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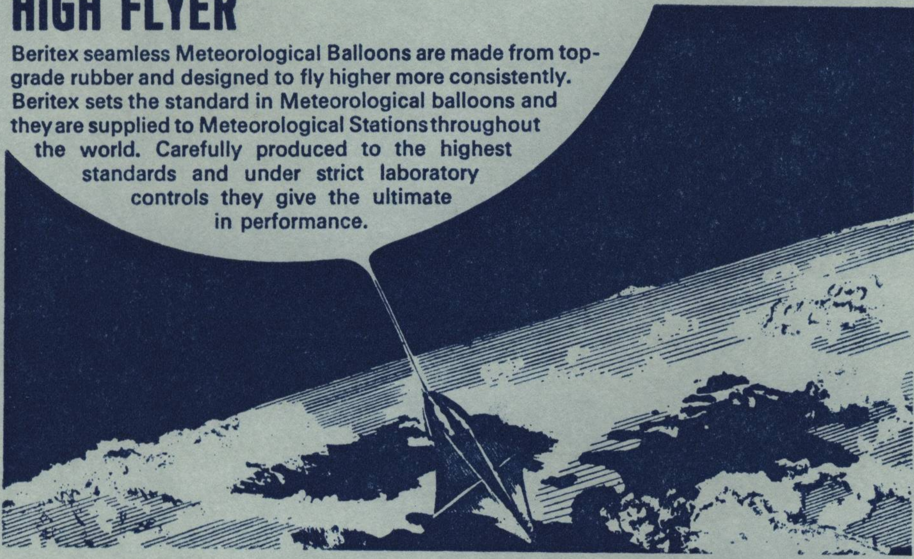

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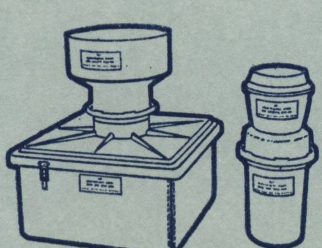

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VARIATIONS IN NIGHT MINIMUM TEMPERATURES PECULIAR TO A VALLEY IN MID-KENT

By A. A. HARRISON

Introduction.—Lawrence[1] has described an investigation into the variation of night minimum temperatures in a hilly district during a radiation night. He found that in the vicinity of Aldenham Reservoir (near Watford) the average increase of temperature with height was of the order of 1 – 2 degF per 100 ft but he also gave examples of very much higher values over short distances, e.g. over a 75 ft height range he found a mean rate of increase of 4½ degF per 100 ft and elsewhere in the area 2½ degF per 100 ft over a height range of 160 ft. In another survey at Much Birch (Herefordshire) Lawrence[2] gave a value of 5 degF per 100 ft. In Champagne, Geslin and others[3] recorded up to approximately 8 degF per 100 ft, though this was over a height of only 16 m (52 ft). Lawrence also derived regression equations relating night minimum temperatures and the height above MSL on radiation nights.

Since a difference of only ½ degF in the average minimum temperature is associated with a significant difference in frost liability,[4] the magnitude of the figures quoted above is quite substantial. Furthermore, in a fruit growing area such as Kent, only a single unexpected late-spring frost is needed to ruin a year's crop.

It is felt, however, that a simple height/temperature correlation can be masked by many variables such as the slope of the ground at right angles to the general direction of a traverse, the incidence of built-up settlements and whether or not there is an effective run-off of the cold air from the area under survey. In other words, if one is to come to grips with the thermal characteristics of a region it must be treated on its own merits.

Survey area.—The area of this survey is situated to the south of Maidstone, Kent, between the Ragstone Ridge in the north and the Forest Ridges in the south. Traverses were made from a point some 1000 yd south of Loose (National grid reference TQ 756508), to a point the same distance east of Goudhurst (National grid reference TQ 732378), passing through the village of Marden *en route*. Tonbridge lies to the west and Staplehurst and Headcorn to the east.

Figure 1 shows the contours of the area and Figure 2 the profile of the route taken. In both figures the sequence of numbers 1 to 23 marks the points of observation.

The route, shown as a dotted line in Figure 1, was planned to avoid built-up areas as much as possible, with the one exception of Marden, a small village with a population of 3500 approximately.

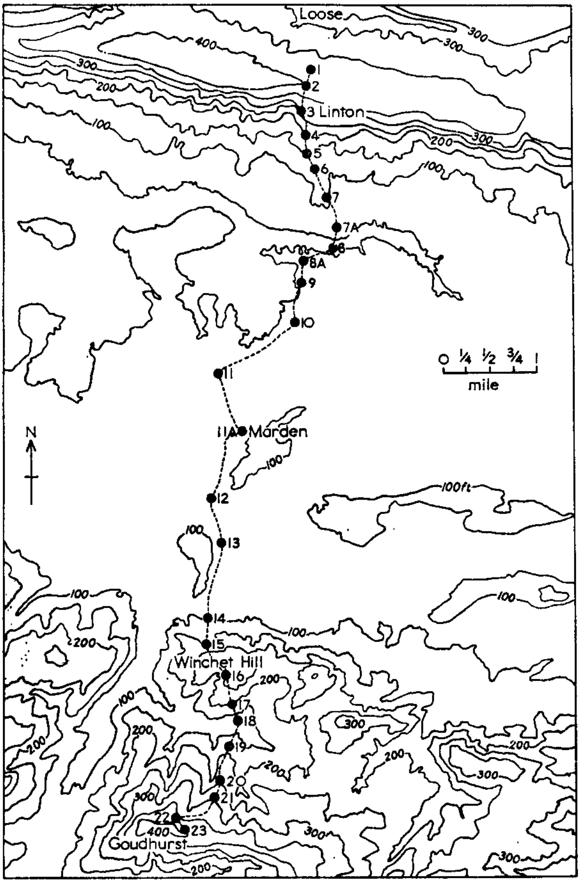

FIGURE 1—MAP SHOWING CONTOURS OF THE SURVEY AREA

Contours are drawn at 50-ft intervals.

All the temperatures were read over a metalled road surface but care was taken to site the observation points in open spaces away from overhanging trees and adjacent high hedges. Much of the land on either side of the road was arable and the road did not pass through any densely wooded areas. There were several orchards near the road but the trees in these were well separated and of no great height.

Instruments.—The instrument used was a balanced-bridge platinum resistance thermometer Mk III attached to the front bumper of a car by an aluminium strut and exposed at a height of 4 ft above the ground.

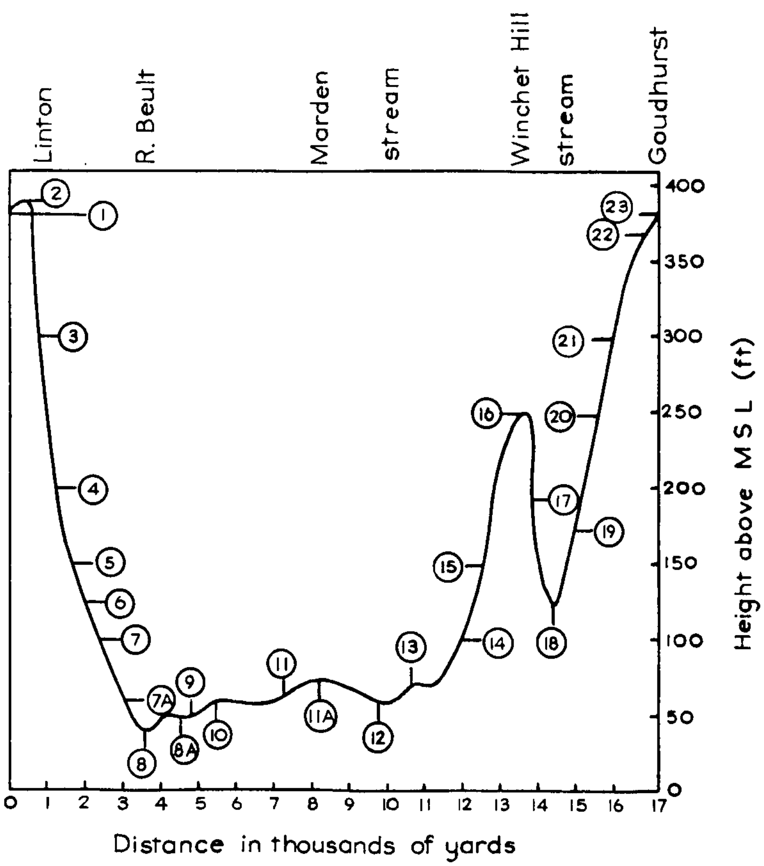

FIGURE 2—PROFILE OF ROUTE

Before the survey was started, comparisons were made with a normal screen thermometer at West Malling and short closed traverses were carried out to determine whether heat from the engine had any effect on the thermometer. It was found that variations in speed and the length of time the engine had been running made no difference to the temperature whatsoever. During 'operational' runs there were a few occasions on which 1 to 2 minutes had to be allowed after reaching an observation point, for the thermometer to react to a dramatic drop in temperature; but it was also noticed that sometimes if the pause was too long, the temperature rose by about 0·3 degC. It is thought that this rise in temperature was due to exhaust gases being wafted over the sensing element of the thermometer (at the front of the car), since it invariably occurred when the car was pointing down hill and the wind was sufficiently light for the katabatic component to be dominant. When this effect was apparent, readings were taken continuously for 2 minutes and the lowest value was accepted.

Technique.—The method used was similar to that employed by Lawrence and also by Chandler in his earlier studies of the climate of London.

The route was covered twice, once in each direction, the car being held stationary for up to 2 minutes at each point of observation while the temperature was read. Thus two readings were taken at each point, one on the outward leg and one on the return leg. Assuming the time taken to cover each leg was the same and that the temperature change at each observation point was linear during the interval between the readings at each point, the mean of each pair of readings gave an indication of the variation of temperature over the whole route at the time the outward leg was completed and the return leg was commenced.

These temperatures do not correspond exactly to night minima; the whole exercise took about 2¾ hours and had to be completed before sunrise to avoid complications due to direct radiation from the sun; but they do give some indication of the surface thermal pattern shortly before the time night minima are normally reached, and for the purpose of this article these late night temperatures are assumed to be the equivalent of night minima.

Results.—Twelve sorties were made during the period 11 May 1965 to 20 September 1966. Six proved to be uncomplicated radiation nights and the results are given in Table I.

