N 01·5°W	0100	13	022–045
			55·5°N 12°E	0030		360–045
			55°N 14·5°E	2100	25	360–045
				2120	30	340–045
				2140	30	340–045
			55°N 04·5°W	0110		
			54·5°N 06°W	2400	12	350–040
				0100	17	350–045
				0130	20	350–050
			54°N 04·5°W	0100	5	345–015
			53°N 01·5°W	0100	6	360–020
				0200	12	340–030
27/28	2234–0200	Steady, slow-moving display seen Ireland and I.O.M., mainly in NW sky, and in tropospheric cloud breaks Edinburgh. Weak veil and brighter bands, with whirl formation suspected around 2300.	56°N 03°W	2310		330
			54·5°N 06°W	2300	14	290–020
				0100	7	340–360
			54°N 04·5°W	2250	11	300–355
				2350	12	325–020
			53·5°N 07·5°W	2300	11	310–015
				0100	7	340–040
				0200	8	350–020
28/29	2250, 0100	Faint patches of NLC in clear sky seen from NE England, and above haze layer (to 5°) from Edinburgh.	56°N 03°W	2250	5+	360
			55·5°N 01·5°W	0100	9	340–040
29/30	2345–0245	NLC visible to low latitudes over UK—seen first from Norfolk just above and parallel to N horizon; developed to herring-bone formation. Stacking of S-shaped bands seen Northolt 0140. NLC visible very brightly 0145–0245 from Plymouth. Intense glow in NNE reduced to bright fibrous strands as sun rose. Southerly stations reported orange tinge at N edge of cloud field. Maximum extension around 0200.	54·5°N 06°W	0200	14	340–030
			53°N 08°W	0200	20	360–030
			52·5°N 0·5°E	0005	2	010
				0145	5	310–020
			52°N 01°E	0020	4	360
				0200	16	330–010
				0225	12	310–360
			51·5°N 02°W	0200	10	340–020
			51·5°N 0·5°W	0045	4	347–352
				0100	5	340–025
				0125	8	330–030
				0200	10	320–020
			51°N 01·5°W	0200	4	016
			50·5°N 3·5°W	0151	10	340–010
			50·5°N 05°W	0145	17	350–070
				0245	12	350–070
30 June/1 July	2300–0220	Display visible only in northern and central Ireland, possibly due to haze interference in many areas. When clear of haze, NLC forms very bright, e.g. around 0200 as seen Aldergrove.	55·5°N 07·5°W	0030	11	350–360
			54·5°N 06°W	0200	9	350–080
				0220	12	
			53°N 08°W	2300	20	330–360
1/2	2250–2400	In Aberdeen two observers, independently, suspected presence of NLC visible through haze at high elevation.	57°N 02°W	2310	70	360–090
5/6	2200–2230	NLC visible Denmark with gradually increasing brightness.	55·5°N 12°E	2200		315
6/7	2320–0300	Prolonged, extensive and bright display of NLC widely reported Scotland, N and central England, though seen dimly through haze in some areas. N–S direction of bands with fibrous cross structure. At 0200 bright band stretched almost to zenith over Leuchars, and at Boulmer 0220–0230 NLC reached high elevation to east and west of station. Whirl formation reported at 0145–0215. Elevation of N edge unreliable due to haze.	57·5°N 03·5°W	0100		
			57°N 02°W	2340	9	340
			56·5°N 03°W	2330	15	310–030
				0030	14	335–015
				0115	17	320–025
				0200	56	320–025
			56°N 03°W		15	
			55·5°N 01·5°W	0145	22½	340–050
				0210	25	360
				0220	45	330
				0230	25	360
			53°N 0·5°W	0200	13	340–060
/10 July	2315	Band of NLC visible NW–NE from Edinburgh.	56°N 03°W	2315	7	345–045
1/12	2100–2220	NLC seen, as soon as sky darkened, to occupy large area of twilit hemisphere—to zenith as seen from W. Yorks. and Berkshire—until obscured by moonlit tropospheric clouds. NLC photographed 2210 W. Yorks.	54°N 02°W	2150	80	
				2203	45	265–030
				2220	20	290–360
			53°N 0·5°W	2200	12	345–360
			51·5°N 0·5°W	2200	65	345–360

TABLE I—*continued*

Date—night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
12/13	2250	NLC visible through breaks in tropospheric cloud (to 13°).	56°N 03°W	2250	13+	045
15/16	2330	Low elevation NLC seen after clearing of tropospheric cloud; thin delicate structure.	57·5°N 03·5°W	0100	12	340–015
	0050–0215		57°N 02°W	0100	12	340–010
			56°N 03°W	2320	10	340
			55·5°N 04·5°W	0145	4	340–010
			55°N 04·5°W	0150		
16/17	0200	Short-lived appearance of NLC in E in break in tropospheric cloud.	57·5°N 03·5°W	0200	10	080–090
18/19	0030	Compact formation NLC from NE horizon to 40° elevation seen Norway.	59°N 09°E	0030	40	045
20/21	2346–0220	Whirl formation seen from northerly stations; more general reporting of bright bands spreading to high elevation over N Scotland and visible from central England. NLC photographed Aberdeen 2353–0219. Observation from Denmark hampered by cloud and moonlight, but brightening NLC bands seen in cloud breaks.	57°N 02°W	2346		020
				0050		320–030
				0150		350–070
			56°N 03°W	0115		360, 020
			56°N 10°E	0005	10	045
				0055	12	340–060
			55·5°N 01·5°W	0100	7½	360–030
				0200	7½	360–030
			53°N 01·5°W	0200	4	020
21/22	2200, 0100	Possible display of NLC bands high in SE seen Norway; faint NLC suspected Edinburgh.	59°N 09°E			
			56°N 03°W	0100		020
24/25	2335–0100	In Denmark bands of NLC seen first through breaks in tropospheric cloud; varying brightness; photographed 0047.	56°N 10°E	2335	6	340–360
				0035	8	360
				0100	10	360
25/26	2135–0105	In Denmark first seen faintly in fine observing conditions to 12° but disappeared 2205. Visible again 2400 with finely striated structure fading later into light sky.	56°N 10°E	2135	12	315–360
				2400	5	315–360
				0030	7	315–360
31 July/1 Aug.	0040–0200	Very bright display of NLC with typical band and billow formation of degree of brightness and extent not previously seen by the observer at this time of year. Series of photographs.	56°N 10°E	0040	5	360–045
				0050	8	
				0113	10	
				0135		340–090
2/3 Aug.	2145	Possible weak display of NLC reported at earlier time from Norway. From 0145 to about 0300 bright NLC bands visible from two of most northerly Met. stations and Fair Isle lighthouse to remarkably high elevation in conditions almost clear of tropospheric cloud.	60°N 01°W	0200	15	020–080
	0145–0305+			0210	19	
				0230	23	
				0245	31	
			59°N 03°W	0145	8	010–040
				0230	12	010–045
				0250	14	020–050
			59°N 09°E	2145	90	360
19/20	0400	Suspected NLC	53°N 01·5°W	0400	22	070

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EVALUATING THE PROBABILITY OF HEAVY RAIN

By M. C. JACKSON

SUMMARY

Some of the weaknesses of the traditional Bilham methods for estimating rainfall depth, duration and return period are discussed. It is shown how much improved estimates for anywhere in the United Kingdom can be made using the methods described in Volume II of the *Flood Studies Report* (Meteorological Office, 1975).

The methods are based on maps of the 60-minute and 2-day rainfalls with return period 5 years. This paper describes how to obtain estimates of rainfall for the same return period for other durations using these two basic maps, and also how to extend rainfall estimates up to return periods of 1000 years. A method of estimating areal rainfall from the already derived point rainfalls is also described.

1. INTRODUCTION

Engineers concerned with urban drainage, sewerage, management of river catchments, planning construction, etc. have for many decades requested information about rainfall amount and return period for different parts of the country and for various durations and sizes of area. (A rainfall with return period T years is one that has a probability of $1/T$ of being equalled or exceeded in any one year.) In the past such enquiries have usually been answered by reference to the Bilham equation and tables, which gave the engineer an estimate of the probability of return period of a specified amount of rain falling in a specified duration. The equation was first presented in *British Rainfall* (Bilham, 1935).

However, the amount of data used by Bilham was limited to only 120 station years; other weaknesses are that only one equation was derived to represent the whole of the United Kingdom, and that durations were limited to two hours or less. Consequently estimates of rainfall with return period greater than 5 years were often in considerable error.

A modified Bilham equation (Holland, 1964) was more complex, adjusting the results when the intensity is greater than 1·25 inches per hour (32 millimetres per hour). However, no other changes were made to improve estimates of rainfall values with return periods greater than 5 years, and, in fact, further rainfall values for durations from 2 hours to 24 hours were obtained by simply extrapolating the Bilham equation beyond 2 hours.

Consequently there has been a need for many years both to collect many more data and to devise techniques for accurately estimating depth, duration and return period information for individual places in the United Kingdom.

In 1969 a major project, the United Kingdom Flood Studies, was established by the Natural Environment Research Council (NERC). The meteorological studies were directed by A. F. Jenkinson of the Meteorological Office, and one of the main products of the three years' work (1970–73) was Volume II (Meteorological Studies) of a comprehensive *Flood Studies Report* (Meteorological Office, 1975). For this work 3000 station years of data from autographic recording rain-gauges and 40 000 station years of daily rainfall data were collected and analysed. Most of the methods described by A. F. Jenkinson and M. C. Jackson in the *Flood Studies Report*, and by Jenkinson (1976), and described briefly in this paper, can be used to give estimates of rainfall and return period for different parts of the country and for various durations and various sizes of area.

More recently some of the calculations have been made by computer, and Keers and Westcott (1977) describe these computer programs.

2. Mapping the magnitude of rainfall events with return period 5 years

Key parameters were needed which could be mapped to give fundamental values on which to base estimates of rainfall amounts with long return periods (as well as being used to standardize the very large amounts of information obtained from the data). The key return period chosen was 5 years, and events for all durations with a return period of 5 years (sometimes called the M5) were linked together.

A return period of 5 years was chosen as a standard since it satisfies two basic requirements: (i) the larger the return period which is used as a standard, the better will be the estimation of events with even larger return periods, (ii) the smaller the return period, the better the chance of estimating its value accurately. The return periods satisfying (i) and (ii) are between 2 and 20 years, and 5 years was chosen for theoretical reasons. (The magnitude of the M5 rainfall event can be estimated by the reader by calculating the geometric mean of the top half of an ordered set of annual maxima—see *Flood Studies Report*, Volume II, Chapter 2.2.)

In order that M5 events can be estimated at any specific place for all durations, the magnitude of the M5 event for each of two durations at that place are calculated, and then, with a relationship derived from all the data, the magnitudes of the M5 event for all the other durations can be estimated (Section 3).

The two key durations chosen for M5 mapping were 60 minutes (Figure 1) and 2 rainfall days (Figure 2), after *Flood Studies Report*, Volume II, Figures 3.6* and 3.3 respectively. Sixty minutes is the shortest duration for which rainfall is usually tabulated. One rainfall day (0900–0900 GMT) would seem the most logical duration for the second key event, with many cyclonic disturbances giving heavy rain which lasts for about a day. However, the rainfall event is often cut in two by an 0900 observation: this problem is overcome by choosing a duration of 2 rainfall days. The 2 rainfall-day event is smaller than the 48-hour event because a 48-hour event can commence at any hour of the day and continue for 48 hours, while the 2 rainfall-day event, although lasting for 48 hours, can only start at the 0900 morning observation. The ratio of the 48-hour event to the 2 rainfall-day event with the same return period is approximately 1·06—see *Flood Studies Report*, Volume II, Chapter 3.3.3. The same happens with rainfall data for 60 minutes compared with a clock hour and with data for 30 days compared with a calendar month.

3. Estimation of the magnitudes of rainfall events with return period 5 years for all durations at any place

Autographic rainfall data from recording rain-gauges in the United Kingdom were analysed extensively to give the table below. Given the values of the M5 rainfall for duration 60 minutes and 2 rainfall days, and the ratio of the two values, Table I allows estimates to be made for durations from 1 minute to 48 hours. Table I is based on *Flood Studies Report*, Volume II, Tables 3.6 and 3.7.

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* The map originally published as 3.6 was inserted in error, and a corrigendum has been issued.

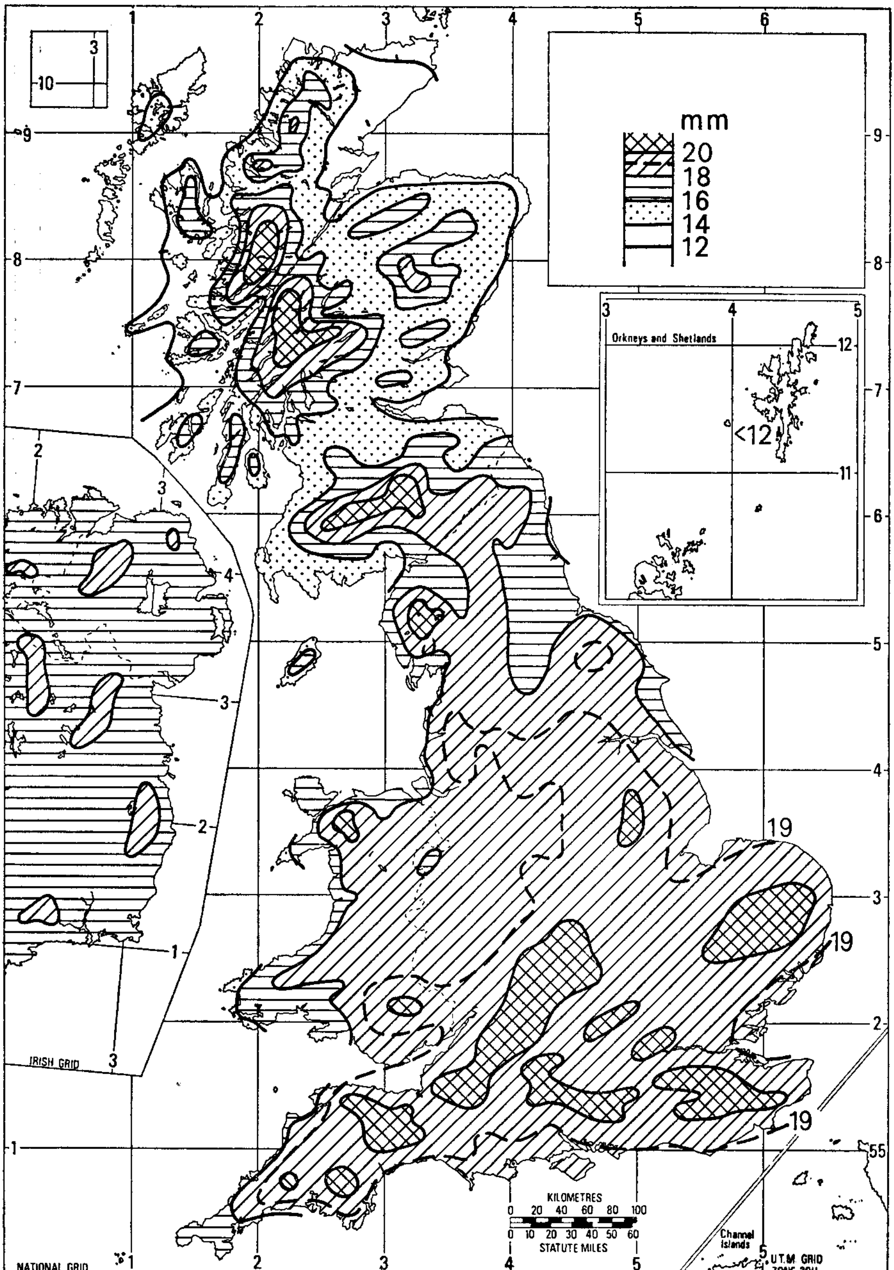

FIGURE 1—MAP OF RAINFALL AMOUNT FALLING IN 60 MINUTES WITH RETURN PERIOD 5 YEARS (M5)

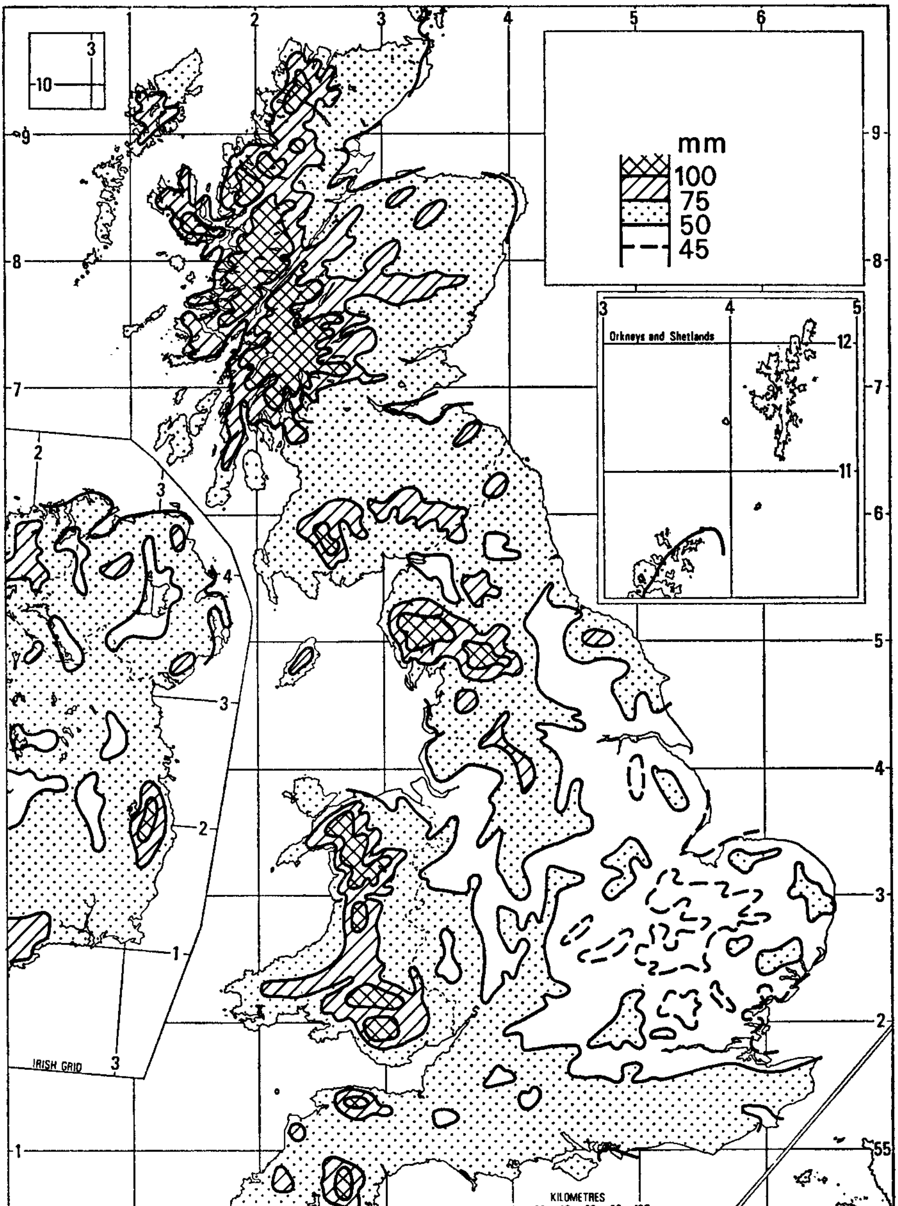

FIGURE 2—MAP OF RAINFALL AMOUNT FALLING IN 2 RAINFALL DAYS WITH RETURN PERIOD 5 YEARS (M5)

TABLE I—METHOD OF ESTIMATING M5 RAINFALL FOR ALL DURATIONS

r	Duration (d) in minutes							Duration (D) in hours					
	1	2	5	10	15	30	120	2	4	6	12	24	48
				x							X		
0·44	12	21	38	54	64	83	120	53	63	68	79	92	106
0·39	11	20	36	52	62	81	123	47	57	63	75	89	106
0·32	11	19	35	50	60	79	126	40	50	56	70	86	106
0·26	11	18	33	47	57	76	130	34	43	50	65	83	106
0·22	10	17	31	45	54	74	134	29	39	46	61	80	106
0·17	9	15	27	41	50	71	139	24	33	40	55	77	106
0·12	7	12	23	35	45	67	149	18	26	33	49	72	106

r = ratio of M5 rainfall for 60 minutes to M5 rainfall for 2 days.
x = ratio (per cent) of M5 rainfall for d minutes to M5 rainfall for 60 minutes.
X = ratio (per cent) of M5 rainfall for D hours to M5 rainfall for 2 days.

The relationship of M5 rainfall with duration at any one station fits a simple numerical model, described in *Flood Studies Report*, Volume II, Chapter 3.6:

$$\ln I - \ln I_0 = -n \ln (1 + BD)$$

where I is the rainfall intensity (mm/h),
I_0 is the rainfall intensity for very short durations (viz. 15 s),
D is the duration in hours,
B and n are factors which are constant for any particular location.

Values of I_0 range from 175 mm/h at stations in south-east England to less than 100 mm/h in Scotland, while n ranges from 0·77 in south-east England to less than 0·60 in mountainous parts of Scotland, and B ranges from 15 in the drier parts of the country to more than 30 in wetter, more mountainous regions.

4. ESTIMATION OF THE MAGNITUDE OF EVENTS WITH OTHER RETURN PERIODS

It is usually necessary to know the magnitudes of rainfall events with return periods longer than 5 years. The rate of increase of rainfall with return period varies from station to station, reflecting the details of the heaviest falls at each station. However, when dozens of stations are gathered together into regions, the regional average rate of increase becomes more or less the same, wherever the region is. Because of this, rainfall data for the whole country were used to establish the ratios of the T-year event to the 5-year event, MT/M5, called the growth factor.

In Figure 3, drawn from Table 2.7 of *Flood Studies Report*, Volume II, the growth factor is shown against the magnitude of the M5 rainfall event: a single set of curves is sufficient to estimate rainfalls with return periods other than 5 years in widely different places, such as Cambridge and Snowdonia, even though their other rainfall characteristics are so different. For example, if the 6-hour M5 event in Snowdonia and the 24-hour M5 event in Cambridge are of the same magnitude, then the events with longer return periods, but still of these same durations, are also of the same magnitude.

In fact there are some small differences in growth factor from region to region; the differences between north and south are just large enough to justify treatment as two separate regions; England and Wales (Figure 3), and Scotland and Northern Ireland (not given)—see *Flood Studies Report*, Volume II, Chapter 2.3. Growth factors were calculated for return periods of up to 1000 years, with

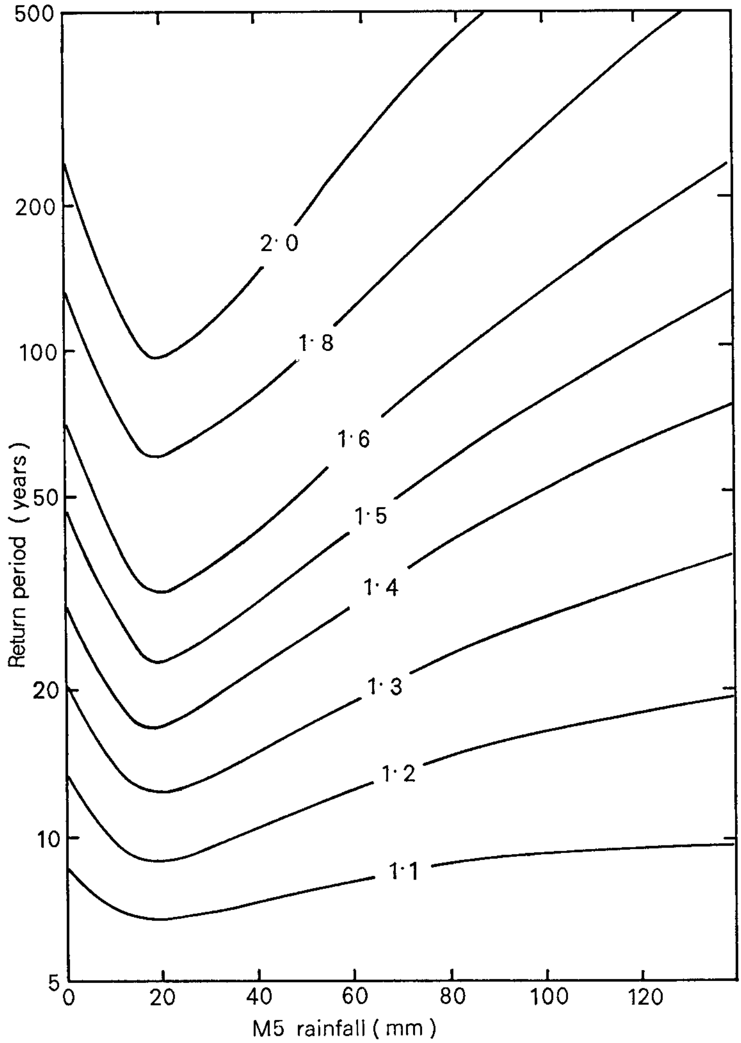

FIGURE 3—RATIO OF *T*-YEAR RAINFALL EVENTS TO 5-YEAR EVENTS PLOTTED AGAINST 5-YEAR RAINFALL (M5) AND RETURN PERIOD; SUITABLE FOR ANY POINT IN ENGLAND AND WALES

rough estimates for as much as 10 000 years: quite clearly the larger the return period, the less confidence we have in the estimate. For further discussion of this, the reader is referred to *Flood Studies Report*, Volume II, Chapter 2.3.

5. MAGNITUDE OF A RAINFALL EVENT OVER AN AREA

Engineers are often more interested in the magnitude of an areal rainfall event over a given catchment than in a point event such as those just described. To meet this requirement, areal reduction factors have been calculated, which depend on the size of the area and the duration of the event. When an areal reduction factor is multiplied by the value for the point rainfall event, the product gives the magnitude of the areal rainfall event with the same duration and the same return period. It must be emphasized that this type of areal reduction factor is used both here and in the *Flood Studies Report*; it is not applicable to individual point-centred storms, but is for catchments which are independent of storm location.

The factor is smallest for small durations and over large areas, approaching unity as the area becomes smaller and the duration larger. Some point-centred reduction factors for the country were produced by Holland (1964), but the factors needed here for this kind of calculation are very different from Holland's. A graph for areas of size between 10 and 2000 km² is shown in Figure 4, which is based on *Flood Studies Report*, Volume II, Chapter 5.2.

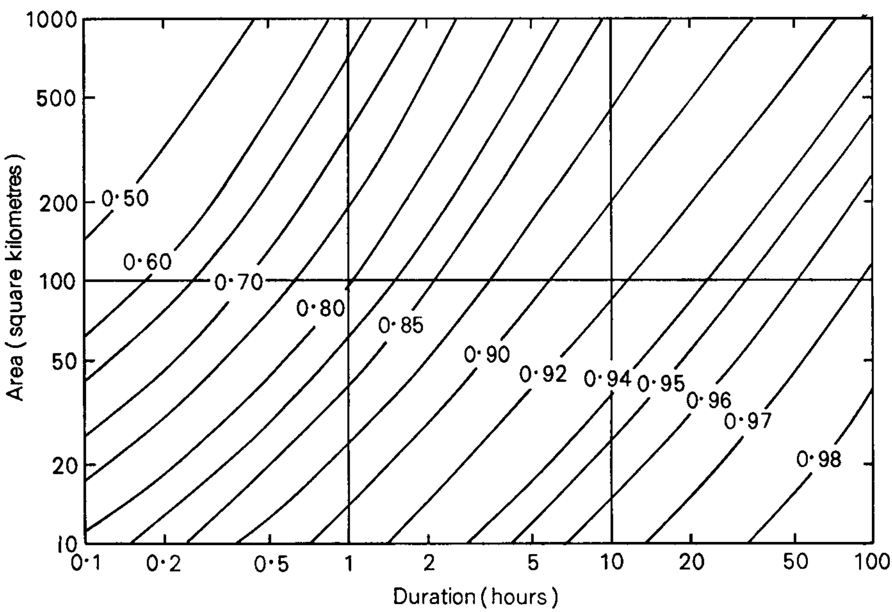

FIGURE 4—AREAL REDUCTION FACTORS: RATIO OF THE AREAL RAINFALL TO THE POINT RAINFALL OF THE SAME DURATION AND RETURN PERIOD

6. SIMPLE EXAMPLES

Example 1

An engineer asks for the magnitude of the 7-hour, point rainfall events in Wellingborough, Northants with return periods of 5, 10, 20 and 100 years.

Wellingborough is found on a map and the national grid reference noted (NGR SP 8968). The 60-minute M5 map is examined (preferably a larger version than Figure 1—copies are available in the Meteorological Office) and a value of about 19·2 mm read off at the appropriate grid reference. Similarly the 2-day map is examined (preferably a larger version than Figure 2—copies are available in the Meteorological Office) and the value of about 44·8 mm read off. Using the ratio of 60-minute to 2-day rainfall, 19·2/44·8 = 43 per cent, a value of 67 per cent can be interpolated from Table I for the ratio of 7-hour to 2-day rainfall. This gives a value for the 7-hour M5 as about 30·0 mm.

Further estimates can now be made of the magnitude of 7-hour rainfall events with longer return period. Figure 3 is a general diagram for England and Wales, showing the ratio of the MT event to the M5 event, plotted against M5 values. Values are read off for M5 = 30·0; MT/M5 is 1·21 when T = 10, 1·41 when T = 20 and 1·97 when T = 100 years. Multiplying the M5 value of 30·0 mm by these factors gives 36·3, 42·3 and 59·0 mm for the magnitudes of the 10-year, 20-year and 100-year 7-hour rainfalls respectively at Wellingborough.

Example 2

An engineer asks for the magnitude of the 30-minute, 60-minute and 120-minute rainfall events with return period of 50 years over a catchment of area 15 km^2 centred near Axminster, Devon (NGR SY 2998).

Axminster is found on the maps of 60-minute M5 and 2-day M5 as in Example 1, the values of 19·0 mm and 63·0 mm are read off. Using the ratio of 60-minute to 2-day rainfall, 19·0/63·0 = 0·30, a value of 78 per cent can be interpolated from Table I for the ratio of 30-minute to 60-minute rainfall, and a value of 38 per cent for the ratio of 120-minute rainfall to 2-day rainfall. These give the size of the point rainfall events for 30-minute, 60-minute and 120-minute events as 14·8, 19·0 and 24·0 mm.

The ratio of M50 to M5 for M5 values of 14·8, 19·0 and 24·0 mm are found from Figure 3 to be 1·70, 1·725 and 1·725, which gives the M50 events as 14·8 × 1·70 = 25·2, 19·0 × 1·725 = 32·8 and 24·0 × 1·725 = 41·4 mm for 30, 60 and 120 minutes respectively.

Reference to Figure 4 shows the areal reduction factors for 15 km^2 to be 0·86. 0·89 and 0·92 for 30, 60 and 120 minutes. Multiplication by 25·2, 32·8 and 41·4 mm gives the areal falls with return period of 50 years as 21·7, 29·2 and 38·1 mm in 30, 60 and 120 minutes respectively.*

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* Note that the application of the methods to larger catchment areas, especially with varied topography, requires more care. Examples are given in *Flood Studies Report*, Volume II, Chapter 8.

REVIEWS

The measurement of airborne particles, by R. D. Cadle. 150 mm × 230 mm, pp. xi + 342, *illus.* John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1976. Price £13·85.

This book is written for scientists and engineers who have to sample airborne particles and to measure their concentration, size and shape. It gives illustrations and diagrams of instruments, the basic theory underlying them, and practical advice on their use. The emphasis is on commercially developed and marketed instruments, and the book will be helpful to anyone lucky enough to have dollars to spend on the generally high-class American instruments in the air pollution field. The treatment is clear and, although sometimes abbreviated, is adequate for the book's purpose and is backed by the standard references. There are no obvious omissions. Some readers may consider that space devoted to manufacturers' photographs and to the basic theory of such well-known instruments as the optical microscope could have been put to better use.

The book is not intended as a textbook on aerosols. Meteorological applications are only briefly referred to. There is a short discussion on the characteristics and evolution of the size distribution of the atmospheric aerosol but there is no discussion on the condensation of water or ice on particles. Holography receives 21 lines of text and two references. Two pages, inserted in a chapter on Optical Microscopy, are devoted to the use of particles to trace atmospheric motions.

Anyone starting work with aerosols or pollution will find this a useful introductory handbook to methods, instruments and to the literature, but meteorologists will need to look elsewhere for full discussion of physical principles and for meteorological applications.

A. C. CHAMBERLAIN

Physical principles of micrometeorological measurements, Developments in Atmospheric Science, 6, by P. Schwerdtfeger. 240 mm × 170 mm, pp. ix + 113, *illus.* Elsevier Scientific Publishing Co, PO Box 330, Amsterdam, The Netherlands. Price: Dfl 75.

There are a number of standard textbooks on micrometeorology but most provide little information on the use of instruments which make the specialized measurements necessary in micrometeorological investigations. Professor Schwerdtfeger's slender volume attempts to fill this gap: in his own words, the book 'has been designed to emphasize the physical basis of precise meteorological measurements, especially those necessary in determining processes relevant to the atmosphere's behaviour close to ground level'. The material of the book is based on a university course and a substantial part is occupied by a description of about thirty experiments intended to be carried out by students. The experiments themselves are used both to illustrate the practical aspects of measurements and as a means of developing some of the principles involved.

Chapter 1 is concerned with air temperature measurements and the transfer of sensible heat and deals, *inter alia*, with topics such as thermal inertia and heating by radiation of thermometers, and heat transfer from plane surfaces.

Chapter 2 discusses the determination of solar and terrestrial radiation and related topics including estimation of the solar constant, and albedo. The book continues with a brief discussion of atmospheric pressure, followed by a section on the measurement of humidity. Chapter 4 introduces the concept of eddy transfer, following on from wind speed measurements and interpretation of the vertical gradient of wind speed. The fifth chapter deals with heat conduction in the ground. The final chapter, which is on the modelling of thermal processes by electrical analogues, reflects a particular interest of the author but seems to be an inappropriate contribution in such a short book.

The general level of presentation is elementary enough for the pace of the volume to be describable as 'leisurely', but this has resulted in a rather superficial treatment of many topics, and significant omissions. As a result, the book fails to live up to the assertion on its jacket that it is of great value as a textbook and reference work for meteorologists. On the other hand, if its remarkable price can be ignored, it provides a useful introduction for newcomers to the field. However, potential readers should be warned that c.g.s. units are used in many places in the text. Also, the sections on wind profiles and turbulent transfers are sprinkled with loose statements which can scarcely provide the sound foundation of knowledge required by the student reader: for example, the implication that only in neutral conditions is the mean vertical velocity near the ground essentially zero (pages 59 and 60), that friction velocity is the geometric mean of the horizontal and vertical velocity fluctuations (implying perfect correlation between them) (page 60), that atmospheric turbulence is isotropic (page 60), that the wind velocity vanishes at a height above the ground equal to the roughness length, and that the roughness length over *developed* waves is dependent on wind speed (for which there is little evidence) (page 61), and that an array of only 100 buckets arranged on the ground upwind of a profile mast will produce, in neutral conditions, a fully modified logarithmic profile of wind speed up to a height of at least 4 m. Blemishes such as these significantly reduce the value of what is otherwise a useful addition to the micrometeorological literature.

N. THOMPSON

NOTES AND NEWS

Retirement of Mr R. Murray

Mr Robert (Roy) Murray, who retired on 28 April 1977, joined the Office as a Technical Officer in September 1939 after graduating at Edinburgh University with an M.A. degree in Mathematics and Natural Philosophy. After a short initial training period in London he went to Headquarters No. 221 Group (Coastal Command), Royal Air Force Donibristle, later Pitreavie, for forecasting duties. Early in 1941 he was posted to the Isle of Islay and remained there for about a year before proceeding to Northern Ireland for relief duties at a number of RAF Coastal Command units. His service in Northern Ireland concluded with a spell at RAF Headquarters and in March 1943 he was commissioned in the RAFVR and sent to India, joining HQ No. 221 Group initially in Bengal. Flt Lt Murray proceeded with this Group to Imphal, Manipur, in November of that year. He remained at Imphal for a year or so and throughout the Japanese siege. He then became the Senior Meteorological Officer with the mobile combined Headquarters 14th Army and 221 Group and travelled by stages through Burma to arrive in Rangoon in mid 1945. On the termination of hostilities he filled the post of Senior Meteorological Officer Burma and was responsible for a number of units scattered throughout Burma, Siam and Indo-China. He was mentioned in dispatches at this time. In February 1946 Sqn Ldr Murray (as he then was) was repatriated and demobilized, and took up civilian duties in the Central Forecasting Branch (Met O 2) at Dunstable. He became a Senior Scientific Officer in September of that year and in 1950 he moved to the Forecasting Research Branch (Met O 21) where he did some first-class work in pioneering the understanding of the dynamics of jet streams which was reported in a classic paper. Promotion to Principal Scientific Officer followed in 1953 with a return to operational forecasting duties. In August 1956 he was posted to Aden to become the Chief Meteorological Officer, MEAF. Two years later he returned for a brief spell to a research post in upper-air climatology at Harrow (Met O 13) and subsequently went overseas again in mid 1959 to Cyprus to occupy the Chief Meteorological Officer post at Headquarters NEAF where he remained for the next four years before returning in August 1963 to the Synoptic Climatology Branch located at Bracknell. He spent the next decade in that Branch contributing to research in forecasting for periods of one month to a season. It is interesting to record that the first 30 day forecast issued to the public (for December 1963) correctly predicted a major change from an exceptionally warm November to an exceptionally cold December and that this was largely due to his confident prediction of an imminent block. Throughout his career in extended-range forecasting his approach was essentially a practical one based on a desire to establish the technique on a sound and objective basis. During this time he published some 30 papers on the detailed climatology of the British Isles, developing objective indices and rules for forecasting monthly and seasonal temperature and rainfall. He was awarded the L. G. Groves Memorial Prize for Meteorology in 1970 (jointly with R. A. S. Ratcliffe) for work relating ocean temperature to atmospheric circulation anomalies.

In May 1973 Mr Murray was promoted to Senior Principal Scientific Officer and took charge of agricultural meteorology and hydrometeorological work as an Assistant Director. He remained in this post until his retirement. During this period he successfully led efforts to establish and introduce computer-based techniques which enabled the services provided to the community in general, and the water and agricultural industries in particular, to be improved in quality, quantity and range. In the last year of his service he was actively involved in many aspects of work resulting from the 1975/76 drought.

There can be few left in the Service who have had as varied a career. It was not until the last 18 months that I came into day-to-day contact with him, and I would like to record my personal thanks for his informed advice and willingly tendered help. We wish Roy and his wife a long and active retirement.

N. E. RIDER

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NOTICES

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THE MAGNITUDE OF THE HORIZONTAL DIVERGENCE AND THE VERTICAL COMPONENT OF VORTICITY IN THE SURFACE WIND FIELD OVER THE OCEAN

By W. V. BURT, T. CUMMINGS and C. A. PAULSON
(School of Oceanography, Oregon State University, Corvallis, Oregon, USA)

SUMMARY

The magnitude of the horizontal divergence and the vertical component of the relative vorticity were computed from observations of the surface wind field over the North Atlantic during September 1972. The computations indicate that for the generally fair prevailing weather conditions, the magnitudes of the vorticity and divergence were approximately inversely proportional to the scale over which they were computed, with scales ranging from 4 to 1000 kilometres.

INTRODUCTION

It has been suggested by Haltiner and Martin (1957) and in the Experiment Design Proposal for the GARP Atlantic Tropical Experiment (World Meteorological Organization, 1972) that the magnitude of the horizontal divergence and vertical component of the relative vorticity (hereinafter referred to as divergence and vorticity) of the wind field varies as L^{-1}, where L is the length scale over which the computation is made. Verification of the L^{-1} relation, by computing vorticity and divergence from the plentiful wind data which are available from land stations, is complicated by terms that appear in the defining equations due to terrain effects. Schaefer (1973) has shown that maps of divergence derived from data over land appear quite different, depending upon the degree to which corrections are made for the differences of the altitude of the stations from which the data have been derived. One might also expect errors due to local terrain features near the measurement sites. These problems disappear over the ocean surface. However, no discussion has appeared from observations over the ocean because of the lack of surface wind measurements made simultaneously at different length scales. The authors were unable to locate in the literature any presentation of data, either over land or sea, illustrating the L^{-1} relationship.

Observations

The Joint Air–Sea Interaction Experiment, 1972 (JASIN 72), sponsored by the Royal Society of London, provided a unique opportunity to estimate, through surface wind velocity measurements, the magnitude of the divergence and vorticity of the surface wind field over the ocean as a function of horizontal scale. The measurements were made from 6 to 19 September in superimposed triangular areas located from 700 to 1200 km west of Ireland. Figure 1 shows the locations where the data were collected.

The measurements were made with cup anemometers and wind vanes mounted on ships and buoys. Table I describes the observational program and equipment used. The horizontal spacing of surface meteorological buoys and weather ships provided wind velocity data on four different size scales, encompassing almost four orders of magnitude from 4 km to approximately 1000 km.

The JASIN area was dominated by an intense high-pressure system during the observational period. However, several low-pressure systems passed close to the area, causing occasional showers. Cumulus clouds were usually present. Wind speeds ranged from 1 to 12 metres per second.

Analysis

The reduction of data was carried out on a digital computer. The divergence and vorticity were estimated without correction for convergence of meridians (Panofsky, 1946), a correction which was negligible for all cases. The equations used were

$$\Delta = \frac{1}{A} \oint \boldsymbol{u} \cdot \boldsymbol{n} \, \mathrm{d}l, \quad \ldots \quad (1)$$

$$\zeta = \frac{1}{A} \oint \boldsymbol{u} \cdot \mathrm{d}\boldsymbol{l}, \quad \ldots \quad (2)$$

where Δ is the horizontal divergence, A is the area of the triangle over which the estimate is made, $\boldsymbol{u}$ is the wind velocity vector, $\boldsymbol{n}$ is a unit vector normal to the perimeter of the triangle, $\mathrm{d}l$ is a differential increment of length along the perimeter, and ζ is the vertical component of the relative vorticity. The vector $\mathrm{d}\boldsymbol{l}$ is defined such that the integration is counter-clockwise around the perimeter when looking down on the triangle. The winds were assumed to vary linearly between observation sites. As a result the integrations in equations 1 and 2 each reduce to a sum of three terms. For the divergence, each term is the product of the normal velocity component at the centre of a particular side of the triangle and the length of the side divided by the area. Vorticities were computed similarly, by use of the mean velocity components tangent to the centre of each side, defined as positive if in the same direction as $\mathrm{d}\boldsymbol{l}$. Although the formalism is different, the procedure used for estimating vorticity and divergence is equivalent to that suggested by Bellamy (1949).

Individual values of vorticity and divergence were averaged over time periods equal to the average length of a side of the triangle divided by the mean wind speed. This procedure is equivalent to averaging the wind observations before computing divergence and vorticity. The averaging was done to reduce errors

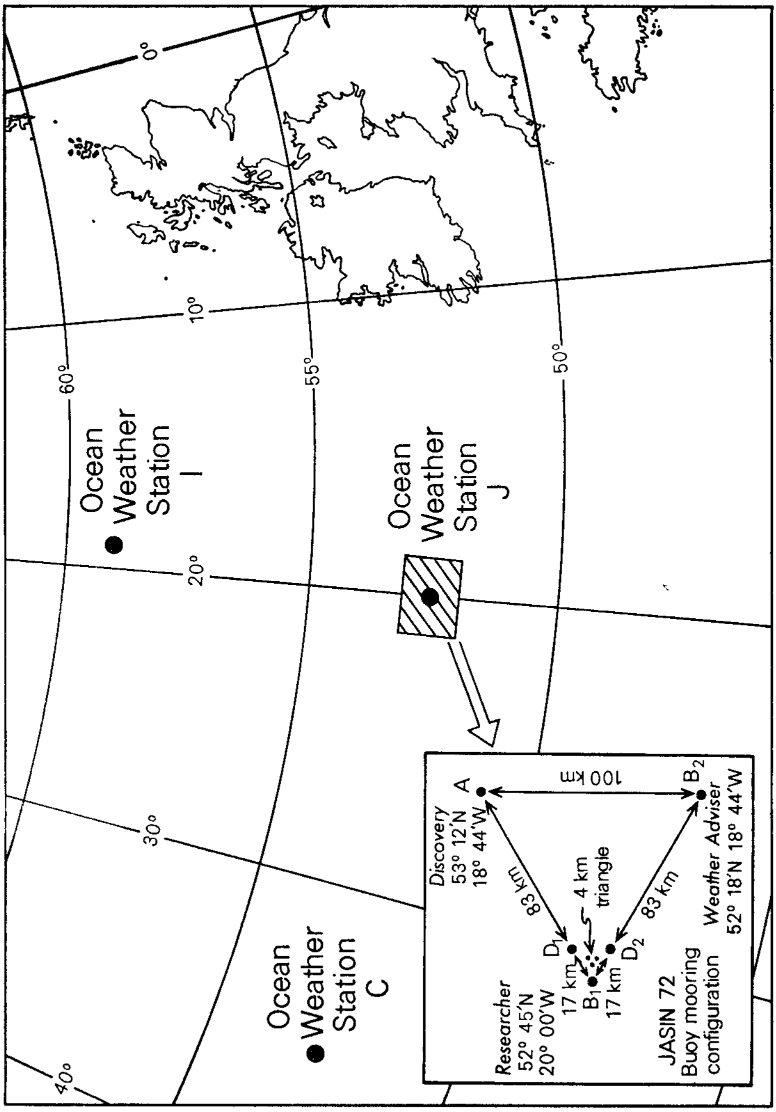

FIGURE 1—POSITIONS OF THE METEOROLOGICAL BUOYS AND PARTICIPATING SHIPS DURING JASIN 72

TABLE I—OBSERVATIONAL PROGRAM AND EQUIPMENT USED DURING JASIN 72

Spacing	Period of record (*inclusive*)	Type of data	Vehicle used
Equilateral triangle 4 km on a side	1635 GMT 6 Sept. to 0835 GMT 7 Sept.	Integrated wind speed and instantaneous wind direction each 6 seconds, geodyne sensors, 3·3 metres above mean sea level recording on magnetic tape.	Free floating 60 ft damped aluminium spar buoys.
Equilateral triangle 17 km on a side	0000 GMT 9 Sept. to 1100 GMT 10 Sept.	Integrated wind speed and instantaneous wind direction each 10 minutes. Aanderaa sensors 2·3 metres above mean sea level recording on magnetic tape.	Large anchored toroid buoys.
Equilateral triangle 100 km on a side	1900 GMT 6 Sept. to 0900 GMT 19 Sept.	Same as 17 km triangle.	Same as 17 km triangle.
Right-angled triangle 1245 × 711 × 1140 km	1800 GMT 6 Sept. to 0600 GMT 8 Sept. 1800 GMT 11 Sept. to 0000 GMT 15 Sept. 1200 GMT 15 Sept. to 1200 GMT 19 Sept.	Two-minute averages of wind speed and direction every 6 hours.	Weather ships on Stations 'C', 'I' and 'J'.

due to velocity fluctuations on scales smaller than the separation of measurement sites. The absolute value of each average was then taken, and the mean and standard deviation of the absolute values corresponding to each length scale was computed. The distributions of the absolute values of the means and the standard deviations were highly skewed towards smaller values.

The results of the computations are plotted in Figure 2. The length scale for each value of vorticity and divergence is taken to be the mean of the sides of the triangle formed by the observation sites and is identified as 'scale length' in Figure 2 and as 'L' below. The lines drawn have a slope of -1, suggesting that divergence and vorticity were approximately inversely proportional to the scale over which they were measured. The nearly linear relationship that is shown over such a large range of scales may be partly related to the fact that no strong weather disturbances passed through the area under study during the period of

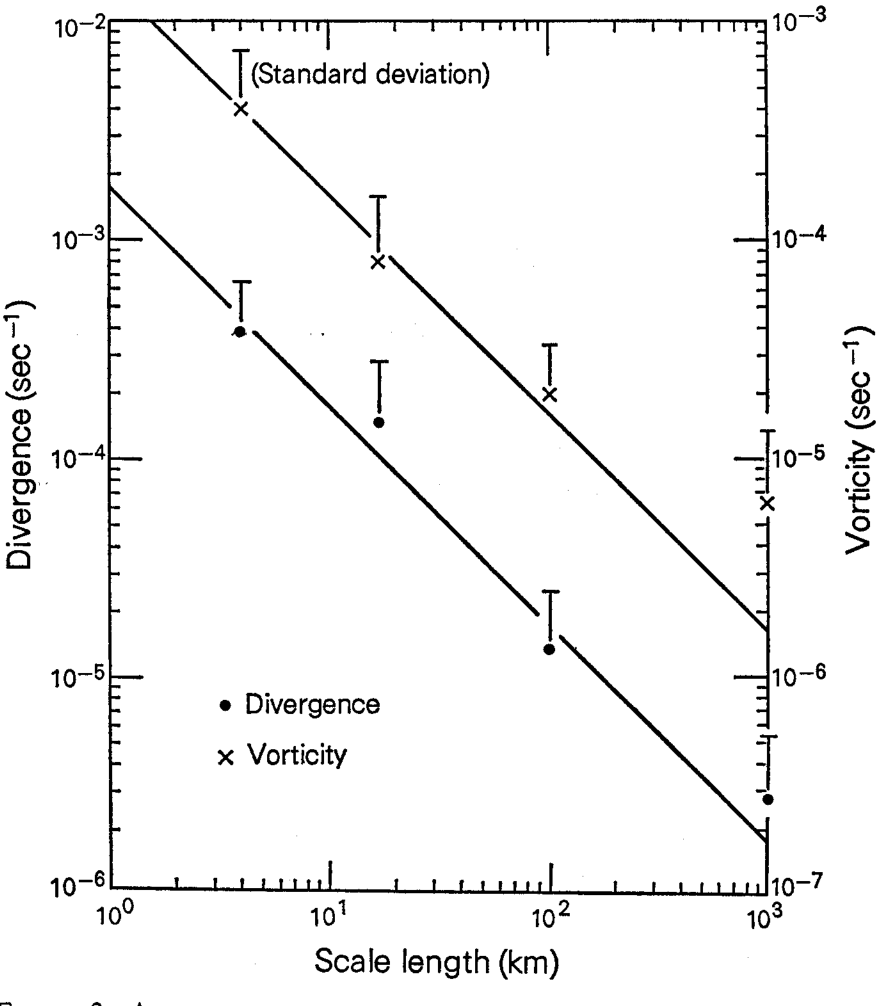

FIGURE 2—ABSOLUTE VALUES OF THE HORIZONTAL DIVERGENCE AND VERTICAL COMPONENT OF THE VORTICITY AS A FUNCTION OF HORIZONTAL SCALE

observations. The statistical significance of the 1000 km value is, of course, low because the plotted point is the average of only five individual estimates.

Uncertainties in the estimates of divergence and vorticity may be estimated from comparisons of long-term averages of wind speed and direction observed at buoys separated by 4 km. These comparisons show that the mean wind speeds agree within 0·05 m/s. The corresponding uncertainty in direction is 13°. An error equation for divergence or vorticity is

$$\text{ERROR} = \pm \frac{4\,\delta v}{L}, \quad \ldots \quad (3)$$

where L is the length scale in question and δv is the uncertainty in wind speed. Substituting 0·05 m/s and 4 km for δv and L respectively, gives an uncertainty of about $\pm$ 10 per cent of the divergence and vorticity estimates. The percentage error is independent of L since both divergence and vorticity vary approximately as L^{-1}. Uncertainties due to errors in direction were estimated by arbitrarily subtracting 13° from one set of observations in the 4 km array. This resulted in a change of 9 per cent in the vorticity and 18 per cent in the divergence computed as in equations 1 and 2. The uncertainty in the vorticity and divergence estimates from the ship observations is estimated to be about as large as the estimates themselves (see Figure 1) because of fewer samples and less accurate measurements.

One may define a characteristic velocity difference, δu, as follows:

$$\text{DIVERGENCE} = \frac{\delta u}{L}. \quad \ldots \quad (4)$$

A similar relation may be defined for vorticity. If divergence and vorticity vary as L^{-1}, then δu is independent of L. The average values of δu for the data in Figure 2 are 1·8 m/s (neglecting the 1000 km values) for divergence and 1·6 m/s for vorticity. The lines drawn in Figure 2 correspond to these values of δu.

Discussion

We have shown that the horizontal divergence and vertical component of the vorticity do indeed appear to vary approximately as L^{-1}, where L ranges from 4 to 1000 km. This result is important in the design of experiments over those parts of the ocean where it is intended to make measurements from which divergence, vorticity, and the curl of the wind stress can be estimated. The result may also be useful to modellers of the lower atmosphere for analysing the effect of sub-grid scale motions on the accuracy of simulations.

The result of our observation that the characteristic velocity difference δu is independent of scale may be crudely compared to power laws for the spectral density of horizontal velocity by assuming $L\delta u^2$ to be proportional to the spectral density. Such a comparison indicates that δu being equal to a constant corresponds to the spectrum density being proportional to κ^{-1}, where κ is wavenumber. For comparison, the $\kappa^{-5/3}$ law for an inertial or locally isotropic range corresponds to $\delta u \propto L^{1/3}$. The turbulence could not, of course, have been locally isotropic for the scales we considered because the scales are much greater than the height of the measurements above the surface.

Care should be taken not to generalize too extensively the results presented here. These results are based on observations which are limited to a particular area during anomalously fair weather conditions. In addition, uncertainties are introduced by approximations in the calculations and errors in the measurements. The significance of the computations for the 1000 km scale is particularly low.

An examination of northern hemisphere surface weather charts for the month of September for ten years indicated that frontal passages affected the JASIN 72 study area (the 100 km triangle shown in Figure 1) about a third of the time during September. During the JASIN 72 study period from 6 to 19 September 1972, only one very weak front with maximum wind speeds of only 6 or 7 m/s passed through the study area. One low passed to the south of the area, giving maximum wind speeds over the area of 9 to 10 m/s for a short period of time. During the remainder of the time, the area was covered by a stationary high-pressure area. Average wind speeds for the whole period were about 4 m/s. Thus one would intuitively expect that the values of divergence and vorticity would be below average for the time of year and latitude for the 4, 17 and 100 km triangles.

Figure 44 in WMO (1972) presents typical values of divergence and relative vorticity. The mean values shown are about two and a half times as great as those shown in Figure 2 of the present paper, for the three smaller triangles.

However, the results from the largest triangle made up of Ocean Weather Stations 'C', 'I' and 'J' are somewhat more in line with the results presented in WMO (1972). Wind speeds were consistently low at Station 'J'. Several weak fronts passed over Station 'I', accompanied by increased wind speeds and changes in wind direction. For most of the time, however, Station 'I' was situated between the high-pressure area over the JASIN 72 study area and low pressure areas to the north and north-east. Wind speeds at Station 'I' ranged up to 15 m/s (Force 7).

The winds at Station 'C' were influenced by several relatively deep low-pressure areas and the passage of several strong fronts. Several sharp changes in wind direction occurred and wind speeds were in the 12 to 15 m/s range (Force 6 and 7) approximately one-fourth of the time.

With each of the three weather ships on Stations 'C', 'I' and 'J' located in consistently different weather situations for most of the JASIN 72 experiment, one might expect higher than average values of divergence and vorticity to occur. This is borne out in Figure 2. The vorticity is approximately the same as that given in WMO (1972) for the same distance scale.

As stated above, care should be taken in generalizing from the results shown in Figure 2. The same is true of the material presented in WMO (1972) on the relationship between scale and magnitude of divergence and vorticity. The diagram in WMO (1972) is based on data from several different latitudes covering only one order of magnitude in length scales. The experimental data were then extrapolated over three more orders of magnitude. Further cause for uncertainty comes from comparing similar graphs in WMO (1972) and an earlier unpublished document on the same subject. The values for divergence and vorticity as a function of scale shown in Bellamy (1949) are only about one-third of those shown in WMO (1972). The mean values shown in Figure 2 of the present paper are almost identical to those shown in Bellamy (1949).

Despite the above qualifications, the results ought to be useful for practical calculations and ought to encourage further efforts to quantify the relationships between divergence and vorticity and the scale over which they are computed.

ACKNOWLEDGEMENTS

We wish to thank Professor Henry Charnock, Director of the United Kingdom Institute of Oceanographic Sciences, for inviting us to participate in JASIN 72, and Dr Raymond T. Pollard, Co-ordinator for JASIN 72, for his assistance in many ways. This research was supported by the Global Atmospheric Research Program of the National Science Foundation under Grant GA 28004, a North Atlantic Treaty Organization Grant # 3 (SA-6-5-02 (3) 39 TK), and by the Office of Naval Research through contract N000 14-76-C-0067 under project NR 083-102.

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551.508.53/4: 551.508.824

THE METEOROLOGICAL OFFICE DIGITAL ANEMOGRAPH LOGGING EQUIPMENT (DALE)

By A. E. BURTONSHAW* and N. MUNRO

SUMMARY

The decreasing availability of manpower and the need for a computer-assimilable system have highlighted a growing requirement by the Meteorological Office for an automated system for recording surface wind information. The Operational Instrumentation Branch of the Meteorological Office has produced a Digital Anemograph Logging Equipment to meet this need. The operation of the system is described in this paper.

1. INTRODUCTION

The Meteorological Office Mk 4 wind system has been used operationally since 1954 and has been installed at most meteorological offices and at a large number of auxiliary observing stations. Other organizations also use this system and their records have helped to improve the national observational network. Wind information from the Mk 4 system is recorded on charts, and the data are subsequently extracted manually.

Recently the reduced availability of manpower has resulted in some auxiliary

* Deceased

and other stations restricting or stopping the analysis of Mk 4 wind charts, although they still keep the instruments and send the records to Bracknell for analysis, thereby increasing the burden on Meteorological Office resources. The closure of certain RAF stations and other observational organizations has increased the value of the remaining network, and consistent computer-compatible wind information, from an integrated system, is necessary to maintain the essential climatological records.

In order to meet this need the Operational Instrumentation Branch of the Meteorological Office has designed electronic equipment which logs on magnetic tape the data at present recorded on autographic instruments and analysed manually (see Plate I).

Three prototype systems have been built. These were installed at Valley (June 1974), Boscombe Down (February 1975), and Stornoway (March 1975). The data tapes were processed at Bracknell and the recorded hourly mean wind speed and direction, and the highest gust, were compared with data derived manually from chart recorders. This analysis showed that the differences between the two sets of data were no greater than would be expected from the specifications of the two systems, and that the data from the digital anemograph logging equipment (DALE) are acceptable for climatological purposes.

2. Requirement

The following features were considered in designing the system:

(a) The system technology should have exceptional reliability and very good long-term stability so that the system may operate unattended for long periods.

(b) The sensors should ensure homogeneity with earlier data.

(c) The system should have an accuracy commensurate with past data records.

(d) The system should operate from the normal mains supply, but continue to operate over breaks in that supply for a reasonable period.

(e) The data should be logged on tape in a computer-compatible format.

The data required are: (i) running mean* of wind speed; (ii) running mean* of wind direction; (iii) maximum gust over a specified period; (iv) direction of maximum gust; (v) time of maximum gust; (vi) the day; (vii) the hour; (viii) the minute; and (ix) station number of the system.

To give flexibility to the system, the period of the running means for speed and direction, the 'maximum-gust sensing period', and output scan intervals were designed to be selectable.

Initially DALE was designed to be compatible with the Meteorological Office Mk 5 wind system at Heathrow (Else, 1974). This system differs from the Mk 4 in that the outputs are in the form of d.c. voltages, whereas the Mk 4 outputs are for wind speed—an alternating voltage increasing in amplitude with increasing wind speed, and for wind direction—50 Hz, single-phase, amplitude-dependent 'synchro' information on three inputs from a transmitter 'magslip'.†

* The term 'running mean' is here applied to a moving time-average, produced electronically, in which the relative weighting of instantaneous values decreases exponentially with lag before the current time.

† 'Synchros' and 'magslips' are commercially produced devices for electrically relaying angular motions in a precise way.

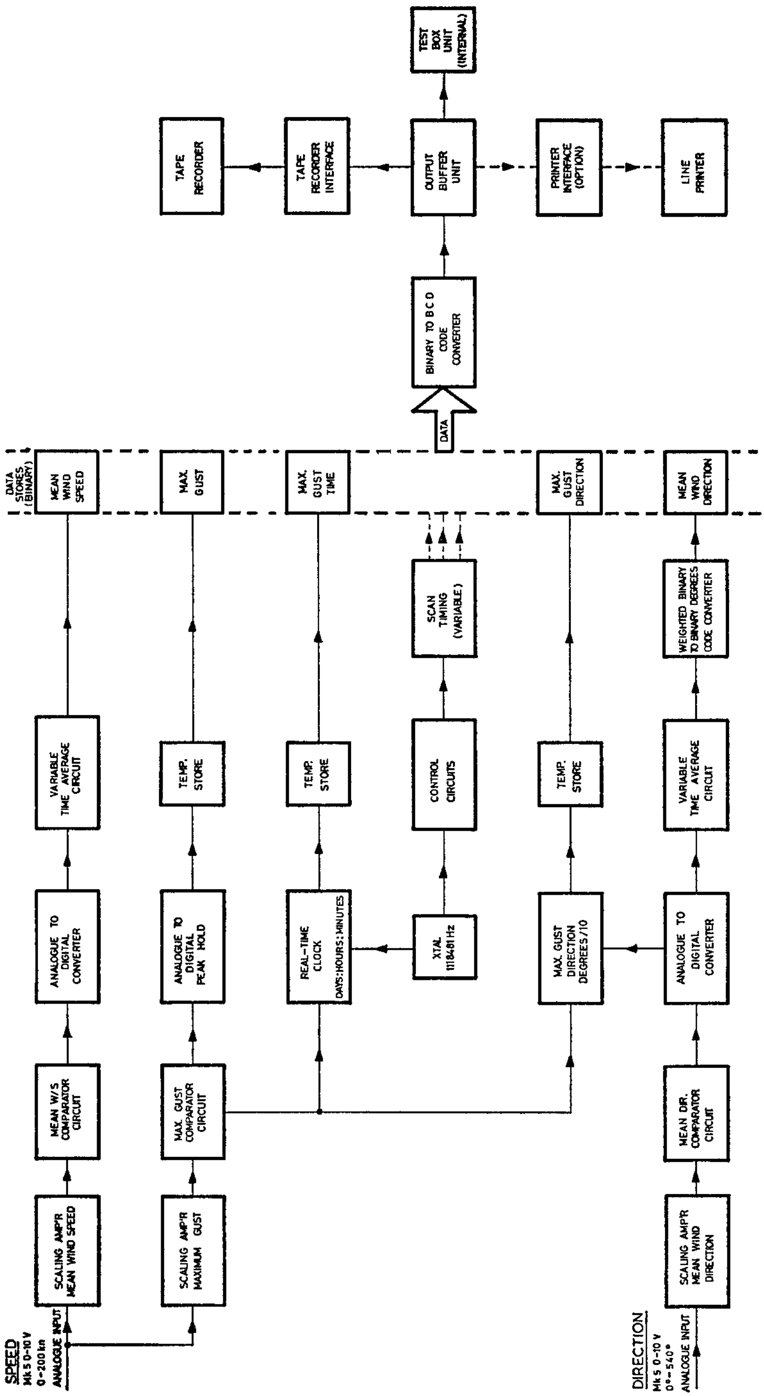

FIGURE 1—DIGITAL ANEMOGRAPH LOGGING EQUIPMENT BLOCK DIAGRAM

BCD denotes binary coded decimal.

The following description of DALE refers to the Mk 5 system outputs, but a suitable interface has been developed which also enables DALE to be used with the more common Mk 4.

3. General description

DALE (see Figure 1) is a five-channel data-logging system, two channels of which (the mean wind speed and direction) are sampled more frequently than the other three channels which relate to the maximum-gust information.

(a) *Mean values of wind speed and direction*

The analogue inputs to DALE are first scaled and then processed by 'analogue-to-digital converters' into binary numbers. Time-averaging of the binary numbers is accomplished by a digital filter circuit whose time-constant can be selected by the user for his individual requirements.

The time-averaged outputs of mean wind speed and direction are fed into individual data stores to await sequential scanning to the output at an interval selected by the user, normally each minute.

(b) *Maximum value of wind speed*

The Mk 5 wind-speed voltage is also fed to a 'maximum gust' circuit where scaling followed by binary conversion takes place, similar to the mean-speed circuitry. The maximum binary value of wind speed is held within the digital conversion circuitry and updated with a new value each time the preceding peak value has been exceeded. When this occurs, the maximum-gust comparator circuit senses and 'holds' the new maximum value, simultaneously transferring 'direction' and 'time' data into their individual stores to await the output scanning sequence, normally every hour, which feeds all the binary data (via a code converter) to the magnetic recorder, and to other output devices if required. The scan sequence for 'maximum-gust information', at the same time, resets the peak-hold circuit to zero, thus allowing successively higher values to be sensed throughout the next period.

(c) *Time*

An internal crystal-controlled oscillator is counted down and used as a 'real-time' clock for display and recording purposes; several subdivisions of the fundamental frequency are used for synchronization, clock and timing pulses for the control and scan sequences within the system. Time is displayed at an internal 'test box' facility, and can be updated manually as required. Day-number throughout the year, hours and minutes are shown and the extra day in leap years is taken into account for reset purposes at the New Year.

(d) *Test box*

Data can be examined 'on demand' from the 'non-volatile' data stores associated with the display, which are cleared only every hour, allowing calibration and testing of the system in the field without translation from the tape being required.

(e) *Printer*

A printer interface can be included for special-purpose applications.

4. Wind speed

(a) *Mk 5 input to DALE*

The Mk 5 wind system converts the frequency from the wind-speed sensor into a 0–10 volt scale, representing 0–200 knots, which is continuously supplied to the averaging and maximum gust circuits.

(b) *Analogue-to-digital scaling*

The d.c. voltage range from the Mk 5 system is too restricted to enable adequate resolution to be obtained from direct conversion of analogue to binary form, so it is necessary for scaling to take place before conversion. The conversion is carried out by an integrated circuit in which 10 V is represented by a 10-bit integer input of 1023, so that, since a count of 1000 is required to provide a decimal representation of the maximum design mean speed of 100 knots with a resolution of 0·1 per cent, it is necessary to amplify the input voltage by a factor of 1·955.

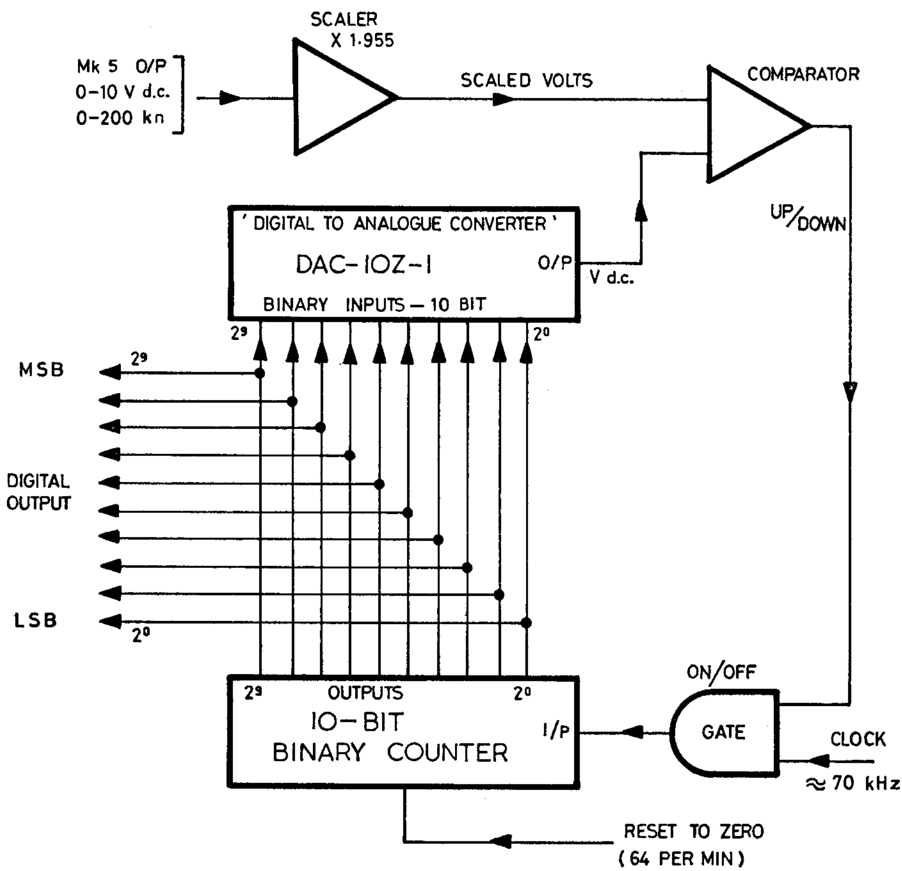

FIGURE 2—DALE ANALOGUE-TO-DIGITAL CONVERSION (MEAN WIND SPEED 0–100 KNOTS)

MSB denotes 'most significant bit' and LSB 'least significant bit'.

