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Urban effects on trends of annual and seasonal rainfall in the London area

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Summary

The large amount of monthly rainfall data available for the period from 1911 to 1970 was used to see if any effects of urbanization are present in annual and summer half-year totals of rainfall in the London area. Difficulties of interpretation due to changes of site and instrumentation caused trends obtained from rain-gauge records to vary by several per cent per decade between points only a few kilometres apart, so comparisons were made with data extracted from maps of percentage of average rainfall in which these errors had been removed. These showed that changes of site and instrumentation accounted for approximately half the variance of trends obtained from rain-gauge data and when these were taken into account the patterns of rainfall trends over London did not display any features which could be attributed to urbanization.

1. Introduction

The possible effects of urban areas on precipitation have been attracting increasing attention recently, particularly in regard to the incidence of short-duration heavy rainstorms of convective origin. It has been suggested that the frequency and severity of convective storms over metropolitan areas combine to give a significant increase in annual rainfall. Such effects, if present, should be taken into account in the production of long, homogeneous rainfall series intended for the study of climatic change, many of which rely heavily on data from urban areas, for example the series for Manchester compiled by Manley (1973, 1976).

Compared with their surroundings, built-up areas are associated with:

(i) Higher values of temperature and absolute humidity.
(ii) Increased concentrations of condensation and freezing nuclei.
(iii) Increased mechanical turbulence.

Thus, it is reasonable to expect that urbanization will increase the frequency and severity of convective rainstorms. A good review of urbanization effects on precipitation in general is provided by Landsberg (1974). Most of the recent work has been done in the USA, in particular project METROMEX, based on the city of St Louis. In an initial study, Huff and Changnon (1972) claimed increases of 6–15 per cent in the summer rainfall totals based on observations from 50 rain-gauges over an area of 28 000 km² from 1941 to 1968. In the latest report from project METROMEX, Changnon *et al.* (1977) used radar and dense networks of gauges to identify areas of high rainfall near an industrial complex during the period 1971–75. More recently, however, Pittock (1977) has shown that changes in rainfall over Washington State which had been ascribed to man's activities can be related to changes in the latitude of the subtropical anticyclone. For the London area, Atkinson has made a number of case studies of convective storms, an investigation into the famous Hampstead storm being the latest (Atkinson, 1977).

In this study use is made of the large amount of monthly rainfall data available in the London area for the period 1911–70. Linear trends of seasonal and annual rainfall are mapped to see if any patterns are present which may be attributable to urbanization. It is appreciated that any climatic change will not necessarily be linear, but over a period of 60 years, this is a convenient approximation to make. In order to interpret the patterns, a statistical background of the kind of variations which could occur by chance is required. The standard error of a trend associated with a perfect rain-gauge can be calculated from a knowledge of the variability of rainfall, but changes in site and instrumentation will make the errors associated with real observations larger. The differences are estimated by comparing trends calculated from rain-gauge observations with trends calculated from data derived from maps of percentage of average rainfall. In the latter data set, errors due to changes of site and instrumentation will have been largely eliminated.

2. Data

Monthly rainfall totals from practically all UK rainfall stations with complete records in the periods 1911–70 and 1941–70 are available in machinable form within the Meteorological Office. The number of stations available is about 700 for the period 1911–70, and 2000 for 1941–70, but they are not uniformly distributed. Their distribution for 1911–70 is shown in Figure 1. Locally dense networks existed in the London area and parts of north-west England which did not allow all the points to be plotted automatically on a 1 : 1·5 million scale map. Figure 1 illustrates a network of about 500 stations which could be plotted on such a map. For an area of 12 000 km² centred on London, 75 stations were available from 1911 to 1970, while during the period from 1941 to 1970 the number rises to 240.

Maps of annual rainfall over the British Isles, expressed as a percentage of average, have been published for the years from 1868 to 1923 by the Royal Meteorological Society (1926) and for subsequent years by the Meteorological Office in *British Rainfall.* With the exception of the year 1941, Ireland was included in the maps published in *British Rainfall* up to 1945. From 1948 onwards, the data for the Republic of Ireland are in the Irish *Monthly Weather Report*; for 1941, 1946 and 1947 the data were kindly supplied by the Irish Meteorological Service. For the United Kingdom the averages used were for 1881–1915 up to 1957 and 1916–50 thereafter. For Ireland, the averages used were for 1881–1915 up to 1955, for 1916–50 from 1956 to 1965, and for 1931–60 thereafter. Annual values were extracted from the maps for 59 points formed by the intersection of lines of latitude and longitude over the British Isles. These were then converted to a percentage of average for the period 1871–1970, and are referred to as the 'map' data.

As part of another piece of work, as yet unpublished, the writer collected series of monthly rainfalls representative of 185 sites in Europe for the period from 1861 to 1970. Comparisons with neighbouring gauges were used to construct long series from which all major inhomogeneities were removed. Records for 48 of the sites which lie within the British Isles are referred to as the 'homogeneous' data.

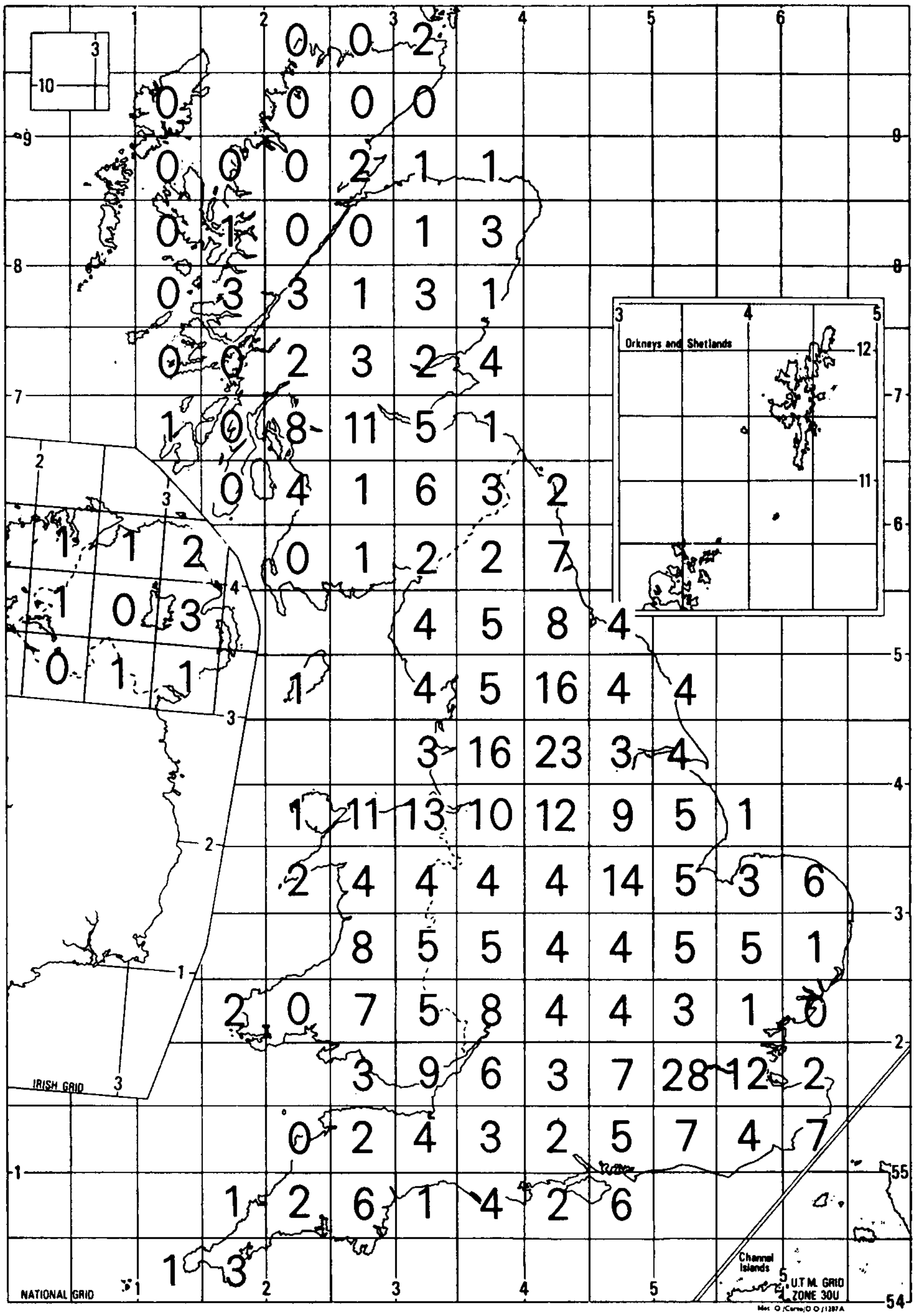

Figure 1. Network of rainfall stations with complete records from 1911 to 1970. The figures represent the number of stations in each square.

3. Spatial coherence of rainfall and rainfall trends

Rainfall is notoriously variable in both space and time. The high spatial variability is illustrated in Figure 2, which shows the rainfall over the United Kingdom for the year 1973 expressed as a percentage of average. The map is based on observations from about 2500 stations, and isopleths are drawn at intervals of 17 per cent, which corresponds approximately to one standard deviation. Points only a few tens of kilometres apart can be seen to have rainfall amounts which differ from one another by up to three standard deviations. When maps are drawn for rainfall summed over different durations and isopleths are drawn at intervals of one standard deviation, the spatial coherence is seen to vary little for time-scales ranging from a month to a decade.

Figure 3 displays the trend of annual rainfall from 1911 to 1970, as calculated by the method of least squares, from a dense network of stations in north-west England. Values are seen to range from − 4·0 to + 5·9 per cent per decade, with very little spatial coherence. The observed trends are due to genuine fluctuations in rainfall plus errors caused by changes of site and instrumentation. In order to aid interpretation of Figure 3, estimates of the standard errors of rainfall trends obtained from a perfect site are made below.

4. Standard errors of rainfall trends

In a linear regression of the form

$$y = ax + b$$

the standard error of the gradient a is given by Snedecor and Cochran (1967) (see pp. 138, 139) as

$$[\mathrm{SE}(a)]^2 = \frac{\Sigma Y^2 - [(\Sigma XY)^2/\Sigma X^2]}{(N-2)\Sigma X^2}, \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where X and Y represent deviations from the mean values of x and y respectively, and N is the number of pairs of observations of x and y. For the case under discussion, the variable y may be equated with rainfall expressed as a fraction of average and x as time in years; x will therefore run from 1 to N, and it may be shown that

$$\Sigma X^2 = N(N^2 - 1)/12.$$

The covariance between rainfall and time will be very small, so that the second term in the numerator of equation (1) may be neglected. Assuming N to be large, equation (1) reduces to

$$[\mathrm{SE}(a)]^2 = 12\,\Sigma Y^2/N^4. \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

$\Sigma Y^2/N$ may be equated with the variance of rainfall expressed as a fraction of average, so we have

$$\mathrm{SE}(a) = (12)^{0\cdot5} C_v/N^{1\cdot5}, \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

where C_v is the coefficient of variation of rainfall. Insertion into equation (3) of $C_v = 0{\cdot}16$ and $N = 60$, figures appropriate to the rainfall data in Figure 3, yields an estimate of the standard error of the trend of 1·2 per cent per decade. Thus the observed trends over north-west England extend through a range of eight standard deviations if it is assumed that there are no errors due to changes of site and instrumentation.