Figure 3, giving the average mean temperature at each position on radiation nights, shows the temperature/height relationship. There is broad similarity between the temperature profile and the height profile except at position 11A, 75 ft above MSL. The average mean temperature at this position is quite

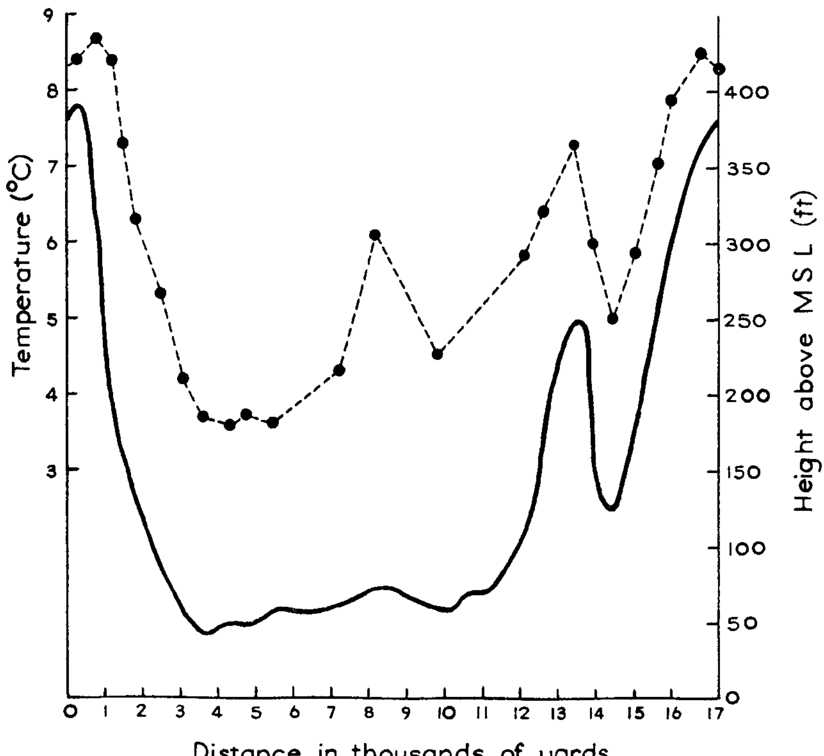

FIGURE 3—AVERAGE TEMPERATURES ON RADIATION NIGHTS
——— Profile
.— —. Temperature

TABLE I—TABULATION OF RESULTS ON RADIATION NIGHTS

Position number	1	2	3	4	5	6	7	7A	8	8A	9	10	11
Height above MSL	380	390	300	200	150	125	100	60	40	50	50	60	60
Date						*degrees Celsius*							
11 May 1965	6·2	6·2	6·3	6·2	5·9	5·5	4·6	3·7	3·0	2·7	2·6	2·7	2·9
5 Oct. 1965	12·6	12·7	13·1	12·3	9·9	8·3	7·0	6·6	6·8	6·8	6·8	7·0	7·4
28 Apr. 1966	6·7	6·5	6·4	6·1	5·3	4·7	4·7	3·1	2·3	2·9	3·3	2·3	4·3
4 May 1966	7·9	7·9	7·9	7·7	6·9	5·9	4·7	4·1	3·3	3·1	3·3	3·5	3·7
19 May 1966	7·0	7·0	7·1	6·8	6·7	6·3	5·3	3·5	3·0	2·5	2·5	2·3	2·7
20 Sept. 1966	9·7	10·1	11·3	11·3	9·3	7·0	5·4	4·4	3·9	3·5	3·6	3·7	4·9

Position number	11A	12	13	14	15	16	17	18	19	20	21	22	23
Height above MSL	75	60	70	100	150	250	200	120	175	250	300	370	380
Date							*degrees Celsius*						
11 May 1965	—	3·1	3·0	3·6	4·4	5·3	4·3	3·5	4·1	5·1	5·7	5·9	6·3
5 Oct. 1965	8·0	7·7	7·7	7·5	7·7	10·3	8·2	6·8	7·3	9·0	11·4	13·0	12·6
28 Apr. 1966	5·0	2·6	4·5	6·1	6·3	6·5	5·1	4·1	5·7	6·5	6·7	6·8	6·7
4 May 1966	6·5	4·5	4·5	5·9	6·7	7·1	5·9	4·9	6·5	7·4	7·8	7·7	7·1
19 May 1966	4·9	3·5	4·5	5·5	6·3	6·7	6·0	4·4	6·1	7·1	7·3	7·3	7·2
20 Sept. 1966	6·3	5·7	5·7	6·1	7·0	8·0	6·3	6·1	—	7·7	8·7	10·1	9·9

disproportional to its altitude. However, position 11A is in the village of Marden, the only urban area on the route, and Chandler[5] in one of his reports on London's climate observed '...... there is no simple, certainly no linear relationship between the extent of an urban area and the intensity of its heat island ...... one can imagine a small settlement, probably no more than a hamlet, warmer by several degrees than its rural setting'.

Temperatures from Figure 3 are plotted against a linear height scale in the scatter diagram comprising Figure 4. It has been well established by Geiger and others,[6] that in general the sides of valleys are warmer at night than both the valley floor and the plateaux on either side. It is not surprising,

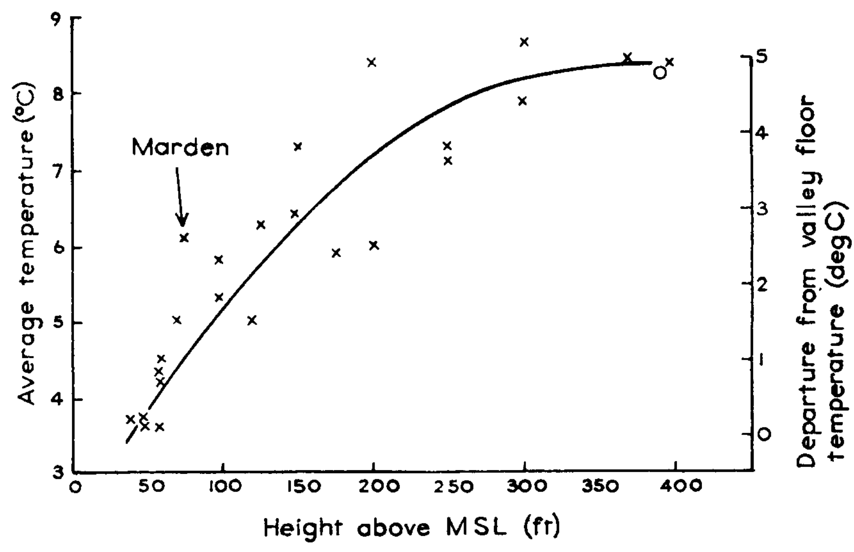

FIGURE 4—TEMPERATURE/HEIGHT CORRELATION ON RADIATION NIGHTS

o denotes two readings

Marden value ignored.

therefore, that this graph is not linear and that the rate of increase of temperature with height decreases as the highest points are approached. Nevertheless, a linear interpolation of the section between 40 ft and 220 ft gives the following regression equation :

$$T = 0{\cdot}022H + 2{\cdot}81 \text{ (degrees Celsius)}$$
$$\text{or } T = 0{\cdot}41H + 37{\cdot}0 \text{ (degrees Fahrenheit)}$$

where T = temperature and H = height in feet.

(The graph shown in Figure 4 could be put to practical use since it gives departures of night minima up the sides of the valley from those on the valley floor — see ordinate on right.)

The most rewarding traverse was that made on 5 October 1965 (Figure 5). The night was calm and clear, though there were some shallow fog patches

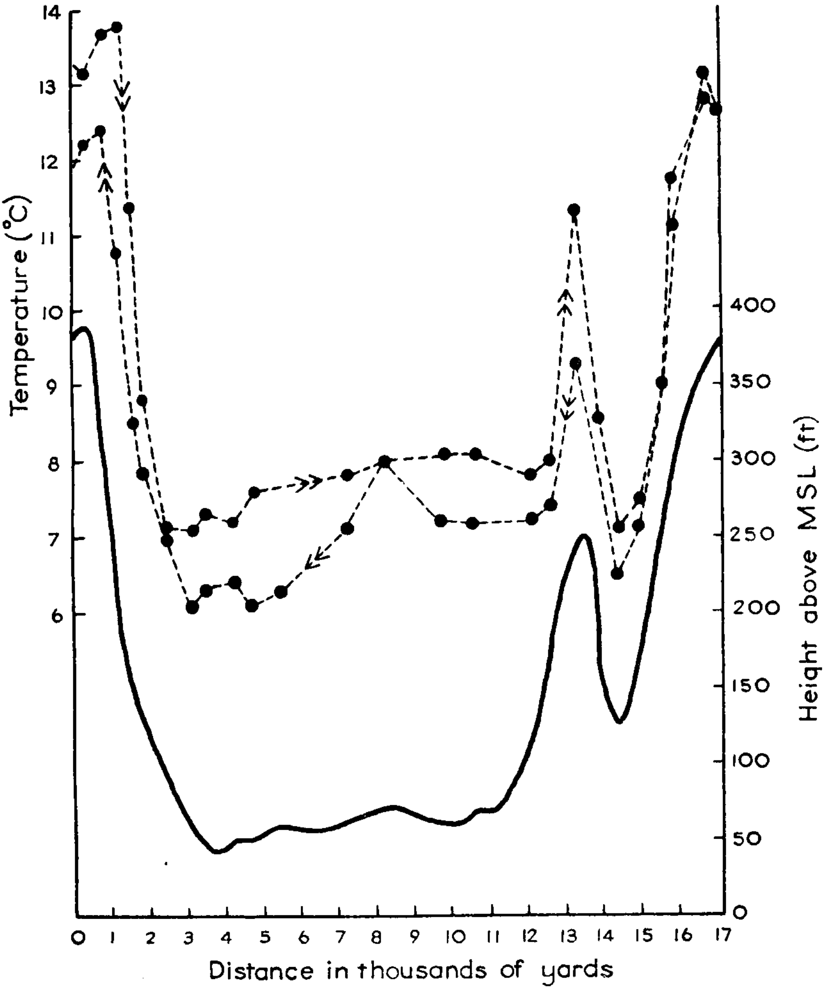

FIGURE 5—TEMPERATURE TRAVERSE MADE ON 5 OCTOBER 1965
——— Profile •— —• Temperature
Actual inward and outward temperatures
Arrows show direction of traverse.

at the bottom of the valley. A high pressure area was centred over southern Scandinavia and a shallow depression covered the Bay of Biscay.

The lowest temperature reached was 6·1°C at positions 7A and 9 on the return leg which compares with minima of 8·4°C at West Malling (304 ft, 5 miles west-north-west of Loose) and 6·6°C at East Malling (122 ft, 4 miles north-west of Loose). Temperatures taken on the traverse at the same altitude as East Malling and West Malling and for the same time are compared with the corrected thermograph readings from these stations in Table II.

TABLE II—COMPARISON OF TRAVERSE TEMPERATURES WITH SCREEN TEMPERATURES AT WEST MALLING AND EAST MALLING ON 5 OCTOBER 1965

Time	West Malling 304 ft		On traverse at same height		Time	East Malling 122 ft		On traverse at same height	
GMT	°C	°F	°C	°F	GMT	°C	°F	°C	°F
0310	11·0	51·8	11·2	52·1	0317	8·3	47	8·6	47·5
0409	11·5	52·7	11·1	52·0	0344	7·8	46	7·9	46·3
0510	11·5	52·7	11·7	53·1	0510	7·2	45	7·3	45·1
0556	10·1	50·1	8·5	47·3	0549	7·8	46	7·8	46·1

It is interesting to note that between positions 4 and 6 (see Figure 5) the mean temperature increased with height at the rate of 5·3 degC (9·5 degF) per 100 ft (over 50 ft) and that between positions 20 and 21 the rate was 4·8 degC (8·6 degF) per 100 ft (over 75 ft). Both these rates exceed the one obtained by Geslin in France. Noteworthy rates of increase of temperature with height on other nights are as follows:

5·2 degC (9·4 degF) per 100 ft over 150 ft on 20 September 1966,
4·3 degC (7·7 degF) per 100 ft over 65 ft on 19 May 1966,
and 3·7 degC (6·7 degF) per 100 ft over 75 ft on 28 April 1966.

The average rate on all occasions between positions 4 and 8A (see Figure 3) was 3·2 degC (5·8 degF) per 100 ft over 150 ft.

The traverses made on nights when radiation was decreased by such factors as wind, cloud, fog and high humidity are not without interest.

On 25 August 1965 a survey was made in good visibility and under cloudless skies but with moderate to fresh north-westerly winds (at West Malling they varied between 20 kt at midnight and 10 kt at 0500 GMT).

The variations of temperature with height were considerably reduced. The thermal peak often found at the village of Marden was lacking, but this is not surprising since Chandler[7] found the heat island of an urban area as vast as London is entirely eliminated by wind speeds greater than 22 kt and Kratzer[8] has given a figure of 16 kt for this at Bremen and Parry[9] one between 8 and 13 kt for Reading.