(c) *Analogue-to-digital conversion*

The two main components in the 'Analogue-to-Digital' (A-to-D) conversion circuitry (see Figure 2) are:

(1) A 'Digital-to-Analogue Converter' integrated circuit (DAC-10Z-1), whose d.c. voltage output is directly dependent upon the binary count at its input (i.e. a maximum 10-bit binary count of 1023 = 10 V).

(2) A 'comparator', which is a two-state switch, either up or down depending upon the differential voltage at the two inputs; the output controls the clock gate, either letting through pulses or inhibiting them.

The action of the circuit is as follows: if the d.c. voltage from the DAC-10Z-1 is lower than the scaled wind-speed voltage, the comparator is forced up, opening the clock gate and allowing pulses into the binary counter, raising the count, and similarly the DAC-10Z-1 output voltage, until such time as the converter and the scaled wind-speed volts are equal, when the comparator is forced down, closing the gate, inhibiting the pulses, and holding the binary count which digitally represents the analogue input parameter. This count is presented as the binary input to the averaging circuit. A continuous clock frequency of approximately 70 kHz ensures that the digital representation of the wind speed is obtained in less than 1/70 second after initiation. It is updated at a rate of 64 times per minute.

(d) *Time-averaging circuit (digital filter)*

The logarithmic time-averaging circuit (Painting, 1974) is essentially a feed-back digital filter whose time-constant is determined by its associated output store length and individual clock frequency. Selectable clock frequencies (sub-divisions of the internal clock) enable the period of averaging, in the range 7·5 seconds to 1 hour, to be chosen by the user. The chosen averaging time is common to both the wind speed and direction and is independent of the period of output scan selected. The output will reach 95 per cent of any step-function input within the selected averaging period.

(e) *Data store and output scan*

The time-averaged output is transferred into the mean-speed data stores and thence to the output buffer unit via a 'Binary Coded Decimal' (BCD) code-converter circuit. The output scan rate can be selected by the user within the range 7·5 seconds to 1 hour, and internal control of the real-time clock ensures transfer of the wind-speed data from the data store to the output devices synchronously at 64 Hz. The data characters are written into the tape circuitry with a data strobe pulse.

Before receiving the data stream, the system electronics automatically scan a fixed BCD 'line-synch' character to aid in the translation and formatting of the recorded data.

(f) *Maximum-gust circuit*

The maximum-gust circuitry is similar to that used for the mean speed. Scaling of the analogue input takes place before digital conversion, the 0–10 volt d.c. scale, representing 0–200 knots, being resolved to one-quarter of a knot.

The scaled wind-speed voltage is fed to one input of the maximum-gust comparator, the other input being connected to the output from the converter circuitry. The effect is similar to that described for the A-to-D converter shown in Figure 2. The counter associated with the converter is only reset at the end of the sampling period, normally one hour, ensuring that the peak value of the analogue input has been selected.

When the scaled wind-speed voltage rises above the previously sensed value, the comparator circuit is forced to open the clock gate, allowing pulses to be fed to the binary counter, raising the digital input to the DAC-10Z-1 and the output voltage until such time as the comparator inputs are the same, when the clock gate is forced to close. When the comparator is switched to the 'count' condition, the time circuit is sampled and the 'minutes count' held within a separate store. Simultaneously the 'direction' is also sensed and latched into its appropriate store to await output scanning.

At the end of the selected period the maximum-gust data are transferred into the data stores and scanned to the output devices at 64 Hz.

Although the comparator circuit has a resolution of a quarter of a knot, the output maximum wind speed is given in whole knots.

(g) *Maximum-gust delay*

To ensure that spurious noise pulses do not trigger the maximum-gust comparator, a delay of 150 milliseconds is incorporated in the circuitry. The circuit may be initiated by any analogue voltage which is higher than the previously stored value, but the circuit will take action to transfer the new value into store only if the new value is still higher than the previous one at the end of the delay period.

5. Direction

(a) *Analogue-to-digital direction scaling*

A 10-bit counter is used with the directional A-to-D circuit, giving a weighted binary output; the 2^9 MSB (Most Significant Bit) is given the value 360, the 2^8 bit 180, the 2^7 bit 90, and so on; the LSB (Least Significant Bit) is valued at 0·7 degree. The value of this system is utilized in changing the 540 degree input scale from the Mk 5 into one of only 360 degrees.

(b) *Analogue-to-digital conversion*

The counter for the direction A-to-D conversion circuit is reset at the same rate as the wind-speed circuit, i.e. 64 times per minute. The digital number is presented to the direction-averaging circuit (similar to the speed averager) which time-averages at the same rate as the speed circuit. The output from the filter is fed into a 'weighted binary to binary degrees' static code-converter circuit, to translate the 'weighted number' to 'binary degrees'. The output from the code converter is fed into the data store to await sequential scanning to the output via the common BCD encoder as described previously.

(c) *Direction of maximum gust*

When the maximum-gust comparator circuit functions, the direction binary count is latched into a separate code-converter circuit which outputs a 6-bit code value into a temporary store. A separate code converter permits asynchronous operation of maximum-gust data at all times. If no further values are received within the hour, this value is decoded and presented as maximum-gust 'direction' to the appropriate data store.

6. Mk 4 wind system direction interface

The preceding discussion has assumed that a Mk 5 wind system provided DALE with the necessary d.c. input voltages for processing. An interface to the existing Mk 4 magslip direction system has also been developed. This circuit (Painting, 1975) converts the single-phase 'synchro' information, received from the Mk 4 direction system, into a d.c. voltage, making DALE compatible with the large number of existing wind systems in general use in the United Kingdom, and thereby making the system available as an 'add-on' unit.

Since DALE can accept up to 10 bits of digital information to the averaging circuits, any binary system for mean speed and direction could be accepted if scaled correctly.

7. 3M cartridge logging system

At a late stage in the development period, the supplies of the tape-recorder unit originally used became unobtainable and a new logging system had to be devised. The 3M cartridge system was chosen as the most suitable recording medium, and interfacing of a prototype new system is completed. The recording specification is of an international standard and format. Data are recorded in ASCII characters (American Standard Code for Information Interchange) in the ANSI format (American National Standards Institute—X3 BI/626) compatible with translation equipment already used within the Meterological Office.

8. Conclusion

A digital anemograph logging equipment (DALE) has been described. This equipment is capable of providing mean wind speed, direction, and gust data of sufficient accuracy to be of use in climatology, and will therefore be an aid in maintaining records where it is becoming increasingly difficult or impossible to do so using existing manpower. The Meteorological Office intends shortly to ask for tenders for a further 20 systems to be manufactured to this design. Within ten years there may be many such systems in use in the United Kingdom.

Acknowledgements

The authors wish to express their gratitude to Mr D. J. Painting who initiated much of the original work in this system.

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551.524.36(425): 551.557.33(213)

THE RELATIONSHIP BETWEEN THE STRENGTH OF THE QUASI-BIENNIAL OSCILLATION IN THE EQUATORIAL STRATOSPHERE AND THE MEAN ANOMALY OF THE MONTHLY MEAN MAXIMUM SCREEN TEMPERATURE AT OXFORD

By J. D. PERRY

SUMMARY

The regression of the mean anomaly of monthly mean maximum temperature at Oxford is calculated for a particular phase of the quasi-biennial oscillation (QBO) on the mean strength of the phase of the QBO in which the anomaly occurred. The calculation was repeated with displacements from minus six months to plus fifteen months and the regression was found to be significant at better than the 5 per cent level between M—4 and M, and between $M + 11$ and $M + 13$ months, where M is the month in which a particular phase of the QBO starts.

Significant correlations at the 2 per cent and 1 per cent levels are found for the regression of the mean anomaly of the monthly mean maximum temperature for the summer months and at the 5 per cent level for the autumn months, on the strength of the prevailing QBO and on the strength of the previous phase of the QBO respectively. The regressions for spring and winter were not significant.

1. INTRODUCTION

The cycle approximating to 2 years in various meteorological quantities, including temperature, rainfall, pressure and stratospheric winds, has been well documented and the reader is referred to an appraisal of the most important papers by Craddock (1968).

The association between the quasi-biennial oscillation (QBO) in the equatorial stratosphere and the surface pressure distribution for the northern hemisphere for the mid-season months, January, April, July and October, was studied by Ebdon (1975) who found significant differences in the pressure distribution during easterly and westerly phases of the QBO in January and July. Further work by Ebdon (personal communication) on the monthly mean temperature for central England during opposite phases of the QBO showed significant differences in July, August and September but not in the other 9 months of the year.

Folland (personal communication), on the other hand, performed a power spectrum analysis on the annual mean temperature for central England for the period 1659 to 1974, and found a peak, among others, at about 26 months which is significant at the 5 per cent level, and this suggests that further examination of the temperature may be profitable.

The comparison of the variation of temperature over the British Isles and the equatorial QBO is made easier if, in the first instance, normal annual variations of temperature are eliminated and the strength of the QBO is compared with the anomalies of maximum surface temperature.

2. DATA

The monthly mean zonal wind components at 30 mb for Canton Island and Gan, as shown in Figure 1 (from Ebdon, 1975), were used as representative of the equatorial stratosphere and were meaned for individual phases of the QBO, that is to say the mean of the monthly mean zonal wind for consecutive months with westerly or easterly components were evaluated irrespective of the length of the particular phase of the QBO. Nine complete cycles of the QBO were available

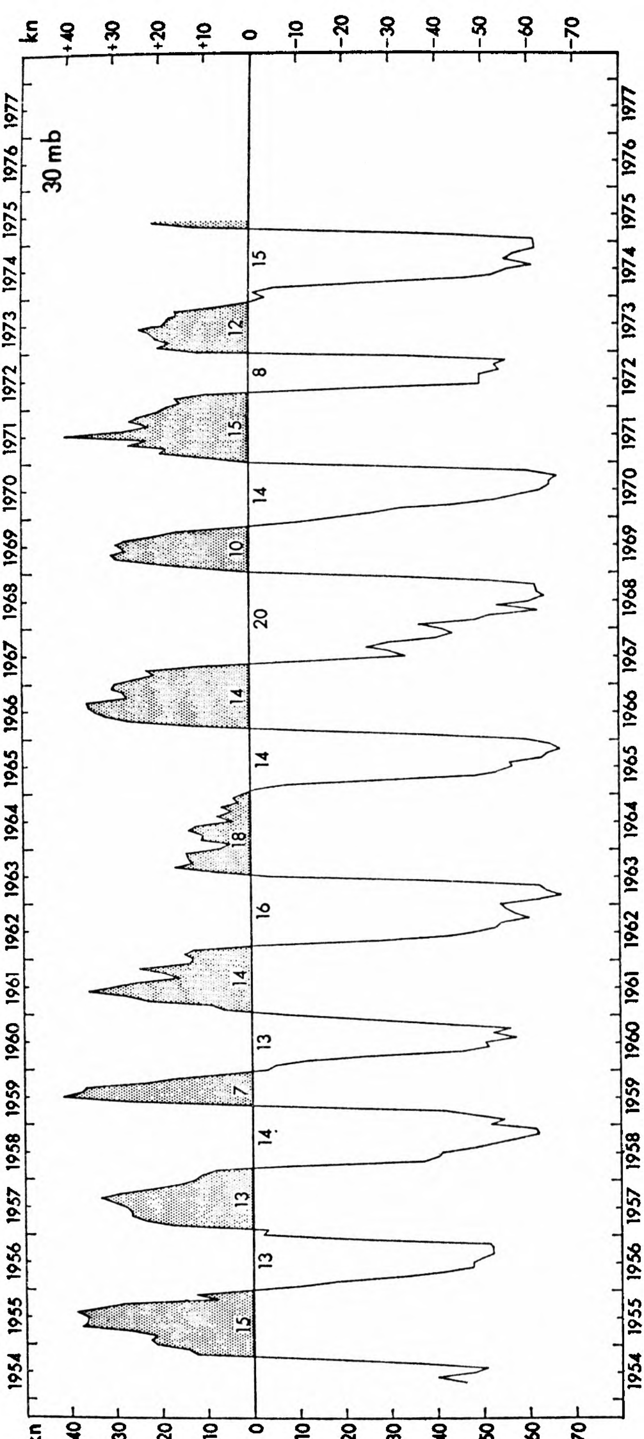


FIGURE 1—30 mb MONTHLY MEAN ZONAL WIND COMPONENTS AT CANTON ISLAND/GAN

Components towards the east are positive and stippled. Figures along the zero line indicate the duration, in months, of westerlies or of easterlies.

from November 1954 to March 1975 inclusive and are shown in Table I with appropriate 'meaned zonal wind'. It was found convenient to use screen maximum air temperatures for Oxford, and averages were calculated for the period in question from which monthly anomalies of maximum temperature were evaluated.

3. Results

The mean anomalies of the monthly mean maximum screen temperature at Oxford for each phase of the QBO, there being nine westerly and nine easterly phases in all, were calculated and are also shown in Table I against the appropriate phase of the QBO, i.e. the anomalies were meaned for the period of each phase irrespective of its length.

Table I—The mean anomaly of maximum temperature in each phase of the QBO

Phase of QBO	Mean zonal wind in knots	Mean anomaly of maximum temperature in degrees Celsius
Westerly		
Nov. 1954–Jan. 1956	+23·2	0·39
Mar. 1957–Mar. 1958	+21·7	0·35
Jun. 1959–Dec. 1959	+26·8	2·17
Feb. 1961–Mar. 1962	+19·1	0·64
Aug. 1963–Jan. 1965	+8·3	—0·18
Apr. 1966–May 1967	+26·2	—0·05
Feb. 1969–Nov. 1969	+20·9	—0·14
Feb. 1971–Apr. 1972	+20·5	0·24
Jan. 1973–Dec. 1973	+15·9	0·35
Mean	+20·3	+0·42
Easterly		
Feb. 1956–Feb. 1957	—33·4	—0·26
Apr. 1958–May 1959	—43·7	0·11
Jan. 1960–Jan. 1961	—33·1	0·14
Apr. 1962–July 1963	—47·3	—1·46
Feb. 1965–Mar. 1966	—45·2	—0·38
June 1967–Jan. 1969	—41·8	—0·34
Dec. 1969–Jan. 1971	—43·3	0·14
May 1972–Dec. 1972	—45·6	—0·69
Jan. 1974–Mar. 1975	—40·7	0·15
Mean	—41·6	—0·29

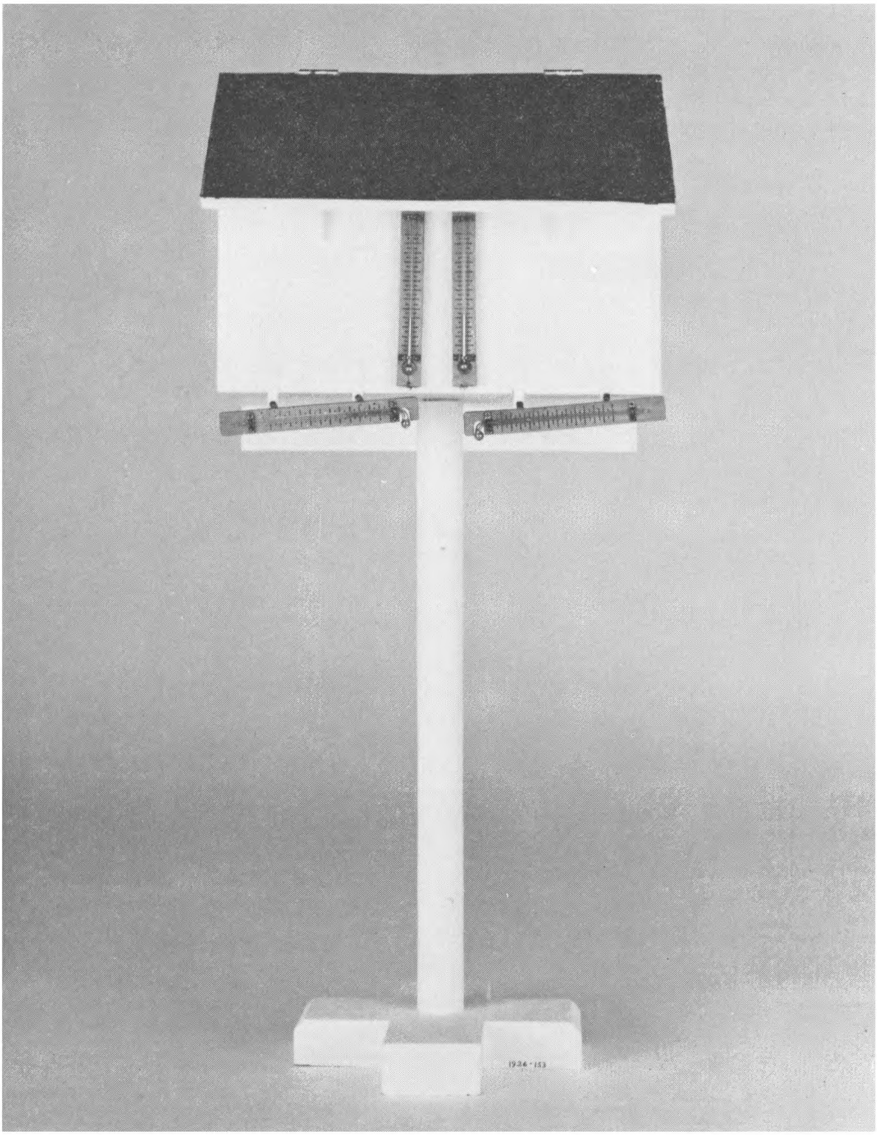
On eight out of eight occasions the mean anomaly of maximum temperature for a westerly phase was algebraically greater than for the preceding easterly phase, and on eight out of nine occasions the mean anomaly was less for an easterly phase than for the preceding westerly phase. The distribution of the mean anomalies for opposite phases of the QBO is shown in Table II.

Table II—Frequency distribution of mean anomalies of maximum temperature (T_{max})

	T_{max}						
	⩽—0·50	—0·49 to —0·25	—0·24 to 0·00	+0·01 to +0·24	+0·25 to +0·49	⩾0·50	Total
Easterly	2	3	0	4	0	0	9
Westerly	0	0	3	1	3	2	9
Total	2	3	3	5	3	2	18

PLATE I—DIGITAL ANEMOGRAPH LOGGING EQUIPMENT (DALE)

(See page 204)



Photograph by the Science Museum, London

PLATE II—THE GLAISHER THERMOMETER STAND

(See page 220)

Photograph by the Science Museum, London

PLATE III—THE GLAISHER THERMOMETER STAND

(See page 220)

To face page 215

PLATE IV—THE METEOROLOGICAL OFFICE STAND AT THE COST 72 EXHIBITION OF AUTOMATIC WEATHER STATIONS

(See page 228)

Table III shows the differences in the mean anomalies for opposite phases of the QBO and emphasizes the change in the actual value of the anomaly between phases, and indicates some degree of persistance in the mean anomaly of maximum temperature.

TABLE III—FREQUENCY DISTRIBUTION OF DIFFERENCE IN MEAN ANOMALIES OF MAXIMUM TEMPERATURE BETWEEN QBO PHASES (ΔT_{max})

	ΔT_{max}						
	⩽−1·00	−0·99 to −0·50	−0·49 to 0·00	+0·01 to +0·49	+0·50 to +0·99	⩾1·00	Total
Easterly following westerly phase	2	2	4	1	0	0	9
Westerly following easterly phase	0	0	0	3	2	3	8
Total	2	2	4	4	2	3	17

The linear regression of the mean anomaly of maximum temperature on the strength of the phase of the QBO in which the anomaly occurred as measured by the mean zonal wind speed during the phase (see Figure 2) was found to be significant at the 2 per cent level for 18 pairs of data giving the following relation,

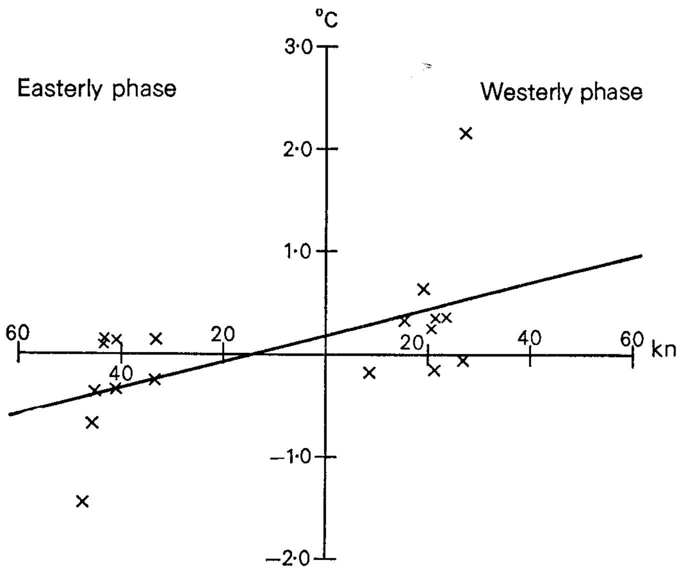


FIGURE 2—REGRESSION OF MEAN ANOMALIES OF MONTHLY MEAN MAXIMUM TEMPERATURE ON THE MEAN STRENGTH OF THE PHASE OF THE QBO IN WHICH THE ANOMALY OCCURRED

which accounts for 33 per cent of the total variance. The standard deviation of the sample is 0·71 and the standard error 0·60.

$$T_{max} = 0{\cdot}01x + 0{\cdot}20,$$

where T_{max} is the estimated mean anomaly of maximum temperature in degrees Celsius and x is the mean strength of the phase of the QBO in knots.

To determine if there is a lag in the relationship, the regression was repeated for periods of the same length as the appropriate phase of the QBO but with displacements from $M-6$ months to $M+15$ months, where M is the month in which each new phase of the QBO starts. The results at Figure 3 show the systematic change of correlation from a maximum at $M-1$ to zero at $M+6$ and to a minimum at $M+12$ months, and suggest an almost-in-phase relation between the QBO and the mean anomaly of maximum temperature with a half cycle of 13 months. The correlation at $M+12$ accounts for 28 per cent of the variance and, using the same notation as before, is given by $T_{max} = -0{\cdot}01x - 0{\cdot}07$. The mean duration of easterly and westerly phases are similar, i.e. 13·1 and 14·1 months respectively, and therefore a regression may be made of the mean anomaly of maximum temperature on the mean strength of the previous phase.

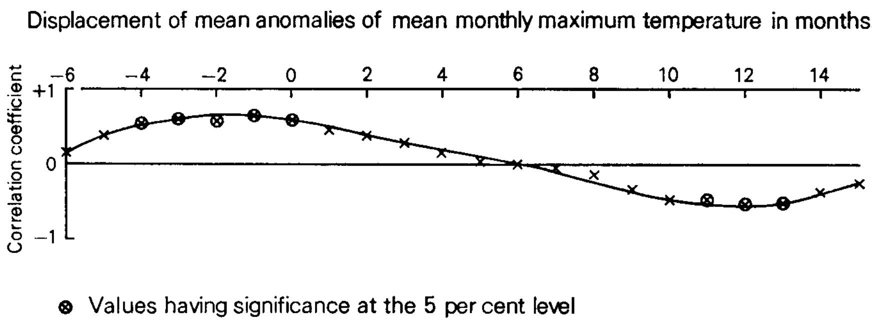


FIGURE 3—CORRELATION COEFFICIENTS OF MEAN ANOMALIES OF MONTHLY MEAN MAXIMUM TEMPERATURE ON THE MEAN ZONAL COMPONENTS OF THE QBO AT 30 mb FOR DISPLACEMENTS BETWEEN MINUS 6 AND PLUS 15 MONTHS

The regression, which is significant at the 5 per cent level, accounts for 23 per cent of the variance and is given by $T_{max} = -0{\cdot}01x_p - 0{\cdot}05$, where x_p is the mean strength of the previous phase of the QBO in knots. Since Parker (1976) has shown that it is possible to predict the onset and duration of a phase of the QBO in advance, some measure of the expected mean anomaly of surface maximum temperature for the following phase of the QBO may be made using a mean value for its strength. Alternatively, the strength of a particular phase may be used to predict the mean anomaly of maximum temperature for the next phase.

The percentage variance accounted for by these regressions is between 23 and 33 per cent; however, as discussed previously, by considering the differences in the mean anomalies of maximum temperature between two consecutive phases, an improved relation is found.

The regressions of the differences in the mean anomaly of maximum temperature for a particular phase, and the mean anomaly of maximum temperature for the previous phase on the strength of the QBO for the particular phase, and on the strength of the previous phase, are given by:

$$\Delta\ T_{max} = 0{\cdot}02x + 0{\cdot}27, \text{ and}$$

$$\Delta\ T_{max} = -0{\cdot}02x_p - 0{\cdot}23.$$

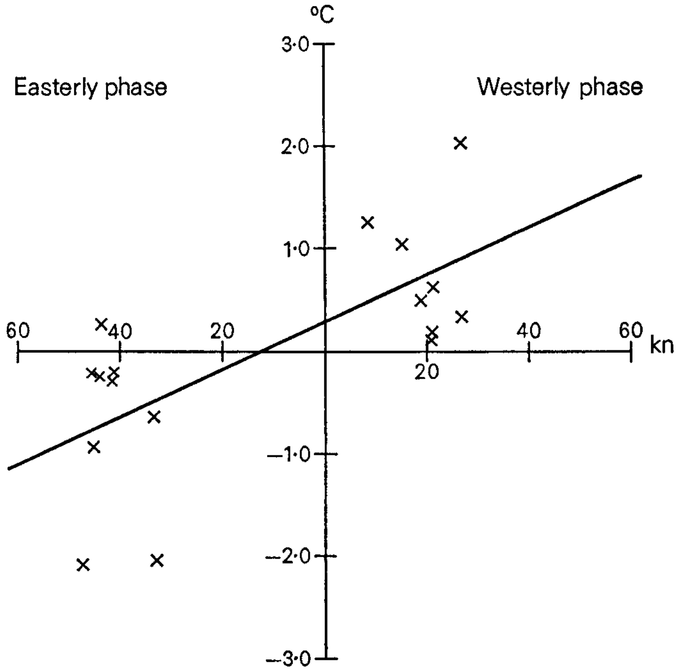


FIGURE 4—REGRESSION OF DIFFERENCES IN MEAN ANOMALIES OF MONTHLY MEAN MAXIMUM TEMPERATURE FOR CONSECUTIVE PHASES OF THE QBO ON THE MEAN STRENGTH OF THE SECOND PHASE OF THE QBO

The regressions, the first of which is shown in Figure 4, are significant at the 1 per cent and 0·1 per cent levels, and account for 48 and 55 per cent of the variance respectively. Since the mean anomaly of temperature for a particular phase of the QBO is known, this value may be added to the result to give an estimated mean anomaly of maximum temperature for the next phase of the QBO, which takes account of the persistence of temperature from one phase to the next.

Similar regressions of mean anomalies of maximum temperature in each season on the mean strengths of the QBO in both the current and previous phases were made, but observations were not included if the QBO changed phase during a particular season. The two summer regressions which give an estimate of the mean anomaly of maximum temperature for June, July and August were significant at the 2 per cent and 1 per cent levels, and account for 31 and 38 per cent of the variance respectively: the regressions are given by $T_{max} = 0{\cdot}01x + 0{\cdot}17$ and $T_{max} = -0{\cdot}02x_p - 0{\cdot}02$, and the first one on the mean strength of the current phase of the QBO is shown in Figure 5.

In the autumn months, September, October and November, the correlation of the mean anomaly of monthly mean temperature on the mean strength of the prevailing phase of the QBO is significant at the 5 per cent level and accounts for 24 per cent of the variance. Regression against the previous phase of the QBO accounts for 19 per cent of the variance and is significant at the 5 per cent level.

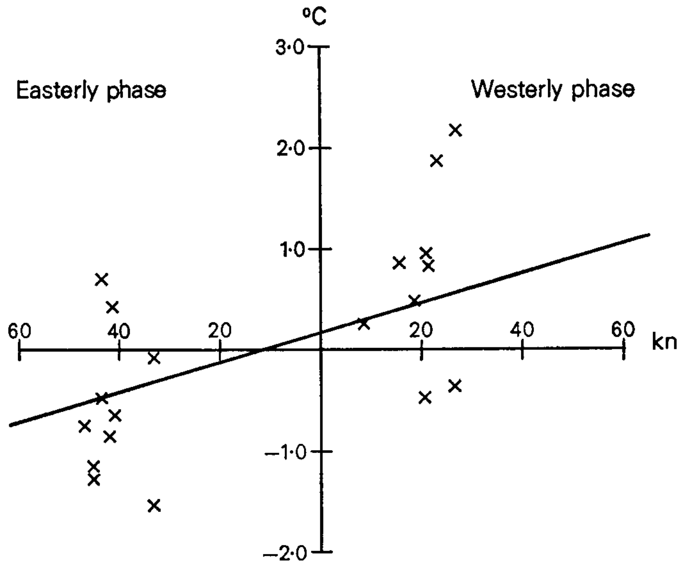


FIGURE 5—REGRESSION OF MEAN ANOMALIES OF MONTHLY MEAN MAXIMUM TEMPERATURE FOR SUMMER ON THE MEAN STRENGTH OF THE PHASE OF THE QBO IN WHICH THE ANOMALY OCCURRED

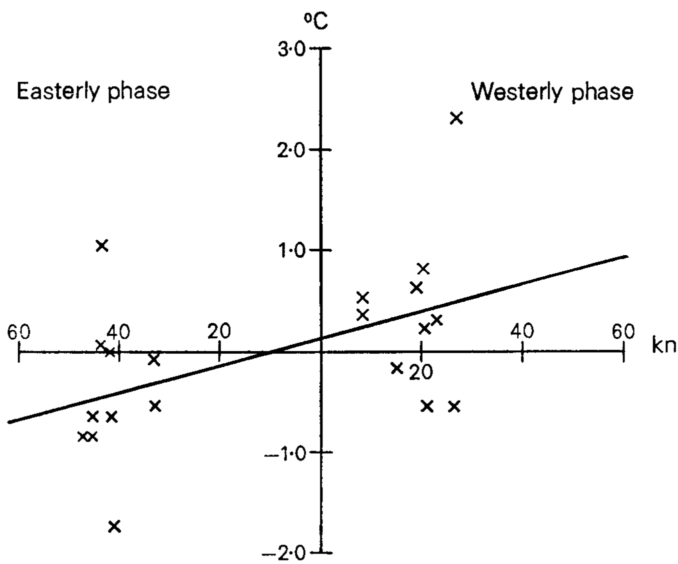


FIGURE 6—REGRESSION OF MEAN ANOMALIES OF MONTHLY MEAN MAXIMUM TEMPERATURE FOR AUTUMN ON THE MEAN STRENGTH OF THE PHASE OF THE QBO IN WHICH THE ANOMALY OCCURRED

The regressions are given by $T_{max} = 0{\cdot}01x + 0{\cdot}13$ and $T_{max} = -0{\cdot}01x_p - 0{\cdot}16$ respectively, and the first one is shown in Figure 6.

The regressions of the mean anomalies of monthly mean maximum temperature for the spring and winter seasons were not significant on either the mean strength of the prevailing phase of the QBO or on the mean strength of the preceding phase of the QBO.

4. Conclusions

Analysis of the mean anomaly of monthly mean temperature for Oxford shows that the mean anomaly for a westerly phase of the QBO exceeded that of the previous easterly phase of the QBO on all eight occasions, and that on eight out of nine occasions the mean anomaly was less for an easterly phase than the preceding westerly phase.

Significance at better than the 5 per cent level was found for the regression of the mean anomaly of monthly temperature on the mean strength of the QBO between $M-4$ months and M months and between $M+11$ and $M+13$ months, where M is the month in which a phase of the QBO starts. When regressions are made of the difference in the mean anomaly of maximum temperature for two consecutive phases of the QBO on the strength of the QBO and on the strength of the preceding phase of the QBO, significance levels of 1 per cent and 0·1 per cent are found which account for 48 and 55 per cent of the variance respectively. These relatively high values suggest that persistence of temperature from one phase of the QBO to the next may be of importance in determining the mean temperature anomaly.

A regression of the mean anomaly of summer mean maximum temperatures (for June, July and August) was found to be significant at the 2 per cent level for the existing phase of the QBO, and significant at the 1 per cent level on the mean strength of the previous phase of the QBO. In autumn, similar regression resulted in significance at the 5 per cent level. The regressions for the spring and winter months on the strength of the prevailing QBO and on the strength of the preceding QBO were not significant.

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MAXIMUM SUMMER TEMPERATURES RECORDED IN GLAISHER STANDS AND STEVENSON SCREENS

By JOYCE LAING

SUMMARY

Two types of structure for mounting thermometers, the Glaisher stand and the Stevenson screen, are described. Summaries of the comparisons of summer maximum temperatures made at various times are given, and an attempt is made to relate the 1868 and 1911 national maxima to present-day observing conditions.

INTRODUCTION

The long, hot, dry summer of 1976, with an extreme temperature of 35·9°C (96·6°F) recorded at Cheltenham on 3 July, has stimulated some interest in high temperatures in past years and, in particular, during the summers of 1868 and 1911 in which the extreme maximum temperatures for the United Kingdom occurred: 100·5°F was recorded at Tonbridge, Kent on 22 July 1868, and 100·0°F was recorded at the Royal Observatory, Greenwich on 9 August 1911, but these temperatures were not measured with thermometers in the standard Stevenson screen exposure.

During the latter part of the nineteenth century many of the temperature records were from thermometers mounted in various types of structure similar to the open Glaisher stand. After the Stevenson screen came into use, a number of investigations were carried out into the variation of the results from these two types of thermometer exposure.

THE GLAISHER STAND

In 1841 a structure for supporting thermometers was brought into use at the Royal Observatory, Greenwich, when James Glaisher was Superintendent of its Magnetic and Meteorological Department. Although known by his name, the stand was in fact designed by Sir George Airy, the Astronomer Royal; a description of the stand was written by Glaisher (1868). In essence, the Glaisher stand consisted of a vertical board about 4 ft above the ground on which thermometers could be mounted, sheltered from above; the stand could be rotated about a central pivot so that the thermometers were always shielded from the direct rays of the sun, but were still exposed to radiation from the ground, part of the sky, and some surrounding objects (see Plates II and III). A lot depended on the conscientiousness of the observer in turning the stand regularly, as the maximum temperature could easily be affected by the early morning or late evening sun striking the thermometers. With local modifications this stand was in use for many years.

THE STEVENSON SCREEN

Thomas Stevenson (1818–87) was a civil engineer who, through his work maintaining lighthouses round the Scottish coasts, developed an interest in meteorology. In 1863 he designed a louvered screen which would give better protection to the thermometers from precipitation and radiation. A major improvement is in the long-wave (thermal) radiation environment of the thermometer. Instead of receiving some radiation from the sky and the ground, all the thermal radiation falling on the thermometer comes from the interior of the screen, the temperature of which is very close to the ambient air temperature. A notice describing this screen was published in the *Journal of the Scottish Meteorological Society* in 1864, together with a note stating that the Society had already recommended the box to its observers for its compactness and low price (Bilham, 1937).

This screen was 15 inches high, 14½ inches long and 7½ inches wide (internal measurements) with double louvered sides, a solid roof (with a ventilator to prevent the build-up of heated air in the screen) and no bottom. The thermometers were mounted on slats and the whole box was supported on four stout posts so that the thermometers were 4 ft above the ground (Gaster, 1879). Modifications to this design were made in 1884 and this modified screen has remained virtually unchanged to the present day (Bilham, 1937 and Meteorological Office, 1956).

Comparison of temperature exposures

Considerable argument (Meteorological Society, 1873, and Stow, 1873) ensued in the late 1800s over which type of screen gave the more accurate value of the temperature of the air, and J. G. Symons organized (with a grant from the Royal Society) an elaborate comparison of screens of various designs at Strathfield Turgiss [old spelling] in Hampshire, the readings being taken by the Rev. C. H. Griffiths during the period November 1868 to April 1870 (Gaster, 1879).

Following these experiments, the Meteorological Office and the Meteorological Society recommended Stevenson's screen for use at observing stations (Meteorological Society, 1876, and Bilham, 1937). However, the Glaisher stand continued to be used at Greenwich to preserve the homogeneous record, and it was not until 1938 that the Stevenson screen was used as the standard.

Various comparisons between the temperatures recorded in a Glaisher stand (G) and those recorded in a Stevenson screen (S) have been made from time to time. One of the difficulties in any comparison is the uncertainty of the exposures in the Glaisher stand. To obtain the best shelter the stand ought, ideally, to be turned continuously. At such places as Greenwich, where observations were made at regular short intervals, the stand would be turned after each reading but, where only one or two observations a day were made, the stand could possibly on some occasions be left long enough without being turned for the sun to reach the thermometers.

The report on the experiments at Strathfield Turgiss in 1868–70 produced the following differences (S—G) in maximum temperature (°F)—see also column 1 of Table I.

	June	July	August	September
Cloudless sky		—1·1	—0·7	
Overcast		—1·4	—1·5	
All aspects	—1·5	—1·2	—0·9	—0·8

Edward Mawley, later President of the Royal Meteorological Society, conducted some comparisons between thermometers in a Glaisher stand and a Stevenson screen in his garden in Croydon, Surrey during the years 1877 to 1881 (Mawley, 1897). He obtained mean differences of between −1·0 and −1·5°F in the maximum temperatures during the summer months (see column 2 of Table I).

Ellis (1891) reported a comparison made at Greenwich during 1887 to 1889 in which he obtained mean differences in the maximum temperatures during the summer months of about −2·0°F (see column 4 of Table I).

Also using Greenwich data, Harding (1912) gave the following comparisons of maximum temperature on days in 1911 when the temperature was over 90°F:

	G	S	S—G		G	S	S—G
21 July	93·7	90·4	—3·3	13 Aug.	90·9	89·3	—1·6
22 July	95·6	91·7	—3·9	7 Sept.	91·6	90·0	—1·6
28 July	91·9	89·3	—2·6	8 Sept.	94·1	92·8	—1·3
9 Aug.	100·0	96·6	—3·4				

Margary (1924) reported a comparison between Stevenson screen and Glaisher stand exposures at Camden Square, London over the years 1881–1920. The differences in the maximum temperature (all occasions), averaged over the years 1881–1915, are given in column 3 of Table I. Several occasions of differences in daily maximum temperatures of −3·5°F or more occurred during this period, the highest being −4·2°F. The following mean differences for occasions when the maximum temperature was 70°F and above gave very similar values to those given in Table I (column 3):

Stevenson screen Max. (°F)	S—G (°F) June	July	Aug.
70–75	—1·1	—1·2	—1·0
>75		—1·3	—1·0

During the three years April 1923 to March 1926 a comparison was made between four types of thermometer exposure at Kew Observatory. J. M. Stagg (1927) analysed the results and gave the temperature differences between the Glaisher stand and the Stevenson screen, as shown in column 6 of Table I. (The differences were calculated in degrees Celsius.) This Glaisher stand was the same as that used at Camden Square since 1858 and which Margary (1924) had used in his work. It was moved to Kew in 1923 and set up in the enclosure, 16 ft due east of the Stevenson screen (with thermometers 4 ft above the ground); a photograph is in the *Observatories' Year Book, 1923* (Meteorological Office, 1926).

From the distribution of maximum-temperature differences (S—G) for the summer (May to August), Stagg gave the following values:

	°C	°F
Mean difference	—1·2	—2·2
1st quartile	—1·4	—2·5
3rd quartile	—0·9	—1·6

Stagg noted that the distribution of differences in temperatures at 1300 h was very similar to that of the differences in maximum temperature, and that during the three years of the experiment the extreme difference at 1300 h was −3·3°C (−5·9°F) on one occasion and −3·1°C (−5·6°F) on two occasions.

An analysis was made of the weather conditions on occasions of large differences in temperature and this showed quite clearly that the differences recorded were due to the effect of radiation on the thermometers in the open Glaisher stand. On fine, dry days in summer, the temperature of the ground around the base of the vertical support would rise considerably, following heating by solar radiation, and thus there would be considerably increased long-wave radiation from the surface. At the same time there would be increased sky and reflected solar radiation. Both these streams of radiation would heat the thermometers themselves and also the back-board on which the thermometers were mounted: together they would more than compensate for the loss of long-wave radiation from the board and thermometers to the clear sky. In general, it may be said that the more intense the solar radiation the greater the resulting temperature differences that were observed.

More recent work on Greenwich temperatures

A Staff Instruction in the Climatological Branch of the Meteorological Office in 1938 required a correction to be applied to Greenwich temperatures used in the compilation of long-period averages so that they would be comparable with those for other stations. Those corrections were based on a comparison made during 1900–13 using monthly mean differences, which produced the differences for maximum temperatures in the summer months as shown in column 5 of Table I.

Table I—Mean differences in maximum temperatures (°F), Stevenson screen minus Glaisher stand (S—G)

	1	2	3	4	5	6
	Strathfield Turgiss 1868–70	Croydon 1877–81	Camden Square 1881–1915	Greenwich 1887–89	Greenwich 1900–13	Kew 1923–26
May	—1·2	—1·2	—0·7	—1·8	—1·7	—2·3 (—1·3°C)
June	—1·5	—1·4	—1·2	—2·0	—1·8	—2·2 (—1·2°C)
July	—1·2	—1·4	—1·3	—2·2	—2·1	—2·3 (—1·3°C)
Aug.	—0·9	—1·1	—1·1	—2·0	—1·9	—2·0 (—1·1°C)
Sept.	—0·8	—0·8	—0·7	—1·2	—1·1	—1·3 (—0·7°C)

An early draft for the *Climatological Atlas of the British Isles* quotes C. E. P. Brooks as suggesting that a correction of −2 to −3°F be applied to the extreme temperatures recorded in the Greenwich Glaisher stand, but this comment was not included in the published version (Meteorological Office, 1952).

At the Royal Observatory, Greenwich, the Glaisher stand was originally set up in the Observatory grounds, but there was some doubt as to the exposure and also as to the effect of radiation from the white buildings near by. In 1899 the stand was moved to the Magnetic Pavilion enclosure, and in 1900 a Stevenson screen was installed about 15 ft north-east of the Glaisher stand (Royal Observatory, Greenwich, *passim*). It was from the published values of mean monthly differences between these two exposures that the Climatological Branch produced the figures quoted above (Table I, column 5). The Stevenson screen values were not published between 1914 and 1938, but thereafter they replaced the Glaisher values as the standard Greenwich temperatures. During the ten years 1900–09 daily values of the differences in maximum temperature between the two exposures were published (Royal Observatory, Greenwich). From these values Tables II and III have now been compiled. Table II gives the mean differences of the higher maximum temperature, and Table III sets out the frequencies of occurrence of the differences between maximum temperatures for Stevenson screen values of 70°F or more.

Table II—Mean differences (S—G) at Greenwich, 1900–09

	Stevenson Max. (°F) 70·0 to 74·9	⩾75·0	⩾80·0	⩾85·0
		Differences (°F)		
May	—1·3	—1·4	—1·5	
June	—1·6	—1·2	—1·1	—3·3
July	—1·7	—1·8	—1·5	—1·6
Aug.	—1·6	—1·4	—1·3	—0·8
Sept.	—0·8	—1·0	—0·9	—1·3

TABLE III—FREQUENCY OF OCCURRENCE OF DIFFERENCES IN MAXIMUM TEMPERATURES RECORDED IN GLAISHER STAND (G) AND STEVENSON SCREEN (S) AT GREENWICH, 1900–09

Stevenson Max. (°F)	Differences (S—G) °F									
	⩾0·0	—0·1 to —0·5	—0·6 to —1·0	—1·1 to —1·5	—1·6 to —2·0	—2·1 to —2·5	—2·6 to —3·0	—3·1 to —3·5	—3·6 to —4·0	⩾—4·1
	Number of occasions									
May										
70·0–74·9	3		7	9	6	4				
75·0–79·9	1		4	2	1	2		1		
80·0–84·9			1	1		1				
June										
70·0–74·9	6	1	7	16	10	12	3	2	2	
75·0–79·9	1	3	6	1	4	1	1		1	
80·0–84·9	2		3		1					
85·0–89·9								1		
July										
70·0–74·9	5	3	10	13	20	12	4	6	1	1
75·0–79·9	1	2	10	11	10	9	9	8	1	1
80·0–84·9	3	4	10	4	7	5	3	1	3	
85·0–89·9			4		1	3				
⩾90·0					1	1				
August										
70·0–74·9	2	11	8	16	17	15	4	3	1	
75·0–79·9	1	7	7	7	3	5	8			
80·0–84·9	1	2	1	7	2	1	1		1	
85·0–89·9	1	1	1		1					
⩾90·0				1						
September										
70·0–74·9	6	7	12	9	5					
75·0–79·9		1	2	2		1				
80·0–84·9	1	1	1	1						
85·0–89·9					1					
⩾90·0			1	1						

The higher temperatures (85°F and above), in general, show smaller differences between the two exposures than the lower ranges of temperature, but the number of occasions is small. Days of high temperature are generally those with little or no cloud and therefore will have greater than average differences between the temperatures, but often the days with the strongest radiation (those giving the greatest differences) will occur when the temperatures are comparatively low: for example, on days of clear polar air.

The greatest difference during the period 1900–09 was −4·2°F which occurred with a Stevenson screen maximum of 74·8°F in July 1908. Unfortunately, August 1911 does not come within this period, but the difference between the maxima on 9 August (Glaisher maximum 100·0°F) has been quoted as −3·4°F (Harding, 1911). The average difference between the Stevenson screen and Glaisher stand maximum temperatures at Greenwich during the summer months is seen to be about 2°F.

REASSESSMENT OF PUBLISHED EXTREME TEMPERATURES

Table I summarized the mean differences in maximum temperatures recorded on Glaisher stands and in Stevenson screens, as found in the various investigations.

The values obtained at Greenwich and Kew are similar, while those for Camden Square, Croydon and Strathfield Turgiss are nearly 1°F smaller. However, as the periods are not the same, a strict comparison cannot be made.

To make a comparison of the temperatures of the summer of 1976 with the published maxima for the United Kingdom (100·0°F in August 1911 and 100·5°F in July 1868) some corrections must be applied to the old recordings.

The summer of 1868

In 1868 Dr G. Hunsley Fielding (1869) was keeping weather records at Tonbridge, Kent. His description of that summer could easily be applied to 1976:

> The intense heat, combined with great scarcity of rain, was most fatal in its effects both upon the animal and vegetable world. The Registrar-General's returns for the quarter ended September 30 showed a fearful increase, in England alone, of 21,000 deaths. In the garden . . . nothing whatever came to perfection, either in size or flavour. Peaches and nectarines, apricots, apples and pears dropped half-developed from the trees; raspberries, currants and gooseberries hung shrivelled on the bushes and the beans and peas hung dwarfed or with empty pods. The lawns were burnt quite brown, as were the neighbouring pastures, and often split into deep furrows, the stock being obliged to feed on winter provender. The springs in many places were quite dried up, occasioning great inconvenience and expense in obtaining water.

His thermometers were mounted in a 'box stand, double with venetian sides' (Fielding, 1869) and he gives the following description of the site:

> My abode is at Tunbridge [*sic*], in the valley of the Medway; it is nearly surrounded by hills, but the immediate vicinity is flat and marshy, the river winding through, at a distance of about a quarter of a mile. . . . A small tributary of the Medway flows at the bottom of the garden to the eastward and southward, on which last there is a millpool through which it runs. The kitchen-garden is at the back of the house, and in it, entirely detached from the house, is my thermometer-stand. The stand faces to the north-east, a narrow gravelled path separating it from the vegetable beds, and about fifty feet distant is a fruit wall. It is double at the back and top, air circulating freely between the pieces. Behind it is a piece of lawn, and about 20 feet distant a low wall and laurel-hedge fencing off the millpool. The instruments . . . are 4 feet from the ground and 75 feet above mean sea-level.

The maximum temperature recorded at Tonbridge was 100·5°F on 22 July 1868, and on the same date Greenwich recorded 96·6°F. Other maximum temperatures recorded on this day are listed in *Symons's Meteorological Magazine* (1868) with descriptions of the types of stand used. F. W. Stow's records at Tunbridge Wells produced a maximum of 92·4°F in a modified Glaisher stand, but that site was 403 feet above mean sea level, considerably higher than Dr Fielding's. Two records from Stevenson screens were quoted: 83·0°F at Worthing and 92·6°F at Audley End, Esssex.

It is difficult to make any comparison of the Tonbridge temperatures with present-day values as it is not entirely clear how much shelter the Tonbridge stand afforded. Dr Fielding's description implies that it was an open stand, while Symons's list suggests that it was similar to Stevenson's screen with louvers all round. The description of the site is rather vague on whether the thermometers were over grass, but the obvious proximity of the gravel path and vegetable beds (especially that year when all vegetation was dried up) must have increased the amount of radiation reaching the thermometers if the stand was at all open.

Both Stevenson screens were in very different localities and no direct comparison can be made with these limited data. The high value at Tonbridge, compared with other maxima on that day, would seem to indicate that it was recorded in an open stand. If this was the case, we can perhaps assume that the same differences occurred between the exposures as at Greenwich where an average of −2·1°F has been calculated for July. This would give a value comparable with a louvered screen exposure of 98·4°F. On the other hand, when in 1911 Greenwich had a similar maximum temperature (100·0°F), the difference between the two exposures was −3·4°F. Applying this correction to the Tonbridge maximum gives a value of 97·1°F.

Daily values of maximum temperature are available for Tonbridge and Greenwich for July 1868 which show that Tonbridge was about 3°F higher, on average, in that month. The Stevenson screen equivalent of the reading of 96·6°F at Greenwich seems likely to be between 93·2 and 94·5°F. Applying a 3°F correction to these figures leads to a Tonbridge value of between 96·2 and 97·5°F. The most probable Stevenson screen equivalent of the Tonbridge maximum temperature would therefore seem to lie between 97 and 98°F.

The summer of 1911

Harding (1912) described the summer of 1911 when a maximum of 100·0°F was recorded at Greenwich. Although temperatures in the south-east were high, London was not affected by the water shortage which was more severe in the north Midlands and caused many people to be thrown out of work. In the same article (page 21), Harding quoted a letter from a Dr F. S. Arnold who wrote about an extraordinary amount of 'unrest in the labour world' and 'police and mob violence . . . which will make the year 1911 long memorable', and who attributed this to the hot weather.

Both the Glaisher stand and the Stevenson screen at Greenwich at that time were located in the Magnetic Pavilion enclosure, about 15 ft apart. On 9 August 1911, when the maximum temperature in the Glaisher stand was 100·0°F, the Stevenson screen maximum was 96·6°F (Harding, 1912), a difference of −3·4°F. Other maximum temperatures recorded on the same date and published in the *Monthly Weather Report* (Meteorological Office, 1911) were 98°F at Epsom (Surrey), Raunds (Northants) and Canterbury (Kent), all in Stevenson screens. A value of 99°F at Isleworth (Middlesex) was quoted in the *Report* (and also by Harding, 1912). An article in *Symons's Meteorological Magazine* (1911) quotes a maximum temperature of 98·8°F from a Kew-verified Six's thermometer in a Stevenson screen at Ponders End (Middlesex).

POSSIBLE ADJUSTMENTS TO EXTREME MAXIMUM TEMPERATURES FOR THE UNITED KINGDOM

From descriptions of the various types of structure for mounting thermometers and the comparisons between them, it is concluded that the measurements of the maximum temperatures currently accepted as the extreme United Kingdom values are higher than they would have been if present-day methods were used. While the thermometers in a Stevenson screen are always and automatically sheltered from direct radiation, this is not always the case for a Glaisher stand, and thus values from an open stand must be rejected as unrepresentative of ambient temperature.

No direct comparison with the maximum temperature of 100·5°F at Tonbridge in 1868 and the present type of exposure is available, and there is some doubt as to the exact positioning and screening of the thermometers. However, assuming the same differences as those calculated for Greenwich, it seems most probable that the equivalent Stevenson screen maximum temperature at Tonbridge on 22 July 1868 was between 97 and 98°F, which is in excess of the 1976 maximum. Since 1868 very warm spells have occurred in 1881, 1911 and 1932.

In 1881 a temperature of 101·0°F was observed in an open stand at Alton, Hants (Symons, 1881) but this has apparently never been considered as a record extreme; indeed, on the same day, 15 July 1881, the nearby station at Alresford had a maximum of only 89·4°F in a Stevenson screen. The highest Stevenson screen maximum for this period reported in Symons (1881) was 95·0°F at Camden Square.

On 9 August 1911 the maximum temperature in the Stevenson screen at Greenwich was 96·6°F (Glaisher stand maximum 100·0°F) which is equal to the 1976 maximum. However, higher values recorded in Stevenson screens were reported: 98°F at Epsom, Raunds and Canterbury. A value of 99°F has been quoted for Isleworth (Meteorological Office, 1911) but no details of the siting of the thermometers are available, nor was it included in Symons (1911) with other high temperatures on that day. This station was administered by the Royal Meteorological Society and had been operating for many years, although the readings were not published regularly in the *Monthly Weather Report*. A temperature of 98·8°F at Ponders End was recorded in a Stevenson screen but the thermometer was not standard and there are no details of the site, except for a comment that it was 'in standard conditions' (Symons, 1911).

In 1932, although it was a generally dull summer, there were some high maximum temperatures in southern England in August. Maxima of 97°F were recorded in standard exposures at many places on 19 August including Camden Square, Regent's Park, Tottenham and Enfield in the London area, and Halstead in Essex.

Accepting the strict conditions that are now required for the siting and recording of air temperatures, only those values recorded by standard thermometers in a Stevenson screen in an unsheltered site should be considered for the extreme maximum temperature. However, a careful comparison of Glaisher stand and Stevenson screen readings suggests that the Stevenson equivalent of some of the old Glaisher maxima still maintain a place in the 'top ten' extreme temperatures.

A realistic estimate of the extreme maximum temperature so far recorded in the United Kingdom is 98°F (37°C)—most of the stations recorded the extreme temperatures in whole degrees Fahrenheit—and the ranking order seems to be as follows:

98°F (37°C)	9 August 1911	Raunds, Epsom, Canterbury;
97–98°F (36–37°C)	22 July 1868	Tonbridge;
97°F (36°C)	9 August 1911	Hillington, Wokingham;
	19 August 1932	Camden Square, Enfield, Regent's Park, Tottenham, Halstead;
96·6°F (35·9°C)	9 August 1911	Greenwich;
	3 July 1976	Cheltenham.

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ORGANIZATION OF THE COST 72 TECHNICAL CONFERENCE AND EXHIBITION AT THE UNIVERSITY OF READING, SEPTEMBER 1976

By K. J. T. SANDS

SUMMARY

A Technical Conference and Exhibition on Automatic Weather Stations was held at the University of Reading in September 1976. Most of the organization of this event was the responsibility of Meteorological Office staff. This article summarizes the work involved.

In September 1973 a contract was arranged between governments participating in European Co-operation in Science and Technology (COST) and the Director-General of the Meteorological Office, to carry out a study of the use of automatic weather stations in COST participating countries. The study was to be concluded by a technical conference and exhibition to be organized by the British Meteorological Office. The study group consisted of delegates from ten countries and the Chairman was Mr G. J. Day, then in charge of surface instrument development in the Office. A sub-group consisting of three members was formed to make arrangements for the running of the conference and exhibition: Mr J. H. Rietman (Netherlands), Dr C. V. Dake (West Germany), and Mr K. J. T. Sands (UK) who was appointed Chairman.

The first meeting of the sub-group took place at the Meteorological Office College, Shinfield Park in September 1975. Two members of the EEC Secretariat attended the meeting. It soon became obvious that, although the overall plan would be decided by the sub-group, the majority of the work involved would have to be undertaken by the UK representative (the Chairman).

The sub-group originally considered holding the Conference at the Meteorological Office College. However, the only period available, mid July, is a popular holiday time for the EEC countries. Reading University was able to offer suitable accommodation, and it was agreed to hold the event there during the third week of September 1976. An offer to help in the organization of the Conference by the International and Planning Branch (Met O 17) was accepted. The advice of other UK Government Departments was sought on the problems of organization and, on their recommendation, a specialist contractor was asked to supply the furnishings.

Concurrently, questionnaires were sent to the official COST representative of each participating country, requesting abstracts of papers to be presented at the Conference and details of exhibits from their commercial and national organizations. Eventually sufficient information was at hand to enable a draft Conference program to be drawn up, along with exhibition-stand layout design.

A further meeting of the sub-group took place in March 1976 and the Conference program and exhibition layout were agreed. Accommodation for the delegates was booked at the University. The Conference was to be presented in three working languages, namely English, French and German; simultaneous translation listening facilities were arranged in the lecture theatre for all delegates.

The Conference, planned to last three days, was divided into four sessions, each dealing with a different aspect of automatic weather stations and having a different Chairman, a specialist in that particular aspect. It had originally been planned to send a complete set of papers to the EEC Secretariat in Brussels for duplication prior to the Conference, and a bound set of papers was to be sent to each registered Conference participant four weeks before the Conference date. The deadline for receipt of papers was 1 June 1976 but by then only about one quarter of the thirty papers promised had arrived, and so a decision was made to duplicate, collate and bind the papers locally as soon as they came in. The duplicating section of the Meteorological Office responded magnificently and in a very short time produced 92 000 copies. The bound volume of papers consisted of 356 pages. Six papers arrived too late for inclusion and were published as a supplement. All the papers were published in the original language, but English translations were prepared and made available at the Conference. A program of the Conference and Exhibition was also prepared for issue at the Conference.

The organization of the Exhibition became very demanding as the event drew closer. Each overseas exhibitor was informed of the procedures to be followed when dealing with the British Customs and Excise. With display material coming from many different countries it was perhaps inevitable that some difficulties would arise but it was nevertheless surprising that large organizations failed to act on the information sent to them and consequently fell foul of our Customs regulations. After much late-night telephoning by the organizers, two exhibitors breathed long sighs of relief when their display material was released from bond at London Airport and delivered to them a few hours before the opening of the Exhibition. Even the use of internationally known forwarding agents did not guarantee a safe passage: one consignment of valuable equipment disappeared from a 'sealed container' on the return journey to Italy, and some weeks later it had still not been traced.

The Conference and Exhibition were formally opened on 22 September by Dr B. J. Mason, Director-General of the Meteorological Office, and Mr C. L. Silver, Chairman of the COST Senior Officials. Twenty-nine papers were presented during the first two and a half days of the Conference, the afternoon of the third day being devoted to a discussion on the opportunities for standardization and co-operation in the development and use of automatic weather stations. Twenty-three stands from eight countries displayed a variety of equipment in the Exhibition and several exhibitors had instruments set up on the grassed area adjacent to the building; the Meteorological Office stand was organized independently by members of the Operational Instrumentation Branch (Met O 16) and is shown in Plate IV.

The Conference office remained open throughout the Conference and dealt with delegates' and exhibitors' problems as they arose; the telephone was in great demand, many lengthy calls being made by foreign exhibitors to their home base.

Co-operation by the staff of the University was first-class and contributed greatly to the success of the event.

The Conference and Exhibition closed at 1600 hours on 24 September. Dismantling of the stands and equipment started immediately and was completed the following morning. A sight typical of the end of a successful Conference and Exhibition was that of an obviously satisfied overseas exhibitor holding an impromptu farewell party for his UK Agent in the grounds of the University, surrounded by his crated exhibits.

REVIEW

Statistical fluid mechanics: mechanics of turbulence, Volume 2, by A. S. Monin and A. M. Yaglom, edited by J. L. Lumley. 230 mm × 160 mm, pp. xi + 874, *illus.* MIT Press, 126 Buckingham Palace Road, London SW1W 9SD, 1975. Price: £25.00.

This volume completes the outstanding *tour de force* of the two Russian authors in which they present an account, without an equal, of the current theory and understanding of turbulence. The first volume had discussed the nature of laminar and turbulent flows in which it can be described statistically.

In over 800 pages this volume goes into the mathematical description in great detail and considers special turbulence fields (homogeneous, isotropic, locally isotropic, etc.) and the theories and hypotheses that have developed around them. The propagation of waves through turbulent fields, and other problems, are considered in detail. Possibly the parts of greatest interest to meteorologists are:

(a) A clear and interesting account of the earlier work on closure schemes for the basic equations governing momentum, heat and moisture. Although these schemes have advanced significantly since the writing of the book, nevertheless it would be no waste of time to read, for example, the detailed background to the Millionshchikov hypothesis that velocity fourth-order cumulants can be put equal to zero. The authors discuss in detail the consequences and why to some degree it fails.

(b) A fairly full account (60 pages) of some of the theoretical and experimental work on diffusion. This is very good reading indeed for the research worker in this field, but it is not intended as a practical manual for the man concerned with the height of his factory chimney!

The translation and editing has been done with great competence by Professor John Lumley of Pennsylvania State University, one of the most respected names in turbulence theory in the world. Generally the printing is satisfactory, and the occasional large changes in print size over several pages at a time, which at first sight seem rather extraordinary and presumably occur as a result of last-minute changes in the text, turn out in practice to be of no consequence or irritation.

In summary, this book is a very valuable piece of work intended for the turbulence specialist and has no competitor of equal standing at the present time.

F. B. SMITH

NOTES AND NEWS

Retirement of Mr R. A. S. Ratcliffe

Mr R. A. S. Ratcliffe, Assistant Director (Synoptic Climatology), retired on 26 May 1977. He had held this post since 1966, and it is as the man responsible for the monthly forecasts that he has become best known, both inside the Meteorological Office and, through his numerous appearances on radio and television, to a wider audience in the general public. The long-range forecaster's task is not easy. Faced with one of the most intractable problems in the whole of science he is, nevertheless, called upon to produce a diagnosis and prognosis to a grinding half-monthly schedule. The margin of success is small; near misses and much insight go by unrecognized, while failures attract more than their fair share of criticism. To maintain one's enthusiasm and conviction over a long period takes more than ordinary resilience and tenacity of purpose. These are qualities that Mr Ratcliffe has brought to long-range forecasting to a striking degree. He has consistently been a formidable apologist for the concept of long-range forecasting and a strong defender of the methods used within the Meteorological Office.

Earlier in Mr Ratcliffe's career he had also been required to face difficult situations and bear his share of heavy responsibilities. Coming into the Meteorological Office in 1938 with a first-class honours degree in Natural Sciences from Cambridge University, he was soon plunged into the maelstrom of agonizing decisions and frequent postings that the Second World War brought to most meteorologists of his generation. Within a few months he found himself responsible for forecasts for aircraft undertaking very long flights over the Atlantic and the Norwegian Sea, at times when observations were few and the forecaster had to make most of his deductions from surface observations. His experience at this time led to his being selected to join the pioneering group set up at Dunstable in 1943 under Dr Sverre Petterssen to provide a unified upper-air forecasting service. Its output was used in many contexts, but most notably perhaps in providing meteorological data for Bomber Command raids on Germany. It was during this time that the basic methods of upper-air forecasting were developed; pressure levels were chosen in preference to fixed heights as the basis for the charts and the 'gridding' technique which became standard practice in the Meteorological Office until the advent of computer methods.

When the sphere of military operations moved to the Far East, Mr Ratcliffe went to the Joint Meteorological Centre in Colombo, and later to Calcutta. After hostilities were over, there came a spell in the United Kingdom, first on the upper-air roster once more, and then as senior meteorologist in RAF Training Command, but he was soon abroad again in Cyprus. His spell of duty there coincided with the worst period of the EOKA campaign and included such traumatic events as the British withdrawal from Egypt, the 1956 Suez campaign, and the upheavals in Iraq and Jordan.

Returning home in 1959, Mr Ratcliffe spent the next eight years as a senior forecaster at Heathrow and then at the Central Forecasting Office, Bracknell. During this time he earned an enviable reputation for his forecasting skill and dependability. One highly competent judge considered him to be 'among the best three or four forecasters ever to have served in the Central Forecasting Office'. In 1966 he was promoted to Senior Principal Scientific Officer and turned his mind from the relatively tangible concepts of 24 and 48 hour prediction to the nebulous uncertainties of atmospheric developments over a month. Once again he quickly made his mark, and in 1970 was awarded (jointly with R. Murray) the L. G. Groves Memorial Prize for Meteorology for his research on the influence of sea-surface temperature anomalies in the Atlantic on weather conditions near the British Isles.

Outside his official duties, Mr Ratcliffe has maintained a particular interest in the activities of the Horticultural Society of which he has been Chairman for most of his time at Bracknell. At flower shows his exhibits, and those of Mrs Ratcliffe, have been outstanding and a source of pleasure and admiration to all the Meteorological Office staff. He has been active on the cricket field and on the tennis courts. Indeed, he is currently Secretary of the Royal Ascot Tennis Club, and still plays occasional matches for them.

A man of wide-ranging interests and enthusiasms, Mr Ratcliffe approached his departure from the Meteorological Office not as an end to activity but as an opportunity to intensify existing pursuits and to take up new ones. To him and to his charming wife Hilary we extend our heartfelt wishes for a long, happy and full retirement.

A. GILCHRIST

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NOTICES

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THE USE OF WET-BULB POTENTIAL TEMPERATURE CHARTS

By T. A. M. BRADBURY

SUMMARY

Charts showing the distribution of wet-bulb potential temperature (θ_w) on isobaric surfaces were found to be a valuable aid in analysis and forecasting. Charts of θ_w at 850 mb show low-level air-mass types more clearly than other charts at present in use and enable frontal analysis to be improved. There was found to be a relationship between the value of the 850 mb θ_w and the probability of precipitation falling as snow. High values of the 850 mb θ_w were observed to be associated with the development of summer thunderstorms. Charts of θ_w at 500 mb and 850 mb were combined to derive an index of potential stability. Charts showing the variation of this stability index over a wide area were found to be useful in defining areas where thunderstorms or significant falls of rain were likely.

INTRODUCTION

For many years the major aids for analysis and prognosis were the contour charts of the 500 mb surface and the thickness of the 1000/500 mb layer. When all the work was done by hand, much of the available time was spent in plotting, analysing and constructing forecast charts for these levels. Now that the majority of surface and upper-air reports are received, checked and stored by computers, which can then produce mechanically plotted and objectively analysed charts, the forecaster has the opportunity to examine the atmosphere in greater detail. There is a limit to the number of charts which can usefully be examined, but it is suggested that charts which summarize the distribution of moisture and stability in the troposphere can form a valuable addition to the present routine.

Wet-bulb potential temperatures* (θ_W) combine information on temperature and vapour content in a single figure which is conservative for adiabatic changes. A chart showing isopleths of θ_W on a single isobaric surface can be used to improve air-mass and frontal analysis. From the distribution of θ_W on two isobaric surfaces one may derive an index of potential stability which can be

* Because of the inevitable errors introduced by the methods of approximation and calculation employed, the theoretical distinction between 'wet-bulb potential temperature' and 'pseudo wet-bulb potential temperature' is of no importance in the present work and the former term will be used for convenience.

used over a wide area. When such a chart is used in conjunction with standard surface and upper-air contour charts, the regions where moderate rain or thunderstorms are likely may be defined with increased confidence.

SELECTION OF ISOBARIC SURFACES FOR θ_W CHARTS

The 850 and 500 mb surfaces were found to be the most useful standard levels for plotting the distribution of θ_W over a sector of the northern hemisphere extending from North America to central Russia. The 850 mb surface was generally high enough to be little influenced by diurnal variations but low enough to be representative of conditions near the base of the troposphere. The 500 mb surface was the highest that could be used throughout the year. Higher levels were above the tropopause for periods during the colder months.