5. A comparison between the 'map' and 'homogeneous' data

These two data sets are the results of efforts to eliminate errors due to changes in site and instrumentation. In the case of the map data, the mapping procedure will have smoothed out any site and instrumental errors, but it may also have smoothed out some genuine rainfall variations. In the case of the

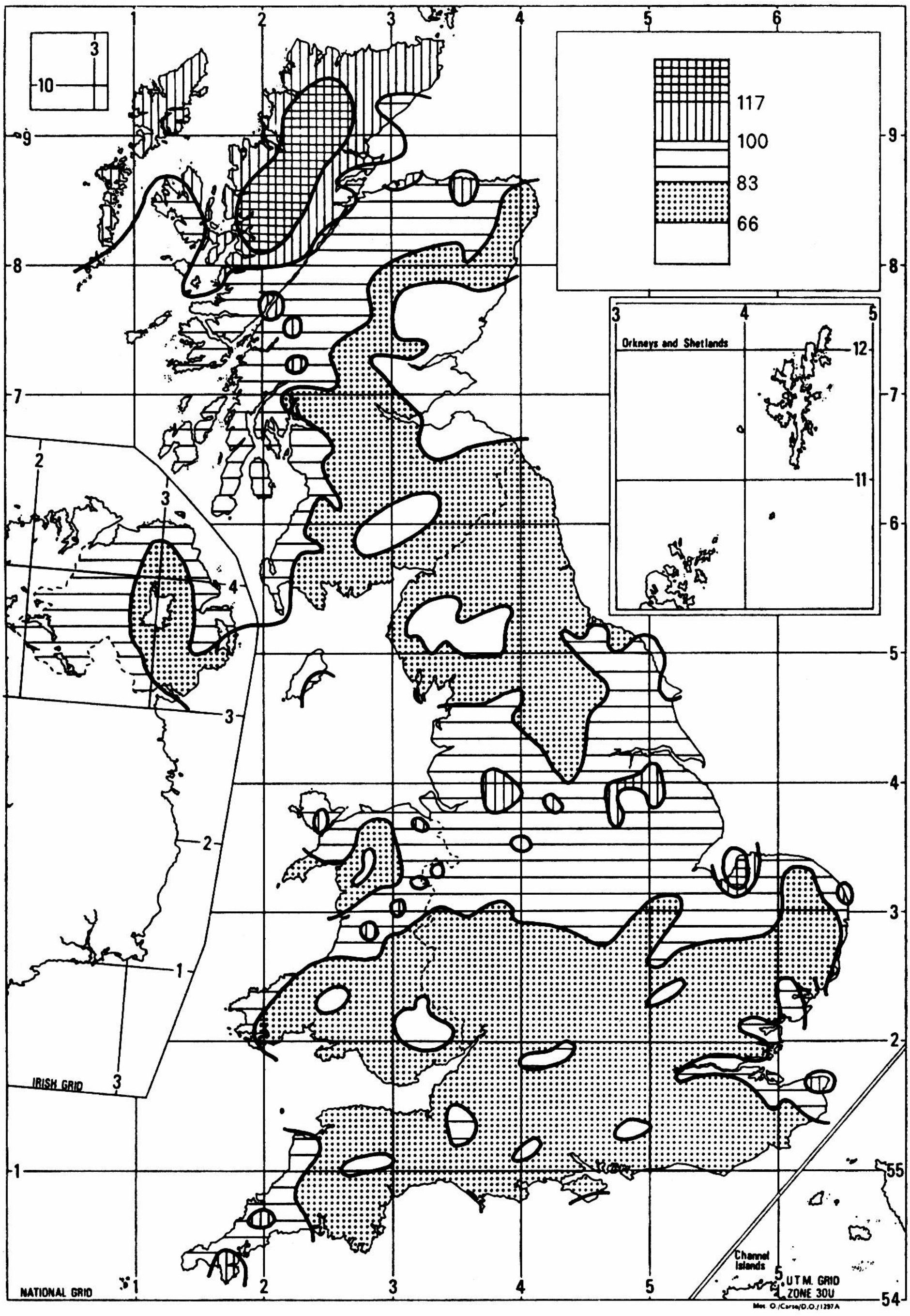

Figure 2. Rainfall for the year 1973 expressed as a percentage of the annual average for 1916–50.

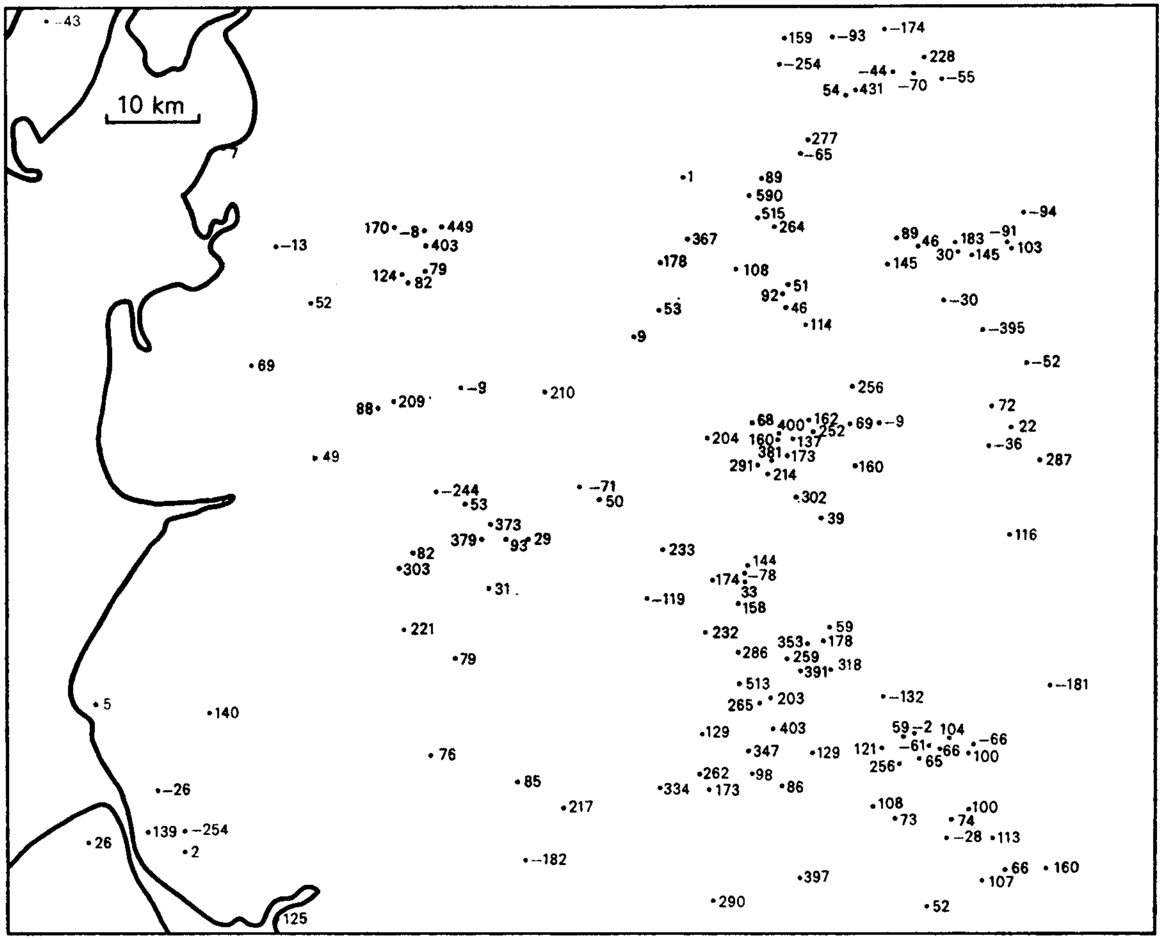

Figure 3. Trend of annual rainfall over north-west England from 1911 to 1970 (per cent per decade × 100).

homogeneous data, no rainfall fluctuations will have been reduced in amplitude, but not all the site and instrumental errors may have been detected. The different methods of construction of the two data sets can be illustrated by calculating the variance of annual rainfall. In the map data, excessive smoothing will result in an underestimate of the true variance, while in the homogeneous data, any uncorrected errors will tend to yield an overestimate of the true variance.

The coefficient of variation of annual rainfall over the British Isles for the period 1871–1970 as obtained from both data sets is shown in Figure 4. Values for the map data are slightly less than those from the stations with homogeneous records, but the closeness of the results indicates that both data sets are of a high standard.

Trends of annual rainfall from the map and homogeneous data for the period 1871–1970 are presented in Figure 5. Both data sets reveal similar patterns, with a belt of negative values stretching from south-west to north-east and separating positive areas to the north-west and south-east. The strong spatial

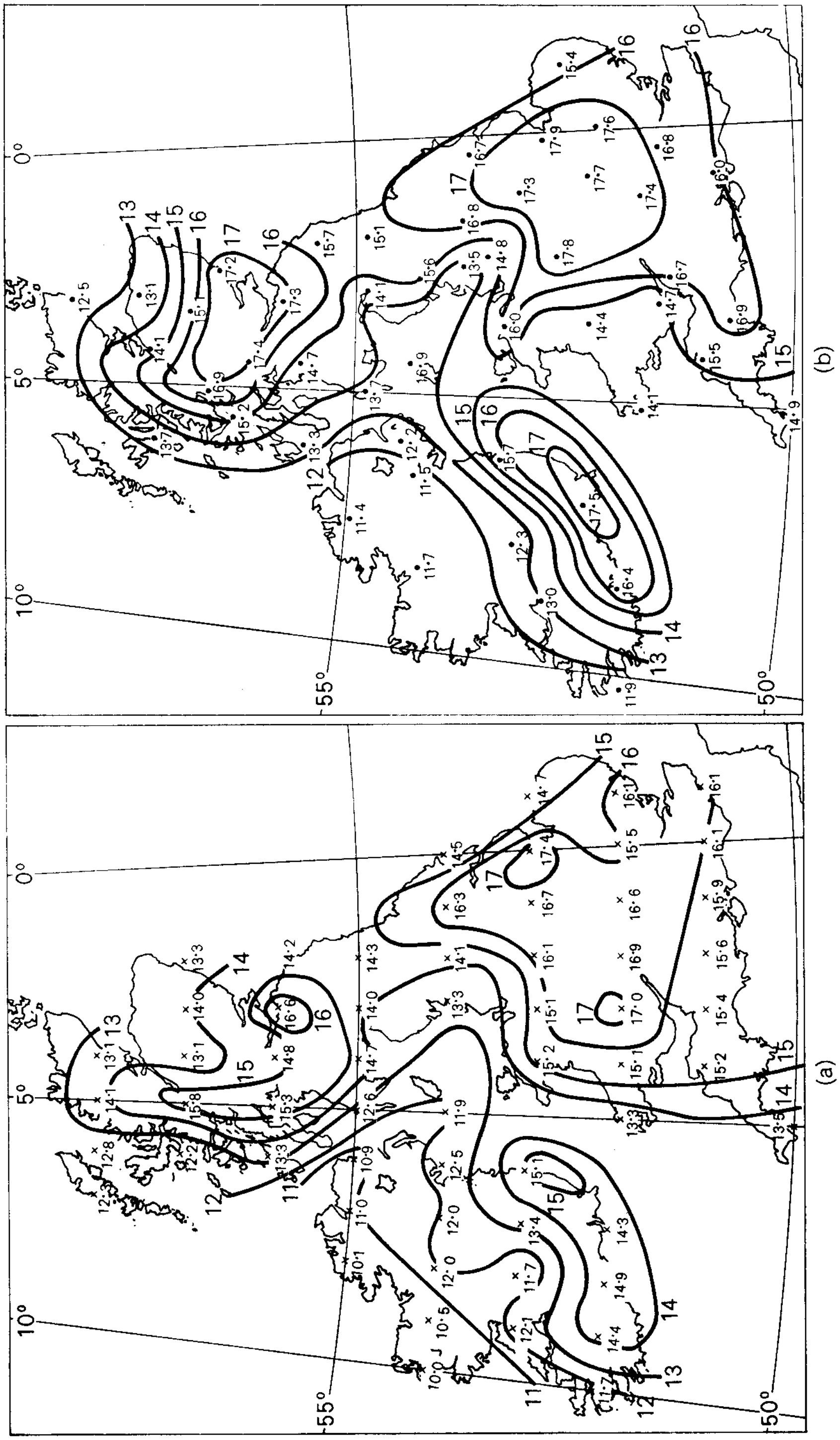

Figure 4. Coefficient of variation of annual rainfall 1871–1970 (per cent)—(a) derived from map data, (b) derived from stations with homogeneous records. Standard error *c.* 1·2 per cent.

