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RAINFALL IN ENGLAND AND WALES DURING THE FIVE MONTHS JULY TO NOVEMBER, 1960, WITH SPECIAL REFERENCE TO SOUTHERN ENGLAND

By R. E. BOOTH

After the wettest winter in England and Wales since that of 1915 – 16, the spring and early summer of 1960 were comparatively warm and dry. The second half of the year however will long be remembered for its exceptional rainfall particularly in southern England during the five months July to November. In contrast rainfall in Scotland was below the average during three of these five months.

Taking England and Wales as a whole, the general rainfall of 26·9 inches over the five months July – November 1960 was more than in any similar five-month period in a series of rainfall estimates going back to 1727. These estimates are probably quite reliable from about the year 1820 but there is naturally less confidence in their reliability as the series extends backwards. In this series since 1727 the nearest approach to a total rainfall for the period July – November as large as that in 1960 was in the year 1852, when records were reasonably reliable and when 26·2 inches were recorded. Hence it seems likely that over England and Wales the period July – November 1960 was the wettest such period for nearly two and a half centuries.

Table I gives in ranking order the ten wettest July – November periods in England and Wales since 1727 and shows the year of occurrence, the total general rainfall in inches during the five-month period, the percentage of the 1916 – 50 annual average rainfall this represents and the percentage of the 1916 – 50 average rainfall during the period July – November. The 1916 – 50 average general rainfall over England and Wales for the period July – November is 17·1 inches and for the year 36·5 inches.

Only two years in the present century, 1903 and 1954, appear in these first ten, but if the table were extended to include the first 25, the following years would also appear: 1930 (12th, 60·2 per cent), 1927 (13th, 60·2 per cent), 1950 (17th, 59·1 per cent), 1946 (21st, 57·7 per cent), 1944 (22nd, 56·9 per cent) and 1924 (23rd, 56·6 per cent). The figures in brackets give the order in the 25-year table and the percentage of the annual average (1916 – 50) of rain which fell during the five-month period July – November of that year.

TABLE I—TEN WETTEST JULY – NOVEMBER PERIODS IN ENGLAND AND WALES SINCE 1727

Year	Rainfall	Percentage of annual average	Percentage of period average
	inches	*per cent*	*per cent*
1960	26·9	73·7	157
1852	26·2	71·9	153
1841	24·3	66·5	142
1775	24·2	66·2	142
1768	24·0	65·9	141
1903	23·6	64·5	138
1875	23·5	64·3	137
1872	23·2	63·7	135
1799	23·2	63·7	135
1954	23·0	62·9	134

Table II gives for England and Wales and for nine districts of Great Britain the percentage of the 1916 – 50 average rainfall for each of the five months July – November 1960, and the number of days of measurable rain above or below the monthly average. The districts are those used in the *Monthly Weather Report* of the Meteorological Office and the values are based on five well distributed stations within each district. The Scottish districts are included to show that rainfall in Scotland was to a large extent below the average during the period being considered.

TABLE II—PERCENTAGE OF AVERAGE MONTHLY RAINFALL AND NUMBER OF DAYS OF MEASURABLE RAIN ABOVE OR BELOW THE MONTHLY AVERAGE

District	July		August		September		October		November	
	per cent	*no. of days*	*per cent*	*no. of days*	*per cent*	*no. of days*	*per cent*	*no. of days*	*per cent*	*no. of days*
North Scotland	92	+ 1	133	+ 3	81	— 5	58	— 1	88	+ 1
East Scotland	106	+ 5	153	+ 7	74	0	198	+ 7	112	+ 4
North-east England	154	+ 7	113	+ 5	124	+ 1	268	+10	138	+ 6
East England	125	+ 7	164	+ 4	193	+ 2	234	+ 9	134	+ 7
Midlands	136	+ 6	123	+ 2	183	+ 1	203	+ 8	151	+ 8
South-east England	148	+ 7	169	+ 6	174	+ 3	230	+ 8	153	+10
West Scotland	114	+ 7	92	+ 2	78	— 2	56	+ 4	141	+ 5
North-west England and north Wales	136	+ 4	133	+ 3	109	+ 1	84	+ 2	184	+ 8
South-west England and south Wales	152	+10	155	+ 5	185	+ 2	213	+ 6	155	+ 9
England and Wales	142		139		150		199		153	

It will be noticed that southern and eastern England was the wettest part of the country nearly every month. In November the rainfall pattern was a little different from the other months with considerably above average rain in the north-west, but even so rainfall in southern England was more than half as much again as normal.

Figure 1 shows the percentage of the 1916 – 50 average rainfall in England and Wales during the five-month period July – November 1960. Southern England particularly stands out as having had rainfall greatly in excess of the average for the period. Two areas, one near Exeter and the other near the Sussex coast, received more than twice their average amount. Rainfall was more than 175 per cent of the average over the greater part of all but two (Cornwall and Kent) of the counties bordering the English Channel, over the Thames and Severn valleys, and locally in Cornwall, Kent, Lincolnshire,

