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AN INVESTIGATION INTO RAINFALL RECORDING AT OXFORD

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SUMMARY

An account is given of the rainfall records in Oxford since the 18th century with special reference to the work of the Radcliffe Observatory (since 1935 the Radcliffe Meteorological Station). A comparison made between measurements from five different rain-gauges in the years 1868–1907 serves to illustrate the potential value of the Oxford record and to reveal some problems of a kind likely to be encountered when more than one gauge has been in use at the same site over a long period.

1. INTRODUCTION

After the record of Oxford weather made by Dr Richard Plot in 1684 the next impetus towards meteorology came from Dr Thomas Hornsby (1733–1810). This remarkable man who, like many of his 18th century contemporaries, held a number of university offices in plurality, became Savilian Professor of Astronomy in 1763 and, as the first Radcliffe Observer, supervised the construction of the Observatory from its foundation in 1772 until its completion in 1794. Hornsby's own rainfall record over the period 1760 to 1805 is not complete and has been the subject of another paper (Craddock, J. M. and Craddock, E., 1977). Some accounts of the rainfall record made by his successors at the Observatory from 1815 onwards have been published by Smith (1969, 1974 and 1975). For the period from 1815 to 1930 these rely entirely on the homogeneous series of monthly rainfall totals published by Knox-Shaw and Balk (1932) which attempts to provide definitive estimates of Oxford rainfall for the months considered. As part of a larger investigation, one of us extracted the records of Oxford rainfall which had been sent to the British Rainfall Organization during the last century, and which are now in the 10-year books which form the main rainfall archives of the Meteorological Office, with the object of using these to obtain numerical evidence of the relationships holding between measurements made at nearby sites. However, there were some disagreements between apparently authentic records, and it was the elucidation of these differences that brought us together. The number of different rain-gauges in use at the Observatory during part of the 19th century and the fact that many of the monthly and daily totals have been published in *Radcliffe Observations,* either annually or quinquennially, prior to the Knox-Shaw and Balk summary to 1930, renders the use of the published and unpublished figures for particular gauges a difficult task and one liable to erroneous interpretation. Much information on the nature and precise siting of the rain-gauges is available in the publications of the Observatory, and other essential information is available in the original manuscript records and observing books held at the School of Geography. However, a few vital pieces of information required considerable research in Oxford libraries and it is possible that some vital scraps of information have been lost or destroyed. The present paper attempts to summarize the facts about the Radcliffe rainfall record, in so far as these can be determined, for the benefit of future investigators, and also makes some comparisons between that record and another Oxford record, which has often been quoted, namely the one maintained at the Botanical Gardens between 1870 and 1953. Initially the record was maintained by a Fellow of Magdalen College and the record has been listed and described as Oxford, Magdalen College.

2. Historical

The history of rainfall measurements at the Radcliffe Observatory is illustrated in Figure 1, which is a sketch based on the 1895 Ordnance Survey Plan of Oxford at a scale of 50 inches to the mile. The Observatory building is unchanged from the time of Hornsby, apart from a small addition to the tower in 1857 to enable meteorological observations to be made there. At the time of writing these Victorian additions are being removed and the tower restored to its original appearance. The surrounding wall on the north side and the adjoining observer's house date from the same period. Figure 1 shows the surroundings as they were for most of the period from 1815 to 1895, although some important changes, described later, have taken place in the present century on the south side of the building. The foundation of the Observatory has been described by Smith (1969) and further facts can be found in Gunther (1923) and in the article on Hornsby in the *Dictionary of National Biography.* The present account mentions only points which affect the observation of rainfall. Hornsby's early rainfall record has been described elsewhere (Craddock and Craddock, loc. cit.) and it seems that after 1775 this was taken at the Observatory. It was this original roof gauge, read intermittently for brief periods between 1806 and 1814, that became the main Radcliffe record from 1815 until 1851. The original gauge was sited 22 ft 6 in. above the ground on the roof of the east wing of the Observatory; it was level with the parapet on the north side of the building and at a distance of 31 ft 8 in. from the central balcony platform of the Observatory from which the tower rises (Rigaud, S. P., *ca* 1834 and 1835). Since then the record has been continued with different rain-gauges and some changes of site until the present day. In all at least seven individual rain-gauges have been used and apart from the period from January 1816 to December 1833, when readings were taken at irregular dates, the gauges have been read daily. However, the hour of observation has varied and there were never more than four gauges in use at one time. During the period when the gauges were read at irregular dates there was no consistent pattern in the intervals between readings. Sometimes the gauge was read two or three times a month and sometimes two or three times a week, depending on the distribution of rainfall.

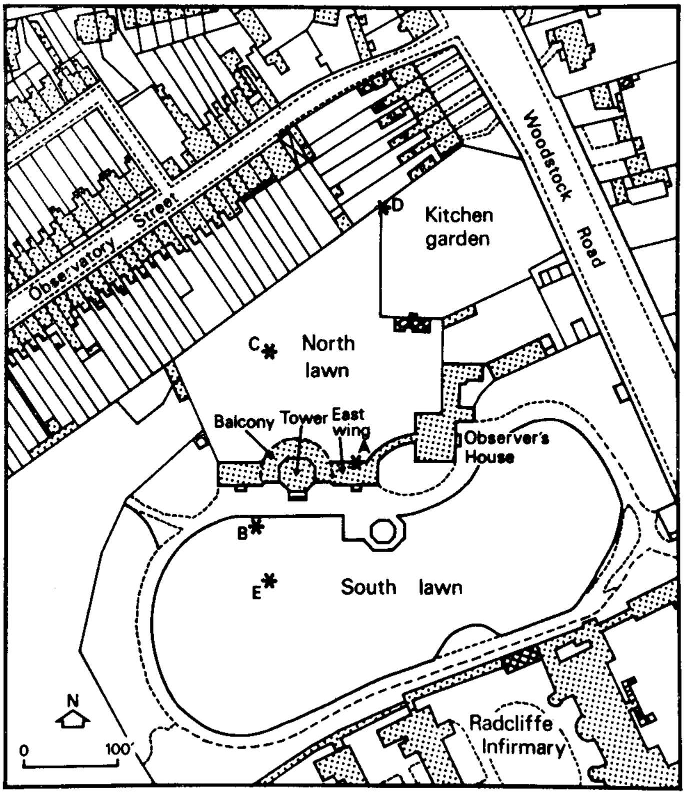

FIGURE 1—PLAN OF THE RADCLIFFE OBSERVATORY AND THE IMMEDIATE VICINITY IN ABOUT 1895

From 1815 until early 1850 there was only the east wing roof gauge. From 1851 until early 1862 there was also a ground gauge, and from then until the end of 1907 four gauges were in simultaneous use. Then the number fell to three, and at the end of 1908 to two. Between 1923 and 1930 the original east wing roof gauge was revived to provide direct comparisons with the modern ground gauge then in use. In 1963 the two remaining gauges, a Beckley siphoning self-recording gauge and an 8 in. gauge, were replaced by a modern tilting-siphon gauge (then known as a 'Dines') and a 5 in. Meteorological Office pattern gauge. The Beckley gauge had been in continuous use since early 1880 and maintenance was proving difficult as the parts were much worn. With few exceptions, the monthly totals from all gauges appear in the published *Radcliffe Observations* and since 1935 in the *Monthly Weather Report*. Various authors have quoted the Radcliffe rainfall record and produced summaries and tabulations which do not always agree with the figures on which they are based. The basic observations seem to have been made with commendable, indeed meticulous, care and devotion; queries which concern tabulations can often be resolved by reference to the original records. The homogeneous record produced by Knox-Shaw and Balk (1932) takes account of only three of the rain-gauges. It is discussed in more detail in section 5.

3. The individual gauges, 1815–1880

Hornsby's original rain-gauge which was in use in 1815 was of 12 inches diameter with a conical funnel 10½ inches deep (Rigaud, 1835) and was sited on the roof of the east wing of the Observatory. Plate I shows the east and central part of the building from the north, with a later extension of the Radcliffe Infirmary in the background. Rigaud (1835) and the Observatory year-books state that a pipe led from the rain-gauge down into the north-west corner of the quadrant room, where the rain was collected and measured. Subsequent alteration and interior decoration in the building have removed all traces of this arrangement, but the exact site of the rain-gauge on the roof was described by Rigaud (1834). This confirms a note in the Meteorological Office records which states that the gauge was about 60 ft from the tower. Its location is indicated at point A on the plan in Figure 1. The tower is over 112 ft high and this site, near a large obstruction, seems a curious choice in view of the insistence by the Secretary of the Royal Society, Dr Jurin (1723) that the exposure of a rain-gauge should be open in all directions. However, this site was probably chosen by Hornsby while the Observatory was being built (progress on the completion of the tower was delayed until 1794 for financial reasons) and it was probably better exposed than the sites of roof gauges previously used by Hornsby in Oxford (Craddock and Craddock, loc. cit.). Hornsby's successor, Professor S. P. Rigaud (1834) discusses this question of the possible sheltering effect of the tower and, by somewhat doubtful arguments and mathematical calculations, comes to the conclusion that 'from these data it may well be doubted whether the rising building diminishes at all the rain which falls into the funnel'. It seems that by 1850 doubts had arisen about the adequacy of the east wing exposure, because in that year a gauge of 10 in. diameter, with rim 11 in. above the ground, was installed on the south lawn near point B. Nevertheless in 1851 the Observer reported that, in his opinion, the loss of catch by the roof gauge due to the presence of the tower was only slight (*Radcliffe Observations* 1851). In 1862 the roof gauge was raised two feet by placing it on, instead of behind, the parapet 'to improve the exposure'. For the same reason the ground gauge was moved in May 1862 from point B to an area near point C on the north lawn, which, apart from an interlude from 1935 to 1939, has been used for rain-gauges ever since. This western part of the north lawn, with its surroundings, is shown in Plate II. In 1862 a third gauge was installed with rim 22 ft above the ground on a lattice above the roof of a disused anemograph hut. This hut is stated in the 1862 *Yearbook* to have been on the north lawn 'at a considerable distance from the Observatory' and was no longer required when the anemograph was installed on top of the tower. A fourth rain-gauge, with rim 112 ft above the ground, was also installed on the tower in 1862. These gauges were of 10 in. diameter, with pipes leading down to collecting vessels. In 1868 when the anemograph hut was demolished, the 22 ft gauge, with its lattice, was moved to a position above the north-west corner of the wall surrounding the kitchen garden of the observer's house (Point D on Figure 1). This ancient wall still exists, although the kitchen garden does not, and can be seen in Plate III, which is taken looking north-eastwards from the balcony platform of the Observatory where the telescopes were wheeled out for observation. In the kitchen garden site the 22 ft rain-gauge was higher than any object nearby, and the exposure was 'free in all directions'. This statement is repeated at intervals of several years in the annual editions of *Radcliffe Observations* and Plate III shows that it is true today. In 1877 a new

Glaisher gauge of 8 in. diameter, with rim 11 in. above the ground, was installed near point C and about five feet from the old 10 in. ground gauge. Comparisons were maintained daily until the end of 1880 when the old 10 in. gauge was removed. At the same time the old east wing roof gauge was taken out of use and a new Beckley self-recording gauge was installed near point C. This had a funnel of 11·3 in. diameter with rim 28 in. above the ground, and generally caught more than the Glaisher gauge next to it. In 1887 the rim of the 8 in. Glaisher gauge was raised from 11 in. to 20 in. above the ground. This may have been on Meteorological Office advice or to make a better comparison with the Beckley gauge.

4. THE RAIN-GAUGES AFTER 1880

From 1880 until 1883 the published observations give totals for the Beckley gauge and after 1883 for the 8 in. Glaisher gauge, together with the totals of the Beckley self-recording gauge and the kitchen garden and tower gauges. Towards the end of 1907 it was discovered that the kitchen garden gauge had sprung a leak near the rim and the decision was taken not to repair it 'as 40 years of daily records should be enough for all purposes'. The year 1908 was the last one in which the tower gauge was maintained, but the Beckley gauge continued in use until 1963 when it was replaced by a Dines tilting-siphon recording gauge. The daily charts for the Beckley gauge were analysed and tabulated up to 1953. Until 1902 this gauge appears to have read rather higher than the 8 in. Glaisher gauge and there are frequent references in the pocket books to minor adjustments to the mechanism. From 1906 onwards the Beckley gauge appears to have functioned much better and to have caught about one per cent more than the Glaisher. After 1920 the modern practice was adopted of adjusting the hourly and daily readings of the self-recording gauge to agree with those of the 8 in. Glaisher gauge. When Dr Knox-Shaw became Radcliffe Observer in 1924 he decided that the rainfall record should be reduced to a common standard, that of the 8 in. Glaisher gauge; and, as there was only a three-year overlap from 1877 to 1880 between the record of the Glaisher gauge and that of the old east wing roof gauge, the latter gauge was revived from 1923 to 1930 and read daily. The daily totals of the roof gauge during this period have never been published but survive in the observer's pocket books. Mr J. G. Balk used them to calculate monthly conversion factors to bring the totals from the roof gauge between 1815 and 1862 to the standards of the Glaisher gauge.