The traverse on 5 November 1965 was carried out beneath low stratus cloud. The cloud was, however, very thin. While West Malling (304 ft above MSL) reported 4 oktas, base 300 ft, at midnight and fog with sky obscured at 0300 GMT, over the survey route only a slight overall milkiness in the sky indicated that cloud was present and the stars were discernible most of the time. It was not until position 9 on the return leg was reached, when dawn was breaking, that the features of any cloud could be seen and of this there was no more than 2 oktas. It was misty over high ground but clear in the valley. Nevertheless, temperatures remained almost uniform, varying only between 3·4° C (38·2° F) and 4·0° C (39·2° F).

Close examination of the actual (inward and outward) temperatures shows that during the period of the traverse the air cooled slightly more over the ridges than in the valley. It is suggested that the surface layer of relatively moist air (usual in anticyclones), absorbing some of the long-wave radiation from the ground, had a uniform upper surface and was also so shallow that the valley floor had a significantly greater amount of water vapour above it than the ridges and a consequently lower rate of cooling. It would seem that a complete coverage of low stratus cloud was not needed to render the height and urban/rural temperature contrasts insignificant; patches of very thin low stratus were quite sufficient.

The sortie attempted on 14 October 1965 was curtailed at the midway point owing to very bad visibility. Mist had thickened into fog late the previous evening and by 0300 GMT Gatwick and West Malling were both reporting visibility 50 yd and sky obscured. On the outward journey there was a marked increase of temperature with height but on the return leg the temperature curve had become much flatter. Furthermore, over most of the route, temperatures were higher on the return leg than on the outward leg, i.e. temperatures had increased with time. The thermograph at East Malling showed a marked rise in temperature starting at 0100 GMT.

While advection may have played some part in causing this rise in temperature, it is unlikely to have been the sole cause.

In their description of the life history of a typical radiation fog, Johnson and Heywood[10] observed that late in the night fog became dense enough to stop an appreciable fraction of the outgoing radiation and towards dawn, when the effective radiating surface had risen from the ground to the upper portion of the fog, the temperature at the surface rose fairly steadily, the rate of increase reaching 2 degF per hour at times. The movement of the effective radiating surface upwards would also explain, to some extent, the flattening of the traverse temperature graph.

On 19 October 1965 an anticyclone dominated south-east England. No fog or cloud, apart from 2 oktas at Manston, was reported south of the Thames estuary. The wind at West Malling was a mere 5 kt from between east and north-east. In the north of the survey route, however, there were somewhat higher dew-points in the surface layers. In consequence temperatures were almost constant in the north of the traverse although the south of the traverse showed the marked variation with height normal on uncomplicated radiation nights.

Conclusions.—On radiation nights, the average increase of temperature with height in this part of Kent is of the order of 1·5 degC (2·7 degF) per 100 ft; but over the lower slopes of the valley surveyed the average is a little more than 3 degC (5.4 degF) per 100 ft. Over short height ranges (between 50 and 150 ft), rates exceeding 5 degC (9 degF) per 100 ft are not uncommon. Wind and high humidity in the lowest few hundred feet, with or without cloud, are very effective agents in preventing these contrasts.

Acknowledgements.—The author wishes to thank Mr G. F. Trowell, Mr G. H. Parker and Miss A. M. Davis for their help.

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AIR TEMPERATURE AT DALLOL, ETHIOPIA

By D. E. PEDGLEY
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This note presents some records of air temperature measured in recent years at Dallol in Ethiopia. Dallol is situated at 14°19′N 40°11′E in north-eastern Ethiopia on the edge of the Danakil Depression (Figure 1), an extensive

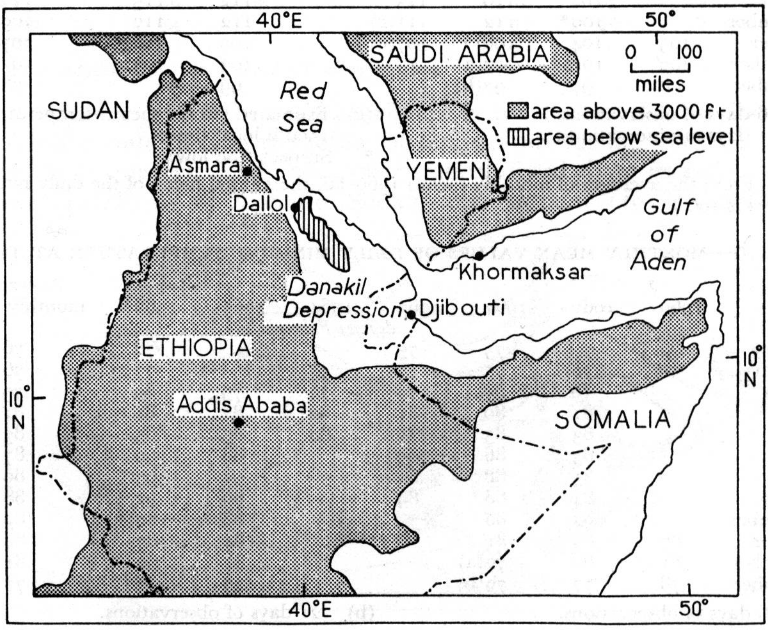

FIGURE 1—MAP SHOWING THE LOCATION OF DALLOL

region below sea level, between the Ethiopian plateau to the west and the southern Red Sea to the east. The lowest part of the depression is a region of salt and gypsum deposits, devoid of vegetation, and with an almost level surface reaching a minimum elevation of about 390 ft below sea level.

Since 1960 the Ralph M. Parsons Company, a prospecting company from the U.S.A., has maintained a climatological station at their base camp, situated at the summit of a rounded salt dome, about half a mile wide, rising out of the salt desert. The altitude of this site is minus 258 ft. Maximum and minimum temperatures have been recorded using standard thermometers kept at a height of four feet in a ventilated screen. Whilst some daily readings were taken to the nearest tenth of a degree Fahrenheit, the majority were to the nearest whole degree. Tables I to IV show monthly means and extremes of daily maximum and minimum temperatures. Gaps in the record occur where the station was inoperative or where records were not available. Although the maximum periods giving monthly values for any one month is only six years, there are enough observations available to illustrate the exceptionally high temperatures characteristic of Dallol.

TABLE I—MONTHLY MEAN VALUES OF DAILY MAXIMUM TEMPERATURE AT DALLOL

	1960	1961	1962	1963	1964	1965	1966	Average of monthly means
					degrees Fahrenheit			
January		98	96	95			99	97
February		97	99	99			95	97
March		101	104	103	102	103	101	102
April		106	108	104	105	103	106	105
May		116	112	108	109	112	114	112
June		115	116	115		115	117	116
July		110	115	113		115	117	114
August		107	110	113		112	115	113
September		100*	112	111(c)		112	112	109
October	105	104	106	107(c)		109	108	107
November	102	102	103(a)			103	103	103
December	98	97	97(b)			99		98

(a) 16 days of observations.
(b) 21 days of observations.
(c) Estimated from mean temperatures at 1500 h local time.
* Suspect (too low).

Note : From the averages of monthly means 1960–66, the annual mean of the daily maximum is 106°F.

TABLE II—MONTHLY MEAN VALUES OF DAILY MINIMUM TEMPERATURE AT DALLOL

	1960	1961	1962	1963	1964	1965	1966	Average of monthly means
					degrees Fahrenheit			
January		77	75	75			78	76
February		76	75	77			77	76
March		78	79	79	78	79	80	79
April		81	80	81	80	82	81	81
May		83	85	82	80	85	85	83
June		85	86	85		88	90	87
July		85	88	89		91	93	89
August		84	86	89		89	92	88
September		92	86			88	89	89
October	87	89	81			84	87	86
November	81	80	79(a)			82	82	81
December	78	77	79(b)			79		77

(a) 16 days of observations. (b) 21 days of observations.

Note : From the averages of monthly means 1960–66, the annual mean of the daily minimum is 83°F.

TABLE III—MONTHLY EXTREMES OF DAILY MAXIMUM TEMPERATURE AND MEAN OF MONTHLY EXTREMES AT DALLOL

	1960	1961	1962	1963	1964	1965	1966	Mean of monthly extremes	Highest observed maximum
					degrees Fahrenheit				
January		102	102	100			103	102	103
February		103	107	104			104	105	107
March		110	118	111	111	110	110	112	118
April		113	114	114	115	112	114	114	115
May		119	120	116	113	119	114	117	120*
June		118	118	117		119	119	118	119
July		117	117	118		118	120	118	120*
August		115	117	117		117	119	117	119
September		110	116			115	119	115	119
October	109	115	114			109	112	112	115
November	106	112				106	108	108	112
December	101	101				105		102	105

* Absolute maximum over period of observations.

TABLE IV—MONTHLY EXTREMES OF DAILY MINIMUM TEMPERATURE AND MEAN OF MONTHLY EXTREMES AT DALLOL

	1960	1961	1962	1963	1964	1965	1966	Mean of monthly extremes	Lowest observed minimum
					degrees Fahrenheit				
January		74	72	73			75	74	72
February		71	73	74			71	72	71
March		75	70	76	73	75	76	74	70
April		75	69	70	70	78	72	73	69*
May		80	80	74	75	82	81	79	74
June		80	83	77		85	85	82	77
July		73	86	85		84	86	83	73
August		75	73	86		80	86	80	73
September		84	83			85	81	83	81
October		80	79			79	83	80	79
November	77	74				77	78	76	74
December	75	73				77		74	73

* Absolute minimum over period of observations.

The annual mean of the daily maximum is 106°F, four degrees above the highest value published in the tables of temperature for the world[1] of 102°F, at Abéché (Figure 2). Only two other stations listed there exceeded 100°F: Merowe (101°F) at 18°N in the Sudan, and Araoune (101°F) at 19°N in

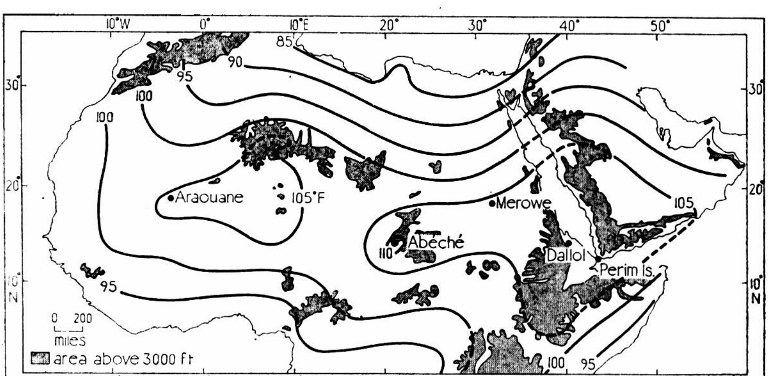

FIGURE 2—DISTRIBUTION OF ANNUAL MEAN DAILY MAXIMUM TEMPERATURE
Temperatures are adjusted to sea level using a lapse rate of 5·4 degF per 1000 ft.

Mali. The mean maximum at Dallol is so high not because the hottest months are particularly hot but because the coolest months are so warm. Over a wide part of northern Africa, for example, many places have temperatures in their hottest months comparable to those at Dallol, but their coolest months are commonly cooler by 5–10 degF. The annual mean of the daily minimum is 83°F; the same tables give only one place with the mean minimum exceeding 80°F, namely Perim Island (81°F) at 13°N in the southern entrance to the Red Sea.

Table III shows that at Dallol, unlike the other three places, the mean *monthly* maximum temperature (mean of the extreme daily maximum in the month) exceeds 100°F in all months. In fact, no month is tabulated without at least one day reaching 100°F, even January and February, the coolest months. The fact that the mean *monthly* maximum is generally only 4–5 degF higher than the corresponding mean *daily* maximum suggests that daily maxima occupy a narrow range of values in any one month. June shows the smallest difference (2 degF). In this month both day-to-day and month-to-month changes of temperature are small. The narrow range within which June daily maxima are confined is illustrated by Table V which gives the number of days, during June 1965 and 1966, that had particular values of the maximum. The mean for the 60 days in these two months was 116°F; 36 days had 115–117°F; 48 days had 114–118°F. On the other hand, March shows the largest difference (10 degF). In this month, both day-to day and month-to-month changes are large. Table V also shows the distribution of daily maxima during March 1965 and 1966. The mean for the 62 days was 102°F; 12 days had 101–103°F; 22 days had 100–104°F; and 35 days had 99–105°F.