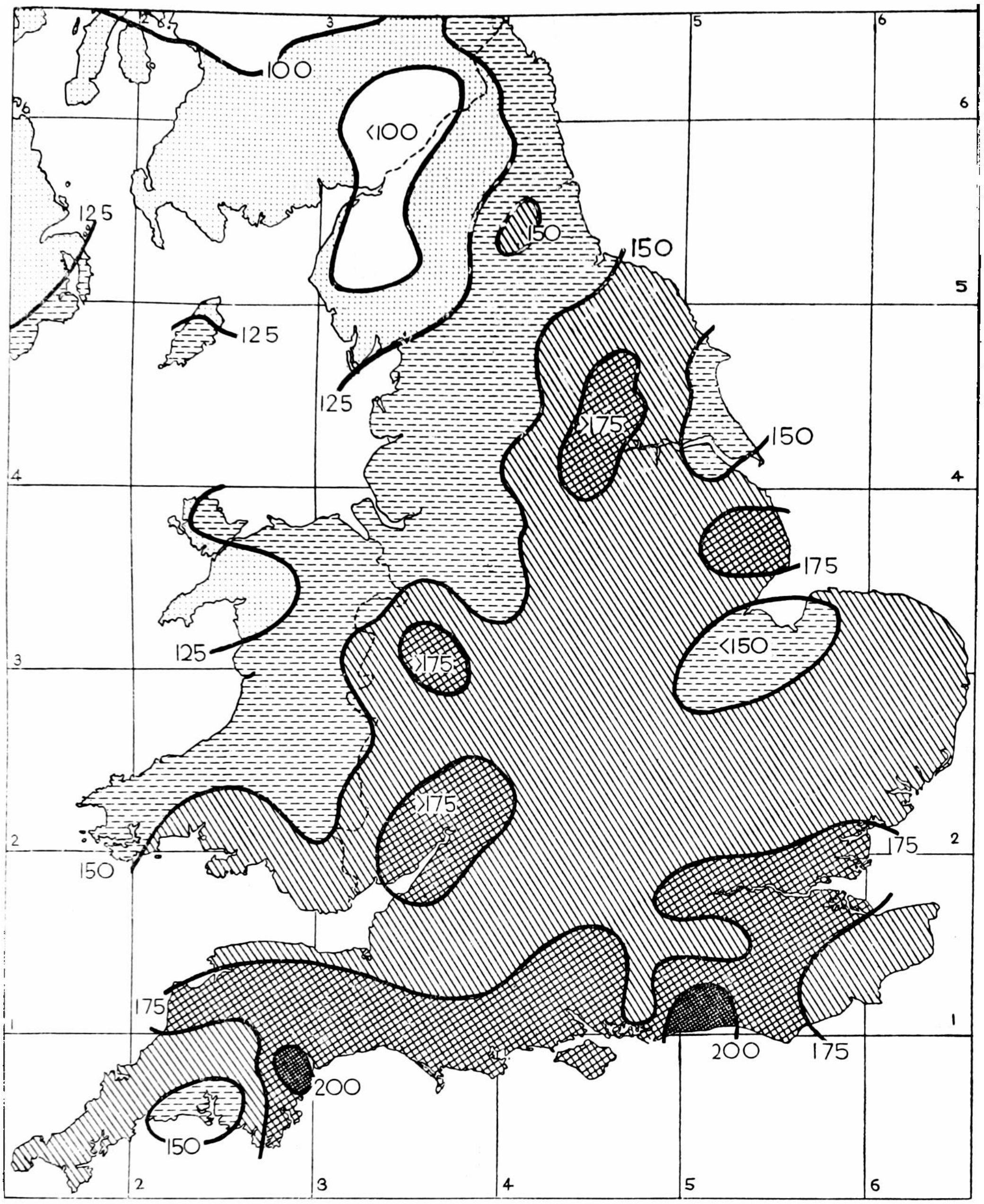

FIGURE 1—RAINFALL FOR JULY – NOVEMBER 1960 EXPRESSED AS A PERCENTAGE OF THE AVERAGE

Shropshire and Yorkshire. Severe floods occurred in all these areas. Only over a small area in the extreme north-west of England was rainfall below the average. A similar map was drawn showing the rainfall during the five-month period as a percentage of the 1916 – 50 average annual rainfall. This shows that rainfall in the five months was more than 90 per cent of the annual average south of Exeter, near the Sussex and Essex coasts and in parts of Lincolnshire. Worthing had almost as much rain during these five months (99 per cent) as falls on an average during the whole year.