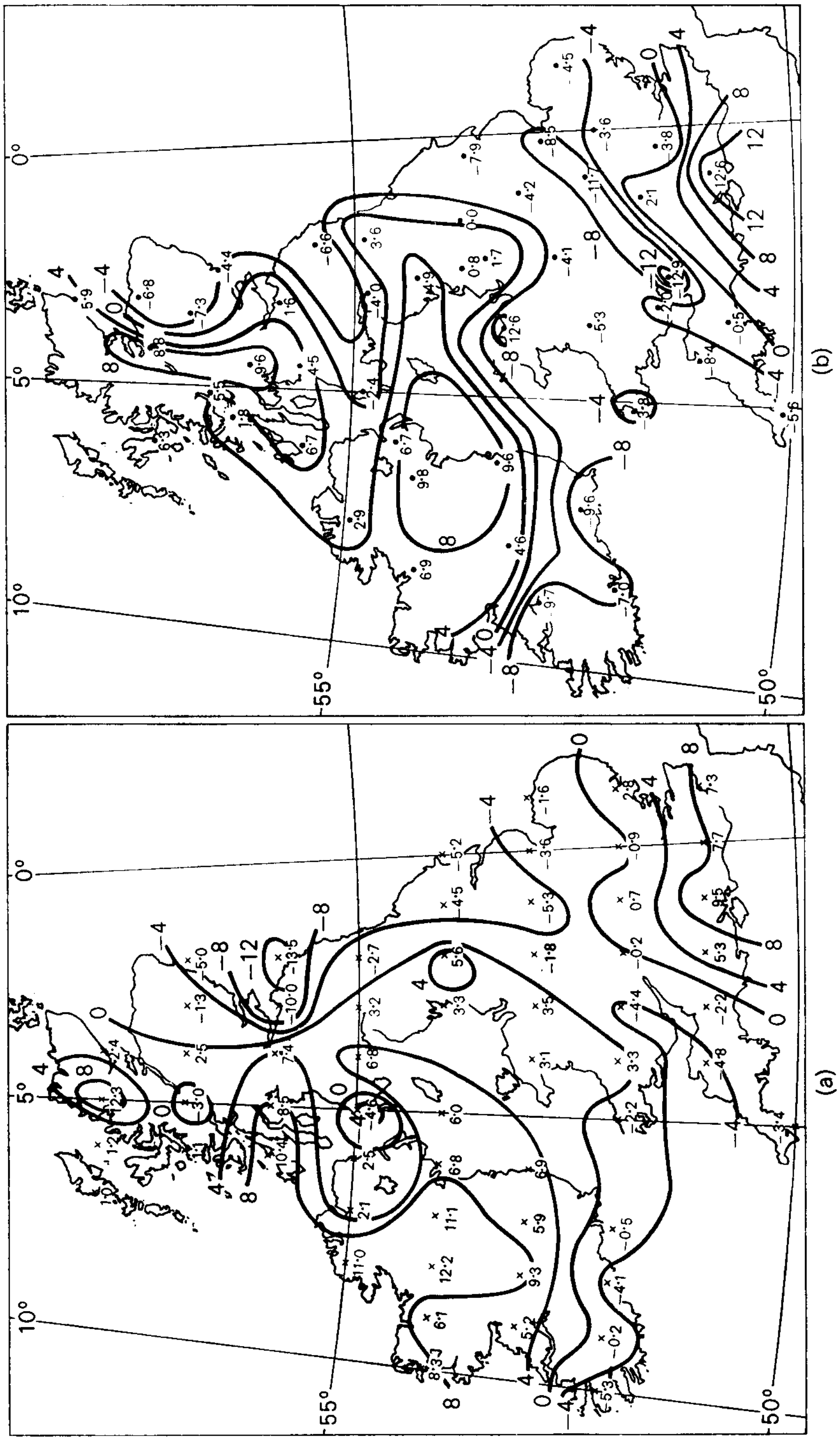

Figure 5. Trends of annual rainfall (per cent per century) from 1871 to 1970—(a) derived from map data, (b) derived from stations with homogeneous records. Standard error *c*. 5·9 per cent per century.

coherence forms a marked contrast to that associated with the 'raw' rain-gauge data presented in Figure 3. The coherence of the homogeneous data is, however, less than that of the map data, probably owing to the great difficulties involved in eliminating all the inhomogeneities from raw rain-gauge data. For this reason, the map data are considered to be slightly superior to the homogeneous data.

6. Effect of site and instrumental changes on trends derived from rain-gauges

If perfect rainfall records were available for every rain-gauge location, then two trends could be calculated, one from the gauge observations and the other from the perfect record. From N rain-gauges in a given area, one could calculate the variance of the trends from the gauge observations and from the perfect records. The variance of the gauge observations would be the larger, owing to the effects of changes in site and instrumentation. The ratio of the two figures would then give the proportion of the variance of observed trends due to genuine changes in rainfall trends across the area.

The map data were taken as an approximation to a perfect rainfall time series. Trends for the period from 1911 to 1970 were computed for 26 points in England and Wales, and their standard deviation about an assumed population mean of zero calculated. This was compared with the standard deviation of trends obtained from a similar number (25) of uniformly distributed but otherwise randomly selected rain-gauge records in England and Wales. Thus the comparison is not between the variances of trends from 'perfect' and gauge observations for exactly the same locations, but for different but uniformly distributed points in England and Wales.

The ratio of the two standard deviations may depend on the number of points and the number of years used. The number of points derived from maps was always 26, but the number of rain-gauges was varied from 25 to 200, while the length of epoch over which the trends were calculated ranged from 15 to 60 years. The results are presented in Table I, and show that the standard deviation derived from the

Table I. *Standard deviation of rainfall trends over England and Wales (per cent per decade) as obtained from various data sets*

Data set	Epoch						
	1911–70	1911–40	1941–70	1911–25	1926–40	1941–55	1956–70
26 points from maps	0·63	1·88	1·93	5·26	7·28	3·75	4·28
25 gauges	1·46	3·12	2·16	8·46	7·68	6·79	5·96
50 gauges	1·49	3·26	2·45	7·74	7·60	5·74	5·79
100 gauges	1·41	3·24	2·46	7·71	7·55	6·04	6·11
200 gauges	1·59	3·38	2·37	7·69	7·99	5·79	5·87
26 points from maps / Average for gauges	0·42*	0·58	0·82	0·67	0·95	0·62	0·72
		0·70**		0·74†			

* 60-year epoch ** mean of two 30-year epochs † mean of four 15-year epochs

gauges varies only slightly with the number used. For this reason the mean of the four sets of figures obtained for the gauges was used in making comparisons with the results from the 'map' data. The absolute values of the standard deviations increase as the length of epoch decreases, but the ratio of the standard deviations of map data to gauge observations ranges from 0·42 for 1911–70 to 0·70 for 30-year epochs and 0·74 for 15-year epochs. There is therefore some suggestion that the proportion of variance accounted for by genuine rainfall fluctuations decreases as the length of epoch increases. As a broad generalization however, it may be said that fluctuations of rainfall and errors due to site and instrumental changes contribute about equally (50 per cent $\approx 0{\cdot}7^2$) to the variance of trends obtained from rain-gauge records. For the epoch 1911–70, the ratio of 0·42 indicates that the standard errors calculated in section 4, which apply only to genuine fluctuations of rainfall, should be more than doubled (multiplied by 1/0·42) to take account of site and instrumental changes. From this it is inferred that the trends displayed in Figure 3 indicate that genuine rainfall trends within the area covered ranged through 4 (as opposed to 8) standard deviations.

7. Annual and seasonal rainfall in the London area from 1911 to 1970

Trends of annual rainfall in the London area during the period from 1911 to 1970 are shown in Figure 6. It reveals small decreases except for an area in north London and to the east of the conurbation. The pattern bears no obvious relationship to the built-up area, and is not significant when the standard error of 1·25 per cent per decade (for a perfect site) is taken into account. This lack of statistical significance is confirmed by Figure 7, which shows trends over the whole United Kingdom during the same period. It shows that the variations in trend which occurred in the London area are typical of those over the rest of the country. Urbanization may be expected to yield an increase in the proportion of the rain falling in the summer half-year, and trends of this quantity in the London area

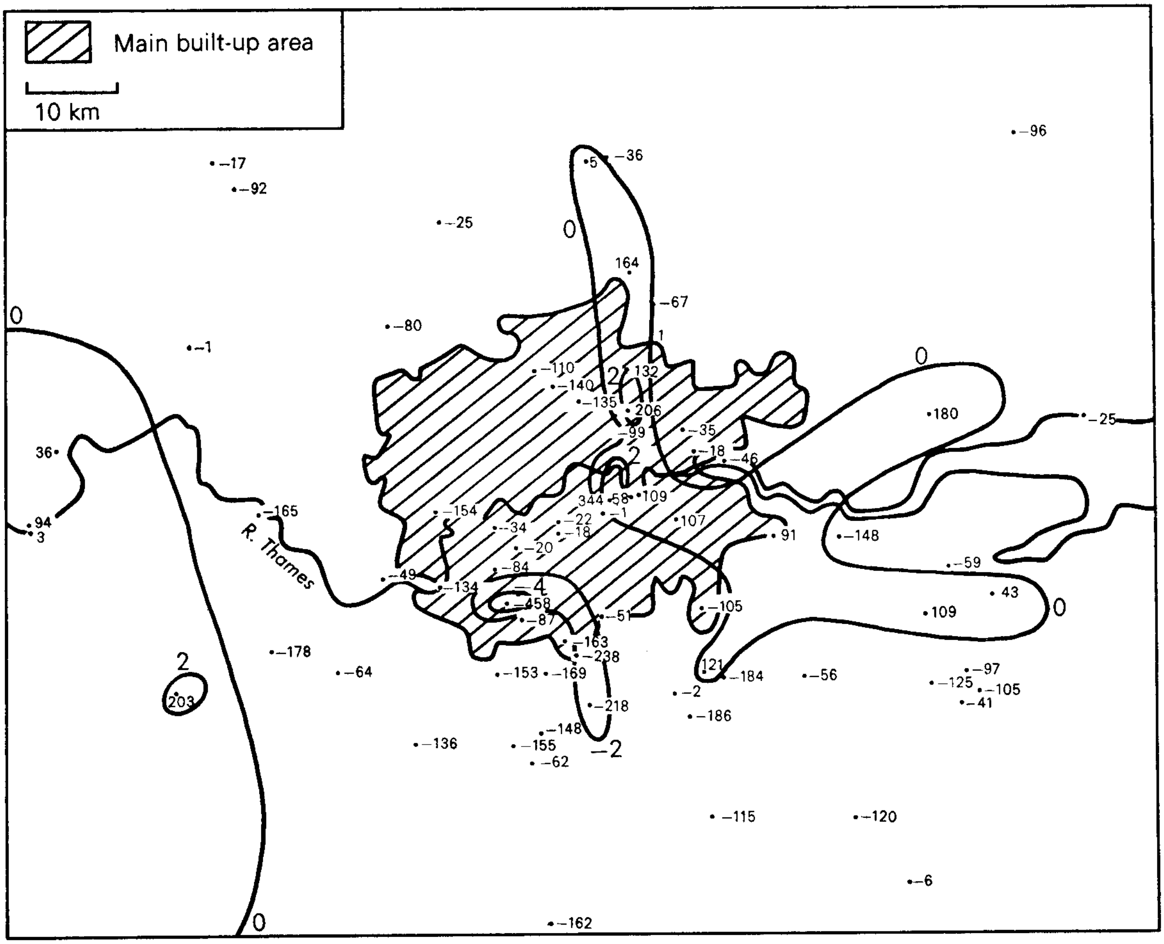

Figure 6. Trend of annual rainfall in the London area (per cent per decade) from 1911 to 1970. Standard error *c.* 1·25 per cent per decade. Station values are expressed in hundredths of one per cent.