TABLE V—DISTRIBUTION OF DAILY VALUES OF MAXIMUM TEMPERATURE DURING JUNE AND MARCH, 1965 AND 1966, AT DALLOL

	June 1965 and 1966											
Maximum temperature °C :	108	109	110	111	112	113	114	115	116	117	118	119
Number of days :	1	0	0	1	1	4	7	12	10	14	5	5
	March 1965 and 1966											
Maximum temperature °C :	89	90	91	92	93	94	95	96	97	98	99	100
Number of days :	1	1	2	1	1	1	2	0	1	1	3	8
Maximum temperature °C :	101	102	103	104	105	106	107	108	109	110		
Number of days :	4	4	5	2	10	6	1	5	0	3		

Allowing for topographic and coastal effects, the highest *annual* means of daily maximum temperature occur along an approximately zonal belt across northern Africa and southern Asia. Over northern Africa, they lie between about 12° and 20°N. At somewhat higher latitudes, although mean maxima during the hottest months are comparable to those between 12° and 20°N, the lower temperatures of the coolest (winter) months reduce the value of the annual mean. Correspondingly, at somewhat lower latitudes, it is the coolness of the equatorial westerlies during the middle of the year that reduces the mean. Over southern Asia, mean daily maxima during the hottest months ('pre-monsoon') are comparable to those over Africa, although again the lower temperatures of the coolest months reduce the annual mean. Over the Arabian peninsula the annual means are probably similar to those of northern Africa.

The highest annual means of the daily maximum temperatures are to be expected in low-lying places, away from coasts, and within the latitude belt, 12° to 20°N across Africa, and possibly also in the south-western part of the Arabian peninsula. Figure 2 gives the distribution of the annual mean over those parts of northern Africa and the Arabian peninsula lying below the 3000-ft contour, based on data from the tables.[1] Temperatures have been adjusted to sea level using the dry adiabatic lapse rate of 5·4 degF per 1000 ft. The dry adiabatic lapse rate was used for adjustment of temperatures to obtain an approximation to the field of annual mean daily maximum ***potential*** temperature. Thus, for Dallol the adjusted temperature is 105 degF. The map shows two areas with adjusted temperatures above 105°F: one over the western Sahara, and the other over north-eastern Africa and south-western Arabia. Over the southern part of the Arabian peninsula the isotherms are very tentative and, in the absence of published data from the Rub al Khali, are based on extrapolation from neighbouring regions. Isotherms have been drawn continuous across the Red Sea, thus eliminating the cooling effect of the sea on temperatures measured at coastal stations, where annual means range from 92°F in the south to 82°F in the north.

It is clear that Dallol lies near the centre of the large eastern region where adjusted temperatures are above 105°F. A temperature of 108-110°F might reasonably be expected at this centre, whence it must be concluded that the observed 105°F indicates a weak cooling influence by the sea. Although the sea breeze at Dallol normally arrives too late (1500–1800 h local time) to affect the current day's maximum, the advection of cooler air will decrease the maximum on the following day and this is particularly so when the broad-scale low-level flow is from the north.

Whereas in no part of the western region is the land surface low enough to produce *screen* temperatures greater than those observed at Dallol, by contrast in the eastern region such temperatures may be reached near Abéché. This station records the highest adjusted temperature of any in the tables[1] (113°F). Such a high value depends in part upon its altitude (the adjusted temperature increases with altitude by 1–2 degF per 1000 ft, depending upon locality), but may also be caused by a descent of potentially warmer air resulting from a blocking by the Marra Mountains of the north-easterlies that blow for much of the year. The land drops below 1000 ft to the north-west of Abéché, so it is possible that places there may have an annual mean daily maximum temperature similar to that at Dallol but this cannot be verified until a more accurate position for the 110°F isotherm has been found. It should also be noted that since Dallol is not quite at the lowest part of the Danakil Depression, it is possible that the annual mean is a fraction of a degree Fahrenheit greater at the lowest point some 20 miles to the south, particularly where old, black lava flows replace the white salt and gypsum.

The mean daily and monthly temperature maxima and minima at Dallol are shown diagramatically in Figure 3. The hottest month is June, since the maxima for July and August are a little less than would be expected if the seasonal cycle had been sinusoidal. The somewhat lower temperatures are a result of the temporary influx of cooler equatorial westerlies when the inter-tropical convergence zone moves far enough north for part of the westerly stream to be able to flow across and around the Ethiopian plateau. Flow around the northern end takes place near Port Sudan, particularly through

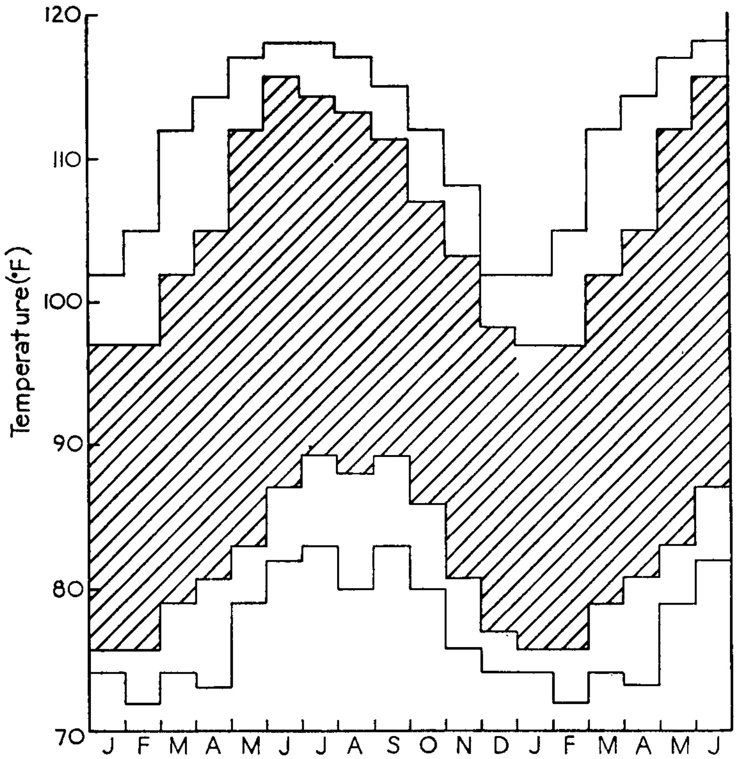

FIGURE 3—ANNUAL VARIATION OF MONTHLY VALUES OF MEAN AND EXTREME DAILY MAXIMUM AND MINIMUM TEMPERATURES AT DALLOL, 1961–66
Figures based on values in Tables I–IV. Limits of shaded columns show monthl yvalues of mean daily maximum and minimum temperatures.

the gap behind Tokar, the stream being subsequently diverted to north-westerly as it flows down the Red Sea rift. It is interesting to note from Table I that during 1966 mean maxima for the months July and August approached the values expected from the sinusoidal curve more closely than in any other year tabulated. This is consistent both with the shortness and below average intensity of the 1966 rains over the Sudan associated with the equatorial westerlies in that year, and with the high maxima recorded in the same months at Khormaksar (Table VI). Indeed, all the months from April to October in 1966 were warmer at Dallol than the 6-year means, contrasting with 1961 when maxima were below average from June onwards (especially July and August). Table VI also shows that July and August 1961 were cooler than average at Khormaksar.

To check whether the 6-year mean temperatures at Dallol are likely to be similar to a long-term mean, the corresponding 6-year and the 20-year (1947 to 1966) means for Khormaksar are compared in Table VI. It can be seen that the 6-year mean at Khormaksar is less than or equal to the 20-year mean in all months, the mean difference being only 0·15 degC, and the greatest difference is only 0·3 degC. The similarity of these means suggests that the 6-year values for Dallol are unlikely to be different from the long-term mean by even as much as one degree Fahrenheit in any month.

TABLE VI—MONTHLY MEANS OF DAILY MAXIMUM TEMPERATURE AT KHORMAKSAR

	1961	1966	6-year mean (1961–66)	20-year mean (1947–66)
		degrees Celsius		
January	28·3	28·2	27·9	28·1
February	29·0	29·0	28·5	28·6
March	29·8	29·6	29·4	29·7
April	31·6	31·5	31·4	31·4
May	34·6	33·2	33·9	34·1
June	37·1	37·1	36·4	36·6
July	34·9	37·1	36·1	36·1
August	34·2	36·2	35·4	35·4
September	35·8	35·1	35·1	35·3
October	33·0	32·9	32·7	32·8
November	29·7	30·4	30·1	30·3
December	28·3	28·2	28·3	28·6

Acknowledgements.—Sincere thanks are due to Dr J. Holwerda of the Ralph M. Parsons Company for so willingly making available the records used in this note. Thanks are also due to the staff of the Company for their interest and hospitality on a number of visits to Dallol, made possible through the courtesy of Mr R. J. V. Joyce, Director of the Desert Locust Control Organization for Eastern Africa. Acknowledgement is also made to the Director-General of the Meteorological Office for the use of records from Khormaksar.

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SAMPLING ERRORS IN MEASUREMENTS OF RAINDROP AND CLOUD DROPLET CONCENTRATIONS

By S. G. CORNFORD

Summary.—The sampling of raindrops and cloud droplets is examined using Poisson statistics. The results are used to calculate levels of confidence in measured raindrop concentrations, to suggest an improved counting technique, to see meaningful scales in the variability of rainfall and to form a basis for the design of new sampling instruments.

Introduction.—In any sample of raindrops or cloud droplets the drops are found to be of differing sizes. In cloud and precipitation physics it is usual to sort the drops into size ranges, to count the number in each size range and to draw a graph of the distribution of drop sizes. Usually the sample is taken at random amongst the array of dispersed drops and it is then often assumed to be representative of a larger volume. Typically, samples consist of several hundred drops and there are almost always many small ones and few large ones. This means that the sample is likely to be representative of the larger volume for the small drops but may be quite misleading for the large ones, even when the drops of each size are dispersed randomly and there are no systematic changes within the volume.

The importance of the errors in sampling the relatively scarce larger drops depends on the use to which the drop size distribution is to be put. If, for example, the mean droplet diameter $\Sigma nD/\Sigma n$ is required (n is the concentration of drops in a small range of diameter about the diameter D), then the errors in sampling the rare large drops are unlikely to be important because they form a small proportion of the total number. On the other hand, the liquid water content of the air involves ΣnD^3, so that if this is required the larger drops become more important. In calculating the rate of rainfall, P, we use $P \propto \Sigma nVD^3$ where V is the terminal velocity of drops with diameter D and the sum is made over all values of D. For raindrops V is very roughly proportional to D so that P is roughly proportional to ΣnD^4 and the large drops become even more important. Figure 1 shows one raindrop distribution presented in each of these three ways.