In 1935 the Radcliffe Observatory moved to Pretoria but, after some uncertainty, it was agreed that the responsibility for continuing the meteorological record should be assumed by the Professor of Geography (School of Geography MSS). A stipend was provided to enable Mr Balk, who had joined the Observatory in 1903 as a computer, to continue as Radcliffe Meterological Observer until his retirement in 1953. Discussion with those who remember him and obituaries published in Oxford newspapers in 1955 show him to have been something of a local character. As a survivor of the old regime he may have been somewhat set in his ways, but the numerous records and notes which survive in his hand show him to have been a most careful and dedicated worker. Since 1935 responsibility for the maintenance of the Radcliffe Meteorological Station, and for the appointment of an observer, has remained that of the Professor and staff of the University School of Geography. The Observatory building and the observer's house were taken over by the newly founded Nuffield Institute for Medical Research in

1935, and more recently by the offices of the University Medical School. The building will shortly be occupied by Green College, a new foundation for clinical medical students. Since 1935 the area of the hospital on the south side of the old observatory has expanded enormously. One consequence of the removal of the astronomical observatory in 1935 was a decision to move the rain-gauges from point C to a point on the south lawn near E. This meteorologically surprising move was a result of *force majeure* since the garden on the north side was to become private. However, as a fortunate result of wartime emergency construction in 1939, it was necessary to move the gauges back to near point C on the north lawn, where they have remained ever since. The importance of this site for the continuation of meteorological records has recently been recognized by a University decree.

Today, although the buildings and the north lawn have changed hardly at all since Hornsby's day, the south lawn and surrounding wall have disappeared beneath Infirmary extensions and a car park. In 1963 the 8 in. Glaisher gauge was replaced by a modern 5 in. Meteorological Office pattern gauge at the same time as the Beckley gauge was replaced by the Dines recording gauge. This was done on instructions from the Meteorological Office which had supplied both Beckley and Dines gauges. Unfortunately it was not considered necessary, by those responsible for this change, to maintain an overlap between the 8 in. and 5 in. gauges, presumably because it was assumed that the results would be so similar as to make this unnecessary.

5. The Knox-Shaw and Balk reductions

The reduction of the rainfall records to provide monthly totals since 1815 was carried out by Mr Balk on the instructions of Dr Knox-Shaw. He must have relied on substantially the same documents which are preserved today. Mr Balk, no doubt as a result of his training as an astronomical computer, showed an attention to detail which, however necessary in astronomy, is rare in meteorology. The principles behind the reductions are succinctly described by Knox-Shaw and Balk (1932). They elected to use records from only three of the rain-gauges which had been in use since 1815, namely those of the east wing roof gauge from 1815 to 1861, those of the 8 in. Glaisher gauge from 1877 until 1930 and those of the 10 in. gauge on the north lawn for the years in between. Two major problems arise in any attempt to render homogeneous the records of these different gauges. Firstly, during the period from 1816 to 1833 when rainfall was not recorded every day, the totals for the east wing roof gauge have to be apportioned between the months. This involves a certain element of intuitive guesswork and a reliance on the brief remarks in the observer's weather diary. To a lesser extent a similar problem arises with the fuller and more reliable daily records later in the 19th century because the time of daily observation was not always the same. Thus, for a period when rainfall was measured from noon to noon, it was often necessary to make a small adjustment to the monthly totals. Inspection of the corrections made in the original pocket books and manuscript records by Mr Balk, and in some cases by his predecessors, suggests that this problem has been treated as carefully and accurately as the surviving evidence will permit.

Once the daily totals have been adjusted in this way to give a reliable monthly total, the readings of the various rain-gauges in use at different periods have to be brought to the standard of the 8 in. Glaisher gauge by the application of conversion factors found from an evaluation of overlapping records. The various conversion factors found by Knox-Shaw and Balk and used in their homogenization have been recalculated and checked and the conclusion reached that in this case too the calculations and conclusions are as reliable and accurate as the evidence permits. A full treatment of these conversion factors would be tedious. However, some examples can be given to illustrate the method and reliability. Knox-Shaw and Balk state that the readings of the roof gauge on the east wing have to be multiplied by a factor, 'which in the mean is 1·130' to reduce them to the standard of the 8 in. gauge on the north lawn. This was deduced from the readings of the re-installed roof gauge between 1923 and 1930. This figure was checked and calculated again from the entries in the observer's pocket books and found to be correct to the second decimal place. They found that 'the factor varied with the month, rather than with the monthly total of rain' and quote a different factor for each month. Our calculation of the monthly factors did not produce quite such a close agreement. In winter months, with little rain and considerable snow, Knox-Shaw and Balk appear to have made some allowance for a greater difference between the two gauges. Doubts, which we both had, whether the comparison of the roof gauge with the ground gauge during the period 1923–30, in the middle of a period when the westerly weather type was particularly frequent, would necessarily be applicable to a period in the mid-19th century, caused us to calculate conversion factors for the periods 1851–61 and 1862–79, when the 10 in. ground gauge was sited at point B and point C respectively. It seems strange that Knox-Shaw and Balk did not use data available for these periods—or if they did, they made no reference to having done so. To our surprise these comparisons vindicated the Knox-Shaw and Balk conversion factor. A comparison of the annual totals of the east wing roof gauge with the 10 inch ground gauge on the south lawn from 1851 to 1861 gave a mean conversion factor for the former of 1·133 while a comparison of the roof gauge and the 10 in. gauge on the north lawn between 1862 and 1879 gave a mean conversion factor of 1·153. In each case the conversion factor would apply to the reading of an 8 in. gauge on the north lawn. To determine these factors it was necessary to make use of the comparison between the Glaisher gauge and the 10 in. gauge on the north lawn between 1877 and 1880 as well as the overlap between the records of the roof gauge and of the 10 in. ground gauge situated successively on the south and north lawns between 1850 and 1880. A direct comparison was possible over the short period from 1878 to 1879 between the east wing roof gauge and the 8 in. Glaisher gauge; this gave a conversion factor for the roof gauge of 1·121. Closer agreement between the Knox-Shaw and Balk mean annual conversion factor of 1·130 and that calculated for other periods can hardly be expected in view of the known limits of accuracy of standard raingauges. An examination of the monthly and annual values of the east wing roof gauge and the various ground gauges in use during all the periods described above shows that there is quite a significant variation about this mean from month to month and even from year to year. The annual correction factor over 37 years had a standard deviation of 0·045. This is to be expected since the frequency of particular wind directions and the predominance of particular weather types are likely to affect the proportion of precipitation caught by the elevated gauge partly sheltered by the tower as compared with one well exposed on the ground. The total amount of precipitation during a month, its intensity, and particularly the amount falling in the form of snow are likely to produce further variations in the difference. One must conclude that, in view of the inherent complexity of the problem, the Knox-Shaw and Balk reductions are probably the best that can be made for the period when the only Oxford rainfall data are those from the east wing roof gauge. However, the need for the application of substantial correction factors to all monthly totals before 1851, factors which are averaged over months or years, introduces an additional source of error in the homogeneous values, compared with corresponding totals for later years. The importance of these errors depends on the manner in which the monthly totals are used, and is discussed further in section 8. There is one further and, as far as the winter months are concerned, probably more serious reservation about the early rainfall figures. From the data it is not clear when snowfall was treated as precipitation and included in the rainfall totals. Certainly on many occasions before 1851 there are references to snow in the observer's pocket books and the manuscript record with no obvious subsequent rainfall entry to suggest that this was measured after it had been allowed to melt. If the observers did not consider that snow should be measured and included as rainfall, and there is some evidence to suggest that this was the case, then in some years at least the winter precipitation values will be significantly reduced. However, the same attitude may have been taken by contemporary observers elsewhere and as A. Bleasdale (personal communication) has pointed out: 'early practices with regard to snow were chaotic and provided G. J. Symons with one of his fields for recommendations and standardization'. The relative dryness of the winters in the early 19th century noted by Smith (1974), and the change of rainfall regime since, may therefore be more apparent than real if in some years a significant proportion of the winter precipitation was unrecorded.

6. The Botanical Gardens (Magdalen) rainfall record

There is a complete daily rainfall record from a ground gauge in the Botanical Gardens at Oxford from 1870 to 1953, and a similar record from a roof gauge, at a height of 34 ft, from 1882 until January 1936. After 1 August 1923, the roof gauge was only read monthly on the first day of each month. Like the early Radcliffe records, monthly values of these gauges are included in the 10-year books in the Meteorological Office archives, and the ground gauge data were published in *British Rainfall;* they have thus been used and quoted by a number of researchers. The early history of this rainfall record is described by Gunther (1904) and there are brief notes which do not add very much to this information preserved with the original manuscript records from 1867 to 1935 in the library of Magdalen College. These records are neat and well maintained and to a large extent duplicate the Radcliffe meteorological observations, since they include wet- and dry-bulb and maximum and minimum temperatures, wind direction and force and the height of the River Cherwell which flows past the site. The observations, like the science laboratories where they were taken, owe their initiation to Dr Daubeny, a Fellow of Magdalen College. In the present century the buildings became part of the University science laboratories and responsibility for the meteorological observations passed to the Curators of the Botanical Gardens, although the record continued to be described as 'Oxford, Magdalen College' which lies just across High Street to the north. Reports to the Meteorological Office by Dr R. T. Gunther in 1907 and the report of a visit by Mr H. E. Carter of the Meteorological Office in 1948 confirm that the ground gauge in use at these times was the same, and it appears to have been the one originally installed in 1870. It was described as a five inch circular gauge with a shallow funnel made by Casella. It was mounted in a concrete block. 'A heavy metal collar with a locking arrangement fits around the top of the gauge almost flush with the rim.' Carter (1948) also noted: 'there could be insplashing in heavy rain from the metal collar and concrete block but this might be offset by outsplashing from the shallow funnel'. Little is known about the roof gauge other than the note by Gunther quoted above which states that the gauge was of five inches diameter on the roof of the Laboratory. Two gauges had been mounted on the College roof between 1867 and 1882 at heights of 57 ft and 64 ft but it was thought that the exposures were poor owing to shelter from chimney stacks. These gauges were only read intermittently. Preserved in the College library are some earlier but intermittent rainfall records from January 1867 until the end of 1869. The observer's manuscript books indicate that from 1870 until the end of 1875 the rim of the ground gauge was 7 in. above the ground but, apparently on the advice of G. J. Symons of the British Rainfall Organization, it was then raised to 12 in. above the ground. All the meteorological observations at the Botanical Gardens were discontinued in 1953 as a result of vandalism; the site was at a spot much frequented by the public. After 1935 the record was maintained by technicians from the University chemistry laboratories and in spite of a search the manuscript records for this period have not been found. The figures used and quoted from 1936 to 1953 have been supplied from the Meteorological Office archives.

The Magdalen rainfall record has been used in the subsequent discussion in this paper to help resolve some problems which arose when comparing the various gauges in use at the Radcliffe Observatory from 1868 to 1907. The Botanical Gardens are situated 1550 metres south-east of the Radcliffe Observatory but at a slightly lower altitude above mean sea level, 58 m as compared with 63 m. Both are sufficiently close to the centre of Oxford to have been in effect urban sites throughout the period of record although, as noted earlier, building on the south side of the Radcliffe Observatory this century has significantly reduced the amount of open space in the immediate vicinity.

7. Comparisons between rain-gauges at the Radcliffe Observatory and the Botanical Gardens

From 1868 until 1907 four rain-gauges were continuously in use at the Radcliffe Observatory although the sites and the individual gauges were not always the same. During this time the 8 in. Glaisher ground gauge, adopted as the standard by Knox-Shaw and Balk, was introduced and it was with a view to investigating the validity of their reduction that comparisons between the annual totals of the various gauges were made. The fact that for the whole of this period two of the gauges were elevated well above ground level in unorthodox exposures adds further interest to the comparison. The comparisons can be summarized in Table I and Figures 2 and 3. Table I lists the annual falls recorded by certain rain-gauges as a percentage of the mean for the period. The gauges are: (a) the Radcliffe ground level gauge (the 8 in. Glaisher reading after 1879, and the 10 in. gauge reading before that, corrected by the factor used by Knox-Shaw and Balk). The figures are, therefore, those of the homogeneous record of these two workers; (b) the reading of the Radcliffe kitchen garden gauge at an elevation of 22 ft; (c) that of the Radcliffe tower gauge at an elevation of 112 ft; (d) the record of the

'Magdalen' ground gauge, and (e) that of the 'Magdalen' roof gauge at an elevation of 34 ft. Figure 2 is a graph showing the catches of the Radcliffe elevated gauges as a percentage of that of the Radcliffe ground gauge.