Monthly percentage rainfall maps show large areas during each of the five

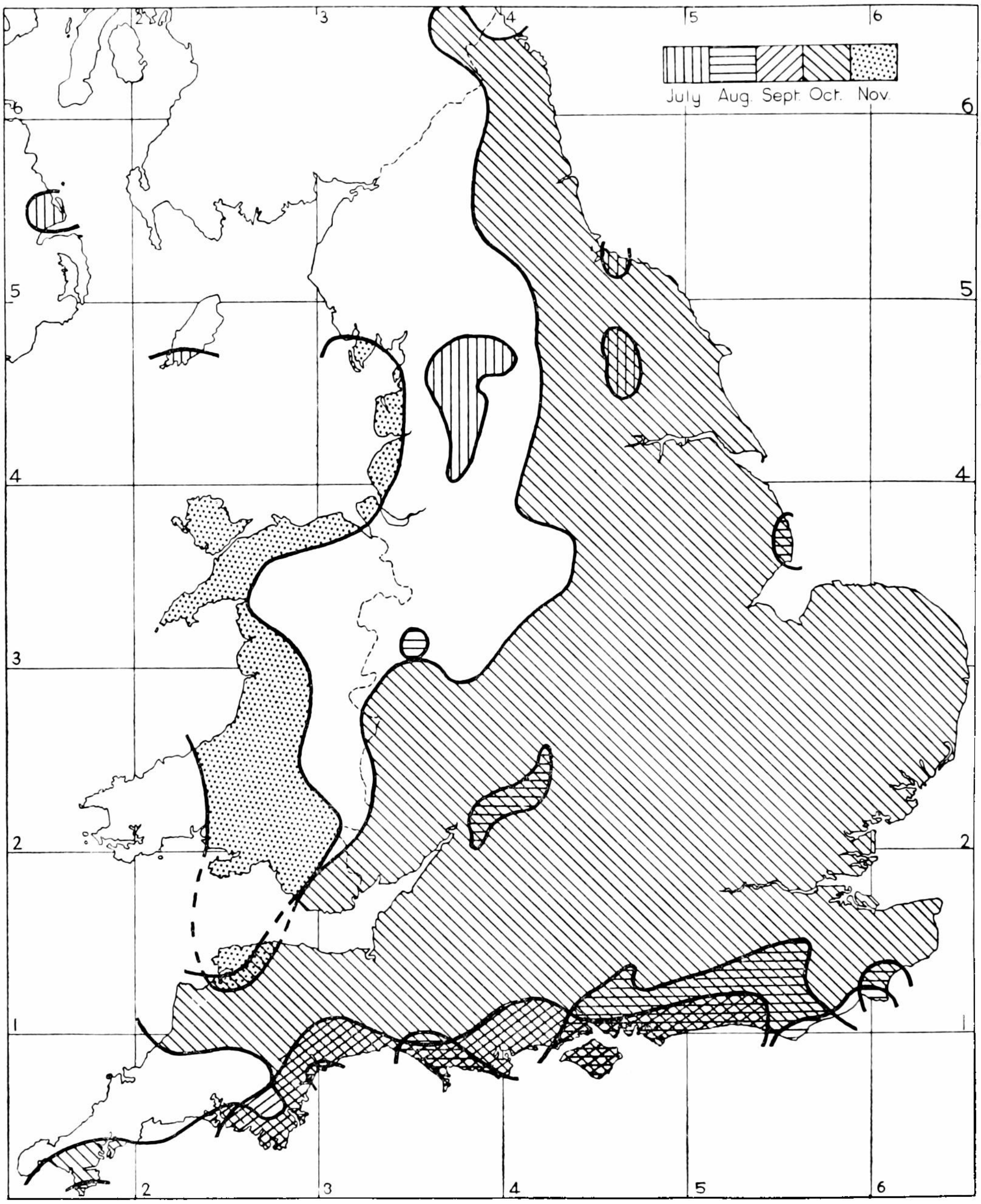

FIGURE 2—AREAS WITH MORE THAN 200 PER CENT OF THE AVERAGE RAINFALL, DURING JULY – NOVEMBER 1960

months July – November where rainfall was more than twice the average. These areas for each of the five months have been superimposed one upon another in Figure 2. It will be seen that more than twice the average amount of rain fell during each of the three consecutive months August, September and October over an area near Exeter, southern Dorset, the southern part of Hampshire and Sussex extending from near Milford-on-Sea to Seaford, and over the Isle of Wight. More than twice the average also occurred during at least two of the five months in parts of Gloucestershire, Lincolnshire and Yorkshire. A striking feature of the map is the large part of the country which had more than twice the average rainfall during October.

Weather was persistently cyclonic in character from July to November and noteworthy heavy rainfall occurred in some part of England and Wales during each of the five months.

July.—Apart from the first few days July was dominated by cyclonic activity, a well developed frontal system or depression reaching the British Isles from the Atlantic every few days.

Weather was cool and wet generally with frequent thunderstorms. On the 6th heavy rain fell continuously from about 0300 GMT until 2359 GMT south of the forest of Bowland, Yorkshire (West Riding); over 5 inches was recorded in 24 hours at a number of places and there was considerable flooding in the area.

August.—An extensive low-pressure area over north-west Europe maintained light, predominantly northerly winds over the British Isles until the 19th, depressions from the Atlantic passing to the south of the country. During the next week winds became generally south-westerly under the influence of an intense Atlantic depression which gradually filled as it moved slowly south-east towards Cornwall. From the 25th until the end of the month a complex but shallow low-pressure area covered much of the country.

The cool, wet and thundery weather continued throughout August. During an unusually severe thunderstorm at Old Maldon, Surrey, on the 7th, about 3¼ inches of rain fell in 2 hours. From the 9th to the 11th there was heavy and persistent rain along part of the south coast, Brighton recording more than 5 inches of rain during this period, more than twice its normal rainfall for the whole month. On the 13th at Harlech, Merionethshire, one inch of rain fell in 15 minutes.

September.—The first week of September was changeable with frontal systems moving east across the country, but the second week was predominantly anticyclonic. Low-pressure systems lay over or near the British Isles during most of the third week but thereafter weather was again anticyclonic until the 26th, after which southern and central districts came under the influence of a complex depression centred off south-west England.

The outstanding feature of September's rainfall was the resulting disastrous series of floods in south-west England at the end of the month. The flooding was mainly due to four days of exceptionally heavy rain beginning on the 27th, some stations during this period recording as much as 5 inches. Figures 3 and 4 are based on a close network of rainfall stations and show the distribution of rainfall in the parts of southern England most affected by heavy rain on the 29th and 30th respectively. On the 29th nearly 4 inches of rain fell in the catchment-area of Dartmoor and over 2 inches in the Teignmouth and Exeter areas, while on the 30th 3 inches or more was recorded in 24 hours over Dartmoor, Exmoor and in the Exeter and Seaton areas.

October.—Apart from the week 10th - 17th when high pressure lay to the west or over the British Isles, a complex low-pressure system persisted for most of October off our south-west coasts and associated troughs and secondaries moved north-eastwards across the country.

Rainfall was three times the average in west Somerset, east Devon, Buckinghamshire, Lincolnshire and the East Riding of Yorkshire. More than four times the monthly average fell in the Exeter area. The sequence of days with exceptionally heavy rain in southern England which began during the last week of September continued until 8th October. Renewed flooding occurred in south-west England and later in eastern England. In thundery outbreaks