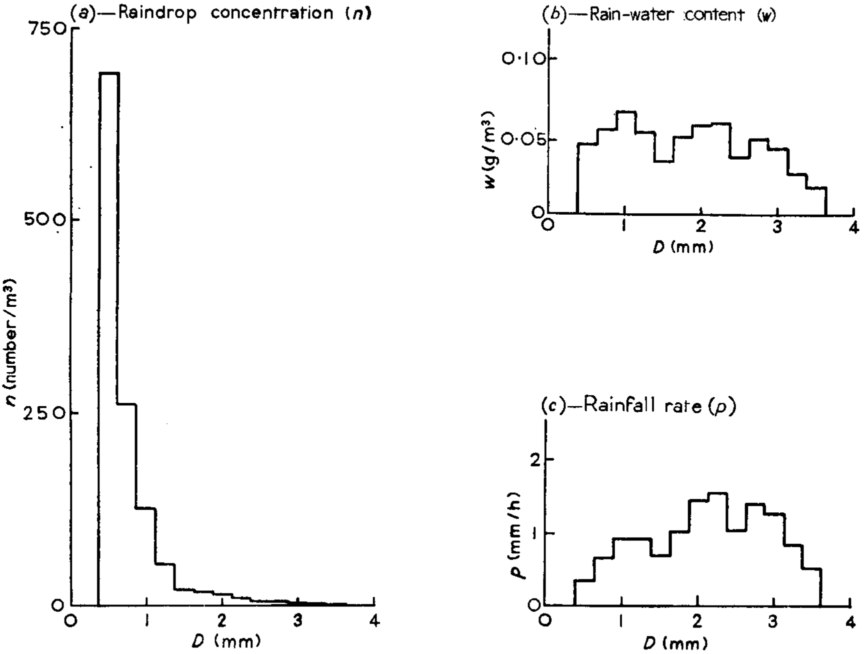


FIGURE 1—RAINDROP DISTRIBUTIONS SHOWING THE RELATIVE IMPORTANCE OF DIFFERENT SIZES IN DIFFERENT CONTEXTS

(a) n is the concentration of drops in each size range, as a number per cubic metre in a ¼-mm range of diameter about D.

(b) w is the contribution to the rain-water content of drops in each size range, as g/m³ in a ¼-mm range of diameter about D.

(c) p is the contribution to the rainfall rate of drops in each size range, as mm/h in a ¼-mm range of diameter about D.

The area beneath all three curves is the same.

To estimate the error in, say, a measurement of the total rainfall rate we need an estimate of the error of each component nVD^3 which makes up the total. This paper is concerned with the errors in sampling n. The technique used is a standard one in statistics but it is thought that the application may be of interest to meteorologists and others involved in measuring particulate clouds. Some of the implications of the technique are used to suggest an improved approach to measuring particle concentrations and the quantities derived from them.

The frequencies of occurrence of rare events.—It is shown in elementary books on statistics, e.g. Brookes and Dick,[1] that if in a large number of trials an event occurs rarely so that the probability of its occurring during any one trial is small, then the frequency of occurrence of the event during a number of sets of trials follows a 'Poisson distribution'. If over a large number of sets of trials the mean number of occurrences per set is m, then the fraction, $\Pi(i, m)$, of the total number of sets in which the number of occurrences will be any chosen whole number i, is given by

$$\Pi\ (i, m) \doteq \frac{e^{-m}m^i}{i\,!} \quad \ldots (1)$$

When a sensitive surface is used to sample drops, the exposure of an element of area of the surface for the time of resolution of the instrument is regarded as one trial. The whole of the sensitive area for that time constitutes a set of trials. The mean 'expected' number of drops in the sample, m, equals vN where v is the volume sampled and N is the mean concentration of drops. Equation (1) gives the probability that in one sample, i.e. exposure, the number of drops found will be i. Equation (1) may also be used to give the probability $\Pi(<r, m)$ that the number of drops found will be less than some predetermined number r :

$$\Pi\ (<r, m) = \sum_{i=0}^{r-1} \Pi(i, m) = \sum_{i=0}^{r_1-1} \frac{e^{-m}\,m^i}{i\,!}.$$

The probability that the number of drops found will be between two predetermined numbers r_1 and r_2, $\Pi(r_1 \rightarrow r_2, m)$, is given by

$$\Pi\ (r_1 \rightarrow r_2, m) = \sum_{i=0}^{r_2} \Pi\ (i, m) - \sum_{i=0}^{r_1-1} \Pi\ (i, m).$$

Similarly the probability that the number found will lie between two fixed proportions of the mean, say am and bm, is given by

$$\Pi\ (am \rightarrow bm, m) = \sum_{i=0}^{am} \Pi\ (i, m) - \sum_{i=0}^{bm} \Pi\ (i, m). \quad \ldots (2)$$

Equation (2) has been used with values of $\Pi\ (i, m)$ tabulated by Pearson and Hartley[2] to give Table I which shows the minimum values of the mean 'expected' number, m, if the sampled number, i, is to lie within $\pm x$ per cent of m on at least y per cent of occasions. For example, if we wish our samples to be within ± 50 per cent of the mean value, m, on at least 95 per cent of occasions then m must be at least 14. We must expect to catch 14 drops before we can expect to be within 50 per cent of the true value and then on about one occasion in twenty we shall be outside our 50 per cent limit.

Thinking along these lines is useful in some ways but in sampling raindrops (and no doubt in many other problems) the true mean, m, is unknown and the argument must be inverted so that m may be estimated.

Estimating the true mean.—The problem may be stated like this. In a sample of air i drops were found. What are the probable limits between

TABLE I—MINIMUM 'EXPECTED NUMBER IN SAMPLE' FOR THE SAMPLED NUMBER TO BE WITHIN *x* PER CENT OF THE 'EXPECTED NUMBER' AT THE *y* PER CENT CONFIDENCE LEVEL

y per cent	*x* per cent 0	1	2	5	10	20	30	40	50	60	70	80	90	100
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1	1	1	1
40					20	5	4	3	2	2	2	2	2	1
50						10	4	3	2	2	2	2	2	1
60						15	7	3	2	2	2	2	2	1
70						25	10	5	2	2	2	2	2	1
80							17	9	6	5	3	3	3	1
90								15	10	7	6	4	4	1
95								23	14	10	8	5	5	3
98									20	15	10	9	7	5
99										19	13	10	8	6
99·5											16	13	10	8
99·9												18	15	11

which the mean number would have fallen if a very large number of samples had been taken?

We have said in equation (1) that the probability of sampling i drops, when the expected number is m, is $\Pi(i, m) = \frac{e^{-m}\, m^i}{i\,!}$. If we consider k to be a fixed value of i, and plot $\Pi(k, m)$ for a wide range of values of m, as shown schematically in Figure 2, we find that $\sum_{m=0}^{\infty} \Pi(k, m)\Delta m \simeq 1$. Indeed, theoretically $\int_0^{\infty} \frac{e^{-m}\, m^k}{k!}\, dm = 1$. Each point on the curve shown in Figure 2 gives

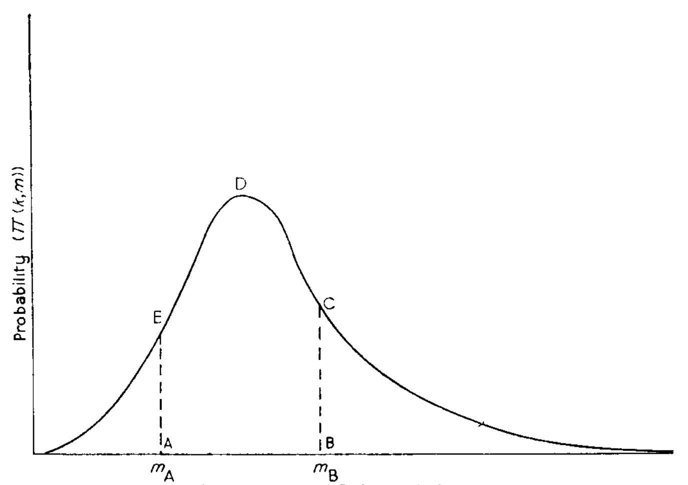


FIGURE 2—PROBABILITY, $\Pi(k, m)$, THAT WHEN k DROPS ARE FOUND IN A SAMPLE, THE MEAN NUMBER OF DROPS IN A LARGE NUMBER OF SIMILAR SAMPLES WOULD BE m

Area ABCDE, as a fraction of the total area under the curve, is the probability that the 'true' mean lay between m_A and m_B.

the probability that if the expected number were m the actual catch would be k. The whole curve shows the distribution of the value of m for the particular value $i = k$. The area ABCDE measured as a fraction of the total area under the curve gives the integral $\int_{m_A}^{m_B} \frac{e^{-m} m^k}{k!} dm$ which is the probability that the expected or mean number m lies between the two particular values m_A and m_B. Thus it is possible to say, for example, that if 10 drops are actually found in a sample the probability that the mean number of drops in many samples of that size would lie between 7 and 13 is

$$\Pi(10, 7\rightarrow13) = \Pi(10, 7) + \Pi(10, 8) + \Pi(10, 9) + \Pi(10, 10) + \Pi(10, 11) + \Pi(10, 12) + \Pi(10, 13)$$

$$= 0{\cdot}071 + 0{\cdot}099 + 0{\cdot}119 + 0{\cdot}125 + 0{\cdot}119 + 0{\cdot}105 + 0{\cdot}086$$

$$= 0{\cdot}724$$

The figures are based on Table 39 of Pearson and Hartley.[2] Thus 72·4 per cent of the drop distributions from which the 10 drops might have been drawn would have had mean concentrations giving between 7 and 13 drops in the volume sampled. Consequently we may say that our measure of 10 represents a population which would give 10 ± 3 drops on 72·4 per cent of occasions — or we may express our result as 10 ± 30 per cent at a confidence level of 72·4 per cent. It is worth noting that it is slightly more probable that the 'true' sample lay between 11 and 13 (0·310) than that it lay between 7 and 9 (0·289). This means that if we set our limits equally on each side of the mean we have a different confidence level for the upper limit from that for the lower limit. Alternatively, if we need the confidence levels to be the same for the upper and lower limits then the limits themselves differ from the mean by different amounts.

This last approach is the one which has been used in constructing Figure 3. This shows, for different values of the sampled number of drops (abscissa i), the upper and lower limits between which the mean, based on many samples, falls at three levels of confidence — 99·8, 99, and 95 per cent. The upper and lower limits have been expressed as ratios of i. Thus if, in a small sampled volume, 10 drops were found, then the mean of a large number of similar samples could be expected to lie between 1·84 and 0·48 times that number on 95 per cent of occasions.

Applications.—

(i) Figure 3 may be used to set confidence limits to the concentration of each size in a drop size distribution, although tables, such as Table 40 of Pearson and Hartley,[2] are probably more convenient for this purpose. An example of this use of confidence limits has been given by Probert-Jones.[3]

(ii) The counting of drop samples is tedious. Figure 3 and the arguments above can be used to reduce the number of drops counted and to ensure that the counting is carried out in the most effective way. Although the most accurate representation of a volume will always be given by the largest possible sample from within it, in a particular instance a smaller sample may be adequate to achieve a desired level of confidence (or alternatively a desired high level of confidence may be unrealistic). For example, it is relatively easy and quick to take samples of rain using the aluminium-foil technique[4,5,6] but the analysis is laborious and is one limitation on more widespread sampling.

An effective way of analysing individual samples is as follows. The centre of each sample is marked and limits are drawn at unit length (say one inch) on each side of the central mark. All indentations in the smallest size range are counted and marked. If there are insufficient indentations in this size range for the chosen level of confidence to be reached, limits are marked a further inch to each side of the centre and the counting extended to include the additional area. Suppose that we wish to know the concentration in this size range to within ±50 per cent and to expect to be within this range on at least 95 per cent of occasions; we must continue to extend our limits in this way until at least 23 impressions have been counted (Figure 3). The procedure is repeated for the next bigger size range using the same initial central mark. In this way, although different volumes of air are sampled to represent the concentrations of the various drop sizes, each volume includes all others containing drops in higher concentrations and all volumes are centred on the same arbitrarily chosen volume. This procedure means that there is the same known minimum level of confidence for all points of the drop size distribution.