TABLE I—ANNUAL PERCENTAGE OF THE LONG-PERIOD MEAN FOR FIVE OXFORD RAINFALL RECORDS

	(a)	(b)	(c)	(d)	(e)
1870	69·4	68·5	59·9	66·1	
1	83·6	84·3	80·2	85·4	
2	117·9	116·9	102·1	119·5	
3	92·7	87·8	80·0	92·5	
4	84·7	83·4	72·4	86·3	
5	130·9	128·0	117·1	133·7	
6	128·3	127·4	122·4	127·9	
7	119·2	117·1	115·6	118·4	
8	106·7	106·9	118·3	113·7	
9	124·3	124·4	109·0	128·8	
1880	124·8	—*	137·6	127·3	
1	105·2	—*	100·6	102·3	
2	127·1	126·2	126·7	134·2	134·4
3	107·5	109·1	112·7	117·6	117·8
4	76·3	76·6	73·9	80·3	74·7
5	104·0	101·0	102·9	107·1	112·8
6	128·9	126·2	132·7	132·4	134·5
7	77·1	82·5	72·3	77·4	79·2
8	110·2	111·2	106·6	112·9	113·7
9	95·0	94·7	95·4	91·7	99·3
1890	71·9	71·9	69·4	70·2	74·8
1	111·7	111·7	110·1	109·6	117·3
2	82·8	85·1	86·6	77·2	80·1
3	71·3	73·1	69·9	68·3	70·9
4	115·2	119·5	123·8	115·0	124·3
5	91·2	93·7	93·5	90·2	94·8
6	95·4	98·5	99·9	90·8	96·6
7	106·4	110·3	113·5	101·1	107·2
8	77·6	81·7	79·4	75·7	80·6
9	84·9	89·3	89·1	84·3	87·1
1900	95·3	99·8	94·2	96·2	101·0
1	89·9	94·7	96·1	88·3	91·4
2	67·3	72·7	71·3	70·1	71·5
3	145·1	149·3	159·2	144·9	155·2
4	91·5	93·2	100·7	87·3	91·7
5	84·5	82·7	88·6	78·6	81·8
6	96·9	92·8	99·1	91·7	95·7
7	108·1	108·3	118·1	105·2	111·3
Mean annual fall over above period (inches)					
	24·77	24·22	16·95	24·25	20·57

(a) Radcliffe ground gauge (Knox-Shaw & Balk)
(b) Radcliffe 22 ft kitchen garden gauge
(c) Radcliffe 112 ft tower gauge
(d) Magdalen ground gauge
(e) Magdalen roof gauge at 34 ft

* Data unreliable owing to leaky gauge.

The graphs and the table show year-to-year fluctuations as is to be expected when the intensity of rain and the frequency of different weather types are as variable as they are in Britain. The first impression from Figure 2 is that the tower gauge at the Radcliffe Observatory was less efficient in the 1870s than subsequently. This could be explained by some undocumented changes in its exposure consequent upon the mounting of a new anemograph on the tower in 1880. A second and more disturbing conclusion is that both the elevated gauges

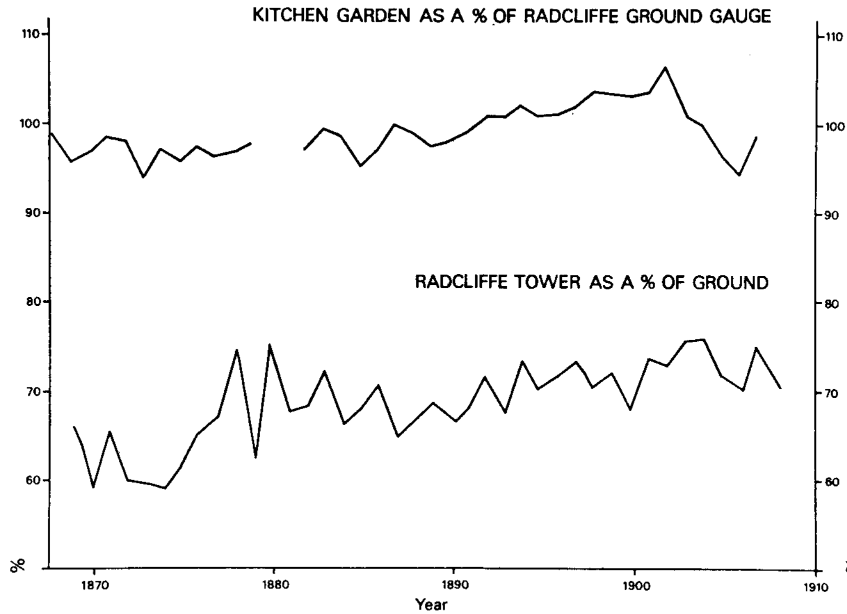

FIGURE 2—ANNUAL RAINFALL RECORDED BY THE ELEVATED GAUGES AT THE RADCLIFFE OBSERVATORY AS PERCENTAGES OF THE ANNUAL FALLS RECORDED BY THE GROUND GAUGE, 1868–1908

became relatively more efficient than the ground gauge from 1892 onwards. The kitchen garden gauge actually caught more than the ground gauge between 1892 and 1903 after which its readings fell back to levels similar to those registered before 1890. It was at first thought that this might have been caused by increasing shelter of the ground gauge from growing trees in the garden. A search of all available contemporary pictures, photographs and records of the garden, which was always kept well tended and ornate, failed to reveal any positive evidence of this although the possibility cannot be rejected entirely. Another possible explanation is that the growth of Oxford in the late 19th century produced changes in the wind profile around the Observatory which may have increased the relative catch of the two elevated gauges. Other possible explanations have been investigated: the rim of the Glaisher gauge was raised from 11 in. above the ground to 20 inches in 1887 and thereafter remained at this level. On more than one occasion it was noted in the observer's pocket books that the tubes leading from the high-level gauges to their collecting vessels had become blocked and had had to be cleaned out; this might have been expected to reduce their catch rather than to increase it, as would the effect of snow being blown out of the high-level gauges. It was noted in the pocket book for 1905 that the glass measure for the 8 in. Glaisher gauge was broken on 15 August and replaced on 18 August by a new measure supplied by the Meteorological Office. The broken measure had, it was noted, been in use for 25 years so that wrong calibration of a measuring cylinder could not have explained a decline in the catch of the ground gauge

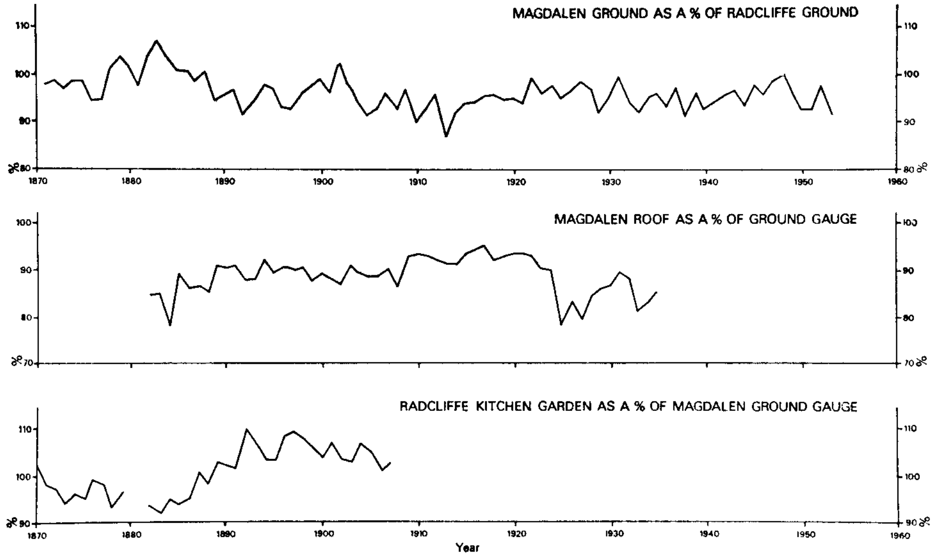

FIGURE 3—ANNUAL RAINFALL RECORDED BY THE 'MAGDALEN' GROUND GAUGE COMPARED WITH THE FALLS RECORDED BY THREE OTHER GAUGES, FOR VARIOUS PERIODS BETWEEN 1870 AND 1953

around 1892. However, it appears that the measuring cylinder used for the high-level gauges was made or calibrated by the Observatory so that any change of measuring vessel during this period might have affected the readings of the upper gauges.

The apparent discrepancy between the ground and high-level gauges has been investigated at some length since it was not referred to by Knox-Shaw and Balk and they may not have noticed it. If there was a decline in the efficiency of the ground-level gauge at this time it would have seriously affected the validity of their reduction of earlier readings to the standard of the 8 in. Glaisher gauge. In order to try to resolve this problem the manuscript records of the two 'Magdalen' gauges were checked and then compared with the Radcliffe rainfall records. The Magdalen ground gauge is probably less reliable than the Radcliffe Glaisher gauge and it was not so well exposed. Figure 3 shows graphs of the annual totals of the Magdalen ground gauge as a percentage of the Radcliffe ground gauge, of the Radcliffe kitchen garden gauge and of the Magdalen roof gauge. This comparison seems to contradict the evidence from Figure 2 that during the latter part of the 19th century and until 1903 the Radcliffe ground gauge was becoming less efficient. In spite of a greater year-to-year variation between the ground gauges at the two different sites, the Magdalen annual rainfall totals are about 95 per cent of those at the Radcliffe Observatory with the exception of a few years around 1880. The period from 1875 to 1885 was one of notably wet summers when rainfall may have been particulaly intense, and this might be an explanation; alternatively the Magdalen gauge may have been defective for this short period. The mean difference between the two gauges is consistent with known and explicable rainfall gradients in Oxford consequent upon the local relief. The comparison between the Magdalen ground gauge and the Radcliffe kitchen garden gauge between 1892 and 1893 suggests that it was this latter gauge that was inconsistent with the record of the ground-level gauges at both sites. The comparison between the Magdalen ground and roof gauges over the period 1882–1924 shows no trend in the difference between the two gauges, but the annual totals for the roof gauge were reduced after 1923 when the gauge was read only once a month instead of daily as before. Presumably this was a consequence of evaporation loss or of the monthly accumulation of small daily totals when the gauge was read daily.

The evidence of Figures 2 and 3 together with the annual percentage figures in Table I seems to point to the conclusion that for a variety of reasons the records of the elevated gauges at the Radcliffe Observatory are not so reliable as that of the ground gauge. This 8 in. Glaisher gauge, together with the Beckley self-recording gauge that stood alongside it, became the standard rainfall record of the Observatory after 1880. The readings of the Glaisher gauge were reported to the Meteorological Office and to the British Rainfall Organization and the Observatory was in regular communication with both organizations. During the period from 1880 to 1914 the Radcliffe was one of the most important meteorological observatories in the country and its observations were included in the *Daily Weather Report*. The Observatory must have been visited and inspected by professional meteorologists at regular intervals, although no correspondence to confirm this survives at Oxford. It seems improbable that the Meteorological Office would have accepted readings from a defective or badly exposed rain-gauge at this station.

On balance it seems more likely that the elevated gauges were imperfect and their records less carefully scrutinized for error and inconsistencies. It is known from a note in the published *Observations*, and from manuscript notes in the pocket books, that in 1880, 1881 and 1907 leaks were discovered near the rim of the kitchen garden gauge and that these rendered the readings for 1880, 1881 and 1907 too great. On the first two occasions the leak was repaired and it is possible that on the third occasion it had existed for some years before it was detected and that it had become progressively worse. These comparisons may be summed up by saying that while there are disrepancies between the records which show that some of the records must have been defective in some years, the agreement after 1889 between the ground gauges at the Radcliffe Observatory and the Botanical Gardens leads us to prefer their testimony, rather than that of the elevated gauges. Moreover, we feel that while the reduction by Knox-Shaw and Balk includes many details which would probably be omitted if the work were done today, these are inessential rather than objectionable. There is scope in the volume of records for a much fuller investigation, but unless this can be carried out, we are inclined to accept the Knox-Shaw and Balk figures as the best available.