In summer months and in low latitudes the 400 mb or even the 300 mb surface appeared useful for locating areas of deep instability, but these levels suffer from errors due to the decrease of accuracy in the reported values of temperature and humidity. These radiosonde errors are generally found to increase with height.

CONSTRUCTION OF θ_W CHARTS

The values of θ_W can be found graphically by using a tephigram but the process is far too slow for routine work. For operational purposes the extraction of data is best handled by the computer, but for experimental work, and when the necessary data are not accessible by machine, the values of θ_W should be read from a Table. Table I allows the user to find the 850 mb θ_W from the temperature and dew-point depression reported at that level in part A of routine radiosonde messages. In this Table the values have been rounded to the nearest whole degree. Values ending in ·5 have been rounded up. For most purposes this Table is adequate since the original observations rarely justify working to a greater degree of precision.

Over most of Europe, western Russia and North America the network of radiosonde stations is close enough for a preliminary sketch of θ_W isopleths to be drawn by direct interpolation aided by continuity. Over the oceans these methods need to be supplemented by extrapolation, guided by the use of satellite data. Preliminary 850 mb isopleths should be superimposed on the first drawing of the surface chart and adjustments made to both to obtain consistency.

Isopleths of θ_W at 500 mb show less direct relationship to the surface chart, and the general pattern bears more resemblance to the contours of the 300 mb surface. The differences are most noticeable over occlusions, which are often marked by a warm tongue in the θ_W isopleths, and near major vortices when the 300 mb low is not concentric with lower-level features. Isopleths showing the difference in θ_W between 850 and 500 mb can provide an index of potential instability (or stability). These lines can be drawn directly, using the values determined from each sounding, but better results may be obtained by gridding the two levels on a light-table. The technique is similar to that employed when contour charts are constructed with the aid of partial thicknesses.

The analyst needs to watch for two common errors in the data. The first is due to a coding mistake which causes the temperature to be read as negative when it should be positive, or vice versa. These coding errors usually produce such a gross distortion of the isopleths that the mistake becomes obvious. The second type of error occurs when the radiosonde drifts off calibration during the ascent. Values at 500 mb and higher are more sensitive to this kind of error than are the

850 mb values. Fortunately errors in θ_W are usually in the same sense as errors in the heights of the 300 or 500 mb surface. Anomalously high values of the 500 mb θ_W generally coincide with reported contour heights which are noticeably higher than surrounding values, and this feature may be used to correct or reject the report.

Use of 850 mb θ_W isopleths

The primary use of these charts is for air-mass and frontal analysis. Frontal analysis is still a subjective process, as can be seen when charts issued by different meteorological centres are compared. The difficulty of satisfactory analysis is increased when the charts in use are on a small scale with only a limited number of observations plotted. The isopleths of the 850 mb θ_W can help the analyst to place fronts with a clearer knowledge of the change of air mass at the frontal boundaries.

Where surface fronts were well defined, the isopleths of the 850 mb θ_W and the contours of the 1000/500 mb thickness showed very similar patterns. In these cases the surface observations alone were usually sufficient to define the frontal position. Where the surface fronts were poorly defined by surface observations, the 850 mb θ_W isopleths appeared superior to the 1000/500 mb thickness lines in locating the position and alignment of the fronts. The θ_W isopleths enabled an analyst to trace the movements of air masses during periods when the front separating them was too inactive to be located by surface observations or cloud patterns. In some cases frontogenesis was apparent some 12 hours earlier on θ_W charts than on surface or 1000/500 mb thickness charts.

850 mb θ_W isopleths and fronts

The following relationships between θ_W isopleths and surface fronts were observed:

(a) The isopleths lay almost parallel to warm and cold fronts for very long distances even when the fronts were aligned north to south.

(b) The gradient of θ_W was greatest in the cold air, and the position of the surface front often coincided with a marked decrease in this gradient. Figure 1 shows an example of this change of gradient to the south of a front which lay from the northern Caspian Sea to Scandinavia and beyond.

(c) The maximum values of θ_W often occurred close to the surface front on the warm side of the boundary. Figure 2 shows an example of this. The appearance of a very narrow, warm, moist tongue in such a position was observed on many occasions. It appeared to fit the model of a low-level jet stream described by Browning (1973). This jet stream consisted of a tongue of anomalously warm moist air where θ_W attained a maximum value in the horizontal.

(d) Where occlusion had occurred, the isopleths of θ_W lay across the line of the front. An example is shown in Figure 3. An old occlusion lay from Leningrad to north-west Germany and a newly formed occlusion had developed off the east coast of Greenland.

Non-frontal patterns of θ_W

Isopleths of the 850 mb θ_W proved useful in showing when the air mass was not homogeneous. The air in warm sectors was generally more nearly homogeneous than the air behind cold fronts, but tongues of drier air were observed in a

TABLE I—TO DETERMINE 850 mb WET-BULB POTENTIAL TEMPERATURE, USING AIR TEMPERATURE AND DEW-POINT DEPRESSION

Air temp. (°C)	Dew-point depression (°C) 00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	25	30
30	35	34	34	33	32	31	31	30	29	29	28	28	27	27	26	26	25	25	24	24	23	22	20
29	34	33	33	32	31	31	30	29	29	28	27	27	26	26	25	25	24	24	23	23	23	21	20
28	33	32	32	31	30	30	29	28	28	27	27	26	26	25	25	24	24	23	23	22	22	20	19
27	32	32	31	30	29	29	28	28	27	26	26	25	25	24	24	23	23	22	22	22	21	20	18
26	31	31	30	29	29	28	27	27	26	26	25	24	24	23	23	23	22	22	21	21	21	19	18
25	30	30	29	28	28	27	26	26	25	25	24	24	23	23	22	22	21	21	21	20	20	18	17
24	29	29	28	27	27	26	26	25	24	24	23	23	22	22	22	21	21	20	20	20	19	18	17
23	29	28	27	27	26	25	25	24	24	23	23	22	22	21	21	20	20	20	19	19	19	17	16
22	28	27	26	26	25	24	24	23	23	22	22	21	21	20	20	20	19	19	19	18	18	17	16
21	27	26	25	25	24	24	23	23	22	21	21	21	20	20	19	19	19	18	18	18	17	16	15
20	26	25	24	24	23	23	22	22	21	21	20	20	19	19	19	18	18	17	17	17	16	15	14
19	25	24	24	23	22	22	21	21	20	20	19	19	19	18	18	17	17	17	17	16	16	15	14
18	24	23	23	22	22	21	21	20	20	19	19	18	18	17	17	17	16	16	16	16	15	14	13
17	23	22	22	21	21	20	20	19	19	18	18	17	17	17	16	16	16	15	15	15	15	14	13
16	22	22	21	20	20	19	19	18	18	18	17	17	16	16	16	15	15	15	14	14	14	13	12
15	21	21	20	20	19	19	18	18	17	17	16	16	16	15	15	15	14	14	14	14	13	12	11
14	20	20	19	19	18	17	17	17	16	16	16	15	15	15	14	14	14	13	13	13	13	12	11
13	19	19	18	18	17	17	16	16	16	15	15	14	14	14	14	13	13	13	12	12	12	11	11
12	19	18	17	17	17	16	16	15	15	14	14	14	13	13	13	13	12	12	12	12	11	11	10
11	18	17	17	16	16	15	15	14	14	14	13	13	13	12	12	12	12	11	11	11	11	10	9
10	17	16	16	15	15	14	14	14	13	13	13	12	12	12	11	11	11	11	10	10	10	9	9
09	16	15	15	14	14	14	13	13	12	12	12	12	11	11	11	10	10	10	10	10	9	9	8
08	15	14	14	14	13	13	12	12	12	11	11	11	11	10	10	10	10	9	9	9	9	8	8
07	14	14	13	13	12	12	12	11	11	11	10	10	10	10	9	9	9	9	8	8	8	8	7
06	13	13	12	12	12	11	11	10	10	10	10	9	9	9	9	8	8	8	8	8	8	7	6
05	12	12	11	11	11	10	10	10	9	9	9	9	8	8	8	8	8	7	7	7	7	6	6
04	11	11	11	10	10	10	9	9	9	8	8	8	8	7	7	7	7	7	6	6	6	6	5
03	11	10	10	9	9	9	8	8	8	8	7	7	7	7	6	6	6	6	6	6	6	5	5
02	10	9	9	9	8	8	8	7	7	7	7	6	6	6	6	6	5	5	5	5	5	4	4
01	9	8	8	8	7	7	7	7	6	6	6	6	5	5	5	5	5	5	4	4	4	4	3
00	8	8	7	7	7	6	6	6	6	5	5	5	5	4	4	4	4	4	4	4	4	3	3
−01	7	7	6	6	6	5	5	5	5	5	4	4	4	4	4	3	3	3	3	3	3	2	2
−02	6	6	6	5	5	5	4	4	4	4	4	3	3	3	3	3	3	2	2	2	2	2	2
−03	5	5	5	4	4	4	4	3	3	3	3	3	2	2	2	2	2	2	2	2	1	1	1
−04	4	4	4	4	3	3	3	3	2	2	2	2	2	2	1	1	1	1	1	1	1	0	0

−05	3	3	3	3	2	2	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	−1
−06	3	2	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0	−1	−1	−1	−1	−1
−07	2	2	1	1	1	1	0	0	0	0	0	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−2	−2
−08	1	1	0	0	0	0	−1	−1	−1	−1	−1	−1	−1	−2	−2	−2	−2	−2	−2	−2	−2	−3	−3
−09	0	0	−1	−1	−1	−1	−1	−2	−2	−2	−2	−2	−2	−2	−2	−3	−3	−3	−3	−3	−3	−3	−3
−10	−1	−1	−1	−2	−2	−2	−2	−2	−2	−3	−3	−3	−3	−3	−3	−3	−3	−3	−3	−4	−4	−4	−4
−11	−2	−2	−2	−2	−3	−3	−3	−3	−3	−3	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−4	−5	−5
−12	−3	−3	−3	−3	−4	−4	−4	−4	−4	−4	−4	−4	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5	−5
−13	−4	−4	−4	−4	−4	−5	−5	−5	−5	−5	−5	−5	−5	−5	−6	−6	−6	−6	−6	−6	−6	−6	−6
−14	−5	−5	−5	−5	−5	−5	−6	−6	−6	−6	−6	−6	−6	−6	−6	−6	−6	−6	−7	−7	−7	−7	−7
−15	−5	−6	−6	−6	−6	−6	−6	−6	−7	−7	−7	−7	−7	−7	−7	−7	−7	−7	−7	−7	−7	−8	−8
−16	−6	−7	−7	−7	−7	−7	−7	−7	−7	−8	−8	−8	−8	−8	−8	−8	−8	−8	−8	−8	−8	−8	−8
−17	−7	−7	−8	−8	−8	−8	−8	−8	−8	−8	−8	−9	−9	−9	−9	−9	−9	−9	−9	−9	−9	−9	−9
−18	−8	−8	−8	−9	−9	−9	−9	−9	−9	−9	−9	−9	−9	−10	−10	−10	−10	−10	−10	−10	−10	−10	−10
−19	−9	−9	−9	−10	−10	−10	−10	−10	−10	−10	−10	−10	−10	−10	−10	−10	−10	−11	−11	−11	−11	−11	−11
−20	−10	−10	−10	−10	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−11	−12	−12
−21	−11	−11	−11	−11	−11	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12	−12
−22	−12	−12	−12	−12	−12	−12	−12	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13	−13
−23	−13	−13	−13	−13	−13	−13	−13	−13	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14
−24	−14	−14	−14	−14	−14	−14	−14	−14	−14	−14	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15
−25	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−15	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16
−26	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−16	−17	−17	−17	−17	−17	−17
−27	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−17	−18	−18
−28	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18	−18
−29	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19	−19
−30	−19	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20	−20

Note: Values have been rounded to the nearest whole number. Values ending in ·5 have been rounded up.

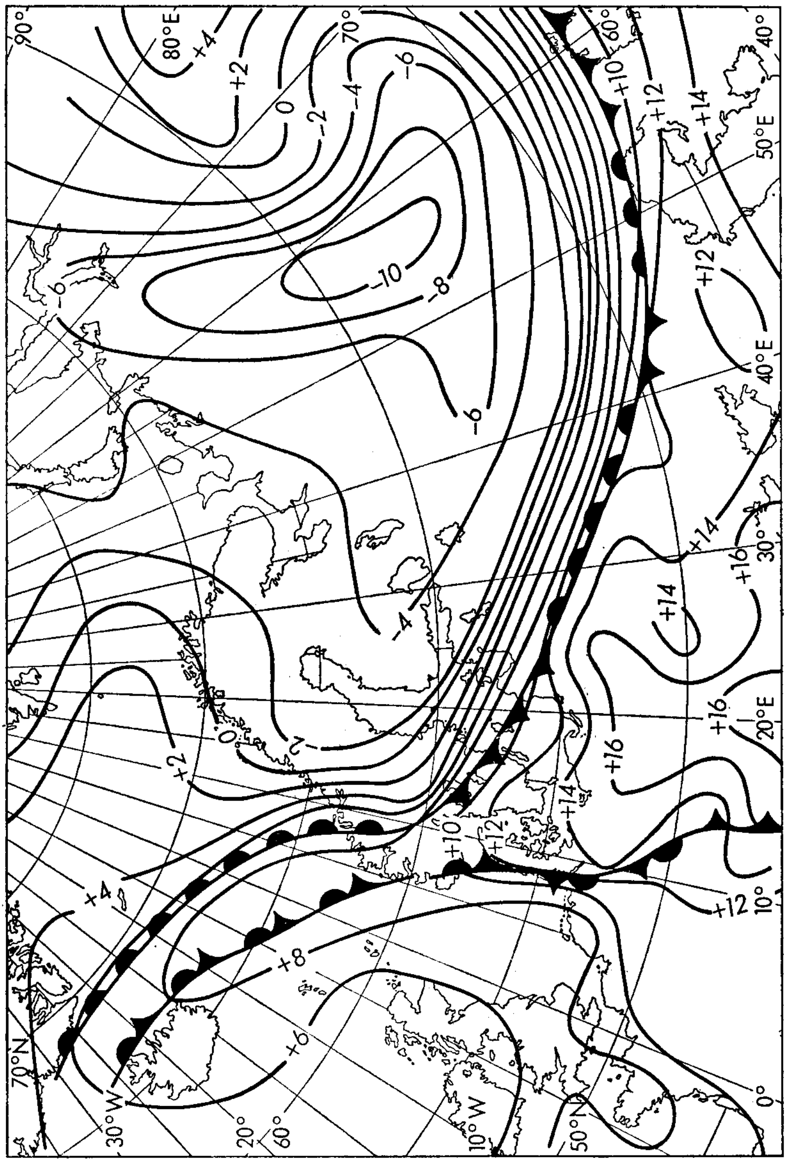

FIGURE 1—850 mb θ_W AT 1200 GMT ON 13 OCTOBER 1976, WITH SURFACE FRONTS, SHOWING STRONG GRADIENT OF θ_W IN THE COLD AIR NORTH OF THE FRONT EXTENDING FROM THE NORTHERN CASPIAN SEA TO SCANDINAVIA

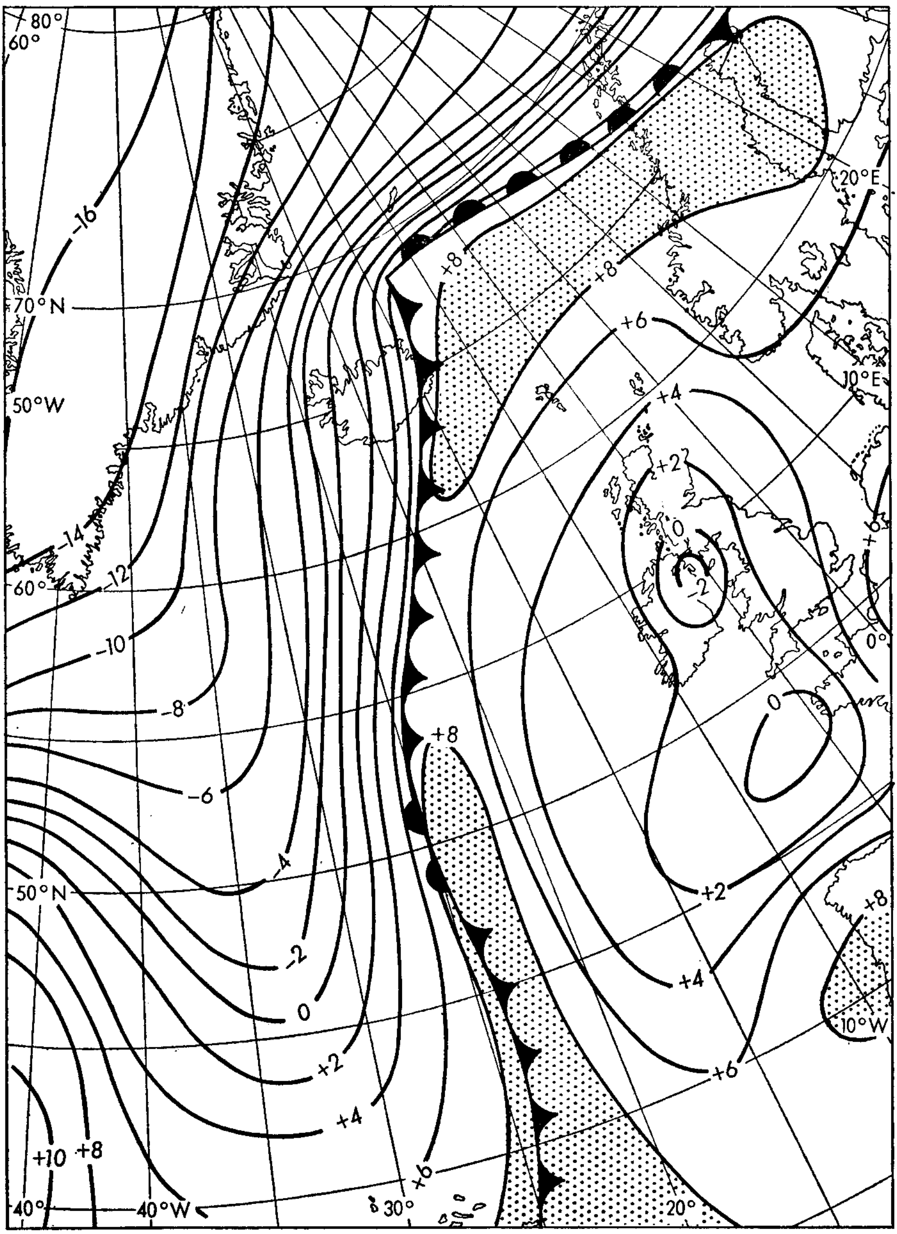

FIGURE 2—850 mb θ_W AT 0000 GMT ON 17 FEBRUARY 1976, SHOWING TONGUE OF WARM MOIST AIR JUST AHEAD OF THE SURFACE FRONT

Areas with values of θ_w of 8°C or more are stippled.

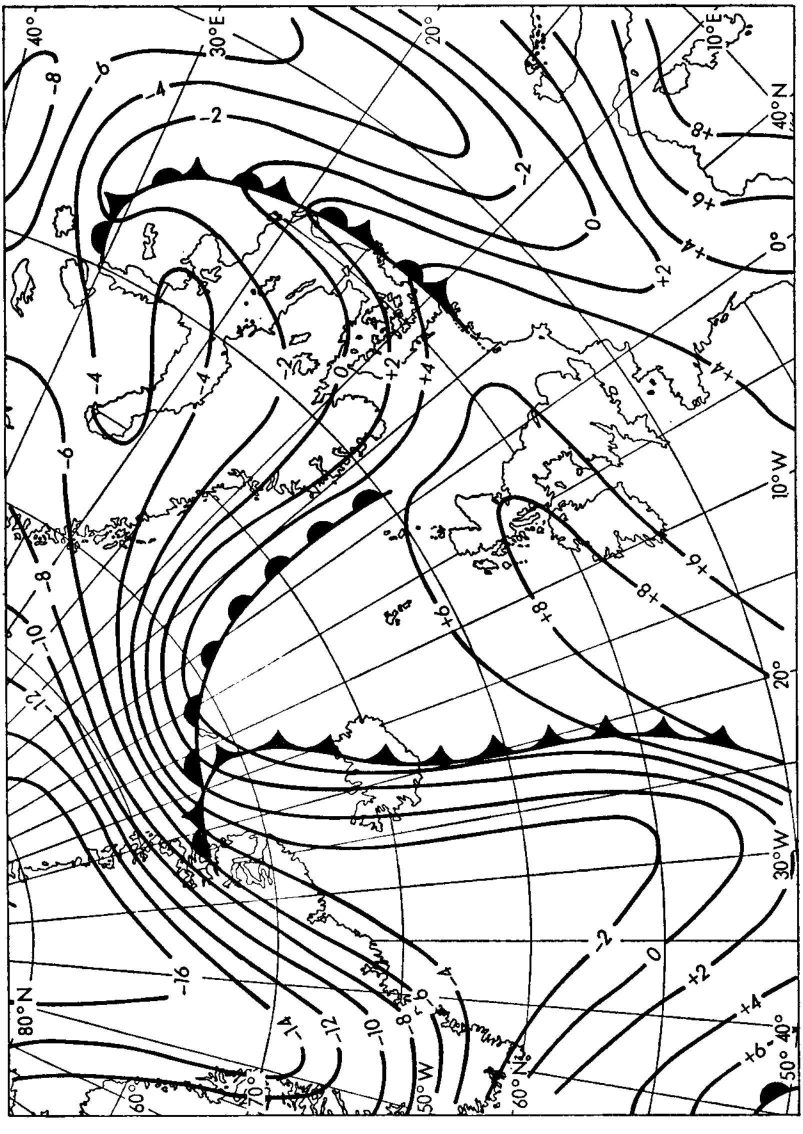

FIGURE 3—850 mb θ_W AT 1200 GMT ON 19 DECEMBER 1975, SHOWING ISOPLETHS CROSSING OCCLUDED FRONT BUT LYING PARALLEL TO WARM AND COLD FRONTS

number of warm sectors. Such dry tongues were usually observed when the warm sector lay on the perimeter of a surface anticyclone. These dry tongues were usually associated with a marked reduction in the amount of low cloud.

NON-ADIABATIC CHANGES OF θ_W

Although θ_W is insensitive to adiabatic changes, it is very sensitive to changes in the vapour content of the air. Rapid changes were observed when cold dry air from the Arctic was advected across a relatively warm sea. Vigorous convective currents rising from the sea surface carried heat and moisture above the 850 mb surface, and θ_W was observed to increase by more than 20°C in air which moved from Canada to western Europe in winter.

Decreases in the value of θ_W were observed to occur more slowly than increases. The most common cause for a fall in the value of θ_W was prolonged precipitation falling from a warm air mass moving over a cold surface. When unusually strong winds brought air from the western North Atlantic to Ellesmere Island, north-west of Greenland, the 850 mb θ_W fell from about 15° to 5°C during its passage from 45°N to 80°N. This represents about half the change which was normally observed when the flow was in the opposite direction in winter.

The value of θ_W as a tracer of air masses is inevitably reduced by these non-adiabatic changes, but such changes enable the analyst to observe the modifications which have taken place in the lower levels of the troposphere.

850 mb θ_W AND SNOWFALL

Lowndes *et alii* (1974) found that the wet-bulb freezing level was the best single predictor for use in deciding whether precipitation would fall as snow. The isopleths of the 850 mb θ_W can also be used for this purpose. The indications are less accurate than the wet-bulb freezing level but are easier to use over a broad area. Table II shows the results from a survey of over 1000 observations of precipitation which occurred at, or very close to, a radiosonde station at the time of the soundings. It was observed that the chief reason for the wide range of values was variations in the lapse rate of θ_W. When the air had passed over a relatively warm sea, precipitation at stations near the coast was of rain rather than snow even when the value of the 850 mb θ_W was close to 0°C. In contrast, areas which were already snow covered, such as eastern Europe and Russia, experienced snow rather than rain even though the value of the 850 mb θ_W was high, if the warm air had had a long passage over a frozen surface.

TABLE II—850 mb θ_W AND THE PROBABILITY OF PRECIPITATION FALLING AS SNOW

	Wet-bulb potential temperature (θ_W) in degrees Celsius										
	9	8	7	6	5	4	3	2	1	0	—1
Probability of snow	0	0·01	0·10	0·14	0·26	0·39	0·57	0·88	0·90	0·96	1·00

850 mb θ_W AND THUNDERSTORMS

Endlich and Mancuso (1968) reported that low-level temperature and moisture fluxes are more directly related to severe storms than are the lapse rate and parcel instability. David (1976) observed that one of a number of parameters associated with severe storms which produced tornadoes in North America was a mean 850 mb temperature of 15°C with a dew-point of 9°C. These figures give a value for θ_W of 18°C.

Although tornadoes are rare in the British Isles and north-west Europe, the incidence of severe summer thunderstorms appeared to be associated with high values of the 850 mb θ_w. Many summer thunderstorms broke out when southerly winds at low levels had advected air with 850 mb θ_w of 16°C or more over Europe, particularly when this warm moist air lay to the east of an advancing upper trough. A number of storms developed near to, or just west of, the centre line of a warm ridge in the 1000/500 mb thickness pattern, a region which might not be supposed to be particularly unstable.

Figures 4, 5 and 6 show examples of thunderstorms which were associated with high values of the 850 mb θ_w. The positions of independently analysed surface fronts have been marked. Thunderstorms reported in synoptic messages or located by the SFLOC network are marked by lightning symbols.

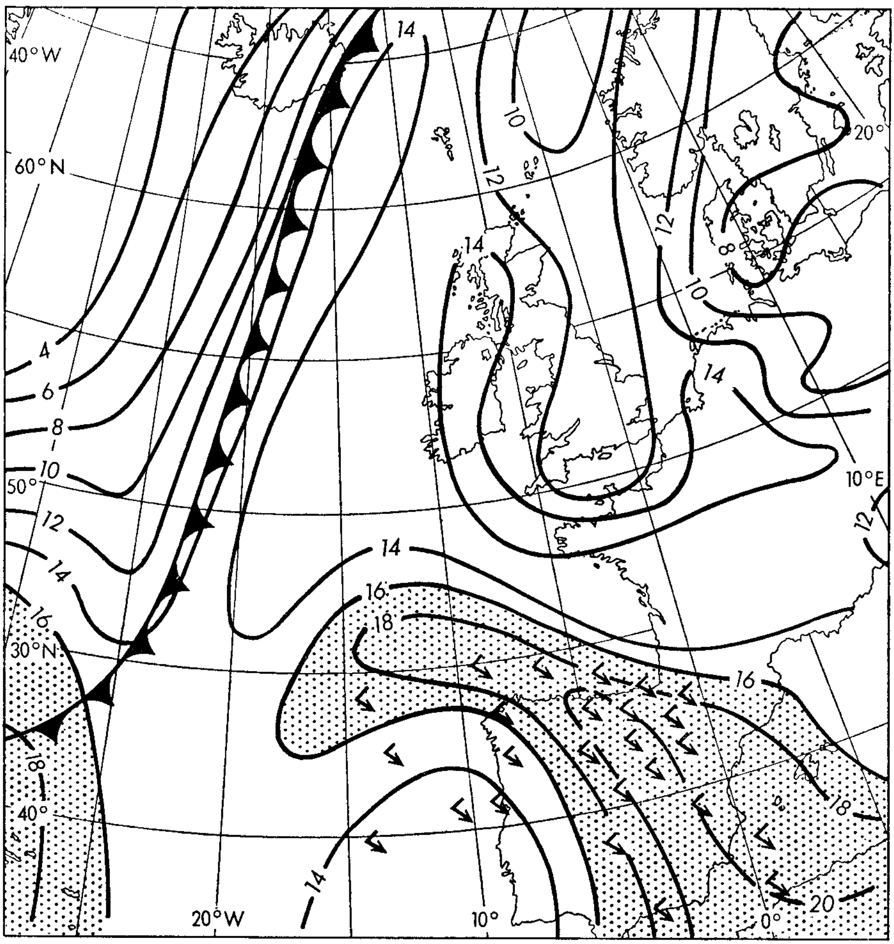

FIGURE 4—850 mb θ_w AT 1200 GMT ON 21 AUGUST 1976, SHOWING POSITIONS OF LIGHTNING FLASHES OBSERVED OR REPORTED BY SFLOC MESSAGES BETWEEN 1200 AND 1730 GMT

Areas with values of θ_w of 16°C or more are stippled.

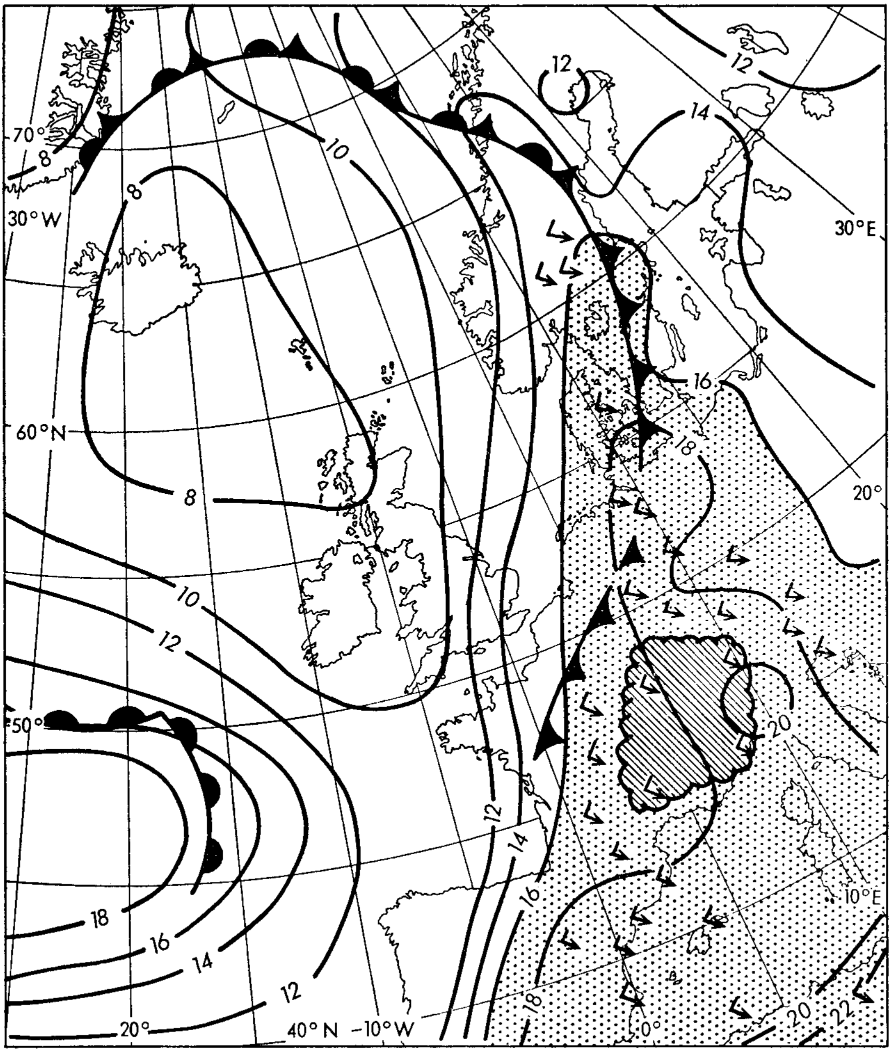

FIGURE 5—850 mb θ_w AT 1200 GMT ON 17 JULY 1976, SHOWING POSITIONS OF LIGHTNING FLASHES OBSERVED OR REPORTED BY SFLOC MESSAGES BETWEEN 1200 AND 1730 GMT

An area of particularly numerous reports over Switzerland and south-east France is shaded. Areas with values of θ_w of 16°C or more are stippled.

A POTENTIAL STABILITY INDEX

The 850 mb θ_w alone failed to show up occasions when thunderstorms occurred in a relatively cool air mass. The use of a potential stability index was found to help in locating areas where the thunder risk was high. This index was obtained by subtracting the value of θ_w at 850 mb from the value at 500 mb. When this figure was negative the air between the two levels was potentially unstable.

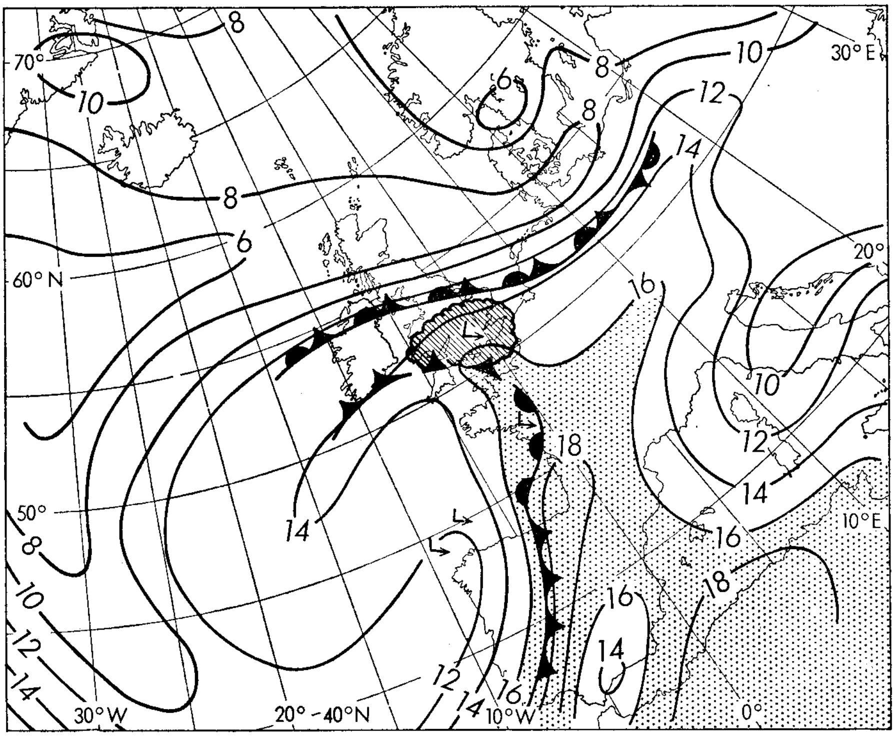

FIGURE 6—850 mb θ_W AT 0000 GMT ON 25 SEPTEMBER 1976, SHOWING AN AREA OF VERY NUMEROUS THUNDERSTORMS WHICH OCCURRED BETWEEN 0000 AND 0530 GMT OVER SOUTHERN ENGLAND

Areas with values of θ_W of 16°C or more are stippled.

Similar indices have been used by Rackliff (1962) and Jefferson (1963) but these differ in using the actual temperature at 500 mb instead of θ_W. They also used the 900 mb θ_W instead of the 850 mb value, but this change was regarded as unimportant, provided that there was no inversion between the two levels.

In order to determine the values of potential stability on thunderstorm days, 544 soundings made between 1973 and 1976 were examined. The results are shown in graphical form in Figure 7. The line marked 'Limit' shows the most unstable cases, and the line marked '5%' shows the values above which thunderstorms were rarely observed.

The slope of these lines shows that the critical value of the potential stability index varied with the 850 mb θ_W. During the summer months, when the 850 mb θ_W was relatively high, thunderstorms were observed only if the air was potentially unstable. In cooler periods, when the 850 mb θ_W was low, thunderstorms were observed when the index showed a few degrees of stability.

A similar result was found when the Jefferson index was calculated, using the formula $T_J = 1{\cdot}6\ (\theta_{W850} - T_{500} - 11)$. However, the Jefferson index showed a greater variability over its range. The standard deviation for the Jefferson index was 2·5 compared to 1·38 for the potential stability index.

It seems probable that the change in the critical values of both stability indices over the temperature range was due to different sizes of cumulonimbus. In winter, when the freezing level is low, thunderstorms can occur in cumulonimbus clouds whose summits do not reach the 500 mb level, or only exceed it by a small margin. In summer, when the freezing level is high, the tops of thundery cumulonimbus often extend far above the 500 mb level.

POTENTIAL STABILITY AND NON-THUNDERY RAIN

During the survey of the relationship between the potential stability index and thunderstorms it was noticed that the index was frequently low on occasions when rain fell but no thunder was reported. A second survey was made to include all occasions when precipitation, other than drizzle, was reported at, or very close to, a radiosonde station at the time of the sounding. Figure 8 shows the results from 800 soundings made in precipitation areas, superimposed on the graph of thundery soundings for comparison. As might be expected, the lines marked '50% ppn' and '5% ppn' show greater stability than the thunderstorm lines, but the difference between the lines decreases as the value of the 850 mb θ_w rises. When the 850 mb θ_w reaches 18°C, the two lines marked '50%' are less than 1°C apart. The graph of non-thundery occasions was not taken beyond this point because at and above 18°C almost all examples were associated with thunder at some stage.

INADEQUACY OF A SINGLE INDEX FOR THUNDERSTORM PREDICTION

It must be stressed that Figure 7 does not provide a thunderstorm index. The figures on which it is based do not show the occasions when the air was potentially unstable but no thunder occurred. It is difficult to establish with certainty that thunder did not occur, and no attempt was made to do so. The graph merely indicates a range of conditions which existed when thunderstorms did occur: from this one may infer that thunderstorms are unlikely outside the range, but not that thunder will occur if conditions lie within the range.

Saunders (1966 and 1967) tested various indices for thunderstorm prediction and found that none produced results as good as the subjective assessments made by forecasters who used indices as a guide rather than as a strict rule. It is clearly essential to use such objective guides in combination with surface and upper-air charts. Table III lists a number of features which appeared to be most often associated with thunderstorms. The Table suggests that surface heating was not by itself sufficient to account for many thunderstorms and that the low-level convergence of moisture provided by a trough was important.

TABLE III—PROBABILITY THAT A THUNDERSTORM WILL BE ASSOCIATED WITH PARTICULAR FEATURES ON SURFACE AND 300 mb CHARTS

Surface charts	*Prob.*	300 mb charts	*Prob.*
Near a trough or low	0·70	Near or ahead of a trough or low	0·76
With general cyclonic curvature	0·11	Behind a mobile ridge or high ..	0·08
Col or indefinite pattern ..	0·09	Behind a mobile trough or low ..	0·06
Straight isobars	0·04	Near a ridge or high	0·05
Anticyclonic curvature	0·05	Other features	0·05
Near a high or marked ridge ..	0·01		

Notes: (a) SFLOC reports were not included in this Table.
(b) The area examined extended from the British Isles to Poland, and from northern Italy to southern Scandinavia.
(c) Fronts are included under troughs, provided that the two coincided.

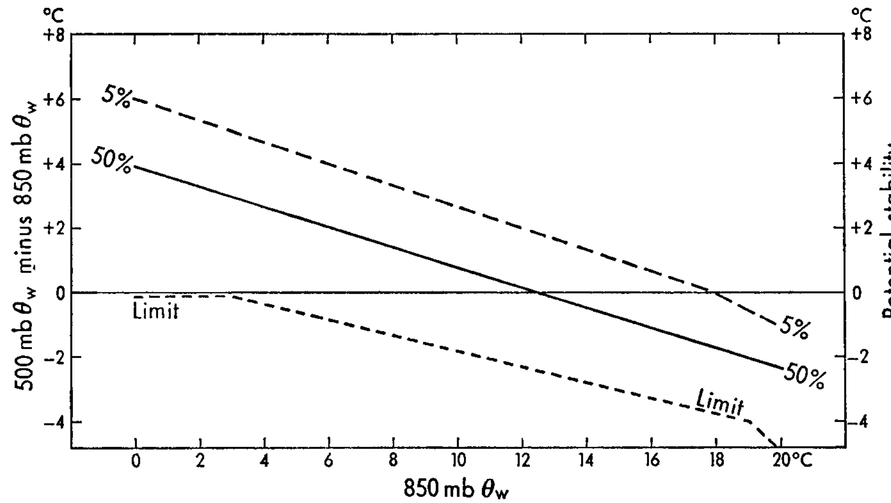

FIGURE 7—RELATIONSHIP BETWEEN 850 mb θ_W AND THE POTENTIAL STABILITY (500 mb θ_W MINUS 850 mb θ_W) ON THUNDERSTORM DAYS

The upper pecked line shows the upper limit of stability which was only equalled or exceeded by 5 per cent of the observations. The lower pecked line shows the most unstable conditions observed during the period. The mean value observed is given by the line marked '50%'.

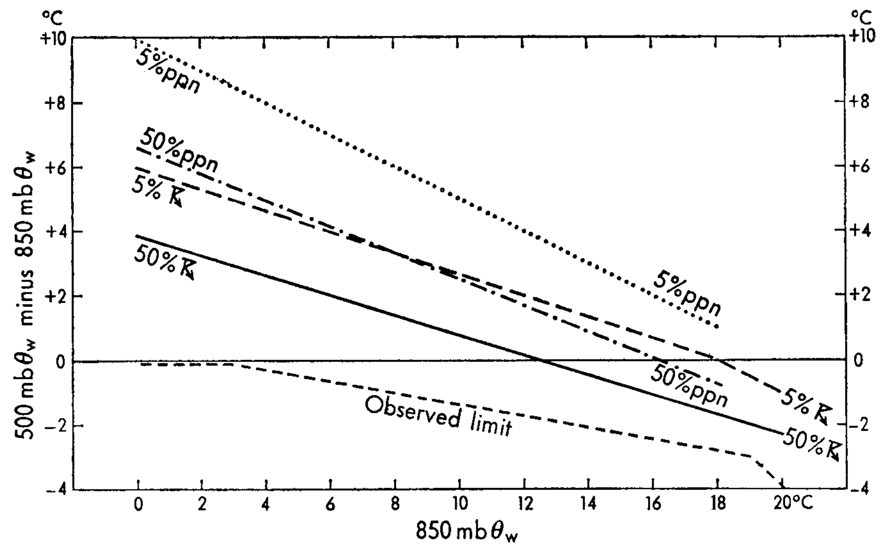

FIGURE 8—RELATIONSHIP BETWEEN 850 mb θ_W AND THE POTENTIAL STABILITY ON THUNDERY AND NON-THUNDERY OCCASIONS

The lines marked '5%' and '50%' with thunderstorm symbols are repeated from Figure 7. The lines marked '5% ppn' and '50% ppn' show the more stable conditions observed when precipitation (other than drizzle) occurred at or very near a radiosonde station at 0000 or 1200 GMT without thunder being reported.

Stability index used in combination with synoptic charts

Figures 9 and 10 show a situation when summer thunderstorms occurred both by day and by night. In Figure 9 the isopleths of θ_w have been added to the 850 mb contour chart, together with the position of the surface fronts. It may be seen that θ_w was high over most of Europe. Figure 10 shows the 300 mb contours. SFLOC reports were not used in this case.

Although the air was potentially unstable over much of Europe, the thunderstorms were only observed near and ahead of the 300 mb low and its associated trough. Although England lay just outside the area of potential instability at midnight, the northward advection of warm moist air from France reached Crawley during the morning and the midday ascent showed potential instability.

Figure 11 shows an example of winter thunderstorms. SFLOC reports are represented by lightning symbols. There are three main areas where SFLOC positions appear. One area is over the Atlantic between about longitudes 12° and 22°W which lay beneath the 300 mb low. The second area is associated with the frontal system shown over south-west England and western France. The third area extends from Italy to Greece and the extreme west of Turkey, near and ahead of the 300 mb trough and the cold front preceding it. Almost every SFLOC report falls within the stippled areas where the potential stability index was 3°C or less. Figure 7 suggests that this value is more appropriate for winter thunderstorms than the value of −2°C used for the August example in Figure 10.

Conclusions

Isopleths of the wet-bulb potential temperature (θ_w) drawn on the 850 mb surface were found to be a valuable aid in the analysis of air-mass characteristics in the lower levels of the troposphere. These isopleths enabled fronts to be located more precisely on small-scale charts which show only a limited number of surface observations.

The value of the 850 mb θ_w was found useful as a guide to the probability of precipitation falling as snow rather than rain. High values of the 850 mb θ_w appeared to be associated with the development of summer thunderstorms over the British Isles and Europe.

Analysis of θ_w at two different levels allows a potential stability index to be derived. The 850 mb and 500 mb levels were found to be the best for use all the year in temperate latitudes. The index of potential stability was obtained by subtracting the 850 mb θ_w from the 500 mb θ_w. The index provided a guide to the risk of thunderstorm development when used in conjunction with routine surface and upper-air charts. The index also showed some value as a guide to non-thundery rain but was of no value when the precipitation fell as snow.

Acknowledgements

I am grateful to Mr J. Tate who wrote the program used to compute values of wet-bulb potential temperature, and also to Dr S. R. Mattingly who provided facilities for visual display and subsequent print-out of wet-bulb potential temperatures calculated from current upper-air data stored in the basic analysis data sets of the computer.

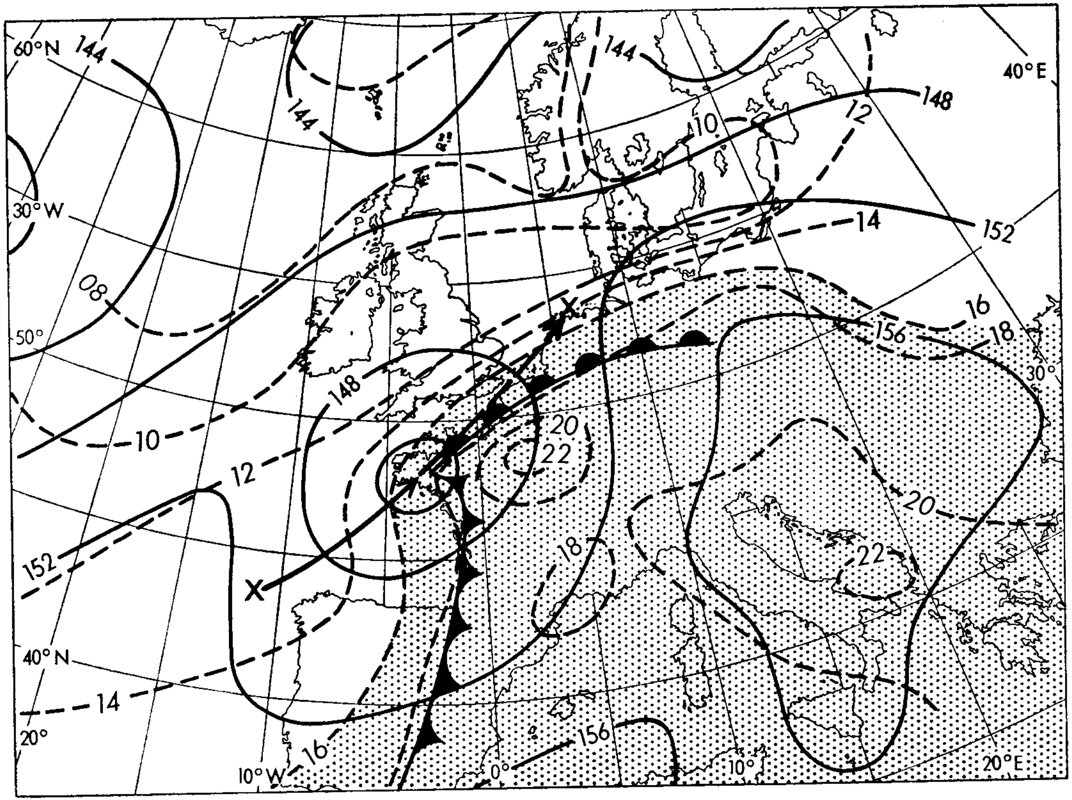

FIGURE 9—CHART FOR 0000 GMT ON 4 AUGUST 1974 SHOWING 850 mb CONTOURS AND ISOPLETHS OF θ_W, WITH POSITIONS OF SURFACE FRONTS ADDED

Areas with values of θ_w of 16°C or more are stippled. Arrows mark the movement of the 850 mb centre during the preceding and subsequent 24 hours.

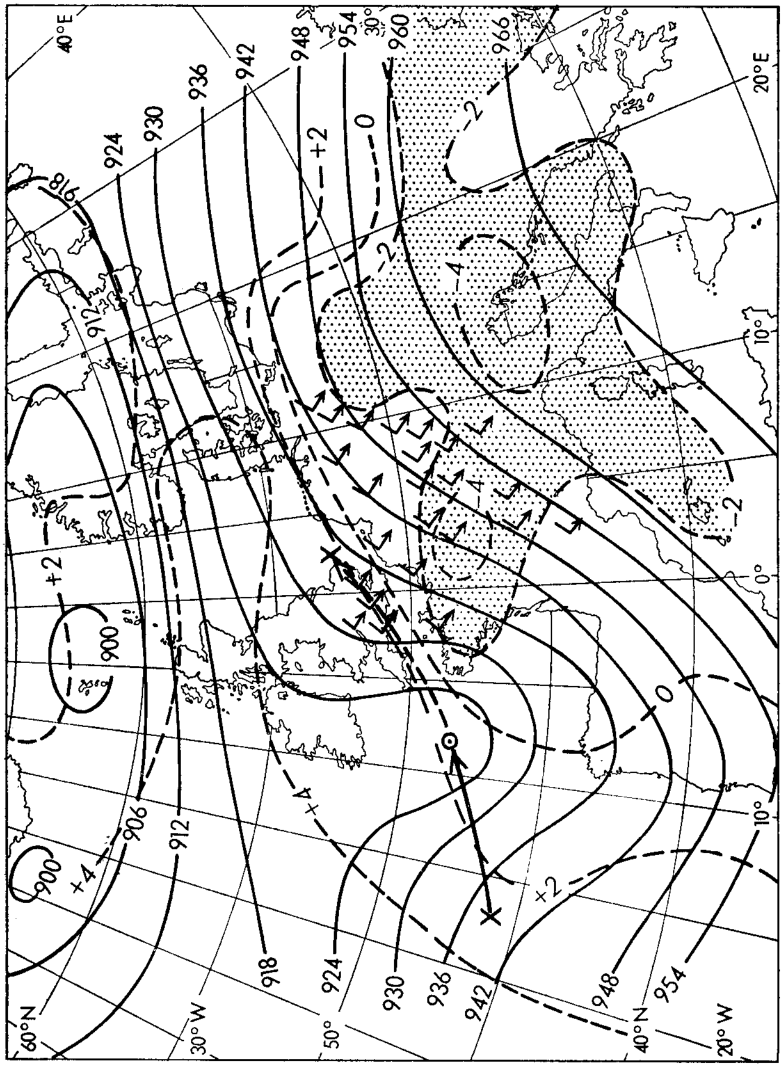

FIGURE 10—CHART FOR 0000 GMT ON 4 AUGUST 1974 SHOWING 300 mb CONTOURS AND ISOPLETHS OF POTENTIAL STABILITY (500 mb θ_W MINUS 850 mb θ_W)

Areas with potential stability values of —2°C and below are stippled. The places at which thunderstorms were reported during the period 0600–1200 GMT are marked with lightning symbols. SFLOC reports were not used in this case. Arrows indicate the movement of the low during the preceding and subsequent 24 hours.

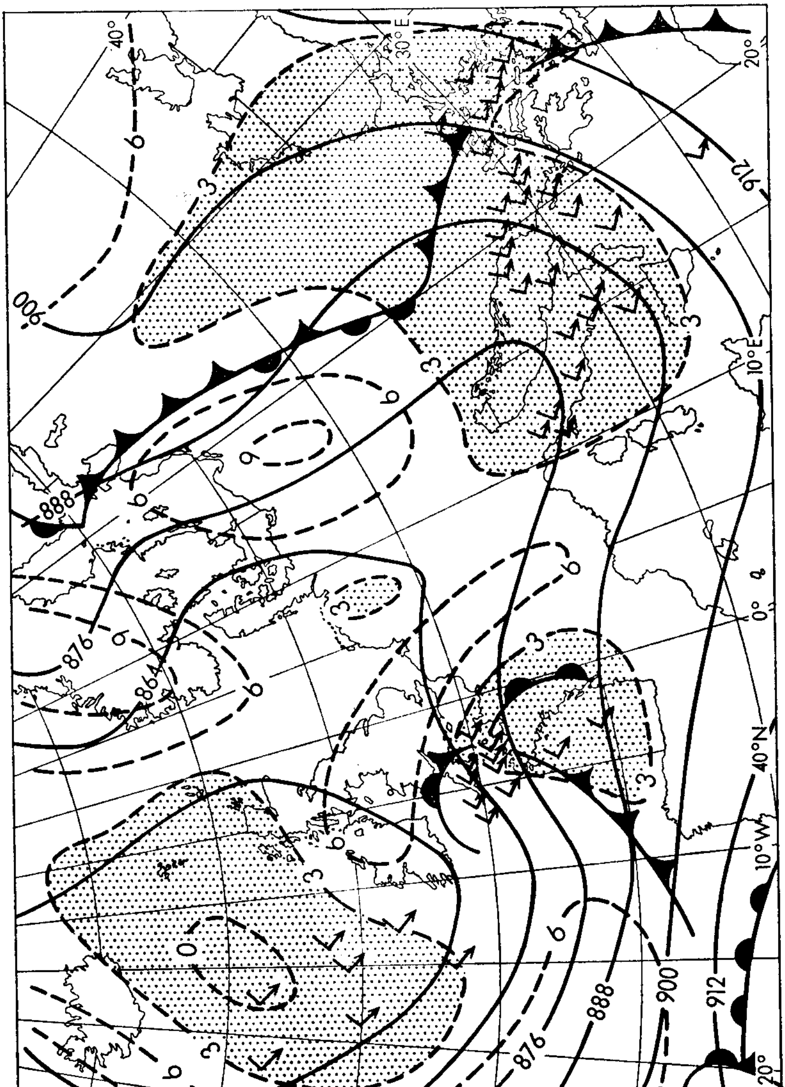

FIGURE 11—CHART FOR 1200 GMT ON 13 JANUARY 1977 SHOWING 300 mb CONTOURS AND ISOPLETHS OF POTENTIAL STABILITY (500 mb θ_W MINUS 850 mb θ_W)

The positions of surface fronts have been added. SFLOC reports for the period 1200–1730 GMT are marked by lightning symbols. The stippled area shows where the potential stability was 3°C or less. This value was found more suitable for use in January than the value of —2°C used in August.

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SOME EXPERIMENTS TO CONTROL THE BUOYANCY OF EXTENSIBLE BALLOONS IN THE STRATOSPHERE

By J. S. FOOT, E. L. SIMMONS and A. E. WHITTAKER

SUMMARY

It is often desirable to control the trajectory of a balloon. Common requirements are: (a) slow ascent or descent to lengthen time of observation, (b) slow ascent or descent to reduce swing of package, (c) floating to give a long period of observation at one altitude, and (d) descent rather than ascent to reduce pollution at the sonde from the balloon. This report looks at some methods that have been used to control extensible balloons.

INTRODUCTION

This report describes some methods which have been used to control the trajectories of extensible balloons in the stratosphere. The design aim was to achieve a slow descent of about 1·5 m s^{-1} from 30 mb to the tropopause. This was required for a pollution experiment being carried out in the stratosphere during daytime. Extensible 2 kg balloons having free lifts between 2 and 4 kg, which gave ascent rates between 4 and 6 m s^{-1} in the troposphere, were used in the study. In this regime, where the flow is turbulent, the ascent rate is not very sensitive to free lift, and different rates can be attributed to different balloon shapes as much as to any other parameter. At lower ascent rates the flow becomes less turbulent, as indicated by the reduction in swing of the system (Foot *et alii*, 1974, and Pettifer and Flavell, 1976), and is very sensitive to the free lift.

The buoyancy is a function of the temperature difference, T_D, between the gas in the balloon and the environment. In particular, the buoyancy is changed by vertical gradients in the stratosphere, by solar heating, ventilation and radiative cooling of the balloon's fabric, and by adiabatic compression or expansion of the gas in the balloon. If T_D remains constant, the balloon will not accelerate, neglecting changes in the drag.

One method of reducing the buoyancy in the stratosphere is to fly two balloons. The first is designed to have near zero free lift after the other balloon has been cut off. The second balloon gives to the combination a strong net free lift. Such an approach has been reported recently by Pettifer and Flavell (1976) where the remaining free lift was +190 g,* as determined from the filling, and the resulting ascent rate was about 1·5 m s^{-1}. The total lift of the gas in the balloon was about 7600 g, and therefore 190 g represents only 2·5 per cent of the total lift. This small proportion is equivalent to a change in T_D of only 5 K in an atmosphere at a temperature of 200 K. The fact that this approach worked suggests that there was some stabilization. One possibility is that there was a balancing between the solar heating, which caused an acceleration upwards, and the ventilation, which reduced T_D as the speed increased. The cooling by expansion would evidently not be fast enough to upset this balance. For a descending balloon, however, although solar heating and adiabatic compression will tend to reduce the velocity, if the balloon descends rapidly enough, the cooling by ventilation will exceed the solar heating and it will accelerate downwards.

In our view, to obtain a floating or slowly descending trajectory, it is necessary to release gas from the balloon in a controlled manner. Provided that there are no sharp temperature changes in the stratosphere, it should be possible to control the speed of descent by controlling this release. Solar heating and adiabatic compression are stabilizing influences.

EXPERIMENT AND OBSERVATIONS

One form of balloon valve consists of a pipe inserted in the balloon neck with a lightly sprung lid on the inside of the balloon. A string from the lid passes across the balloon and is secured at the top. By adjusting the length of the string, the valve can be made to operate at any height. Once open, the free-lift gas is vented out through the pipe. The more constricting the pipe, the longer the time taken to remove the free lift and the higher the balloon rises above its opening altitude. The valve will finally shut between this level and the opening level. It appears that a long narrow pipe shuts after a large negative buoyancy has been gained, whereas a short wide pipe results in almost floating conditions. A valve opening at about 70 mb with the equivalent of 2 kg free lift to dispense requires a pipe about 75 mm long and 48 mm in diameter to give an initial descent rate of 1·5 m s^{-1}. This behaviour has been modelled and the results are shown in Figure 1. Balloons controlled in this manner by a single-action valve do give surprisingly good results, particularly at night-time when there is no solar heating. On one occasion at night a balloon descended initially at 0·4 m s^{-1} but slowed after an hour to 0·25 m s^{-1}. In the daytime the deceleration can be more rapid but its extent is rather variable. For experiments at night or requiring only a limited height range in the daytime, this simple technique may prove useful.

A more complex system has been built and tested which measures the descent rate and opens or closes a valve, depending on whether the speed was slower or faster than a particular rate. The descent rate, $-\mathrm{d}z/\mathrm{d}t$, is given by:

$$-\frac{\mathrm{d}z}{\mathrm{d}t} = -\frac{\mathrm{d}z}{\mathrm{d}p} \times \frac{\mathrm{d}p}{\mathrm{d}t} = \frac{H}{p}\frac{\mathrm{d}p}{\mathrm{d}t},$$

* 'Buoyancy' and 'free lift' are forces, and their appropriate SI unit is therefore the newton. However, they are actually measured by finding suitable weights to balance them, and it is convenient for the practical worker to state their measure in units of mass (grams or kilograms).

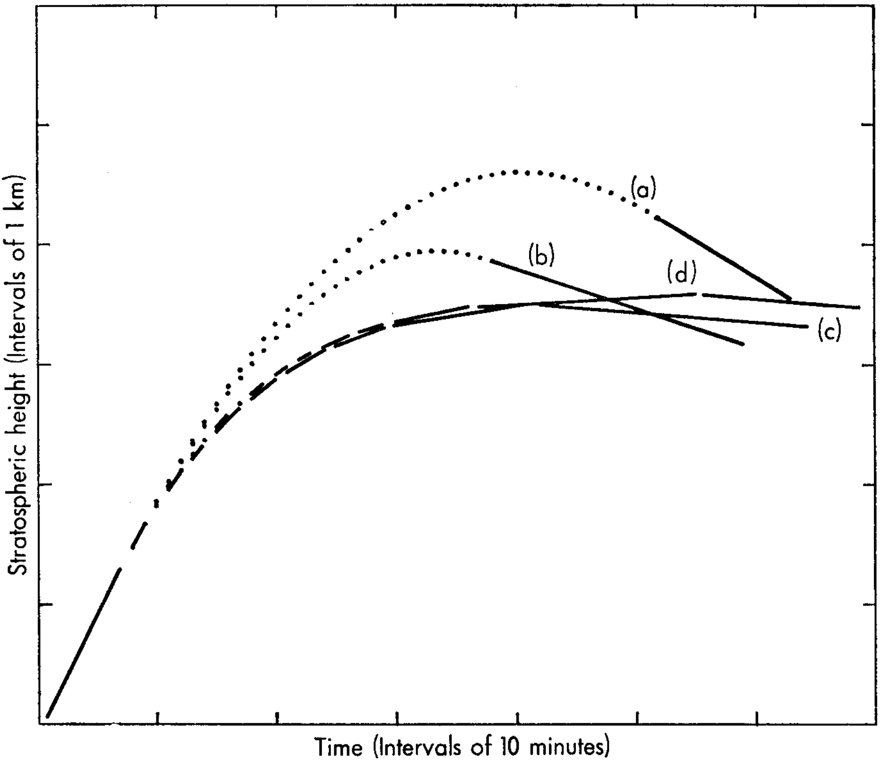

FIGURE 1—COMPUTER SIMULATION OF THE BEHAVIOUR OF A POPPER-TYPE BALLOON NECK VALVE

The initial free lift was assumed to be half the gross load, and the volume discharge rate was assumed constant when the valve was open. Time steps were taken every minute; the continuous lines show where the valve was closed. Curves (a), (b), (c) and (d) refer to rates such that the time taken to lose free lift at the initial opening pressure would be 30, 25, 17 and 10 minutes respectively. The atmosphere was assumed isothermal with a scale height of 6 km.

where p is the pressure at the height z, and H is the scale height ($\approx$ 6 km). Differentiation of the slowly varying analogue output of the pressure sensor is achieved by a pulse-counting technique which avoids the necessity of very low leakage sample-and-hold circuitry. A frequency, f, is generated where $f \propto p^k$, k being a constant, and is counted for two constant equal periods, τ, separated by a time, t, obtained by counting f until it reaches a number N. If these two counts are n_1 and n_2 then:

$$\frac{dp}{p} = \frac{1}{k}\frac{(n_2 - n_1)}{\tau f}.$$

Hence
$$-\frac{dz}{dt} = \frac{H(n_2 - n_1)}{kfT\tau} = \frac{H(n_2 - n_1)}{kN\tau}.$$

The pressure sensor for use with this technique must have low hysteresis, low short-term random variability and low attitude sensitivity. A vibrating wire sensor developed within the Cloud Physics Branch (Whittaker, 1977) has these qualities and, in addition, generates the required frequency directly. An evacuated high-compliance bellows applies tension to a tungsten wire via a pivoted beam. A wire vibrates in a transverse magnetic field, and its vibrations are sensed with a piezo-electric bimorph.* Vibration is maintained by passing a current obtained from the amplified output of the bimorph through the wire. The frequency is proportional to the square root of the pressure, so that $k = 0{\cdot}5$. The values chosen to give a descent rate of 1·2 m s^{-1} are:

$$N = 2^{14},\ \tau = 4\ \text{s, and}\ n_2 - n_1 = 6.$$

The latter condition is detected by feeding the frequency into an 8-bit up/down counter. This is pre-set to an initial count of 5 and counts up for 4 seconds, waits until a second counter has counted 2^{14} of the basic frequency, and then counts down for 4 seconds. The most significant bit of the up/down counter is then 0 if the descent rate is below the desired value, and 1 if it is above. This digital logarithmic differentiator has the advantage that it uses the averaged output of the pressure sensor; assessment of the descent rate is made approximately every 20 seconds and operates a valve in the neck of the balloon pneumatically. Pressure is applied from a reservoir though a solenoid valve to metal bellows in the balloon valve. A constriction between the reservoir and the solenoid valve gives the system an inherent time-constant for opening operations, requiring about 1 minute to open the valve half-way while allowing it to shut instantaneously. This reduces the effect of any error in the pressure differentiating system.

A number of flights of this system and its prototypes have been conducted. Results obtained from a flight from Beaufort Park during the afternoon of 24 May 1976, when the frequency of the pressure sensor and the valve operations were telemetered, are described. The valve was opened when the sonde reached 100 mb and was set to control at a descent rate of 1·2 m s^{-1}. The valve remained shut below 140 mb. Figure 2 shows the descent from near the top of the trajectory. The valve took about 20 minutes to remove the free lift of 3 kg. Also plotted is the descent velocity, the approximate duration and time of the valve operations, and the temperature sounding obtained from the midday Crawley sonde.

The points of interest are:

(a) The valve first shut approximately 45 seconds after the highest altitude.

(b) Many valve operations were made but only the long ones dispensed much gas because of the pneumatic time-constant. These long operations became less frequent as the balloon descended.

(c) The descent rate initially was about 1·5 m s^{-1} but it accelerated to around 1·8 m s^{-1}. These values are larger than the design figure of 1·2 m s^{-1} because the up/down counter had a maximum error of 2, which meant that the balloon would gradually take up the rate defined by a count difference of 8, not 6. This rate is 1·6 m s^{-1}. There was also some noise in the system.

(d) The acceleration at 16·0 km to 1·8 m s^{-1} correlated with the balloon moving into a warmer environment.

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* A bimorph is a strip composed of two layers of oppositely polarized material, arranged so that an electromotive force is produced when the strip is bent.

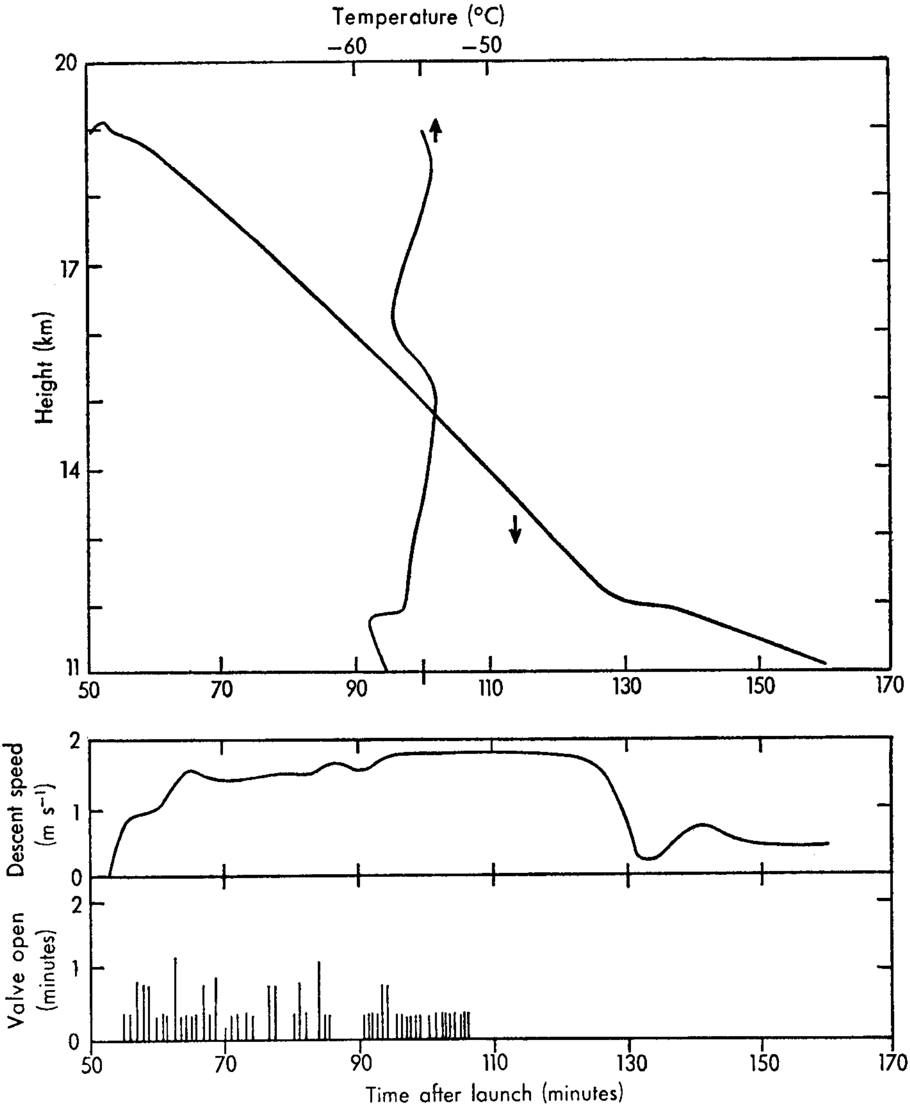

FIGURE 2—TRAJECTORY, TEMPERATURE PROFILE, DESCENT RATE AND VALVE OPERATION FOR CONTROLLED DESCENT

(e) At 14·2 km the valve was disenabled, and from this height down to 12·0 km there was no slowing of the balloon.