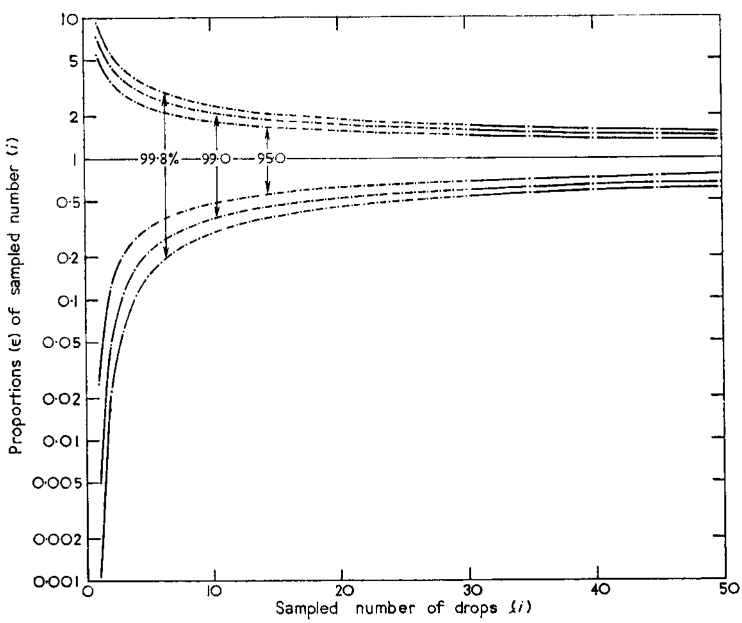


FIGURE 3—PROPORTIONS, ε, OF THE SAMPLED NUMBER OF DROPS, i, BETWEEN WHICH THE 'TRUE' MEAN LIES ON 95, 99 AND 99·8 PER CENT OF OCCASIONS

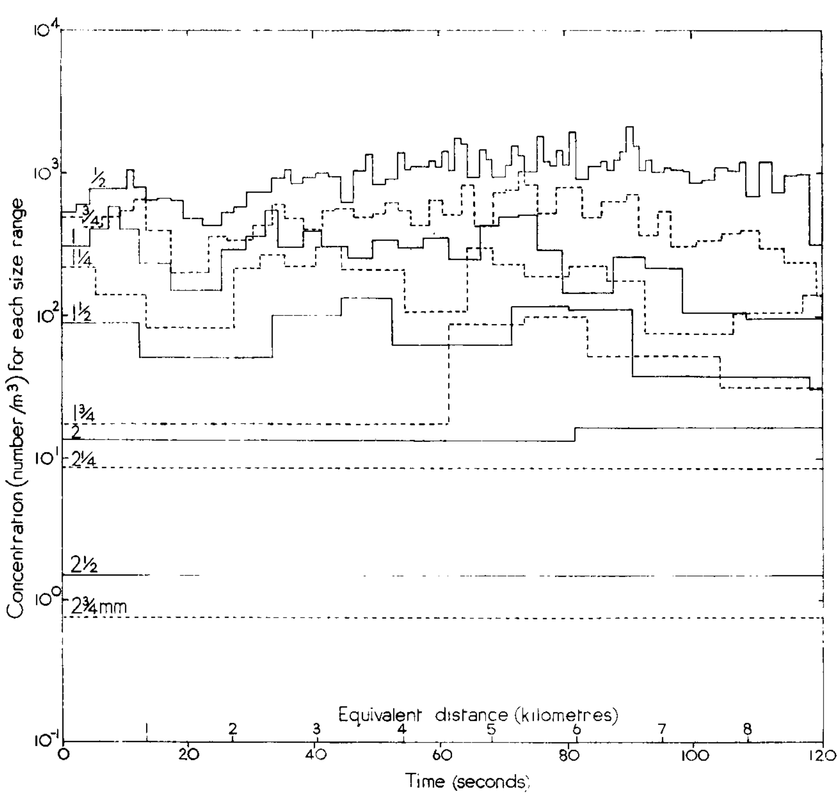
As i, increases the probable proportional error in estimating the 'true' mean decreases only slowly after $i \simeq 10$. Even with $i = 50$, on 5 per cent of occasions the true means would be more than 50 per cent greater or 24 per cent less than i. Within the range $10 < i < 50$ the selection of a suitable minimum 'satisfactory sample' is arbitrary. In this article the number used is : $i = 23$, which on 95 per cent of occasions gives ε (upper) = 1·5 and ε (lower) = 0·64. Thus for $i \geqslant 23$ the true mean lies at least within 50 per cent of i on 95 per cent of occasions.

(iii) The approach described in (ii) leads to what is possibly a new concept of rainfall rate. To a conventional rain-gauge, rain might just as well be a continuous fluid. If, on the other hand, rainfall rate could be measured literally at a point then the rate would be extremely high as drops arrived at the point and zero for relatively long intervals in between. The description of rain then is different depending on the time and space scales on which the rain is considered. A sampling theory approach leads to the idea that the minimum scale on which the rain can be viewed as approximating to a fluid is set by the rain itself. From this point of view, rainfall rate is a statistical concept, analogous to temperature in the way in which it sums up and measures for use on a large scale many events occurring on a very much smaller scale. The concept is only valid when applied to volumes which are large enough for the drop concentrations to be known at the desired confidence level. The minimum volume is then smaller for the densely packed small drops than for the rarer large ones. Consequently spatial changes in the contribution to the total rainfall rate exist on a smaller scale for the small drops than they do for the larger ones.

(iv) The same approach is of practical use in analysing the results of continuous sampling instruments. This is illustrated by Figure 4 which shows three different ways of presenting the concentrations of drop sizes measured during a run through a shower at 2700 ft near Aldermaston on 23 June 1966. An aluminium foil recorder was run continuously for 2 minutes during which time the aircraft travelled over 8 km. In constructing Figure 4(*a*), the counts for successive seconds were added until, after say j seconds 23 was equalled or exceeded. A mean concentration for the j seconds was then calculated and the process was repeated starting at the $(j+1)$th second. This left only the last sample on the right-hand side (and therefore the single count for $2\frac{1}{4}$, $2\frac{1}{2}$ and $2\frac{3}{4}$ mm drops) with less than 23 drops. In constructing Figure 4(*b*), which is for $1\frac{1}{4}$-mm diameter, the first concentration was obtained as for 4(*a*). The second concentration was found in the same way but beginning at the 2nd second and not the $(j+1)$th. The third concentration was found, beginning at the 3rd second and so on until a series of overlapping means was completed, with each mean based on at least 23 drops. In Figure 4(*b*) the number of seconds over which a mean was taken is shown by the length of each line, except where the mean concentration is the same for several samples, when lines are superimposed. It is considered that displays in the form of Figure 4(*b*) are perhaps the most satisfactory way of setting out the results of continuous sampling instruments, conveying as they do the inevitable uncertainty involved. Figure 4(*c*) shows a simplified form of Figure 4(*b*) for all diameters. Smooth curves have been drawn by eye through arrays such as those in Figure 4(*b*), with the error of each line in the array borne in mind, and the curves for the various sizes have been placed together in Figure 4(*c*). Each curve in Figure 4(*c*) represents an estimate of the change of concentration of that size through the shower. Taken together the curves show the changing drop size distribution across the shower.

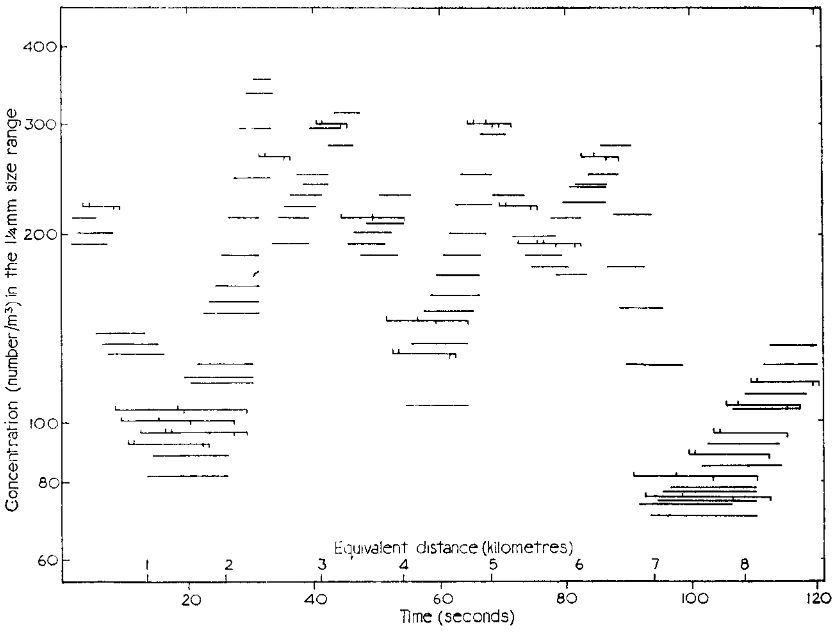
Any of these ways of interpreting the data may be used to calculate rainfall rates, precipitating water contents and so on. As an illustration of the relative importance of the various drop sizes in contributing to the total rainfall and its variability, the concentrations of Figure 4(*a*) have been used to calculate rainfall rates. These are shown in Figure 5. The main contribution comes from drops with diameters between $\frac{3}{4}$ and $1\frac{3}{4}$ mm so that on this occasion it was the scale on which we could sample these drops adequately which mainly determined the scale on which the major changes in rainfall rate could be measured.

(v) The concept outlined in (iii) may be used in the design of instruments intended to measure the spatial variability of rain. Radars, for example, in general sample a large volume and so do not suffer from the sampling errors inherent in the smaller aircraft-samples. However, a large-volume sample means that variability on scales smaller than the sample cannot be resolved. This may be a serious loss since local high concentrations (similar to the 'curtains' of rain seen in heavy showers at ground level) may be important in the overall generation of rain. Existing aircraft methods suffer from a similar disadvantage. Usually a small area is presented to the airflow and the sampled volume is the product of this area, the speed of the aircraft through the air and the time for which the sampling surface is exposed. This results in a

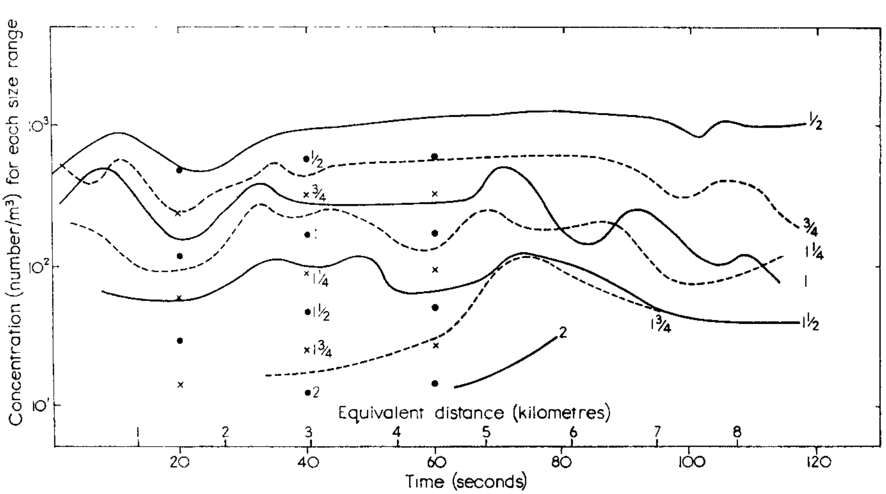


(*a*) The number on each curve gives the central drop diameter of a $\frac{1}{4}$-mm range. Successive samples of each drop size each contain at least 23 drops (excluding the last sample on the right hand side for all diameters and so the single measurement for diameters $2\frac{1}{4}$, $2\frac{1}{2}$ and $2\frac{3}{4}$ mm). Concentrations should be in error by less than 50 per cent on 95 per cent of occasions.