8. Discussion

This paper is concerned above all to set out the facts about one of the longest and best-kept collections of meteorological data that exists for any place in Great Britain. Possible applications are explored only lightly, but the following are some of the main prospects.

(1) Although the Radcliffe rainfall records discussed here start in the year 1815, the paper by Craddock, J. M. and Craddock, E. (1977) provides an

extension back to 1767 with the annual totals from 1776 to 1804 to the same rain-gauge and site as was used later from 1815 onwards. The Radcliffe rainfall records fall into two parts: the first, that of the east wing roof gauge, started in 1776 and continued, with some unfortunate breaks, until 1880; the second is of ground gauges, and started in 1850 and is continuing still. During these 200 years, the immediate surroundings of the gauges have changed little, and changes in the surrounding terrain are less in extent and better documented than they are for most town sites. Hence the Radcliffe records are unusually suitable for investigating changes on the climatic time-scale.

(2) The records from 1868 to 1907 provide evidence on the problem of correcting a record for the elevation of the gauge, which arises with many early rainfall records. While the problem has been known for 200 years, most investigations have covered a few years, at most, and produce discordant results due, probably, to differences in the surrounding terrain. Table I shows that the high-level gauges agree very well with the more conventional exposures in showing the wettest and driest years, and that the agreement could be improved still further if the departures for the high-level gauges were scaled down somewhat. This subject deserves examination with the inclusion of similar comparative records made elsewhere.

(3) Investigations based on daily rainfall and temperatures etc. can be made using a range of basic data which does not exist in most places.

In conclusion, we may remark that the fact that this paper is concerned so much with the defects of rain-gauges may give the impression that the Radcliffe observations are slipshod and unreliable. The truth is exactly the opposite, because it is the number of carefully kept and comparable observations which has enabled us to piece the story together, and to bring to light minor discrepancies which in most circumstances would be incapable of being detected. These observations can help to elucidate unanswered questions of the British rainfall regime of the last two centuries, and could provide the material for several Ph.D. theses, besides the work on the above topics which the authors hope to undertake. It must be emphasized that nearly all British rainfall records for years before 1800 were made with elevated rain-gauges, and that the correction of such records to the standards of a 1 ft gauge is an essential part of any serious attempt to probe the rainfall regimes of the past.

9. Acknowledgements

The authors wish to acknowledge help in finding relevant information from the following: the staff of the Rainfall Quality Control Unit in the Meteorological Office; Miss Elspeth Buxton, Librarian of the School of Geography, University of Oxford; Mr G. L. Harriss, Librarian, Magdalen College; and the staff of the Bodleian Library, Oxford.

Valuable assistance in checking manuscript records and in calculation was given by Mr J. Samson, Radcliffe Meteorological Observer, 1975–76, and Mr T. G. Smith.

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COMPUTER PROCESSING OF SATELLITE IMAGE DATA

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(Meteorological Office, Bracknell)

SUMMARY

The automatic processing by a small computer of visible and infra-red image data from meteorological satellites is described. The process includes digitization, projection, and output in a variety of forms. Output via a facsimile recorder has been in experimental operational use since November 1976. The technique is compared with the current operational procedure.

INTRODUCTION

This paper describes the automatic processing of satellite image data (visible and infra-red) from NOAA 5 and Meteosat in the PDP 11/40 computer laboratory operated by the Systems Development Branch (Met 0 22) of the Meteorological Office. Similar techniques have been developed by other meteorological services: those described here are adapted to the needs of the United Kingdom service. In the case of NOAA 5 data the resulting pictorial output is already in use in the Central Forecasting Office (CFO), supplementing the directly received pictures, as viewed from space, which have been generally available for some years.

THE CURRENT OPERATIONAL PROCEDURE

In the current procedure operated in CFO, a forecaster specialized in the analysis of satellite pictures takes the direct earth-views, examples of which are shown in Plate IV, and adds a latitude/longitude grid by means of an overlay chosen from a standard set. This grid is located relative to two timing marks shown in Plate IV as lines of alternate black and white which are added automatically at the satellite ground receiving station at RAE, Lasham in Hampshire. Sometimes the marks, which are actual scan lines for the presumed times at which the satellite crosses latitudes 65 and 40 degrees north, are several seconds out, or missing altogether, which can cause problems in locating the grid. The next step is the construction of a composite nephanalysis which incorporates eye-interpretation of cloud patterns from successive (visible and infra-red) pictures and involves a rather awkward transformation from the earth-views to a 1:20 million polar stereographic map projection. Both the original pictures and the nephanalyses are used by forecasters in CFO, although only the latter can be superimposed on their normal working charts. The former contain details which cannot be represented on a nephanalysis and are valued tools in spite of their distorted perspective. Whereas nephanalyses are sent by facsimile broadcast to all official outstations, only selected stations receive the pictures themselves.

THE COMPUTER AND THE ASSOCIATED PROCEDURE

The PDP 11/40 is a small but powerful computer of the type often referred to as a 'mini-computer'. It has a wide range of peripheral devices attached to it, those of significance in the present context being shown in Figure 1. Its main use is for

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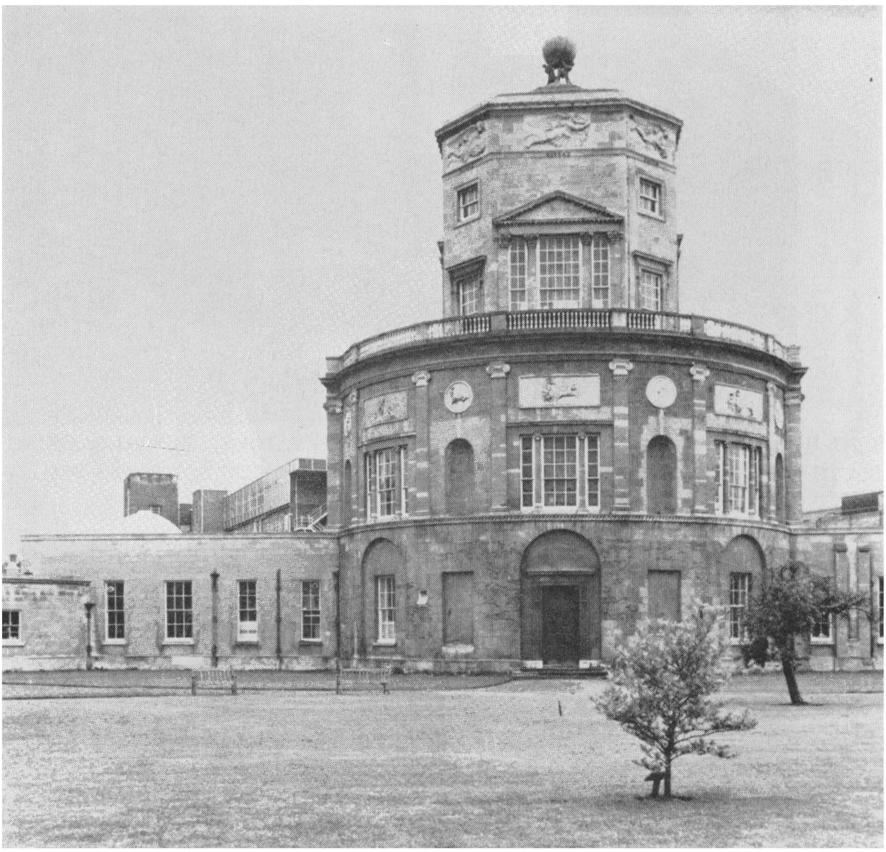

PLATE I—THE RADCLIFFE OBSERVATORY IN OXFORD IN 1978, LOOKING SOUTH AND SHOWING THE EAST WING, THE BALCONY AND THE TOWER

The design of the tower of the observatory is roughly based on the Horologium of Andronicus of Cyrrhus at Athens, built in the first century B.C. and usually called the 'Tower of the Winds'. The Horologium still stands in a good state of preservation near the Roman agora at the foot of the hill of the Acropolis, and a drawing of it is used as the emblem of the Royal Meteorological Society. In ancient times it had a sundial, a water clock (for cloudy days) and a wind vane in the form of a Triton. (See Plates II and III between p. 300 and p. 301 in the *Meteorological Magazine* for October 1970.) (See page 260.)

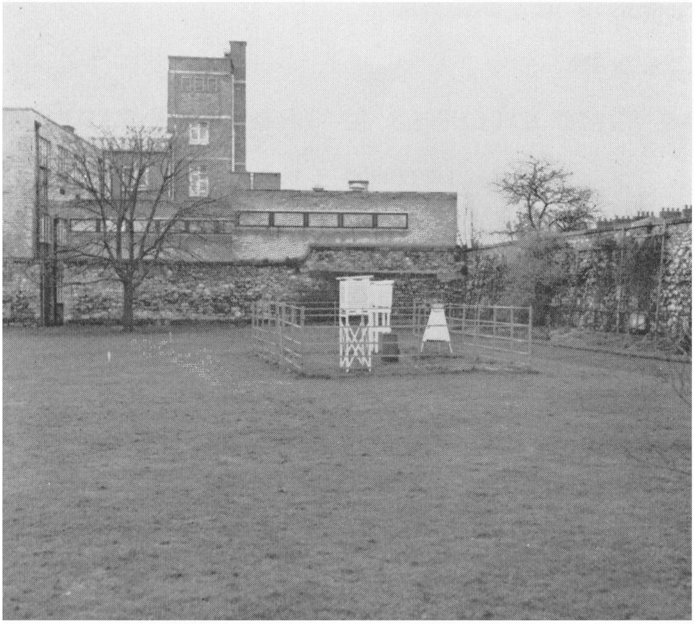

PLATE II—THE NORTH LAWN OF THE RADCLIFFE OBSERVATORY, OXFORD, LOOKING SOUTH-WEST TO SHOW THE RAIN-GAUGE AND THE NORTH-WEST BOUNDARY WALL

(See page 260)

PLATE III—LOOKING NORTH-EAST FROM THE BALCONY OF THE RADCLIFFE OBSERVATORY, OXFORD, TO SHOW THE KITCHEN GARDEN WALL AND THE SURROUNDINGS

(See page 260)

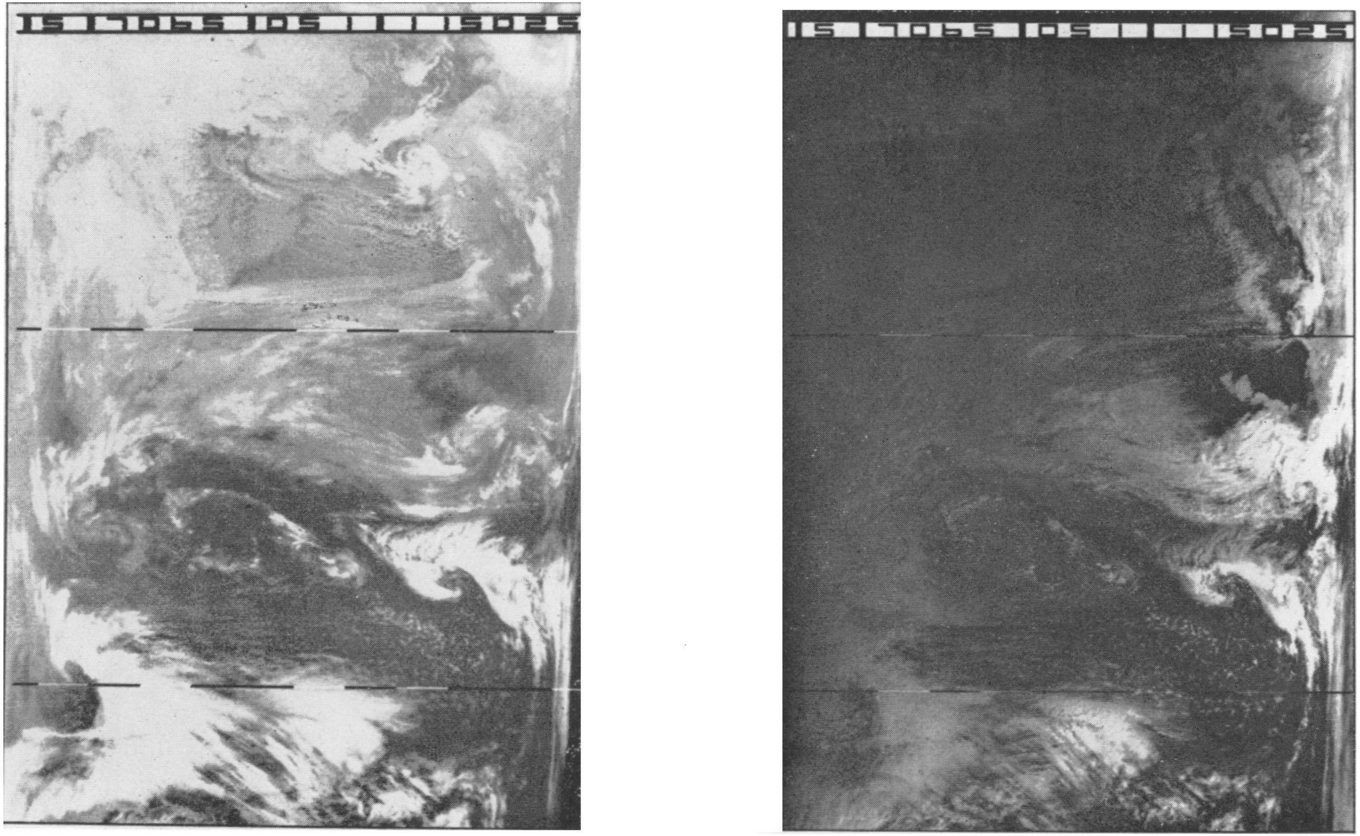

PLATE IV—SINGLE ORBIT BEFORE PROJECTION AT 1120 GMT ON 20 FEBRUARY 1978, INFRA-RED AND VISIBLE PICTURES

The British Isles may be seen at the right-hand side just below the upper timing marker. (See page 272)