(f) At 12 km the balloon almost floated owing to the sudden environment temperature decrease of about 3 K at the tropopause. The Crawley ascent shows this discontinuity at 11·8 km. A change from 214 K to 211 K corresponds to an increase of approximately 1·5 per cent in the buoyancy of the gas in the balloon. The total buoyancy was of the order 6 kg, so that the free-lift change, which almost stopped the balloon, was about 90 g.

(g) In the troposphere, once the effect of the sharp discontinuity had been traversed, the descent rate increased to around 2·3 m s^{-1} in the progressively warmer troposphere.

CONCLUSIONS

It is clear from this work that, to obtain slow rates $<2{\cdot}0$ m s^{-1} from an extensible balloon in the stratosphere, the buoyancy required is of the order 100 g. As such, sharp temperature structures of the order of 3 K can completely change the behaviour of slow balloons. Solar heating and ventilation are important in determining the buoyancy, but compression or expansion of the gas in the balloon is generally too slow to be important.

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THE CONTRIBUTION OF EXTRATROPICAL SEVERE STORMS TO THE STRATOSPHERIC WATER-VAPOUR BUDGET

By S. R. MATTINGLY

SUMMARY

By using a climatology of Indian storm tops penetrating into the stratosphere, it has been estimated that severe extratropical storms contribute in the region of 23 per cent as much water vapour to the stratosphere as the Hadley cell circulation. Considering the uncertainties of the calculation, this value agrees reasonably well with values calculated by other authors, and shows that such storms may be a far from negligible source of stratospheric water vapour.

INTRODUCTION

There are a number of possible mechanisms of moisture supply to the stratosphere. These include: (a) upward transport in the Hadley cell circulation in tropical regions, (b) oxidation of methane by excited atomic oxygen and OH molecules in the stratosphere, (c) exchanges of tropospheric and stratospheric air through the tropopause gaps associated with the subtropical and polar jet streams, and (d) direct injection by mixing of stratospheric air with storm tops which penetrate the tropopause.

In mechanism (a) the water vapour must pass through the 'cold trap' of the tropical tropopause and hence most of it is frozen out. Brewer (1949) gives this as the reason why the stratosphere is so dry. This hypothesis is supported by the similarity of the typical value of mass mixing ratio of 3×10^{-6} g/g measured for most of the lower stratosphere (see, for example, Harries, 1976 and Mastenbrook, 1968), and the saturated mixing ratio of 2×10^{-6} g/g at the tropical tropopause. Quantification of this source by Weickmann and Van Valin (1972), hereinafter referred to as WV, using the method of Newell (1970), gives a water-vapour flux of $2{\cdot}2 \times 10^{11}$ kg/year.

Mechanism (b) is not well quantified because global production rates of methane are not particularly well established, but WV give a value of $1{\cdot}1 \times 10^{11}$ kg/year, half the value due to the Hadley cell.

Mechanism (c) is even less well understood. It is evident that very large amounts of air are exchanged between troposphere and stratosphere through the tropopause gaps. Danielsen (1968) calculates that 75 ± 25 per cent of the stratospheric mass is exchanged each year by all processes. Reiter (1975) gives a value of 73 per cent, of which about 20 per cent is due to mechanism (c). It is therefore very difficult to assess the net transport of water vapour by this mechanism. WV assume no net flux occurs, but they indicate that this figure is the difference between a large inflow and a large outflow and hence subject to considerable error. Since Reiter (1975) calculates that mechanism (c) exchanges about half as much mass as mechanism (a), it at least seems unlikely that the former mechanism dominates the latter in respect of water-vapour transport.

This paper attempts to assess the contribution of mechanism (d), which has also been studied by Sissenwine *et alii* (1972), Kuhn *et alii* (1971) and by WV, and is mentioned in Reiter (1975). The methods and results of these authors will be discussed after the description of the method used in this study.

Occurrence and general features of extratropical storms

Many areas in the tropics have upwards of 200 thunderstorm days a year, but the most destructive storms are found outside the tropics in regions near the subtropical jet streams. The main areas affected are: (i) Europe, which has severe thunderstorms on a few days a year (some of these occurring in the British Isles); (ii) the United States of America, which has the greatest observed frequency of tornadoes and large hail in the world; (iii) India, especially in the pre-monsoon season; and (iv) Australia, China, South Africa and Uruguay.

The tops of convective clouds can be divided into two types. In the first, each top is essentially transient and has a lifetime of a few minutes before falling back and being replaced by a similar top. It is believed (Fujita, 1974) that the lifetime of these tops is related to the Brunt–Väisälä frequency, or to the frequency of stable oscillation about the tropopause. In the second type the protrusions are considerably larger in diameter (15 km compared to 5 km) and much longer lived. They occur when the storm becomes well organized and are called 'super cells' (see, for example, Roach, 1967).

In order to obtain information about the nature of storm tops, a study was made of 25 Indian storms measured by Cornford and Spavins (1973). The average linear dimension of the radar echo of transient tops at the tropopause was plotted against the distance of the penetration into the stratosphere by each of the tops. The result is shown in Figure 1. The correlation between the two variables is $+0{\cdot}94$, which is significant beyond the $0{\cdot}1$ per cent level, and the best-fit straight line is:

$$L = (h + 105)/0{\cdot}2719, \qquad (1)$$

where L is the linear dimension at the tropopause in metres, and h the penetration in metres.

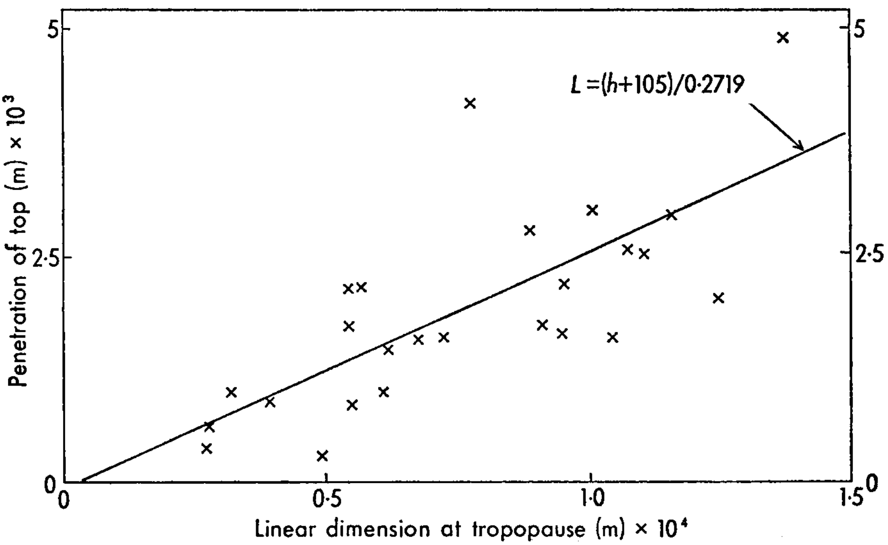

FIGURE 1—PENETRATION THROUGH THE TROPOPAUSE (h) AS A FUNCTION OF LINEAR DIMENSION AT THE TROPOPAUSE (L)

It is interesting to note that one of the storms, which was not included in the data despite having a linear dimension of $3 \cdot 0 \times 10^4$ m at the tropopause, only penetrated some 4000 m into the stratosphere. It seems reasonable to assume that this top is a super cell and has reached the maximum penetration possible, while all the other tops are transient and have not attained their maximum penetration.

Long *et alii* (1965) state that the American radar echoes of tops penetrating into the stratosphere have a base diameter to height ratio of 5:1. Lee and McPherson (1971) state that Malaysian tops are somewhat thinner. From equation (1) it appears that Indian tops are also somewhat thinner than the American ones.

CALCULATION OF WATER-VAPOUR INPUT TO THE STRATOSPHERE

As the detailed physics of the penetration process is not well understood, it was decided to rely on measurements of water-vapour column density upwind and downwind of penetrating tops. Such measurements have been made by Kuhn *et alii* (1973) and by Barrett *et alii* (1972). A total of five tops which penetrated well into the stratosphere have been measured.

The input of water vapour from a penetrating cloud top was modelled by assuming that, as the air travelled through the top, it picked up water vapour by mixing and evaporation of entrained ice crystals, and that the amount of water vapour picked up was the same over the whole area of the cloud. This leads to an expression for the rate of water-vapour injection, W:

$$W = hLV\rho \text{ g s}^{-1}, \quad .. \quad .. \quad .. \quad .. \quad (2)$$

where h is the penetration in metres of the top through the tropopause, L is the linear dimension of the top at the tropopause in metres, V is the stratospheric wind speed relative to the top in metres per second, and ρ is the mass of water vapour per unit volume picked up by the air in its passage through the top. In this study V was assumed to be 10 m s^{-1}, which was appropriate for the rather low wind shears measured by Cornford and Spavins (1973) in India. The value of ρ was calculated from the data of Kuhn *et alii* (1973) and Barrett *et alii* (1972) to be $2{\cdot}4 \pm 0{\cdot}8 \times 10^{-9} \text{ g cm}^{-3}$.

Instead of attempting to estimate the lifetime of each top, radar climatologies, which measure (at the same time each hour) the number of tops which are penetrating the tropopause to varying degrees, were employed and the measured number of tops was assumed to last for the ensuing hour. Thus, if n tops are seen by radar over a given area to be penetrating the tropopause by a distance h, we have that the water vapour injected into the stratosphere in that area during the ensuing hour will be:

$$I = 3600nhLV\rho \text{ g.} \qquad \text{(3)}$$

Using the assumed values of V and ρ, and the relation between h and L (equation (1)), gives:

$$I = 318nh(h + 105) \text{ g.} \qquad \text{(4)}$$

Climatology of Indian storm-top penetrations

Kantor and Grantham (1968) give an extensive climatology of American storm-top heights and these data were employed by Sissenwine *et alii* (1972) in their study of water-vapour injection into the stratosphere. In order to obtain an independent assessment, the unpublished climatology of Calcutta storm tops by D. K. Rakshit (personal communication to S. G. Cornford) was used here. This climatology is preferred to that of Bhattacharyya and De (1966) since the latter measurements are believed to underestimate the heights reached (Cornford, personal communication). The number of storm tops, measured on an hourly basis, which penetrate the tropopause in a year by a given amount are shown in Table I.

Table I—The number of storm tops per year which penetrate a given amount into the stratosphere at Dum-Dum, Calcutta

Penetration (m)	Number per year
0–610	19
610–1220	17·5
1220–1830	15·5
1830–2440	14
2440–3050	11
3050–3660	7·5
3660–4270	2
	Total 86·5

From equation (4) we can thus calculate the water vapour injected into the stratosphere by storm tops which penetrate to varying degrees through the tropopause. The results are collected in Table II.

TABLE II—WATER-VAPOUR INJECTION INTO THE STRATOSPHERE IN A YEAR BY STORMS WHICH PENETRATE A GIVEN AMOUNT THROUGH THE TROPOPAUSE

Penetration (m)	Water-vapour injection (kg)
0–610	$0{\cdot}8 \times 10^6$
610–1220	$5{\cdot}2 \times 10^6$
1220–1830	12×10^6
1830–2440	21×10^6
2440–3050	27×10^6
3050–3660	28×10^6
3660–4270	10×10^6
	Total $1{\cdot}0 \times 10^8$

It is interesting to note that a considerable proportion of this injection is contributed by the very high tops, and this water vapour is more likely to remain in the stratosphere than that injected into the transition layer between troposphere and stratosphere which can be many hundreds of metres thick.

Figure 13.1 on page 391 of Palmén and Newton (1969) shows those areas of the world which are subject to severe storms, and the total area outside the tropics can thus be roughly computed. The area which is observed by the Dum-Dum radar is about 0·2 per cent of the total.

Therefore we estimate, by this method, that severe extratropical storms contribute $1{\cdot}0 \times 10^8 \times 100/0{\cdot}2 = 5{\cdot}0 \times 10^{10}$ kg/year, or 23 per cent as much water vapour to the stratosphere as the estimate of WV for the Hadley cell.

This is admittedly a rough estimate but it suggests that the direct injection of water vapour into the stratosphere by convective clouds is an important source of stratospheric moisture.

COMPARISON WITH OTHER WORKERS

WV assume that a 100 m thick layer of the storm anvil mixes with the stratospheric air. They take as a representative sample a storm studied by Fujita (1972) with an anvil area of 60 000 km^2. They then estimate the effect of 100 storms per day of this size around the globe penetrating into the stratosphere. This gives a global water-vapour flux of $8{\cdot}8 \times 10^{11}$ kg/year, or four times their Hadley cell flux.

Sissenwine *et alii* (1972) give a detailed climatology of tropopause penetrations over the United States, based on the work of Kantor and Grantham (1968). They also consider the shape of the penetrating tops, and hence calculate the amount of tropospheric air taken up into the stratosphere annually. This value is then converted to a global value on an area basis. Finally, they assume that 1 per cent of this injected water vapour is released into the stratosphere. This gives the result that the storms inject 70 per cent of the WV Hadley cell flux.

Reiter (1975) estimates that small-scale disturbances, such as tropical storms, exchange annually a small amount of air between stratosphere and troposphere, perhaps nearer 1 per cent than 5 per cent of the stratospheric mass, compared to the 38 per cent exchange by the Hadley cell circulation. Sissenwine *et alii* (1972) give a value of ½ per cent. It is because this air is so rich in moisture that the contribution to the water-vapour budget is relatively large.

The 36 500 storms per year assumed to penetrate the stratosphere by WV agrees fairly well with the 67 000 storms calculated by Sissenwine *et alii* (1972) and the 43 000 estimated in the present paper.

The injection of water vapour by an average storm is given by WV as 7×10^7 kg, and this is considerably larger than the $1{\cdot}2 \times 10^6$ kg estimated in the present paper and the $2{\cdot}2 \times 10^6$ kg assumed by Sissenwine *et alii* (1972). Kuhn *et alii* (1971) give a value of $2{\cdot}0 \times 10^5$ kg for Oklahoma storms by assuming that each cell has an area of 100 km^2 and injects 20×10^{-4} g cm^{-2} of water vapour. This seems to be a minimum value as they assume no downstream spread of the water vapour.

Using the method described in the present paper for calculating water-vapour injection, together with the extensive climatology of Kantor and Grantham (1968) gives an estimate of 30 per cent of the WV Hadley cell flux. This represents, in the author's opinion, the least arbitrary estimate of the contribution of severe storms to the stratospheric water-vapour budget, although it is still a far from satisfactory one.

Conclusion

Using a climatology of Indian storm tops penetrating into the stratosphere, it has been estimated that severe extratropical storms contribute in the region of 23 per cent as much water vapour to the stratosphere as the Hadley cell circulation. This value, considering the uncertainties of the calculation, agrees reasonably well with values calculated by other authors, and shows that such storms may be a far from negligible source of stratospheric water vapour.

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NOTES AND NEWS

Seychelles joins WMO

The Seychelles became a Member of the World Meteorological Organization on 17 March 1977 and will, in consequence, take over the UK seat on the WMO RA I Tropical Cyclone Committee for the South-west Indian Ocean.

Meteorological services for civil aviation in Cyprus

The remaining UK responsibilities for meteorological services for civil aviation in the Republic of Cyprus ceased on 4 January 1977 when the Cyprus Meteorological Service took over responsibility for Sigmet Warnings in the Nicosia Flight Information Region.

The meteorological office at Salālah

Meteorological Office staff at the observing office at Salālah in the Sultanate of Oman were withdrawn on 29 March 1977. From that date the office was taken over as a going concern by Pan American Airways on behalf of the Oman Government and is being run as a forecast office for the developing civil airport.

New posts in agricultural meteorology

Three new scientific posts in agricultural meteorology have been agreed, with effect from April 1977, for work with the Agricultural Development and Advisory Service of the Ministry of Agriculture, Fisheries and Food. They are at Reading, Cambridge and Harrogate.

Improved system for estimation of evaporation and soil moisture deficits

The scientific basis of an improved operational system for estimating evaporation and soil moisture deficits was discussed in a paper presented at a meeting of the Meteorological Research Committee on 31 January 1977. The operational system is undergoing trials and is expected to replace the existing Soil Moisture Deficit Bulletin which is primarily of value to agriculture and the water industry.

Warnings of synoptic developments for the Central Electricity Generating Board

Arrangements have been made for the Central Electricity Generating Board to be provided during the afternoon in winter, when commercially important decisions have to be made, with advance warnings of hitherto unexpected developments in the synoptic situation. These warnings will be issued by the Central Forecasting Office and relayed through the London Weather Centre.

Stratospheric air sampler

Development of a balloon-borne device for obtaining samples of air in the stratosphere have begun, and analysis of the samples is expected to provide data on the concentration of several species of importance to the photochemistry of the upper atmosphere. Emphasis in the design is being placed on simplicity, low weight and cost so that existing radiosonde facilities may be used. A prototype device has been built and is under test.

GATE data from the Meteorological Research Flight

By the end of March 1977 all 40 flights carried out by the MRF Hercules aircraft during GATE (the international co-operative project for the Atlantic Tropical Experiment), held in 1974 and based at Dakar in Senegal, had been fully processed. The magnitude of this task can be appreciated from the fact that for each hour of flight 2·3 million words of data were collected, processed and recorded on magnetic tape, and that the 40 missions flown resulted in more than 350 flying hours. The data have been distributed in their completed form to the two World Data Centres at Moscow and Washington, and also to those sub-groups which have direct interest in the parameters measured.

Low-level measurements of turbulence over the sea

Over the past two years a series of flights has been conducted with the Hercules aircraft of the Meteorological Research Flight at low levels (30 m to 1000 m) over the sea to measure turbulence in a variety of meteorological conditions.

The flights in weakly suppressed conditions with little or no cloud have shown that there were marked differences between the turbulence spectra measured on runs along and across the wind, the latter exhibiting structure at wavelengths considerably greater than those measured along wind.

Reception of VHRR pictures at Lasham

The satellite receiving station at Lasham is now equipped to receive segmented Very High Resolution Radiometer (VHRR) pictures from NOAA 5. These are supplied to the Central Forecasting Office and to the extended network of out-stations which receive special satellite facsimile transmissions; these stations are also supplied with low-resolution scanning radiometer pictures. VHRR images are restricted to about 1000 × 1400 km segments because of the inability of Post Office lines to pass the large amount of information available from VHRR instruments.

European Centre for Medium-range Weather Forecasts

The Property Services Agency (PSA) of the Department of the Environment is building the European Centre for Medium-range Weather Forecasts at Shinfield Park, Reading. The complex, designed in PSA's Southern Region Office, will comprise a computer hall, administration building, and conference and teaching accommodation. On completion in November 1978 it will house the 100 staff employed by the 16 member nations who are at present housed temporarily in Bracknell. Sponsored by the Ministry of Defence, construction is being carried out by John Laing Construction Ltd at a cost of just under £2 million.

The computer hall and supporting work space will total approximately 2000 square metres, and advanced methods of air-conditioning will be used. Stand-by generators, switching and transformers are to be located in a separate building.

The administration building includes the director's suite, library, offices and boiler-house. The conference block consists of main entrance, class-room, dining-room and kitchen, conference room and lecture hall. Both the conference room and lecture hall will be provided with translation and projection facilities, and will be ventilated from plant at roof level.

The site is located next to the existing Meteorological Office College at Shinfield Park. Care has been taken to retain specimen trees on the site and as many as possible of the other trees around the boundary. (See *Meteorological Magazine*, **103**, (1974) p. 28.)

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CONTENTS

NOTICES

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THE METEOROLOGICAL MAGAZINE

Vol. 106, No. 1262, September 1977

SIR GRAHAM SUTTON, C.B.E., F.R.S.

Sir Graham Sutton, C.B.E., F.R.S. died on 26 May 1977. Born in 1903 at Cwmcarn in Monmouthshire, Oliver Graham Sutton (he preferred to be known as Graham Sutton) received his early education at the local elementary school and at Pontywaun Grammar School. Thence he went to the University College of Wales at Aberystwyth and subsequently to Jesus College, Oxford where he completed his formal training as a mathematician. From 1926 to 1928 he held a lectureship in Pure Mathematics at Aberystwyth. Then he joined the Meteorological Office and within a short time was posted to the Chemical Defence station at Porton. It was there that he laid the foundations of the scientific work which was eventually to earn him an international reputation. The Meteorological Department at Porton was greatly concerned with atmospheric diffusion in the lower layers of the atmosphere, and Sutton applied his mathematical skill with considerable success to extending G. I. Taylor's theory of turbulent diffusion.

It was at Porton that Sutton first met N. K. Johnson (later Sir Nelson Johnson), the man he was eventually to succeed as Director of the Meteorological Office. Johnson had been at one time in charge of the Meteorological Department at Porton and had moved on to become Director of Experiments at the same station. Sutton eventually became Head of the Meteorological Department and later, in 1942, succeeded Johnson as Director of Experiments.

Temporarily Sutton left the world of meteorology to become the first Superintendent of Tank Armament Research in 1943, and later Chief Superintendent of Radio Research and Development in 1945. Following the cessation of hostilities, Sutton was appointed Bashforth Professor of Mathematical Physics at the Royal Military College of Science, Shrivenham in 1947. Here he remained until 1953, combining with his other duties those of Scientific Adviser to the Army Council in 1951 and Dean of the College in 1952–53.

In 1953 Sir Nelson Johnson retired from the post of Director of the Meteorological Office and Professor Sutton succeeded him. Eventually this second period in meteorology was to last almost as long as his earlier career at Porton. His very varied experience was to serve the Office well. Johnson had laid the foundations of the post-war Office but a very great deal remained to be done. Looking back, one can see Sutton's guiding hand in the interchange of men and ideas between the research and services sides of the Office, the development of meteorological services for the non-aviation customer, the unification of the three parts of the Office from London, Harrow and Dunstable, and the introduction of the first electronic computer. Internationally too he carved a name for himself as a member of the Executive Committee of the WMO from 1953 to 1965. This latter work he probably enjoyed more than he would freely admit: he was a logical thinker and a good advocate.

Some who worked with Graham Sutton found him a little unapproachable and difficult to get to know. Basically he was a rather shy man and protected himself with the armour of reserve. Behind this façade, however, there was a kindly and considerate man, a loyal colleague and—for those who worked closely with him—a rock of dependability who was never flustered. In discharging the wide duties of Director (later Director-General) of the Meteorological Office he fought hard in the interests of his staff—more so perhaps than was always generally realized since, given the circumstances of the time, he was not always able to achieve what he wanted. It is significant that he was President of the IPCS from 1957 to 1961. His human relationships were occasionally enlivened by an impish sense of humour. While in hospital recovering from an appendicitis operation he once told a nurse that the reason why the blankets always fell off the bed on the same side was the direction of rotation of the earth.

Sir Graham (he was knighted in 1955) retired from the Meteorological Office in 1965. He had intended his retirement to be complete but the world does not willingly relinquish the services of one who has achieved eminence both as a scientist and as an administrator. The Natural Environment Research Council (NERC) had been created that year and Sutton was persuaded to act as Chairman of this Council for one year. In the event he filled this post for three years and remained for another three years as a member with special responsibilities for hydrology and atmospheric sciences. There is no doubt that he found this work a very agreeable extension of his career as a scientist and administrator in the world of meteorology. Equally his wide experience and considerable abilities served the newly formed Council well in its earliest years.

Having relinquished the position of Chairman of NERC, Sir Graham was able to carry out his original intention when he retired from the Meteorological Office. In 1969 he left Berkshire and returned to his native Wales where he and Lady Sutton set up home in Swansea. He had been a member of the Council of the University College of Wales, Aberystwyth from 1958 to 1964, and in 1967 he was elected Vice-President of the College. I am indebted to the late Sir Ben Bowen Thomas, President of the College, for information about the last part of Sutton's career. The resumption of activities at Aberystwyth was a natural one. Not only had he received his university education there but so also had his two brothers and his sister. More important, it was there he met the lady who was to become his wife. As Vice-President of the College he showed great concern for students' welfare and was also able to draw on his experience gained in the Meteorological Office while acting as Chairman of the Buildings Committee. On matters of academic policy he showed the wisdom and foresight which had characterized his work in the Meteorological Office. He retired from the Vice-Presidency in 1976 on account of ill health.

During his career Sutton also found time to serve as Chairman of the Atmospheric Pollution Research Committee (1950–55), as a member of the Nature Conservancy (1956–59), and as Justice of the Peace. He wrote various scientific papers and books. These latter included *Micrometeorology* (1953), *Mathematics in action* (with D. S. Meyler, 1953) and *Compendium of mathematics and physics* (1957).

Inevitably many marks of appreciation fell to him during his lifetime. The following honours and awards indicate the esteem in which he was held: F.R.S. (1949), C.B.E. (1950), President of the Royal Meteorological Society (1953–55), Knight Bachelor (1955), President's Gold Medal, Society of Engineers (1957), Symons Gold Medal, Royal Meteorological Society (1959), International Meteorological Organization Prize (1968), Frank A. Chambers Award, Air Pollution Control Association (1968). He also became an Honorary Member of the American Meteorological Society, an Honorary Life Member of the New York Academy of Sciences, and he received honorary degrees from the universities of Leeds and of Wales.

In 1931 Graham Sutton married Doris, daughter of T. O. Morgan, and they had two sons. Lady Sutton, with her husband, graced many Meteorological Office functions. Our sympathies are with her and their sons.

A. C. BEST

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A HOMOGENEOUS RECORD OF MONTHLY RAINFALL TOTALS FOR NORWICH FOR THE YEARS 1836 TO 1976

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SUMMARY

An account is given of the preparation of a series of monthly rainfall totals approximating to those which could have been recorded with a modern standard rain-gauge at the observing station in Heigham Cemetery, Norwich in the years 1836 to 1976.

1. INTRODUCTION

This series of monthly rainfall totals to represent Norwich is one of several now under preparation which are intended to facilitate comparisons between the climates of these and former times. It is published in part fulfilment of a contract with the Natural Environment Research Council for the production of long homogeneous rainfall records to represent different districts in Great Britain. The background is outlined in a paper by Craddock (1976) which shows, by reference to annual rainfall totals only, the availability of ancient rainfall records in different parts of England. For eleven districts, which include East Anglia, there are rainfall measurements taken within the district for each year before the present back to 1830, and for some districts the records extend back much earlier, till 1725 in fact. This paper seeks to increase the knowledge of past rainfall at Norwich by producing monthly as well as annual totals, and by concentrating on making reliable estimates for a representative key site, instead of surveying rainfall over the whole of England.

2. THE EVIDENCE

The first record of rainfall at Norwich was made by W. Arderon for the years 1750 to 1762, and published in the *Philosophical Transactions of the Royal*

Society. Then one unknown observer kept a record at Aylsham from 1787 to 1790, and another did so in Norwich from 1791 to 1799. After 1799, East Anglian rainfall records are missing, apart from one at Epping from 1820, and those by Orlando Whistlecraft at Thwaite, near Mendlesham (1830–81), until W. Brooke started observations in Upper Surrey Street, Norwich in 1836. He was followed by an observer at the Norwich Literary Institute in 1840, and every year afterwards there have been at least two rainfall observers active in Norwich. By the publication of a meteorological magazine in 1860, which still continues in essence in the annual volumes of *British Rainfall*, G. J. Symons gave a great impetus to the measurement of rainfall and the standardization of rain-gauges. During the 1870s the Revd. Canon Du Port actively encouraged the development of what became the Norfolk Rainfall Organization. This work was continued after Canon Du Port's death in 1898 by a Norwich Solicitor, Mr A. W. Preston, who in turn gave place to Col. H. C. Copeman in 1930 to perform a task which Mr T. W. Norgate performs today. Thus it is that in recent years there have been far more good rainfall records for stations in and around Norwich than could be considered in the present study, while for years before 1860 it is often hard to find reliable information of any kind. The rainfall stations considered in this paper are shown in Figure 1 in a form which shows which stations were operating in which years. Most have been used in comparisons made to confirm the reliability of the records used in the final result, and to suggest the best correction factors where necessary. The need for comparison and correction will be clear from the following paragraph.

3. The development of rain-gauging

In 1723, Dr James Jurin, the Secretary to the Royal Society, issued to his members an 'invitation to make weather observations according to a common plan'. He recommended a rain-gauge which had some surprisingly modern features, but all he said about its exposure was that it should be placed where no obstacle could prevent rain from any direction from reaching the gauge. Now the modern understanding of the position, as outlined, for example, by Painter (1975), is that the amount caught by a rain-gauge is considerably affected by eddies in the wind passing over the gauge, eddies which may be generated by surrounding objects, or by the gauge itself, in the general sense that the stronger the wind, and the smaller the droplets, the greater the deficiency. A rain-gauge exposed without protection on the flat ground around Norwich, or on an isolated roof, is sure to collect less than a similar gauge in a situation such as a large garden or forest clearing, where the wind speed is reduced by obstacles which are not near enough to intercept any of the rain. William Arderon made his rainfall observations in 1750 when, as reported by Parson Woodforde in 1780, the city gates were still shut at night, and during the nineteenth century most Norwich rainfall observers were gentlemen of means, living in houses lying within or near to the present ring road, and hence well within the present-day built-up areas. It is unlikely that any observers from 1850 onwards would start with gauges at ground level which were over-exposed, and which hence would benefit by protection. The trend must usually be in the other direction, that over the years the growth of trees and the erection of buildings tends to intercept the rain and to reduce the catch from what may originally have been a satisfactorily exposed gauge. Whereas many early rainfall records depended on home-made gauges of primitive design, the efforts of G. J. Symons and others led to the increasing adoption of well-made gauges from firms such as Negretti and Zambra which conformed to known standards and had a long working life. Hence the problems of reducing rainfall records for different years to a common standard tend to reduce to the following:

(a) the average annual rainfall at the site of the gauge may be different from that at the chosen key site;

(b) the gauge may be exposed under non-standard conditions: it may be sheltered by surrounding buildings or trees, or exposed to violent winds; in either case it is likely to catch less rain than it should; and

(c) the quality of the recording, though satisfactory to start with, may deteriorate with time, nearly always in the sense that the actual catch becomes progressively less than the true value.

The method described goes far towards overcoming all these problems, of which the last is by far the hardest.

4. The method of reduction

Given rainfall records made at two sites during a number of years, the ratios of corresponding annual totals are expressed as percentages, and plotted against the year number; the points are then joined to make the graph easier to read. If three or more records exist for the same period, then one record is chosen as standard, the annual totals being used as denominator in comparisons with all the others. Comparisons among the other records are also made on occasion, but it is rarely necessary to examine all possible comparisons. An example of such comparisons is shown in Figure 2, and they are considered in detail, after this discussion of principles.

Now the ratio of the total rainfall amounts caught at two sites in the same year must have an expected value, which is approximately the ratio of the climatic values at these sites. If the two sites are both in Norwich, where the climatic average rainfall is near 26 inches, the expected value of the ratio must be near unity, but even if the sites are widely separated, the ratio in individual years must fluctuate at random about some definite value. If the fluctuations are not at random about the ratio of the climatic values but tend to be always positive or negative, or to change with time, then either one of the climatic values has been wrongly estimated, or one or both of the rain-gauges has been wrongly installed, or the quality of one or both of the records is changing with time. These possibilities can be seen far more easily by looking at graphs plotted in the style of Figure 2 than they can from the table of figures on which the graphs are based, and this is a very sensitive method of finding features in rainfall records which call for explanation. If the graph suggests that the ratio of the annual catches at two sites has remained stable over several years, there is some justification for estimating the ratio as accurately as possible, from the data during the period of agreement, and using this ratio to extend one record by means of estimates based on the other. When, however, the ratio seems to be changing with time, the reason for the change must be investigated and allowance made for it.

5. The Norwich key site in recent years

The first reason for choosing the rain-gauge site in Heigham Cemetery to represent Norwich is that it lies near the city in an open space which is likely to remain unchanged for many years to come. A second reason is that a good

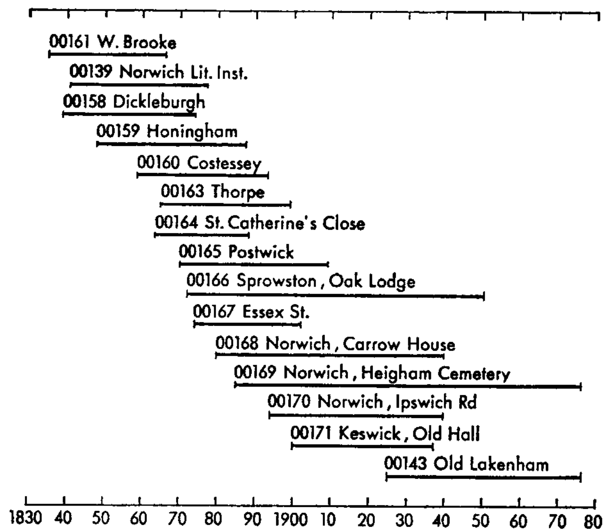

FIGURE 1—NORWICH RECORDS USED IN THIS STUDY

(The numbers 00161 etc. are unique identification numbers.)

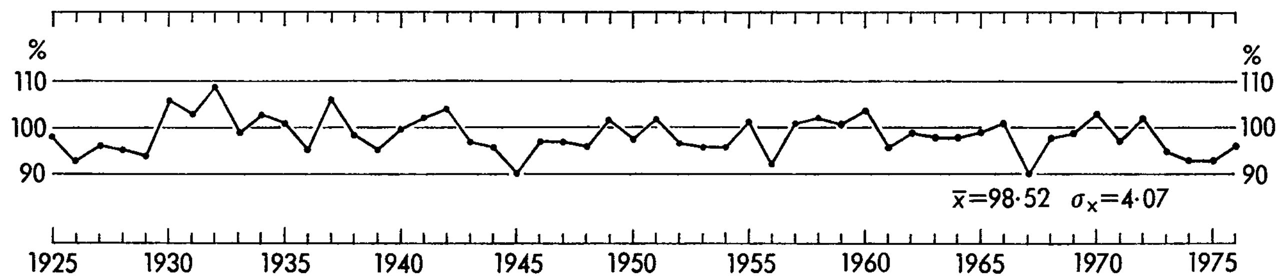

FIGURE 2—ANNUAL RAINFALL TOTALS AT OLD LAKENHAM AS PERCENTAGES OF THOSE AT HEIGHAM

record has been kept at or near the same site since the year 1885. Figure 2 makes it possible to judge the validity of this record for the years since 1926. It gives the ratio of the annual catches at Old Lakenham, tabulated by Mr A. E. Attoe, the observer there, over the corresponding totals for Heigham, extracted from the Meteorological Office archives. The average ratio for the 57 years is 98·52 per cent, with a standard deviation of 4·07 per cent. The graph suggests a maximum soon after 1930 followed by a decrease until about 1945, but because of random year-to-year variations this may be no more than a statistical accident. It is interesting to relate this to the remarks made about the Heigham observing site by the official inspectors. In 1926 the note read, 'Gauge in planting-out garden adjoining lodge of cemetery. Exposure excellent.' In 1958 it read,' Over-sheltered in all directions. No available sites', and in 1970, 'Site sheltered by glass-houses etc. and overshadowed by beech trees to E'. Since the Heigham totals are in the denominator in the ratios in Figure 2, any reduction in the relative catch there should produce an upward trend in the graph, which clearly has not occurred. The probability that two long-period records should change their character in the same year and in the same direction and to the same extent seems small, and the natural inference from Figure 2 is that both Heigham and Old Lakenham are reliable records, at least during the years 1930 to 1972, and that if any uncertainty attaches to the years outside this period it is Old Lakenham which is suspect.

6. Comparisons between records

The standard deviation of the ratios in Figure 2, 4·07 per cent, is typical of those found in several such comparisons, where the stations concerned are a mile or two apart. The mean value, 98·52 per cent, is only a little below 100 per cent, but the difference is probably significant because in Figure 2 there are only 18 points above the 100 per cent line, against 33 points below. Figure 3 shows a similar comparison between the annual totals at Heigham for the years 1895 to 1950 with those of four other stations. The nearest is that kept by J. Willis at Southwell Lodge in Ipswich Road from 1894 till 1940 which shows a feature noticeable in many early records: that the annual catches decline steeply for a few years before the record ends. The most likely explanation is that the observer is prevented by age or infirmity from remedying defects which in earlier years he would have corrected. If the years 1938–40 are excluded, the standard deviation of the ratio (Ipswich Road/Heigham) × 100 is 3·52 per cent, one of the lowest found in this experiment. There is no suggestion of any general change in the Heigham standard between 1895 and 1950, although the Heigham totals in 1933 and 1934 seem anomalously low. It should be noted, when comparing records from closely grouped stations, that an unexpectedly high value at one station may be due to an isolated thunderstorm, whereas a correspondingly low total, which (if genuine) would imply anticyclonic conditions which extend over a wide area, can hardly occur at one station without affecting the others. Furthermore, the existence of the Norwich Rainfall Organization and the publicity it receives is likely to result in any local anomaly being observed and remarked upon. If, for example, a garden shed erected next to the rain-gauge leads to a reduced annual catch, the observer may draw the inference and rectify the situation, perhaps before any query is received from the Meteorological Office. The addition of 5 per cent to the annual catches at Heigham for 1933 and 1934 would bring points for these years in Figure 3 into

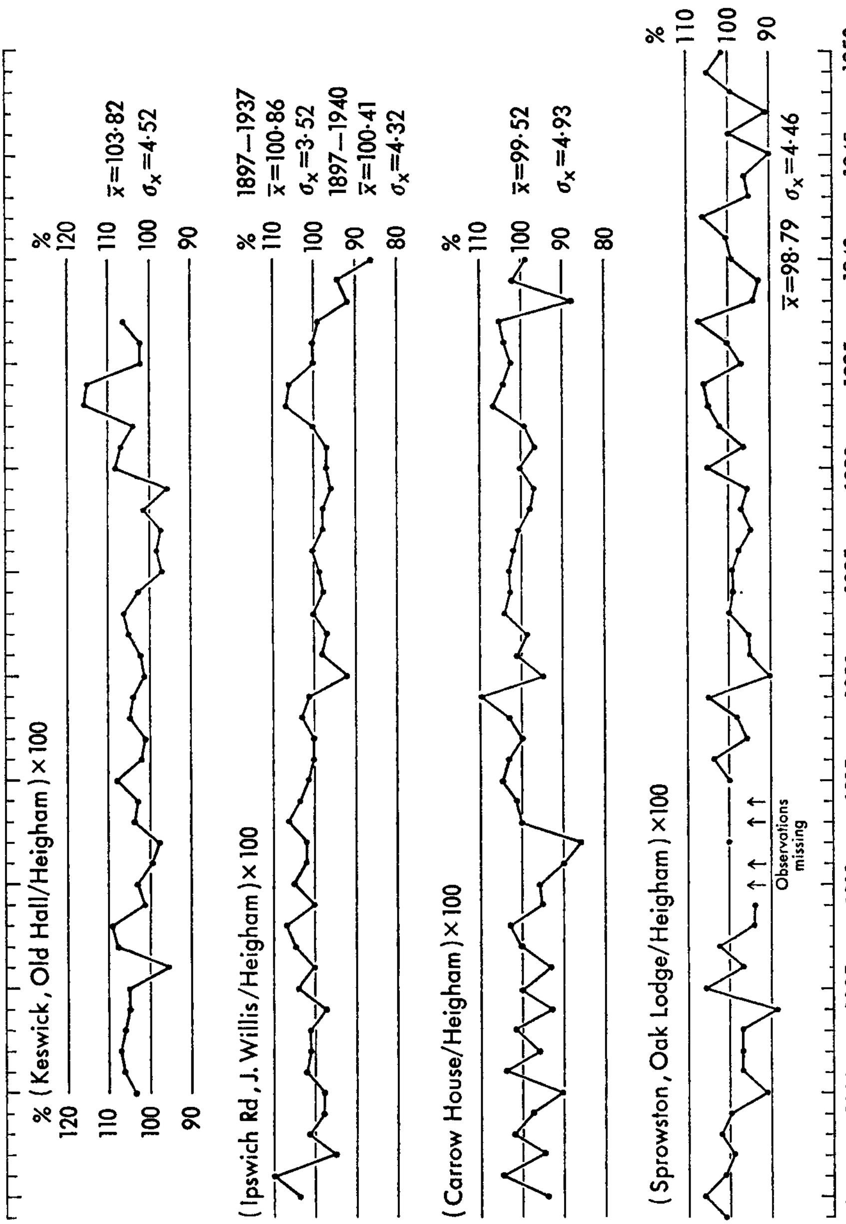

FIGURE 3—RECORDS FOR 1895–1950 COMPARED WITH HEIGHAM

line. The dip in the graphs in 1920 show that the Heigham total was relatively high in that year, but comparison of the 1920 monthly totals at Heigham with those at Carrow House shows that the excess total was nearly all due to excess rain in July, August and September. This rain was probably convective in origin, and no adjustment seems called for.

With the adjustment to 1933 and 1934 the Heigham figures are accepted back to 1885, and the problem then arises of finding the best early records to adjust to the Heigham site. Figure 4 shows a comparison for the period from 1873 onwards of four stations' records with that at Sprowston, Oak Lodge, which in later years was consistent with Heigham. None of these shows rapid deterioration with time, and any of them could be used to extend Heigham back to 1878.

The most satisfactory record for years before 1877 seems to be that made at the Norwich Literary Institute (NLI) from 1841 to 1877. This rain-gauge was on the roof, 30 feet above the ground; while it caught consistently less than a gauge at ground level, the elevation seems to have ensured that the exposure did not change materially during the 37 years. Comparisons show that the catch in 1865 was very deficient while the observation for 1841 is doubtful. With these exceptions, the main problem is to estimate the correction factor to bring the NLI observations into line with the Heigham record. The even earlier record made in Surrey Street by W. Brooke from 1836 to 1866 seems to have undergone

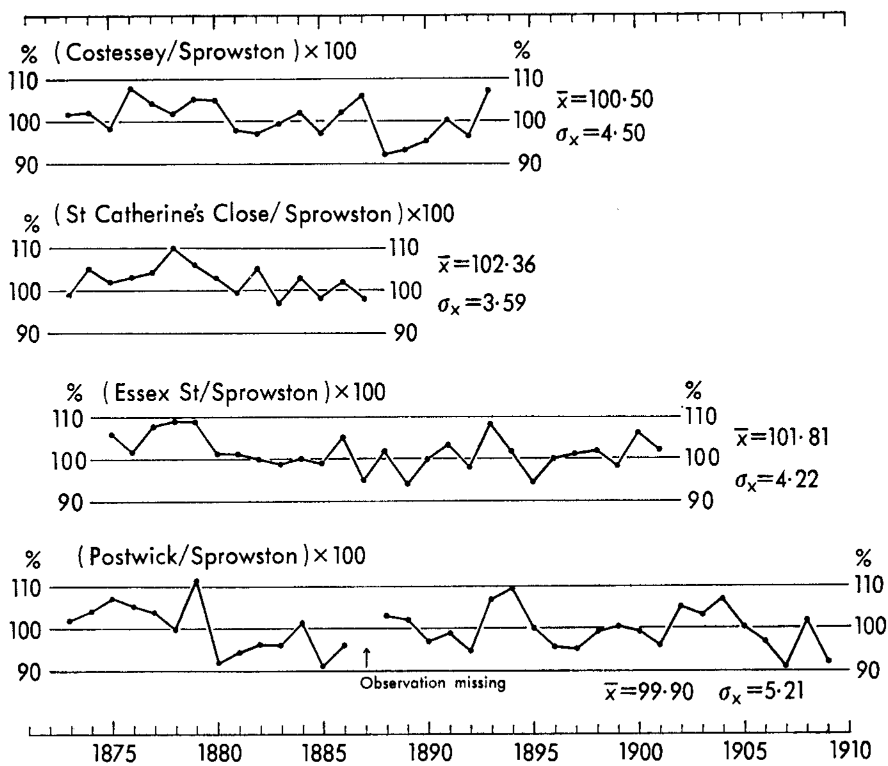

FIGURE 4—RECORDS FOR 1873–1902 COMPARED WITH SPROWSTON, OAK LODGE

a change in exposure in 1850.* Only the earlier part, for which there is no alternative, is used. The conversion factor to bring any record in Figure 4 into line with Heigham is the product of the mean ratio given with that of Sprowston to Heigham (0·9852), so that the factor for the record by F. Dix in Essex Street is 1·00303, not significantly different from unity. For H. Culley's record at Costessey the factor is 0·9901.

In Figure 5, covering 1858 to 1893, with H. Culley's Costessey record as base, the ratio back to the Heigham standard (and excluding the 1865 value) is $0{\cdot}9901 \times 0{\cdot}9152 = 0{\cdot}9061$. The comparison between Costessey and Lady Bayning's record at Honingham shows no long-term trend and, although the stations are 7 miles apart, the standard deviation, 5·90 per cent, is comparable with other records of the same period. Finally, Figure 6 shows a comparison between Mr Brooke's record in Surrey Street and that at the Norwich Literary Institute, first on the basis of Brooke's totals as given, and secondly on the basis that all Brooke's totals before 1851 are increased by a factor of 1·1555. The first

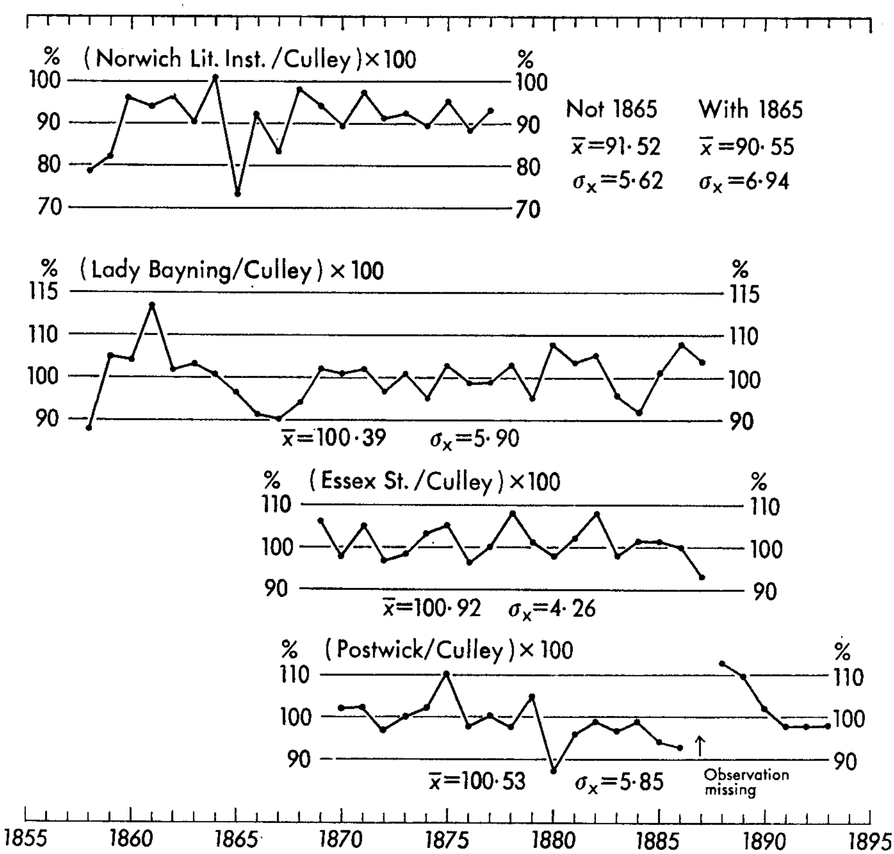

FIGURE 5—RECORDS FOR 1858–83 COMPARED WITH COSTESSEY (H. CULLEY)

* He may have changed from a roof gauge to a gauge at ground level. The observations up to 1850 are multiplied by 1·1555 to give the record referred to as 'Brooke 2' in Figure 6.

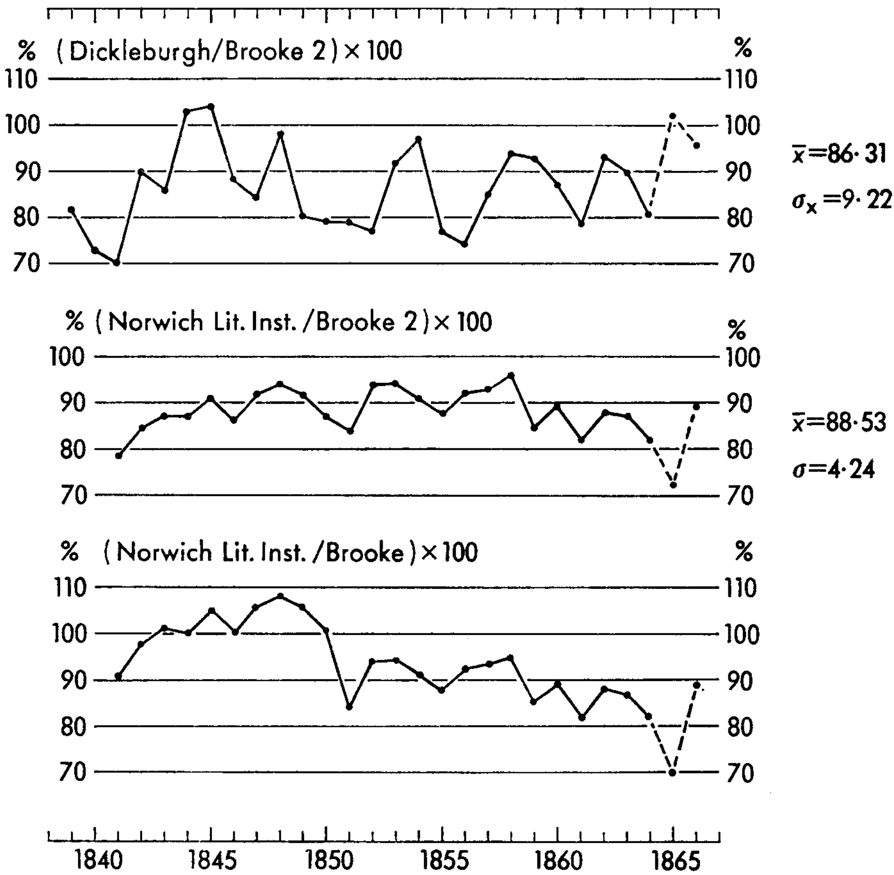

FIGURE 6—RECORDS FOR 1839–66 COMPARED WITH NORWICH, SURREY STREET (W. BROOKE)

comparison suggests a change in the ratio after 1850, which, on this evidence alone, could be either an increase in the relative catch by Brooke's gauge or a decrease in that at the Institute. However, a second comparison (not shown) between Brooke's original record and that of F. Dix at Dickleburgh, 17 miles away, suggests the first explanation,* and the final graph which compares the modified Brooke record with Dickleburgh suggests that, although there are important variations, there is no overall trend. The record kept by H. Culley covering the years 1858–93 seems to be very consistent, with a mean catch very close to that expected at the Heigham site. It does not show the defect in 1865 which occurs in the record at the Literary Institute, and the official records show that although Culley used a home-made gauge in 1858 he replaced it by a model by Negretti and Zambra in 1859. For these reasons the Costessey record is preferred from 1858 onwards, so that the final homogeneous record is made up as follows:

* The entries in *British Rainfall* show that W. Brooke had two rain-gauges after 1850, one near the ground and the other at roof level, and the inference is that his recorded figures relate to the roof gauge up to 1850 and the ground gauge from then on.

1836–1841	W. Brooke × 1·1290
1842–1858	Norwich Literary Institute × 1·1036
1859–1884	H. Culley × 1·0100
1885–1976	(except 1933 and 1934) Heigham Cemetery
1933 and 1934	Heigham Cemetery × 1·050.

The complete record is given in Table I, in inches.

7. Conclusion

The homogenization is probably accurate to within one per cent for years back to 1859, with rather more uncertainty about the conversion of the totals from the Norwich Literary Institute back to 1842. For the years 1836 to 1841, based on totals given by Mr W. Brooke, the average is probably about right, but there are unexplained variations between years which require more attention and may be very hard to elucidate. The same applies with even more force to the isolated records before 1836 back to 1750 which are not considered here. The present homogenization must be looked on as the best which can be offered at the moment, with the promise that something better may be produced later for years before 1842.

Acknowledgements

Acknowledgement is due to the Hydrometeorological Branch of the Meteorological Office for copies of most of the records used, taken from the official archives, and to Mr A. E. Attoe of Norwich for copies of records in his personal collection.

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Table I—Homogeneous monthly rainfall totals for Heigham Cemetery, Norwich, 1836–1974

	J	F	M	A	M	J	Jy	A	S	O	N	D	Total
1836	2·03	2·11	3·99	1·98	0·90	3·75	2·03	0·77	4·18	4·20	3·95	2·99	32·88
1837	3·61	2·56	1·07	1·90	1·47	1·98	3·05	2·82	1·73	2·54	2·60	2·82	28·15
1838	2·62	1·52	1·26	1·84	0·53	3·44	1·16	2·94	2·85	2·20	2·31	1·69	24·36
1839	1·75	1·47	2·37	1·02	1·30	3·27	4·01	3·07	2·99	2·20	2·99	2·82	29·26
1840	2·54	1·10	0·81	0·14	3·36	1·91	2·42	1·16	3·38	2·71	3·16	2·71	25·40
1841	3·42	1·99	1·64	1·74	1·87	2·29	5·95	4·29	4·22	7·81	3·49	3·90	42·61
1842	1·16	1·05	2·53	1·68	1·21	1·53	4·09	1·41	4·25	3·07	3·38	0·63	25·99
1843	1·99	2·81	1·11	2·21	4·25	2·30	1·94	4·78	2·16	4·24	3·89	0·26	31·94
1844	2·46	1·32	2·17	0·26	0·54	0·99	2·44	2·67	1·49	4·41	3·12	0·57	22·44
1845	2·21	0·72	0·17	1·80	4·24	1·08	2·01	4·24	1·11	2·37	1·36	3·24	24·55
1846	2·74	0·76	1·30	3·19	1·27	1·55	1·53	2·41	1·45	3·90	1·81	2·27	24·18
1847	1·27	1·07	1·19	1·79	2·89	3·06	0·55	1·67	1·81	2·28	1·93	2·70	22·21
1848	1·19	2·62	3·07	2·92	0·71	4·45	2·46	3·60	2·83	6·19	2·11	2·10	34·25
1849	1·71	0·62	2·04	2·89	5·45	1·30	2·37	1·69	2·09	3·60	2·13	4·41	30·30
1850	1·88	1·23	0·74	1·95	3·37	0·63	6·68	1·78	1·93	2·46	2·84	2·30	27·79
1851	2·39	0·81	3·30	2·94	1·35	1·75	4·04	2·60	1·06	3·13	3·79	0·57	27·73
1852	3·44	2·79	0·71	0·38	1·53	3·07	0·87	3·97	5·71	3·94	5·55	1·96	33·92
1853	2·17	3·07	1·29	3·02	0·67	2·42	5·37	3·45	1·70	3·53	1·45	1·49	29·63
1854	1·98	1·08	0·53	0·55	5·54	0·57	0·82	4·29	0·74	2·55	2·75	3·43	24·83
1855	1·18	1·91	1·40	0·29	1·42	3·03	3·87	1·62	0·92	3·59	2·98	1·96	24·17
1856	2·35	1·26	0·41	1·18	3·72	1·67	3·10	2·53	3·56	2·26	3·01	2·04	27·09
1857	4·19	0·22	0·68	2·43	0·98	1·94	2·14	2·66	5·44	3·10	1·61	0·38	25·77
1858	0·41	0·41	1·19	1·45	2·53	1·20	3·61	2·44	0·93	2·87	1·84	2·03	20·91
1859	0·99	1·36	1·35	3·45	0·94	1·53	2·68	2·40	2·90	2·51	2·02	3·15	25·28
1860	2·49	2·21	2·45	1·24	3·17	4·96	1·93	3·04	3·05	1·93	3·15	2·38	32·00

TABLE I—*continued*

	J	F	M	A	M	J	Jy	A	S	O	N	D	Total
1861	1·15	2·42	2·13	1·05	0·88	1·39	3·45	0·25	2·58	0·52	4·68	1·36	21·86
1862	1·11	0·40	4·20	0·96	2·74	1·88	1·04	2·25	1·80	2·54	1·52	2·03	22·47
1863	2·39	0·45	0·96	0·99	0·74	2·97	0·75	2·00	1·59	2·29	1·96	1·10	18·19
1864	0·49	1·28	1·91	0·09	2·31	1·01	1·13	0·86	1·82	0·84	2·08	0·80	14·62
1865	2·07	2·91	2·60	0·42	1·24	1·23	3·63	3·11	0·03	6·08	2·07	1·18	26·57
1866	2·68	4·19	1·14	1·56	1·86	2·93	2·05	1·23	2·46	1·02	3·37	2·65	27·14
1867	3·94	1·24	1·54	2·29	2·90	0·95	3·06	1·85	2·71	2·53	1·06	3·02	27·09
1868	2·14	1·50	2·08	1·92	0·80	0·71	0·56	2·85	2·29	2·64	2·26	4·52	24·27
1869	1·70	2·40	3·13	1·27	2·84	1·71	0·59	1·68	3·10	2·93	2·65	4·52	28·52
1870	1·22	0·81	1·56	0·89	0·62	1·13	1·93	2·20	1·63	3·89	1·44	4·19	21·51
1871	0·74	1·90	0·97	3·15	1·04	3·53	2·82	0·63	3·95	1·67	2·58	1·29	24·27
1872	2·07	0·94	4·00	2·28	2·10	3·16	3·32	3·71	2·84	3·18	4·21	3·78	35·59
1873	2·01	1·92	2·04	1·35	1·90	1·69	2·00	2·05	3·05	2·31	1·29	0·67	22·28
1874	1·08	1·09	0·86	1·05	1·96	2·08	1·12	1·36	3·22	1·67	3·19	2·47	21·15
1875	2·25	1·30	0·57	0·70	1·50	1·59	5·13	0·70	2·44	3·60	5·86	2·41	28·05
1876	1·85	2·91	2·86	3·26	1·13	1·78	3·41	2·00	5·19	1·26	2·56	3·48	31·69
1877	2·77	2·68	2·37	2·67	1·83	1·99	2·88	3·60	2·93	2·18	2·31	2·30	30·51
1878	2·09	1·17	1·15	0·99	3·63	1·61	0·53	5·11	2·34	2·36	7·73	2·10	30·81
1879	1·06	2·96	0·74	2·41	2·58	3·92	4·67	5·12	3·46	1·38	2·26	0·70	31·26
1880	0·11	1·74	0·73	1·90	0·76	3·61	4·67	2·77	2·26	5·10	1·98	2·34	27·97
1881	1·57	3·48	1·39	1·03	0·65	1·68	2·15	3·68	2·59	2·86	2·20	3·04	26·32
1882	1·75	1·45	1·27	3·22	1·62	2·91	2·77	1·75	2·40	5·89	3·72	3·81	32·56
1883	1·90	2·76	1·97	1·73	1·06	2·76	2·69	0·71	3·39	3·63	3·73	2·83	29·16
1884	1·38	0·51	1·32	2·01	0·87	0·52	2·19	1·47	2·72	3·05	2·33	2·47	20·84
1885	2·33	2·37	1·31	1·31	2·99	0·95	1·02	0·60	4·59	6·64	2·92	1·36	28·39
1886	2·67	0·23	1·35	1·47	2·54	0·52	3·98	1·82	1·75	2·94	2·61	3·84	25·72
1887	1·75	0·62	1·91	1·19	2·17	0·41	1·19	2·27	2·56	2·81	2·11	1·35	20·34
1888	1·36	2·00	2·53	1·60	0·95	1·00	3·95	2·20	1·84	2·13	2·67	1·14	23·37
1889	0·86	1·57	1·03	2·03	3·37	1·11	3·56	2·50	3·20	2·73	1·79	1·35	25·10
1890	2·57	0·74	2·74	0·97	1·61	2·82	3·33	1·87	0·98	1·87	3·59	0·56	23·65
1891	1·84	0·02	1·74	0·99	3·45	0·87	5·19	3·05	0·98	3·81	1·63	2·98	26·55
1892	0·92	2·05	1·15	1·82	1·71	3·41	2·69	2·26	2·03	7·82	1·30	1·25	28·41
1893	2·23	2·42	0·41	0·07	0·96	1·47	4·54	2·11	1·37	1·51	4·32	1·78	23·19
1894	1·70	1·16	0·93	2·25	2·63	2·42	3·70	2·33	1·85	2·59	3·05	3·13	27·74
1895	3·63	0·53	1·91	1·17	0·87	0·58	3·67	4·65	0·45	3·84	2·05	1·82	25·17
1896	1·02	0·43	3·45	1·17	0·66	2·32	1·09	1·76	3·56	3·15	1·62	3·25	23·48
1897	2·15	2·20	2·14	1·69	0·91	2·38	0·93	2·15	3·42	0·85	1·53	1·51	21·86
1898	0·93	1·14	2·10	1·07	2·99	3·23	1·50	1·50	0·17	2·15	2·56	2·14	21·48
1899	1·89	1·33	1·55	2·70	1·57	0·94	2·23	0·57	3·17	2·70	2·61	1·73	22·99
1900	3·06	3·23	1·05	2·03	1·77	3·13	2·01	4·65	0·56	2·25	2·08	2·87	28·69
1901	0·67	1·56	2·13	2·31	0·88	1·52	1·18	1·18	0·98	2·04	2·24	3·80	20·49
1902	1·30	0·69	1·05	1·29	4·18	2·28	2·22	3·24	1·15	1·47	1·49	1·31	21·67
1903	1·60	0·36	1·70	2·51	1·75	2·74	5·06	3·12	3·04	4·65	1·71	1·07	29·31
1904	1·40	2·83	1·79	0·75	1·69	0·67	2·98	3·07	2·09	1·42	1·64	2·09	22·42
1905	0·98	1·54	1·84	2·08	1·21	3·41	0·70	2·40	2·28	3·61	1·92	0·89	22·86
1906	3·73	2·64	1·79	0·66	2·88	2·09	1·05	2·10	1·12	2·99	4·37	2·79	28·21
1907	1·25	1·46	1·20	3·53	2·53	2·40	1·57	1·08	0·43	3·11	2·52	2·45	23·53
1908	0·85	1·99	2·17	2·57	1·60	1·23	3·38	2·31	2·23	1·23	1·44	1·42	22·42
1909	0·78	0·61	3·02	1·33	1·24	2·93	3·02	1·83	1·59	4·01	1·29	4·92	26·57
1910	2·74	2·02	0·82	2·36	3·61	1·68	3·77	1·14	1·40	1·59	4·05	4·16	29·34
1911	2·09	1·75	2·77	1·40	1·37	3·03	0·70	0·74	2·13	2·57	3·16	3·78	25·49
1912	2·64	1·42	2·25	0·40	0·92	2·19	3·74	11·36	2·65	1·77	3·04	2·44	34·82
1913	2·92	0·76	2·08	2·33	1·13	0·70	2·45	1·53	2·62	3·36	2·26	0·80	22·94
1914	2·06	1·60	3·46	0·74	0·94	1·58	2·81	0·82	1·12	2·37	2·91	6·36	26·77
1915	3·00	3·30	2·00	0·70	2·18	0·95	3·68	2·52	1·46	2·01	2·82	3·99	28·61
1916	1·71	4·54	3·58	1·75	2·41	3·08	1·03	2·87	1·73	2·53	2·81	3·02	31·06
1917	2·07	1·18	3·09	2·10	0·69	1·63	2·30	4·64	2·30	3·42	2·01	1·42	26·85
1918	2·58	1·09	0·73	3·17	0·71	1·11	3·34	1·54	4·40	2·49	2·05	3·80	27·01
1919	2·66	3·22	1·85	1·68	0·68	1·29	2·53	1·82	0·73	3·38	2·96	4·61	27·41
1920	2·25	0·69	1·16	3·37	1·63	1·93	3·28	2·00	2·47	0·75	0·79	3·05	23·37
1921	2·02	0·37	1·09	1·64	1·11	0·55	0·55	1·48	1·29	1·51	2·00	1·89	15·50
1922	5·33	2·66	2·15	2·43	0·56	1·45	7·51	1·46	2·75	1·46	1·91	2·50	32·17
1923	1·67	3·47	1·49	0·97	1·32	0·80	2·97	2·36	1·73	3·49	3·19	3·00	26·46
1924	2·23	1·92	0·70	1·89	3·75	1·53	2·30	2·49	5·06	4·57	1·38	2·76	30·58
1925	1·06	1·91	1·73	2·29	2·15	0·55	1·80	2·40	3·12	1·49	3·68	2·63	24·81
1926	2·64	1·93	0·38	2·74	1·49	2·54	1·60	2·42	0·95	2·75	3·09	1·34	23·87
1927	2·20	2·10	2·12	1·57	0·71	4·89	2·37	3·47	6·62	2·71	5·02	2·30	36·08
1928	3·51	1·50	1·50	1·36	1·87	2·34	2·02	1·67	1·15	2·68	2·83	3·29	25·72
1929	1·90	0·75	0·05	1·21	1·04	0·94	4·06	1·27	0·65	3·15	3·48	5·03	23·53
1930	1·85	0·95	1·35	2·11	3·01	1·01	3·98	2·46	5·25	0·91	3·70	1·86	28·44
1931	2·34	2·27	0·60	3·39	3·37	2·31	3·34	3·22	2·27	1·04	1·79	1·76	27·70
1932	0·79	0·77	1·92	3·12	3·65	0·48	3·39	1·88	2·52	4·17	1·43	0·65	24·77
1933	0·78	2·22	2·00	1·32	1·77	2·04	1·35	0·53	2·32	2·75	1·98	0·57	19·63
1934	1·44	0·89	1·20	2·35	2·33	2·16	1·17	1·69	1·64	1·80	1·75	3·75	22·17
1935	2·94	1·85	0·56	2·28	1·41	2·85	1·03	1·08	3·25	2·79	3·67	1·73	25·44
1936	2·63	2·39	0·40	1·44	0·64	3·94	3·92	1·70	2·41	2·08	2·82	1·46	25·83
1937	3·70	2·54	2·77	2·23	3·16	1·08	1·52	1·02	1·70	1·55	1·90	3·10	26·37
1938	2·21	1·22	0·35	0·52	1·89	1·00	3·17	1·06	2·59	2·90	2·15	3·61	22·67
1939	5·65	0·88	2·15	3·13	0·72	2·11	1·20	2·92	1·88	6·68	4·24	2·51	34·07
1940	1·81	1·42	2·89	1·48	0·80	0·31	3·89	1·32	1·00	2·17	6·01	2·19	25·29

TABLE I—*continued*

	J	F	M	A	M	J	Jy	A	S	O	N	D	Total
1941	2·26	2·36	2·92	0·78	1·91	0·64	1·18	3·96	0·42	3·44	1·92	1·23	23·02
1942	3·32	1·16	1·81	0·72	2·24	1·22	3·34	0·83	1·56	3·67	2·68	2·08	24·63
1943	3·80	0·62	0·80	0·93	1·98	1·44	1·41	1·52	2·31	1·61	2·81	1·27	20·50
1944	2·15	1·59	0·78	1·88	1·09	1·71	1·73	1·10	3·51	3·60	4·36	1·60	25·10
1945	2·49	1·76	1·92	2·59	2·15	1·79	0·88	3·95	2·42	3·05	1·08	2·54	26·62
1946	1·58	3·76	0·89	0·56	1·53	2·84	5·80	3·70	2·55	1·06	3·52	2·99	30·78
1947	1·89	2·51	4·56	2·01	0·51	1·34	1·53	0·04	0·83	0·41	1·23	1·98	18·84
1948	3·70	1·06	0·67	0·88	2·69	2·16	1·98	3·29	1·59	1·60	0·99	1·19	21·80
1949	1·01	1·00	1·41	1·81	1·52	0·97	2·33	1·69	1·15	3·16	2·43	1·77	20·25
1950	1·31	3·31	0·36	1·80	1·71	2·46	4·89	2·56	3·37	1·01	4·15	2·20	29·13
1951	3·05	3·12	3·56	3·44	1·72	0·97	2·22	3·13	2·09	0·76	3·53	1·29	28·88
1952	2·86	1·07	2·61	1·62	1·36	1·39	2·04	2·13	2·68	2·51	4·18	2·60	27·05
1953	1·46	1·60	0·59	2·22	1·25	2·18	2·70	2·67	1·78	2·26	1·37	1·03	21·11
1954	1·61	2·21	2·42	0·55	2·06	2·22	2·71	5·29	1·77	2·17	4·51	1·84	29·36
1955	1·85	2·21	1·87	0·43	2·05	2·58	0·28	0·88	1·94	4·66	0·84	1·82	21·41
1956	3·10	2·11	0·84	0·93	0·80	2·33	2·85	5·99	1·43	2·27	1·43	1·98	26·06
1957	1·82	2·34	2·02	0·21	1·19	2·23	2·58	2·33	3·51	1·44	2·20	2·50	24·37
1958	2·43	3·71	1·36	1·06	3·28	2·57	2·83	2·43	1·92	1·89	1·21	2·66	27·35
1959	3·20	0·18	1·35	1·59	0·38	1·13	1·60	1·34	0·05	1·74	2·43	3·01	18·00
1960	3·94	1·77	0·99	1·19	0·36	1·20	3·43	3·44	3·56	4·35	2·99	3·80	31·02
1961	3·56	1·37	0·50	1·79	1·22	1·22	2·46	2·68	3·31	4·48	2·56	2·98	28·13
1962	2·23	1·41	1·40	1·57	1·78	0·37	2·54	2·55	2·53	1·16	2·28	1·98	21·80
1963	1·06	0·72	2·31	2·00	2·07	1·63	1·63	4·11	1·58	1·58	2·68	1·11	22·48
1964	0·51	0·94	3·10	2·84	1·15	3·63	1·12	1·50	0·66	2·42	1·65	2·64	22·16
1965	2·14	1·27	2·34	2·44	2·28	1·93	3·93	2·49	3·68	0·80	2·90	4·88	31·08
1966	1·39	3·10	0·92	2·07	1·13	2·64	2·97	2·77	1·03	2·96	4·36	2·79	28·13
1967	1·34	2·12	0·78	2·32	3·44	0·70	1·28	1·60	2·37	3·90	2·42	1·95	24·22
1968	2·18	1·69	1·04	1·23	1·92	2·95	4·17	4·09	6·55	1·98	2·41	2·63	32·84
1969	2·10	2·95	2·27	2·24	3·76	1·40	3·47	3·35	0·30	0·44	3·47	2·68	28·43
1970	1·70	2·32	1·91	2·54	0·94	0·61	1·74	1·82	1·10	1·85	5·67	2·59	24·79
1971	3·05	0·81	1·74	0·89	0·81	2·10	1·96	2·99	0·86	2·21	4·59	1·35	23·36
1972	2·81	1·28	0·99	1·82	2·41	1·41	2·95	1·28	0·96	0·37	2·97	1·41	20·66
1973	0·74	1·12	0·47	2·83	2·70	0·88	3·37	1·16	3·87	1·96	1·07	1·80	21·97
1974	1·70	2·30	1·05	0·25	0·64	1·64	2·44	3·12	2·62	5·19	4·18	1·70	26·83

551.521.11:551.524.2(425 + 426)

THE SPATIAL VARIABILITY OF DAILY TEMPERATURES AND SUNSHINE OVER UNIFORM TERRAIN

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SUMMARY

Daily maximum and minimum temperatures and daily sunshine durations have been analysed at a network of stations over an 8000 km² area of uniform terrain in eastern England. Inter-station differences and correlations have been used to calculate standard errors of interpolation between stations of given separations. Some conclusions are offered concerning the required inter-station spacings in the UK climatological network.