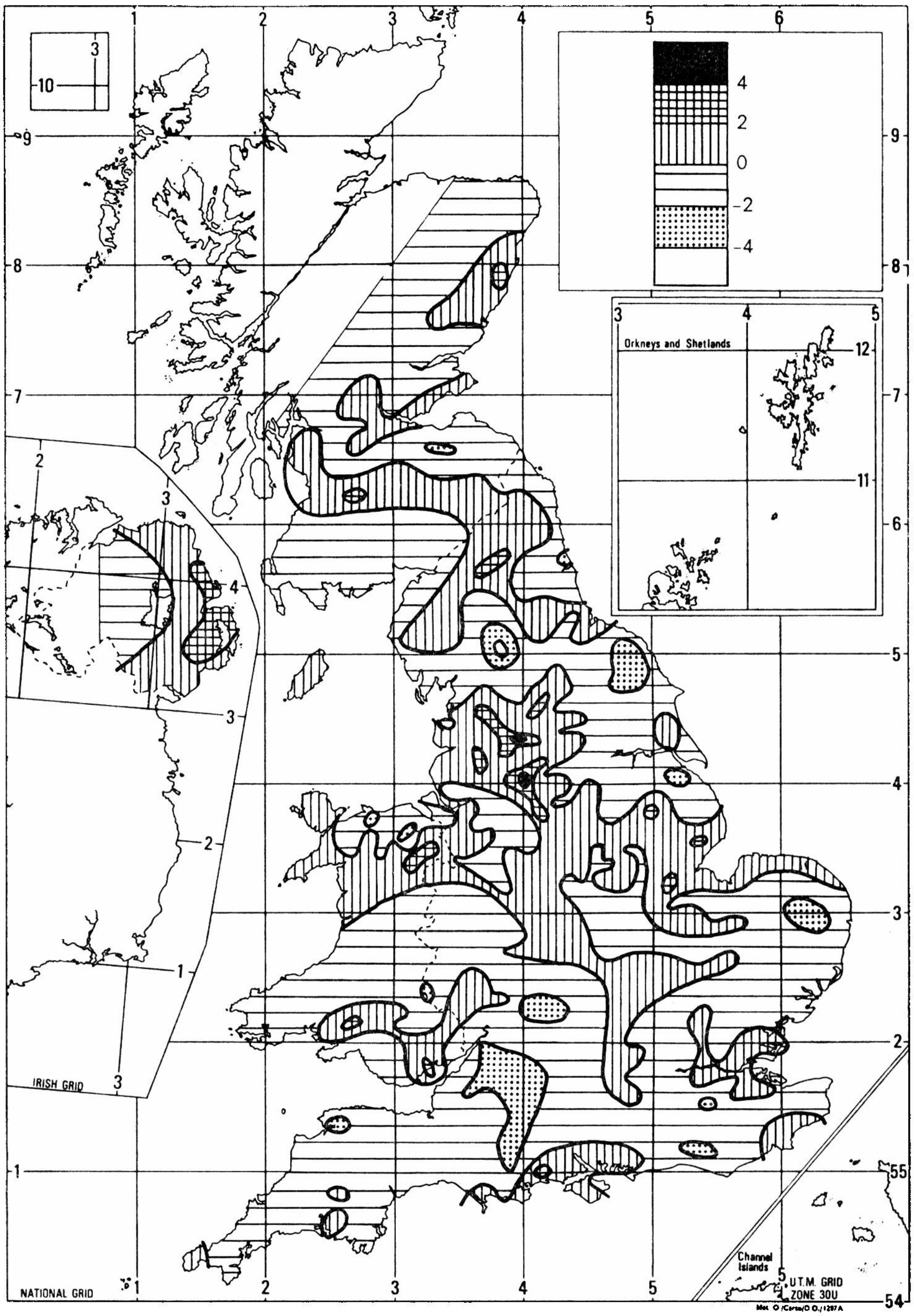

Figure 7. Trend of annual rainfall (per cent per decade) from 1911 to 1970.

for the period 1911–70 are displayed in Figure 8. It can be seen that the summer half-year rainfall (defined as that for April–September) is increasing at the expense of that in the winter half-year (October–March) over the whole of the area, but this increase is at a minimum to the north-north-east of London. The variations are well within those to be expected from a consideration of the standard errors, however, and they are also typical of the variations which occur over the rest of the United Kingdom.

In order to gain further information on the temporal variation of rainfall, the London area was divided into 9 regions as indicated by the broken lines in Figure 8. Rainfall was expressed as a percentage of station average and meaned over all stations within each area, and five-year means for the year and the summer half-year/whole year are presented in Figure 9. The results are based on the 1911–70 network of stations up to 1940 and the 1941–70 network thereafter. During the 1941–70 period, results from the smaller network of stations were very similar to those from the larger. It is unfortunate that the density of stations is poorest in the north-east of London (only 1 from 1911 to 1940), but good

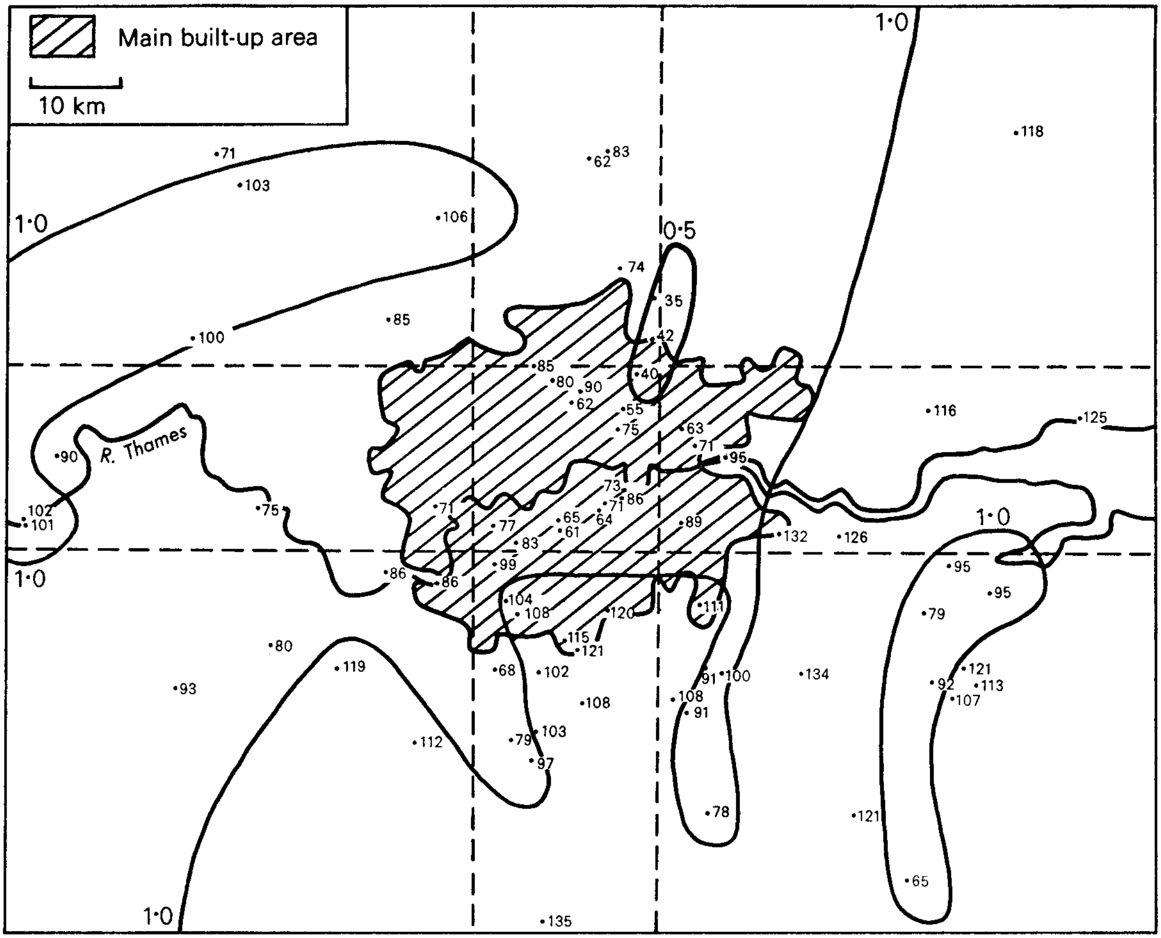

Figure 8. Trend of proportion of rain falling in summer half-year from 1911 to 1970 in the London area (per cent per decade). Standard error *c.* 0·7 per cent per decade. Station values are expressed in hundredths of one per cent.

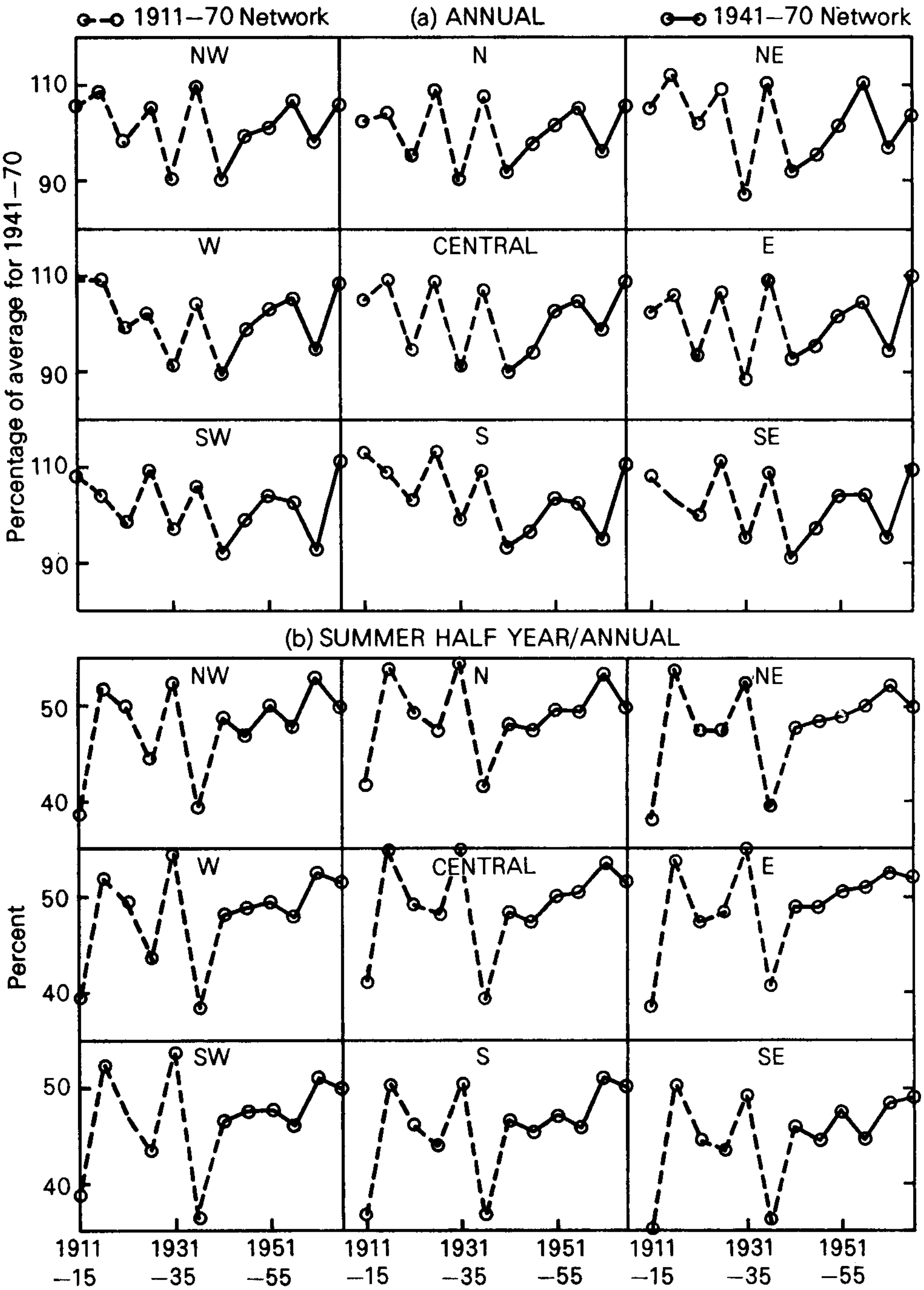

Figure 9. Five-year means of rainfall in the London area.

comparisons can be made between London itself and the area to the south-west. The graphs display a strong spatial coherence, and no features which can clearly be attributed to urbanization are apparent.

8. Conclusions

The spatial coherence of trends derived from rain-gauge records was found to be very poor. During the period from 1911 to 1970, values differed by several per cent per decade at points only a few kilometres apart. Errors due to changes of site and instrumentation were found to account for about half the variance of the observed trends.

During the period from 1911 to 1970, no effects of urbanization were revealed in the annual and summer half-year totals of rain in the London area. The investigation was, however, far from exhaustive. The most likely area for effects to be observed is in the frequency of high-intensity, short-duration rainstorms during summer, and this part of the subject was not examined. The main purpose here was to see if any changes in the short-duration rainfall climatology had affected annual and seasonal rainfall totals. On the basis of the data available for the London area, this may be said to be not the case, and homogeneous rainfall series produced without regard to urbanization effects will still be suitable for investigations into climatic change on the annual and seasonal time-scale.

Acknowledgements

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An improved gravimetric rain-gauge

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Summary

A gravimetric rain-gauge (GRG) was developed and tested at Kew Observatory in the early 1970s. Results obtained from this gauge have been promising but it proved difficult to adjust and maintain satisfactorily and had a capacity of only 50 mm of rainfall. The Operational Instrumentation Branch of the Meteorological Office have developed and redesigned parts of the gauge to overcome these difficulties and this paper contains a description of the gauge in its new form.