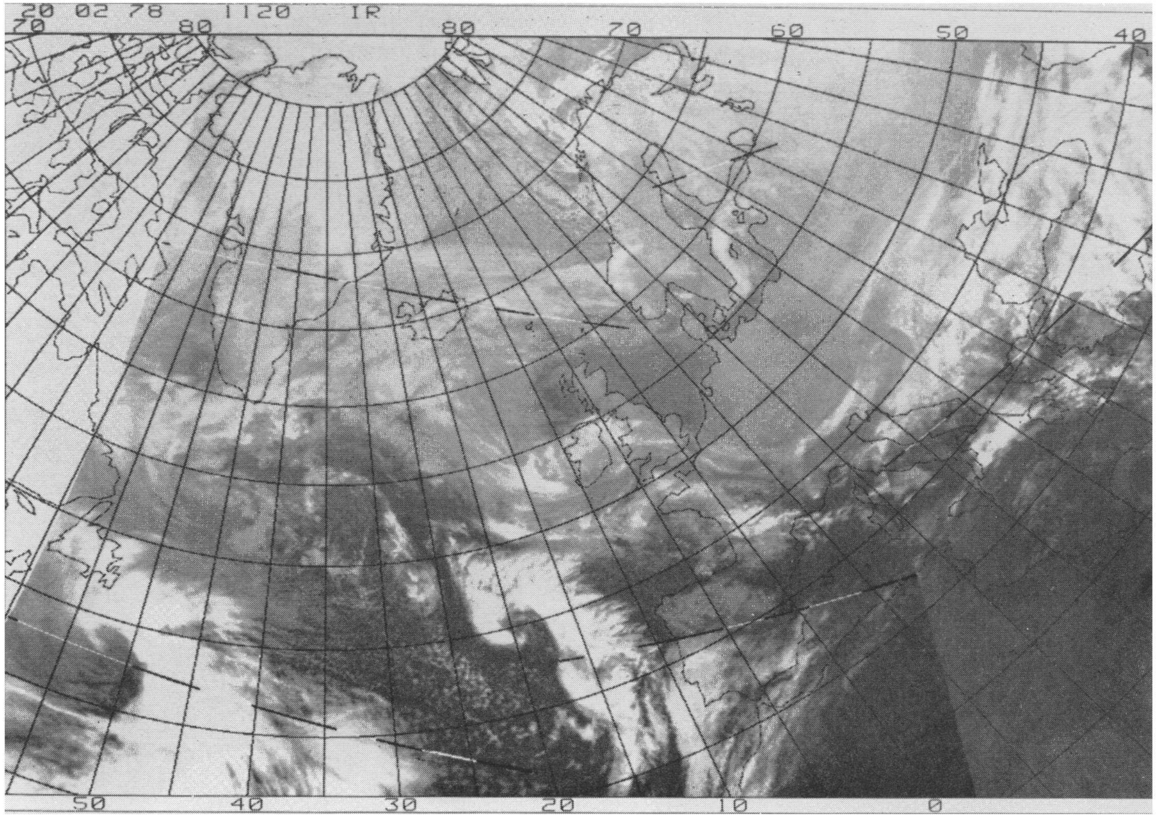

Plate V (a)—Composite picture of three orbits after projection on 20 February 1978 (infra-red)

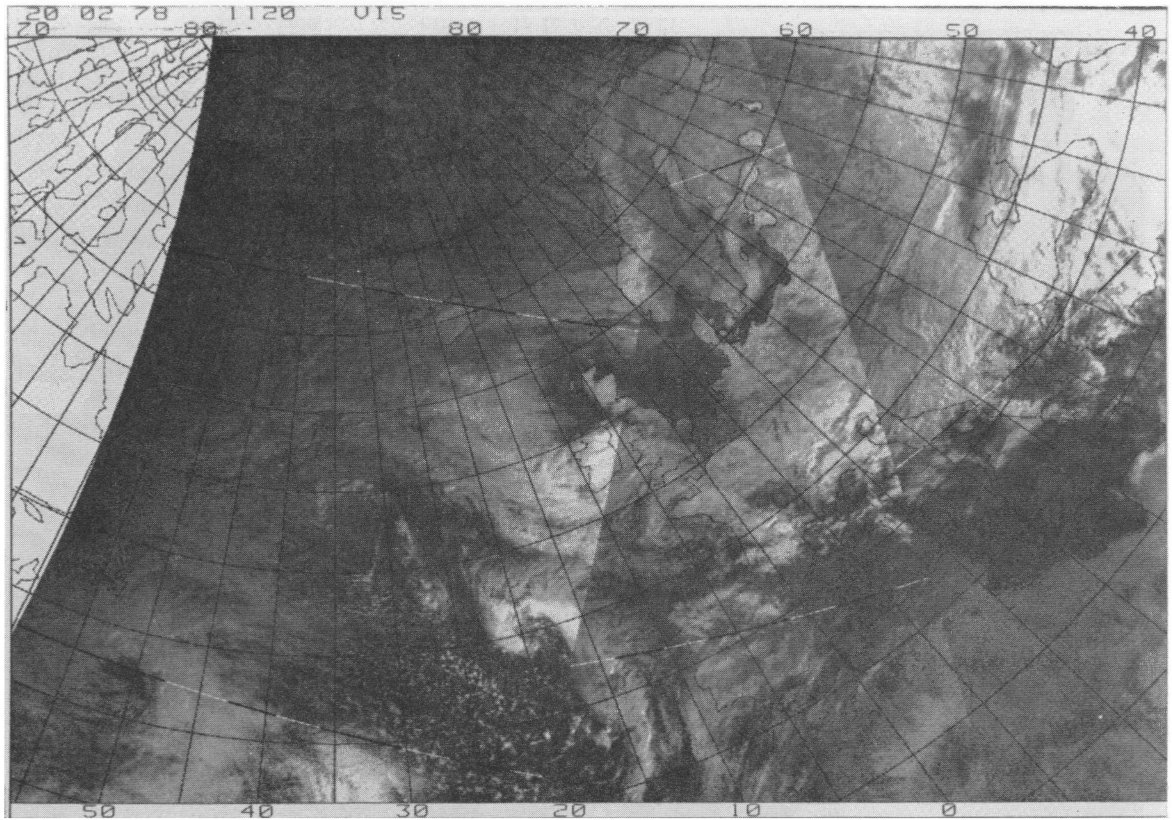

PLATE V (b)—COMPOSITE PICTURE OF THREE ORBITS AFTER PROJECTION ON 20 FEBRUARY 1978 (VISIBLE)

(See page 275)

PLATE VI—ALTOCUMULUS MAMMA OVER BRACKNELL (BEAUFORT PARK), 17 SEPTEMBER 1974

Rays from the setting sun illuminating altocumulus mamma from below made an impressive display over Bracknell, Berkshire around 1800 GMT on 17 September 1974. The photograph was taken at 1805 GMT looking westwards towards Beaufort Park, where the 18 GMT observation reported 2/8 stratocumulus at 3000 ft and altocumulus with altostratus, 3/8 at 10 000 ft and 7/8 at 15 000 ft. The surface wind was 330 degrees 2 knots. A weak cold front was to the west, and slight rain had fallen from 1715 to 1735 GMT.

Photograph by C. S. Broomfield

Photograph by C. J. Richards

PLATE VII—SUNSET FROM READING, BERKSHIRE ON 17 JUNE 1973

Photograph by C. J. Richards

PLATE VIII—HEAT THUNDERSTORM AT NAPHILL, HIGH WYCOMBE, BUCKINGHAMSHIRE AT 1930 GMT ON 9 JUNE 1970

Vigorous convection is evident within the cloud mass, with a recently formed anvil canopy spreading out from the cloud top.

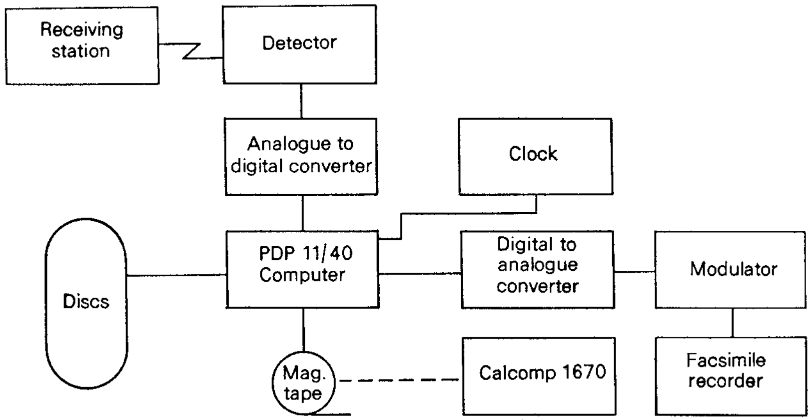

FIGURE 1—SATELLITE PROCESSING SYSTEM

studies of the application of small computer-based systems within the Meteorological Office. In this role it has served as the prototype system for satellite image processing.

There are three main stages, namely data acquisition, data processing and associated map projection, and final output and display in pictorial forms. These are described in a non-technical way; detailed discussion of the special circuitry used for data acquisition, the mathematics of projection and the computer programs is contained in a paper by Wiley and Ponting (1977). The procedure is designed to automate the above-mentioned manual operations, a task well suited to a computer because of the large amount of data processing and arithmetic involved.

DATA ACQUISITION

Data from meteorological satellites are received at Lasham and transmitted by land-line to Bracknell. This transmission is in the form of an amplitude-modulated signal on a 2400 Hz carrier wave, which is the standard facsimile technique. The PDP 11/40 is connected to this line via equipment in the Bracknell Telecommunications Centre. Special circuitry has been built in Met 0 22 which detects the peaks of the carrier thus eliminating, for example, the systematic variations in the carrier frequency due to the Doppler effect. This circuitry also detects a special 300 Hz signal which is used as a marker by both NOAA 5 and Meteosat.

The data are converted to digital values by an analogue-to-digital converter which can be set to sample the incoming data at the peaks of the signal. The digital values are then stored on computer-compatible media (magnetic disc or tape) for subsequent processing. This conversion and storage must be accomplished in real time, that is to say the computer program controlling the flow of data must process each block of data before the reception of the next block of data has been completed.