INTRODUCTION

The problem of determining the optimum number of observation points to document the meteorology of an area of land surface adequately has long occupied both the synoptician and the climatologist. The former is concerned that observations should be sufficiently close in time and space to enable the position and development of significant weather features to be adequately defined for forecasting purposes. (What is 'significant' in this context obviously depends on the space and time scales under consideration, and what is 'adequate' must be decided by comparison of the attainable standard error of the combined analysis and forecasting process with the standard error acceptable to the user of the forecast.) The climatologist is concerned that observations should be available from all sub-areas which are considered to have recognizably different climates and that the effects of topography on the various climatic elements should be quantifiable to allow adequate estimates to be made at points with no data. (Here, what is 'adequate' must be decided by consideration of the interpolation accuracy required by the user of the information, bearing in mind the standard errors of the observations themselves.)

It is perhaps self-evident that an increase in the network density would result in improved accuracy of interpolation between stations, and so any discussion on 'optimum' densities should be accompanied by a consideration of the increased costs necessary to operate a denser network and the economic benefits likely to accrue from the denser data. In practice, of course, it is almost impossible to quantify these economic benefits, either in the synoptic or climatological context. The planning of observational networks, therefore, has tended to be a rather pragmatic process, governed by subjective considerations of what extra data appear necessary to 'fill a gap' in the existing network, and by the availability or lack of suitable observers and sites at the desired locations. The current development of accurate and reliable automatic weather reporting and recording instruments implies that station selection in the future should not depend so much upon these non-meteorological constraints, and instruments may be sited so as to provide the maximum benefit purely in terms of the meteorological information derived. Thus a more quantitative understanding is required of the spatial variability of the principal land surface meteorological elements, so that a more rational policy of observational network design may be pursued. We need to know the accuracy with which interpolation within the existing network can be achieved for the various elements and, as a corollary, the network spacings necessary to achieve stated levels of interpolation accuracy over various types of terrain.

The 650 or so stations in the UK climatological network are sited at an average density of about one per 400 km^2, but owing to the considerable dependence on voluntary observers, the network is very much weighted towards the more populous low-altitude areas, with a lower density in upland regions. Owing to the greater spatial variability of climate in topographically complex areas, this situation is thus the very reverse of what is required to achieve the estimation of climate between stations with reasonably uniform accuracy over the whole country. This paper describes the preliminary analysis of the spatial variability of three climatological elements—daily extreme temperatures and sunshine duration—over an 8000 km^2 area of uniform topography where variabilities can be expected to be smaller than elsewhere in the UK; the results will thus define the upper limit to station separations required to achieve an acceptable level of interpolation accuracy.

PREVIOUS NETWORK DESIGN STUDIES

A short general discussion on the basic problems of network design can be found in Alaka (1970). Although primarily concerned with upper-air networks, his paper presents some ideas useful in the consideration of surface networks, and emphasizes the interdependence of station separation, observational accuracy and attainable (or required) accuracy of interpolation.

The planning of surface climatological networks by statistical analysis of available observations has been pioneered by Czelnai and co-workers (Czelnai *et alii*, 1963) and by Gandin, particularly in the latter's WMO *Technical Note* (1970). The essence of the Gandin approach was the use of two alternative measures of similarity between simultaneous values recorded at existing stations. They were the correlation coefficient (R) and the adjusted mean-square difference (S); these are defined by:

Correlation between N values of x at stations i,j:

$$R_{i,j} = \frac{\overset{N}{\Sigma}(x_i-\bar{x}_i)(x_j-\bar{x}_j)}{[\overset{N}{\Sigma}(x_i-\bar{x}_i)^2 . \overset{N}{\Sigma}(x_j-\bar{x}_j)^2]^{\frac{1}{2}}},$$

and adjusted mean square difference between N values at stations i, j:

$$S_{i,j} = \frac{1}{N}\overset{N}{\Sigma}[(x_i-\bar{x}_i)-(x_j-\bar{x}_j)]^2.$$

The variation of these parameters with station separation (L) enables the correlation and (so-called) structure functions, $R(L)$ and $S(L)$, to be defined; these could then be inserted into expressions derived by Gandin to give estimates of root-mean-square (r.m.s.) errors of interpolation for any required station separation. Separate expressions were presented to enable errors of interpolation to be calculated at the mid point of a line joining two stations, or at the mid points between three or four stations sited on a triangular or square grid respectively. Both linear and optimum interpolation* were considered, the S-function being used to derive errors in the former case, and the R-function in the latter case. For example, the expression for linear (E_{lin}) and optimum (E_{opt}) r.m.s. errors of interpolation at the mid point between two stations of separation L were:

$$E_{lin}^2 = S\left(\frac{L}{2}\right) - \frac{1}{4}S(L) + \frac{1}{2}\sigma_F^2$$

and

$$E_{opt}^2 = \sigma^2\left[1 - \frac{2\,R^2(L/2)}{1 + R(L) + (\sigma_F/\sigma)^2}\right],$$

where σ^2 is the variance, and σ_F is the standard error of observation of the element concerned at a typical point in the network.

In practice, however, if the variance of the element is reasonably uniform over the area considered, it can be shown that:

$$S\,(L) \approx 2\sigma^2\,[1-R(L)],$$

and, if also R and S are *linear* functions of L, then a simple relationship can be derived between E_{opt} and E_{lin}, i.e.

$$E_{opt}^2 \approx [1-R(0)]^2 + R(0).E_{lin}^2.$$

If $0{\cdot}9 < R(0) < 1{\cdot}0$, E_{lin} is very close to E_{opt}, and, since linear interpolation is much easier to carry out routinely, it is acceptable to use linear rather than

* In 'linear interpolation' in two dimensions the value to be interpolated at any point is derived by fitting a first-order surface (i.e. a plane) to the surrounding observations, the coefficients of the horizontal co-ordinates being determined by a least-squares error analysis over all the data points used.

In 'optimum interpolation' a formula is used that is a linear combination of the actual values at the surrounding data points, the coefficients or weights being derived from statistical theory by minimizing the mean-square error of interpolation over all occasions in the sample.

optimum interpolation when the above conditions regarding $R(0)$, σ^2 and linearity of $S(L)$ and $R(L)$ are satisfied.

Gandin's published examples of network analysis have dealt mainly with monthly mean data at stations typically hundreds of kilometres apart, but other workers, notably Czelnai (loc. cit.) and Hutchinson (1973) have analysed spatial variability of temperatures on the daily time scale in Hungary and Zambia respectively, albeit still on space scales which are large compared with typical inter-station distances available in the United Kingdom. It thus remains to be demonstrated that R- and S-functions for the principal meteorological elements behave coherently over uniform terrain for station separations below 100 km. The difficult problem of interpretation of these functions in areas of complex topography also requires attention.

In a slightly different approach to the question of network analysis, Sneyers (1973) assumed *ab initio* that the correlation function was linear for the Belgian climatological network, and that it could be defined simply by considering the correlation between data from two stations of known separation. This assumed function was then used to calculate the error of interpolation for a 'typical' station separation, which was shown to be acceptably small when compared with the generally recognized error of observation of the element concerned. (Monthly mean daily maximum temperatures, monthly rainfall amounts and monthly maximum wind speeds were investigated.)

DATA

The Gandin approach to the estimation of errors of interpolation has been used in this investigation and, as explained above, it seemed logical to select for initial attention data from an area of minimum topographic variation. Accordingly, the largest area in the United Kingdom possessing uniform terrain and reasonably uniform climate was chosen. Figure 1 shows the area concerned—East Anglia—stretching from Stamford and Bedford in the west to around Norwich in the east. Twenty-two climatological stations within this area (see Table I) were found to have daily data of acceptable quality over a period of at least 4 years within the period 1959–74. Nine of these stations had records covering the full 16 years. All stations observed daily maximum and minimum temperatures (where the day is conventionally taken to be the 24 hours ending at 09 GMT), and 17 stations also measured daily durations of bright sunshine, using a Campbell–Stokes recorder.

TABLE I—CLIMATOLOGICAL STATIONS USED IN SPATIAL VARIABILITY ANALYSIS OF DAILY TEMPERATURES AND SUNSHINE DURATIONS

Station number		Alt. (m)	Station number		Alt. (m)
3007	Terrington St Clement	3	3115	Broom's Barn	75
3024	Marham	23	3127	Honington	50
3031	Santon Downham	24	3234	Boxworth	44
3037	West Raynham	76	3245	Mepal	−2
3055	East Dereham	53	3248	March	2
3063	Morley St Botolph	48	3253	Cambridge Botanic Gdn	12
3071	Scole	27	3254	Cambridge NIAB	26
3075	Sprowston	28	3357	Monks' Wood	40
3078	Coltishall	17	3374	Wyton	40
3084	Burlingham	27	3456	Cardington	29
3107	Mildenhall	5	4396	Wittering	64

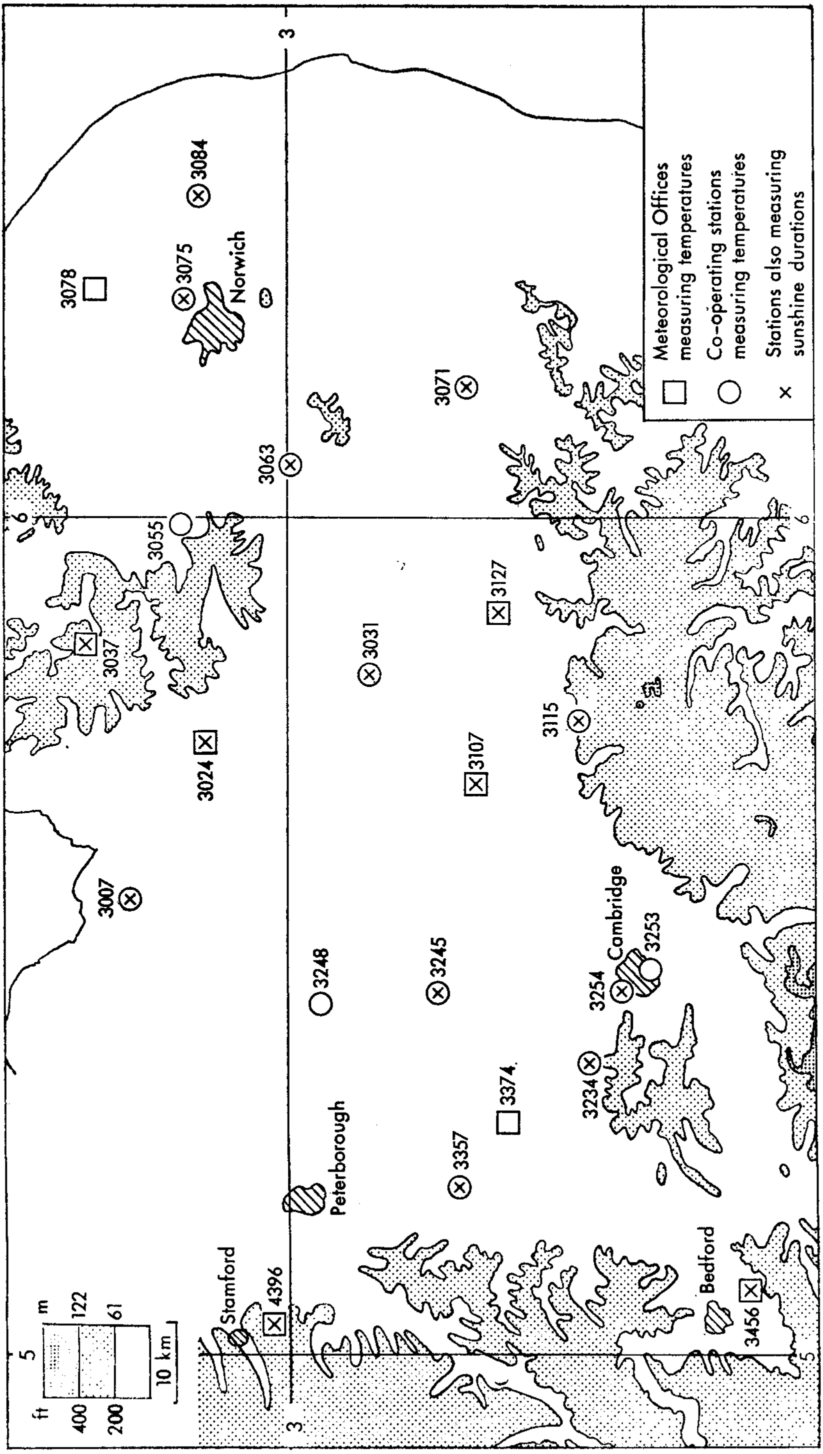

FIGURE 1—CLIMATOLOGICAL STATIONS USED IN STUDY OF SPATIAL VARIABILITY

ANALYSIS OF TEMPERATURES

January and February were taken to represent winter conditions, and July and August summer conditions. Since daily values of temperature are serially correlated, the use of N consecutive days' values would not yield N independent samples of spatial variability. Although there is considerable variation from year to year, typical autocorrelation coefficients for daily temperatures fall from about 0·65 for a lag of 1 day to about 0·2 for a lag of 3 days. (Coefficients are smaller in summer than in winter, and those for minimum temperatures smaller than those for maximum.) It was considered adequate to use values at 3-day intervals from all available stations to ensure that samples for spatial variability analysis were reasonably independent, both synoptically and statistically.

Using these values, for each station pair the correlation coefficient (R) and adjusted mean-square difference (S) were computed over the period of record common to both stations. If at least 50 pairs of values were available, then R and S were plotted as a function of station separation. Twenty-two stations would give a theoretical maximum number of 231 plotted points, but in practice this number was reduced to about 150 because some station pairs were recording simultaneously for a period too short to achieve the '50 pair' criterion.

Figures 2(a) and (b) show the R and S plots for winter minimum temperatures. It can be seen that the R plot displays a well-defined upper boundary, which can be taken as indicating the maximum correlation obtainable between stations of a given separation possessing very similar local exposure characteristics and attaining the highest possible standards of observational accuracy. These stations might be considered to constitute a 'best possible' network in East Anglia. Extrapolated to zero distance, this upper boundary gives $R(0) = 0{\cdot}99$. The lower boundary of the R plot is not so sharply defined. Figure 2(b) shows that the majority of the plotted S values lie within well-defined upper and lower linear boundaries, the latter defining the behaviour of the 'best possible' network. Those not lying between these boundaries were found to arise from comparisons of one single station with all others. That station was Santon Downham, whose frost hollow characteristics have been discussed by Oliver (1966). The correlation coefficients between data from Santon Downham and from all other stations have been plotted with a distinguishing symbol in Figure 2(a), and it can be seen that, although lying towards the lower edge of the R values, they do not stand out as clearly from the rest of the population of points as do the corresponding S values in Figure 2(b).

The same analysis for summer daily minimum temperatures gave rise to very similar R and S plots with Santon Downham appearing anomalously, particularly on the latter. Analysis of summer and winter maximum temperatures in the same fashion showed no such anomalous behaviour, all points lying within well-defined upper and lower linear boundaries for the S plots and below an upper boundary for the R plots.

The linear relationships with distance, defined by the upper R boundary and the lower S boundary, were used in the Gandin formulae to obtain r.m.s. errors of interpolation between stations 100 km apart; the relationship between R and distance to estimate errors arising from optimum interpolation, and the relationship between S and distance to estimate errors from linear interpolation. Table II confirms that optimum interpolation is only very slightly better than linear interpolation for daily temperatures over uniform terrain, and also that very

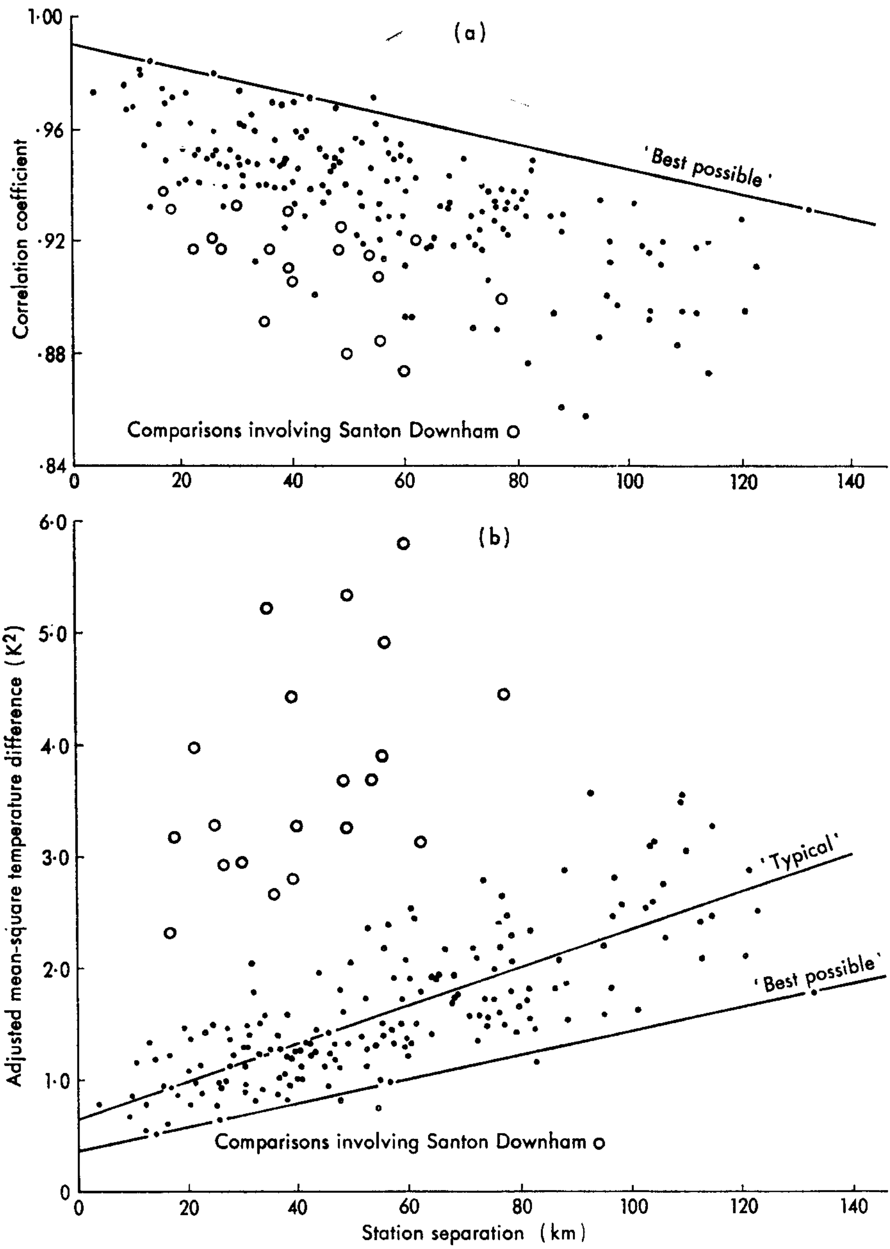

FIGURE 2—CORRELATION COEFFICIENTS (a) AND ADJUSTED MEAN-SQUARE DIFFERENCES (b) BETWEEN WINTER DAILY MINIMUM TEMPERATURES AT PAIRS OF STATIONS IN EAST ANGLIA

TABLE II—COMPARISON OF r.m.s. ERRORS OF INTERPOLATION (K) OF DAILY TEMPERATURES AT MID POINTS BETWEEN (a) TWO STATIONS 100 km APART, AND (b) THREE STATIONS ON A TRIANGULAR GRID OF SPACING 100 km—DERIVED FROM 'BEST POSSIBLE' NETWORK OVER UNIFORM TERRAIN AND GANDIN'S FORMULAE

		Daily maximum temperatures		Daily minimum temperatures	
		Winter	Summer	Winter	Summer
Linear interpolation	(a)	0·50	0·65	0·78	0·79
	(b)	0·49	0·64	0·76	0·75
Optimum interpolation	(a)	0·48	0·64	0·72	0·75
	(b)	0·44	0·62	0·67	0·71

little accuracy is to be gained by interpolating between three stations in a triangular spacing, rather than along a line joining two stations. Further discussion will therefore be based on consideration of linear interpolation in one dimension.

Figure 3(a) shows how the r.m.s. error of linear interpolation within the 'best possible' network varies with station separation. The errors for summer and winter daily minimum temperatures are clearly not significantly different, and are greater than the errors arising from the estimation of maxima. This is to be expected in view of the much greater dependence of screen minima on the nature of the underlying ground surface and immediate local topography. The interpolation error curves for summer and winter maxima are close over short distances and diverge with increasing station separation, with the summer errors being greater than the winter. This may be understood qualitatively by considering that a measured maximum temperature in the summer is much more dependent on the local radiation balance, which in turn is sensitive to changes of albedo arising from differences in soil type and ground cover. In winter, the advective component of the heat balance is more important, spatial differences are naturally smaller and so interpolation errors are also less.

The extrapolation of the curves to zero distance provides an estimate of the r.m.s. differences which might be expected between measurements made from 2 thermometer screens at the same site. Smith (1951) reported results of just such an experiment at Kew, and his results can be compared with those from the present study. His r.m.s. differences were with respect to an assumed 'true' value given by the mean of simultaneous observations, and so to give inter-station differences they should be multiplied by $\sqrt{2}$. It can then be seen from Figure 3 that the Kew r.m.s. difference in maximum temperatures (denoted by X) coincides almost exactly with the extrapolations to zero distance derived from the East Anglian 'best possible' network. That is, accuracy of interpolation between stations is limited purely by the accuracy of the instrument and the reading and recording process. For minimum temperatures, however, the East Anglian extrapolation to zero distance gives a value much higher than the Kew figure (denoted by N), indicating that even with a 'best possible' network over uniform terrain, the inherent variability due to the unique character of each observing site is the limiting factor to interpolation accuracy.

The mean of the daily maximum and minimum temperatures is a close approximation to the mean temperature for the day, and so the r.m.s. error of interpolation of a daily mean temperature can be considered to be half the square root of the sum of the squares of the errors arising from interpolation of the two extremes. The r.m.s. error as a function of station separation in the 'best

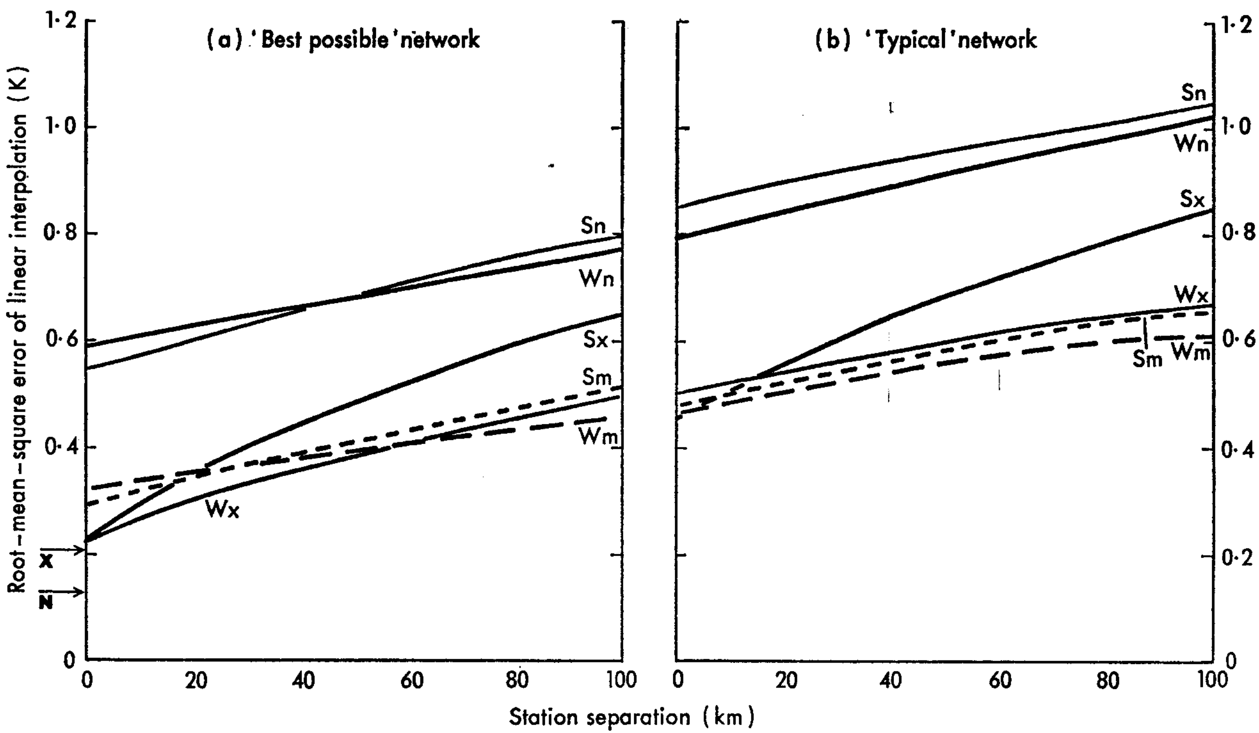

FIGURE 3—ROOT-MEAN-SQUARE ERRORS OF LINEAR INTERPOLATION (K) OF DAILY TEMPERATURES BETWEEN TWO STATIONS OF STATED SEPARATION IN UNIFORM TERRAIN

W—Winter x—Maximum temperatures
S—Summer n—Minimum temperatures
m—Mean temperatures

X and N denote r.m.s. differences between temperatures measured in different screens at Kew for daily maxima and daily minima respectively.

possible' network is shown by the dashed curves in Figure 3(a). The curves for winter and summer are not significantly different.

For network planning purposes it is desirable to know what interpolation errors are likely to arise from a 'typical' rather than a 'best possible' network, and so the 'typical' *S*-function was defined by linear regression of the plotted *S* values on distance, neglecting 'frost hollow' outliers on the minimum temperature plots. Resulting correlations between *S* and distance lay between 0·90 (for summer maxima) and 0·74 (for summer minima) with about 140 pairs. The r.m.s. errors of linear interpolation arising from the *S*-functions so defined are shown in Figure 3(b) and, as in Figure 3(a), appropriate curves for daily mean temperatures have been added. The r.m.s. errors for a 'typical' network are, in general, about 0·15–0·20 K greater than for the 'best possible' network.

Table III shows the station separations necessary to achieve given r.m.s. errors of linear interpolation from a 'typical' network, and it is clear that, in general terms, for daily extreme temperatures over uniform terrain there is little interpolation accuracy to be gained by having a station spacing of less than about 20 km (i.e. a station density greater than about the current national average). For those uniform areas with densities *greater* than this value, some stations can be considered redundant, since a decrease in inter-station separation cannot result in improved interpolation accuracies due to either instrumental (maximum temperatures) or exposure (minimum temperatures) constraints, as discussed earlier. To achieve the same level of interpolation accuracy for daily mean temperatures, the required observing network can clearly be very much sparser.

TABLE III—STATION SEPARATION (km) REQUIRED TO ACHIEVE THE STATED r.m.s. ERROR OF LINEAR INTERPOLATION ON DAILY TEMPERATURES AT MID POINTS BETWEEN STATIONS IN 'TYPICAL' NETWORK IN UNIFORM TERRAIN

	r.m.s. error of linear interpolation (K)					
	0·5	0·6	0·7	0·8	0·9	1·0
Winter maxima	*	50	120	190	280	370
Winter minima	*	*	*	*	40	85
Winter means	15	85	175	275	390	515
Summer maxima	10	30	55	80	115	150
Summer minima	*	*	*	*	20	70
Summer means	10	55	110	180	255	340

* Stated accuracy not attainable with 'typical' network.

ANALYSIS OF SUNSHINE DURATIONS

There were certain problems associated with the analysis of daily sunshine durations in the manner described above for temperatures. The frequency distribution of daily sunshine durations is markedly non-normal, being bounded both below (by zero) and above (by the maximum possible value for the latitude and time of year), and possessing a large contribution from zero values (i.e. sunless days). The procedure adopted to select a suitable sample of days for analysis was as follows. Firstly, only every third day was considered, to ensure synoptic and statistical independence of the sample (although the autocorrelation coefficient of sunshine durations is only about 0·20 for a lag of one day); secondly, each value was expressed as a percentage of the maximum possible duration for the time of year, in order to allow grouping of values from different months; and, thirdly, all values of less than 5 per cent were neglected, to avoid undue weighting of the *R* and *S* calculations by the influence of sunless days. It was considered desirable to perform separate analyses for winter and summer days, and 4-month periods (November–February and May–August) were chosen to provide adequate sample sizes after the above filtering process had been carried out.

As for temperatures, *R* and *S* calculations were performed for all possible station pairs and those values (about 120) derived from more than 50 pairs were plotted versus distance; Figure 4(a) and (b) are the plots for summer data. There is again a well-defined upper (lower) linear bound to the *R*(*S*) plot approximately defining the behaviour of a 'best possible' network, but this linearity cannot be extended below a station separation of about 25 km, since unacceptable intercepts at zero distance would result (i.e. *R* greater than unity, *S* less than zero).

Since the reported daily sunshine duration is the result of a hand-and-eye analysis of the burn on the sunshine card, and there is less immediately 'local' climate influence on sunshine than on temperature (due to soil, ground cover and topography), it might be expected that the station pairs displaying maximum correlation for a given separation are those which attain the highest standards of analysis accuracy. In fact, individual stations do not contribute to the definition of the upper limit to the *R*-function more often than would be expected by chance, and Meteorological Office stations do not, in general, display higher correlations than co-operating stations of the same separation.

The *R* and *S* functions for the 'typical' network have been deduced by linear regression of the plotted values on distance, with resulting correlations of 0·90 and 0·95 for winter and summer, respectively. As for temperatures, the r.m.s. errors of linear and optimum interpolation were compared by inserting the *S*- and *R*-functions into the appropriate Gandin formulae, and Table IV shows that the use of optimum interpolation again gives relatively small improvement in r.m.s. errors over linear interpolation. (The errors have been reconverted from percentage of maximum possible duration to hours by assumption of 9 and 16 hours as typical winter and summer maximum durations respectively.)

TABLE IV—COMPARISON OF r.m.s. ERRORS OF INTERPOLATION (hours) OF DAILY SUNSHINE DURATIONS AT MID POINTS BETWEEN (a) TWO STATIONS 100 km APART, AND (b) THREE STATIONS ON A TRIANGULAR GRID OF SPACING 100 km—DERIVED FROM 'TYPICAL' NETWORK OVER UNIFORM TERRAIN AND GANDIN'S FORMULAE

		Summer	Winter
Linear interpolation	(a)	1·49	1·11
	(b)	1·46	1·09
Optimum interpolation	(a)	1·48	0·99
	(b)	1·44	0·95

The variation with station separation of r.m.s. error of linear interpolation is shown in Figure 5 for the 'typical' network and indicated schematically for the 'best possible' network, since the uncertainty over the behaviour of the *S*-function below 25 km implies that r.m.s. errors for stations less than 50 km apart cannot be calculated with confidence. Except at small station separations, interpolation errors for summer days are greater than for winter days, as might be expected in view of the importance of solar radiation in determining local cloud conditions via surface heating.

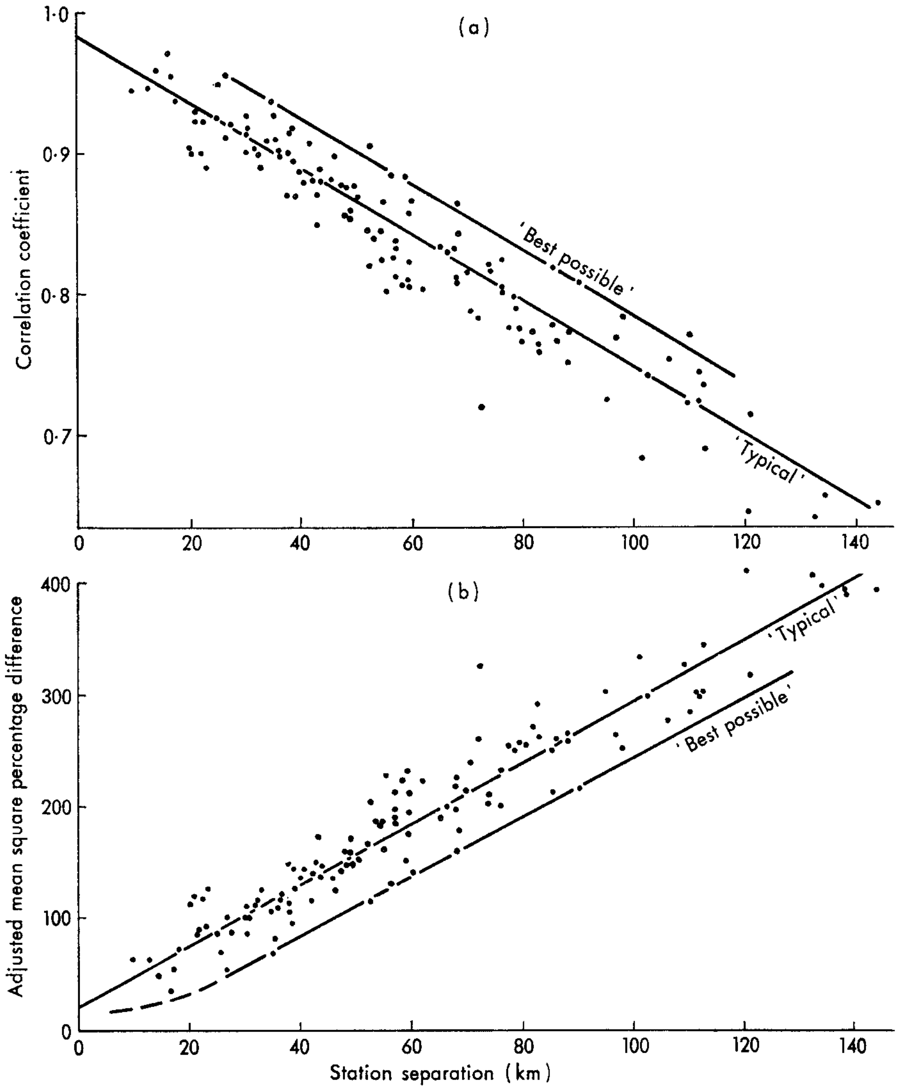

FIGURE 4—CORRELATION COEFFICIENTS (a) AND ADJUSTED MEAN-SQUARE DIFFERENCES (b) BETWEEN SUMMER DAILY SUNSHINE DURATIONS (EXPRESSED AS PERCENTAGE OF MAXIMUM POSSIBLE) AT PAIRS OF STATIONS IN EAST ANGLIA

Because of the difficulty of extrapolating the 'best possible' r.m.s. error curves, it is not possible to compare deduced interpolation errors at zero separation with observed r.m.s. differences between two instruments at the same site. However, it is interesting to note in this context that the quality control applied to sunshine card analyses at Meteorological Office Headquarters allows a r.m.s. difference of about 0·25 hour a day between analyses of the same card by different analysts. This criterion was selected many years ago on the basis of experience, and is clearly not inconsistent with what might be deduced from an extrapolation to

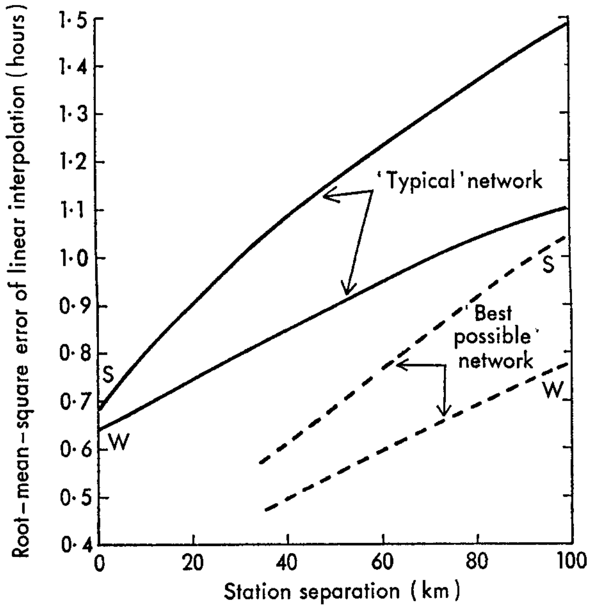

FIGURE 5—ROOT-MEAN-SQUARE ERRORS OF LINEAR INTERPOLATION (hours) OF DAILY SUNSHINE DURATION BETWEEN TWO STATIONS OF STATED SEPARATION IN UNIFORM TERRAIN

W—Winter (9-hour day) S—Summer (16-hour day)

zero distance of the 'best possible' curves in Figure 5. The 'typical' curves imply that stations in general, with the methods of analysis instruction currently in use, are not capable of attaining a r.m.s. difference between analyses of less than about 0·65 hour a day, although some part of this error may be attributable to faulty setting-up of the instrument.

LONGER TIME SCALES

For some application, notably the calculation of evaporation for hydrological and agricultural interests, spatially representative climatic data meaned over a time scale of perhaps a week or more are required. Knowing the r.m.s. errors of interpolation for daily data, it is possible to calculate the corresponding values for n-day means and thus to define the network density required to give acceptable levels of interpolation accuracy on this longer time scale. The standard error, σ_n, of the mean of n consecutive observations in a persistent series is (Brooks and Carruthers, 1953, p. 326):

$$\sigma_n = \frac{\sigma_1}{n^{\frac{1}{2}}}\left[1 + \frac{2r}{1-r}\left(1-\frac{1}{n}\cdot\frac{1-r^n}{1-r}\right)\right]^{\frac{1}{2}},$$

where σ_1 is the standard error of the individual observations and r is the autocorrelation coefficient for a lag of one day.

Autocorrelation coefficients for a lag of one day were computed for each month over a 19-year period at Wittering, and the typical values adopted for use are shown in Table V, along with the derived station separations necessary for given r.m.s. interpolation accuracies for 7-day mean values.

Using the simple approach to potential evaporation (PE) calculations described in MAFF *Technical Bulletin* No. 16 (1967), it is possible to show that an error of 0·4 hour a day in mean sunshine duration over 7 days corresponds approximately to an error of 1 mm (or 5 per cent of a summer average value) in 7-day PE in East Anglia. It can also be shown that an error of 0·5 K in 7-day mean temperature gives rise to a PE error of about 1 mm. These figures, taken in conjunction with Table V, imply that if temperature and sunshine data are available from the same network of stations, then the error in a PE estimate at a point between stations is very much more dependent on the sunshine interpolation error than on the temperature interpolation error. To equalize the contributions to the PE error, the sunshine-measuring network would need to be much denser than the temperature-measuring network.

TABLE V—STATION SEPARATIONS (km) REQUIRED TO ACHIEVE THE STATED r.m.s. ERROR OF LINEAR INTERPOLATION ON 7-DAY MEAN VALUES AT MID POINT BETWEEN STATIONS IN A 'TYPICAL' NETWORK IN UNIFORM TERRAIN

	Typical autocorrelation coefficient (lag = 1 day)	r.m.s. error of linear interpolation			
Temperatures (K)		0·4	0·5	0·6	0·7
Winter maxima	0·65	45	140	260	400
Winter minima	0·60	*	*	50	125
Winter means	0·70	55	170	300	470
Summer maxima	0·50	50	95	160	230
Summer minima	0·35	*	50	160	290
Summer means	0·55	80	180	310	460
Sunshine durations (hours)		0·4	0·5	0·6	0·7
Winter	0·15	55	110	180	265
Summer	0·25	10	35	65	100

* Stated accuracy not attainable.

CONCLUDING REMARKS

The results presented here allow the network planner to assess, in terms of interpolation accuracy, the consequences of increasing or decreasing the density of a temperature- or sunshine-measuring network. The findings obviously apply only to uniform terrain, and the behaviour of the *R*- and *S*-functions in complex topography remains to be investigated. However, these results allow a lower limit to be fixed to the number of stations required to achieve a given accuracy of interpolation at any point within an area.

ACKNOWLEDGEMENT

The programming work for this investigation was undertaken by Mr W. H. Mills.

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REVIEWS

The climate of the British Isles, edited by T. J. Chandler and S. Gregory. 230 mm × 160 mm, pp. vi + 390, *illus.* Longman Group Ltd, Fourth Avenue, Harlow, Essex CM19 5AA, 1976. Price: £5.95.

This book consists of essentially self-contained chapters by 15 authors. This leads to some repetition where the subjects overlap and to a little unevenness of presentation. It is undoubtedly destined to be the most comprehensive single collection of data for a long time to come. It does not, however, make exciting reading; in particular, the relentless description of data, much of which is also presented in tables or diagrams or both, is at times overwhelming.

There are seven chapters on the principal weather elements. They are in the main very thorough and systematic, giving statistics on annual, seasonal and monthly means, fluctuations, extremes and diurnal variations by means of tables and charts for a dense network of stations.

Only here and there did I react sufficiently to something, or to its absence, to comment here. For example, in 'Wind', I was disappointed not to find some account of severe local winds such as the famous Sheffield and Glasgow gales, or of whirlwinds and tornadoes; but this is not a weather book. 'Radiation', 'Temperature' and 'Evaporation, Humidity and the Water Balance' are all efficiently dealt with; the short section on human comfort indices whets the appetite for more. 'Visibility' is concerned almost entirely with fog, rather than the industrial and continental aerosol hazes so common in dry conditions. There is a note on the dramatic improvement in London visibilities since the Clean Air Act of 1956, but also a surprising (possibly unintentional) implication of a 10–11 year cycle in pollution. 'Cloud and Thunder', an odd combination, contains none of the drama of those elements—such things are admittedly awkward to quantify. I feel that much more could and should have been made of this opportunity; surely statistics exist on the occurrence of different cloud types and on the distribution and frequency of lightning discharges? 'Precipitation' is the longest of the chapters, giving amongst much else the elusive answers to such common questions as what are the frequencies of extreme falls, wet spells and droughts. The principal synoptic situations giving rise to frontal, convective and orographic rain are described, though, probably because the data do not exist, there are no figures for the relative contributions from each. Snowfall receives mention in proportion to its occurrence, though in view of its impact on the community I feel that it deserves considerably more. There is no mention of hail.

Four chapters are devoted to regions which might be termed special in some way. Coasts with their sea-breezes and sea fog (e.g. haar), and inland waters, which are mainly too small to have any significant moderating effect, are well treated. Upland climates are considered mainly from the point of view of the restriction of the growing season. 'Topographic Climates' would have benefited from some revision to eliminate a few obscurities and what look like repetitions. Amongst the numerical data here, there is an irritating mixture of units and a mistake or two. 'The Climate of Towns' is an excellent review of urban climates, covering all important environmental elements. 'Regional Climates' seems to add little to earlier material.

'Synoptic Climatology' in a way sets the scene for the whole of the book, describing the large-scale circulation and common weather types over the British Isles. Singularities, persistence of types and seasonal lag relationships are noted, as is the inevitable subject of cycles, solar or otherwise. The possible roles of anomalies of sea temperature and ice cover are mentioned. In this chapter, and even more so in that on 'Recent Climatic Change', the authors are grappling with rapidly evolving subjects, so it is not surprising that much can be found to debate. The bewildering picture of fluctuations of circulation indices and of all the main weather parameters on various time scales leaves the impression that a lot is still to be done in sorting out the signal from the noise; even so, I feel that these two chapters provide a reasonable introduction.

Only half a dozen misprints were noted; among the dozen or so obvious mistakes and omissions, the conspicuous errors in the conversion factors on page 75 are all corrected if Wm^{-2} is read as $W\,h\,m^{-2}$; on page 76, and subsequently, 'intensity' is wrongly used (should be 'irradiance'); on page 320, the quoted lead content for the London atmosphere must be too high by several orders of magnitude; and in Figure 10.6, the late Ocean Weather Station 'I' is shown in the wrong place.

I found the large, closely spaced, spidery type of the main text rather unpleasing and tiring on the eye, whilst parts of the index and references are in an offendingly bold type. The diagrams, on which the book relies so heavily, though adequate, could have been much better. Some are unnecessarily big and rather more are too small (indeed, a hand lens is a great help for seeing some detail). Most of the contoured diagrams would have been strikingly clarified by shading, and strategically placed labels could have saved much searching amongst the small print of the legends.

There is a very full index and reference list, and the book can be recommended as excellent value for the moderate price.

K. J. BIGNELL

Radiative processes in meteorology and climatology, Developments in Atmospheric Science, 5, by G. W. Paltridge and C. M. R. Platt. 245 mm × 170 mm, pp. xvii + 314, *illus.* Elsevier Scientific Publishing Co, PO Box 330, Amsterdam, The Netherlands, 1976. Price: Dfl 103.00.

Radiative processes play an important role in the meteorology and climatology of the terrestrial environment. The source of energy which drives the weather systems is the radiation received from the sun, while the sink to the system is the long-wave energy to space, regulated by variations in atmospheric opacity due to compositional changes, clouds, aerosols and surface conditions. The importance of radiative effects in climatic variations will require all students of the subject to possess an understanding of the physical processes involved. But radiative transfer is poorly discussed for applied atmospheric physicists in the available texts. Books on general meteorology cover the subject in a single chapter, while the treatises by Chandrasekhar and by Goody, although comprehensive, are thought to be too theoretical. Paltridge and Platt have attempted to provide a text at the level required by experimental atmospheric physicists which has a balance between basic physical processes and their mathematical representations. I believe this book has been quite successful in reaching this objective, but fails in omitting to provide detailed critical discussions which are an invaluable aid to readers when choosing between various theoretical methods and parametrizations.

The subject matter of the book is covered in 10 chapters, supplemented by some useful appendices. The initial three chapters provide a suitable introduction to the subject, covering the basic properties and terminology. Like many books I have read so far, this text seems to treat experimental data as if they possessed accuracy. For example, in discussing the characteristics of the models used to study the radiation budget of the earth, no comment is made on the possible uncertainties in the cloud data which form an essential ingredient of thedy stu

Chapter 4 introduces the reader to the mathematical description of radiative transfer for single scattering of radiation by cloud/aerosol particles and then the development of multiple scattering methods. It is surprising that the authors have omitted to discuss the scattering of radiation by irregularly shaped particles, particularly cylindrically shaped objects which are important in ice clouds. The discussion of the numerical methods is brief and disappointingly sketchy, and the authors have missed an excellent opportunity here to use some physical insight when discussing those techniques which would be valuable when constructing simpler parametrizations later in the book.

The next set of chapters takes us through the effects of solar radiation in the atmosphere (Chapter 5), Radiation at the Ground (Chapter 6), Long Wave Radiation in the Clear Atmosphere (Chapter 7), Clouds and Long Wave Transfer (Chapter 8), and Atmospheric Aerosols (Chapter 9). The discussions of the topics are reasonably comprehensive, but the examples used to illustrate the discussions are almost all taken from theoretical predictions. The reader would have no idea of the accuracy of the methods or their ability to reproduce measurements. How can anyone draw conclusions on the suitability of theoretical methods in the absence of experimental data?

The final chapter on Radiation and General Dynamics adequately covers the problems of radiative equilibrium, radiative convective equilibrium, radiation within the boundary layer, and the interaction between radiation and the formation of clouds. But why did the authors omit any detailed discussion of the role of radiation in the general circulation of the atmosphere? The title of their book implies its presence.

After reading the book and studying certain aspects of it in detail, I looked again at the authors' purpose in writing the text. They suggested that the book would be aimed at experimental atmospheric physicists in order to provide them with an understanding of radiative processes. Certainly they have had some measure of success in providing a reasonably good description of the theoretical methods. But the omission of experimental data with which to verify the methods or aid the discussion is very odd. Furthermore, as I have previously pointed out, the absence of certain topics seems to suggest that the book may be misnamed. In spite of these misgiving, it is a timely and useful book which the specialist will find to be a useful addition to his bookshelf.

G. E. HUNT

The climate of Japan, Developments in Atmospheric Science, 8, edited by E. Fukui. 250 mm × 170 mm, pp. ix + 317, *illus.* Elsevier Scientific Publishing Co, PO Box 330, Amsterdam, The Netherlands, 1977. Price: $52.95, Dfl 130.00.

This is an unusual subject to appear in a series on 'Developments in Atmospheric Science', but nevertheless the book is a useful addition to the very limited literature in English on the climate of Japan. It consists of 13 chapters by eight authors which cover the synoptic and physical climatology of Japan, its climatography, and aspects of climatic change and local climate.

Inevitably in a book of this nature there are variations of style and approach by the different authors, so that the two introductory chapters have a strong environmental bias stressing the diversity of Japan's climate and the effect of the seasons on the life of the people. This is not followed by an examination of individual climatic elements as might be expected from the title, but, instead, by the synoptic seasons of Japan—the winter monsoon, the Bai-u rains, the midsummer dry spell, and the typhoons and Shûrin—are examined in considerable detail.

Climatic elements are discussed in the chapters on the heat balance, the water balance and flow patterns, though these titles are misleading as the amount of space given to the heat-balance components is relatively small compared to that on temperature, precipitation, sunshine and the radiation balance. There is a brief chapter on air pollution and urban climate, followed by a long section on the climatography of Japan and its climatic divisions, with a concluding chapter on climatic fluctuations which covers the period from the Quaternary to recent changes.

With such a large amount of information, the book undoubtedly achieves its objective of providing an English language monograph on the climate of Japan. It is much more extensive than the section in 'World Survey of Climatology', Volume 8 (*Climates of Northern and Eastern Asia*), by the same publishers, and it does have an up-to-date approach to the subject. Also in its favour, the book is nicely produced and printed, with the diagrams being generally clear although some suffer through excessive reduction (Japan is not a convenient shape for book diagrams), and a few have deficient or incorrect keys. The style of English is very good, although the reviewer had some initial problems over the term 'decade' referring to a 10-day period rather than its more usual meaning. The amount of duplication between chapters is small, apart from unavoidable overlap on the circulation.

One serious omission is an adequate locational map for places mentioned in the text. Many climatological stations are in towns which are too small for a standard atlas but, despite a geographic index, no reference is made to their precise location. Surprisingly, no comment is made about satellite observations despite the claim that this is an up-to-date monograph. It is certain that greater insight into the circulation features of the area around Japan has been gained through the improved spatial coverage provided by these instruments. Less surprising is the lack of reference to publications in English about Japan; for example, *The water balance of monsoon Asia*, by M. M. Yoshino, does not receive any reference in the chapter on the water balance.

However, these are small criticisms and, in general, the book is likely to remain a useful work of reference about the climate of Japan for many years to come.

P. A. SMITHSON

AWARD

We note with pleasure that the twenty-second International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded this year to Dr George P. Cressman, Director of the National Weather Service of the National Oceanic and Atmospheric Administration (NOAA) of the United States of America.

NOTES AND NEWS

Secondment of Dr G. E. Hunt

Dr G. E. Hunt, of the High Atmosphere Branch, has been seconded from the Meteorological Office to take charge of the new Laboratory for Planetary Atmospheres in the Department of Physics and Astronomy, University College, London.

ANNOUNCEMENT

Readers of Meteorological Office Scientific Paper No. 36—*A computer-based model for design rainfall in the United Kingdom*, by J. F. Keers and P. Wescott (Met O 900)—should know that there is a mistake in the printing of equation i of Table I on page 3. The following is the correct version:

$$\log M_{5,\,\mathrm{D})} = \log D + \log (A_{48}/48) + \\ + \log (721/1 + 15D) \log (48A_1/A_{48})/\log(721/16).$$

The error occurred solely in the presentation of the equation and does not affect the calculations.

OBITUARY

We regret to record the death on 3 May 1977 of Miss J. M. Noad, Higher Scientific Officer, London/Gatwick Airport. Miss Noad was well known for her athletic achievements in the field of tricycling and was awarded the George Simpson Cup by the Meteorological Office Social and Sports Club in 1971. Before working as a forecaster she had spent some years in the Research Directorate at Bracknell.

THE METEOROLOGICAL MAGAZINE

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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

By B. G. WALES-SMITH

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.

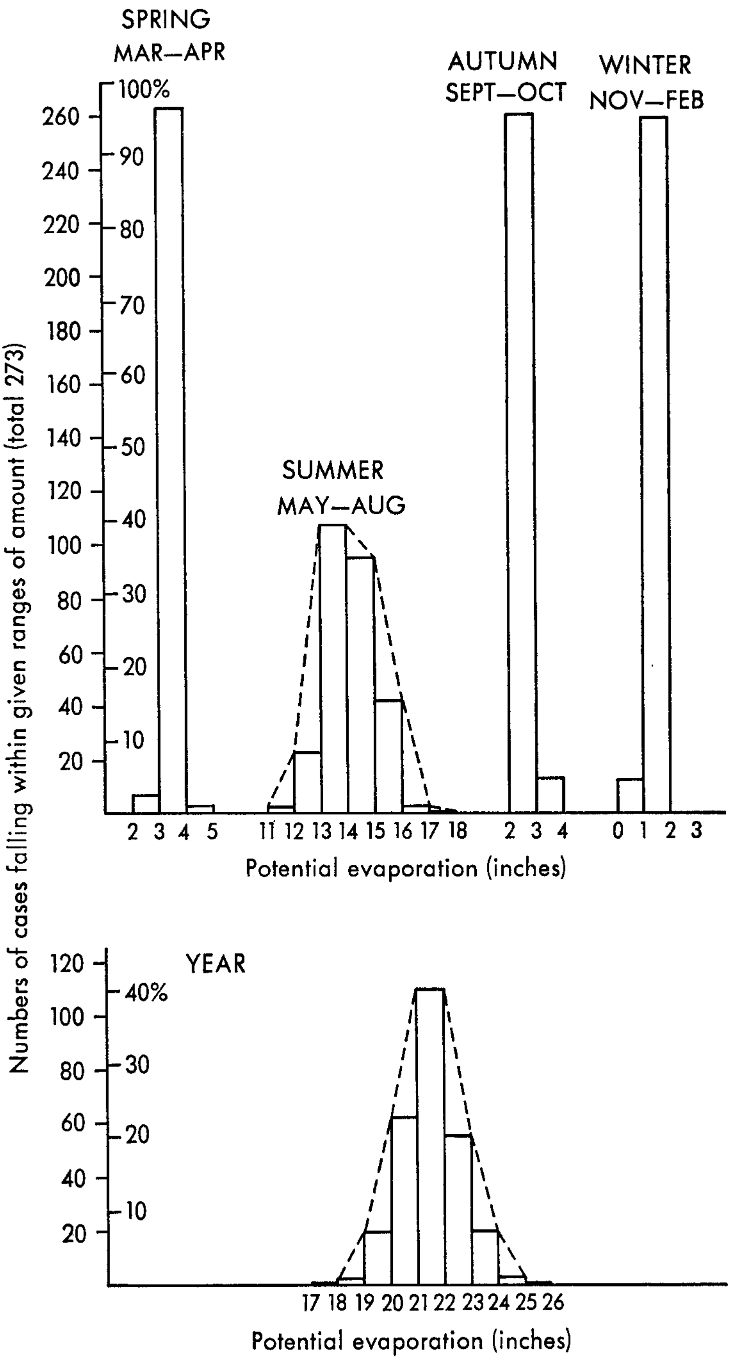

FIGURE 1—FREQUENCY DIAGRAMS OF SEASONAL AND ANNUAL TOTALS OF POTENTIAL EVAPORATION REPRESENTATIVE OF KEW, 1698–1970

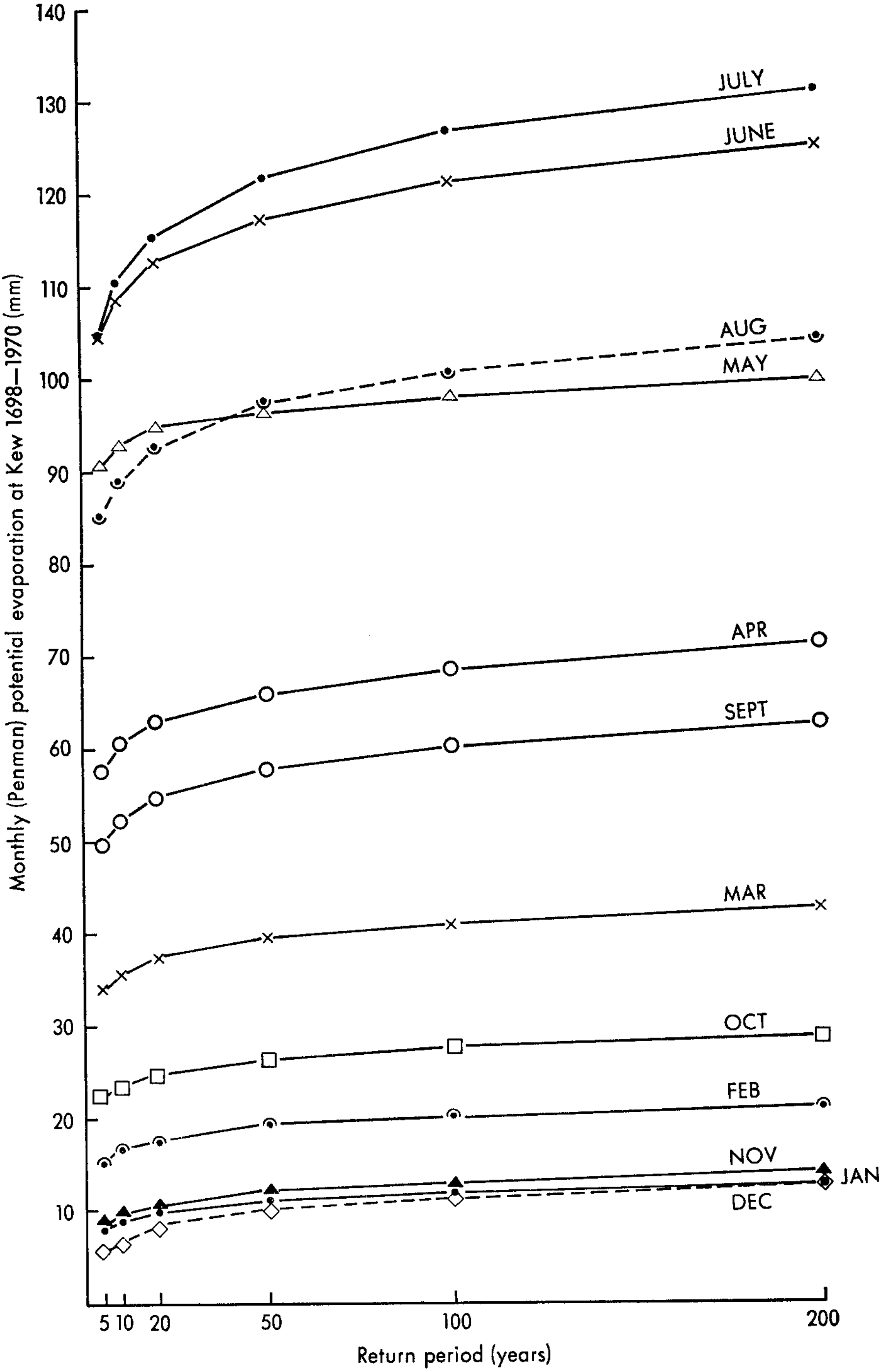

FIGURE 2(a)—HIGH POTENTIAL EVAPORATION—AMOUNTS LIKELY TO OCCUR OR BE EXCEEDED, IN GIVEN MONTHS, FOR RETURN PERIODS UP TO 200 YEARS, AT KEW

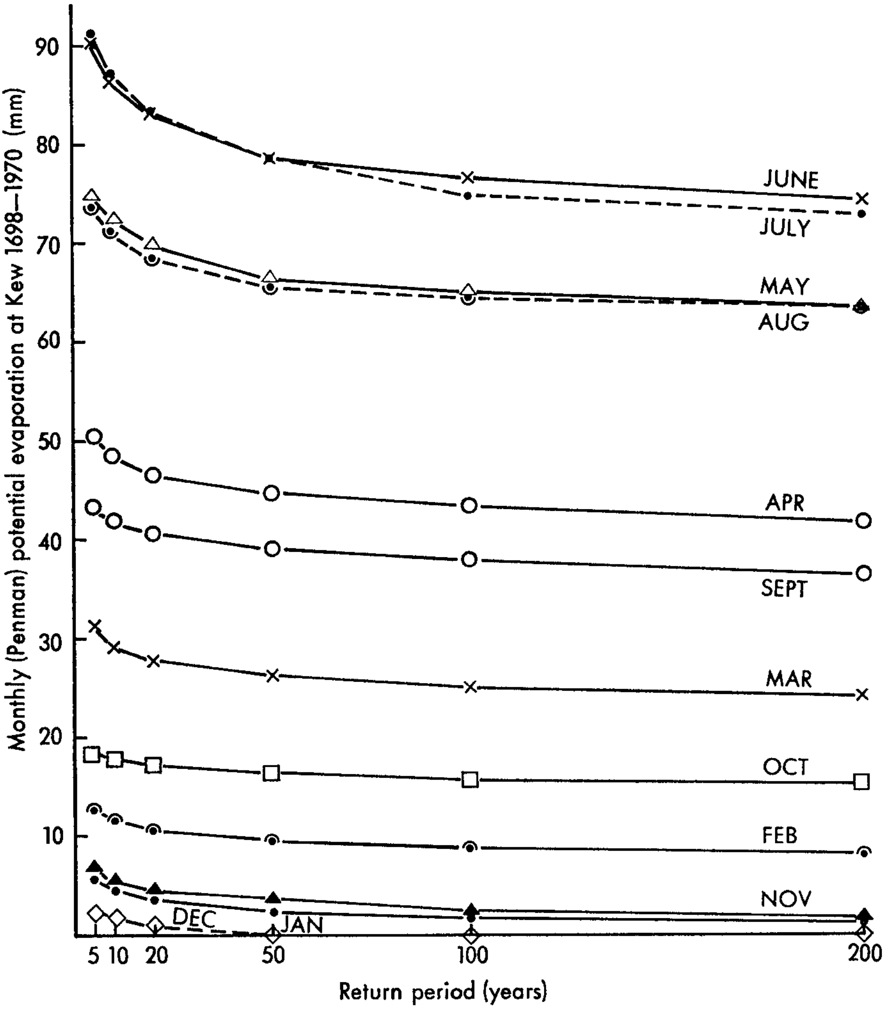

FIGURE 2(b)—LOW POTENTIAL EVAPORATION—AMOUNTS LIKELY NOT TO BE EXCEEDED, IN GIVEN MONTHS, FOR RETURN PERIODS UP TO 200 YEARS, AT KEW

(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

Duration	Probable extreme values High evaporation *mm*	Low evaporation *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).

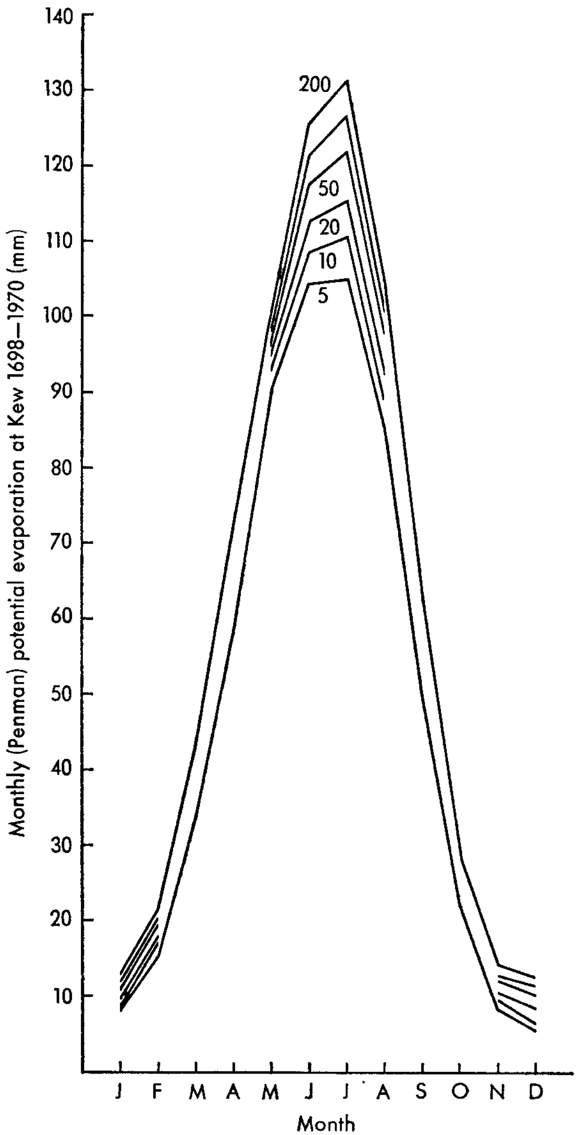

FIGURE 3(a)—HIGH POTENTIAL EVAPORATION—AMOUNTS LIKELY TO OCCUR OR BE EXCEEDED IN EACH MONTH OF THE YEAR FOR GIVEN RETURN PERIODS, AT KEW

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.