Introduction

One of the greatest difficulties associated with rainfall measurement is defining the extent to which the gauge affects the flow around it and hence the rainfall it catches (Kurtyka, 1953; Green, 1969). Attempts to overcome this problem fall into two main categories. One method is to shield the gauge from the horizontal component of wind speed by placing metal (Nipher-type) or natural (turf-wall) shields around the gauge. The main drawback of this method is that the shields themselves produce perturbations in the flow. The other method is to sink the gauge into the ground, so that the rim is level with the surface, to reduce its effect on the airflow. This method is not entirely successful because the hole made by the collecting funnel still affects the airflow and there is some insplash into the funnel. Insplash can be reduced by placing a venetian blind or slat arrangement around the gauge but this, too, affects the airflow. The GRG does not overcome these problems but attempts to minimize them. The first GRG was developed at Kew and has been described by Crawford (1972); see also Painter (1975). The gauge had a large collector pan, about 120 cm in diameter with a wire-mesh top surface. A layer of gravel was spread over the mesh and the pan rested on a weighing machine located in a pit so that its top surface was level with the surrounding gravel-covered area. The pan was weighed automatically on a counter platform weighing machine. The counter-balance weight was held in a 'jockey' which was moved along the balance arm by a motor to the position in which the arm was horizontal. Any movement of the arm from the horizontal was detected by one of two photoelectric cells and a positive or negative d.c. voltage was then applied to the motor so as to move the jockey towards the balance position. The position of the jockey along the balance arm was an indication of the accumulated rainfall in the gauge and was monitored by a precision multi-turn potentiometer linked to the motor. The GRG recorded cumulative rainfall automatically and had only a small effect on the airflow over the area. As the gauge and surrounding area had similar surfaces, insplash into and outsplash from the gauge approximately cancelled out. The main drawbacks of the gauge were that it had a rather low capacity (50 mm of rainfall) and that the jockey tended to overshoot the balance position, continuously 'hunting' for the balance position but not finding it. This produced a wide trace on the chart record with the width dependent on the position of two mechanical stops on the balance arm. With very careful adjustment of the stops, the trace could be made quite narrow but for continuous, reliable operation of the gauge, frequent readjustment of the stops was found necessary.

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Modifications to the GRG

The modified gauge is shown diagramatically in Figure 1, and Plate I shows the gauge before installation. The operational logic of the device is shown in block diagram form in Figure 2. The collector pan has been made smaller, 90 cm in diameter, and lighter; it is now manufactured from fibreglass instead of the original galvanized iron. This reduces the ratio of pan weight to rain weight and with an increase in length of the balance arm to 55 cm allows the capacity of the gauge to be doubled without loss of resolution.

The stability of the system has been increased by slinging the weight below the balance arm and hence moving the centre of gravity of the arm to below the pivot point. A weight of about 50 gm on the pan

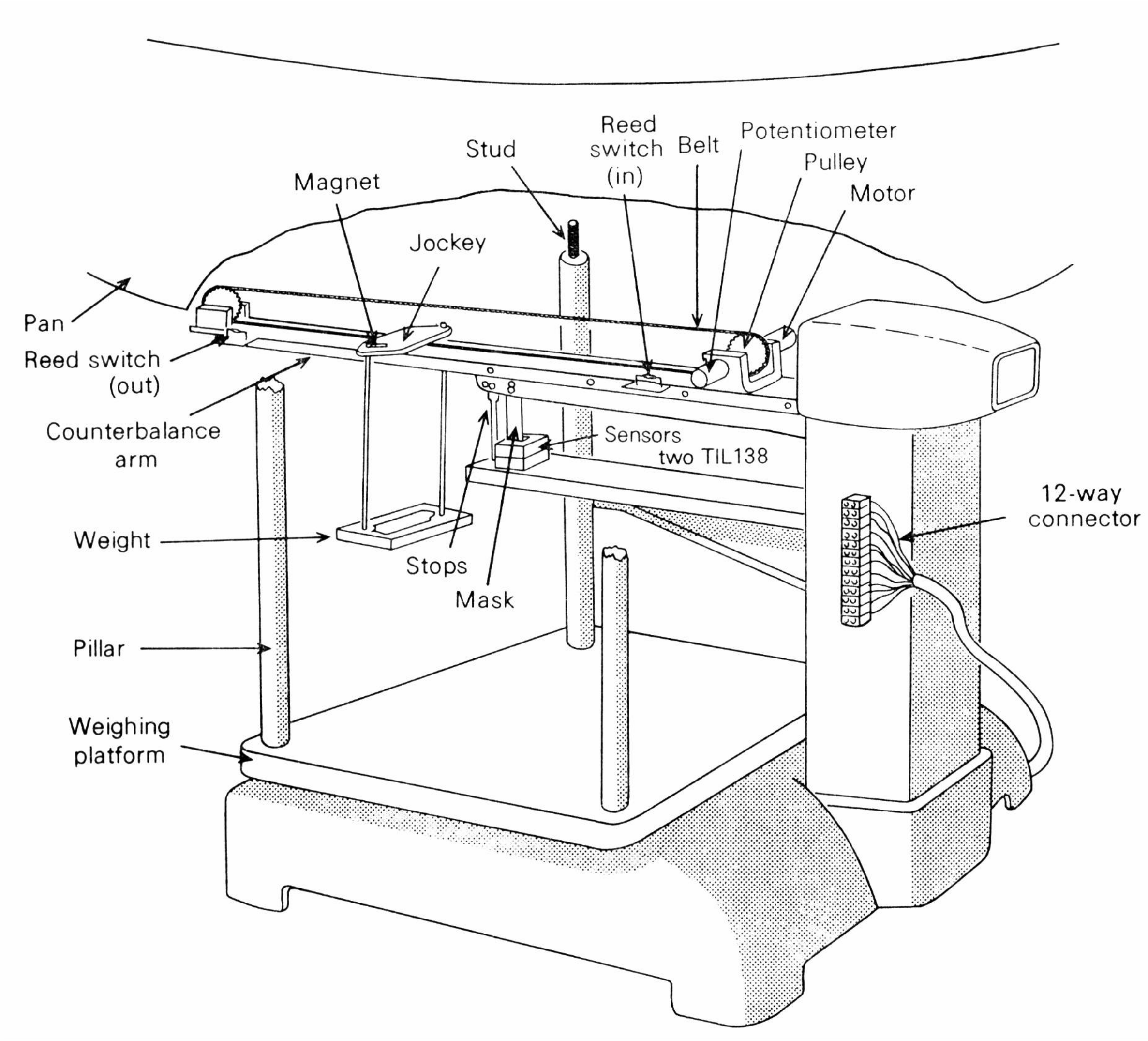

Figure 1. The gravimetric rain-gauge.

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Plate I. The gravimetric rain-gauge complete with control electronics. The top pan is 90 cm in diameter. (See facing page.)

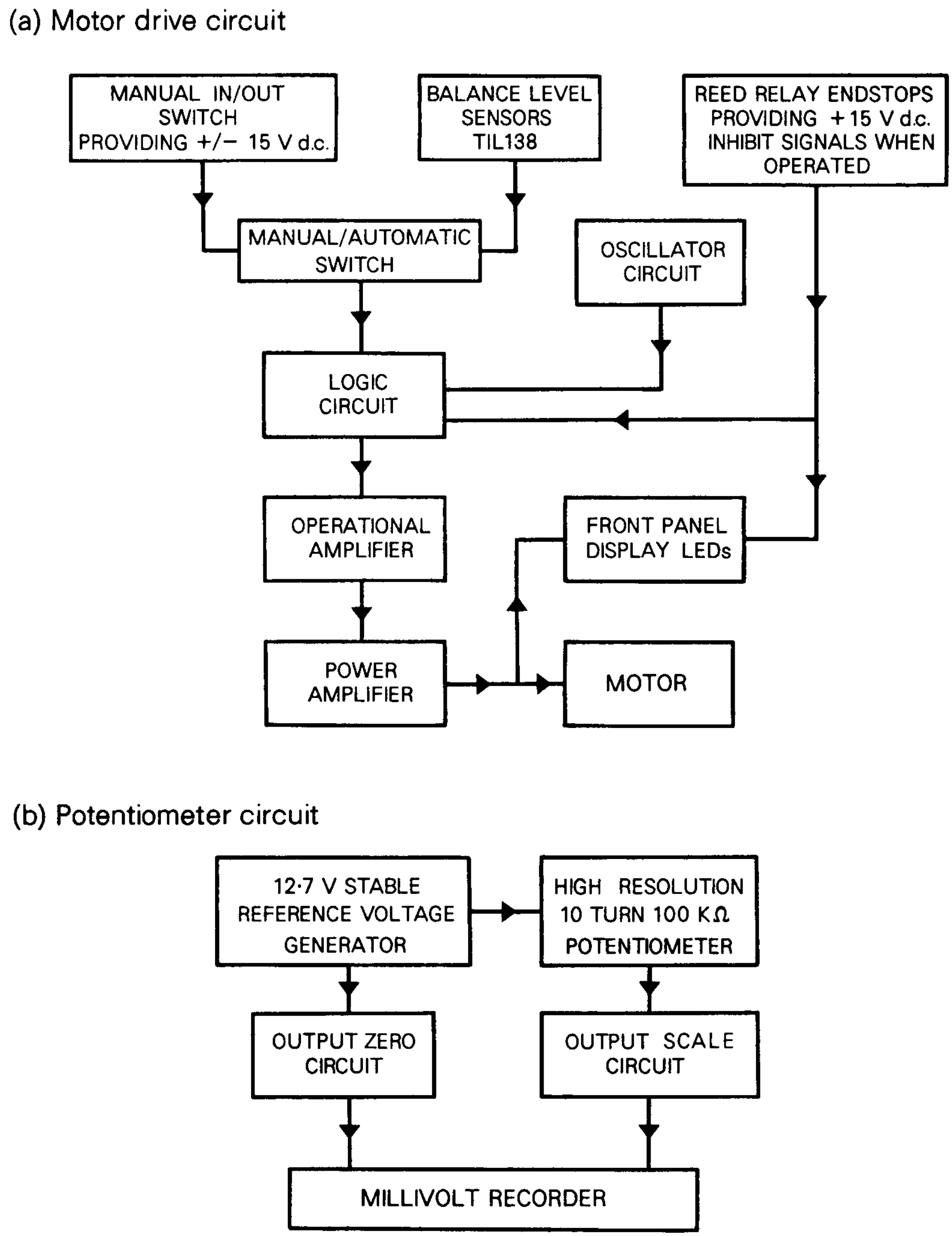

Figure 2. Block diagram of the operation of the modified gravimetric rain-gauge.

causes the balance arm to move between its upper and lower physical stops. The region over which the sensor controls the balance arm is smaller than this, though the actual resolution is limited to some 20 g, equivalent to 0·03 mm of rainfall, by friction in the weighing machine.