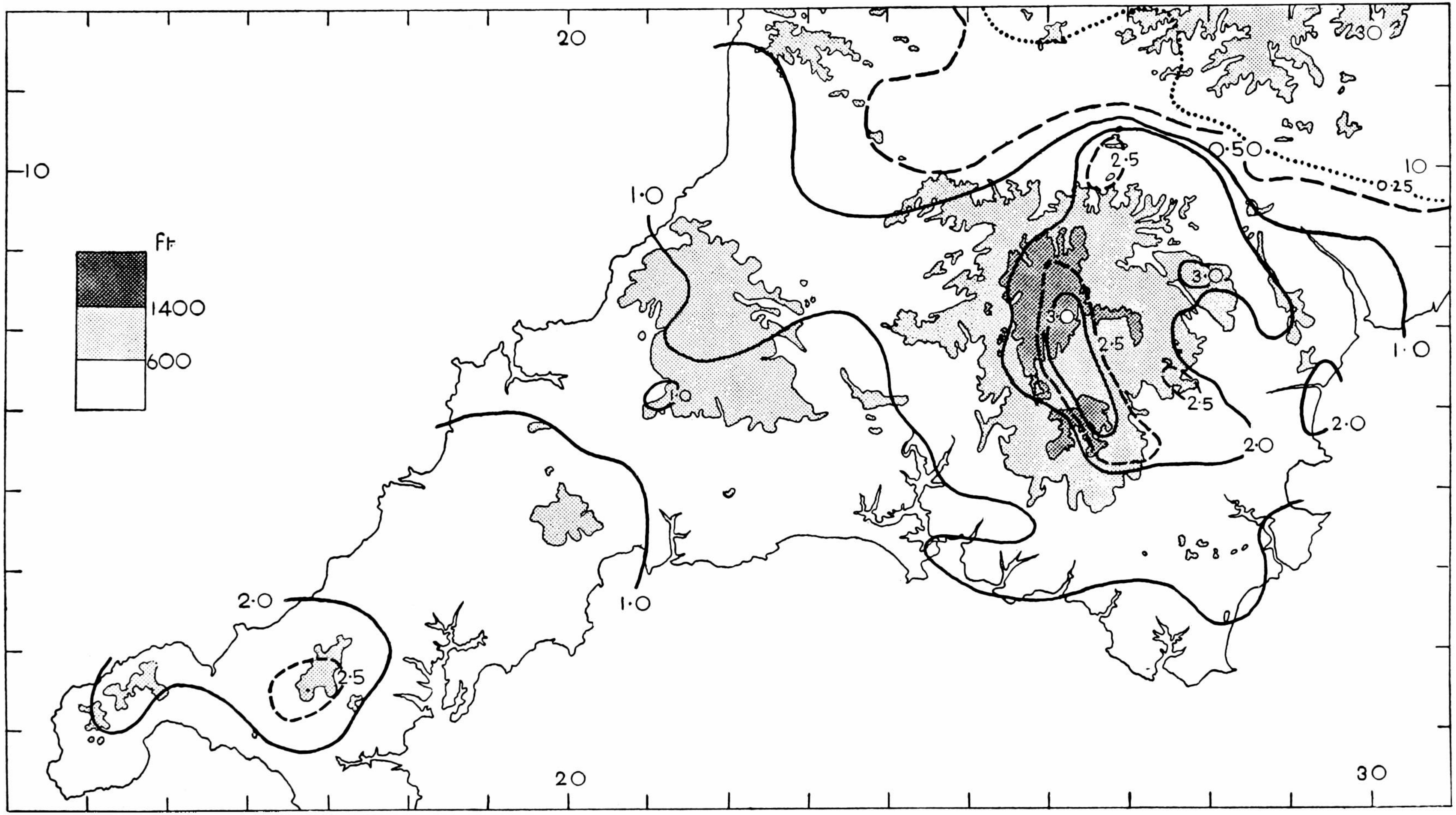

FIGURE 3—RAINFALL (INCHES) FOR THE 24 HOURS BEGINNING 0900 GMT,
29 SEPTEMBER 1960

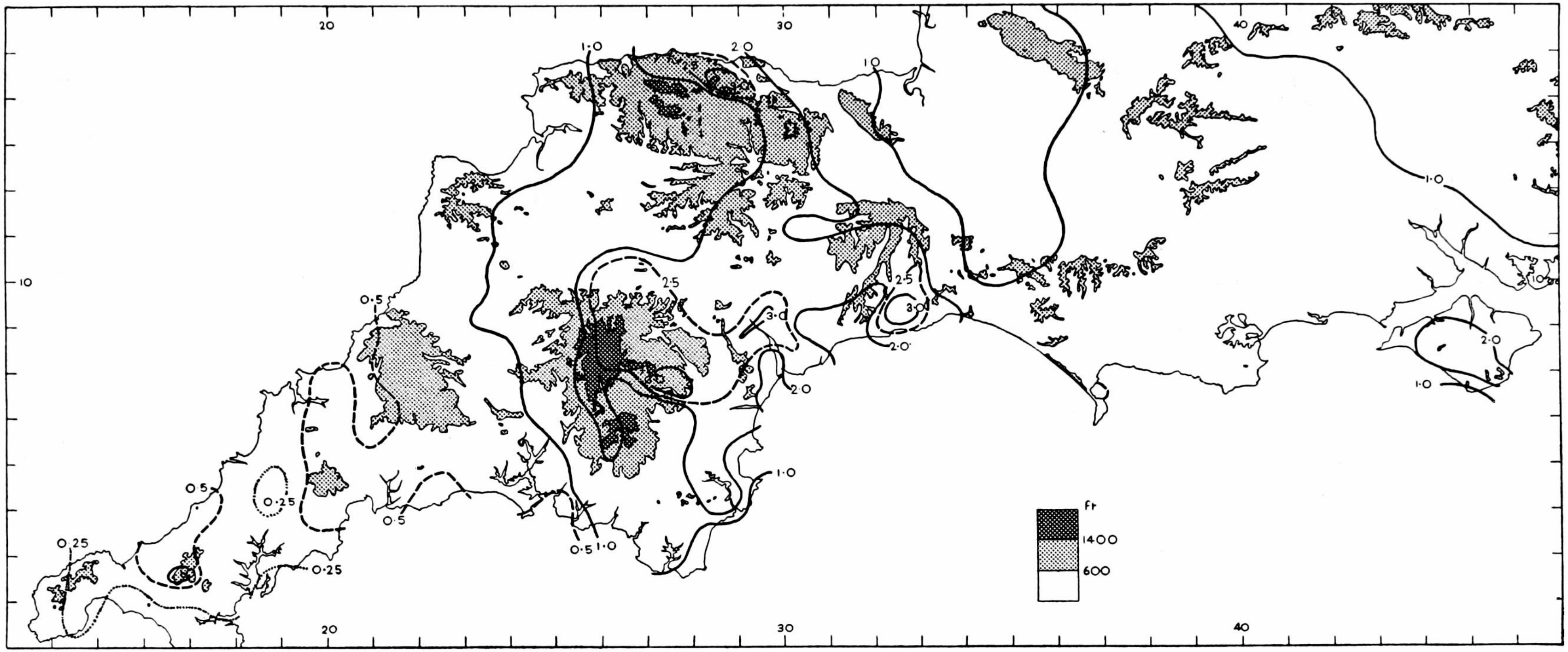

FIGURE 4—RAINFALL (INCHES) FOR THE 24 HOURS BEGINNING 0900 GMT, 30 SEPTEMBER 1960

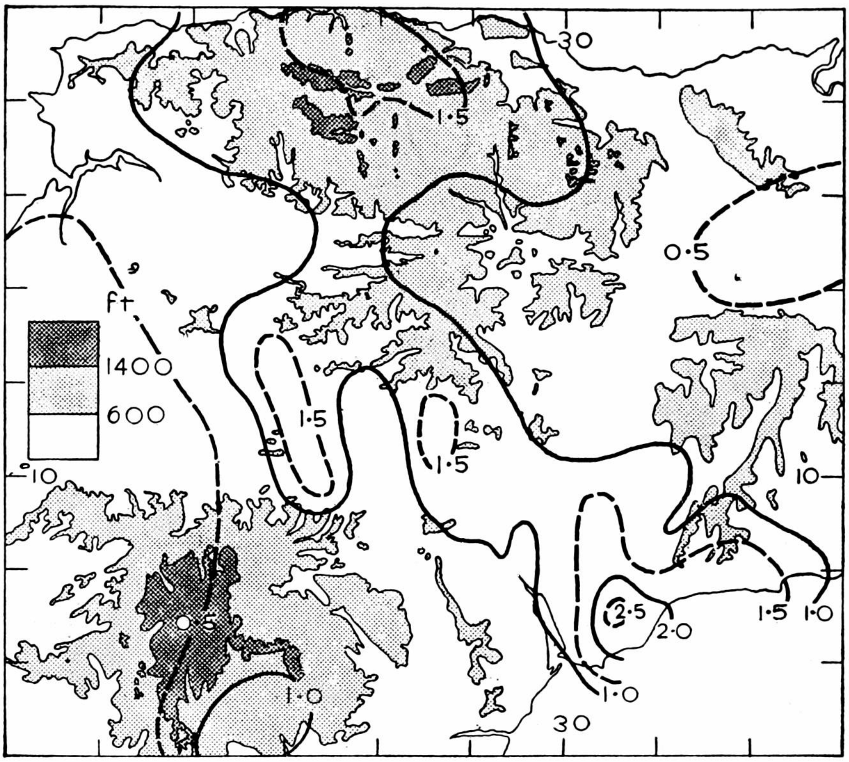

FIGURE 5—RAINFALL (INCHES) FOR THE 24 HOURS BEGINNING 0900 GMT, 6 OCTOBER 1960

during this period many places had more than 3 inches of rain in a few hours. Figures 5, 6 and 7 are maps of daily rainfall on the 6th, 8th and 26th respectively for parts of Devon and adjacent areas. Following the extremely heavy rain which fell over much of Devon on the 26th, rivers continued to rise and many in the county were at a higher level than recorded this century and in Exeter flooding was very serious.

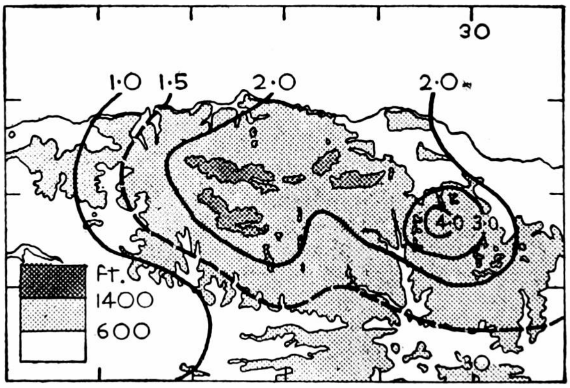

FIGURE 6—RAINFALL (INCHES) FOR THE 24 HOURS BEGINNING 0900 GMT, 8 OCTOBER 1960

November.—November weather also was mostly cyclonic in character with a well developed frontal system crossing the country every few days.