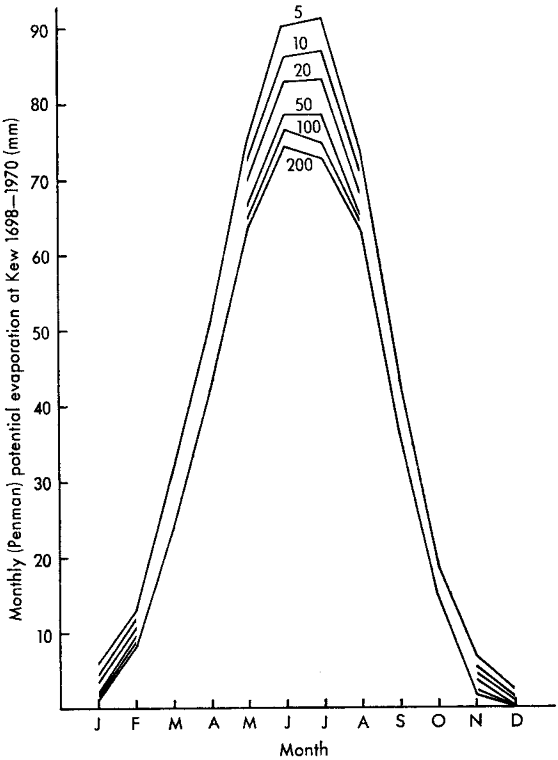

FIGURE 3(b)—LOW POTENTIAL EVAPORATION—AMOUNTS LIKELY NOT TO BE EXCEEDED IN EACH MONTH OF THE YEAR FOR GIVEN RETURN PERIODS, AT KEW

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	39·1	47·2	54·9	73·4	109·2	75·2	168·1	286·5	397·8	496·6	565·1
1959	*1970*	*1959*	*1959*	*1964*	*1966*	*1942*	*1909*	*1957*	*1959*	*1959*	*1959*
28·7	38·1	44·7	54·1	70·6	107·2	72·4	164·9	271·5	387·3	475·2	532·6
1970	*1961*	*1910*	*1884*	*1884*	*1964*	*1893*	*1893*	*(1762)*	*1957*	*1911*	*1911*
27·4	36·6	43·2	52·6	69·9	104·4	67·1	163·3	270·0	382·3	470·9	519·2
1910	*1911*	*1911*	*1964*	*1961*	*1959*	*1957*	*1942*	*1893*	*(1762)*	*1957*	*1957*
26·9	36·3	42·9	52·3	69·6	104·1	66·3	162·1	269·5	379·2	465·8	517·4
1967	*1959*	*1884*	*1911*	*1911*	*1965*	*1909*	*1943*	*1970*	*1921*	*1893*	*(1846)*
25·9	34·5	42·9	51·1	69·1	102·9	65·8	159·5	269·0	377·2	464·1	516·9
(1735)	*1910*	*1970*	*1910*	*1959*	*1884*	*1949*	*1957*	*1942*	*(1846)*	*(1846)*	*1893*
25·9	34·5	41·9	47·5	65·0	102·4	64·8	157·2	268·7	374·4	463·3	516·1
(1798)	*1946*	*1966*	*(1874)*	*1965*	*1911*	*1912*	*(1762)*	*(1846)*	*1911*	*1921*	*1899*
					Least potentially evaporative						
14·7	19·6	21·1	25·4	36·8	65·5	41·7	104·9	180·3	253·5	324·4	364·7
(1740)	*1948*	*1925*	*1925*	*1925*	*1951*	*1879*	*1879*	*1879*	*1879*	*1879*	*1879*
15·2	21·1	22·6	27·9	38·6	67·3	42·2	108·5	199·6	280·7	344·7	385·3
(1817)	*1925*	*1953*	*1879*	*1953*	*1952*	*1918*	*(1837)*	*(1816)*	*(1816)*	*(1816)*	*(1816)*
16·0	21·3	23·1	27·9	38·9	67·3	42·4	111·3	200·4	285·2	354·1	394·2
1895	*(1740)*	*1889*	*(1875)*	*1951*	*1953*	*(1837)*	*(1817)*	*1923*	*1888*	*1888*	*1888*
16·0	21·6	23·4	28·2	39·6	70·9	43·9	114·3	204·0	291·6	356·6	402·1
1889	*1949*	*(1873)*	*1951*	*1879*	*1950*	*(1701)*	*1932*	*(1740)*	*(1821)*	*(1817)*	*(1817)*
16·3	21·8	23·9	28·7	40·1	71·1	45·0	116·6	204·7	292·6	364·7	406·9
(1840)	*1953*	*1948*	*1952*	*1948*	*1918*	*(1713)*	*(1782)*	*(1837)*	*(1817)*	*(1812)*	*(1812)*
16·8	22·6	23·9	29·2	40·6	73·4	45·0	116·6	207·3	297·2	365·5	412·7
1888	*1918**	*(1740)*	*1953*	*1952*	*1948*	*(1702)*	*(1698)*	*(1821)*	*1932†*	*1954*	*(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	379·2	—	—
								1970	*1921*		
—	—	—	—	—	—	—	—	269·0	374·4	—	516·9
								1942	*1911*		*1893*
25·7	—	—	—	—	—	—	—	266·9	371·3	463·3	516·1
1961								*1959*	*1970*	*1921*	*1899*
24·4	—	—	47·0	—	—	—	155·2	264·2	371·1	461·0	515·6
*1903**			*1902*				*1882*	*1960*	*1893*	*1899*	*1921*
					Least potentially evaporative						
16·0	—	—	—	—	—	—	—	—	—	—	—
1895											
16·0	—	—	—	—	—	—	114·3	200·4	285·2	354·1	394·2
1889							*1932*	*1923*	*1888*	*1888*	*1888*
16·8	21·6	—	28·2	—	—	45·7	119·1	208·8	297·2	365·5	413·8
1888	*1949*		*1951*			*1889*	*1877*	*1926*	*1932*	*1954*	*1954*
17·0	21·8	23·9	28·7	—	—	45·7	119·6	211·1	297·9	371·3	415·5
1919	*1953*	*1948*	*1952*			*1884*	*1930*	*1898*	*1916*	*1889*	*1889*
17·0	22·6	25·4	29·2	—	—	46·5	120·7	212·3	298·5	375·4	416·7
1953	*1918*	*1904*	*1953*			*1919*	*1926*	*1932*	*1889*	*1890*	*1916*
17·3	22·6	25·9	29·7	—	—	46·5	123·4	212·9	299·7	375·7	418·3
1951†	*1892*	*1879*	*1904‡*			*1926*	*1941*	*1878§*	*1954*	*1920*	*1931*

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

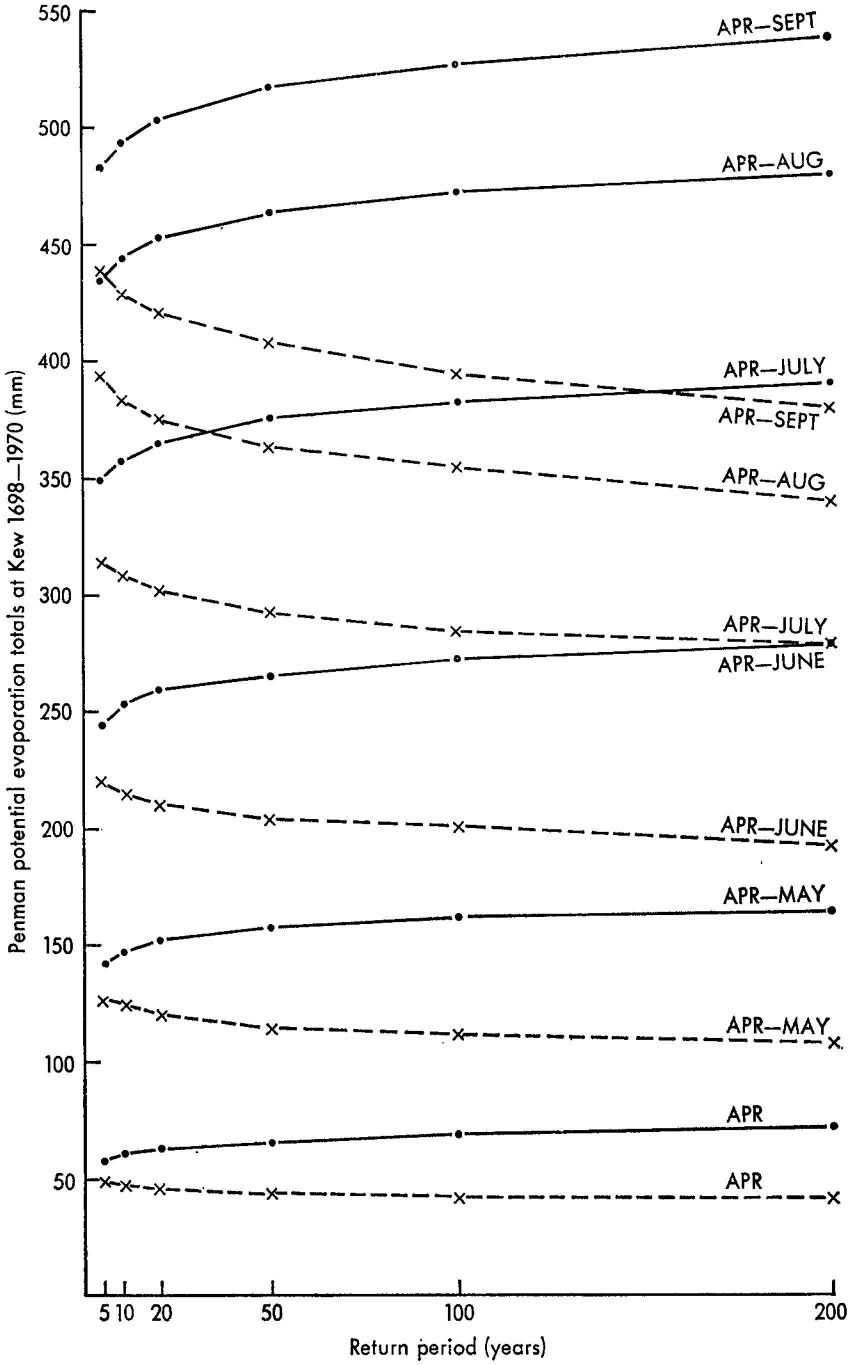

FIGURE 4—AMOUNTS OF POTENTIAL EVAPORATION AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS
• —— • likely to occur or be exceeded × – – × likely not to be exceeded

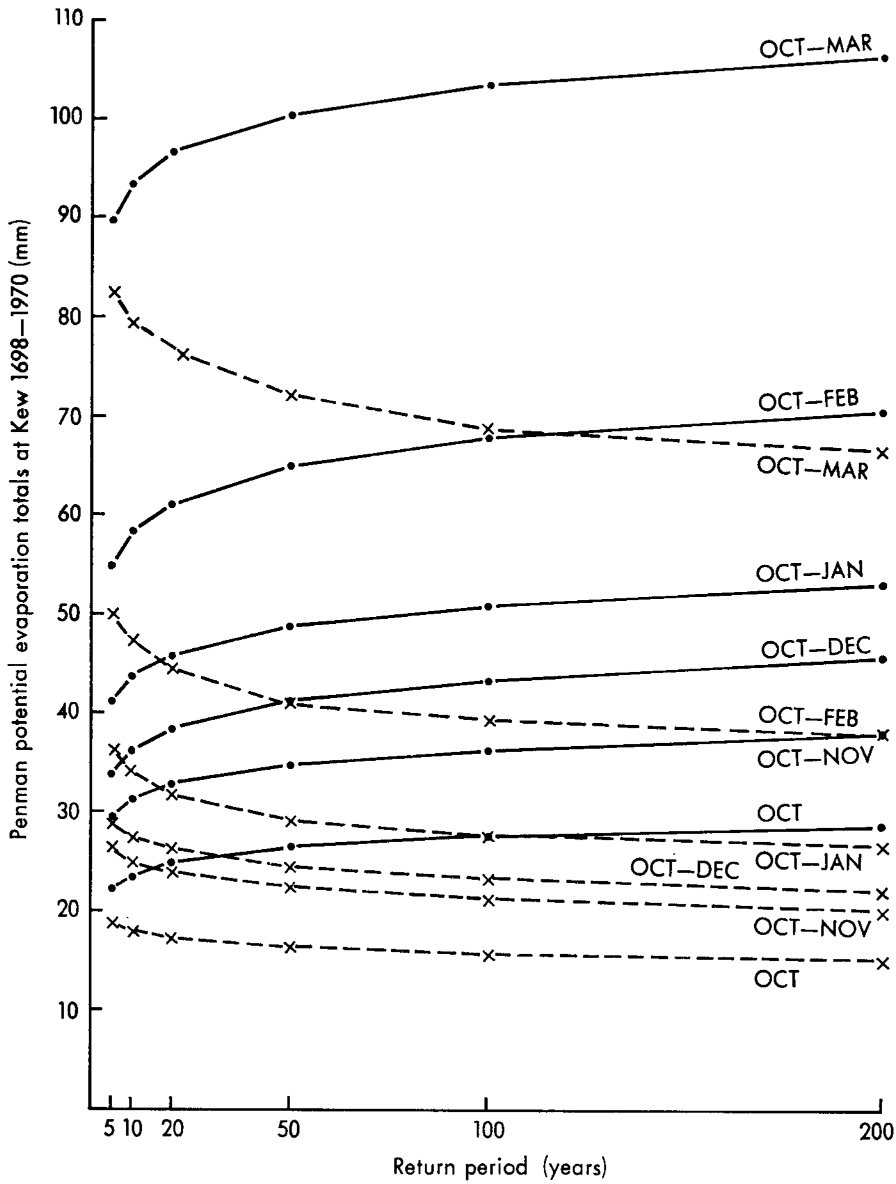

FIGURE 5—AMOUNTS OF POTENTIAL EVAPORATION AT KEW IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

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

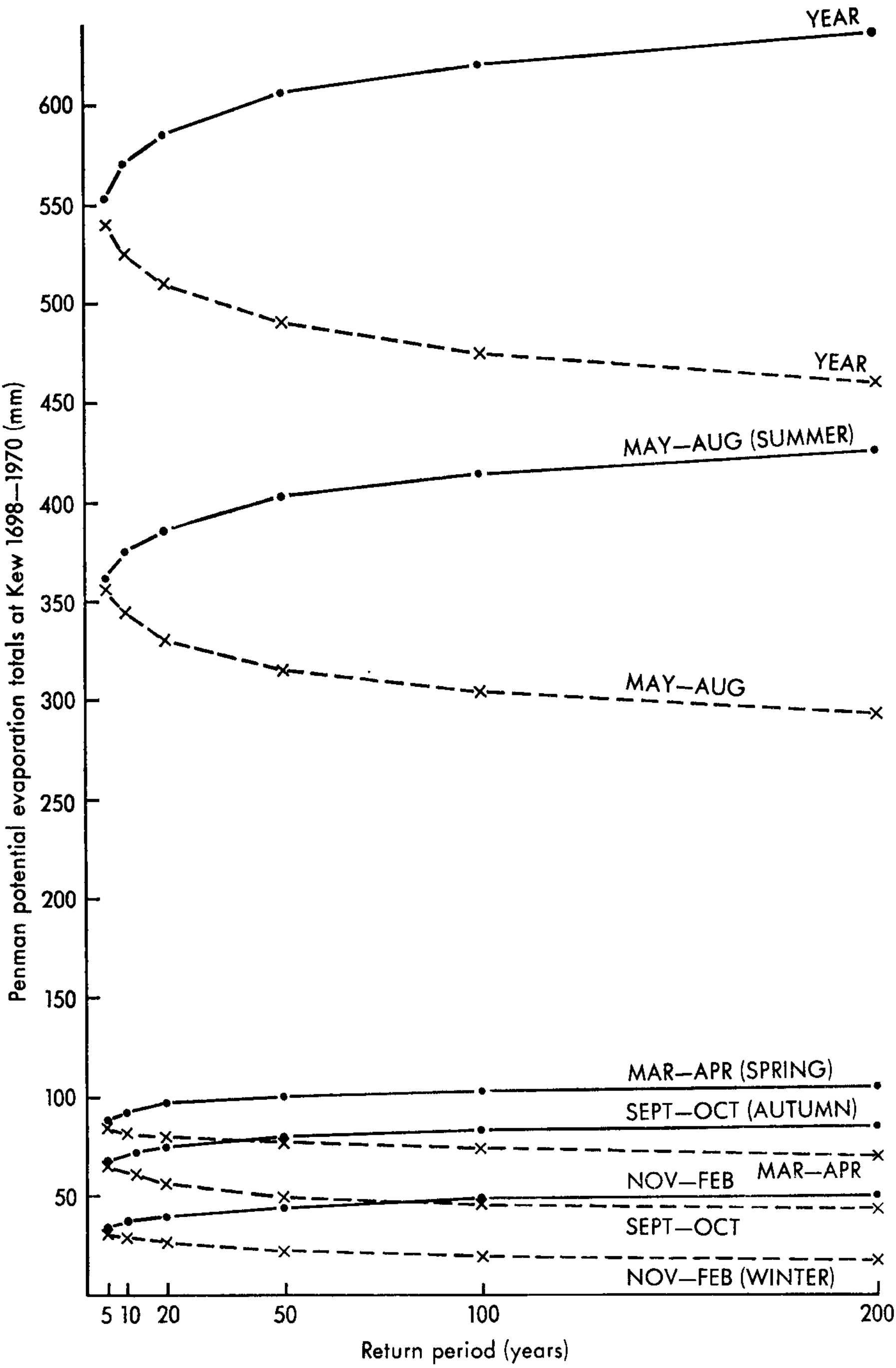

FIGURE 6—AMOUNTS OF POTENTIAL EVAPORATION AT KEW IN A YEAR AND IN GIVEN SETS OF CONSECUTIVE MONTHS FOR RETURN PERIODS UP TO 200 YEARS

• —— • 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

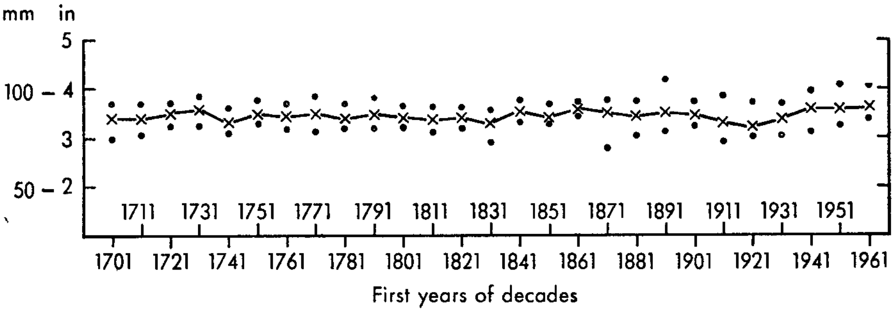

FIGURE 7—SPRING POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages : decadal extremes

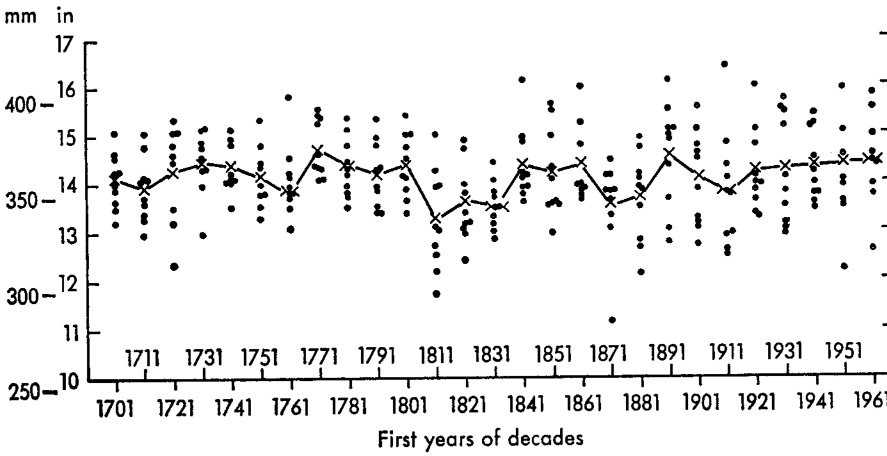

FIGURE 8—SUMMER POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages · summer totals

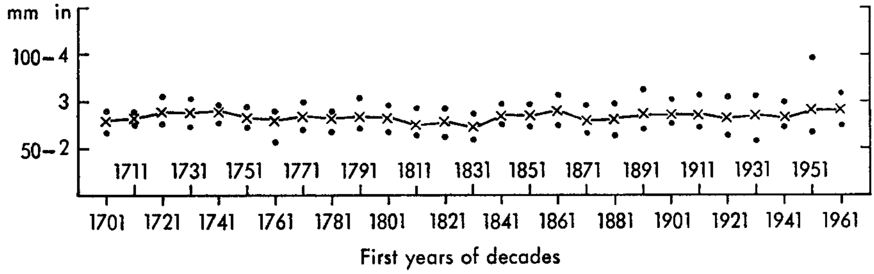

FIGURE 9—AUTUMN POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages : decadal extremes

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

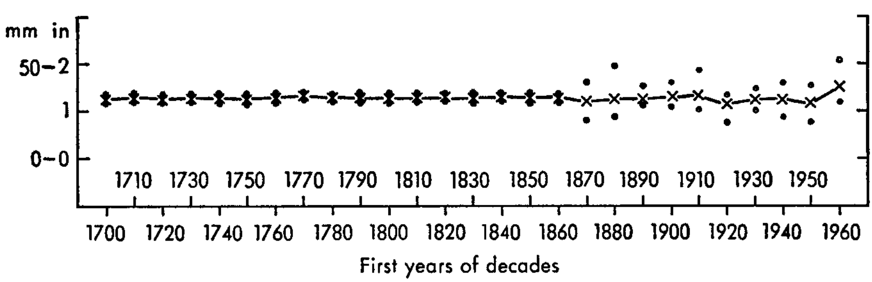

FIGURE 10—WINTER POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages : decadal extremes

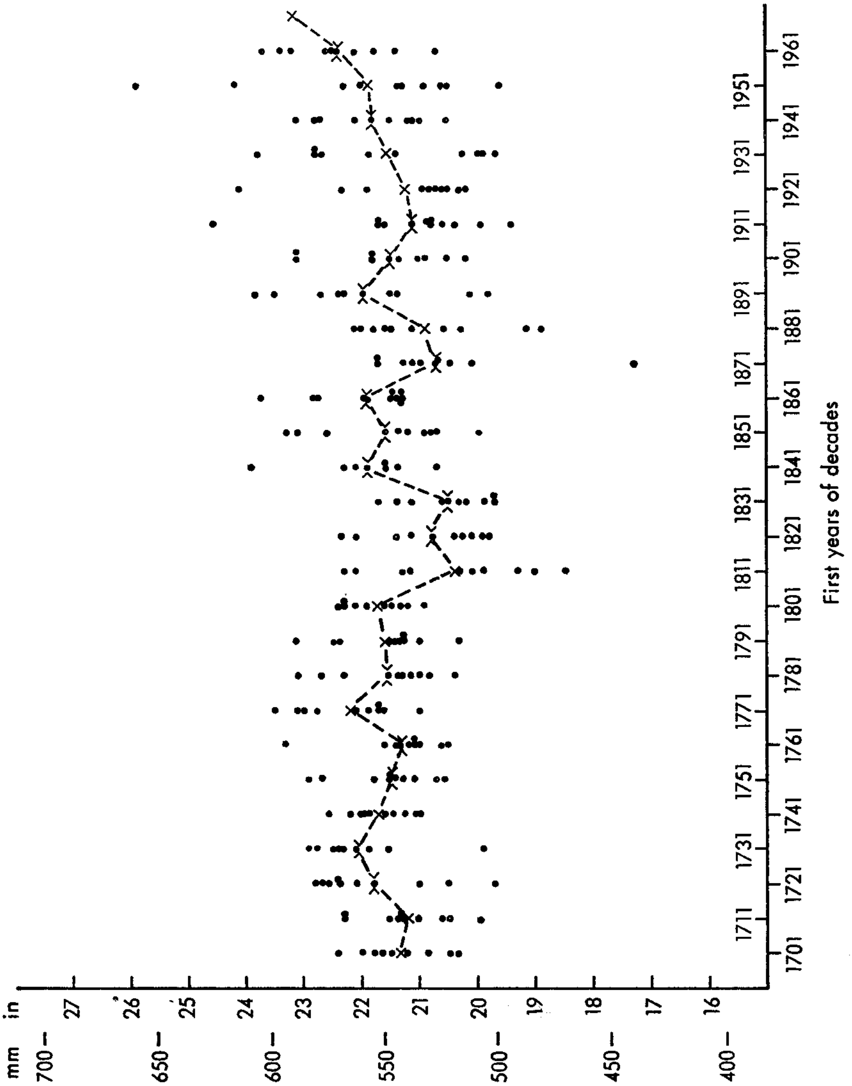

FIGURE 11—ANNUAL POTENTIAL EVAPORATION REPRESENTATIVE OF KEW
× —— × decadal averages · annual totals

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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551.583.14:551.588

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.

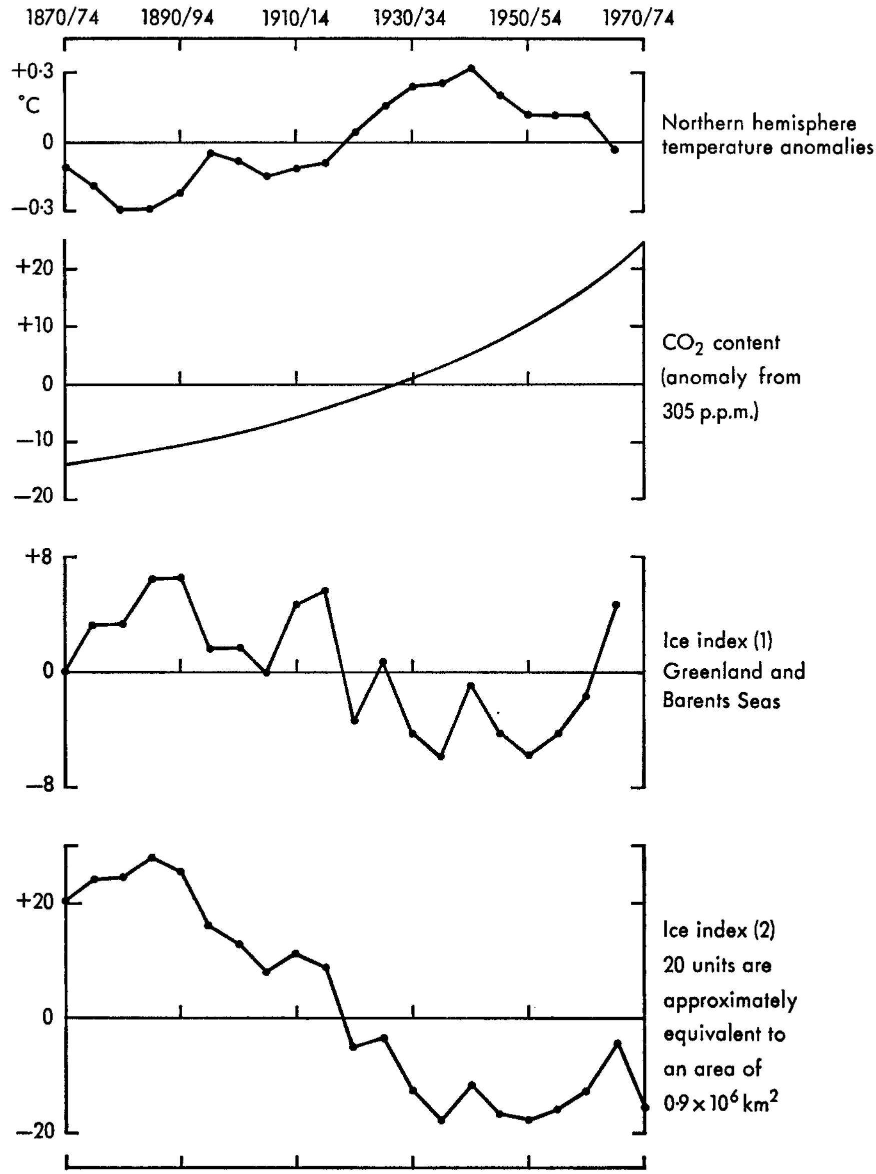

FIGURE 1(a)—FIVE YEAR MEANS OF QUANTITIES USED IN THE STUDY
Units are more fully explained in Table I.

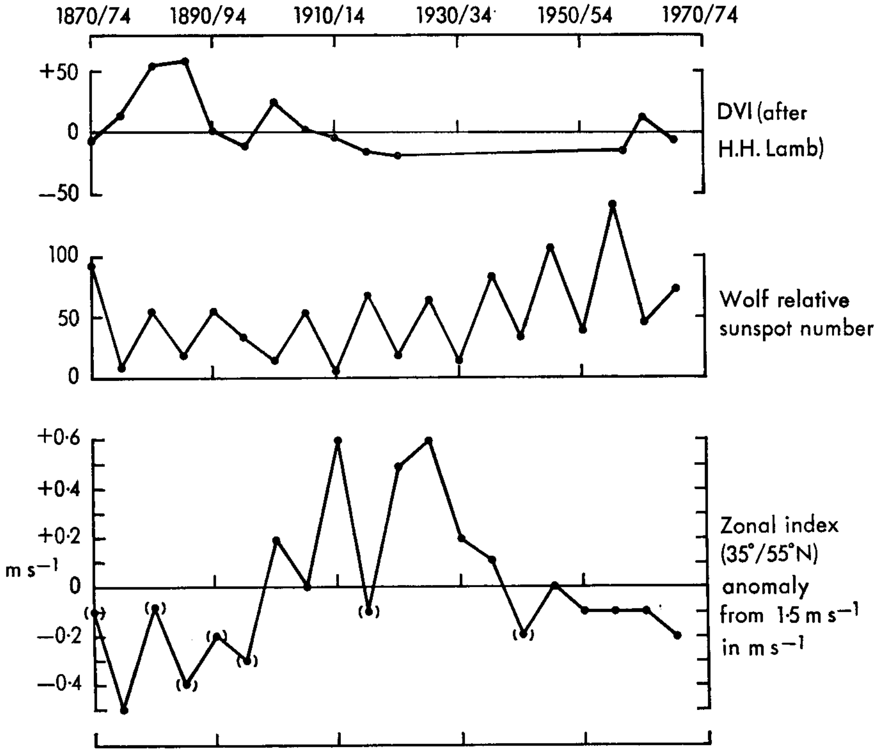

FIGURE 1(b)—FIVE YEAR MEANS OF QUANTITIES USED IN THE STUDY
Units are more fully explained in Table I.

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 $1{\cdot}5\ m\ s^{-1}$.
Ice index: (1) arbitrary units—anomalies from 100 year average. In (2) 10 units $\approx 0{\cdot}45 \times 10^6\ km^2$.

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 $0{\cdot}2 \times 10^6\ km^2$ for the Barents Sea and $0{\cdot}25 \times 10^6\ km^2$ 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 $0{\cdot}45 \times 10^6\ km^2$ 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. $2 \times 10^6\ km^2$ 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 $-0{\cdot}0006$ 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. $- 0{\cdot}168$ Ice index (1) $+ 0{\cdot}0564$
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 $+ 0{\cdot}0142$ (Wolf No. coefficient is $- 0{\cdot}0004$ but not significant)
6 $T = 0{\cdot}0049\ CO_2\ (2) - 0{\cdot}0005$ DVI $- 0{\cdot}0120$ Ice index (2) $+ 0{\cdot}0361$

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.

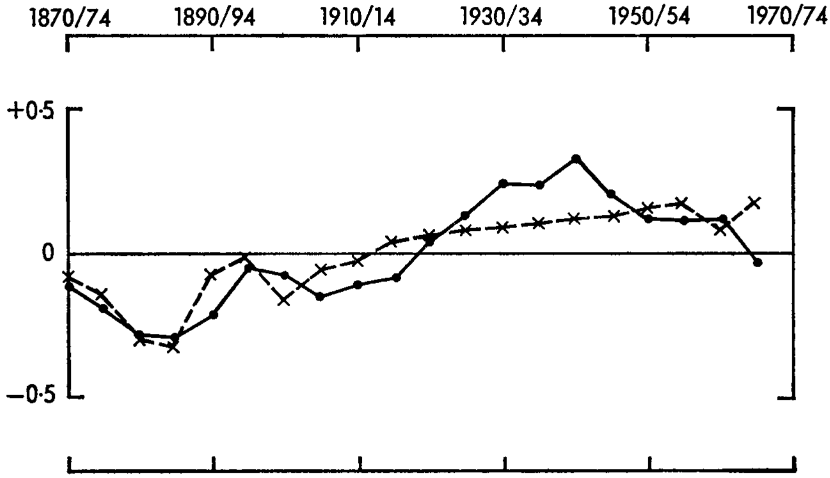

FIGURE 2—ACTUAL TEMPERATURE ANOMALIES AND VALUES PREDICTED FROM MULTIPLE REGRESSION EQUATIONS WITH ICE INDEX EXCLUDED

• —— • 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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THE EXCEPTIONAL HEAT-WAVE OF 23 JUNE TO 8 JULY 1976

By M. S. SHAW

SUMMARY

The heat-wave of 23 June to 8 July 1976 was associated with a stable high-pressure system over England and Wales, both at the surface and at high levels. Minor day-to-day changes in the velocity of the surface wind determined the location of the hottest areas. Temperature returns from about 630 official and co-operating stations in the United Kingdom were examined and they showed that, on a criterion of number of days with temperature equal to or greater than 32°C (90°F), the 1976 heat-wave far exceeded all others. Although the highest individual temperature of 35·9°C at Cheltenham on 3 July was lower than the most probable United Kingdom record, individual records were broken at more than 30 stations and temperatures having return-periods of more than 50 years were recorded over most of southern England and also over parts of the Scottish Borders and the Highlands. More than twice the average amount of sunshine was recorded over most of England and Wales. Humidities were generally low, and occasionally exceptionally so.

INTRODUCTION

One of the outstanding features of the weather over the British Isles during the remarkable summer of 1976 was a prolonged heat-wave which lasted for more than two weeks over parts of central and southern England during late June and early July. It now seems certain that this hot spell was both the longest and the most extensive heat-wave experienced in the United Kingdom for at least 100 years and probably much longer. Temperatures exceeded 32°C at one or more stations in the United Kingdom on every day from 23 June to 7 July inclusive, and Cheltenham (Gloucestershire) had 11 such days including 7 in succession from 1 July.

Starting on 23 June over East Anglia the heat-wave intensified to reach a peak over eastern England on 26 June and then extended to Wales, south-west and northern England, south and east Scotland and Northern Ireland by 29 June and to the remainder of the Scottish mainland by 1 July. Over England and Wales, temperatures fell slightly for two or three days from 29 June before reaching a second peak on 3 July when maxima were higher than in June in many western districts. The hot spell came to an end when cooler air spread slowly from the Atlantic to reach Northern Ireland by 6 July and almost all remaining parts of the United Kingdom by the 9th.

Although the highest temperatures were confined to parts of East Anglia, the Midlands and central southern England, local long-period temperature records were broken at numerous stations throughout the United Kingdom including places as far apart as the west of Cornwall, the Scottish Highlands and Co. Fermanagh. Coastal temperatures were generally lower than those inland, but on several days sea-breezes were not effective and remarkably high temperatures occurred, particularly along the south coast of England.

Skies remained almost cloudless over much of central and eastern England, parts of East Anglia, Kent and East Sussex having an average of more than 14 hours' bright sunshine a day over the 16 day period. A few very isolated thunderstorms broke out during the second week in eastern and central parts of England but over most of the area the air remained unusually dry and stable throughout the heat-wave. On 30 June exceptionally dry air reached the surface over a wide area of East Anglia and southern England, relative humidities of less than 20 per cent being reported from many stations over a period of several hours.

2. Synoptic situation and evolution of the heat-wave

(a) *General upper-air and surface developments*

During the first half of June a ridge of high pressure was maintained across Biscay, northern France and southern England under a weak anticyclonic upper flow; little or no rain fell over these areas which were already suffering from a severe rainfall deficiency extending back for over twelve months, and high temperatures were recorded on several days although no prolonged hot spell occurred. A temporary change in the situation took place between 17 and 20 June as an upper westerly flow became established over the British Isles and on the 19th a small wave depression crossed South Wales, the Midlands and East Anglia, bringing moderate falls of rain to many places in southern England. A steady rise of pressure took place behind the depression, and by the 21st a broad belt of high pressure was established from Spain to the southern North Sea with low pressure in mid-Atlantic and over Finland.

The upper-air pattern at this time showed an almost stationary vortex over the Atlantic to the south-west of Iceland, a mobile trough over the Baltic, and, between these features, a developing upper ridge over the British Isles. Over the next week this ridge amplified and swung slowly south-east as geopotentials increased over western Europe, and by 28 June a large upper high covered England, Wales and northern France while Scotland and Northern Ireland lay under a light westerly flow. Weak fronts moving east continued to affect Scotland and Northern Ireland until the end of June, but on 1 July the upper ridge extended north-westwards so that the upper high covered the whole of the United Kingdom. Eastern parts of England and Scotland subsequently remained under the influence of this high until 8 or 9 July and upper-air ascents remained very dry and stable; elsewhere, however, moister, unstable air ahead of a very slow-moving upper trough edged slowly and erratically into western and central districts, giving increasing cloud and a few isolated thunderstorms. By 8 July the centre of the upper high had moved to the north of Scotland, leaving a broad ridge across the North Sea, and, as geopotentials continued to increase over Iceland and Norway and to decrease over the North Sea, a south-westerly flow extended slowly east to reach all parts of the United Kingdom by 10 July.

Underneath this stable upper-air pattern, surface pressure changes were relatively small. However, as the location of the hottest areas from day to day was largely determined by the speed and direction of the surface winds, even small changes affecting the positions of the high centres were important. The heat-wave could be divided into two separate and almost equal phases, and the evolution of the 16 day hot spell shown by the sequence of charts in Figure 1 is discussed in the following sections. The eight days shown in Figure 1 were selected to document significant variations in the pattern of the highest temperatures, and so are not at regular intervals throughout the period.

(b) *The first phase of the heat-wave, 23–30 June*

The high-pressure centre which had developed over the English Channel on 21 June drifted slowly east into northern Germany by the 23rd and light southerly winds brought hot, dry air from northern France across a large area of south-east England and East Anglia, where temperatures rose to above 30°C in many places (Figure 1(a)). By 25 June a flat area of high pressure with very light, variable winds covered the whole of England and Wales, and under cloudless skies temperatures rose to be several degrees higher than on previous days; the whole of London together with parts of East Anglia reported temperatures higher than 32°C for the first time. The heat-wave reached its first peak on the following day, 26 June, when temperatures rose by a further 2°C over the whole of eastern England (Figure 1(b)); over 30 stations reported maxima $\geqslant$34°C and except in a coastal strip from Lincolnshire to Sussex, maxima at all stations south-east of a line from Bournemouth to Hull exceeded 32°C. During the day a weak cold front crossed Scotland and Northern Ireland and, as pressure rose behind the front, the axis of the dominant ridge of high pressure was transferred northwards, and light north-easterly winds set in over southern England. The effect of these winds was apparent on 27 and 28 June as maximum temperatures fell slightly in the east but rose to almost unprecedented levels at south coast resorts and over much of south-west England and South Wales (Figure 1(c)).

Up to this time the heat-wave had been largely confined to the southern half of England and South Wales, but as a centre of high pressure became established over the central North Sea during 28 and 29 June temperatures over much of northern England, North Wales and parts of Northern Ireland rose above 28°C for the first time during the heat-wave. Further south, however, temperatures fell from their previous levels as strengthening north-easterly winds blew from the North Sea; much of East Anglia, the London area and south-east England were 4°C cooler on 29 June than on previous days. The last day of June proved to be the 'coolest' day of the heat-wave. A cold front moved south across Scotland to become stationary near the English Border and, to the north of this front, a mobile anticyclonic cell moved east to reinforce and intensify the high pressure over the northern North Sea. Temperatures over Scotland fell sharply behind the front while maxima over Wales and western England also fell as strengthening easterly winds spread across the country (Figure 1(d)); Northern Ireland, however, remained in light south-easterly winds to the south of the front, and temperatures rose to record levels at some stations in the west of the Province.

(c) *The second phase, 1–8 July*

Pressure remained high on 1 July over the northern North Sea and strong easterly winds continued to blow over England and Wales, but over Scotland maximum temperatures were substantially higher than on the previous day as the frontal zone returned northwards and warm, southerly winds spread to all parts

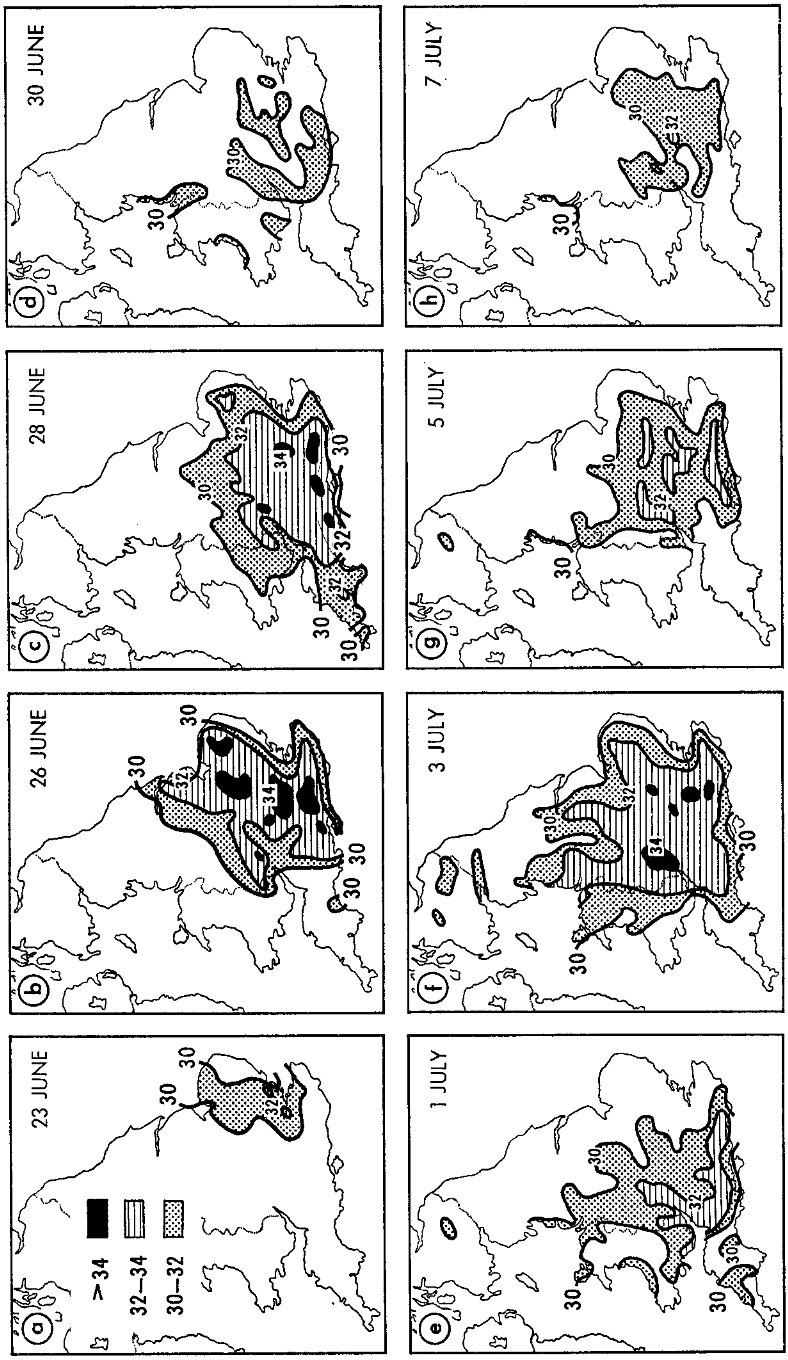

FIGURE 1—MAXIMUM TEMPERATURES (°C) ON SELECTED DAYS DURING THE HEAT-WAVE OF 1976

(Figure 1(e)). A change took place in the pressure pattern over the next two days as the high over the North Sea declined and moved away south-east while a new anticyclone developed between Iceland and Norway. A very light south-easterly flow brought hot, dry air north from northern France and the Low Countries to all areas of the United Kingdom and temperatures on 3 July rose to their highest levels of the entire heat-wave at many stations, particularly in the west. Figure 1(f) shows that temperatures in excess of 32°C were reported from an area of approximately 50 000 km^2 extending from Somerset and Lancashire in the west to Kent and Norfolk in the east. A few isolated thunderstorms broke out in central and eastern England but most places remained sunny and dry.

On 4 July a ridge of high pressure built southwards across the North Sea from the anticyclone to the north of Scotland and this pattern was subsequently maintained with only minor changes until 8 July. Light to moderate easterly winds accompanied by cloudless skies and maximum temperatures only slightly below their peak values persisted over most of England, Scotland and Wales throughout this period (Figure 1(g)). South-west England, west Wales and Northern Ireland meanwhile became progressively more cloudy with rain or thunderstorms at times as an occlusion edged very slowly into these districts from the west. Temperatures in Northern Ireland returned to normal on 6 July but the encroachment of cooler, Atlantic air further south was so slow and irregular that it took a further two days for the front to clear Wales and south-west England (Figure 1(h)). Ahead of the occlusion temperatures still remained very high on 8 July, but a strengthening upper south-westerly flow carried variable cloud and occasional light rain steadily north-east to all parts of the country during the 9th to bring the remarkable heat-wave to a surprisingly quiet and uneventful end.

3. The data and checks applied to them

Monthly returns of data are received at the Climatological Services Branch, Bracknell, and at offices in Edinburgh and Belfast, from approximately 630 Meteorological Office and co-operating stations in the United Kingdom. A quality control check is carried out on all these data to ensure consistency of observations at any one station and to query large discrepancies between observations at neighbouring stations. Such objective quality control methods are, of necessity, fairly coarse and during the period of the hot spell a more detailed check on the reported temperatures was carried out by using charts of maximum temperature which were plotted for each of the 16 days from 23 June to 8 July inclusive. All temperatures that appeared questionable on these daily charts were carefully examined in the light of the temperature pattern of neighbouring stations, the synoptic situation and site characteristics. Sequences of daily maximum temperature observations at individual stations were also examined and compared with similar sequences for nearby stations as a further method of assessing doubtful readings. Several particularly high temperatures checked in this way were considered unacceptable, including the temperature of 36·0°C at Plumpton (East Sussex) referred to by Ratcliffe (1976) and a summary of the case for not accepting this value has been given by Shaw (1977).

Maximum-temperature observations for a selection of stations throughout the 16 day period are given in Table I. Only reports from Meteorological Office and co-operating stations whose observing sites and procedures are periodically inspected by professional staff have been used in this paper.

TABLE I—DAILY MAXIMUM TEMPERATURES (°C) FOR 23–30 JUNE (A) AND 1–8 JULY (B)

	Grid Ref.										*Average*
Manchester	SJ 818850	(A)	24·5	25·3	26·9	26·6	28·3	29·2	31·3	29·7	29·1
Airport		(B)	30·0	31·5	32·2	30·2	30·2	30·6	29·8	28·7	
Derby	SK 359367	(A)	28·0	28·9	30·4	30·9	31·4	31·5	30·9	28·9	30·5
		(B)	30·5	31·9	32·7	30·9	31·1	30·6	29·7	30·2	
Lincoln	SK 962719	(A)	28·9	28·7	30·1	32·0	31·9	27·0	28·1	25·8	28·6
		(B)	26·5	29·3	30·5	28·1	27·8	27·5	27·0	27·8	
Shrewsbury	SJ 517136	(A)	25·0	26·5	28·9	28·7	30·4	30·5	31·1	29·7	29·7
		(B)	30·9	31·6	32·8	31·0	29·9	30·2	29·1	28·1	
Coventry	SP 348743	(A)	27·7	28·1	30·5	32·4	32·0	32·1	30·2	29·9	30·9
		(B)	31·0	32·6	33·0	30·5	31·7	31·5	30·2	30·2	
Cambridge	TL 456572	(A)	31·0	30·5	33·0	34·0	33·8	32·0	30·5	30·0	31·8
(Botanic Garden)		(B)	29·7	32·5	33·5	33·8	32·4	31·7	30·6	30·5	
Cheltenham	SO 946218	(A)	28·2	29·4	31·6	34·6	34·0	34·5	32·3	30·5	32·7
		(B)	32·1	35·7	35·9	34·1	33·0	34·3	32·7	30·9	
Oxford	SP 509072	(A)	28·8	29·5	32·0	34·0	34·3	33·1	30·7	30·2	31·8
(Radcliffe Obsy)		(B)	30·4	33·0	33·4	32·4	32·5	32·6	31·1	30·8	
Kew	TQ 171757	(A)	31·3	30·5	32·8	34·6	34·2	33·1	29·1	29·3	31·7
(North Wall screen)		(B)	29·2	31·2	34·1	33·2	31·6	32·3	30·6	30·7	
Exeter	SY 001933	(A)	25·9	24·5	28·4	32·1	33·5	33·0	31·4	29·6	29·3
		(B)	30·0	29·2	31·9	30·1	30·2	28·6	24·6	25·4	
Southampton	SU 416112	(A)	26·1	27·1	30·1	34·9	35·5	35·6	32·2	32·1	31·5
(Mayflower Park)		(B)	32·6	31·5	30·8	31·5	33·1	32·6	30·7	26·9	
Gatwick Airport	TQ 265407	(A)	29·5	30·1	32·2	33·8	33·3	33·5	29·2	28·2	31·3
		(B)	29·7	32·3	33·9	32·2	30·9	31·7	30·0	29·8	

For each station the top row of temperatures is for 23–30 June, and the bottom row for 1–8 July. The average for the whole 16 day period is given in the final column.

4. COMPARISON WITH PREVIOUS HEAT-WAVES

(a) *Highest temperatures reached*

Figure 2 shows the highest temperatures reached at stations throughout the country during the period from 23 June to 8 July inclusive. Variations within the area of highest maxima in southern England are largely a reflection of topographical detail, the highest values being reported from low-lying inland stations in East Anglia, the Thames and Severn valleys and southernmost counties from Somerset to Sussex. It has been suggested by Hopkins and Whyte (1975) that a temperature reduction of 1°C for each 100 m increase in altitude is appropriate for extreme values of maximum temperature. A check during this particular heat-wave using the highest maxima at 10 pairs of neighbouring high-level and low-level inland stations produced an average fall with height of 1·1°C/100 m, but the range of lapse rates was substantial (0·5 to 1·75°C/100 m) which indicates that altitude is only one of several factors to be considered. The unusually high temperatures attained at some coastal stations show up on Figure 2 and these will be discussed more fully in section 5 of this paper.

The highest accepted temperatures recorded in the United Kingdom on each day during the heat-wave are shown in Table II and a list of the highest temperatures overall appears in Table III. From these tables the following points are of particular interest:

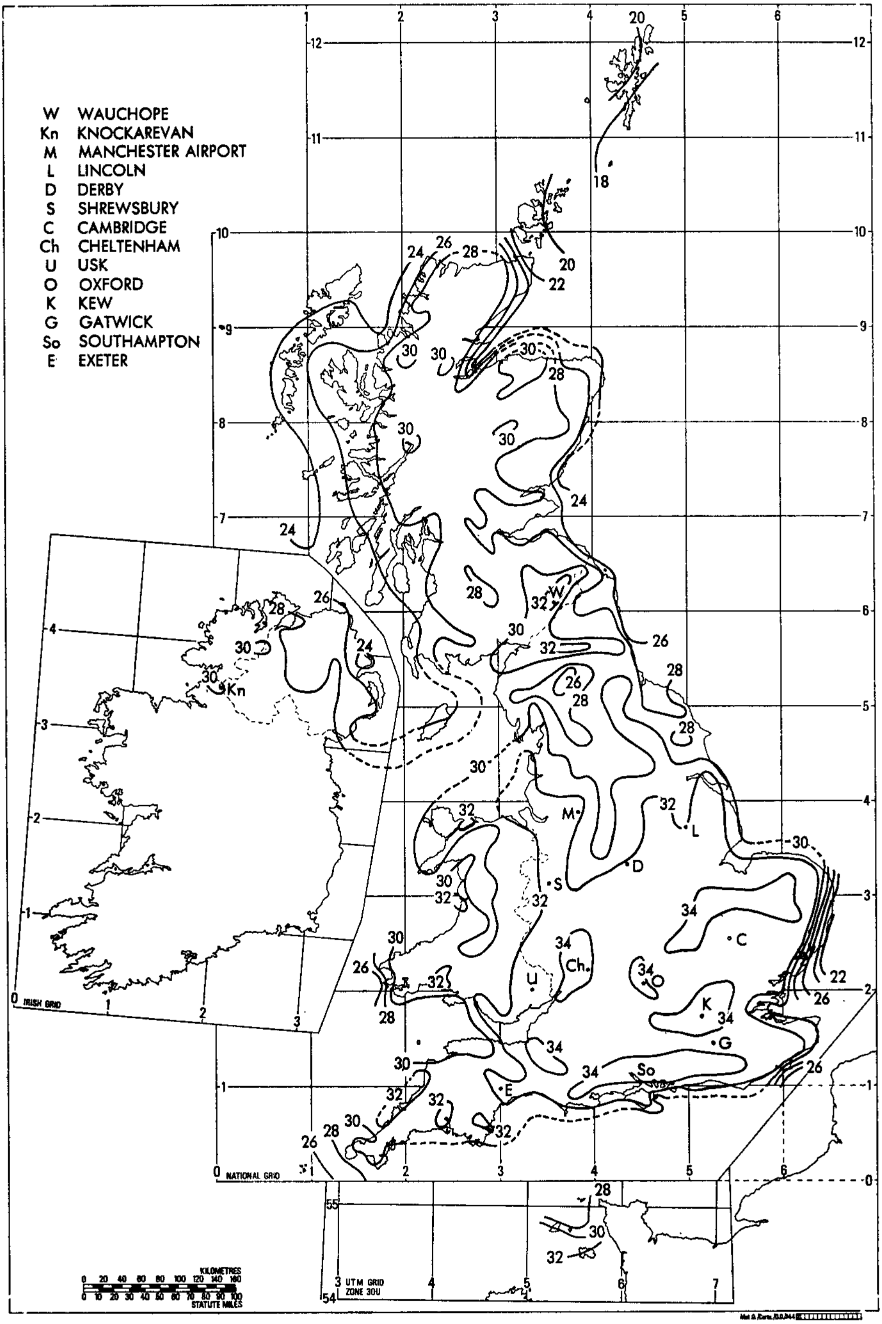

FIGURE 2—HIGHEST TEMPERATURES (°C) REPORTED DURING THE 16 DAYS FROM 23 JUNE TO 8 JULY 1976

TABLE II—HIGHEST MAXIMUM ON EACH DAY OF THE HEAT-WAVE

Date	Max. temp. °C	Location
23 June	32·2	Maldon (Essex)
24	32·4	Gillingham (Kent)
25	33·5	East Bergholt (Suffolk)
26	35·4	North Heath (West Sussex); East Dereham (Norfolk)
27	35·5	Southampton, Mayflower Park (Hampshire)
28	35·6	Southampton, Mayflower Park
29	33·6	Totnes (Devon)
30	32·1	Southampton, Mayflower Park
1 July	33·5	Yeovilton and Cannington (Somerset)
2	35·7	Cheltenham (Gloucestershire)
3	35·9	Cheltenham
4	34·1	Cheltenham; North Heath
5	33·1	Southampton, Mayflower Park; Benson (Oxfordshire)
6	34·3	Cheltenham
7	32·7	Cheltenham
8	31·1	Benson

TABLE III—HIGHEST TEMPERATURES OVERALL DURING THE 1976 HEAT-WAVE

	Temperature °C	Location	Date
England	35·9	Cheltenham	3 July
	35·7	Cheltenham	2 July
	35·6	Southampton, Mayflower Park	28 June
	35·5	Southampton, Mayflower Park	27 June
	35·4	North Heath; East Dereham	26 June
	35·3	Southampton Weather Centre	27 June
	35·1	East Dereham	27 June
	35·0	North Heath	2 July
		Waddon (Greater London)	26 June
Wales	33·6	Usk (Gwent)	3 July
	33·5	Usk	28 June
	33·2	Port Talbot (West Glamorgan)	2 July
Scotland	32·4	Wauchope (Borders)	2 July
	32·1	Kelso (Borders)	2 July
	31·6	Lossiemouth (Grampian Region)	1 July
		Kelso	3 July
Northern Ireland	30·8	Knockarevan (Co. Fermanagh)	30 June
	30·0	Strabane Convent (Co. Tyrone)	30 June
	29·2	Knockarevan	1 July

(1) The highest temperature, 35·9°C (96·6°F) at Cheltenham on 3 July, falls well short of the often quoted United Kingdom record for July (or for any month) of 100·5°F (38·1°C) recorded at Tonbridge (Kent) on 22 July 1868. This reading and other extreme maximum temperatures reported in the United Kingdom since the middle of the last century have been critically re-examined in a recent paper by Laing (1977), particular attention being paid to the various types of thermometer stand or screen used. Laing concludes that 'a realistic estimate of the extreme maximum temperature recorded so far in the United Kingdom' is 98°F (37°C) set on 9 August 1911; the Tonbridge reading is assessed as having been between 97 and 98°F and remains the highest July reading.*

* For temperature values reported during previous heat-waves to the nearest whole °F, the equivalents in °C have been calculated to the nearest ½°C.

(2) The highest *June* temperature, 35·6°C (96·1°F) at Southampton on the 28th equals that reached at Camden Square (London) on 29 June 1957, the previous highest June temperature ever officially recorded anywhere in the United Kingdom.

(3) The maximum of 33·6°C (92·5°F) at Usk on 3 July falls only fractionally short of the temperature of 93°F (34°C) reached at Newport (Gwent) in July 1923 which is believed to be the highest ever recorded in Wales.

(4) The temperature of 32·4°C (90·3°F) at Wauchope (Borders) on 2 July was the highest for any month in Scotland since 1908 when 91°F was recorded at Dumfries.

(5) The temperature of 30·8°C (87·4°F) at Knockarevan (Co. Fermanagh) on 30 June was the highest ever recorded in any month in Northern Ireland since records began there.

(b) *The length of the heat-wave*

Although neither the start nor the finish of the hot spell was marked by very large temperature changes, the period was nevertheless fairly well defined. Figure 3 shows the number of consecutive days having maxima ⩾28°C during the period from 23 June to 8 July inclusive; 59 stations are included in the areas having 16 such days but at no station did the spell extend to 17 days, although a few places in eastern Britain did exceed 28° C on 9 July. If the threshold is raised to 30°C the long spell is broken in most eastern districts but three stations (Cardington (Bedfordshire), Hoddesdon (Hertfordshire) and London/Heathrow Airport) recorded 16 successive days with maxima ⩾30°C, and, further west, 14 or 15 days were widely reported over central southern England. At the 32°C level no coherent pattern emerges, but most stations in southern England from Devon to Essex, and including the Greater London area, had 3 or 4 consecutive days and at many places two such periods were broken by the cooler days at the end of June. The longest unbroken sequences of maxima ⩾32°C were 7 days at Cheltenham (Gloucestershire) and 6 days at Innsworth (Gloucestershire), Benson (Oxfordshire), North Heath, Rogate and Fernhurst (all in West Sussex) and at Mayflower Park in Southampton.

In Scotland the longest spell of hot weather occurred in the south and south-west, where several stations reported 11 successive days, from 28 June to 8 July, with maxima over 25°C; in the south-east, where temperatures in general were slightly higher, the spell was reduced to 8 days owing to the much lower temperatures on 30 June. Over Northern Ireland the hot spell also started on 28 June and continued unabated until 5 July; several inland stations in the south and west had 8 successive days when 25°C was reached, and at two stations temperatures of 28°C were exceeded on each of the 7 days from 28 June to 4 July.

A temperature of 32·2°C (90°F) is quite rare in the British Isles and it is almost certain that no spell of more than 4 consecutive days with temperatures in excess of 90°F had ever been reliably recorded in a Stevenson screen anywhere in the country before 1976. Since the middle of the last century many letters and articles have been published concerning occasions of great heat, but reference can be found to only six occasions on which 4 and one occasion on which 5 successive days have been recorded. These instances are listed in Table IV together with the longest spells during the 1976 heat-wave. It will be seen that

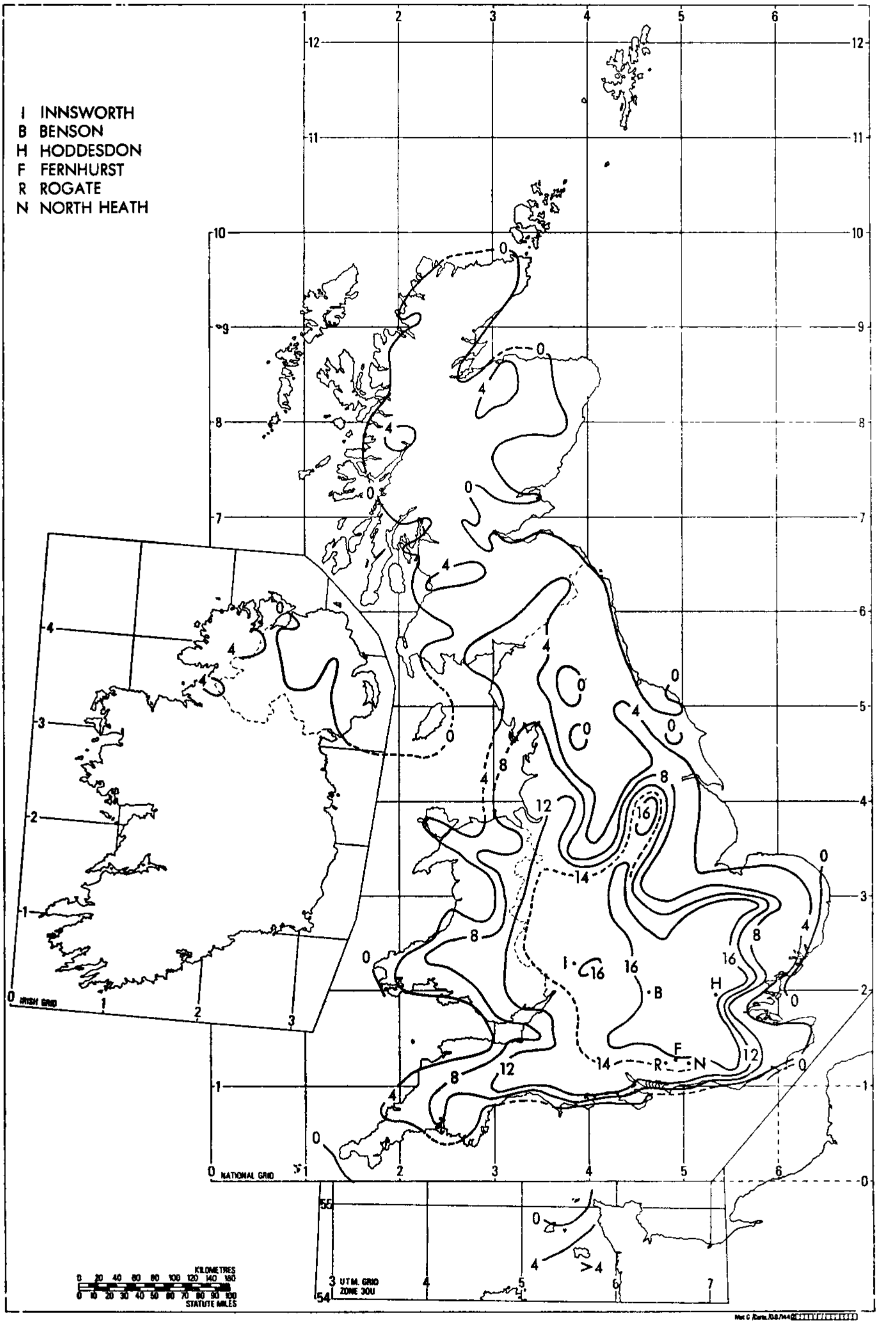

FIGURE 3—NUMBER OF CONSECUTIVE DAYS DURING THE HEAT-WAVE HAVING MAXIMUM TEMPERATURES $\geqslant 28°C$ (82·4°F)

TABLE IV—SPELLS OF CONSECUTIVE DAYS WITH TEMPERATURE ⩾ 90°F (32·2°C)

Duration	Dates	Location	Type of screen or stand	Reference
5 days	13–17 June 1868	Tonbridge (Kent)	Non-standard	Fielding (1869)
4 days	2–5 Aug. 1868	Tonbridge	Non-standard	Fielding (1869)
	14–17 July 1876	Beckenham (Kent)	Glaisher	Bicknell (1881)
	31 Aug.–3 Sept. 1906	Greenwich	Glaisher	Bonacina (1947)
		Old Southgate	Stevenson	Butler (1906)
	7–10 July 1934	Bridgwater (Somerset)	Stevenson	Lewis (1934)
	31 May–3 June 1947	Greenwich	Glaisher	Bonacina (1947)
6 days	1–6 July 1976	Innsworth	Stevenson	
		North Heath	Stevenson	
	2–7 July 1976	Cheltenham	Stevenson	
5 days	2–6 July 1976	8 stations	Stevenson	

only two of the spells in the first part of the table were recorded using Stevenson-type screens. Direct comparisons are available between Stevenson and Glaisher readings at Greenwich in 1906 and 1947, and they show that four successive temperatures of 90°F or more were not recorded in the Stevenson screen on either occasion, and if the corrections suggested by Laing are applied to the Tonbridge and Beckenham temperatures these spells also reduce to fewer than four days. On this basis the spells at Old Southgate in 1906 and Bridgwater in 1934 remain as the previous longest, and further evidence of the outstanding heat-wave in 1906 is given by Marriott (1907) in the form of maps of maximum temperatures over the British Isles for each of the four days from 31 August to 3 September 1906. From the maps it appears that maxima exceeded 90°F on each of these days over a substantial area of Cambridgeshire and southern Lincolnshire, but it is not stated whether or not the data were restricted to Stevenson screen readings but merely that the maps were 'based upon the returns from more than 250 stations'.

It seems clear from the above comparisons that, using the criterion of 32°C or 90°F, the 1976 heat-wave far outstripped all previous documented events. At a lower temperature level the sequence of 17 consecutive days (22 June to 8 July inclusive) during which 10 London stations including the North Wall screen at Kew, registered maxima ⩾80°F (26·7°C) also appears to be quite unprecedented in the London area. From the Glaisher stand at Greenwich, Brazell (1968) cited two spells each of 15 days in July 1859 and July 1868, while the previous record at Kew was only 10 days, 5–14 July 1923. Published temperature information of this type is very scarce for stations outside the London area, but it is known that a previous record of 8 consecutive days ⩾30°C set in 1911 at the Radcliffe Observatory, Oxford, has now been superseded by the 1976 spell of 14 days (Samson, 1976).

These are, admittedly, only a few isolated comparisons with past events, but such evidence as there is points inescapably to the conclusion that the June–July heat-wave of 1976 provided the longest unbroken spell of very hot weather since at least the middle of the last century. Before then, temperature comparison, particularly of extremes, becomes progressively more difficult, but Ratcliffe (1976) has suggested that the length of the hot spell may be without equal for at least 250 years.