The United States NOAA 5 satellite has a near-polar orbit (see Figure 2) and views the earth by rotating a scanner on an axis tangential to the orbital path, as shown in Figure 3. Each complete revolution monitors data from an infra-red

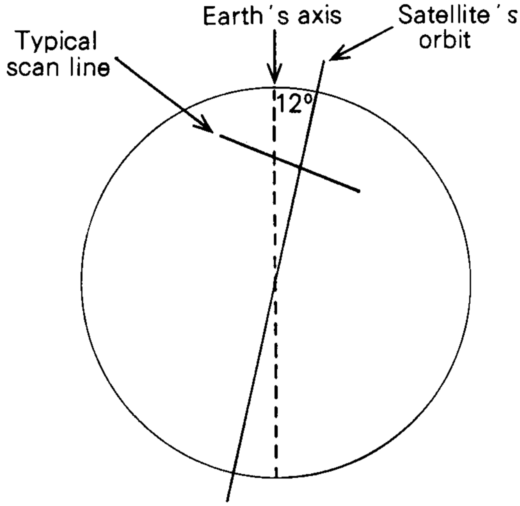

FIGURE 2—NOAA 5 SATELLITE ORBIT

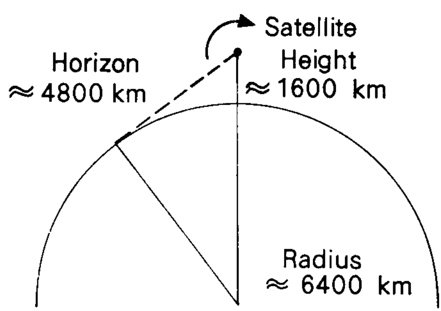

FIGURE 3—SCANNING RADIOMETER SYSTEM

and a visible sensor, half a revolution for each sensor. A complete revolution takes 1·25 seconds, providing 3000 samples (peaks on the 2400 Hz carrier). To reduce the quantity of data to be processed and to speed up the computation, successive pairs of digital values are averaged. After the 300 Hz signal which marks the start of each scan there is a space view, the signal level of which indicates the type of data (black for the visual, white for the infra-red) which follows. The space-view values are also used to check for a genuine signal instead of noise. The digitized information is scaled to be in the range 1 to 254, different values corresponding to different grey levels in the picture, although in practice only part of this range is used. The original resolution of the data directly below the satellite is about 8 km for the infra-red sensor and 4 km for the visible. After averaging, the resolution in the visible is degraded to about 6 km.

The European Space Agency satellite Meteosat transmits successive lines of data every 0·25 second: each scan therefore provides 600 digitized samples. For southern England the resolution is about 6 km east–west and 10 km north–south. For areas further north the resolution becomes progressively poorer; no useful data can be recovered north of about 65°N.

DATA PROJECTION

Once digital data are available they can be processed by computer as required and the results output in pictorial forms or stored for further processing. The following description is for NOAA 5 data only, since the processing for Meteosat is conceptually very similar.

NOAA 5 data are processed to produce pictures as shown in Plate V. The procedure is rather similar to that used by the forecaster in producing a composite nephanalysis. The first orbit (the most eastward) of the day is projected on to the chart, including the edges where detail is blurred owing to the effect of the curvature of the earth on the field of view of the satellite. The next orbit is then added, overlapping at its easterly edge the previous picture. The extent of overlay is to the limits of reasonable resolution of the new picture and was determined in consultation with CFO. Where the computer product differs from the nephanalysis lies in the fact that the latter incorporates data from both the infra-red and visible sensors for the day-time orbits whereas the former produces separate pictures for each sensor. The coastline and latitude/longitude grid are superimposed to enable the forecaster to align and locate the final product. In Plate V (b) (visible picture), the boundaries between consecutive orbits are clearly discernible because of the change in illumination from one orbit to the next (about two hours). This effect is especially noticeable in the northern hemisphere winter when the solar elevation is low.

The required map projection is a 1:20 million polar stereographic one as used in CFO. In order to project the satellite picture the position of the satellite has to be determined as accurately as possible. This is done by recording the exact time at which the start of the picture is received and then using previously observed orbital parameters, so-called ephemeris data, provided by the American Space Defense Center, to calculate the position of the satellite. These ephemeris data are often out of date, since they are only received about once a week and are based on ground observations of the orbit made three to four weeks earlier. Also, because of the high speed of the satellite relative to the earth, a small error in the receiving start-time can give a large positional error which would degrade the final product. The relevant date and time are obtained by interrogating a clock, within the PDP 11/40, which tends to lose about one second a day. To maintain the required accuracy of the internal clock it is synchronized each hour with a much more accurate external radio clock transmission from Rugby which gives the month, day, hour and minute every minute with a pulse every second. (The circuitry to receive and decode the Rugby broadcast was specially constructed within Met 0 22.) The ability to correct automatically is especially important following a power failure, since it enables the PDP 11/40 to recover without manual intervention at nights and weekends when it runs unattended.

To reduce the processing time it was assumed that the radius of the earth and of the satellite orbit are constants, and that each scan line is instantaneously produced. For a given point on the map the digital value at the nearest point on the nearest scan line is taken as the required value without further correction. The effect of these approximations is to introduce a very small error not discernible to the forecaster; the processing time is, however, significantly reduced, resulting in earlier availability of the computer products.

OUTPUT AND PICTORIAL DISPLAY

The output from the PDP 11/40 is available in several forms depending on the application, namely on facsimile paper, on microfilm (from which photographic enlargements may be produced), on a graphics (VDU) display, or as digital values on any normal computer medium.

For operational use in CFO, hard copy with adequate resolution is required as quickly as possible. A standard facsimile recorder suffices for this. Normally, higher-grade facsimile paper is used because it gives better contrast than the standard grade. The charts, being on the normal CFO scale and map projection, are then directly usable within CFO by forecasters as an aid to analysis; for example, to position surface frontal features, upper troughs, ridges, vortices, and, sometimes, jet streams (see Singleton, 1975) or to produce nephanalyses.

Photographic and archival output can be achieved via the Calcomp 1670 microfilm plotter which is part of the main computing facility of the Meteorological Office, COSMOS. The output from this plotter can be positive for making slides or negative for prints such as the plates in this article. The quality is much better than from a facsimile recorder but takes more than an hour longer to produce.

For output to either of the above devices, the contrast and range of the grey-scale in the picture can be easily adjusted. If a feature is to be enhanced the range can be narrowed to only a few levels round the required level. For example, to emphasize the boundaries of sea-ice, the grey-scale is adjusted so that the difference between the appearance of sea and ice is larger than that in the normal pictures.

For a quick look, particularly for better resolution, a colour visual display terminal attached to the PDP 11/40 is available on which ranges of digital values may be displayed in different colours. Because of the limited resolution of this device only a part of the NOAA 5 satellite picture can be displayed if the full resolution is to be approached. Users can select which part of the picture is to be displayed and which colours correspond to what range of digital values. By these means particular terrains and quite narrow signal ranges can be minutely investigated. No hard copy is, however, available from this terminal.

For research use the digital data themselves are available. Such data on magnetic tape have been supplied to several branches of the Meteorological Office to aid research into and development of applications of satellite image data.

DISCUSSION AND CONCLUDING REMARKS

Computer-processed pictures from NOAA 5 have been produced regularly since November 1976. Of the various delays that occur before the data are available to the forecaster, the time taken to acquire the data and output them to a facsimile recorder is unavoidable. Only the times involved in the projection and the method of display are alterable.

The present computer system takes 25 minutes to process one orbit, both infrared and visible pictures, after which it takes 20 minutes to output the results. The process thus takes at least 45 minutes longer via the computer than the present direct output to a specially modified facsimile recorder. However, the picture may be displayed on a VDU as it is processed, parts within a few minutes of being acquired. If a faster computer were obtained and dedicated to the processing of the satellite image data it would be possible both to speed up and to overlap the projection of the data with the acquisition or output phases, leading to quicker production of the final hard copy.

The present manual gridding procedure is not very accurate since it relies on the positioning of the timing markers and the matching of overlays. With the current computer system the accuracy of the automatic gridding and map projection is consistently good provided that the parameters which describe the orbit of the satellite are updated frequently enough.

The pictures produced by the computer from NOAA 5 data have certain clear advantages over the directly received pictures. For example, it is very easy for the forecaster to follow the movement of cloud systems from day to day as the pictures are always viewable relative to the same chart background. Also, the removal of the distortion caused by the curvature of the earth makes cloud patterns much easier to recognize. Nothing, of course, can be done either way to correct for the loss of resolution caused by the curvature.

The form of the computer output is very flexible. The output can be stored and produced whenever required in a variety of forms, each as often as required. Also the contrast and range of the grey-scale is easily adjusted to emphasize individual features and to reflect the change in illumination with the different times of year.

Acknowledgement

Any project of this size is always a team effort. The author wishes to thank those members of the Systems Development Branch who have assisted in any way with the project and the preparation of this paper.

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THE RELATIONSHIP BETWEEN VISIBILITY AND SURFACE WIND AT GÜTERSLOH IN WINTER WITH PARTICULAR REFRENCE TO SMOKE POLLUTION

By M. G. WALLER
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SUMMARY

All synoptic observations at Gütersloh for the period December to February 1971–75 were analysed to obtain the percentage frequencies of visibilities below specified limits in relation to the surface wind, distinguishing between occasions with and without precipitation.

These are presented in the form of diagrams. Relatively high frequencies of poor visibility are discussed with particular regard to known smoke sources, and an investigation is made of the effect of precipitation in association with pollution.

INTRODUCTION

Despite local and federal laws governing the control and emission of smoke and pollutants in Germany, visibilities are often seriously reduced near and downwind from industrial areas. It is not uncommon for parts of the industrial Ruhr to experience visibility reduced to fog limits owing to pollution in stable winter conditions.

The visibility at Gütersloh is often reduced by advected smoke pollution which is most noticeable during the winter months. During these months the low-level flying training programmes are often curtailed owing to poor visibility. The runway at Gütersloh is aligned east to west and an additional hazard occurs when atmospheric pollution coincides with cloud-free skies and the sun is at a low elevation. The slant visibility in these cases is often reduced so that a prohibition on visual circuits is enforced.

PURPOSE OF THE INVESTIGATION

It was considered that a statistical analysis of visibility in relation to surface wind speed and direction, limited to the winter months, would indicate the sources of smoke pollution which are close enough to cause serious deteriorations in visibility at Gütersloh. Knowledge of the positions of these smoke sources, together with the frequency of occurrence of winds which transport the pollution to Gütersloh, should be a useful forecasting aid. There may be other stations where a similar analysis may improve the forecasting of visibility. The resulting improved forecasts of visibility could then be given more weight when the daily flying programs were being planned and perhaps lower the number, and therefore the cost, of abortive sorties.

GEOGRAPHICAL SITUATION

Gütersloh airfield lies 72 m above mean sea level on the sandy alluvial flood plain of the River Ems, which is one of the southernmost corners of the North German Plain, bounded in the south by the Sauerland Uplands. To the east the Sauerland Uplands merge with the Westphalian Uplands which consist of a number of ridges extending to the north-west. Thus a natural bowl is formed open from west-south-west to north-west. This is known geographically as Münster Bay.

There are large urban and industrial areas stituated on the low-lying ground of the region, the largest and most well known being the Ruhr industrial complex which lies some 70–130 km to the south-west of Gütersloh.

The significant features of the region are shown in Figure 1.

Factors affecting pollution

The level of pollutant concentration in the atmosphere due to a smoke source is governed, according to Pasquill (1972), by three main factors:

(a) General drift in the prevailing airstream with progressive spreading sideways and vertically.

(b) Chemical and physical transformation in the air-borne stage.

(c) Removal from the atmosphere by various natural processes.

The distribution due to (a) will vary according to a number of factors, the main ones being the strength of the wind and the turbulent and convective motions of the atmosphere. The latter are themselves determined by the strength of the wind, the nature (roughness) of the underlying surface and the stability of the atmosphere.

The analysis presented in this paper ignores a number of these factors and indeed takes no account at all of any factors associated with the pollutant source. The investigation makes use only of the wind, precipitation and visibility during 15 winter months at Gütersloh. It takes no account of time of day or of holidays, both of which are significant factors in the generation of smoke pollution. It takes no account of the trajectory of the air.

Analysis

The 3-hourly synoptic observations of surface wind and visibility at Gütersloh for the period December–February 1971–75 were extracted and classified. Figure 2 shows the frequency of each wind direction (10° sector) expressed as a percentage of the total number of observations extracted. The visibility ranges used were those associated with a colour code which is widely used by military aviation (N.B. The colour code is also dependent on the height of significant cloud, so that the colours denoting visibility ranges in this paper do not always equate to the actual colour state at Gütersloh.) Table I shows the minimum visibility associated with each colour.