The month had a stormy end and beginning. Some of the heaviest rainfall

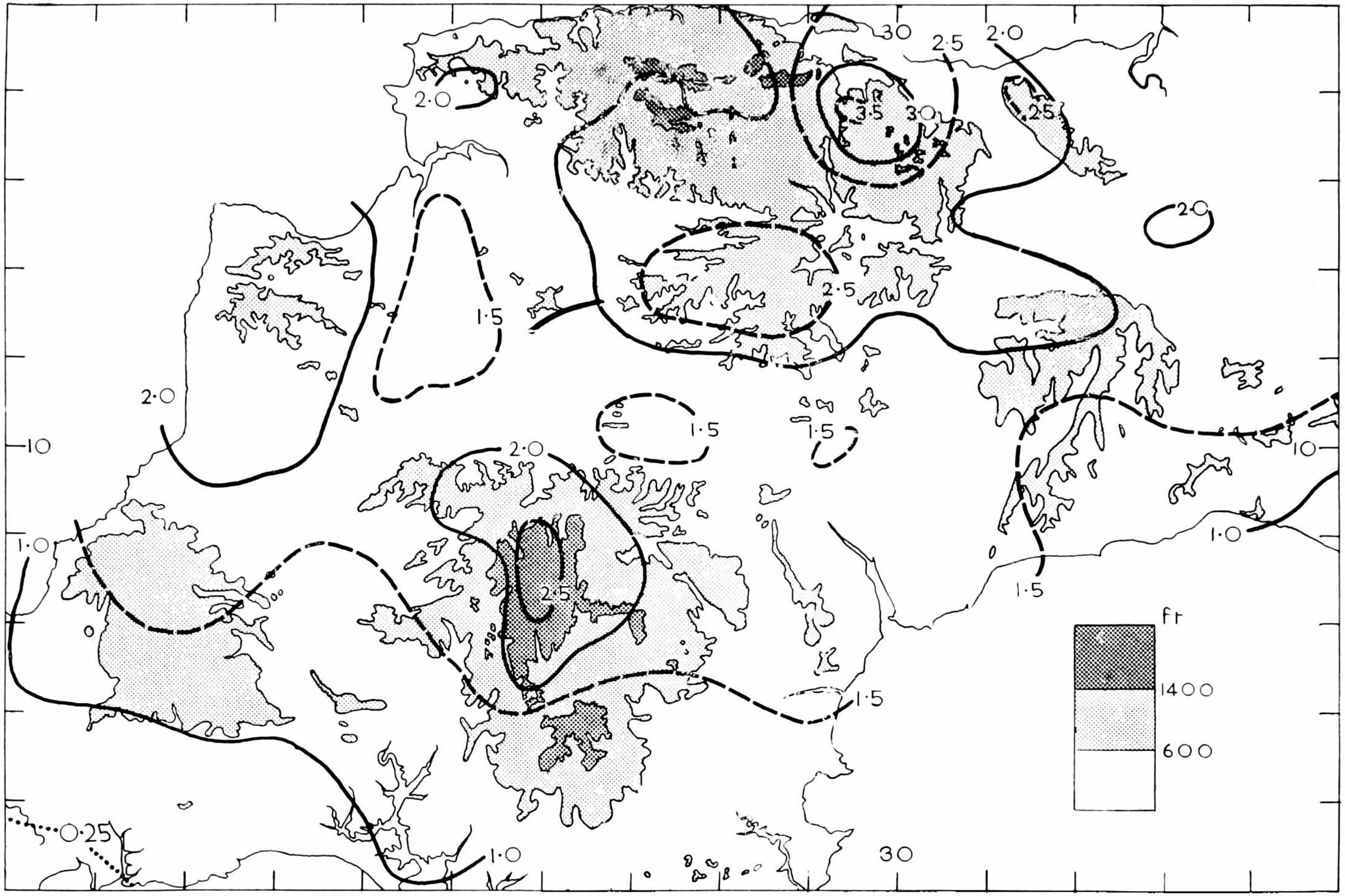

FIGURE 7—RAINFALL (INCHES) FOR THE 24 HOURS BEGINNING 0900 GMT, 26 OCTOBER 1960

To face p. 101]

Photograph by J. Konieczny

CLOUD DEVELOPMENT AT LITTLE RISSINGTON ON 11 JULY 1960

(see p. 120)

of the month occurred during the first three days, and it was particularly heavy in Wales and north-west England on the 1st. In Kent and Sussex on the 2nd there was extensive flooding, while on the 3rd 1·1 inches of rain were recorded in 35 minutes at Stanmore, Middlesex. Flooding occurred in many parts of the country during the month, but not on such a scale as in south Devon in October. In Devon the floods amounted to a disaster of the first magnitude. The greatest damage was near Exeter and in east Devon, but reports of flood damage were received from many areas of the country. About 2,000 houses were flooded, some being completely destroyed and others damaged beyond repair, and considerable damage was done to business premises, livestock and agricultural land. The floods are reported to have done more damage to Devon's railway system than occurred throughout the last war, and the dislocation to have been more serious than experienced at any time this century.

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HAIL IN RELATION TO THE RISK OF ENCOUNTERS IN FLIGHT

By A. F. CROSSLEY, M.A.

Introduction and summary.—The minimum size of hailstone likely to damage a supersonic aircraft needs to be determined in relation to existing or projected aircraft materials, and the chance of encountering hail larger than this minimum should be ascertained as far as possible. An article in *The MATS Flyer*[1] includes in a diagram cases of damage with hailstones as small as 0·05 inches (1 mm) diameter. This implies that practically any hail encountered is liable to damage existing aircraft with cruising speeds in the neighbourhood of 250 knots. If this speed is increased for supersonic aircaft by a factor of 4 to 8, the possible damage from hail, of whatever size, becomes evident. Strengthening the aircraft sufficiently to give protection from the impacts is likely to be practicable only for stones up to a certain rather small size, but there are considerable advantages if this size can be taken as at least 1·5 cm diameter. Stones larger than this would need to be avoided with the help of radar detection or otherwise, or by restricting flights to those areas, seasons or time of day in which large hail is not expected. For supersonic aircraft, the risk of encountering hail concerns the climb and descent stages in all latitudes and also flight up to about 55,000 ft in subtropical and equatorial latitudes; in higher latitudes, cruising flights above about 40,000 ft would almost always be within the stratosphere and so out of reach of hail on nearly all occasions.

Forms of hail.—Hail occurs in various forms which may be classified as follows[2]:

Hail. More or less spherical stones of ice, but sometimes of irregular shape, ranging in diameter from about 1 mm to 25 mm or more. The stones are usually composed of alternate layers of clear and opaque ice, but occasionally they consist entirely of clear ice.

Small hail. Semi-transparent round or conical grains of ice a few mm in diameter. Each pellet usually consists of a nucleus of soft hail (graupel) surrounded by a thin layer of clear ice which gives it a glazed appearance.

Ice pellets (American term sleet) are transparent, more or less globular grains of ice up to about 5 mm in diameter. The interiors may be liquid and the ice shell may burst on striking a hard surface.

Soft hail, graupel or snow pellets. These are white, opaque, rounded or conical pellets of diameter up to about 6 mm. They consist of a central crystal covered with frozen cloud droplets (rime). They are easily compressible and apt to shatter on striking a hard surface.

The remainder of this note is concerned mainly with "hail" and "graupel" only.

Density of hail.—This can vary from about 0·1 to 0·9 gm cm^{-3} according to structure. Ordinary hail is often assumed to have a density of 0·7 to 0·9, the latter figure corresponding with clear ice; soft hail or graupel is often assumed to have a value of 0·3.

Size of hail.—*The size of hail observed at the ground* usually refers to the largest stones in any particular fall. Diameters up to about 5 inches (13 cm) have been reliably reported. Mason[2] quotes the following figures for the frequency distribution of the sizes of the largest hailstones observed in the Denver area, Colorado, during 1949 – 55.