(c) *The spatial extent of the heat-wave*

Although the hot spell lasted longer and was more intense over central and eastern England then elsewhere, long-standing temperature records were broken at many stations throughout the United Kingdom. Hopkins and Whyte (1975) have published a map giving the extreme maxima (reduced to mean sea level) which may be expected to occur on average only once in 50 years (based largely on an analysis of data from the period 1941–70) and an accompanying graph enabling temperatures for different return period to be estimated. Using these methods a chart (Figure 4) was prepared to show the approximate return period of the extreme maxima recorded during the 1976 event. Over a large area extending across southern England from Land's End to Eastbourne and north through the Welsh Border country to Lancashire a return period of over 50 years is indicated; within this area temperatures corresponding to a return period of 100 years or more were achieved along most of the south coast from Plymouth to Brighton and also over a small area embracing Malvern and Cheltenham. Separate areas at the 50 year level over Norfolk, the Scottish Borders, northern Scotland and the extreme west of Northern Ireland show clearly that the rare nature of the event was in no way confined to the areas from which the highest temperatures were reported. Indeed over much of the latter area, including London, the maximum temperatures reached in 1976 could be expected to recur, on average, every 25 to 50 years although at certain stations (for example Kew) more exceptional maxima were recorded.

Although the 1976 heat-wave occurred rather early in the summer, all-time temperature records were equalled or broken at more than 30 long-period stations (i.e. stations having at least 50 years' data) and these are also marked in Figure 4. They include Stonyhurst (Lancashire), 111 years of data; Southampton and Kew (North Wall screen), 106 years each; Cheltenham, 98 years; Worthing, 96 years. Most of the previous records had been set in the notably hot Augusts of 1911 and 1947. For the month of June the heat in the southern half of the United Kingdom was quite unparalleled. New temperature records for the month were set at 53 out of 70 long-period stations south of a line from Aberystwyth to the Wash, and at 10 of these stations the new record was more than 3°C higher than any previously measured temperature.

3. Coastal temperature variations

Although temperatures at coastal stations were, in general, lower than those inland, Figure 2 shows that unusually high temperatures were recorded along several stretches of coastline; at many places these high values were only reached on one or two days but at several resorts in southern and north-western England temperatures rose higher than 30°C on as many as 8 consecutive days. In both these areas the gradient wind had a strong and persistent offshore component for many days, and before sea-breezes could become established the gradient-controlled winds had first to be overcome. On some days no onshore winds at all were reported from these coasts, while on others, sea-breezes, accompanied by temperature falls of up to 5°C, set in only relatively late in the day after unusually high temperatures had already been attained. Sea temperatures around the coasts of Wales and southern and western England rose by an average of 3°C during the course of the heat-wave to reach a general level of 16 or 17°C.

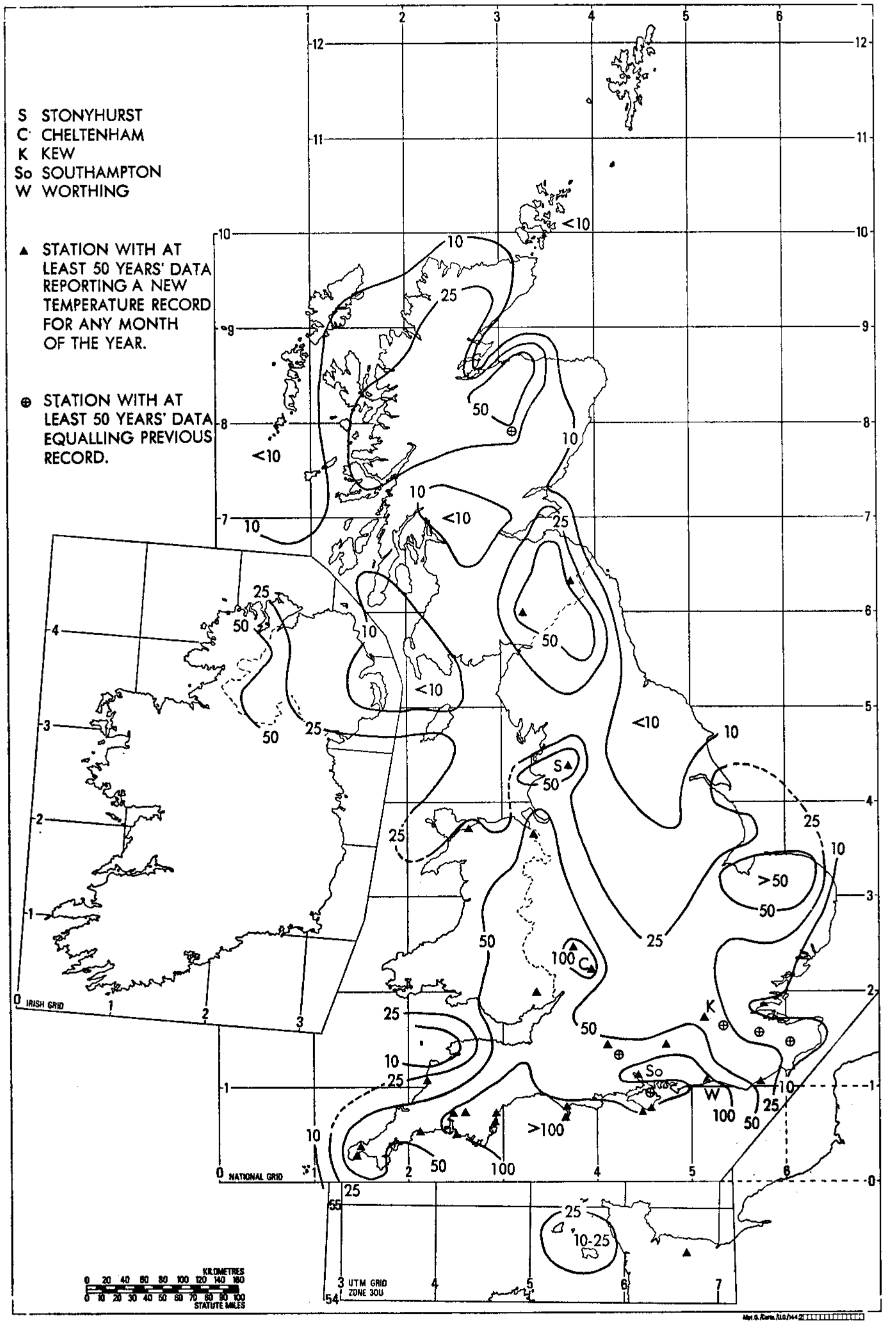

FIGURE 4—ESTIMATED RETURN PERIOD (IN YEARS) OF THE HIGHEST TEMPERATURE DURING THE 1976 HEAT-WAVE

Many of the highest coastal temperatures were reported from the south coast of England, where almost every station between Brighton and Weymouth exceeded 32°C at least once during the heat-wave and even such exposed sites as St Catherine's Point on the Isle of Wight and Portland Bill reached 30°C for the first time on record. Further west almost all stations in Devon and Cornwall also recorded temperatures of over 30°C, an extremely rare event in the peninsula, and maxima exceeded 32°C in some sheltered river valleys and on the north Cornwall coast. The highest temperature occurred, in general, on 27 and 28 June as light north-easterly winds advected the very hot, dry subsided air south-westwards from inland counties of southern England; the only occasion when comparable temperatures seem to have been reached was between 16 and 18 August 1947 during a similar synoptic situation with high pressure over the North Sea and an east to north-easterly airflow across southern England. In the north-west temperatures around the Irish Sea coasts of North Wales and Lancashire were several degrees higher during the 1976 heat-wave than in August 1947; consistently high temperatures between 29 June and 8 July reached a peak of 33·7°C at Blackpool on 3 July.

A good example of the critical effect of a change in wind direction on temperature can be seen from the hourly temperature and wind observations on 26 June at Spurn Point, the coastguard station at the end of the long shingle spit at the mouth of the Humber. Table V shows that the change in wind direction from south-west to east between 14 and 15 GMT resulted in a fall of 6·8°C in the hour. The temperatures reached before the change in wind direction were quite exceptional for such an exposed maritime site. No maximum thermometer is read at Spurn Point at present but the highest hourly value of 30·2°C has only been exceeded once since 1880 (87°F = 30½°C on 18 August 1893), while 86°F (30°C) was attained in July 1911 and June 1957.

Almost all east coast stations from Norfolk to the Scottish border had high temperatures on 26 June with winds from the south or south-west and similiar conditions also prevailed over Lincolnshire and Norfolk on 23 June. On most days, however, the winds were from an easterly point and temperatures remained considerably lower on the east coast than elsewhere. Day-to-day variations in temperature during the early part of the heat-wave were considerable and Table VI shows the maxima recorded at three stations between 22 and 27 June together with the mean winds measured each day at Coningsby in Lincolnshire between 15 and 16 GMT. Between 26 and 27 June the average temperature change at these sites was 8·8°C while the fall at inland stations averaged only about 1°C. Large variations in maxima from day to day also occurred on the north-facing shore of the Moray Firth in Scotland. Table VII shows a comparison between temperatures at the coastal site of Lossiemouth and at Grantown-on-Spey, approximately 40 km to the south; the high coastal temperatures all occurred when air from the south was warmed still further by descent in the lee of the Grampian mountains.

A few stretches of North Sea coastline remained persistently cool throughout the period of the heat-wave. At Aldeburgh (Suffolk) and Gorleston (Norfolk) the temperature never rose as high as 23°C on any day during late June or early July, and on many days the difference in maximum temperature between this section of the East Anglian coast and the nearest inland stations approximately 20 km away was as high as 10°C.

TABLE V—WIND AND TEMPERATURE OBSERVATIONS AT SPURN POINT (NORTH HUMBERSIDE) ON 26 JUNE 1976

Hour GMT	Wind direction (degrees true) and speed (knots)	Temperature °C
11	200/05	27·2
12	230/10	29·3
13	230/09	30·2
14	230/05	29·2
15	100/08	22·4
16	Calm	21·9
17	080/05	22·8

TABLE VI—DAILY MAXIMUM TEMPERATURES (°C) AT THREE EAST COAST SITES AND MEAN WINDS AT CONINGSBY BETWEEN 15 AND 16 GMT, 22–27 JUNE 1976

	22nd	23rd	24th	25th	26th	27th
Cromer	25·7	31·2	24·0	26·8	31·8	24·4
Skegness	24·9	29·9	22·0	23·5	29·9	21·0
Cleethorpes	25·0	28·5	25·5	27·5	32·5	22·5
Winds at Coningsby	210/08	230/11	110/09	090/11	240/09	120/06

TABLE VII—DAILY MAXIMUM TEMPERATURES (°C) AT LOSSIEMOUTH AND GRANTOWN-ON-SPEY AND MEAN WINDS AT LOSSIEMOUTH BETWEEN 15 AND 16 GMT, 30 JUNE–10 JULY 1976

	30th	1st	2nd	3rd	4th	5th
Grantown-on-Spey (A)	24·3	29·2	28·3	30·0	23·9	28·8
Lossiemouth (B)	18·6	31·6	21·2	17·2	24·7	30·0
Difference (A) – (B)	5·7	–2·4	7·1	12·8	–0·8	–1·2
Winds at Lossiemouth	070/13	210/08	070/08	070/06	360/07	130/14

	6th	7th	8th	9th	10th
Grantown-on-Spey (A)	29·1	29·9	28·0	27·8	20·2
Lossiemouth (B)	27·1	17·5	18·6	28·8	20·9
Difference (A) – (B)	2·0	12·4	9·4	–1·0	–0·7
Winds at Lossiemouth	010/07	020/07	080/08	130/19	070/06

TABLE VIII—LOWEST REPORTED VALUES OF RELATIVE HUMIDITY (RH) ON 30 JUNE 1976

	Time GMT	RH %	Dry-bulb temperature °C	Dew-point °C
Honington	1400	08	27·0	–9
Cardington	1700	11	28·5	–5
Stansted	1600	11	27·7	–5
Kew	1600	11	29·2	–5
Boscombe Down	1700	12	29·0	–3
Heathrow	1500	12	30·5	–2
Heathrow	1600	12	29·9	–2

6. Bright sunshine

Durations of bright sunshine during the period of the heat-wave were very high over England and Wales while over Scotland and Northern Ireland totals were well above average in the east and south falling to near average in the north and west. The last nine days of June were almost completely cloudless over the whole of England and Wales but from the beginning of July onwards south-west England and Wales had much more cloud and only average amounts of sunshine. The remainder of England, however, continued to be almost clear of cloud for the first eight days of the month and parts of south and east Scotland also had abundant sunshine during this period.

Taking the 16 day period of the heat-wave as a whole, most of eastern Wales and the whole of England with the exception of south-western counties from Cornwall to Dorset and also parts of the Cumbrian coast had an average of over 12 hours' bright sunshine each day; this figure represents approximately 200 per cent of the 1941–70 average and 70 per cent of the maximum possible sunshine for the time of year. Sunshine amounts increased towards the south-east where most of Kent and East Sussex and also eastern parts of Norfolk and Suffolk exceeded 85 per cent of the possible sunshine, while the Midlands and remaining parts of East Anglia and south-east England recorded between 80 and 85 per cent.

The highest sunshine totals for the 16 day period from 23 June to 8 July inclusive, and the percentages of possible sunshine, were as follows:

227·8 hours at Scole (Norfolk)	87·5 %
227·6 hours at Wattisham (Suffolk)	87·8 %
227·4 hours at Eastbourne (East Sussex)	88·9 %
227·1 hours at Bexhill (East Sussex)	88·8 %
226·1 hours at Folkestone (Kent)	88·2 %
225·8 hours at Hastings (East Sussex)	88·1 %
225·3 hours at Wye (Kent)	87·6 %
224·3 hours at Lowestoft (Suffolk)	86·4 %.

The highest percentage of the 1941–70 average sunshine during this period occurred in north-west England and the north Midlands where Manchester had 239 per cent and Nottingham 235 per cent of average (Ratcliffe, 1976).

7. Very low humidities during the heat-wave

Throughout most of the heat-wave relative humidities at inland sites at the time of maximum heating were in the range 25 to 35 per cent, comparable with those recorded during the hot spells of August 1975 and August 1976 and well below the average for very hot weather. The average wet-bulb depression during the heat-wave at Heathrow, Honington and Birmingham (Elmdon) was 11·2°C and this compares with a 1960–74 average of 9·2°C for occasions when temperatures exceeded 28°C. On three days relative humidities of less than 20 per cent were observed quite widely over central and southern England and most notably on 30 June when exceptionally dry air was observed at the surface for several hours over a considerable area from East Anglia to south-west England. Figure 5 shows the minimum relative humidity recorded at stations in southern England and South Wales on 30 June (as calculated from hourly dry- and wet-bulb temperatures using hygrometric tables) and the lowest values overall are listed in Table VIII. At Heathrow the relative humidity remained below 15 per cent for 5 consecutive hours, at Cardington for 4 hours and at Stansted, Kew and Honington for 3 hours.

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Photograph by C. A. Stumbles

PLATE I—STRATOCUMULUS UNDULATUS AT ST MAWGAN
(See page 360.)

PLATE II—PARTICIPANTS IN THE CIMO VII MEETING, HAMBURG, 1–12 AUGUST 1977

From left to right: Dr D. N. Axford (UK), Mr G. W. Kronebach (WMO Secretariat) and Mr A. H. Hooper (UK) (see page 356).

Photographs by Conti-Press, Hamburg

PLATE III—EXHIBITORS' STANDS AT THE METEOREX 77 EXHIBITION, HAMBURG

(See page 356).

PLATE IV—CIMO VII GROUP, HAMBURG, 1–12 AUGUST 1977

Dr D. N. Axford is in the back row, immediately to the right of the tree trunk; Lt Cdr R. A. Young, RN is standing next to Dr Axford on the reader's right, and Mr A. H. Hooper is seventh from the left in the second row counting from the front. (See page 356.)

To face page 345

PLATE V—TECIMO GROUP, HAMBURG, 27–30 JULY 1977

Dr D. N. Axford is at the extreme left of the second row counting from the front, Mr A. H. Hooper is also in this row, and Lt Cdr R. A. Young, RN is in the middle of the back row. Dr M. Hinzpeter, Mr H. Treussart and Mr G. W. Kronebach are standing together in the middle of the front row. (See page 356).

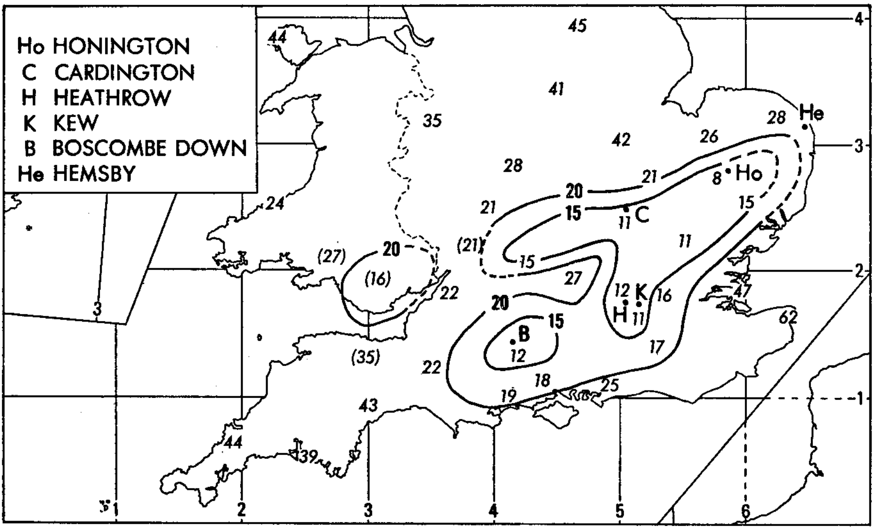

FIGURE 5—LOWEST VALUES OF RELATIVE HUMIDITY REPORTED ON 30 JUNE 1976

Bracketed figures refer to stations which report only at certain fixed hours.

The 11 GMT radiosonde ascent at Hemsby showed a layer of very dry air above 1010 mb (approximately 150 m), the lowest dew-point being −18°C at a height of approximately 750 m, and a very similar sounding was also obtained at Cardington earlier in the morning at 0540 GMT. A trajectory analysis showed the source of this air to be the large anticyclone which had been almost stationary over the central North Sea for several days. The minimum reported humidities at the surface were very close to those shown on the two ascents and it is clear that a considerable mass of the dry air was, most unusually, brought from a height of several hundred metres right down to the surface on 30 June, probably by a combination of further anticyclonic subsidence and mixing of the air in the lowest layers in 10 to 20 knot north-easterly winds. Timing of the arrival of very dry air at different stations seems to indicate that several different masses of air were probably brought to the surface in different parts of southern England and South Wales during the day, although many reports can be explained by a spread of dry air south-westwards from a single source over East Anglia.

Apart from 30 June very dry surface air was reported on 2 July and 7 July. On both days relative humidities of less than 20 per cent were recorded for several consecutive hours over parts of East Anglia and on the 7th the area of low humidities discussed by Hunt (1977) extended across much of the Midlands also. The lowest values of relative humidity reported on these days (as calculated from hourly dry- and wet-bulb readings) were 14 per cent at Honington on both 2 and 7 July and 15 per cent at Cardington and Birmingham (Elmdon) on 7 July.

To put all these low values into the context of previous such occasions, the Climatological Atlas of Great Britain (1952) lists 5 days between the years 1921 and 1942 on which relative humidities of less than 20 per cent were measured over southern England. More recently values of only 4 per cent, believed to be the lowest measured in the United Kingdom this century, were observed on 29 March 1965 both at Manchester Airport and at the high-level station on Great Dun Fell (847 m above mean sea level). Details of these occasions, with notes on the synoptic situations prevailing at the time, have been given by Pick (1931), Read (1934 and 1942), Drummond (1942), Hawke (1944) and Suttie (1965).

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MARKED BACKING OF WESTERLY AND NORTH-WESTERLY WINDS OVER THE IRISH SEA DUE TO DIFFERENTIAL HEATING OVER LAND AND SEA

By A. K. KEMP

(Meteorological Office, Royal Air Force, Valley)

SUMMARY

It has been noticed at Valley that in summer if the surface wind during the morning is between west and north-west, by afternoon the wind has usually backed to south-west. This article attempts to explain this phenomenon and investigates the statistical significance of its occurrences.

INTRODUCTION

The forecast for the afternoon of 10 July 1969 seemed ideal for a first sail with my family on my newly acquired small sailing cruiser. The wind should have been west-north-west force 4, which would have made the waters near the south coast of Holyhead Island well sheltered, and should have ensured a comfortable night at anchor in Rhoscolyn Cove, which is only exposed to the south.

As we left the shelter of the straits between Holyhead Island and Anglesey and entered the open sea, I found that instead of an easy sail on smooth waters we faced a beat against a force 4–5 south-westerly wind and a short steep chop. Later in the afternoon conditions at Rhoscolyn anchorage were almost untenable and my wife quickly vetoed any idea of cooking a meal aboard. After a thoroughly miserable evening with the crew close to mutiny, relief came around dusk as the wind veered to the west; the sea soon became calm and a peaceful night followed.

The next day almost the same sequence of events occurred and with my reputation as a forecaster and skipper at stake, I was strongly motivated to find out why my wind forecasts had been so badly wrong!

INVESTIGATION

During the period 10–12 July 1969 a large anticyclone became established to the south of Ireland (see Figure 1) and a warm rather moist west-north-westerly airstream spread across the British Isles. Western coastal areas remained mainly cloudly but over many inland and eastern areas the afternoons became warm and sunny. Figures 2, 3, 4 and 5 show isobars and isotherms for 10 July and 00 GMT on 11 July (although isotherms over the Welsh hills will be much more complex than shown here). The formation of an isobaric trough between 12 and 18 GMT close to the east coast of Ireland is clearly indicated and this trough can be closely related to the marked thermal high over eastern Ireland, the strong thermal gradient just east of the Irish coast and the relatively low surface temperatures over the coast of west Wales. By 00 GMT on 11 July the isobaric trough has disappeared as have the strong thermal gradients. This sequence of events was repeated on the following two days as can be seen from Figure 6. Here the surface wind direction at Valley and the temperature difference between Dublin and Valley are plotted against time. The two stations are well situated to indicate the strength of the thermal gradients across the Irish

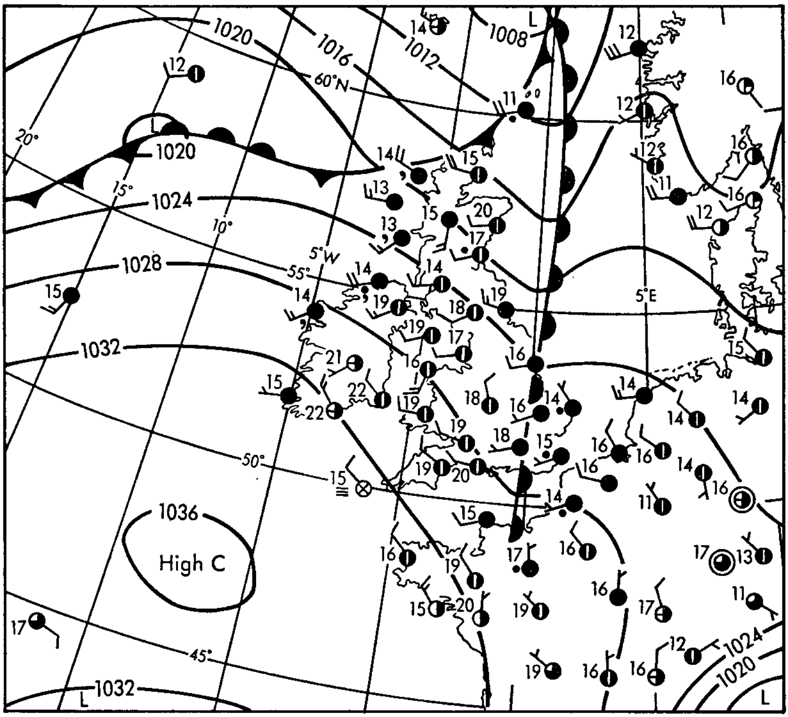

FIGURE 1—SYNOPTIC SITUATION AT 18 GMT ON 10 JULY 1969

Sea. On each day the maximum backing at Valley occurred at about 18 GMT, about or soon after the time at which the maximum temperature would be occurring over land.

The two series show a high negative correlation of —0·87 (dominated by the short-period changes rather than by the long-period change) which for the sample of 21 pairs has less than one chance in 1000 of arising by accident if there is really no relationship between them. Although it seems unlikely it is, of course, possible that the relationship is less direct than has been supposed and that the effect is due to some third factor which is common to both. At least they exhibit a high degree of covariation.

The basic reason for the formation of the isobaric trough appears to be differential heating between land and sea, and in summer this will tend to occur every day except under completely overcast conditions. A simple method of investigating this is to consider wind changes which occur at Valley between 09 and 18 GMT and relate these changes to the temperature difference between Valley and Dublin. If two periods are chosen, one winter and one summer, then the probability of westerly surface winds backing in summer should be much higher than in winter.

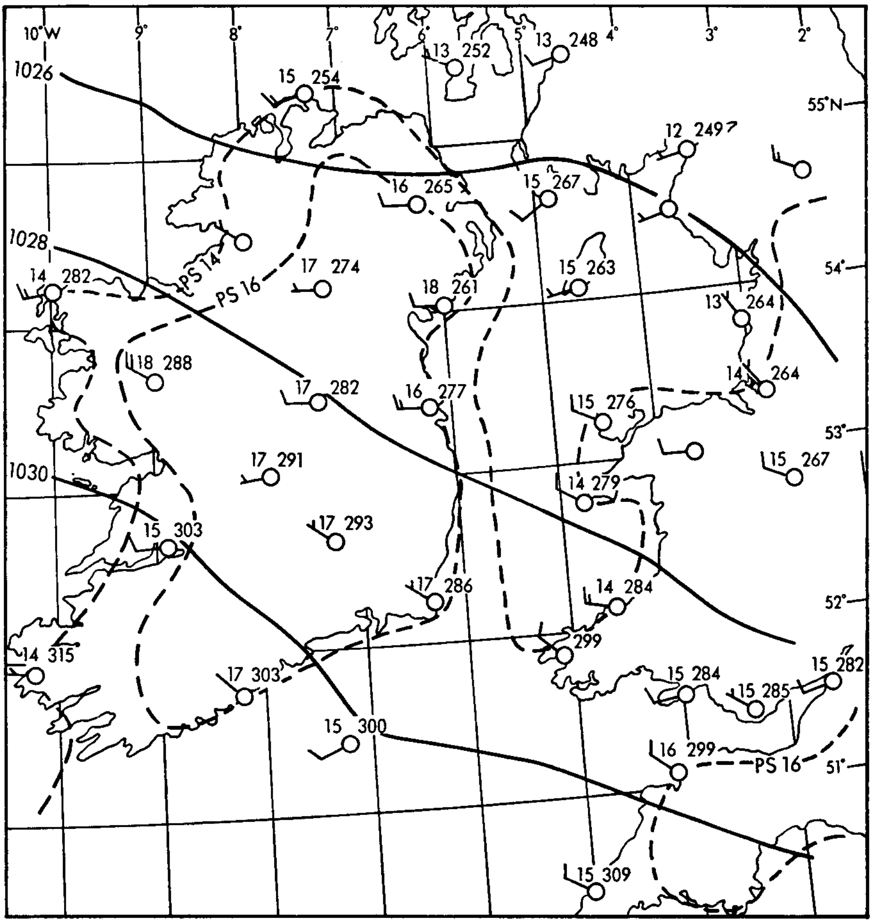

FIGURE 2—SYNOPTIC SITUATION AT 09 GMT ON 10 JULY 1969

——— isobars - - - - isotherms

A ten year period was chosen, 1965 to 1974, and a computer print-out obtained of all days when the 09 GMT wind at Valley was 10 knots or greater and between 260° and 320°. The periods selected were December to February and June to 15 August inclusive. The choice of directions was not critical and speeds of 10 knots or greater were considered to avoid days of light variable winds and possible large effects from sea-breezes. (The sea-breeze at Valley frequently occurs on days with light gradients. It usually sets in as a south-westerly wind which soon veers to north-west.) The second half of August was excluded because with decreasing solar radiation at this time and with sea temperatures close to a maximum, strong thermal gradients between land and sea are less likely to occur.

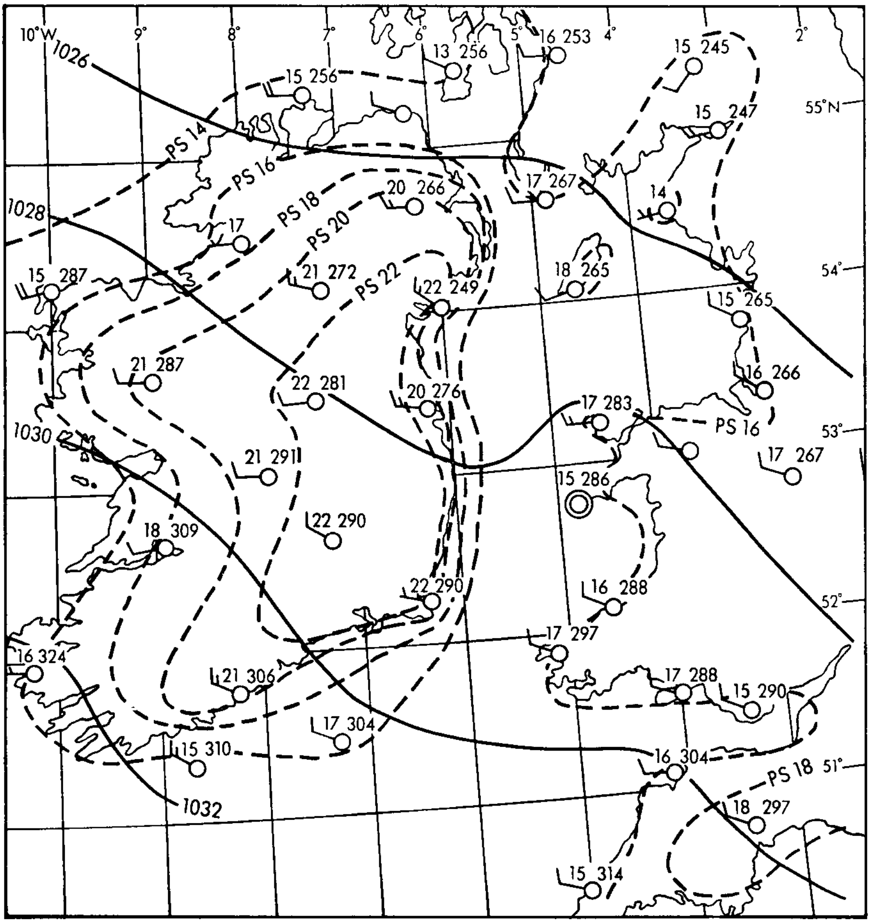

FIGURE 3—SYNOPTIC SITUATION AT 12 GMT ON 10 JULY 1969

——— isobars - - - - isotherms

In the latitude of the British Isles, the prevailing trough/ridge pattern associated with mobile westerlies implies that a north-westerly wind is more likely to back than to veer over a period of say 9 hours. In an attempt to eliminate this natural backing tendency it was decided to exclude from the investigation all days when a front, frontal trough or closed isobar was crossing Ireland or the Irish Sea. This would also exclude most days with thick frontal cloud when differential heating would be minimal. In practice the selection of such days was made by examining the 12 and 18 GMT charts as drawn on the *Daily Weather Reports* (*DWRs*) and considering the area defined by 4½°W, 10½°W and 51½°N, 55½°N.

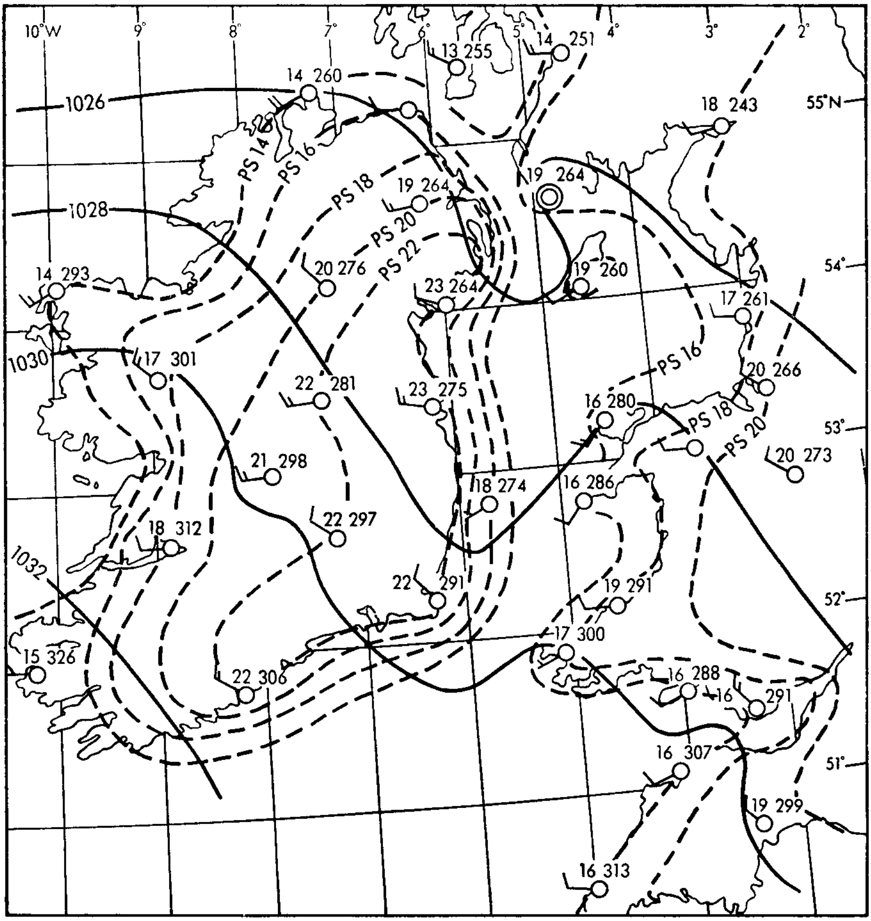

FIGURE 4—SYNOPTIC SITUATION AT 18 GMT ON 10 JULY 1969

——— isobars - - - - isotherms

From the data remaining the wind direction change between 09 and 18 GMT (backing was taken as negative) and also the 18 GMT Dublin minus Valley temperature difference ($T_D - T_V$) were extracted from the *DWR*s.

RESULTS AND DISCUSSION

Figure 7 shows a plot of all the data. The two sets of results show striking differences.

For the winter period 109 days were considered. Backing by 10° or more occurred on 43 days (39 per cent) and veering by 10° or more occurred on 45 days (41 per cent) i.e. no bias towards backing is evident. The mean value of $T_D - T_V$ was —1·7°C partly because by 18 GMT in winter rapid diurnal cooling is occurring at Dublin whereas at Valley with the wind off the sea little change is taking place.

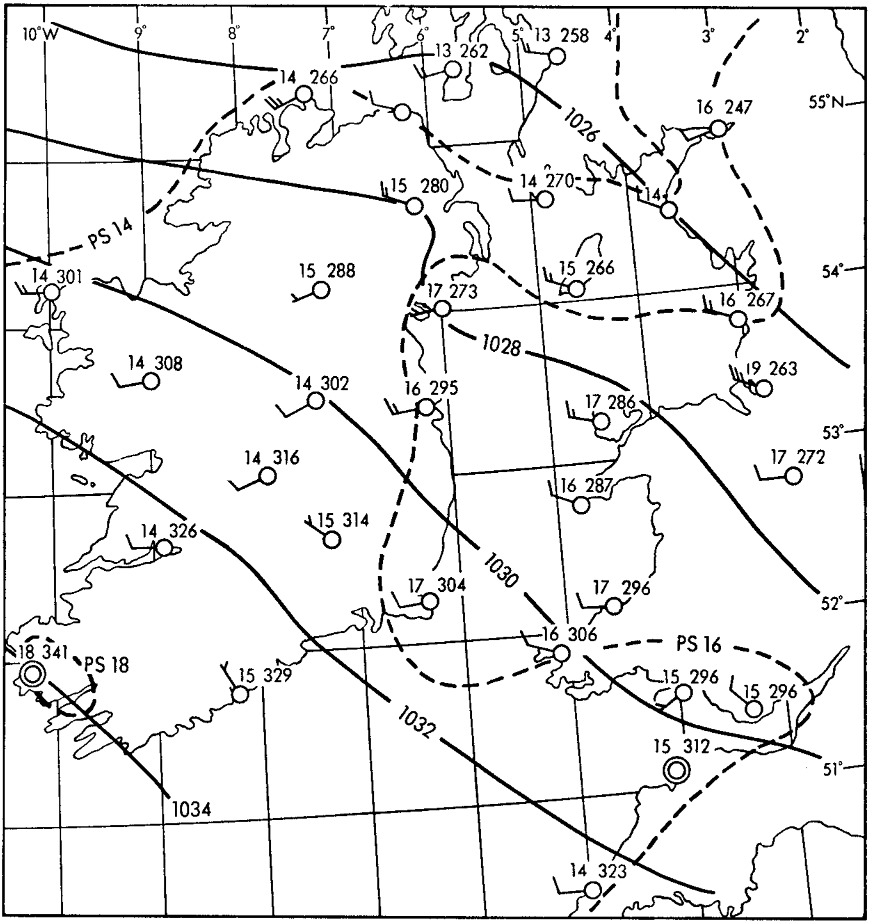

FIGURE 5—SYNOPTIC SITUATION AT 00 GMT ON 11 JULY 1969

——— isobars - - - - isotherms

For the summer period 76 days were considered. Backing by 10° or more occurred on 63 days (83 per cent) and veering by 10° or more occurred on 12 days (16 per cent). The mean backing was 47° and the standard deviation 40°. A statistical *t*-test on the null hypothesis that there is no bias towards backing indicates that such a large mean has less than 1 chance in 1000 of arising by accident of the sample. The mean value of $T_D - T_V$ was 1·3°C. However, over this sample, which includes a variety of synoptic situations (rather than the single situation prevailing from 10 to 12 June 1969) the amount of backing is not closely related to the temperature difference. At times large values of backing occurred with only a small $T_D - T_V$ value. Nevertheless a linear regression of $T_D - T_V$ on the change of wind direction yields a correlation of 0·25 which is statistically significant at the 5 per cent level.

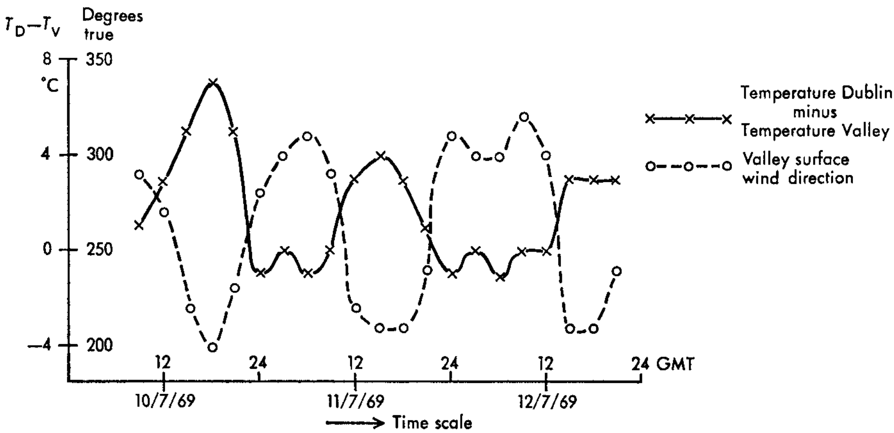

FIGURE 6—ASSOCIATION BETWEEN SURFACE WIND DIRECTION AT VALLEY AND TEMPERATURE DIFFERENCE BETWEEN DUBLIN AND VALLEY FROM 10 JUNE TO 12 JUNE 1969

Figures 8 and 9 show an example of a day when temperature gradients were fairly weak and yet a marked isobaric trough developed over the Irish Sea. On this day the air mass was of polar origin, and showers occurred in the windward coastal areas of Ireland throughout the previous night. By mid morning, as the showers extended to eastern Ireland, a minor pressure trough developed near the eastern Irish coast and apparently remained between Ireland and Wales until it died out during the evening. It is suggested (without much theoretical support) that strong convection occurring over land will lead to a fall of pressure over the land relative to the sea and thus reinforce the Irish Sea trough.

On the few occasions when backing did not occur, it was usually found that the gradient wind over Ireland had veered to a northerly point. This meant that the thermal trough development occurred over southern and not eastern Ireland.

Although the results obtained apply strictly to Valley only, it is probable that they could usefully be applied to the Irish Sea and the west coat of Wales, south of Anglesey. For example, in summer sailing races take place frequently between Holyhead and Dun Laoghaire (near Dublin). It would be of considerable advantage for a competitor to know that despite a shipping forecast giving north-westerly winds, the winds over the route during the afternoon would very likely be south-westerly. Similar effects should occur over any similar land–sea configuration. Thus for example it might be possible to demonstrate that, with northerly winds over the English Channel area, surface winds tended to back to westerly over coastal areas of northern France during summer afternoons.

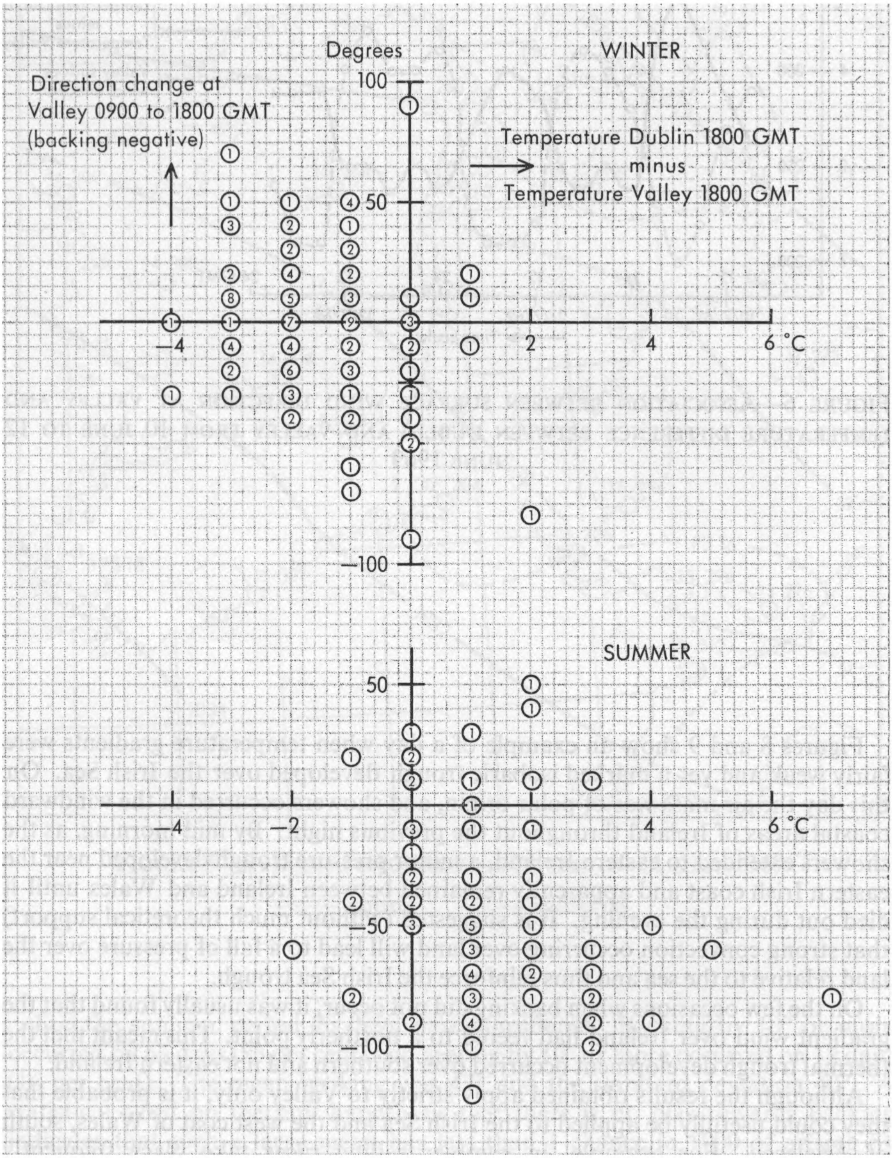

FIGURE 7—RELATION BETWEEN DIRECTION CHANGE AT VALLEY FROM 09 TO 18 GMT AND TEMPERATURE DIFFERENCE BETWEEN DUBLIN AND VALLEY AT 18 GMT

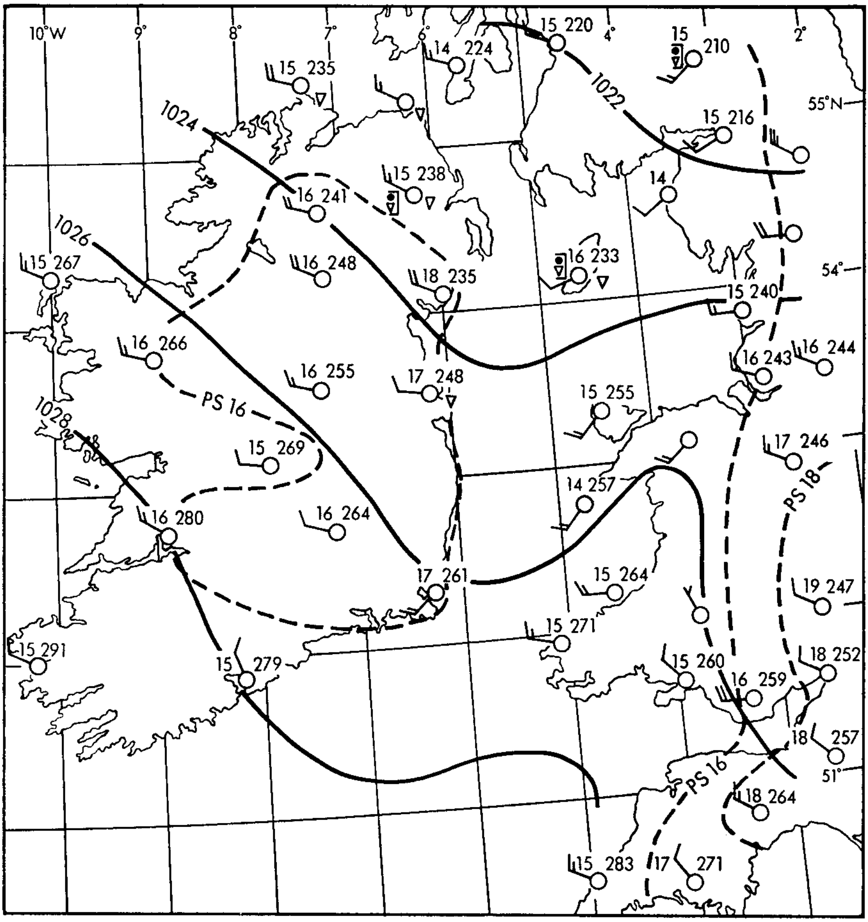

FIGURE 8—SYNOPTIC SITUATION AT 15 GMT ON 27 JUNE 1969

——— isobars - - - - isotherms

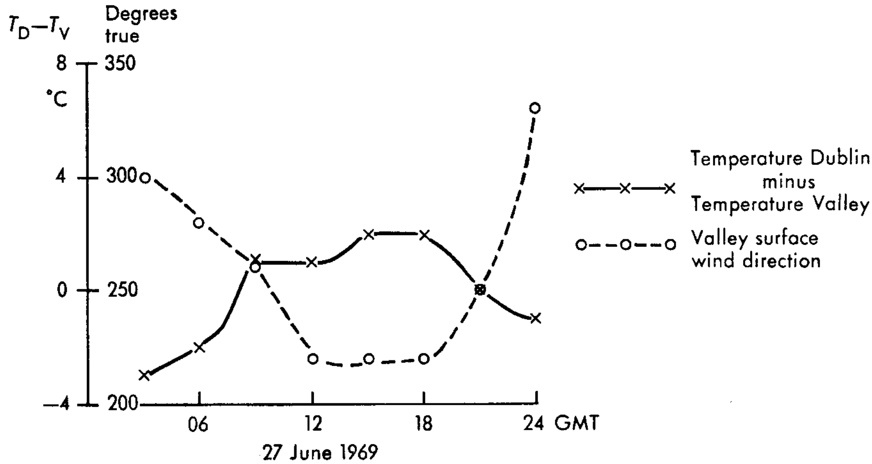

FIGURE 9—ASSOCIATION BETWEEN SURFACE WIND DIRECTION AT VALLEY AND TEMPERATURE DIFFERENCE BETWEEN DUBLIN AND VALLEY ON 27 JUNE 1969

ACKNOWLEDGEMENT

The author would like to thank Mr C. L. Hawson of the Meteorological Office, Bracknell for his assistance and advice in the preparation of this paper.

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THE WORLD METEOROLOGICAL ORGANIZATION TECHNICAL CONFERENCE ON INSTRUMENTS AND METHODS OF OBSERVATION (TECIMO), HAMBURG, FEDERAL REPUBLIC OF GERMANY, 27–30 JULY 1977

By D. N. AXFORD

A Technical Conference on Instruments and Methods of Observation (TECIMO) was held in Hamburg from 27 to 30 July 1977. The conference was arranged to precede the seventh session of the WMO Commission for Instruments and Methods of Observation (CIMO VII) which was also held in Hamburg from 1 to 12 August 1977. In parallel an international exhibition of instruments (METEOREX 77) was organized by the host country from 28 July to 3 August, thus covering the last three days of TECIMO and the first three days of CIMO VII.

The Technical Conference was well attended, with over 120 participants from more than 35 countries. The UK delegation consisted of Dr D. N. Axford, (Assistant Director, Operational Instrumentation), Mr A. H. Hooper (Observational Requirements and Practices Branch) (both of the Meteorological Office) and Lt Cdr R. A. Young, RN (Directorate of Naval Oceanography and Meteorology). It was opened at 9.30 a.m. on Wednesday 27 July 1977 with speeches of welcome from Mr H. Treussart, the President of CIMO and Dr M. Hinzpeter, the Conference Director. This first day of the conference was introductory, covering a wide variety of subjects. The United Kingdom was well represented in the morning with a paper on the joint project organized by the Institute of Hydrology and Heriot-Watt University to develop a suitable Automatic Weather Station (AWS) for the severe environment on Cairn Gorm, a paper on the microprocessor-based AWS being developed in the UK Meteorological Office, and a further paper on the Mk 3 radiosonde with special emphasis on the software involved. The afternoon session included a description of the new facilities for atmospheric research and instrument comparisons which are being installed for the Atmospheric Observatory of the National Center for Atmospheric Research (NCAR) at Boulder, Colorado, USA, an up-to-date review by Dr E. Jatila (of the WMO Secretariat) of the WMO FGGE (First GARP Global Experiment) Navaid Sounding System, and an interesting paper by Mr H. Treussart on methods of transmission and presentation of weather radar data.

On Thursday and Friday the papers were divided into four themes. The first theme concerned 'Development of New Sensors for Basic Parameters' and was chaired by Dr M. Hinzpeter. In fact there was little sign of any new breakthrough in this area, although the session was enlivened by a fascinating five minute film showing a composite weather radar display produced by the Meteorological Research Unit at Malvern.

The second theme 'Acquisition and Processing of Data associated with Automatic Surface Systems' was chaired by Mr A. H. Hooper (UK). Here the continuing world-wide progress and development of AWS became apparent. Papers from (amongst others) France, Canada, New Zealand and Finland showed that the requirement for automating the measurement of meteorological variables is well recognized. There is a variety of approaches for meeting this need. Hardwired modular analogue systems for use in remote sites were described by participants from Canada and New Zealand, and the French and Finnish papers described micro-computer-based AWS similar to those being developed in the United Kingdom. A particularly interesting paper (in the writer's opinion) was that by D. J. McKay and J. D. McTaggart-Cowan on 'An intercomparison of radiation shields (screens) for AWS'. It described a trial involving an array of 19 sensors and screens varying from the standard Stevenson screen to the Israeli Thaller screen, and the measurement of the distribution of temperature errors in the various screens from an accurate reference temperature. Much comment was provoked by the histograms of the various mean hourly errors, and of maximum and minimum errors. They showed 90 per cent of hourly readings within $\pm 0{\cdot}5$°C of the reference for all screens, and for some screens 90 per cent of hourly readings are within $\pm 0{\cdot}2$°C of the reference (which meets the WMO requirements for automatic weather stations). It was clear that none of the available screens, ventilated or unventilated, meet the stated WMO requirement of $\pm 0{\cdot}1$°C for synoptic measurements.

The third theme 'Methods of measuring upper-air parameters, direct and remote techniques' was chaired by Dr F. Finger (USA). It was interesting to hear the French and Americans describing their automated and semi-automated systems, and to recognize that the United Kingdom Meteorological Office has not been alone in finding the road to a fully automated upper-air system to be long and difficult. A paper from the USSR described a different approach in which the raw data from three sonde stations are fed to a centralized computer system for processing. A lot of discussion was generated by Mr E. A. Spackman's (UK) paper on 'The Compatibility and Performance of Radiosonde Measurements of Geopotential Height in the Lower Stratosphere'. The paper describes results from a computer program which, twice a day since 1975 for a large number of radiosonde stations in the northern hemisphere, has been measuring the difference between (a) values of the geopotential of the 100 mb and other stratospheric standard levels as reported by the stations and (b) values at the same points derived from the objective computer analysis. Differences have also been measured between observed geopotentials at 00 GMT and 12 GMT for each of the radiosonde stations. The results showed interesting variations between one sonde type and another, between the various national results, and even between one large area and another using the same sonde. Discussion centred around the feasibility of these results being fed back on a routine basis to the regional national centres in order that corrections can be applied where necessary.

The final session was on the 'General Operational Aspects of Meteorological Instrumentation' and was chaired by Dr D. G. Rozhdestvensky (USSR). It included a summary paper by Dr H. Yates (USA) on the new generation of US Operational Satellites.

In the intervals between the formal papers and proceedings, and also after they were all concluded, there was time to visit the METEOREX 77 Exhibition where 80 exhibitors and firms had stands and displays covering all aspects of meteorological instrumentation. This was particularly useful in that various points arising from some of the papers could be taken up immediately with the designer or manufacturer. For example the Canadians' description of their low-level Mini-Sonde System was greatly enhanced by a quick visit to see it on the Canadian stand. This overlapping of conference, exhibition and CIMO itself was greatly appreciated.

The organization and administration of the conference and exhibition, under the direction of Dr M. Hinzpeter and the National Meteorological Institute of the Federal Republic of Germany was excellent. The UK participants found the conference papers, the exhibition and the numerous discussions with other workers in the same field stimulating and enjoyable, and, of course, there was also the opportunity to see the sights of the City of Hamburg, which has beautiful parks and lakes, and to verify the words of the song 'In Hamburg sind die Nächte lang'. (See Plates II–V.)

REVIEWS

The physics of atmospheres, by J. T. Houghton, 240 mm × 170 mm, pp. xiii + 203, *illus.*, Cambridge University Press, Bentley House, 200 Euston Rd, London NW1 2DB, 1977. Price: £6.50.

In this small book Professor Houghton attempts to introduce the major areas of study involved in the physics of electrically neutral atmospheres to undergraduate and postgraduate students. Although the treatment is brief, this aim is achieved. Much of the book is devoted to radiative processes and in addition to being an introduction to this topic the book will be a reference for non-specialists.

Basic ideas and simple radiative-equilibrium models are treated in the first two chapters and a chapter on thermodynamics introduces the effects of water vapour on atmospheric structure. This chapter also includes a discussion of the components of the atmospheric energy budget but this would have been better included in the dynamics section where related topics are discussed.

The treatment of the upper atmosphere is a catalogue of the physical processes in this region and although the range of processes is made clear the relative importance of each mechanism is not obvious. The section requires a more extensive background knowledge than most of the others. The condensation and coalescence mechanisms of droplet growth are described under the title 'clouds' but the important dynamical processes are ignored. The effects of cloud on radiative transfer are described in some detail but the influence of radiation in creating fogs is not mentioned.

Almost half-way through the book the subject of dynamics is introduced with an explanation of partial derivatives and a derivation of the equations of motion in a rotating frame of reference. The geostrophic approximation and the thermal wind equation are derived in a conventional manner. Perturbation methods are used in the subsequent chapter to obtain wave solutions of these equations with carefully stated approximations. This will form a useful introduction to the subject although the inclusion of the diagram, from a COSPAR report, purporting to show gravity waves, will not aid the interpretation of these ideas. Turbulence is introduced in Chapter 9 by reference to the turbulent boundary layer and the author develops the theories of eddy stresses and the Ekman spiral. The treatment is basic but can be extended through the use of problems at the end of the chapter. The turbulent nature of larger-scale flows, both two- and three-dimensional and the energy spectrum are briefly mentioned.

Barotropic and baroclinic instability are discussed in a chapter on the general circulation and some fundamental properties are derived for systems of simple geometry but there is little to relate them to atmospheric observation. An account of the development of numerical models is given but this is confined to models of large-scale flows. Mesoscale and smaller-scale models, and the differences in the physics on such scales are scarcely mentioned. The treatment of the so-called physical processes in numerical models is rather unbalanced, with an extensive treatment of radiation, but convection (not all models use a simple convective adjustment) and the effects of topography (not all models employ sigma co-ordinates) are confined to single paragraphs. The observations required for numerical models during the Global Atmospheric Research Program (GARP) are discussed in the subsequent chapter. A good basic account is given of the retrieval of temperature and atmospheric-composition data from satellite observations but the remote determination of surface pressure or winds is not discussed. The final chapter on atmospheric predictability describes attempts being made to improve numerical models but in my opinion fails to emphasize the necessity of undertaking fundamental studies of the processes determining the predicability of the atmosphere.

An extensive and up-to-date bibliography is provided and in an appendix extensive tables of atmospheric properties are given but in a book of this type it is doubtful whether tables of model atmospheres or spectral-band information are necessary.

To summarize, this is a readable book which provides a useful summary of the many processes occurring in the atmosphere. It is well presented with generally clear diagrams and the problems provided to amplify and extend the text will be appreciated. The main drawback of the book, as with many attempts to summarize a wide field, is the lack of balance, reflecting as it does the author's interests. The book will be a useful introduction to radiative processes for many, and indeed may serve as a reference in this subject to the non-specialist. It is to be hoped that the remainder will sufficiently whet the appetite of the reader that he will be encouraged to read the more detailed books and papers referred to.

P. R. JONAS

Stratocumulus undulatus at St Mawgan

The photograph which is reproduced as Plate I in this issue was taken at St Mawgan, Cornwall at 0819 GMT on 20 April 1977 looking in a north-easterly direction. The cloud is a good example of stratocumulus undulatus. At the time of the photograph the surface wind was 210° 7 kn, dry-bulb temperature 10·4°C, wet-bulb temperature 9·2°C, relative humidity 85 per cent, and MSL pressure 1030·6 mb. The cloud was estimated to be at about 3500 ft ($\approx$1000 m). The surface analysis for 00 GMT shows a slow-moving very weak warm front oriented SW/NE and lying close to St Mawgan. The radiosonde ascent made at the same time at Camborne shows an inversion and increase in moisture at 890 mb which was obviously associated with the front; the stratocumulus appeared to form near this inversion.

C. A. STUMBLES

Obituary

It is with great regret that we have to record the death on 9 June 1977 of Dr T. W. Harrold, Principal Scientific Officer, of the Operational Instrumentation Branch (Met O 16).

Terry Harrold joined the Office in 1961 and from 1962 to 1971 was stationed at the Meteorological Research Unit at Malvern where he worked on a variety of problems involving the use of radar. His great ability and the quality of his published work on the measurement of rainfall and frontal air motion, and on severe storms in Oklahoma, were recognized in 1967 by the award of the L.G. Groves Second Memorial Award. In 1971 he took the degree of Ph.D. of London University (Imperial College). In 1972 he was awarded the Buchan Prize of the Royal Meteorological Society jointly with Dr K. A. Browning.

In October 1971 Dr Harrold was promoted P.S.O. and joined the Agriculture and Hydrometeorology Branch where he was put in charge of the Meteorological Office team concerned with the Dee Weather Radar Project; he made a major contribution to the success of the project which demonstrated the ability of radar to provide good estimates of areal rainfall over hilly terrain.

In August 1975 he was posted to the Operational Instrumentation Branch where he worked on the development of automatic weather stations for use on land and at sea.

In addition to having high scientific ability, and the gift of thinking quickly and clearly, Terry Harrold was possessed of much personal charm; colleagues who sought his help and co-operation or who talked to him socially always felt they had his complete attention.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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RAINFALL AT OXFORD FROM 1767 TO 1814, ESTIMATED FROM THE RECORDS OF DR THOMAS HORNSBY AND OTHERS

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SUMMARY

An account is given of an examination of the surviving meteorological records made by Dr Thomas Hornsby, leading to the estimation, from this source and from other evidence, of monthly rainfall totals for the Radcliffe Observatory for the years from 1767 to 1814, linking with the Radcliffe instrumental record which has continued from 1815 to the present day.

1. INTRODUCTION

The record of meteorological observations made at the Radcliffe Observatory, Oxford from 1815 onwards is the longest and probably the best documented of any for a single site in Great Britain. This attempt to extend the record backward into the past began as part fulfilment of a contract made with one of us (J.M.C.) by the Natural Environment Research Council to produce homogeneous rainfall records for as far back as the evidence will justify. Each district presents problems of its own, and for the Oxford area there is a clear distinction between the period from 1815 onwards, for which there is an almost complete series of daily observations to the present day, and the period before 1815, for which the evidence is fragmentary, incomplete and often indirect. This paper deals with the early period in which the direct evidence consists almost entirely of the surviving manuscript records of Dr Thomas Hornsby. These records, which are now kept in the Library of the School of Geography at Oxford, were made by Dr Hornsby for his own use, and lack most of the information on units, sites and instruments which should appear in a record intended for publication. There are gaps where Hornsby failed to take the observations, gaps where some of his original records have been lost, and incredible readings which have to be replaced by reasonable estimates. Nevertheless, the authors feel that the series of estimated monthly rainfall totals for the Radcliffe Observatory site will bear comparison with those for the years after 1815, and the paragraphs which follow provide the justification for the values offered for the years from 1767 onwards. The investigation falls into two parts:

(i) The interpretation of Dr Hornsby's manuscripts and the conversion of his figures into modern units familiar to the readership, and

(ii) The estimation, from this and other evidence, of what would have been caught in each month from 1767 to 1814 by a modern rain-gauge with rim 1 ft above ground in today's observing site at the Radcliffe Observatory.

These steps we carried out in order, and when the first stage was complete, we sent copies to Professor Gordon Manley, Mr C. G. Smith of Keble College, Oxford and Mr B. G. Wales-Smith of the Meteorological Office for information and comment. Professor Manley provided a copy of a rainfall record made at Shirburn Castle, about 12 miles from Oxford, which was previously unknown to us, and more recently Mr C. G. Smith has provided us with the results of his own researches into sources in Oxford, including a revised version of the Shirburn record, which confirm our main inferences. Mr Wales-Smith has provided data for stations around Oxford which form the basis for our estimates for the years for which credible measurements at Oxford or Shirburn are lacking.

2. The background

According to the Dictionary of National Biography, Thomas Hornsby was born in Oxford in 1733. C. G. Smith, in a private communication, states that he entered Corpus Christi College, Oxford in 1750, took his B.A. in 1753 and his M.A. in 1757. By the next year Hornsby must have met the Revd William Borlase (1695–1772), rector of Ludgvan, near Penzance, whose 'Natural History of Cornwall' was published in Oxford in 1758. It is not clear how they met, and developed their interest in rainfall measurements, but Borlase, who was elected a Fellow of the Royal Society in 1750, and who had started his own weather record on 10 January 1753, consulted Hornsby on the design of an 'ombrometer', or rain-gauge. Much of Borlase's correspondence has survived in libraries in Cornwall, and extensive extracts have been quoted by Oliver (1969). Dated letters establish the development of Hornsby's ideas on rain-gauging. Hornsby was elected a Fellow of Corpus Christi College, and in 1761 he observed the transit of Venus at the private Observatory of the Earl of Macclesfield at Shirburn Castle. This observatory was set up in about 1739 with the advice of James Bradley, the Savilian Professor of Astronomy. In 1763 Hornsby was elected a Fellow of the Royal Society, and in the same year he succeeded Bradley as Savilian Professor. It seems that Hornsby must have married at about this time, since his elder son was born in 1766, and on marrying he would have had to vacate his college rooms. He must have occupied the house which from the time of Edmund Halley had been leased by New College to the University for the Savilian Professor and this is the most likely site of the rain-gauge he used from the year 1767. Borlase, writing on 27 July 1767, commented that Hornsby's situation was 'much surrounded by buildings and walls', a state liable to affect his meteorological observations, and it seems that his house was not ideal for astronomical observations either since, according to C. G. Smith, Hornsby observed the transit of Venus on 3 June 1769 from the Tower of the Schools (Bodleian Library). In 1772 Hornsby was appointed to be the first Radcliffe Observer, and laid the foundation stone of the Radcliffe Observatory in the same year. It seems that the main Observatory building was largely complete by 1779 although, because of shortage of money, the external decoration was not completed until 1794. However, the Observer's House was ready for occupation by

1776, and it may be that the burden of moving house, added to Hornsby's other commitments, led to the cessation of his rainfall observations in that year. The building and the telescopes, which were the finest of that time, included two quadrant instruments, and the total cost was £28 000, a figure which may be compared with Bradley's stipend as Savilian Professor, which was £100 per annum. In 1782 Hornsby was appointed Sedleian Professor, a post which made heavy demands on his time, and in 1783 he became Radcliffe Librarian. Five papers by him were read before the Royal Society, at dates between 1763 and 1773, while several sources suggest that his courses of lectures gained considerable renown. He had also undertaken to edit Bradley's 'Astronomical Observations' for the Clarendon Press, but because of ill health (he was epileptic) or more probably, sheer overwork, the first volume did not appear until 1798, after more than 20 years' delay. Hornsby died in Oxford in 1810.

3. The hornsby manuscripts

These are the bare facts of a mainly astronomical career, but Hornsby's interest in meteorology must date from before 1758, when he informed Borlase of the dispatch of a rain-gauge. Hornsby's weather records, or at least the ones known to have survived, are contained in two ledgers and some loose sheets which are now kept in the Library of the School of Geography in Oxford. The ledgers contain many pages of what seem to be astronomical calculations, with some weather notes which appear to have been inserted later, as if the blank pages were being put to use after the books had served their main purpose. Most of the loose sheets seem to have been torn from similar books, although there is nothing to show whether this was done by Hornsby himself, or subseqently. Taken in order, the weather notes cover the year 1760 and part of 1761, then an almost complete daily record for 1767 to 1776, and another from July 1794 to 1805. There is also a single loose sheet on which Hornsby has extracted the annual rainfall totals for 1795 to 1802, but also gives totals for the preceding years 1785 to 1794, and other sheets on which some of the monthly rainfall totals for years between 1795 and 1802 are summed to obtain the annual totals. These appear to be rough working sheets. The entries consist mostly of the date and time, followed by the barometric pressure and the temperature, the wind direction, and the rainfall, if any, and finally the state of the weather. Occasionally notes and phenological observations are written across the columns, but with these exceptions, there is nothing to explain how the observations were taken, and the units in use have to be deduced from occasional initials above the columns, from a few conversion tables which Hornsby obviously made for his own use, or from the observations themselves. With the agreement of Mr C. G. Smith, we visited the School of Geography several times, and examined the Hornsby manuscripts minutely, with the results to be described. Hornsby, as an astronomer, was used to carrying out calculations to a great many places of decimals, a habit that is most necessary in astronomy—which after all, was his main preoccupation—but rather out of place in meteorology. However, we should remark that while we carried out our work with the help of modern technology, such as electric light, motor transport, ball-point pens and electronic calculators, Hornsby probably had to manage with candles, a horse, quill pens and his own skill in calculation, so that the question we constantly had to ask ourselves was 'What would an intelligent man do in this situation, with the resources at his command?'.

4. A GOOD LOOK AT THE RECORD

As mentioned already, the record falls into three parts, as follows:

(i) The first part starts in January 1760 (or at least, the part which has survived does so). This is obviously the work of a young and inexperienced man, because, while the writing is firm and neat, the entries show that Hornsby was not sure what he was looking for. This part includes measurements of rain, which, in all probability, were made with the rain-gauge of 3 inches square, referred to in the correspondence between Hornsby and Borlase mentioned by Oliver (1969). This gauge led to a pipe which descended from the roof into a collecting vessel in his room, a system used earlier by Towneley (1694) and Derham (1698), as well as in the later record at the Radcliffe Observatory from 1815 until 1879.* It is a fair inference that Hornsby made all his rainfall measurements with instruments of this kind, though not necessarily in the same place, or with collecting vessels of the same dimensions or pattern. The observations are kept regularly during 1760, but become scrappy in 1761, and peter out in March.