TABLE I—MINIMUM VISIBILITIES ASSOCIATED WITH THE COLOUR CODE

Colour	Minimum visibility
BLUE	8 km
WHITE	5 km
GREEN	3·7 km
YELLOW	1·8 km
AMBER	0·9 km
RED	ZERO

For wind speeds of 1–6 knots and also for 7 knots or more, the frequencies of the various visibility ranges were obtained for each wind direction (10° sector) as a percentage of the total observations for that particular direction and speed range. The analysis was carried out separately for observations not associated with precipitation and for those associated with precipitation. Observations associated with snow (88) were not included in the analysis. The frequencies were

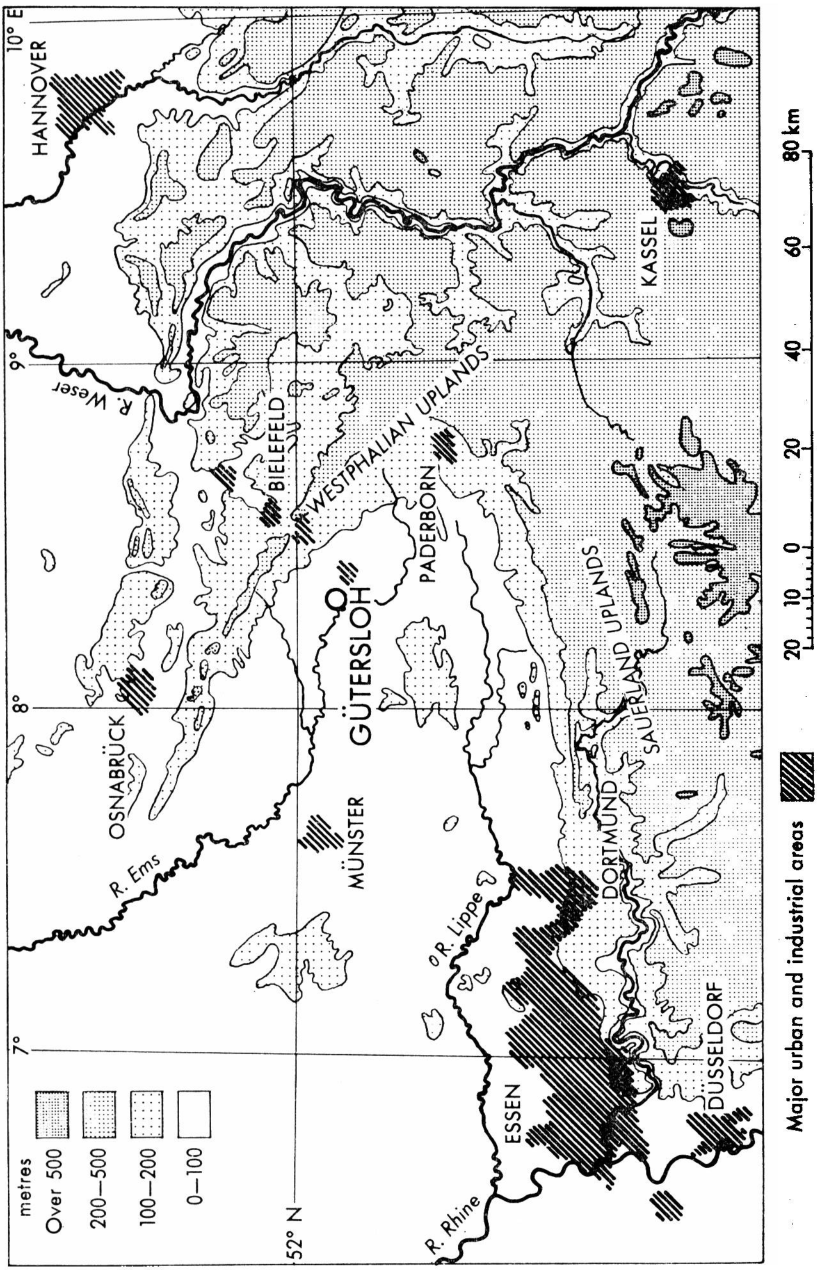

FIGURE 1—MAJOR FEATURES OF THE GÜTERSLOH REGION

plotted against wind direction on a radial type of bar diagram, the visibility ranges shown being limited to the lowest four. The bearing and names of the major urban and industrial smoke-producing areas were marked on the periphery.

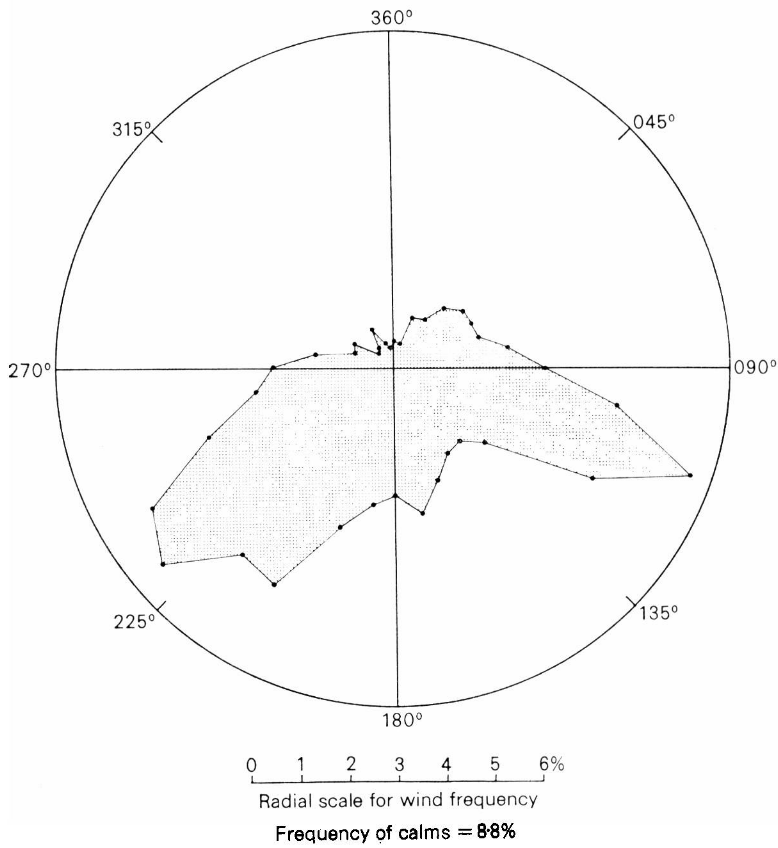

FIGURE 2—PERCENTAGE FREQUENCY OF WIND DIRECTION AT GÜTERSLOH IN WINTER (DECEMBER–FEBRUARY 1971–75)

Figure 3 shows the frequencies plotted against wind direction for 1011 occasions associated with winds of 1–6 knots and no precipitation. The frequency of each wind direction expressed as a percentage of the total number of wind observations (not associated with precipitation) in the range 1–6 knots is superimposed on the diagram as a dot linked to neighbouring values by broken lines.

Figure 4 is a similar diagram for 1630 occasions associated with winds of 7 knots or more and no precipitation. For occasions with precipitation, the 110 observations associated with wind speeds of 1–6 knots were considered too sparse for a diagram to be worth while. However, there were sufficient observations (452) to produce Figure 5 for occasions with wind speeds of 7 knots or more, but wind directions with less than four observations were omitted, restricting the diagram to 100° to 300°. Otherwise the diagram is similar to Figures 3 and 4.

For both Figures 4 and 5, the frequency of each wind direction expressed as a percentage of the total number of wind observations (fulfilling the associated precipitation conditions) in the range 7 knots or more is superimposed on the diagram as in Figure 3.

DISCUSSION AND INTERPRETATION OF DIAGRAMS

Wind frequency

The frequency of the wind direction for all cases is presented in Figure 2. The asymmetry of the pattern is most distinctive. The two main peaks are at 230° and 110°. These are no doubt enhanced by topographical effects, but suggest an east-south-east continental winter regime with incursions of milder air from the south-west. The winters included in this analysis have been relatively mild and one would not expect the south-west peak to be as well marked over a longer period.

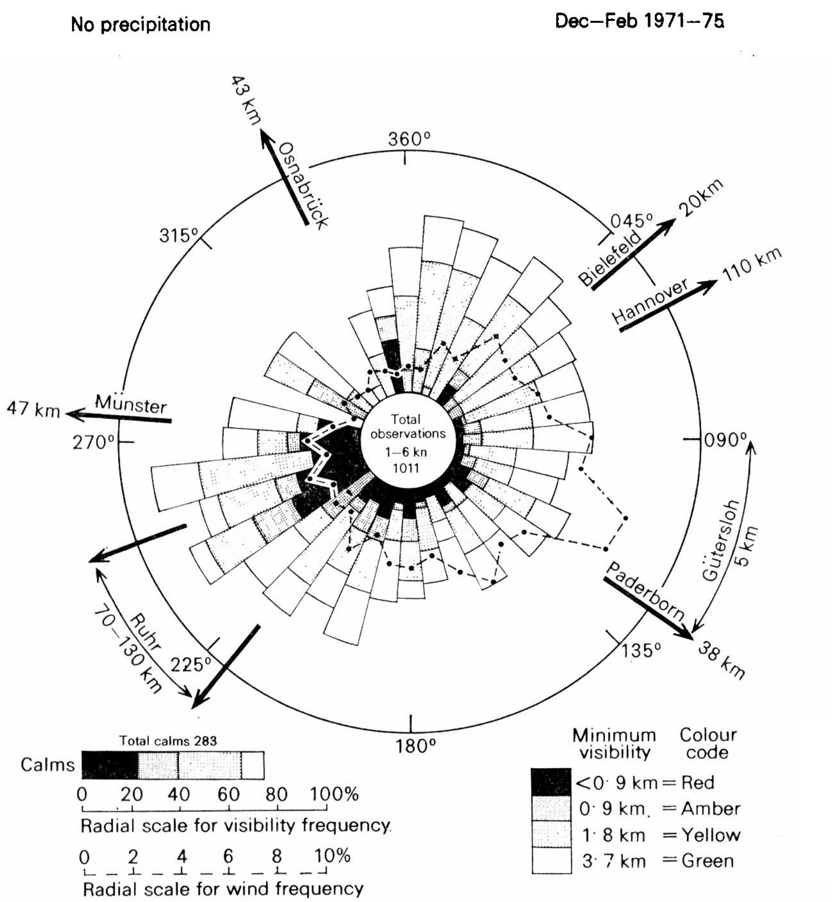

FIGURE 3—VARIATION WITH WIND DIRECTION OF THE PERCENTAGE FREQUENCY OF VARIOUS VISIBILITIES AT GÜTERSLOH IN WINTER (WINDS 0–6 kn)

Note. The visibility frequencies are not frequencies of colour state.

It has frequently been noticed that with a west-south-west gradient flow, the surface wind at Gütersloh has a tendency to back to just east of south in certain conditions. The analysis reveals a minor peak in frequency in this direction.

A major point of note is that a surface flow from 290° through to 020° was very infrequent during the period analysed.

Figure 3 shows that the frequency of the lighter winds had a peak at 110°–120° which suggests a predominantly quiet anticyclonic flow, whereas in contrast, Figure 5 shows that the frequency of the stronger winds, for occasions associated with precipitation, had a peak at 230° as would be expected with the bulk of the precipitation coming from incursions of milder air from the south-west.

Visibility on occasions with no precipitation

Examination of Figures 3 and 4 reveals the following points:

As might be expected visibility tends to be worse with light winds than with the stronger winds. This is true for nearly all directions.

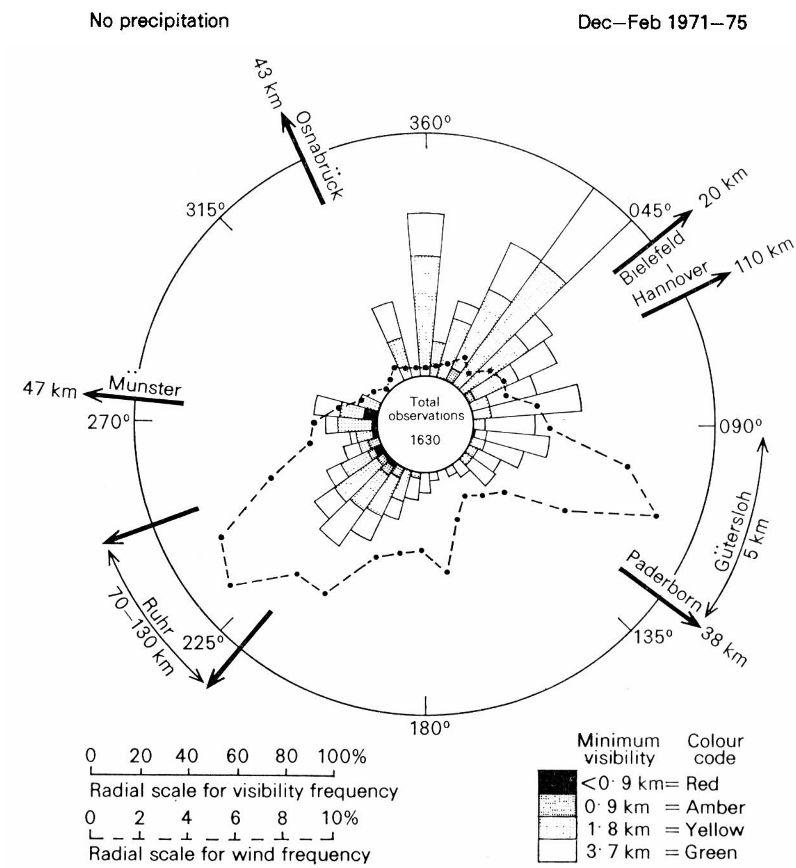

FIGURE 4—VARIATION WITH WIND DIRECTION OF THE PERCENTAGE FREQUENCY OF VARIOUS VISIBILITIES AT GÜTERSLOH IN WINTER (WINDS ⩾ 7 kn)

Note. The visibility frequencies are not frequencies of colour state.