The motor drive

The circuit for the motor drive is shown in Figure 3. Square-wave pulses are generated by an

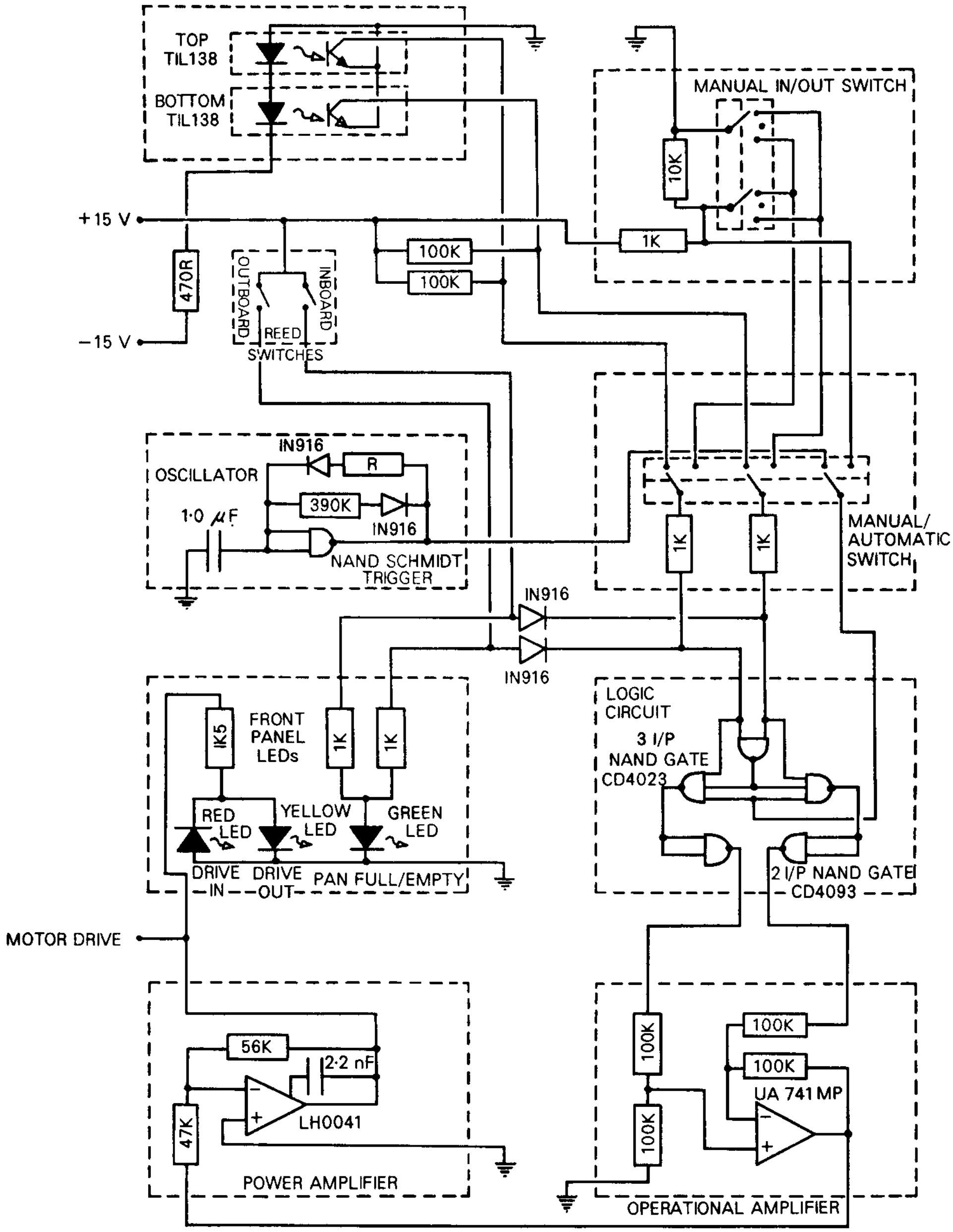

Figure 3. Motor drive circuits.

oscillator circuit using a Schmidt trigger NAND gate. The combination of 390 kΩ and 1·0 μF gives a pulse frequency of 2·56 Hz while the resistor R determines the pulse length. At present the value of R is 39 kΩ giving a pulse length of 39 ms. This produces a motor drive speed equivalent to a rainfall rate of 155 mm/h. At this speed there is a tendency for the jockey to overshoot the balance position. The motor drive speed can be reduced by substituting smaller values of R, so increasing the likelihood of the balance position being found at the first attempt. However, this introduces the risk that the gauge may not be able to respond rapidly enough to short, intense periods of rainfall. This problem could be overcome by recording rate of rainfall as well as cumulative rainfall and arranging for greater values of R to be switched into circuit as the rainfall rate increases.

On the Kew GRG, the position of the balance arm was sensed by two photosensitive cells operated by torch bulbs. These have been replaced on the modified GRG by a pair of light-emitting diode (LED) and phototransistor devices (TIL 138). The signals from the phototransistors and from the reed relays at each end of the balance arm together with pulses from the oscillator are fed into two inputs of a logic circuit. Governed by the combination of signals it receives, the logic circuit puts pulses on to the positive or negative inputs of an operational amplifier which, in turn, operates the power amplifier which supplies the current to the motor. The reed relays are operated by a magnet fixed to the jockey and, when operated, produce signals which inhibit further movement of the jockey away from the centre of the arm. This does not prevent the jockey from being moved back towards the centre of the arm. If neither phototransistor produces a signal, or if both produce one, the output of the logic circuit remains low and no current reaches the motor.

It is necessary, during calibration or after emptying the collector, to be able to drive the jockey at a fast rate. This is done by replacing the signals from the phototransistors and oscillator on one or other of the inputs to the logic circuit (and hence the motor drive) by 15 V d.c.

Control and display facilities

The switches which provide the choice of manual or automatic drive to the motor are mounted on the front panel of the control box together with 3 LEDs which show whether the jockey is moving 'in' or 'out', or if it has reached one or other of the reed relay stops.

The 0–100 mV range of output from the control box (see below) is equivalent to a range of 0–100 mm of rain and can be displayed or recorded on any suitable millivolt meter, chart recorder or data logger, including the MODLE data logger currently in use within the Meteorological Office.

The potentiometer circuits

The circuit for the measurement of the jockey position is shown in Figure 4. This circuit was designed to provide an output of 0–100 mV for 0–100 mm of rain, which corresponds to the full travel of the jockey along the balance arm, with small adjustments for zero and scale. The position of the jockey along the balance arm, and hence the accumulated rainfall in the gauge, is measured by a high-resolution 10-turn 100 kΩ potentiometer linked to the motor. The gearing is such that about 5 turns are used. A stable 12·7 V reference voltage is generated by a 6·2 V zener diode with an operational amplifier and is supplied to the potentiometer. It is also used, after reduction by an operational amplifier, to provide a small, adjustable zero offset to the output. The return signal from the potentiometer slider is reduced by an operational amplifier and provides the scale adjustment. The zero and scale outputs provide the low and high sides of the recorded gauge output respectively. They are both effectively isolated from the common ground used throughout the gauge and this reduces noise pick-up and interference.

Modified GRG performance

The gauge was calibrated in the laboratory by adding weights in 5 kg stages up to 60 kg and then

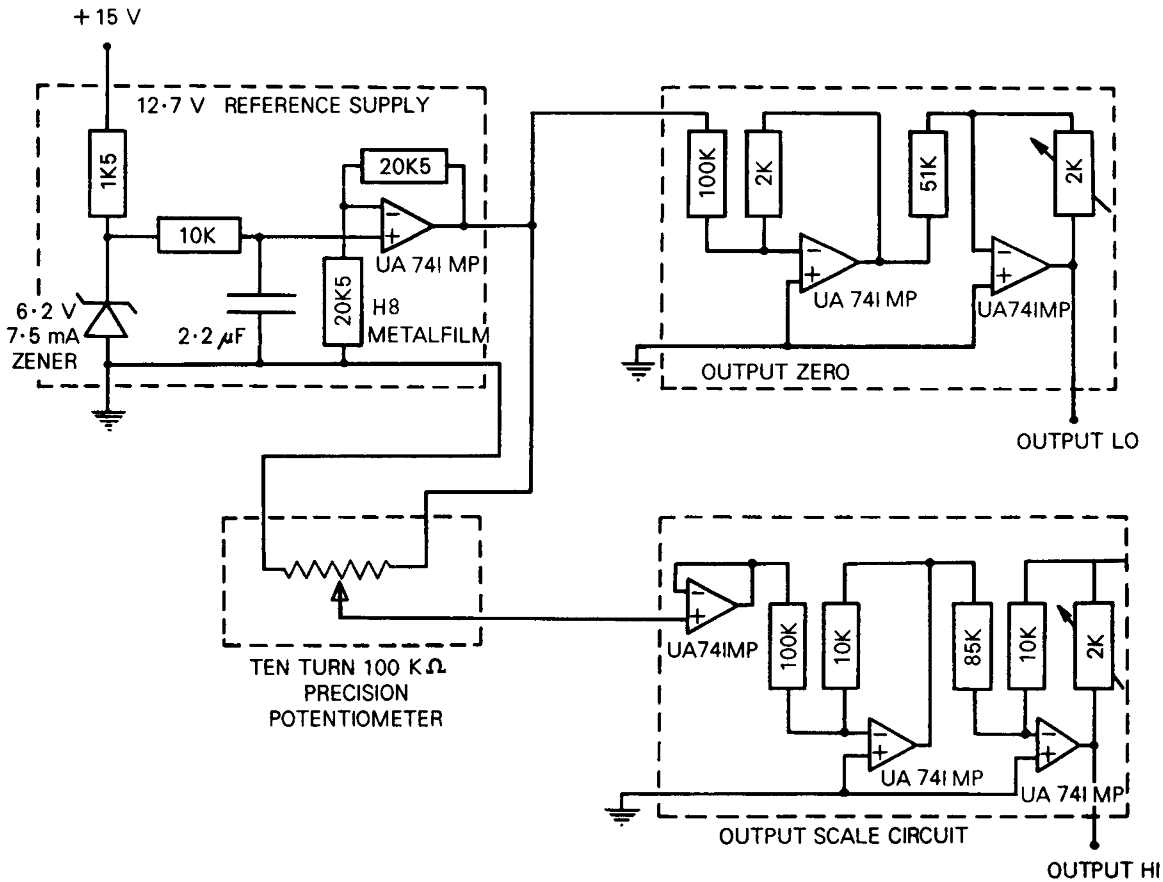

Figure 4. The potentiometer circuits.

adding 3·9 kg to make up the weight equivalent to 100 mm of rainfall (63·9 kg). The weights were then progressively removed in the same manner, 3·9 kg first and then in 5 kg stages. The output of the gauge was recorded when the balance position was found at each stage. The differences between the gauge output and theoretical value (theoretical value minus gauge output) were calculated for each stage and are expressed as a percentage of the gauge capacity, 100 mm, in Table I.

Table I. *Differences between the gauge output and theoretical value, expressed as percentages of the gauge capacity (100 mm).*

	Increasing weight	Decreasing weight
Extremes	− 0·02 to + 0·10	− 0·03 to + 0·15
Mean (n = 13)	+ 0·03	+ 0·06
Standard deviation	0·03	0·05

The differences between gauge output for a particular weight as the weights were increased and decreased gives an idea of the hysteresis or backlash in the gauge. The weights used to calibrate the gauge were checked and found to be within the range — 0 per cent to + 0·016 per cent of their nominal weights.

The gauge was installed in the field and the output logged at 1-minute intervals on a Kent chart recorder. From the start the gauge appeared to be very sensitive, easily detecting and showing dew formation at night and evaporation the following morning. Very little rain fell in the first six weeks after installation but the chart record from the gauge compared well with that from a nearby (Dines) tilting-siphon rain-gauge on the few occasions on which rain was recorded. The results of a subsequent comparison between the GRG and a manually read standard five-inch check gauge exposed at 30·5 cm without a turf wall are shown in Figure 5. The latter was read daily and the hourly values taken from the GRG record were totalled to provide equivalent daily figures. From Figure 5 it can be seen that a simple regression line fitted to the data indicates a systematic offset of about 0·10 mm between the gauges and a general increase of about 6 per cent in the catch of the GRG over that of the five-inch gauge. The offset of 0·10 mm is typical of the offset which has been found before in comparisons between the five-inch manually read gauges and 'automatic' gauges. For example, work done to evaluate prototypes of the Meteorological Office Mk 5 tipping-bucket gauge established an offset of between 0·05 mm and 0·15 mm between this gauge and a standard five-inch check gauge. Experiments (unpublished report by B. Tonkinson) have shown that a systematic error of this size can be attributed to the water which remains