(ii) The observations in 1767 show all the signs of being a fresh start. They start at the beginning of the year, at the top of the page, and continue without much change of content. Evidently, by this time Hornsby had decided what his observing routine was to be, and intended to keep to it. His pages were ruled by hand, and some years are in the bound ledgers, in what appear to be the pages left unused after his astronomical calculations. There are two or three observations per day, with hardly any gaps, although there are two or three places where he has not formed a monthly total from his daily values on account of his having spent part of the month at 'Sherburn'. From 1769 there are some gaps during the summer, including one when Hornsby made the considerable journey to Ludgvan to visit William Borlase on 28 July 1770. From 1775 there are plain signs that Hornsby, though still maintaining the content of his record, was suffering from overwork. There are spaces left for results which have never been worked out, and in 1776 the register comes to an abrupt halt, without explanation.

(iii) The third section of the register probably started at the beginning of 1785, although the part preserved in the Hornsby manuscripts starts in July 1795. The reason for thinking this lies in the single sheet on which Hornsby, in about 1803, listed his annual rainfall totals, presumably in the hope of seeing whether they followed any recognizable pattern. There is no trace of the daily workings or monthly summations for 1785 to 1793, but the sum for January to June 1794 is carried from another sheet, now lost, and added to the actual total for the months July to December, for which the daily records have survived. It is reasonable to think that daily entries once existed for the whole period 1785 to June 1794, perhaps in another ledger. Hornsby must have known the year in which he resumed his observations, and would hardly have headed his sheet with 1785 if there had been no data for that year. This point is emphasized for the reason discussed in section 8, that he seems to have missed out one of his annual totals. Hornsby's handwriting changes over the 45 years covered by these records, and by 1805 was that of a very old man, who found it a burden to put

* *Note.* Another rain-gauge at ground level was also used from 1851.

pen to paper. There is no terminal paragraph, like that with which Samuel Pepys ended his diary, but Hornsby's entry in August 1805 suggests a man at the end of his physical resources.

5. Making sense of the data

For the first period, January 1760 to March 1761, entries seem to have been made only on the days on which rain fell, the receiver being emptied after each fall. A typical reading for 29 January 1760 is 42·1 and for 18 February 1761 is 0 47¾ while the monthly totals range from 0 49¼ to 3 03. There is no indication of the units used, but Hornsby's monthly totals agree with the constituent daily figures only if his larger unit is 72 times the smaller. The explanation can be inferred from a letter to a third party (St Albyn) by William Borlase, who consulted Hornsby in matters of instrumentation. This is given verbatim by Oliver (1969) 'My vessel that receives the rain is exactly 3 inches square at the upper orifice, which being in number of 9, as soon as I have 9 inches in the tube or bottle, I conclude that (there is) one cubical inch of water in the area of one square inch. The collecting vessel was of tin and was made for me in the year 1758 by the Revd Mr Hornsby, now Savilian Professor at Oxford from a pattern which he made use of in his own apparatus'. This implies that the measuring vessel was of 1 square inch in cross-section, and at least 9 inches deep, so that unless it had a glass insert, it must have been very difficult to read. Probably Hornsby decided very soon that he must find a better solution to the problem of measurement. Writing on 17 October 1758, he described the construction of his own rain-gauge, and explained how, by pouring into his measure known quantities of water, he could graduate it first into 9 one-inch divisions, each equivalent to 1/9 inch of rain, and then 'by eye' subdivide these into 8, so that he could measure to a scale accuracy of 1/72 inch. These extracts imply that the first section of Hornsby's record started in the year 1758 if not earlier. It is also noteworthy that the directions will apply to the graduation of any glass tube of reasonably constant cross-section, and it seems likely that Hornsby, like Borlase, used a graduated glass tube reading directly in inches. There may be more information in his original letters, if these are included in the volumes of Borlase's correspondence which have survived, since Oliver (1969), who provides the extracts, was interested in Borlase rather than Hornsby. We hope to work through Borlase's original correspondence at a later date. On 18 June 1767 Hornsby wrote to Borlase suggesting that it was best if rain-gauges were graduated by weight 'using a hydrostatical balance on the assumption that a cubic inch of rain weighed 253 grains'. These facts enable his early readings to be reduced to inches in Table I.

Table I—Monthly totals recorded in 1760 and 1761, in inches, not corrected for elevation of gauge

	J	F	M	A	M	J	J	A	S	O	N	D	ANN
1760	1·03	1·47	0·52	—	1·29	1·62	0·21	0·23	1·53	2·34	0·75	1·00	—
1761	0·03	0·85	0·67	—	—	—	—	—	—	—	—	—	—

These observations were probably made by Hornsby in his college rooms (of which the exact location cannot be determined from the College records), with the collecting funnel of the rain-gauge above the roof; a loss of catch of at least 10 to 20 per cent seems probable, compared with a modern gauge in a standard exposure.

6. Problems of site and measurement

When Hornsby resumed his record in 1767 he must have been living in the house provided by the University for the Savilian Professor, and probably had his rain-gauge there. The record starts in January 1767 with what looks like a burst of enthusiasm, but soon settles down to a regular routine. It seems that the rain was measured after each considerable fall, and the units look puzzling, as the columns, which usually are not headed at all, are sometimes headed 'inches' and 'pwt'. A typical entry is 0 34¾ for 13 February 1767, and comparison between daily and monthly totals soon shows that the smaller unit is now 1/36th part of the larger. Evidently Hornsby graduated his measuring cylinder to read directly in inches of rain and thirty-sixths. At the end of July 1767 he notes 'On 30th I found that the rain from a fault in the tiling came into the room on the outside of the tin tube, and from thence into the glass. I therefore had a piece of tin put on yesterday in order to prevent it in future. In hard rains I fear this has happened before, particularly in June—perhaps in January and February'. This extract supports the description of the gauge which he gave to Borlase in a letter dated 3 March 1767. Hornsby continued with these units, apparently until January 1775, but then comes a very important change, without any comment, because the entry for February 1775 reads:

	lb	oz	dwt	gr
Weight of rain and glass	9	3	4	10
Weight of glass	3	11	6	21

7. The final choice of site and gauge

From this date until September 1776, the entries are by weight, with conversions into inches in most months. A typical entry, for October 1775, is 10 0 21 6 = 2·462460. These entries show that the equivalence of one inch of rain is a weight of just over 4·09 lb, whereas with a circular rain-gauge of 12 inches diameter, one inch of rain weighs 4·0906 lbs. The use of a measuring cylinder of 1 inch cross-section is clearly not a practical proposition with a rain-gauge of this size, but it is interesting to find, among the records, a scrap of paper which suggests that Hornsby took the trouble to investigate the matter. This scrap bears a calculation, without heading, which finds how long such a cylinder would have to be if it was to measure up to 12 lb of water. The answer comes to nearly 7 feet, so perhaps Hornsby envisaged himself grovelling on the floor, or climbing a ladder, to measure his rainfall, and decided to stick to measurement by weight. The appearance of a 12 inch circular gauge in 1775 is very significant, since the building of the Radcliffe Observatory started under Hornsby's direction in 1772, and after two years some of the rooms must have been fit for occupation. The gauge on the East Wing of the Observatory, which was in regular use from 1815 up to 1879, was of this diameter, and had a tube leading from it to a receiver in the quadrant room, which would have been needed for two of the telescopes installed by Hornsby, so there is a strong probability that the gauge installed by Hornsby in 1775 was left in place after he stopped making observations in 1805, and brought back into use again in 1815. Support for this view exists in the form of some intermittent observations dating from 1811, until the continuous record was resumed, actually in April 1814. We are indebted to Mr C. G. Smith for a reference to Gunther (1923) who states in a footnote 'On Dec. 31, 1774 P. and J.

Dolland supplied a copper funnel for a pluviometer for £2 12s 6d'. Rigaud (1835) describes a copper funnel which, if our inference is correct, is the same funnel, as having a mouth 12 inches in diameter and a depth of 10½ inches and gives its exact position above the East Wing of the Observatory. This must be the gauge which continued in use until 1879, and was replaced by Knox-Shaw and Balk during the 1920s to estimate the factors needed to correct the readings to modern standards. These factors are discussed in section 10, but a mean factor for all months of 1·130 seems adequate. Values as observed up to 1776, without correction for exposure etc. are given in Table II.

TABLE II—MONTHLY TOTALS FROM JANUARY 1767 TO SEPTEMBER 1776

	J	F	M	A	M	J	J	A	S	O	N	D	ANN
1767	(5·12)	(5·13)	1·72	0·55	3·13	5·81	(5·76)	2·92	2·20	3·56	0·86	0·24	(37·00)
1768	2·14	1·95	0·13	2·49	1·23	4·13	2·40	1·25	5·35	3·31	2·66	2·16	29·21
1769	1·08	1·64	0·85	0·61	1·79	2·78	—	—	—	0·43	1·71	2·05	—
1770	0·63	0·90	1·89	0·76	1·88	2·95	0·60	(0·84)	—	0·76	6·02	2·33	—
1771	0·43	0·71	1·16	0·76	0·68	2·06	0·90	1·97	(0·69)	3·29	0·42	0·89	13·96
1772	3·05	2·80	2·33	1·24	1·42	1·22	0·97	2·26	3·88	2·72	5·19	1·01	28·09
1773	0·97	0·49	0·35	1·46	4·85	0·81	0·98	2·53	2·51	1·39	3·93	1·63	21·90
1774	2·78	2·03	2·77	0·49	0·35	1·27	1·38	2·11	7·01	0·35	1·28	(0·00)	21·82
1775	2·25	1·34	2·21	2·48	1·26	2·54	1·29	4·36	4·64	2·46	2·27	0·09	27·19
1776	(0·00)	2·89	2·09	0·29	0·89	3·46	2·35	3·83	1·79				

8. A PROBLEM OF COPYING

As mentioned in section 4, Hornsby seems to have been suffering from overwork in 1776, which is not surprising in view of the number and variety of his commitments, and Mr C. G. Smith points out that he also had the burden of a domestic removal, since the Radcliffe Observer's house was ready for occupation in that year, and the minor annoyances inevitable when working in a partly finished Observatory building. This probably explains why he stopped making his rainfall observations, and did not resume until 1785. The evidence for this resumption lies in a single sheet of paper on which, in about 1803, he extracted the annual totals from 1785 on. It seems that he wrote the year numbers first and then the yearly totals, because it happened that the annual totals for 1794 and 1795 were very much alike, and that he got the preceding totals one year out of step. However, the mistake can be corrected, by reference to some of his monthly summations and to the annual totals recorded at the closest neighbouring stations, Stroud and Shirburn. Comparative annual totals are given in Table III (a) and his monthly totals from 1795 to 1805 in Table III (b).

9. HOMOGENIZATION—THE RELEVANT EVIDENCE

The investigation has so far described what was actually observed by Dr Hornsby, and has given in inches of rain what he measured with several rain-gauges in different situations. To produce figures for the period 1767 to 1814 which are comparable with the measurements being made at the Radcliffe Observatory today, conversion factors must be applied to Hornsby's data, and reliance must also be placed on evidence from some of the stations listed in Table IV. None of these stations is very close to Oxford, and it is not suggested that the daily rainfall at any of these stations would provide a good estimate of the rainfall at Oxford on the same day. Nevertheless, the ratios of annual totals at these stations to those at Oxford show a measure of constancy which is evident in Table III (a), and which can be expressed in numerical terms. The monthly variation of rainfall within the year also show a good deal of consistency over

TABLE III—MONTHLY AND ANNUAL RAINFALL TOTALS FOR OXFORD 1785–1805 AS GIVEN BY DR HORNSBY WITHOUT CORRECTION

(a) Annual totals 1785–94 (assigned to the right years)

	1785	1786	1787	1788	1789	1790	1791	1792	1793	1794
Hornsby	16·495	20·697	19·528	12·305	27·755	17·095	20·518	25·465	19·952	22·023
Shirburn	20·24	22·18	23·88	16·50	29·13	20·72	22·70	30·84	23·52	26·32
Stroud	24·13	30·88	29·64	18·51	37·99	26·23	30·04	34·06	28·41	27·57

(b) Monthly totals July 1794–August 1805

	J	F	M	A	M	J	J	A	S	O	N	D	ANN
1794							2·785	1·760	2·340	3·015	3·820	1·045	22·023
1795	0·450	2·095	1·860	1·590	0·045	4·885	1·845	1·975	0·210	3·785	1·735	1·740	22·215
1796	2·675	1·284	0·420	0·200	2·100	0·750	3·075	1·545	1·060	1·910	0·665	2·115	17·795
1797	1·330	0·280	1·600	1·325	1·175	3·775	2·275	2·490	5·088	0·850	1·880	2·950	25·018
1798	1·910	0·0930?	0·410	1·515	1·610	1·020	4·325	0·800	2·085	3·670	3·935	1·030	23·240
1799	1·610	2·425	0·950	2·545	1·915	0·490	3·130	3·090	5·600	3·090	2·000	0·650	27·495
1800	2·480	0·470	1·470	2·500	1·750	0·580	0·040	1·120	2·705	2·370	5·350	2·155	22·990
1801	1·263	0·380	1·180	0·190	2·580	1·430	2·010	1·895	1·555	1·700	2·615	1·810	18·608
1802	0·320	1·805	0·240	0·240	1·565	1·585	2·995	0·225	0·255	1·430	1·500	2·075	14·235
1803	1·835	1·435	0·205	0·605	0·710	2·510	1·560	0·665	0·800	0·250	3·935	3·850	18·360
1804	2·580	0·595	2·830	1·850	1·935	0·525	3·155	1·860	0·290	2·675	2·380	0·755	21·430
1805	1·865	0·920	0·560	1·495	1·370	1·595	1·320	1·845					

the distances which appear in Table IV, and justifies the production of homogeneous monthly totals for Oxford. Our procedure is to find the ratios of corresponding annual totals for two stations for as many years as are available, and to examine the sequence and measure the interannual variability of these ratios. Where there is no apparent change in the ratio with time, and the interannual variability is small, then the mean ratio provides a conversion factor which can be applied to totals observed at one station to provide estimates for the other. This technique, which will be described in detail elsewhere, provides a very sensitive means of detecting faults in rainfall records and obtaining estimates for missing or incredible totals, provided that there are several overlapping records of reasonable length within a small area. The stations listed in Table IV are more widely spaced, fewer in number and more variable in quality than would be chosen by preference, but still are well within the area of significant association, which can be estimated from data for more recent years. We decided to keep our estimates independent of the long and important Lyndon record, and after considering all, relied only on Stroud, Lambeth and Sunbury to supplement Hornsby. The basis for our estimates for each year from 1767 to 1814 is given in Table V.

TABLE IV—RECORDS GIVING EVIDENCE ON OXFORD RAINFALL 1760–1814 (1916–50 AVERAGE FOR OXFORD IS 26·67 INCHES)

Station	Observer	Period	Bearing and distance from Oxford	1916–50 average *inches*
Stroud	Dr Hughes	1771–1773, 1775–1813	W 44 miles	33·58
Longleat	Jeremiah Cruse	1789–1799	SW 61 miles	35·13
Selborne	Gilbert White	1780–1792	SSE 46 miles	37·86
Odiham	?	1787–1789	SSE 44 miles	
Shirburn Castle		1780–1795	SE 12 miles	
Lambeth	Symons's MS.	1765–1782	SE 52 miles	23·42
South Lambeth	?	1782–1791	SE 52 miles	23·60
Sunbury	J. Cowe	1797–1838	ESE 43 miles	23·75
Lyndon	T. Barker	1736–1798, 1800	NE 64 miles	26·19
Kimbolton, Hereford	?	1781–1788	WNW 74 miles	

TABLE V—BASIS OF HOMOGENEOUS RAINFALL TOTALS FOR OXFORD FOR A STANDARD METEOROLOGICAL OFFICE GAUGE AT THE RADCLIFFE OBSERVATORY FOR 1767–1814

Years	Basis	Conversion factor	Notes
1767–74	Hornsby (Table II)	1·32	Missing months 1767–76 estimated from Lambeth
1775–76	Hornsby (Table II)	1·130	
1777–79	Stroud & Lambeth		Est. = Stroud × 0·3905 + Lambeth × 0·5674
1780–84	Shirburn Castle	0·977	
1785–94	Hornsby (Table III (a))	1·130	Annual totals divided between months in proportion to Shirburn Castle
1795–Aug. 1805	Hornsby (Table III (b))	1·130	
Sept. 1805–March 1813	Stroud × 0·3905 + Sunbury × 0·4922		
Apr. 1813–March 1814	Sunbury × 0·9844		
Apr. 1814–Dec. 1814	Oxford × 1·130		

10. ESTIMATION FOR THE YEARS 1775 TO EARLY 1805

The factor 1·130 applied to Hornsby's totals for 1775–76 and 1795–1805 depends on the inference made in section 7 that Hornsby's 12 inch gauge was in the same site as the rain-gauge used from 1815 onwards (and may indeed have been the same gauge). The correction of measurements made at this site has been discussed by Knox-Shaw and Balk, and their figures appear on page 95 of the Appendix to the volume of the Radcliffe Meteorological Observations for 1926–1930. They give a table of monthly factors ranging from 1·115 in August up to 1·150 in December and January, but the mean value of 1·130 for all months is probably as accurate as the data will justify. For the years 1785 to 1793, we have Hornsby's annual totals (corrected by the above factor), but no monthly totals, whereas at Shirburn Castle 12 miles away there are monthly totals from October 1779 to October 1795 which were certainly made with Hornsby's knowledge and probably under his direction. The original records are in the Bodleian Library (MSS. 26131–26159 under Savile MSS. 63 to 94) and the authors are grateful to Professor G. Manley and Mr C. G. Smith for sending them copies. An entry on the flyleaf states that a new circular funnel of 12 inch diameter was put on the 'ombrometer' on 15 September 1779, and that it emptied into a glass tube graduated to read directly in inches of rain and hundredths. Apparently the catch was measured every few days, presumably when the glass was nearly full, but as the total capacity was only 1·2 inches it could have been filled to overflowing in thunderstorms. Perhaps this explains Hornsby's calculations, mentioned in section 7, when he was considering the installation of his own 12 inch gauge and calculating the safe length for a tubular receiver. The Shirburn record seems to be deteriorating towards the end. A comparison between the Shirburn annual totals for 1785 to 1794 and Hornsby's corrected totals is given in Table III (a) and the reduction factor of 0·977, which brings the two 10-year totals into line, is applied to all the Shirburn monthly values.

11. Estimation for 1767–74 and late 1805–1814

The correction factor for Hornsby's record from 1767 to 1774, when he was using an older rain-gauge, may be estimated from the records at Stroud and Lambeth which extend both before and after the end of January 1775 when he changed his rain-gauge. However, the first step is to estimate totals for the months between 1767 and 1774 when Hornsby's values are either missing or incredible. This was done by means of the Lambeth record, the conversion factor for the wanted months in each year being found from the ratios of the totals at Oxford and Lambeth in the months with observations for both stations. These estimates have been inserted in Table II. For the months between August 1805, when Hornsby's record ceases, and April 1814 when the continuous record begins, there are odd months for which rainfall totals are preserved with the Hornsby manuscript in the Library at the School of Geography, Oxford. With some hesitation we have ignored these, and our estimated monthly totals from September 1805 to March 1813 are the average of estimates from Stroud and Sunbury, about equidistant from Oxford to west and east. The entire homogeneous series for 1767 to 1814 is given in Table VI.

12. Discussion

The rainfall observations at the Radcliffe Observatory, Oxford provide a fund of detailed information from gauges within a small area. These records can have few rivals in respect of the length of the period covered, and in the high proportion of original notes which have been preserved. For most years since 1851 measurements have been taken daily with a gauge, standard in construction and exposure, in a site within a few feet of that now in use. This is obviously the most reliable part of the record; for the years 1815 to 1850 only the 12 inch gauge with rim 22 ft above ground level on the East Wing of the Observatory was in use, and the correction of the readings of this gauge to modern standards involves the use of the monthly correction factors estimated by Knox-Shaw and Balk or more simply, their average factor of 1·130 used here. It must be emphasized that such correction factors can provide no more than an approximation to the truth, because when two rain-gauges at the same site are exposed to different wind regimes, as they are when the elevations are different, the gauge subjected to the stronger wind will catch relatively a lower proportion of the smaller droplets, and a higher proportion of the larger drops, so stability in the ratio of the catches can be expected only if these are measured over a period long enough to contain representative samples of wind speeds and drop sizes. The monthly and annual totals given in Table VI must be subject to errors which are larger than those in similar estimates based on modern data, but the method of reduction should ensure that these errors are randomly distributed and unrelated to one another, so that their effect is diminished when these data are used, for example, in comparisons with rainfall data for other parts of the British Isles etc., or for estimating rainfall totals for the seasons.

13. The significance of the Hornsby record

In a previous paper (Craddock, 1976) the evidence for the England rainfall of the 18th century was surveyed, and attention was directed to the break in the records around the year 1800, in that few observing sites which were in use for many years before then were also in use for long afterwards. The inference in the

TABLE VI—OXFORD HOMOGENIZATION

	J	F	M	A	M	J	J	A	S	O	N	D	ANN
1767	2·84	3·64	2·27	0·73	4·13	3·08	5·16	3·85	2·90	4·70	1·14	0·32	34·76
8	2·82	2·57	0·17	3·29	1·62	5·45	3·17	1·65	7·06	4·37	3·51	2·85	38·53
9	1·43	2·16	1·22	0·81	2·36	3·67	1·97	2·40	5·10	0·57	2·26	2·71	26·66
1770	0·83	1·19	2·49	1·00	2·48	3·89	0·79	1·08	2·68	1·00	7·95	3·08	28·46
1	0·57	0·94	1·53	1·00	0·90	2·72	1·19	2·60	0·91	4·34	0·55	1·17	18·42
2	4·03	3·70	3·08	1·64	1·87	1·61	1·28	2·98	5·12	3·59	6·85	1·33	37·08
3	1·28	0·65	0·46	1·93	6·40	1·07	1·29	3·34	3·31	1·83	5·19	2·15	28·90
4	3·67	2·68	3·66	0·65	0·46	1·68	1·82	2·79	9·25	0·46	1·69	1·86	30·67
5	2·54	1·51	2·50	2·80	1·42	2·87	1·46	4·93	5·24	2·78	2·57	0·10	30·72
6	3·80	3·27	2·36	0·33	1·01	3·91	2·66	4·33	2·02	0·90	2·24	1·94	28·77
7	1·20	1·49	1·76	1·93	4·51	2·94	3·33	1·51	0·74	3·77	1·43	0·91	25·52
8	2·60	0·79	1·11	0·83	1·83	1·95	4·19	0·10	1·26	2·89	4·09	3·17	24·81
9	0·43	0·46	0·57	1·88	2·27	2·61	4·86	1·44	2·45	3·12	2·81	4·98	27·88
1780	1·09	0·62	1·08	2·35	1·34	1·41	2·03	1·16	2·85	2·79	2·34	0·07	19·13
1	1·62	1·71	0·08	1·11	1·82	3·29	1·74	1·36	2·61	0·31	2·88	1·83	20·36
2	2·02	0·61	2·67	2·50	3·68	1·32	5·01	4·28	2·45	1·15	1·43	0·77	27·89
3	1·55	3·09	1·30	0·56	2·30	1·71	2·28	2·00	0·59	0·63	1·52	0·92	18·45
4	1·48	0·64	1·92	3·16	2·25	2·39	2·26	2·34	1·44	1·95	2·64	1·86	24·33
5	1·49	0·94	0·23	0·26	0·70	1·48	1·29	2·14	4·26	2·34	1·74	1·76	18·63
6	3·01	0·62	1·28	0·86	2·44	1·28	0·52	1·75	3·15	4·04	2·24	2·21	23·40
7	0·30	1·81	2·54	0·80	1·48	1·04	5·22	1·08	1·38	2·38	1·44	2·60	22·07
8	0·67	2·17	0·77	0·42	0·40	2·34	0·78	3·37	2·01	0·17	0·50	0·31	13·91
9	2·65	2·05	1·82	1·33	2·62	5·02	4·45	1·28	3·11	3·75	1·54	1·75	31·37
1790	1·38	0·19	0·40	1·88	2·67	1·16	2·20	2·19	0·65	0·61	3·48	2·51	19·32
1	3·24	1·55	0·41	1·51	0·93	0·60	2·82	1·45	0·71	3·22	4·54	2·20	23·18
2	3·01	0·53	1·79	2·99	1·92	2·75	2·94	3·28	3·73	3·57	0·87	1·39	29·77
3	2·32	1·23	1·66	1·95	1·74	0·62	2·41	1·63	4·42	0·93	1·673	1·90	22·52
4	0·50	1·00	1·29	2·08	2·11	0·61	2·69	1·87	2·70	3·15	4·81	2·07	24·88
5	0·51	2·36	2·10	1·80	0·06	5·53	2·09	2·23	0·24	4·28	1·95	1·97	25·12
6	3·02	1·45	0·47	0·23	2·37	0·85	3·47	1·75	1·20	2·16	0·72	2·38	20·11
7	1·50	0·32	1·81	1·50	1·32	4·26	2·57	2·81	5·75	0·96	2·16	3·32	28·24
8	2·16	0·00	0·46	1·71	1·82	1·15	4·78	2·03	2·36	4·15	4·4	1·16	26·24
9	1·82	2·75	1·07	2·88	2·16	0·55	3·54	3·49	6·33	3·49	2·26	0·73	31·07
1800	2·80	0·53	1·66	2·83	1·98	0·66	0·05	1·27	3·06	2·68	6·05	2·43	26·00
1	1·42	0·43	1·33	0·21	2·92	1·62	2·27	2·14	1·75	1·92	2·95	2·05	21·01
2	0·36	2·05	0·27	0·27	1·77	1·80	3·38	0·28	0·26	1·62	1·69	2·34	16·09
3	2·07	1·62	0·24	0·69	0·80	2·84	1·76	0·76	0·90	0·28	4·44	4·35	20·75
4	2·92	0·67	3·20	2·09	2·18	0·60	3·56	2·10	0·33	3·02	2·69	0·85	24·21
5	2·11	1·04	0·63	1·68	1·55	1·80	1·49	2·09	1·73	1·83	0·88	1·99	18·82
6	3·39	1·40	1·77	0·91	1·03	0·73	3·61	1·86	1·54	1·02	2·85	3·57	23·68
7	1·24	1·23	0·47	0·38	3·37	1·25	1·79	1·59	2·47	1·89	4·05	1·36	21·09
8	0·99	0·94	0·35	2·87	2·01	1·31	3·07	2·12	2·53	3·51	2·31	1·31	23·32
9	4·33	2·61	1·26	3·51	1·31	1·48	3·20	3·22	3·23	0·17	1·49	2·77	28·58
1810	0·65	1·52	2·29	2·25	1·83	1·11	3·49	2·57	1·19	2·13	5·41	3·42	27·86
11	1·55	2·13	1·41	1·77	3·83	2·09	3·32	1·97	1·86	3·41	2·51	1·55	27·40
12	1·61	3·51	2·85	1·67	2·83	3·07	2·03	1·42	0·95	4·37	2·35	0·45	27·11
13	1·16	3·61	0·75	1·32	2·14	1·13	1·91	0·88	1·51	4·60	1·10	0·61	20.72
14	2·38	0·31	1·27	2·50	1·04	2·32	2·67	1·27	1·59	2·33	1·50	3·32	22·50

present paper, that Hornsby's record from 1775 to 1805 refers to a gauge in the same site and exposure as that used from 1815 to 1850, provides a valuable addition to the records known to span this gap and justifies the time spent on the patching of this fragmentary record. Finally, it should be noted that the figures in Table VI are quite independent of others being made at the same period, for example, at Lyndon, Manchester and Liverpool, and almost independent of the homogeneous series for Kew published by Wales-Smith (1971). Hence, resemblances between the series, which may be brought to light by any of the various forms of spatial analysis, must be meteorological in origin, and not due to the derivation of data from a common source.

14. ACKNOWLEDGEMENTS

Acknowledgement is due to Professor G. Manley, to Mr C. G. Smith of Keble College, Oxford and to Mr B. G. Wales-Smith of the Meteorological Office, for assistance with data and constructive comment; to the Librarian at the School of

Geography, Oxford, for access to the Hornsby manuscripts; and to the staff of the Meteorological Office for access to and copies of relevant records in the official archives.

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AN UNUSUAL LIGHTNING INCIDENT IN SINGAPORE

By J. E. PAKIAM and A. RAJARATNAM

(University of Singapore)

SUMMARY

An account is given of a lightning strike which fatally injured a soldier and badly damaged his equipment. An estimate is made of the energy needed to produce the damage and it is shown that this is well within the limit of that likely to have been available.

INTRODUCTION

It is unusual for lightning to strike a person directly and even more unusual for it to leave some evidence of the physical nature of the lightning channel. In November 1973, during a heavy thunderstorm, a group of Armed Forces personnel was struck by lightning, one man suffering the full impact of the strike, with subsequent death. Evidence of the lightning strike was gathered from eye-witness reports, the medical report and condition of clothing, weapon and helmet. From measurements made on the helmet it was possible to estimate (i) the nature and size of the lightning flash, (ii) the temperature structure of the lightning channel, (iii) the action integral $\int I^2\, dt$, and (iv) the energy required to create the hole in the helmet.

PLATE I—HOLE CAUSED BY LIGHTNING STRIKE TO HELMET

(See page 373.)

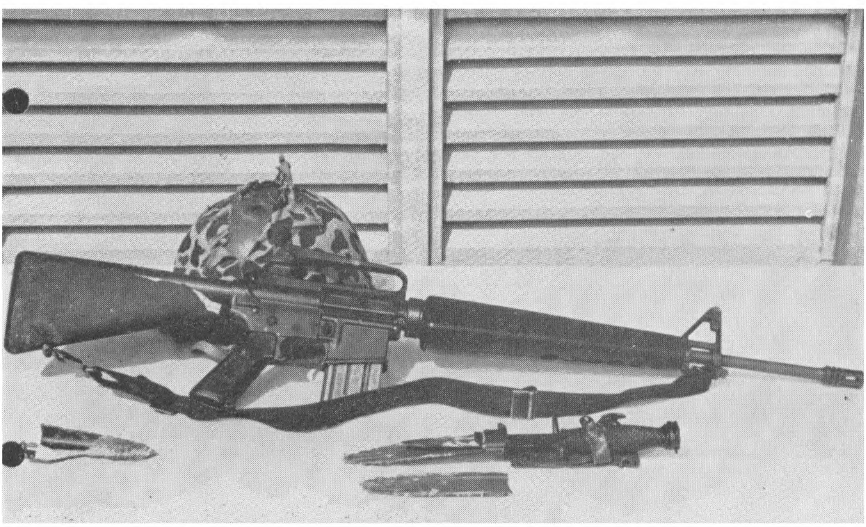

PLATE II—DAMAGE BY LIGHTNING STRIKE TO HELMET, RIFLE AND BAYONET

Note hole in helmet (cloth covering partly torn) and damage to rifle butt and bayonet scabbard. (See page 373.)

To face page 373

PLATE III—TOWNELEY HALL, NEAR BURNLEY, LANCASHIRE

(See page 378.)

The incident

At 1530 hours local time on 19 November 1973, while on training on the top of a small hill about 100 m above sea level, the group was struck by lightning during a thunderstorm. One man was struck directly and died subsequently while 24 others were injured, none seriously. From written eye-witness reports, the circumstances related to the incident are as follows:

(1) Rain began falling on the hill around 1500 hours Local Standard Time and lightning was observed to strike a tree close to the group position.

(2) As the group began to descend the hill to seek shelter, a flash struck a soldier, and 24 other men close by were thrown to the ground, probably by ground-induced currents. With the exception of the man directly struck, all the men recovered quickly and ran for help.

(3) When medical help arrived in a few minutes, the injured man was unconscious. Mouth-to-mouth resuscitation was applied and the man was moved to hospital but was pronounced dead on arrival.

Bodily injuries

The dead soldier had his uniform torn and tattered all the way down from the chest to the knees. Part of the hair was burnt and one side of the body (face and chest) was blue-black in colour and the helmet and weapon were found to be damaged.

The other injured men all reported 'feeling an electric current passing through' or 'feeling numb', sensations which are typical of 'step voltages' (Golde and Lee, 1976). On being thrown to the ground some lost consciousness for a few seconds but all recovered quickly. No serious injuries resulted to the 24 men, who were medically examined and discharged.

Damage to the weapon and helmet

On examination of these objects it was immediately obvious that the dead soldier had sustained a direct lightning strike. A small hole was discovered on the top of the helmet and several melt points in the steel were present (Plate I). The plastic inner liner under the steel helmet was undamaged. One side of the helmet (near the buckle for the strap) was blackened and the buckle itself appeared to have been blown off. The rifle had several melt points on all its sharp edges (end of barrel, trigger etc.) and the butt had been damaged. The bayonet had part of its scabbard blown off (Plate II). The boots showed no sign of damage.

From the damage, it appears that the lightning currents must have flowed from the helmet down one side of the face and body, to the weapon (which was probably slung over the shoulder), and down the butt, before jumping to the ground. Such an explanation seems reasonable in view of other similar incidents reported in the literature (Golde and Lee, 1976).

The helmet

The helmet was examined in greater detail, as it provided some evidence for the size and temperature of the lightning flash. Seven different burn areas were noted on the top of the helmet, one hole also being present. Three other small burn areas were noted on the side of the helmet and the rear.

Each burn area was found to consist of a number of patches of different colours. Generally there existed a central blackened area, surrounded by a silvery patch, then by a reddish patch and finally by a slightly black-grey area, darker than the surrounding green-grey of painted steel.

The hole and surrounding burn patches were all approximately circular and from the planimetered areas the diameters could be computed for equivalent circular areas.

In the interior of the helmet a large irregularly shaped dark area (about 16 cm^2) near the strap was noted.

Diameter of different burn patches. Measurements of the various hole and burn areas were taken and the equivalent diameter for circular areas calculated. The results for the 10 different burn areas are presented in Table I.

TABLE I—DIAMETER OF BURN PATCHES ON HELMET

Area No.	Diameter of hole *mm*	Diameter of darkened area *mm*	Diameter of silvery area *mm*	Diameter of reddish area *mm*	Diameter of black-grey area *mm*
1	7·12 (outside of helmet) 4·50 (inside of helmet)	—	8·74	10·3	≈14·0
2	—	4·22	5·52	6·0	D*
3	—	—	1·78	D	D
4	—	Extremely small	2·52	D	D
5	—	Extremely small	2·98	D	D
6	—	—	3·90	D	D
7	—	—	2·00	D	D
8	—	—	1·38	D	D
9	—	Extremely small	4·22	D	D
10	—	—	3·56	D	D

* D = Difficult to estimate, because areas very diffuse.

LIGHTNING DIAMETER MEASUREMENTS IN THE LITERATURE

Few measurements of the diameter of the lightning channel have been made.

Photographic measurements showed the diameter to vary from between 3 cm and 16 cm (Schonland, 1950 and Evans and Walker, 1963). Orville *et alii* (1974) more recently reported photographic evidence of return strokes with diameter in the range 6 to 7 cm. Direct lightning strikes (return strokes) on fibreglass screens were made by Uman (1964) and these have shown (a) nearly circular holes, and (b) equal numbers of holes with diameters in the ranges 2–3·5 cm and 2–5 mm. Uman also discussed the problem of the definition of the term 'diameter' since clearly there is no definite boundary between the stroke and the air surrounding it. Measurements of strikes on metal electrodes (Hill, 1963) showed that the diameter was of the order of millimetres, and measurements of scars on trees struck by lightning indicated values in two ranges 0·5–3 mm and 1–8 cm (Taylor, 1965). Uman (1969) has cautioned on the deduction of channel diameters from electrode measurements. In a theoretical computation of the diameter of the return stroke Oetzel (1968) showed that the diameters of first

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return strokes lie in the range 1–4 cm, with subsequent return strokes in the range 0·2–0·5 cm. Other measurements of the diameters of the lightning return stroke have been reviewed by Orville *et alii* (1974).

Measurements made on diameter and temperature

The measurements reported here are in the class of electrode measurements. Nevertheless, with the reservations expressed by Uman, it is possible to obtain a rough idea of the diameter of the lightning flash which struck the soldier.

A wide range of values of the core temperature of a flash have been postulated (Uman, 1969) and a value of 25 000°C would be reasonable. The hole would correspond to an area having experienced a temperature of $>$3000°C (the boiling point of steel). Assuming that the silvery patches were formed by melting steel, such an area could be regarded as having had a temperature of $>$1500°C. Red patches would correspond to Fe_3O_4 formed at temperatures up to $\approx$570°C. The grey-black patches (Fe_2O_3) would be formed when temperatures of $>$220°C occurred. With these assumptions, it was possible to plot a graph of radial temperature distributions within the lightning flash (Figure 1).

From the graph, it is obvious that the temperature falls off very rapidly with distance from the core, the central core of high temperature being of very small diameter. If a temperature of 2000 K is assumed to be a limit for the diameter of the lightning channel, then such a temperature corresponds to a lightning channel diameter of about 1 cm (Uman, 1969). This compares favourably with the experimental measurement of this study ($\approx$0·8 cm for a temperature of 2000 K, Figure 1).

Calculation of action integral $\int I^2 dt$

Golde (1973) has noted that the action integral $\int I^2 dt$ is generally used to evaluate holes formed in thick metal by lightning.

As a first step in the calculation of $\int I^2 dt$, the electrical charge that passed through the hole was estimated. The diameter of the hole on the outside of the helmet was 7·12 mm with an area of 40 mm^2; the composition of the helmet was an unknown steel alloy of thickness 1·3 mm. Golde (1973, page 53) has presented the results of Hagenguth regarding the relation between charge and size of hole burnt in metal sheets of different composition and thickness. From Hagenguth's results it was estimated that the charge passing through the hole was about 75 coulombs. This is a little higher than the average charge transferred per flash (31 C) found by Wang (1963) for Singapore.

As the second step, the maximum current and the duration of the lightning flash were estimated. Since the charge transfer of 75 C was more than twice the average for Singapore, the lightning flash could be considered to have had, say, a 10 per cent frequency of occurrence. No statistics for peak current have been obtained at Singapore but, from Golde (1973, page 17), a peak current of about 75 kA was estimated. A mean current of about half this value can be assumed. The time of current flow would be about 10^{-3} s, a plausible value.

Using these values of mean current and time, the action integral $\int I^2 dt$ works out to be about $1{\cdot}4 \times 10^6$ A^{2}s, which is within the range for negative discharges (Golde, 1973, page 19).

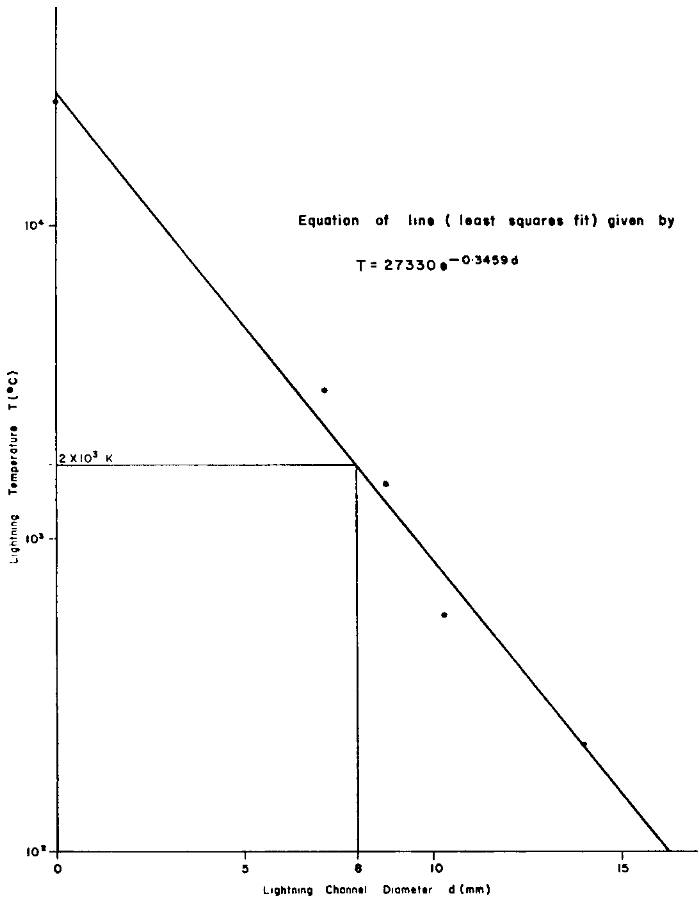

FIGURE I—RADIAL TEMPERATURE DISTRIBUTION WITHIN LIGHTNING FLASH

CALCULATION OF ENERGY REQUIRED TO FORM HOLE IN HELMET

The average surface area of the hole was 0·28 cm^2, so that the approximate volume of the steel vaporized was 0·0364 cm^3. Assuming the latent heat of vaporization to be 351 kJ mol^{-1} the total energy required to form the hole will be rather more than $351 \times (0{\cdot}29/56)$ kJ $\approx$ 2 kJ.

The probable maximum electrical energy associated with the lightning flash would be $IVt = 7{\cdot}5 \times 10^8$ J, assuming a value of 10^7 volts for V. The minimum value would probably have been about 10^8 J. This energy would have been dissipated over the whole path of the lightning stroke from cloud to ground which was probably several kilometres long. The height of the soldier and his bayonet would have been about 2 m so that the energy available for creating the hole, killing the man and damaging his equipment would be about 10^{-4} to 10^{-3} of 10^8 J, i.e. 10^4 J to 10^5 J, certainly well in excess of the quantity estimated above as necessary to create the hole.

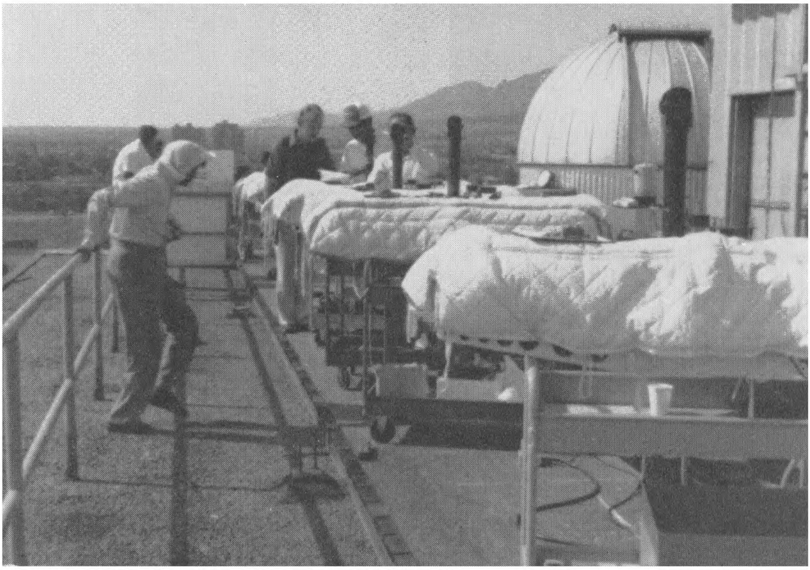

PLATE IV—INTERNATIONAL COMPARISON OF DOBSON OZONE SPECTROPHOTOMETERS, BOULDER, COLORADO, AUGUST 1977

(See page 385.)

PLATE V—INTERNATIONAL COMPARISON OF TOTAL OZONE MEASURING INSTRUMENTS, BELSK, POLAND, JULY 1974

Mr J. H. Convery is standing behind the UK instrument at the right of the photograph, and Miss A. Mani, the WMO Rapporteur on Measurements of Atmospheric Ozone, is seated in the foreground. (See page 385.)

PLATE VI—THE METEOROLOGICAL OFFICE EXHIBIT AT THE SILVER JUBILEE EXHIBITION AT THE ROYAL SOCIETY, LONDON

The exhibit is being explained by the Director-General of the Meteorological Office and Treasurer of the Royal Society, Dr B. J. Mason, C.B., F.R.S.

PLATE VII—ANOTHER VIEW OF THE METEOROLOGICAL OFFICE EXHIBIT

(See page 380.)

Conclusions

From measurements made of a direct lightning strike on to a metallic helmet, a lightning diameter of $\approx 0{\cdot}8$ cm was deduced. In view of the many assumptions made in the study, the deduced value compares favourably with other measurements reported in the literature.

Rough estimates indicate that a charge transfer of 75 C over a period of about 1×10^{-3} s was responsible for the formation of the hole. With a peak current flow of 75 kA, the action integral $\int I^2 dt$ was calculated to be about $1{\cdot}4 \times 10^6$ A^2s, which is within the range for negative discharges.

Another calculation showed that the energy required for the formation of the hole was about 2 kJ. Energy of about 10^4 to 10^5 J was involved in damaging the human body, weapon and bayonet.

Acknowledgements

The authors are grateful to the Ministry of Defence of the Republic of Singapore for permission to examine reports, weapon and helmet. Technicians Mr Yee Cheong Inn and Mr V. Thomas are thanked for measurements on the helmet and photography respectively. The Figure was drafted by Mr Tow Fui. We are indebted to Dr R. H. Golde for his helpful criticisms and invaluable suggestions in improving the manuscript.

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RAINFALL RECORDING IN THE BRITISH ISLES 1677–1977

By R. P. W. LEWIS

The year 1977 must not be allowed to pass into history before mention has been made in the *Meteorological Magazine* of the tercentenary of the start of systematic rainfall recording in the British Isles.

Rain-gauges of a sort are known to have been used in India in the 4th century B.C., in Palestine in the 1st century A.D., in China by A.D. 1247 and in Korea by A.D. 1441. They were, however, apparently unknown in Europe until the 17th century when Benedetto Castelli made some measurements in Italy in 1639.

In 1662 Sir Christopher Wren demonstrated an elaborate recording rain-gauge of his own design and construction to the Royal Society, but it does not seem to have been used to make systematic regular measurements. In January 1677, however, Richard Towneley* of Towneley Hall, near Burnley, Lancashire (see Plate III) began to make careful observations of the rainfall at his home and kept and published records of montly totals from that time until April 1704. Towneley was doubtless familiar with Wren's work but the details of his own gauge were almost certainly original; it would seem to have collected the rain falling at the level of the roof of Towneley Hall (Biswas, 1970). In a report published in the *Philosophical Transactions of the Royal Society* in 1694 he wrote:

'I fixed a Round Tunnel of 12 inches Diameter to a Leaden Pipe, which would admit of no water, but what came through the Tunnel, by reason of a part soder'd to the Tunnel itself, which went over the Pipe, and served also to fix it to it, as well as keep out any wett that in stormy weather might beat against the under part of the Tunnel, which was so placed that there was no building near it that would give occasion to suspect that it did not receive its due proportion of Rain that fell through the Pipe some nine Yards perpendicularly, and then was bent into a window near my chamber, under which convenient Vessels were placed to receive what fell into the Tunnel; which I measured by a Cylindrical Glass, at a certain mark containing just a Pound or 12 Ounces *Troy*, and had marks for smaller parts also. By the help of this Cylindrical Glass I thus kept my account of what Rain fell, and generally twice or thrice a Day; when I took several other Observations, both of the *Thermometer*, *Barometer*, Winds, &c.'

Plate III shows a black-and-white photograph of a colour reproduction of a painting of the north-east aspect of Towneley Hall executed by J. M. W. Turner in 1799. In about 1700 a fourth wing which had completely enclosed the inner courtyard was pulled down. This wing contained a room known as 'Mr Towneley's chamber' and, presumably, the 'tunnel' was fixed to its roof. Professor

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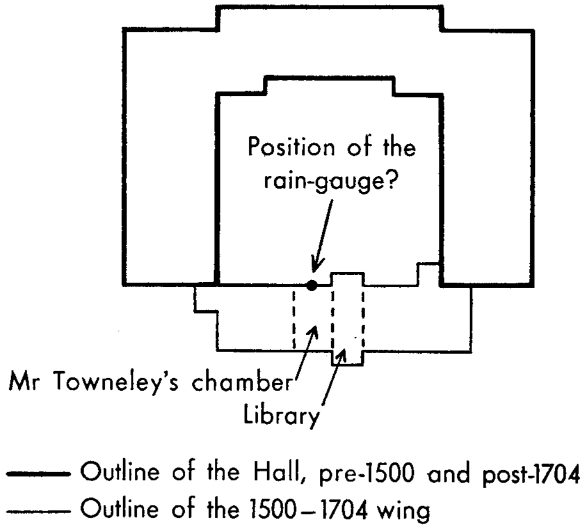
* The spelling of Richard Towneley's surname varied from one contemporary source to another. However. S. P. E. C. W. Towneley, Esq. of Dyneley, Burnley, Lancs. has informed us that the spelling 'Towneley' was used by his ancestor on his book-plate, and we have in consequence adopted it for this article.



PLAN VIEW OF TOWNELEY HALL FROM A SKETCH PLAN KEPT AT BURNLEY

Gordon Manley has visited the Hall and has estimated that the tunnel was probably above the level of the battlements which now adorn the remaining wings. (Acknowledgement is made to the Towneley Hall Society for permission to photograph their colour reproduction of a Turner painting.)

Although Towneley obviously knew the importance of eliminating both leaks and water that might run down the outside of his tunnel and of making sure that the mouth of the tunnel was unobstructed, he was unaware of the serious effects of 'over-exposure' and of the action of wind eddies in reducing the catch of gauges that were placed high up on buildings or poles; these effects were not indeed properly elucidated until the mid-nineteenth century and most early gauges were placed on roofs or high walls to avoid vandalism or mischievous interference. Ever since Towneley's day, systematic rainfall observations have continued to be made somewhere in the British Isles, the longest series being that at the Radcliffe Observatory, Oxford, which is continuous from 1815 to the present day and extends in a broken form back to 1795; the Meteorological Office now collects and analyses records from more than 7000 gauges in Great Britain and Northern Ireland, and information of immense value is provided for agriculturists, hydrologists, civil engineers, insurance companies, and many others. It is doubtful whether so shrewd a scientist and observer as Towneley would have been surprised at the great developments of modern hydrometeorology, but he would certainly have been gratified to know that so much has developed fom the small beginnings at Towneley Hall.

A fuller account of the rainfall measurements of Towneley Hall is given by Folland and Wales-Smith (1977).

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SILVER JUBILEE EXHIBITION AT THE ROYAL SOCIETY, LONDON

By F. R. HAYES

In May and June 1977 the Royal Society mounted an Exhibition illustrating scientific developments in the United Kingdom during the past twenty-five years in celebration of the Silver Jubilee of Her Majesty the Queen. In common with other bodies the Meteorological Office was invited to provide an exhibit. For most of the period of the Exhibition there were 12 exhibits but additional ones, making a total of 22, were provided for a conversazione in May and a Ladies' Evening in June at which 1200 guests were present.

Exhibits covered many aspects of scientific achievement. Of interest were live displays of a pulsar and a quasar tracked by the 250 ft telescope and a short-baseline interferometer at Jodrell Bank, and a demonstration of chemical changes, of a few picoseconds' duration, detected by mode-locked lasers.

Several exhibits concentrated on the development of instruments arising from scientific discoveries. The smallest radar ever made was on show, incorporating the discovery of indium phosphide as a microwave source, and liquid crystals as low-power visual display. Powered by small solar cells, it stands about 25 cm high! Fibre optic communication, precision aircraft guidance by microwaves and the BBC 'Ceefax' system were among other developments on display.

Molecular biology was not to be left out, and a range of analytical methods and discoveries in this field was shown, including a rapid and simple method of determining nucleotide sequence in DNA, and the structure and assembly mechanism of Tobacco Mosaic Virus. An exhibit from the field of biology showed the discovery of drugs used in the treatment of high blood pressure.

The Meteorological Office exhibit covered three aspects of modern weather forecasting: satellites, radar, and numerical forecast models. The centrepiece was a video film showing animated output from the 10-level operational forecast computer model; it demonstrated how satellite and radar techniques are related to the production of more reliable forecasts. Experimental numerical models shown were the fine-mesh boundary-layer model for short-period forecasting and the general-circulation model for long-period forecasting. Modern instruments, and a mock-up of automated data retrieval from the computer data banks completed the exhibit. The preparation of the artwork and the construction of the stand were carried out by Met O 18d (Cartographic Section). (See Plates VI–VII.)

REVIEWS

Introduction to meteorology (*second edition*), by Franklyn W. Cole. 225 mm × 160 mm, pp. xx + 495, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1975. Price: £5.25.

This textbook is designed for college and university liberal arts students, who have little prior knowledge of mathematics and physics. Consequently space has to be devoted to explaining basic principles and to the reader with any acquaintance with the physical sciences gained at school these parts will make rather dull reading. In spite of this limitation, Professor Cole, who is Professor of Meteorology and Engineering, Foothill College, Los Altos Hills, California, attempts a wide survey of meteorological topics. The first section, which deals with the general properties of the atmosphere and measurements of pressure, temperature, humidity and wind is followed logically by a section on physical processes in the atmosphere. The third and fourth sections deal with Atmospheric Motion and Circulation and with Weather Disturbance and Change. The last part deals with the application of meteorology to forecasting, to climatology and to the environment.

In the review of the first edition (*Meteorological Magazine*, Volume 100, 1971, pp. 125–126) the main criticism levelled at this book was its parochial nature, as it rarely looked beyond the boundaries of the United States. This criticism must still stand but the addition of many useful satellite pictures and the extra chapter on 'Climate and Climate Controls' have subtly widened the scope of the book. Unhappily, there is still a lack of uniformity in the system of units employed. Temperature in degrees Celsius and Fahrenheit, pressure in millibars and inches and wind speed in knots and miles per hour all find a place. This confusion must be a serious drawback in using this book as a text associated with a formal course.

On the other hand the book has many good qualities. Even though constrained to use an essentially descriptive approach the author imparts a clear understanding of the principles of atmospheric physics in the first two sections. The lack of mathematics is more keenly felt in dealing with dynamical meteorology but some well-chosen diagrams help to give a good approximation of three-dimensional motion in the atmosphere. In the chapter on forecasting one must commend the juxtaposition of satellite photographs of cloud cover and the corresponding synoptic charts. It is a great pity that the idea is spoilt by the poor quality of printing of the charts. The glossary of physical and meteorological terms provided at the end of the main text is also a valuable feature.

In summary, the changes made in the second edition have undoubtedly increased the value of the book, but more needed to be done. For example, the type of reader for whom the book is designed would acquire no idea of the all-pervading impact of electronic computers in meteorological communication, data processing and numerical forecasting. Consequently he would fail to appreciate the ability of his National Meteorological Service to render him assistance in his chosen profession. Although the book makes interesting reading, it cannot be recommended as a primary text.

P. D. BORRETT

Annual Report of the Central Water Planning Unit for the year ending 31st March 1976. 295 mm × 210 mm, pp. 66, *illus.*, Central Water Planning Unit, Reading Bridge House, Reading, Berks. RG1 8PS, 1976.

This report on the second year of the Unit's work will be of interest to anyone with a serious concern for the water resource planning of England and Wales. The Unit was formed in the reorganization of the water industry (following the Water Act of 1973) to provide a 'service of planning expertise to the Government, the National Water Council and the Water Authorities'.

The text contains 32 illustrations including photographs, maps and clearly designed diagrams. It has obviously been conscientiously proof-read since a sheet of corrigenda appears inside the front cover.

The Unit is closely associated with the Meteorological Office at all levels. The Director is the Director-General's Hydrological Advisor for the World Meteorological Organization and there has been a fruitful relationship, especially with the branches concerned with Synoptic Climatology and with Agriculture and Hydrometeorology.

The second section of the report deals with 13 projects which include the feasibility of constructing reservoirs in the Wash Estuary, synthesizing river flow records from the longer and more numerous meteorological records and the much-discussed topic of water transfer between major rivers. There are four technical appendices presenting additional information on Severn to Thames water transfer simulation studies, a geology index for river flow studies, nitrates in water supplies, and river-regulation losses.

Signs of co-operative efforts between the Unit and the Office are to be found in several parts of the report; examples include the recognition that current meteorological methods underestimate the winter evaporation (page 20), operational losses in river-regulation systems (page 24), the very important Dee Weather Radar project (page 26) and the studies of the variability of long-duration rainfall (pages 30–32).

Many meteorological readers will find the map on page 21 of special interest. Reproduced from the 1865 *Report of the British Association for the Advancement of Science*, it shows the rainfall measuring stations operating in that year. Some will be surprised to see how well most parts of Great Britain were represented, whilst others, aware that we now count the network in thousands, may be equally surprised that almost every station could have its own dot on such a small-scale map as recently as 112 years ago.

The report is to the point and highly readable.

B. G. WALES-SMITH

Ministry of Agriculture, Fisheries and Food Technical Bulletin 35, The Agricultural Climate of England and Wales (Areal Averages 1941–70), by L. P. Smith. 250 mm × 160 mm, pp. vi + 147, *illus.*, Her Majesty's Stationery Office, Atlantic House, Holborn Viaduct, London EC1P 1BN, 1976. Price: £2·40.

Over the years the Agricultural Meteorology Section of the Meteorological Office in general, and L. P. Smith in particular, have made immensely valuable contributions to our understanding of the farming climate and weather of

Britain. They have drawn information from a wide range of sources, including the national network of crop-weather stations, and have presented it in the form of intelligible summaries that have been widely used by research workers, advisory officers and the farming community. Much useful information and advice has also been enshrined in a long series of memoranda that have deserved a wider circulation than they were usually given.

This Bulletin is the latest, and best, of the Meteorological Office's agricultural publications, and it is a fitting monument to the years of devoted work by Smith and his colleagues. The Bulletin carefully defines the main meteorological variables that are considered to affect farm decision-making and animal and crop husbandry. It then gives a short account of each of these attributes in the course of some 30 pages, and finally provides an astonishing amount of detailed information about the so-called 'areal' averages for each of the 56 homogeneous weather regions into which England, Wales and the near-by islands have been divided.

No comparable compendium has been published before for Britain (or elsewhere?), and the Bulletin will be invaluable in a variety of ways for a long time to come. The information could be specially useful in such managerial exercises as choosing the best site for a particular crop, or in selecting crops which would have a high potential on any particular site. Selecting crops for sites, and vice versa, has been the staple of decision-making since farming began, but it has perforce been based on hard-earned experience and empirical wisdom until now, in the absence of firm information about local climates and weather. This Bulletin goes far towards providing a new and sounder base for the management decisions involved.

The choice of the best crops for a site is particularly relevant to farm management, since the individual farmer and grower is not usually concerned with areal averages but with what he should do, and the likely consequences of his actions, on a particular farm or field. It is easier to characterize small areas if they form part of the flat plane surface of infinite extent so beloved of the theoretical physicist, and the Bulletin has understandably sought to simplify its daunting task by reducing all data to averages for level ground. However, much of Britain is rolling, hilly or mountainous, and it should not be beyond the wit of man to find a usable method of extrapolating from such data to allow for the effects of aspect, altitude, slope and distance from the sea—indeed, a start has already been made on some of these effects (e.g. on pages 6 and 18). The Bulletin observes that 'It is difficult to quantify the effect of slope and aspect, as no observational details are available . . .', but steps should perhaps be taken to start collecting such data when the Meteorological Office seeks new topics on which to work in the agricultural field.

There are other limitations to what meteorologists can do for agriculture, as the author is only too well aware. For instance, it is stated that 'Maximum and minimum air temperatures were not treated separately, as they are too much dependent on local site characteristics' (page 2), yet it is precisely those extremes that may make or mar a farming operation. The Bulletin would gain in value if ways could be found of providing guidance on the probable occurrence of such extremes.

It has recently been announced that the agrometeorological cover of the MAFF Agricultural Development and Advisory Service has been expanded. This Bulletin should provide the officers in that service with a powerful new tool.

They, and many others, have cause to be grateful to L. P. Smith and his colleagues for this Bulletin, and for their other contributions to agrometeorology.

J. P. HUDSON

Earth, the living planet, by Michael Bradshaw. 275 mm × 215 mm, pp. 302, *illus.*, Hodder and Stoughton Educational, Mill Road, Dunton Green, Sevenoaks, Kent, 1977. Price: £4·95 (paperback).

This book is written as a reader for sixth form and college courses in physical geography and environmental science. It has several aims: to establish basic ideas and themes, thereby leading the reader to field observations and to regular perusal and assessment of the popular scientific press; to attempt an explanation of the environmental 'coincidences' which have led to the life-forms of this planet; and, by placing the debate on conservation and pollution on a more informed footing, to put the reader in a position to be more capable of assessing the question 'will the living planet die?'.

The first quarter (seven chapters) of the book is devoted to a non-mathematical treatment of basic meteorology, the atmospheric heat-engine, air–sea interactions, weather systems, cloud microphysics, weather modification, and forecasting (at about the level of *Elementary Meteorology* (HMSO)). The next eight chapters look at world climates, past and present, and implications for the future.

'Ecology of life on earth' is the subject of the latter half of the book. Starting with an introduction to the various life-forms we study the constraints on life which, in addition to energy and nutrient chains, affect the biosphere—climate, soil, the interrelationships of animals and plants, and finally the influence of man. The final chapters discuss the distribution of living creatures on the earth's surface and their adaptation to optimum and extreme conditions and conclude with a study of the teeming oceanic life and possibilities of enhancing oceanic production.

The book has a clear format, copious well-explained diagrams, graphs, tables and monochrome photographs, as well as over 80 colour pictures in a block near the centre of the book, and covers subjects ranging from soil classification and woodland tree types to pictures of cloud formations, from earth and from space, illustrating the scales and forms of atmospheric motions.

Many of the figures and pictures are accompanied by questions requiring careful study and interpretation of the text and figures. Perhaps more emphasis could have been placed on suggestions for simple experiments and investigations in which the reader could demonstrate or explore for himself some aspects of the text (as, for example, in L. P. Smith's *Weather Studies*).

A good bibliography is presented for readers wanting a broader or deeper treatment of various topics; it has several sections covering source books and more advanced texts (published since 1970).

Those of us who are involved in what are essentially interdisciplinary studies such as agricultural meteorology have some idea of the value of meteorological studies to a world growing increasingly short of food; Michael Bradshaw here introduces the student and general reader to interdisciplinary studies and emphasizes the necessity of this approach in order to investigate the delicate equilibrium in which nature is maintained and in which man is increasingly able to interfere.

It is to be hoped, though, that students will appreciate that many aspects covered in the chapters can be, and have been, placed on a strong mathematical foundation and that they will not regard 'environmental studies' as purely descriptive, an easier option for examination work.

Perhaps the author becomes too enthusiastic in his attempts to explain the 'incredible' coincidences which have combined to produced life on earth. A question for the student might be to assess the probability that there are 10^9 Michael Bradshaws distributed round the universe and all writing books (with their various combinations of extremities) about their 'living planet' and enthusing at the amazing coincidences that have led to life as they know it!

For the student and general reader the volume certainly presents a useful introduction to the physical, chemical and biological forces and processes which interact to produce and maintain life. The author summarizes the possible implications of man's misuse of some of these interactions in a balanced and unsensational manner and should put the reader in a better position critically to assess future development.

J. R. STARR

Meteorological Magazine: price increase

As from January 1978 the price of an issue of the *Meteorological Magazine* will be £1 and the annual subscription will be £13·14 including postage.

NOTES AND NEWS

International comparison of Dobson ozone spectrophotometers

Mr J. H. Convery of the High Atmosphere Branch of the Meteorological Office visited the NOAA Environmental Research Laboratory, Boulder, Colorado, USA in August 1977 and took part in an international comparison in the course of which Dobson spectrophotometers from Canada, Australia, India, Japan, the German Democratic Republic, Norway, Egypt and the United Kingdom were operated alongside the USA 'standard' instrument. The comparison was sponsored by the World Meteorological Organization, and the UK instrument performed satisfactorily throughout the lengthy sets of simultaneous observations (see Plate IV). Plate V depicts an earlier international comparison which took place in Belsk, Poland in 1974.

Association of British Climatologists

The Association now forms the Specialist Group in Climatology of the Royal Meteorological Society. The Steering Committee comprises:

B. W. Atkinson	*Chairman*
L. F. Musk	*Secretary*
Joan Kenworthy	*Treasurer*
C. Finch	
F. H. W. Green	
K. Smith	
P. A. Smithson	

Future meetings include one provisionally entitled 'Climatological research in the Meteorological Office' to be held on 6 January 1978. Enquiries about this meeting and membership of the group should be sent to L. F. Musk, School of Geography, University of Manchester, Manchester.

Retirement of Mr W. D. S. McCaffery

Mr W. D. S. McCaffery, Assistant Director, Personnel Management, retired on 18 November 1977 after a career of more than 38 years in the Meteorological Office. His concern for the efficiency of the Office coupled with a warm understanding of the interests of the staff made him ideally suited to personnel management, a field in which he specialized for the last nine years of his service. Under his guidance the merger of the scientific classes was successfully accomplished and the Office was able to lead the way with many post-Fulton reforms in career development.

Sinclair McCaffery graduated with first-class Honours in Physics at the University of Durham and joined the Office a few weeks before the outbreak of the second world war. With little preparation, he was sent overseas to Malta where he spent four years in operational forecasting under the most difficult conditions, having on one occasion to evacuate a severely damaged building during the height of a blitz and maintain a service through the succeeding night. He was commissioned into the RAFVR in 1943 and served as a Flight Lieutenant at HQ 18 Group until just after the end of the war. In the reconstruction period, he rejoined the Civil Service as a Senior Scientific Officer spending three years in Negombo, and two years at Pitreavie. In this period he went noticeably out of his way to assist his staff with their studies and his posting to the Training School in 1952 was therefore particularly appropriate. On promotion to Principal Scientific Officer in 1955 he joined the senior forecasting roster in Met O 2 and proved to have the ideal temperament for this exacting task which he performed with distinction for no less than eight years. In 1963 he moved to the Techniques and Training Branch (Met O 8) to apply this wide synoptic background and experience to the task of examining forecasting techniques at outstations and to the solving of local forecasting problems. After a brief spell back in the training field and another in charge of London Weather Centre he joined Met O 10 and soon made his mark as an able administrator. He was promoted to Senior Principal Scientific Officer in 1972.

It has been a pleasure to work closely with Mr McCaffery for the past two years. His quiet, unassuming manner, his impartiality and his sound judgement will be missed in Met O 10 and by the Office as a whole.

We wish him and Mrs McCaffery a very long and happy retirement.

A. C. HUGHES

OBITUARY

We regret to record the death on 23 June 1977 of Mr M. Tyrala, Assistant Scientific Officer.

Mr Tyrala was Polish by birth, and joined the Meteorological Office in May 1947 after serving in the wartime Polish Air Force. At the time of his death he was stationed at Linton-on-Ouse, North Yorkshire.

We regret to announce the death on 24 July 1977 of Mr M. H. Heard, Higher Scientific Officer, who was at the time Officer-in-Charge at Boscombe Down. Mr Heard joined the Meteorological Office as a Scientific Assistant in October 1957, was promoted to the grade of Assistant Experimental Officer in March 1967 and to Higher Scientific Officer in November 1971. During his career in the Office he was occupied in synoptic and forecasting work at a variety of outstations in the United Kingdom and also in West Germany.

It is with regret that we record the death of Mr J. F. Fisher, Senior Scientific Officer, on 5 August 1977.

Mr Fisher joined the Office on 1 April 1947 as Assistant Experimental Officer after wartime service in the Royal Air Force, where he had attained the rank of Flying Officer. In 1951 he transferred to the Colonial Service as Meteorological Officer to Nyasaland and rejoined the Office in 1955, being promoted to Senior Experimental Officer in 1956. Mr Fisher served in a variety of forecasting posts at home and overseas, on weather ships, and in the Meteorological Research Flight. At the time of his death he was working at the London Weather Centre.

CORRECTION

Meteorological Magazine, October 1977, page 319. In the last line of Table IV the term for $CO_2(2)$ should be prefixed by a minus sign.

THE METEOROLOGICAL MAGAZINE

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

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