With light winds the highest frequencies of poor visibilities are in the sector south-west to west and are undoubtedly associated with Ruhr pollution.

The stronger wind diagram shows the higher frequencies of poor visibilities appearing in several well-defined sectors. The two major peaks are centred on 040° and 220° with minor peaks around 270°, 340° and 360°. Relating these peaks to the major urban and industrial areas the 040°, 220° and 270° peaks are backed by some 5–20 degrees from the Bielefeld–Hannover, Ruhr and Münster areas respectively. In particular the 220° peak is backed by about 15 degrees from the mean direction of the Ruhr industrial area which lies between about 220° and 250°. It is concluded that these peaks are due to the advection of pollution from these areas although the precise track is complicated by the terrain. It should also be mentioned that the surface wind at Gütersloh is often more backed from the gradient wind direction than might be expected.

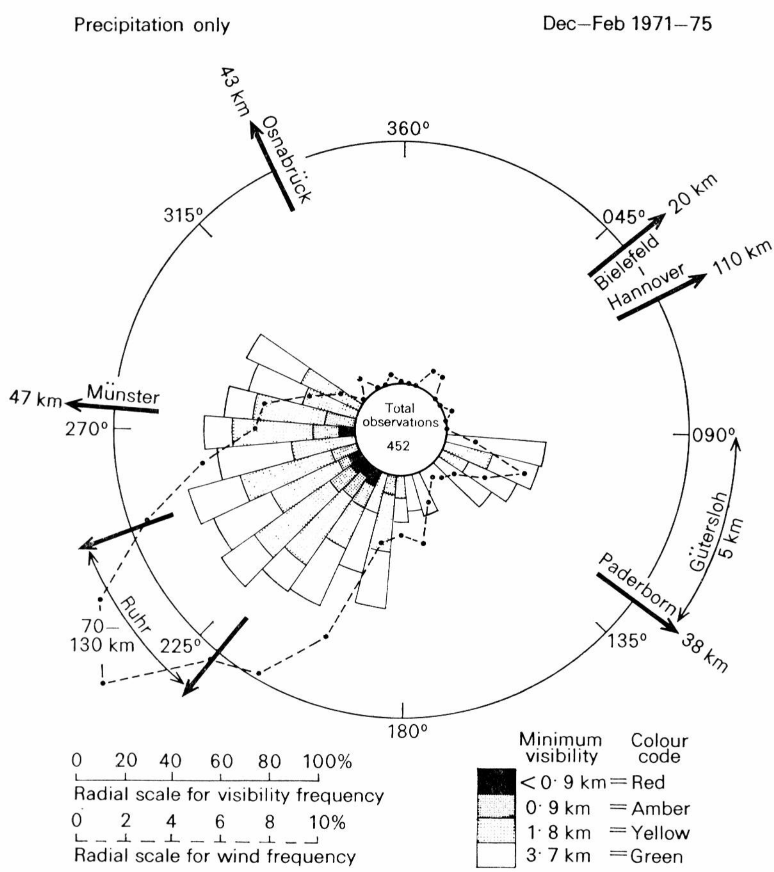

FIGURE 5—VARIATION WITH WIND DIRECTION OF THE PERCENTAGE FREQUENCY OF VARIOUS VISIBILITIES AT GÜTERSLOH IN WINTER (PRECIPITATION ONLY, WINDS ⩾ 7 kn)

Notes. (1) The visibility frequencies are not frequencies of colour state.
(2) The visibility frequencies are shown for the wind directions 100°–300° only, i.e. for wind directions with four or more observations.

The minor peak at 360° is difficult to relate to pollution but the Hannover area is thought to be the source. In marked stable conditions an east-north-east gradient flow usually gives a wind of north-north-east at Gütersloh. However, on some occasions the surface wind backs by 90 degrees or more under the influence of the Westphalian Uplands and is reported as 360° or even 350° at Gütersloh. On these occasions pollution from the Hannover area could reach Gütersloh after a long complex trajectory.

Visibility on occasions with precipitation

Caution is needed in interpreting the results of this section as the number of observations during the period was small.

In order to investigate the effect of precipitation in association with pollution, a comparison was made between Figures 4 and 5. This was limited to wind direction from 210°–260° for which the visibility frequencies were based on a reasonable number of observations for both diagrams. Within these limits, it has been shown that the wind direction associated with the peak frequency of poor visibility, and presumably with the greatest smoke pollution effect due to the Ruhr area, is backed some 15 degrees from the direction of the centre of the Ruhr area which extends from 220° to 250°. Assuming that this backing applies to the Ruhr area as a whole, the sector 210°–230° should be favourable for pollution whilst that for 240°–260° should not. The contrast is well marked in Figure 4 and to a lesser degree in Figure 5. To examine in more detail the effect of precipitation on visibility reference is made to Table II.

TABLE II—A COMPARISON OF THE EFFECT OF PRECIPITATION ON VISIBILITY FREQUENCIES FOR WIND DIRECTIONS ASSOCIATED WITH HIGH AND LOW SMOKE POLLUTION FROM THE RUHR (WINDS $\geqslant$ 7 kn)

		Percentage frequency of visibility categories							
		No precipitation				Precipitation			
		G	Y	A	R	G	Y	A	R
High pollution	210°	34	21	4	0	61	36	16	6
	220°	41	23	5	2	63	49	15	4
	230°	36	26	4	1	72	47	16	5
Average		37	23	4	1	65	47	16	5
Low pollution	240°	25	18	6	3	67	40	9	4
	250°	15	9	5	2	71	49	10	0
	260°	11	9	2	2	57	25	0	0
Average		17	12	4	2	65	38	6	1

N.B. G = Green or less i.e. 0–5 km. Y = Yellow or less i.e. 0–3·7 km.
A = Amber or less i.e. 0–1·8 km. R = Red i.e. less than 0·9 km.

For the sector 210°–230°, the frequencies of the various visibility categories are all higher for occasions with precipitation. The increase for the colour code green or less is from about 30–40 to 60–70 per cent. For the sector 240°–260°, the frequencies for the various visibility categories, excepting colour code red, are also higher for occasions with precipitation. Here, however, the increase in frequency for colour code green or less is even greater, i.e. from about 10–20 to 60–70 per cent, reaching about the same frequency as for the other sector. It is concluded that precipitation has a much greater reducing effect on visibility when the air is not already heavily polluted. It is noteworthy, however, that the incidence of really poor visibility at Gütersloh (when the wind is 7 kn or more) is highest when high pollution and precipitation occur together. This is contrary to Jefferson (1961) whose results for Manchester Airport suggested that when the visibility is already only moderate due to other causes such as smoke haze, no further reduction is to be expected. The Manchester figures, however, took no account of wind speed. It is also contrary to Ross (1967) who suggested that in industrial areas the haze may be thick enough at times to obscure the effects of precipitation on visibility. While this may be true the present investigation does not support the suggestion.

There is some evidence of a minor peak at 110° which could be associated with local pollution from Gütersloh town. The peak is, however, of doubtful significance because of the small number of observations on which the frequencies for the adjoining sectors were based.

Experience of forecasting at Gütersloh suggests that cold frontal clearances are often delayed, owing to the up-slope and funnelling between the Westphalian and Sauerland Uplands. This may account for the continuing high frequencies round to 300°, although the 290° and 300° frequencies were based on only nine and four observations respectively and may not be significant.

Conclusions

Although only a limited analysis of visibility in relation to surface wind at Gütersloh was undertaken, it has served to indicate the major sources of atmospheric pollution that affect the visibility. The diagrams presented can be used in winter as a forecasting aid, in that greater weight can be given to the surface wind when forecasting visibility in various synoptic conditions.

The diagrams can also help to predict the visibility in the surrounding area. For instance, if Gütersloh is experiencing a visibility within 'green' limits and has a surface wind of 200°, there would be a high probability of the visibility being within 'yellow' limits or worse in a band orientated in a SW/NE direction and about 70 km in width situated just to the west of Gütersloh. This is on the assumption that the Ruhr pollution plume is being advected just to the west of Gütersloh.

The forecasting of the surface wind at Gütersloh is a difficult problem in itself owing to the effect of the surrounding terrain, and the value of the diagrams will probably be most apparent in short-period forecasting. A number of visibility deteriorations occur in winter during mid-morning similiar to those that affect some airfields in eastern England (Saunders, 1971). Reference to the diagrams will show if the onset of flow, due to the diurnal increase in wind speed and turbulence after sunrise, is from a direction from which pollution may be advected.

Acknowledgement

The author is grateful to the staff of the meteorological office at Gütersloh and to Mr C. L. Hawson for their assistance and advice while preparing this paper.

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REVIEW

Journal of Arid Environments, Volume 1, Number 1, March 1978. 250 mm × 175 mm, pp. 104, *illus.* Academic Press, London, New York and San Francisco. Price: Volume 1, four issues, inland £14.50, inclusive of postage and packing; abroad £18.15, inclusive of postage and packing.

This is the first number of a new journal published by the Academic Press under the editorship of Professor J. L. Cloudsley-Thompson of Birkbeck College, University of London. The new journal, according to an editorial, is intended as a forum for multidisciplinary and interdisciplinary dialogue where research workers, whose major interests lie in the desert environment and the problems it poses, may publish the results of their research, and where comprehensive reviews may also be published that will be intelligible to advanced students, technologists, administrators and research workers regardless of their own particular specializations and disciplines. In addition to an Associate Editor (Anne Cloudsley) the editorial board comprises 19 names almost all of whom appear to be specialists in the life-sciences. There is no professional meteorologist on the board, but there are three geographers with interests in climatology. However, the first paper in the journal, by Sharon E. Nicholson and entitled 'Climatic variations in the Sahel and other African regions during the past five centuries' is based on work done at NCAR, Boulder, Co. There is little or no meteorology in the other seven papers—or in the list of nine forthcoming papers—but they have a wide range of interest, covering topics as varied as Islamic water law, the diversity of rodent species in northern Israel, and the decomposition of elephant carcases in Kenya. There are also nine full-length book reviews as well as a 'shorter notice'.

From a perusal of the first number it seems that the *Journal of Arid Environments* is unlikely to contain much of professional interest to meteorologists, although the occasional article on climatology may well appear from time to time.

R. P. W. LEWIS

AWARD

We note with pleasure that the 23rd International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded to Dr Alf E. G. E. Nyberg, Director-General of the Swedish Meteorological and Hydrological Institute from 1955 to 1977. Dr Nyberg served as President of the WMO Regional Association for Europe from 1956 to 1963 and as President of WMO from 1963 to 1971. He has undertaken several technical co-operation missions to developing countries on behalf of WMO and has published many papers on meteorology, in particular on aerological and synoptic questions and on the relations between meteorological factors and atmospheric pollution.

OBITUARY

We regret to record the death on 3 April 1978 of Mr D. H. Philips, Higher Scientific Officer, of the Observational Requirements and Practices Branch (Met O 1). Mr Philips joined the Office as an Assistant in September 1947, and served in a wide variety of stations at home and overseas, including weather ships and radiosonde and CRDF establishments; he also worked for several years in the Editing Section (Met O 18b). He was promoted to HSO in October 1976 and at the time of his death was in charge of the section that deals with Automatic Weather Stations.

We regret to record the death on 15 April 1978 of Mr W. Conner, Scientific Officer, of the Civil Airport, Benbecula. Mr Conner joined the Office in April 1941 and served at a large number of outstations in the United Kingdom and also, for a time during the war, in Iceland. While at Benbecula he took a leading part in organizing youth movements, and helped to arrange various outdoor activities for them.

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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'.

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