TABLE I—DISTRIBUTION OF HAILSTONE SIZES FOR THE DENVER AREA, COLORADO, 1949 – 55

	Diameter *in.*	No. of cases
Grain	<¼	10
Currant	¼	122
Pea	½	282
Grape	¾	149
Walnut	1 – 1¼	38
Golf ball	1¾ – 2	26
Tennis ball	2½ – 3	4

For India during the period 1833–97, Brooks[3] gives the following figures for 509 reported falls, but adds that presumably many lesser storms escaped notice.

Diameter (inches)	0 – ½	½ – 1	1 – 1½	1½ – 2	2 – 3	3 – 4	4 – 5	>5
Number	240	117	70	24	26	19	9	4

Cumulative frequencies from these data are shown in Figure 1.

Of 330 falls of hail spread over 12 days of storm and recorded[4] within 100 miles of the Radar Research Station, East Hill, Bedfordshire, 298 had a maximum diameter less than about 1 cm, 27 between 1 and 2 cm, and five up to 4 cm.

Douglas and Hitschfeld[5] describe 71 falls of hail on one day in central Alberta in which the stones were estimated to be of the size of a pea (6 mm) in 21 cases, grape (20 mm) in 42 cases, and walnut (30 mm) in eight cases.

There appear to be no data available concerning the size distribution of hail in any single fall.

The size of hail encountered in flight may be inferred from the damage sustained. Many case histories of damage to aircraft in the United States are listed by Souter and Emerson[6]; in 11 cases the maximum hail size was inferred from photographs of damage and ranged from about 1·3 to 1·8 inches diameter, but larger sizes have probably been encountered in flight, as mentioned below.

An analysis of the size of hailstones inferred from damage to United States aircraft is given in *The MATS Flyer*[1] in a diagram which is headed "103 cases 1954 to 1957", but only 96 are discernible. These are set out in Table II.

TABLE II—SIZE OF HAIL ENCOUNTERED IN FLIGHT (USAF)

Height	Diameter in inches $\pm\frac{1}{4}$								
	$<\frac{1}{4}$	$\frac{1}{2}$	1	$1\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	4
thousands of feet	*number of cases*								
50 – 40			1						
40 – 30		5	5	1	2				
30 – 20	1	4	2	2	1				(1 ?)
20 – 10	8	3	3	4	1		1		
10 – 0	10	20	12	8		1			1
Total	19	32	23	15	4	1	1	0	1
	percentage								
Total	20	33	24	16	4	1	1	0	1

This table cannot be expected to give a fair representation of the distribution of hail encounters with height, since the aircraft flights are not uniformly distributed over the various height ranges, the actual distribution being unknown. The cumulative frequencies of hail size, taking all heights together, are shown in Figure 1, but it should be remembered that these observations take no account of the smallest, non-damaging hail; nevertheless 20 damaging cases of less than $\frac{1}{4}$ inch diameter are included. The differences between the three curves of Figure 1, although considerable, are not surprising in view of the different conditions to which they apply, and the difficulties of observation.

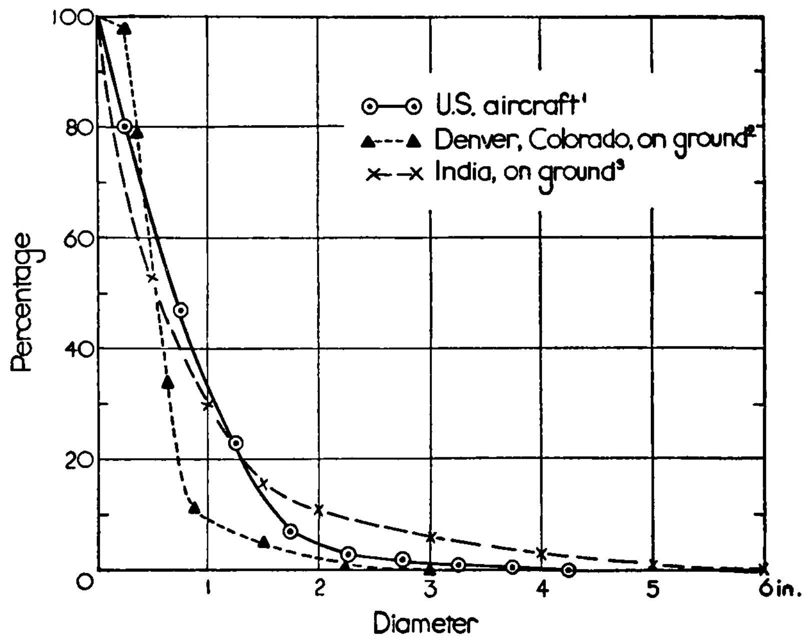

FIGURE 1—CUMULATIVE FREQUENCY OF LARGEST HAILSTONES

Upper limit of size of hail. In their work on the terminal velocity of hailstones, Bilham and Relf[7] inferred on theoretical grounds an upper limit of about 5 inches diameter to the possible size of hailstones. This accords quite well with observations, only one case of substantially greater size having been reported, and that is of doubtful authenticity.

Duration of falls of hail.—An analysis[4] of 251 falls of hail in the neighbourhood of East Hill, Bedfordshire, showed that the most frequent duration was was 2 min, while almost 50 per cent of the falls were of 3 min or less. If five cases exceeding 30 min, which probably involved more than one storm cell, are excluded, the average of the remaining 246 cases is 5·6 min. The duration in any case is affected by the movement of the storm; when this factor is eliminated, the average duration comes to about 7 min.

Mason[2] quotes an analysis by Beckwith of some 450 falls in the Denver area, Colorado; durations ranged from 10 sec to one extreme case of 45 min of continuous hail, the most frequent duration being 5 min.