FIGURE 4—DROP SIZE DISTRIBUTIONS AND CONCENTRATIONS MEASURED CONTINUOUSLY FOR 120 SECONDS IN A SHOWER ON 23 JUNE 1966



(*b*) Overlapping samples for 1¼-mm diameter beginning each second and each containing at least 23 drops. Where samples overlap, the beginning of each sample is marked with an upward stroke and the end with a downward stroke. Note that the vertical scale is about four times that used in Figures 4(*a*) and (*c*).



(*c*) The curves for each size are drawn by eye through arrays such as (*b*), bearing in mind the probable error of each line. They show the changing drop size distribution across the shower. Dots and crosses represent the concentration of drops with diameters at ¼-mm intervals from ½ mm upwards in Marshall-Palmer drop size distributions corresponding to the rainfall rates measured at $t = 20$, 40 and 60 s. Diameters are indicated at $t = 40$. The number on each curve gives the central drop diameter of a ¼-mm range.

FIGURE 4—(*continued*)

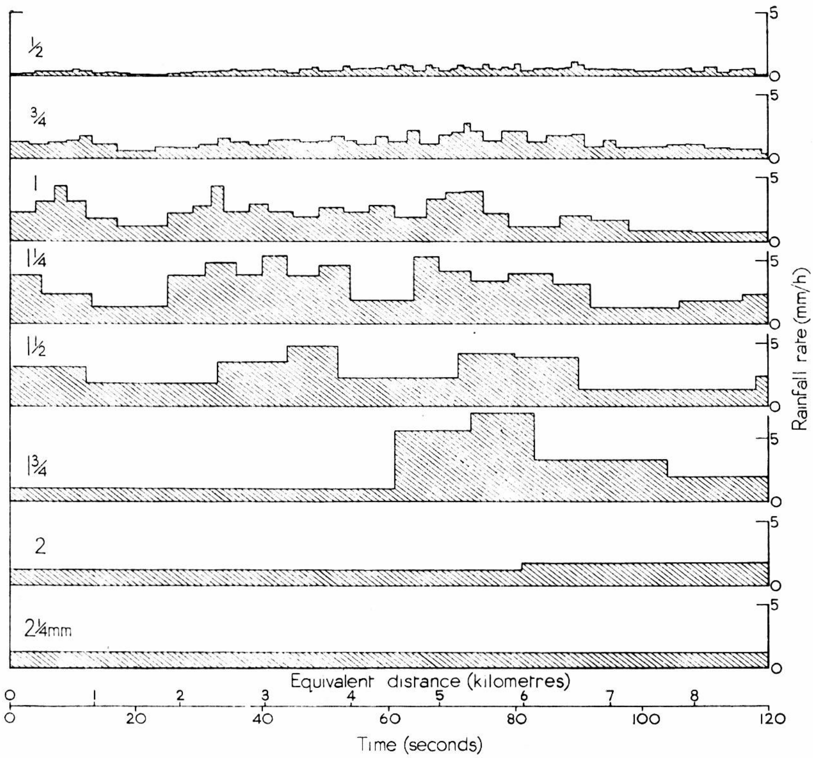


FIGURE 5—CONTRIBUTION OF EACH DROP DIAMETER TO THE RAINFALL RATE AND ITS VARIABILITY DURING A SHOWER ON 23 JUNE 1966

The diagram for each drop diameter is based on the concentrations shown in Figure 4(*a*). Drops of diameter 2½ and 2¾ mm contribute a constant rate of 0·3 and 0·2 mm/h respectively over the 120-s period. Figures on the left indicate the central diameter for a ¼-mm range.

long rod-shaped sampling volume, so that in order to have an adequate number of drops to satisfy the statistical requirements the minimum length scale over which real changes can be detected is greater than that over which they occur in the atmosphere. This is the case with the measurements shown in Figure 4. Just as with the radar the small-scale variability, if any, is not resolved. For maximum resolution the sampled volume would be cubic. The sampling surface would be square and the length of side used would be that of the minimum volume necessary to sample adequately a specified number of drops.

The design of suitable instruments must also take into account several other factors. We have seen from Figure 3 that 23 drops are sufficient to give an estimate to within 50 per cent of the true concentration at the 95 per cent confidence level. To maintain this accuracy the instrument must be designed and operated so that at least 23 drops are sampled on most occasions. For this to be so on 95 per cent of occasions, for example, Poisson summation tables (e.g. Table 7 of Pearson and Hartley[2]) show that we must arrange to sample an average of 33 drops. Of course on most occasions this involves sampling more than the 23 drops that are needed to achieve the desired level of confidence.

In practice there is no possibility at ordinary aircraft speeds of making adequate cubic samples using square impacting surfaces. One fundamental difficulty is that the collection efficiency of a sufficiently large square surface would not be good as small drops would be swept around it. An instrument to study the variability of dropsize distributions and rainfall rate will have to represent a compromise between resolving power and collection efficiency. For a high collection efficiency the collecting surface should be ribbon shaped. The volume swept out then takes the form of a horizontal square plate with the distance moved forward by the aircraft during the sampling time equal to the length of the ribbon. A further compromise may be needed between the resolving power and the length of the ribbon which can actually be used on an aircraft, so that the plate shaped volume becomes oblong. Several instruments with different ribbon widths probably represent the best solution. For Meteorological Research Flight aircraft moving at about 75 m/s two ribbon widths are in use at present, 2·5 and 0·5 cm. In Table II are shown the lengths of such ribbons, and the corresponding sampling times, which will achieve an accuracy of ±50 per cent at the 95 per cent confidence level in 95 per cent of samples.

TABLE II—IDEAL RIBBON LENGTHS AND SAMPLING TIMES FOR DROP SAMPLING SURFACES MOVING AT 75 M/S

(a) Ribbon width 2·5 cm — raindrop sampling.

Average drop concentration	Ribbon length	Sampling time	Drop diameter with various rainfall rates			
			0·1 mm/h	2 mm/h	10 mm/h	50 mm/h
m^{-3}	*cm*	*seconds*	*mm*			
1	$3·6\times10^3$	$4·8\times10^{-1}$	1·1(0·1)	2·2(0·06)	2·9(0·05)	4·2(0·03)
10	$1·1\times10^3$	$1·5\times10^{-1}$	0·8(0·3)	1·5(0·2)	2·1(0·1)	3·0(0·08)
10^2	$3·6\times10^2$	$4·8\times10^{-2}$	0·5(0·4)	0·9(0·2)	1·2(0·2)	1·7(0·1)
10^3	$1·1\times10^2$	$1·5\times10^{-2}$	0·2(0·1)	0·2(0·01)	0·3(0·01)	0·4(0·00)

The diameters represent the centres of ¼-mm ranges of diameter; they are based on a Marshall-Palmer drop size distribution.
The figures in brackets show the proportion of the still air total rainfall rate which is in the form of drops of the indicated diameter and concentration.

(b) Ribbon width 0·5 cm — cloud droplet sampling.

Average drop contration	Ribbon length	Sampling time
cm^{-3}	*cm*	*seconds*
1	8·1	$1·1\times10^{-3}$
10	2·6	$3·4\times10^{-4}$
10^2	$8·1\times10^{-1}$	$1·1\times10^{-4}$
10^3	$2·6\times10^{-1}$	$3·4\times10^{-5}$

The figures in brackets in Table II show the proportion of the still air total rainfall rate which is in the form of drops of the indicated concentration and diameter ; they show that, at least for the Marshall-Palmer[7] drop size distribution on which they are based, the concentrations shown on the left include almost all the rainfall. Ribbon lengths of 36 m are of course impracticable but ribbons considerably wider than 2·5 cm are quite efficient collectors of large raindrops so that ribbon lengths could be reduced in proportion and maximum resolution at least approached. The sampling times for cloud droplets are very much shorter than those used at present. This means that at this level of accuracy a continuously recording instrument could resolve real spatial differences in the drop size spectrum on distance scales down to 10 cm.

Conclusions.—The way in which a sensitive surface samples raindrops and cloud droplets has been examined using rare event statistics. The results may be used to set confidence levels to the various measured concentrations, to devise a more efficient counting technique than the one in current use, to see meaningful scales in the variability of rainfall and to form a basis for the design of new sampling instruments.

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FIFTH WORLD METEOROLOGICAL CONGRESS

By D. G. HARLEY, B.Sc.

Introduction.—In the World Meteorological Organization (WMO) the World Meteorological Congress is the supreme body. It is the general assembly of delegates representing Members, and meets at intervals not exceeding four years. Membership is restricted to States and Territories maintaining their own Meteorological Service, and the principal delegates should, in accordance with the WMO Convention, be the Directors of these Meteorological Services.

The Fifth World Meteorological Congress met in the Palais des Nations, Geneva, from 2 to 28 April 1967. At the opening the Members numbered 117 States and 12 Territories (including British Caribbean Territories, Hong Kong, and Mauritius). On 22 April newly independent Barbados also became a Member State. The actual attendance was from 105 States and 7 Territories (10 more than at Fourth Congress), observers from 4 non-member countries, and representatives from 13 international organizations. The delegation of the United Kingdom was led by Dr B. J. Mason, Director-General of the Meteorological Office, who was assisted by Instr. Capt. G. P. Britton, R.N., Director of the Meteorology and Oceanographic Service (Navy), Mr C. W. G. Daking, Mr B. M. Day and Mr D. G. Harley. Messrs A. A. Acland and J. R. H. Evans of the United Kingdom Mission in Geneva were advisers and Miss J. M. Prior acted as secretary to the delegation.

The work of Congress includes a great number of items necessary for the healthy running of the Organization, but naturally a few of these are of particular importance, and each Congress has its own character marked by those great themes which currently predominate. In the following account the major features of Fifth Congress are described first, and then the lesser but also important discussions.

Major features.—World Weather Watch (WWW) was the dominating topic. Fourth Congress in 1963 had decided that plans should be drawn up, with the help of a Planning Unit in the Secretariat, for major improvements in the world weather observational and forecast system; and as the concepts involved were progressively refined, the plans became more detailed and many preliminary arrangements were made. With the help of consultants and planning meetings of experts the detailed implications were explored, and finally Congress was presented with a basic document prepared by the Executive Committee laying down the principles on which WWW should be developed, and also a plan for the next four years. The momentum acquired by the idea of WWW in the intervening years was such that Congress accepted the basic document without dissent, although modifying it in detail for clarity and flexibility. Such decisions were made on the plan as were necessary to enable governments to go ahead with confidence in implementing the main operational elements :

(*a*) the global observational system (GOS)
(*b*) the global telecommunication system (GTS)
(*c*) the global data-processing system (GDPS).

In the GDPS section there are listed the functions and names of the World and Regional Meteorological Centres whose products are to serve the requirements of the National Meteorological Centres. The World Meteorological Centres, as was already known, are to be Melbourne, Moscow and Washington. The plan for Regional Meteorological Centres envisages 21 and includes for the European region Bracknell, Moscow, Offenbach and Stockholm. The GTS plan includes a main trunk circuit interconnecting World Meteorological Centres and appropriate Regional Telecommunication Hubs and Regional Meteorological Centres, regional telecommunication networks, and national networks. Congress defined the functions of the various elements and the engineering principles to be applied, and listed nine Regional Telecommunication Hubs, including Bracknell, to have receiving and transmitting capabilities on the main trunk circuit and its branches.

A global observational system already exists, in a sense, and the GOS elements of the WWW Plan lists in detail those improvements which are urgently needed to provide adequate material for the GDPS. Throughout the plan provision is made for adjustment as ideas, equipment and techniques develop. Concerning implementation of the plan, on which all depends, Congress decided that the basis should be voluntary financing by means of national efforts on Members' own territories, in space, on the oceans and in Antarctica, supported where necessary by assistance from the United Nations Development Programme (UNDP) and bilateral or multilateral aid, and backed up by a Voluntary Assistance Programme (VAP) supplied by contributions in cash or in kind and administered by the Secretary-General under the directions of the Executive Committee. The major Members promised substantial support to all components of WWW, including the VAP. Contributions to the latter are to be made without conditions. Members will be invited to indicate later this year their intentions under the various programmes, and pledge the general level of their contributions to VAP, which it is estimated will need annually $1 million in cash and $4 million in equipment and services, during the first four years.