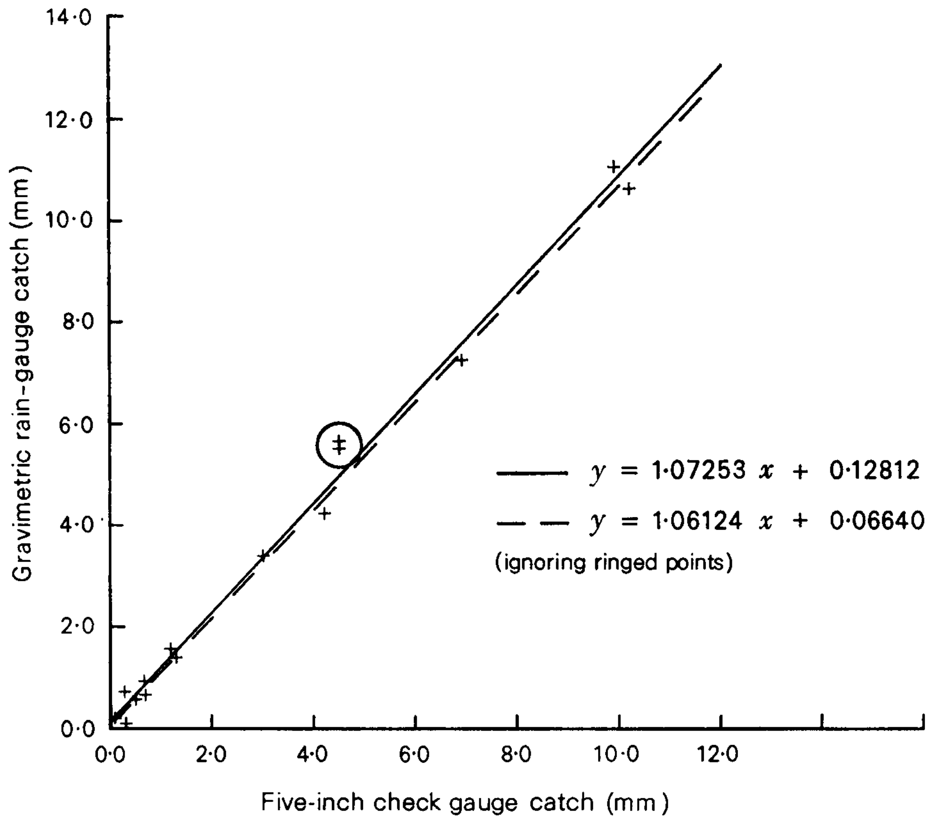

Figure 5. Comparison of catches of gravimetric rain-gauge and five-inch rain-gauge (5 January to 7 March 1979).

in the bottle of the five-inch gauge when it is read and which subsequently either evaporates or is recorded as a 'trace'. The general difference of + 6 per cent between the GRG and the check gauge is consistent with the previously published evidence (Robinson and Rodda, 1969) that a ground-level gauge will catch about 5 per cent more than a well-exposed standard five-inch gauge.

The regression fit gives somewhat smaller values of both slope and offset if the points at 4·5 mm rainfall are excluded. These observations were taken in windy conditions, circumstances which would be expected to decrease the catch of the five-inch gauge and, because of the differential pressure problem discussed below, cause the GRG to over-read.

Two problems came to light after the gauge was installed. The pressure differential between the free atmosphere and the pit underneath the collector pan in which the gauge was located needed to be only 3 μbar to produce an apparent weight change equivalent to 20 g, the resolution of the gauge. Hence, even in light winds, the gauge is frequently pushed off the balance position by gusts. This leads to a small scatter of points about the balance position on the chart record. The scatter has so far not exceeded the equivalent of $\pm$ 0·05 mm of rain and it disappeared in calm conditions or when the gauge was shielded from the wind.

The resolution of this instrument is therefore limited at present by wind effects across the measuring pan.

The second problem was that several weeks after installation, the cast-iron weighbridge was found to be severely corroded with rust. The gauge was therefore removed and was thoroughly cleaned and treated with anti-corrosion paint. Insufficient time has elapsed since this treatment was completed for a decision to be made whether this approach to the corrosion problem has been successful or whether more expensive approaches such as the manufacture of the weighbridge from cast alloy or brass will be required.

Conclusions

The modifications described here have made it possible for the counterbalance mechanism of the GRG readily to find and stay at the balance position when rainfall or evaporation takes place. This reduces wear on the motor and means that the positioning of the mechanical stops on the gauge is no longer critical. All necessary adjustments can be carried out on the electrical circuits in the control box rather than on the gauge in the field. The capacity of the gauge has been doubled without loss of resolution.

The first modified GRG was installed at Beaufort Park in October 1978 and preliminary results have been encouraging. A trial between three such GRGs and other Meteorological Office rain-gauges is planned to last about one year and these results will be published in due course.

Acknowledgements

The assistance of members of the Operational Instrumentation Branch of the Meteorological Office with this work is gratefully acknowledged.

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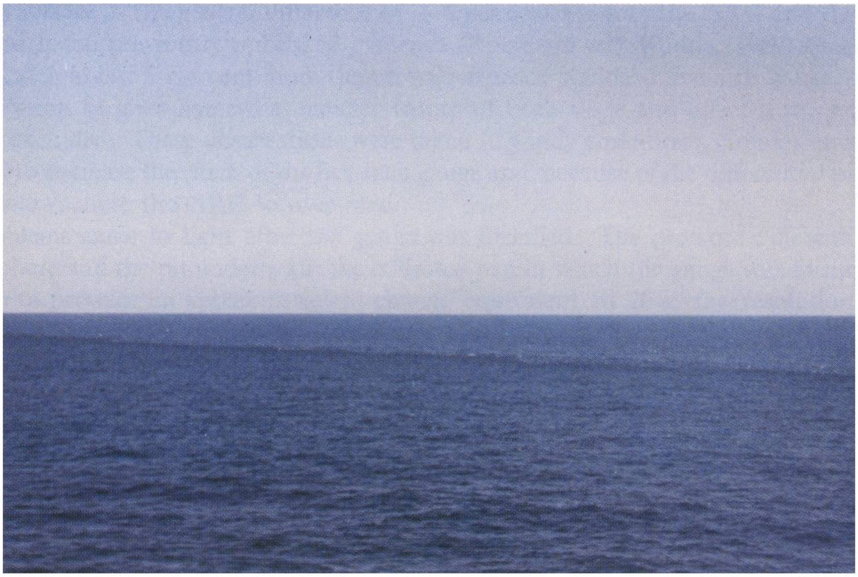

Plate II. The dark band in the sea surface seen from the aircraft at a height of 150 m, viewing to the north-north-west (see facing page).

Plate III. The boundary between the two types of sea surface seen at close quarters during the run at 30 m above sea level, viewing due west (see facing page).

Kurtyka, J. C.	1953	Precipitation measurements study. Illinois State Water Survey Division, Urbana, Illinois, *Report* No. 20.
Painter, H. E.	1975	Preliminary results from a gravimetric rain-gauge. *Meteorol Mag*, **104**, 69–78.
Robinson, A. C. and Rodda, J. C.	1969	Rain, wind and the aerodynamic characteristics of rain-gauges. *Meterol Mag*, **98**, 113–120.

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An anomalous condition of the sea surface observed from an aircraft

By H. Griffiths

(Meteorological Research Flight, Royal Aircraft Establishment, Farnborough)

Summary

A pronounced dark-blue band in the sea surface near the equator was observed from the Meteorological Research Flight Hercules aircraft. The sea surfaces on either side of the band were distinctly different in colour. Aircraft measurements revealed a difference in surface temperature of about 1 °C between the two masses of water.

An unusual feature in the sea surface was observed near the equator (0°26′N, 18°44′W) on 9 September 1979 during the detachment of the Meteorological Research Flight Hercules aircraft to Dakar, Senegal. Two different colours of sea surface were separated by a pronounced dark-blue band a few hundred metres wide orientated roughly east–west and extending to the horizon in both directions. No significant cloud formations were observed in association with the differing sea surfaces, the sky being clear apart from a few patches of small cumulus. Plate II shows the dark band viewed from a distance of a few miles at a height of 150 m. The water just to the north of the band appeared quite turbulent, showing many white crests, although elsewhere the sea was relatively calm. Later in the day the band was seen to branch.

A track was flown approximately at right angles to the band at a height of 30 m. Plate III is a photograph taken from the aircraft just before crossing the band, and illustrates the two distinct shades of sea surface. Both Plates II and III were taken with a hand-held camera viewing from the side of the aircraft. Throughout the run at low level the Barnes radiometer viewing vertically downwards from the aircraft was recording. This instrument is sensitive to radiation in the 11 μm atmospheric window and is used to measure the equivalent black-body temperature of the sea surface from low levels. Figure 1 is a plot of equivalent black-body temperature against time for the run at a height of 30 m, and clearly shows a discontinuity in temperature of about 1 °C between the two areas of sea, the warmer water lying to the north. It can be seen that the rise time of the discontinuity is about 5 s. This is a real feature of the sea surface since the Barnes radiometer has a response time of only 120 ms. Moreover, the field of view of the radiometer is 2°, so at this height and speed areas of sea viewed on successive samples are widely spaced.

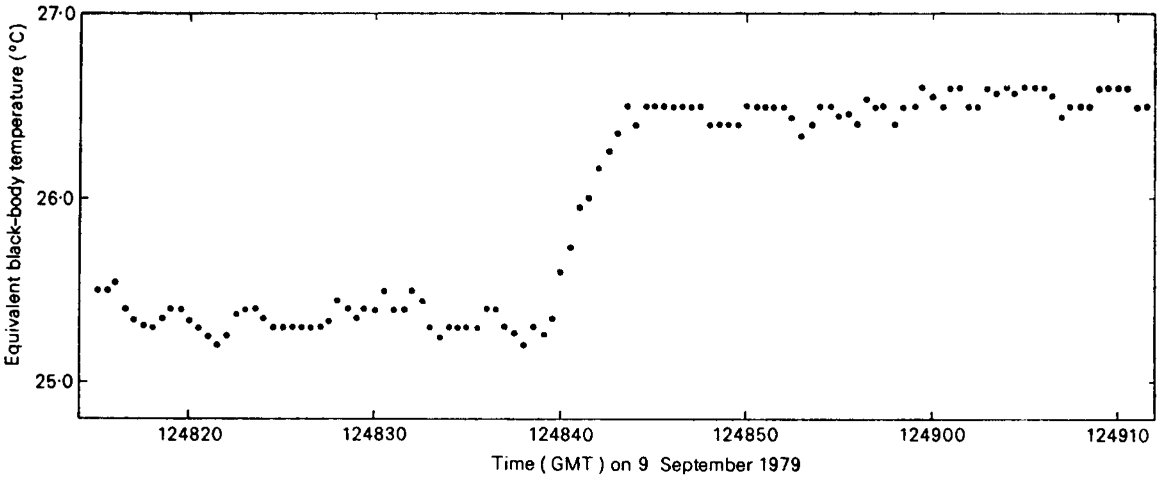

Figure 1. Equivalent black-body temperature of the sea surface as a function of time measured by the Barnes radiometer. The measurements were obtained at a height of 30 m above sea level, with a heading of 333° and a ground speed of 89 m s^{-1}.

The wind at this level was 017°/10 m s^{-1}, that is to say blowing from the warmer to the cooler water. The mean air temperature and specific humidity did not appear to be affected by the change in the temperature of the sea surface, being 24·6 °C and 14·1 g kg^{-1} respectively over both regions of sea. However, an analysis of the vertical component of the wind velocity (w) measured by the aircraft reveals significant differences between the two regions. The aircraft's wind-finding system is sampled at a rate of 20 Hz thus providing about 500 samples of w for each region from a total of about 1 minute of data. Figure 2 shows normalized histograms of w summed in intervals of 0·06 m s^{-1} for both regions of sea. A constant was added to all the measured values to set the mean vertical component of the wind velocity over the cooler water arbitrarily to zero. For the second distribution the mean value of w is only slightly different at 0·05 m s^{-1}.

Both distributions are noticeably skewed towards positive w as would be expected if ascent is accompanied by slower descent over a larger area. We may compare the two distributions using a chi-square test, and this shows the differences between them to be significant at the 0·1 per cent level. Because of this highly significant result it is meaningful to compare the variances of the distributions. For the cooler water the variance of w is 0·032 $m^2 s^{-2}$. However, the corresponding value for the warmer water is 0·060 $m^2 s^{-2}$ indicating that in this case a 1 °C rise in sea surface temperature has almost doubled the turbulent kinetic energy contained in the vertical component of the wind velocity.

Although the discontinuity in the temperature of the sea surface was particularly well defined, to make any useful inferences about its effect on the boundary layer would require more information than was obtained on this occasion.

It is possible that the sea-surface phenomenon was associated with either the westward South Equatorial Current or the eastward Equatorial Counter-current both of which occur in this part of the ocean at this time of year.