Global Atmospheric Research Programme.—This project, known as GARP, concerns an experiment designed to test the state and motion of the entire atmosphere below 30 km for a limited period (6 or 12 months) and to use the data acquired to study the stability and predictability of the large scale circulations. It is part of the research programme of WWW. Congress agreed that an organizing committee should be set up jointly by WMO and ICSU (International Council of Scientific Unions) to plan and manage GARP, with the help of a small full-time joint planning staff within the WMO Secretariat. One result of setting up this committee would be the possibility of dispensing with some others, such as the Advisory Committee. The number of capable top-level scientists available is small, and there is some concern at the amount of time they already spend on committee work.

Review of the technical structure of WMO.—The technical work of WMO is largely carried out by eight Technical Commissions having a host of sub-committees and working groups and by six Regional Associations, all of which report to the Executive Committee. The Executive Committee also has its own special panels and working groups and receives advice on research and education from a high-level Advisory Committee. It has long been evident that this structure is too slow and cumbersome, and is ill fitted to carry out the heavy additional responsibilities of WWW. Congress therefore instructed the Executive Committee to set up a panel of experts to study the structure and functioning of the Organization in relation to its scientific and technical work and to review the working of all the major organs of WMO, i.e. Congress, the Executive Committee, Regional Associations, Technical Commissions and the Secretariat. The Executive Committee is to present the panel's report to Sixth Congress together with its own recommendations.

There was widespread support for this timely piece of self-criticism; it is to be hoped that a more streamlined and effective organization will result.

Elections.—Of all the routine duties of Congress the election of the President, Vice-Presidents and members of the Executive Committee is one of the most important. With the increase in membership of the Organization it was recognized that some increase in the size of the Executive Committee was desirable, and one more Vice-President and two more members were added, making a total of 24. The rules concerning the numbers from each Region were left unchanged, thus decreasing the predominance of the European Members. In the elections, which are entirely of persons in their individual capacities, Dr A. Nyberg of Sweden was re-elected President, defeating Mr M. F. Taha of the United Arab Republic by 58 votes to 46. Mr W. J. Gibbs of Australia defeated Academician E. K. Fedorov of U.S.S.R. for the post of First Vice-President. Dr Fedorov was elected as Second Vice-President and Mr N. A. Akingbehin of Nigeria was unopposed for the new Third post. The six Presidents of Regional Associations being already *ex officio* members of Executive Committee, the following Directors were elected: F. A. A. Acquaah (Ghana), L. de Azcárraga (Spain), B. H. Andrada (Argentina), M. Ayadi (Tunisia), J. Bessemoulin (France), J. Marden dos Santos (Brazil), B. J. Mason (U.K.), L. S. Mathur (India), Ramanisarivo (Madagascar), Y. Shibata (Japan), E. Süssenberger (Federal Republic of Germany), M. F. Taha (U.A.R.), J. Van Mieghem (Belgium), R. M. White (U.S.A.). There are now seven Commonwealth Directors out of the 24 forming the Executive Committee.

Appointment of the Secretary-General.—The Executive Committee expressed its complete confidence in Mr D. A. Davies, and there being no other candidate, he was reappointed unanimously with enthusiasm for four more years. He has been Secretary-General continuously since 1 January 1956.

The programme and the budget.—The budget of WMO provides only for the central activities of the Organization, consisting largely of the activities of the Secretariat and the servicing of sessions of constituent bodies. Operational activities being the function of the Members, and technical assistance and training being largely financed through UNDP, the budget is small in relation to the activities in which the Organization is concerned. The New Development Fund initiated at the previous Congress was not renewed, because its functions will be superseded by WWW arrangements. New items include $200,000 for the GARP planning committee, on condition that ICSU puts up a like amount, and $500,000 for long-term fellowships of a type not available under UNDP. Large alterations on previous budgets arose from the need to increase the size of the Secretariat to keep up with the work, and the increasing use of the four languages of the Organization. This has a major effect on the cost of interpretation at meetings, and more of the publications, especially technical operational ones, are to be printed in several languages. The *Bulletin*, as an information medium on the activities of WMO and other noteworthy activities in meteorology is to be published in four languages, and perhaps expanded.

The maximum expenditures approved for the next four years total $11,817,000, nearly double the total for 1964–67 plus the New Development Fund. Members' proportional contributions are to be on the same scale as before, which takes into account that the wealthiest Members also contribute most to the work of the Organization by other means, such as giving the time of their staffs.

Lectures.—The first International Meteorological Organization lecture was delivered by Professor E. N. Lorenz of the U.S.A. on 'The nature and theory of the general circulation of the atmosphere', and was followed by questions and answers. The brilliant lecture was a summary of a monograph which is to be published by WMO.

Another innovation was that four discussions on scientific subjects were held during Congress, introduced by lecturers as follows :

Cloud physics by Dr B. J. Mason
Meteorology applied to agriculture by Mr L. P. Smith
The use of satellite data in weather forecasting by Mr A. W. Johnson and
Meteorological satellite systems of the future by Dr M. Tepper
Weather modifications by Academician E. K. Fedorov.

The first was an unplanned addition to the programme, when Dr Lorenz fell ill a few hours before he should have spoken, Dr Mason stepped into the breach, having fortunately brought his slides and films with him for another purpose. Mr Johnson showed a fascinating motion picture formed from stills from the ATS satellite stationary over the Pacific — a day's pictures in a few seconds. The discussions brought the delegates into close contact with some of the things the whole Organization really exists for.

Minor features.—Many of these are by no means minor in importance. Rather they are so called because they are dealt with in the normal programme of Congress.

Technical matters.—The up-dating of the Technical Regulations on the basis of recommendations of the Technical Commissions is most important because it is largely these that ensure harmony between the day-to-day operational work of the national meteorological services. Because of the long-lasting effects of changes, it is usually more important to get them right than to make them quickly. Reconciliation of the needs of the different Commissions is not always easy. Almost all changes put up this time were accepted, but action on automatic weather stations was deferred as not all aspects had yet been considered. The introduction to the Technical Regulations was improved by adding notes on the status of Annexes, Appendixes and Guides, and there was added a set of guiding principles developed by previous Congress, concerning the process of amendment of the Regulations.

The use of metres per second instead of knots for reporting wind speed was again discussed but with less heat than before. No change was made for the present. On instruments, the need was stressed for more uniform results in the routine operation of radiosondes, the differences being due not only to the instruments but to the skill of the operators.

Agrometeorology which not long ago almost ceased to have a Commission, was discussed with great interest because of the pressure of world population on food supplies. Considering the wide variations in the world in the application of meteorology to agricultural problems, Congress developed a resolution calling for increased national and international programmes jointly with other interests concerned. Internationally these include the Food and Agriculture Organization, UNESCO and the United Nations Development Programme. Hydrometeorology, which is also vitally concerned with the basis of economic life in many countries, was also discussed with great interest, and it was agreed that WMO should continue to play its full role in the International Hydrological Decade.

In the discussion of maritime meteorology, whose field of interest covers much the greater part of the globe, the voluntary contribution of shipping to the world-wide observing programme was recorded with appreciation. Now that oceanographers increasingly want current routine information it was recognized that they and the meteorologists must be careful to co-ordinate and limit their demands on the observers. An important part of the GDPS element of WWW will be to strengthen the services provided to marine activities.

Aeronautical meteorology is dealt with not only by WMO but also, as a service to aviation, by the International Civil Aviation Organization (ICAO). The developing Area Forecast System comes in the area of mutual interest, and is closely related to the GDPS element of WWW. There is plenty of scope for friction between the two sides in such a situation, and Congress was much concerned to avoid it happening. ICAO was represented by Mr U. Schwarz successor to Mr G. J. W. Oddie as Chief of Meteorology in ICAO. That liaison by frequent personal contact between staff of the two organizations would help smooth out difficulties, was generally agreed, and visits on suitable occasions from Geneva to Montreal were thought the best means of doing this.

Antarctic meteorology.—Fourth Congress had decided on a Standing Committee for the Antarctic, but the necessary unanimity among Members concerned was absent, so the Executive Committee set up a Working Group on Antarctic Meteorology. This had worked well and Fifth Congress thought that it should be continued. The Group is composed of representatives of Members signatory to the Antarctic Treaty. The task is to continue the co-ordination of meteorological activities in an area covered by no Regional Association and where stations set up by the various States have now been making surface and upper air observations routinely for many years. The area includes everywhere south of 60°S.

Training.—This subject was of great interest to Members, especially the developing countries, because of its critical importance for the development of their meteorological services. The WWW plans can only increase the demand at all levels. International funds for training come mainly from the United Nations Development Programme, but meteorological projects are administered through WMO. The demand is particularly large in Africa and South America, and considerable efforts have gone to meeting it, including seminars, fellowships, expert missions and the setting up of Chairs of Meteorology and Regional Training Centres. In the Secretariat an Education and Training Co-ordination Office is to be set up, and a library of training material assembled. A comprehensive WMO Guide to Meteorological Education and Training is to be developed, including detailed syllabi prepared by the Technical Commissions. Meanwhile, the status of Technical Note No. 50, by Professor Van Mieghem, was left unchanged.

Long-term fellowships, for which provision was made in the Budgets, are a means of giving higher education to promising recruits. There is a serious problem of retaining them in the national meteorological service when that education is complete.

General matters.—No major changes were made in the WMO Convention, apart from the enlargement of the Executive Committee, although a number of minor improvements were agreed. Similarly, changes in the General Regulations were mainly to clarify or tighten up various points. Pending the review of the technical structure as a whole, only small changes were made in the terms of reference of the Technical Commissions, mostly to make clear where lies the co-ordinating responsibility when a topic touches several Commissions. The Commission for Synoptic Meteorology is to co-ordinate matters relating to the global observational, data-processing and telecommunications systems of WWW. The name of the Commission for Aerology (CAe) was changed to the Commission for Atmospheric Science (CAS). Some changes were made in the rules about setting up and disbanding Working Groups of Technical Commissions, to give the Presidents more control.

The United Nations, in its task of co-ordinating the activities of all the U.N. Specialised Agencies, is trying to get the Agencies to adopt more uniform systems of financial control, and proposes an Inspection Unit to visit the Agencies. Congress agreed to co-operate (WMO already largely conforms) but insisted that the Inspection Unit should not inspect WMO without the benefit of specialist advice from someone familiar with its scientific and technical activities.

The headquarters building of WMO in Geneva, opened in 1960, is already inadequate, and will soon become more so. Two methods of extension were discussed, together with the question of purchasing the existing building, which although designed for the use of the Organization, is rented from the Canton of Geneva. Agreement in principle was given by Congress, but a postal ballot will be necessary later on the detailed proposals. The alternative is the rental of offices nearby.

Social activities.—The members of the Secretariat and their wives worked hard not only in Congress, but outside, especially in reviving flagging delegates by taking them out at weekends into the beautiful mountain country around Geneva. A number of excursions and entertainments were organized also during the week for wives of delegates.

Among the usual numerous evening receptions an outstanding event was the Swiss reception at the Castle of Chillon, near Montreux on Lac Leman. A special train took delegates and wives, from Geneva around the lake past Lausanne, to the mediaeval castle and back. The castle stands dramatically on a small point on the lake shore below the mountain. It was floodlit, guards and trumpeters in ancient costume welcomed the guests, the cooks roasted whole sheep in the great halls, and food and wine were plentiful. It was a memorable evening.

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