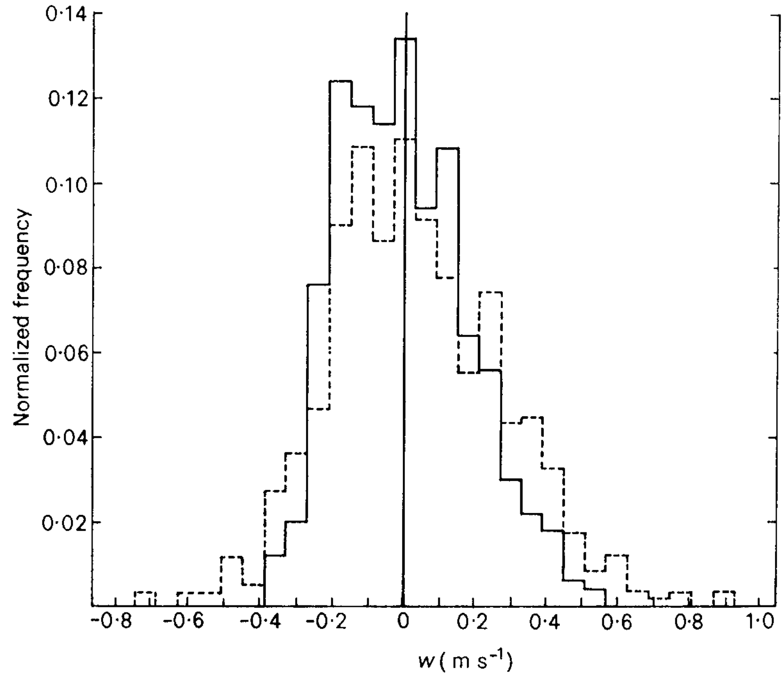

Figure 2. Histograms of the vertical component of the wind velocity (w) for the two areas of sea measured at a height of 30 m above sea level.
- - - - - warmer water, 580 samples ——— cooler water, 500 samples

Reviews

Geophysical fluid dynamics, by J. Pedlosky. 240 mm × 160 mm, pp. xii + 624, *illus.* Springer-Verlag, Berlin, Heidelberg, New York, 1979. Price DM 79·50, US $43·80.

Fluid dynamical phenomena abound in the outer layers and interiors of planets and stars. The observational evidence takes very many forms and only in the case of phenomena occurring at or near the Earth's surface, including those with which meteorologists and oceanographers are concerned, have detailed direct observations of flow velocities, pressure, etc. been made over useful periods of time. The term 'geophysical fluid dynamics', which was coined about a quarter of a century ago, has no precise definition, but in its widest sense it is a useful label for the study of basic hydrodynamic (and magnetohydrodynamic) processes underlying fluid dynamical phenomena encountered in the study of planets and stars, including Earth and Sun, as elucidated by theoretical investigations and related laboratory and numerical work. Geophysical fluid dynamics laboratories are now found in many institutions and the use of the prefix 'geo' when objects other than the Earth are involved bothers only the pedants (cf. geometry!).

Good books with misleading or ambiguous titles (e.g. 'Sound reproduction', 'Earth') are not uncommon and this may be one of them. But the title 'Geophysical fluid dynamics' is certainly shorter and more voguish and eyecatching than 'Some carefully worked mathematical problems in the study of rotating stratified fluids for graduate students with an interest in large-scale motions in the Earth's atmosphere and oceans', which more accurately describes the main contents of this valuable contribution to the literature by a leading worker. The first chapter is a short one giving a good account of the standard basic dynamic and thermodynamic equations governing the flow of a rotating stratified fluid and introducing basic parameters such as the Rossby (or Kibel) number and the Rossby (or Prandtl) radius of deformation. This is followed by another short chapter presenting several standard theorems governing vorticity, circulation (Kelvin), potential vorticity (Ertel) and relationships governing geostrophic flow (Taylor–Proudman theorem, thermal-wind equation). The rest of the book, apart from a bibliography and index, comprises six long chapters averaging 80 pages in length. The first of these, Chapter 3, entitled 'Inviscid shallow-water theory', considers several types of small-amplitude wave motion, including the well-known Poincaré, Kelvin and Rossby waves, introduces Rossby's useful 'beta-plane' for simplifying the equations governing motions on a sphere and discusses resonant interactions associated with weak non-linearity. Dissipative effects enter for the first time in Chapter 4 ('Friction and viscous flow'), which gives the theory of the Ekman boundary layer, including the important process of boundary-layer suction, and considers applications to 'spin-down' and other processes in homogeneous fluids involving frictionally induced changes in potential vorticity as well as the decay of Rossby waves and the structure of side-wall boundary layers when non-linear effects are negligible (Stewartson layers). The southward Sverdrup drift in simplest 'beta-plane' models of the wind-driven circulation of the oceans (in which density variations are neglected) is associated with Ekman suction at the surface. The return flow occurs in a highly ageostrophic western boundary current reminiscent of the Gulf Stream in the Atlantic Ocean and the Kuroshio Current in the Pacific Ocean; Chapter 5 presents a systematic treatment of the original theoretical model of this phenomenon, due to Stommel in 1948, and of the many subsequent variations on that theme, including some numerical studies.

Chapter 6 entitled 'Quasi-geostrophic motion of a stratified fluid on a sphere' treats a variety of problems bearing on dynamical meteorology and oceanography, including Rossby waves in a stratified fluid, forced stationary waves in the terrestrial atmosphere, theorems governing interactions between waves and zonal flows and the structure of the ocean thermocline. 'Instability theory' is considered in some detail in Chapter 7, where the mathematical analysis of incipient baroclinic waves in continuous systems (Eady and Charney) and two-layer systems (Phillips) is given and some effects due to friction and non-linearity are also discussed. Chapter 8, the final chapter, treats 'Ageostrophic motion', including continental-shelf waves, theory of frontogenesis and waves in equatorial regions.

The publisher's claim that this book 'offers a clear and logical contribution to understanding geophysical fluid dynamics' is, in this reviewer's opinion, justified; but only when it is read in conjunction with other important material more closely linked with observations and experiments can the book provide 'students and scientists with the necessary background for understanding and pursuing research in oceanography and meteorology'.

R. Hide

Man's impact on climate. Proceedings of an International Conference held in Berlin, June 14–16 1978. (Developments in Atmospheric Science, Vol. 10), edited by Wilfrid Bach, Jürgen Pankrath and William Kellogg. 245 mm × 170 mm, pp. xxiv + 328, *illus.* Elsevier Scientific Publishing Company, Amsterdam and New York, 1978. Price US $53·25, Dfl 120.00.

This book comprises the proceedings of an international conference held in Berlin in June 1978. The conference was organized by the Federal Environmental Agency of the Federal Republic of Germany to 'document its interest in pressing world problems universally affecting the world community'. It is not surprising therefore that most of the contributors are working in German research institutions.

A summary of the conclusions and recommendations of the conference, including a set of principles for assessing climate impact programs, precedes the main text. This is followed by Part I, 'Climate history, theory and modelling'. It includes interesting contributions from Hasselmann, on the problems of multiple time-scales in climate modelling, and from Wetherald and Manabe, on the sensitivity of a general circulation model with a simple interactive cloud scheme to changes in CO_2 concentration. Part II, 'Mechanisms of Man's impact', considers man-made changes to the gaseous and particulate composition of the atmosphere, and their impact on climate. It also includes papers by Egger and by Jill Williams which assess the effect of waste heat from energy parks on the circulation of the atmosphere. The final section (Part III), 'Potential consequences and the future climate', is concerned mainly with the effect of future energy policies on atmospheric carbon dioxide concentrations, and thence on climate.

All the papers are in English, and have been reproduced using a photographic process. The text and diagrams are clear, though some of the printing is extremely fine, and the labelling on several of the diagrams is microscopic. There are other minor flaws; for example the paper by Eiden on the influence of trace substances was produced on a typewriter with the zero key missing (a lower case letter 'O' is used instead), and Grassl's paper on aerosol particles and changes in planetary albedo includes diagrams which are labelled in German.

This is not a book for the reader with only a casual interest in man's impact on climate. As befits the proceedings of a conference, the topics covered are diverse and most of the papers are technical, and there are other texts which provide a more coherent and readable introduction to the subject. However, some of the contributions, such as those by Flohn (past warm climates), by Zimen and by Hampicke (on the carbon cycle), and by Rotty and by Niehaus (on energy demand and carbon dioxide concentrations), are reasonably digestible and can be recommended as more general reading. There is little that is new to interest the specialist. At best it provides a useful review of various aspects of the subject to date, but at about £30, it is a book to borrow rather than to buy.

J. F. B. Mitchell

Notes and news

Kew Observatory

It has been decided with great regret that, as a contribution towards the staff cuts required by the Government, the Meteorological Office station at Kew Observatory will close at the end of this year. The history of the Observatory is recorded in articles in the issues of the *Meteorological Magazine* dated June and July 1969. Since then the National Radiation Centre has been moved from Kew to Beaufort Park and the work at the Observatory has consisted of synoptic and climatological observations, a few specialist measurements (such as atmospheric electricity, evaporation, soil temperature and air pollution) and instrument evaluation. The greatest loss will, of course, be the termination of a climatological record going back over 200 years. Fortunately, the Director of the Royal Botanic Gardens at Kew has kindly agreed to maintain a climatological station, and observations started there on 1 March 1980. Thus climatological records will be continued in the same area.

Retirement of Mr Alan Ward

Mr Alan Ward, Chief Meteorological Officer, London (Heathrow) Airport, retired from the Meteorological Office on 3 May 1980 at the end of a meteorological career spanning 42 years.

Alan Ward joined the Office as an Assistant Grade III in May 1938 following an education in science subjects at the Holywell County School, Wales. After service at aerodromes in eastern England he was selected in 1942 for training as a forecaster and posted to Dyce, near Aberdeen. Promotion to Assistant Grade II at the end of 1942 and commissioning in the Royal Air Force Volunteer Reserve as Pilot Officer in April 1943 led to several further short-lived postings to aerodromes in Britain in locations extending from Scotland to Devon. In the course of these he was promoted to Flying Officer.

In September 1944, Mr Ward was sent as a forecaster to Gibraltar where further promotions to Assistant Grade I and Flight Lieutenant soon followed. He remained at Gibraltar until 1953 with a short break in 1947 for demobilization and reappointment in the new post-reconstruction grade of Experimental Officer. During this period he became expert in dealing with the peculiarly difficult problems associated with the rock and its environs, writing about them in several reports and articles, some of which were published in the *Meteorological Magazine*. These dealt with such diverse topics as sea-breezes, fog, stratus, the flow around the rock, the use of upper-air patterns in forecasting, orographic cirrus and the Blue Sun phenomenon.

Back in England from 1953 Alan Ward pursued his forecasting career at London (Heathrow) Airport, where he was promoted in 1955 to Senior Experimental Officer, and at the Headquarters, Bomber Command, High Wycombe, where in January 1961 he became a Chief Experimental Officer. Soon after, he was appointed to Headquarters, 38 Group at Royal Air Force, Odiham, where he was responsible for setting up and leading a small mobile forecasting team able to go into the field at short notice according to current military need. His close association with the Royal Air Force continued during service as Senior Meteorological Officer in charge of the Main Meteorological Office at Changi in Singapore from 1963 to 1966, a period in that area of some tension which resulted from the policy of confrontation with Malaysia of President Soekarno of Indonesia. Alan Ward's experience and personal qualities fitted him very well for his next appointment as Chief Meteorological Officer of SHAPE on secondment during 1966–69 to NATO. In this post he was commissioned as Group Captain.

In July 1969 Mr Ward's career took an abrupt change of direction when he was selected to lead the non-aviation public service work in this country as Head of Met 0 7a. He filled this post with distinction, his administrative skills, shrewd judgement, clear direction and powers of negotiation all being deployed to best effect. He was largely responsible for the preparation of the *Public Service Handbook* which encapsulated the wealth of procedure and regulations arising in the development of the diverse services provided by the Office for industry, commerce and the general public.

The peak of Alan Ward's career was reached in March 1976 when he became Chief Meteorological Officer at London (Heathrow) Airport on promotion to Senior Principal Scientific Officer. In this post he has been required to steer the Principal Forecasting Office through a difficult and unsettling period. This has involved the planning for a move of the Office with its complex organizational and communications problems and increasing degrees of automation while experiencing constant pressure for economies of both cost and manning.

Alan Ward is one of a large number for whom the Office has unwittingly played matchmaker, having met his wife Margaret during an overseas tour in Gibraltar. Alan and Margaret have contributed much to the social life and the welfare of the offices and communities in which they have found themselves and the writer, amongst many, will remember them for past kindnesses. We wish them a very long and enjoyable retirement; they both plan to be active, with two of their four children yet to complete their education, and to remain at their home in Ascot.

D. H. Johnson

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'.

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