Duration of hail encounters.—The duration of encounters in flight is given by Souter and Emerson[6] for 30 cases. Reported durations ranged from 15 sec to 10 min, 78 per cent were of 2 min or less, and the average was 2 min. True air speed at the time of passing through the hail was reported in 21 cases; the range was from 160 – 360 mph with an average of 229 mph. The computed air distance through the hail ranged from 1 to 28 miles, with a mean of 7 miles; in two-thirds of the cases the distance was 5 miles or less. In seven penetrations of cumulonimbus cloud in Malaya which encountered hail, durations in precipitation ranged from 20 to 222 sec and air distances from 1 to 12 miles (Frost[8]). In five of these cases, rain or snow were reported as well as hail, and it is not clear whether the hail was continuous throughout each of the stated durations.

Observations of the ground pattern of falls of hail show that the width of the hail shaft when it strikes the ground is most frequently about 1 to 2 miles. Souter and Emerson[6] quote a study by Lemons of 2105 damaging hailstorms in the United States; the widths (across wind) ranged from a few yards to 75 miles, while 50 per cent were within 1 to 3 miles. From this sort of evidence, one might imagine the hail core of a typical cumulonimbus cell in the mature stage to be of roughly circular section with a diameter of about 1 to 3 miles, but it seems that agglomerations of neighbouring cells can on occasions produce a more extensive area of hail. However, the inference from the pattern of hail at the ground of the pattern in the cloud may not be valid (see page 107).

The polar regions.—Hail at the surface is rare. What there is, is probably associated with frontal conditions, rather than with convection related to surface heating. Much of the hail is likely to be of quite small size or in the form of graupel. Observations from the north of Canada, slightly south of the arctic circle, indicate a frequency up to three days a year. Hail at higher levels is no doubt similarly rare, and it seems likely that there is no risk to present-day aircraft in these high latitudes. The risk to supersonic aircraft would need to be assessed in relation to hail size, and as a guess the maximum size here is put at about 1 cm diameter. At the same time, the polar regions in this connexion should be regarded as loosely defined.

Middle latitudes.—Hail is most common in the latitudes between the polar and equatorial regions. Distinction should be drawn between "large" hail and "small" hail, the latter including graupel and ice pellets. Large hail, which causes damage at the ground, is mainly confined to the interiors of the continents, and is said to be most frequent between latitudes 30° and 40° N. Small hail, on the other hand, appears to be more frequent over the oceans. Annual frequencies of hail do not appear to have been collated over the world as a whole; the average number of days with hail is around 5 – 10 in the continental areas mostly affected, with increases to 15 – 25 in some coastal regions which include the small varieties of hail in their records, and still larger values (again probably mostly of small hail) over parts of the oceans. The highest number so far noticed is 31 days per year at weather station J (52½° N, 20° W), and in the Falkland Islands, both averaged over a 10-year period.

Seasonal variation differs according to locality. Damaging hail over the continents occurs mainly in late spring and summer when surface heating and convection are most active, but there are exceptions; for example, places with Mediterranean-type climate get their hail in winter and spring. Hail over the north-east Atlantic is mainly a winter phenomenon. For example, the average number of days with hail in each month at weather station J over a 10-year period is as follows:

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						number of days						
6·4	5·8	2·6	4·0	1·3	0·2	0	0	0·5	1·5	3·2	5·4	30·9

Hail is almost entirely absent from June to September, and is most frequent in January and February. In the Falkland Islands the seasonal variation is less marked.

Diurnal variation. According to Souter and Emerson[6] "it is generally agreed that 50 per cent of all hailstorms occur between 1400 and 1800 local standard time and less than 10 per cent between midnight and noon". This remark probably refers to large hail in the United States of America, but is likely to be roughly applicable to other continental areas. From a graph given for the United States, it is deduced that 85 per cent of damaging hailstorms occur between 1300 and 2200 hours. On the other hand, "small" hail over coastal areas and oceans probably has no pronounced diurnal variation.

North Atlantic air routes. Routine observations received at London Airport from civil aircraft on North Atlantic routes in January and July, 1955 – 57, were analysed for the frequency of reports of hail. This element was included on three occasions in January and four in July out of a total of 16,346 meteorological observations. There was also a total of eleven reports of thunderstorms and it is possible that the aircraft may have encountered hail in some of these, since there is no provision for reporting both hail and thunderstorm simultaneously in the codes used (POMAR or AIREP). The hail reports by themselves indicate a frequency of occurrence of 1 in 2300 observations. The aircraft heights for all observations ranged from 6000 to 25,000 ft and on the occasions when hail was reported, from 8000 to 19,000 ft. There is no information in these reports on the size or type of hail encountered, or of any damage sustained.

Damage to BEA Viscounts. During the four years 1955 - 58, there were six occasions of damage by hail in 157,000 flights, or roughly 500,000 flying hours. These cases, together with one earlier one, are described by Harrower and Evans[9, 10]. The incidents occurred near Lyons, Limoges, Basle, Zurich, Frankfurt, Hamburg, Barcelona, at dates from 5 May to 18 August. No information is available to the writer regarding encounters with hail which did not damage the aircraft.

Damage to BOAC aircraft. Argonauts and Constellations have suffered severe damage on average once in every 30,000 flying hours; Comet I's had one case of damage in 25,000 hours' flying, which occurred[4] on climb from Rome between 2000 and 12,000 ft. A list of hail incidents to BOAC aircraft is given in the Appendix (page 109).

Hail size over the oceans. Reports of hail damage to aircraft in flight over the United States show a distribution in space which compares favourably with the distribution of large hail at the surface (Souter and Emerson[6]). The same publication states that no cases of significant damage to aircraft had been reported over the North Atlantic and North Pacific Oceans adjacent to the United States. Similarly with BEA and BOAC aircraft, reports of damage appear to be confined to continental and coastal areas, no cases of damage over the open oceans having occurred, so far as is known. The absence of damage may in part be attributable to deliberate avoidance of the more intense convection clouds, but it seems unlikely that this is the whole explanation. Hence it appears that encounters with large hailstones are likely to be confined to land areas, and especially to those parts where large hail is most frequent at the surface.

Reports from North Atlantic routes discussed above, together with the information given in the appendix, show that hail is encountered over this ocean, but absence of reports of damage suggests that the hail is of small size. This is supported by the absence of hail at the surface at weather station J in summer, although it is encountered in flight in that season. It follows therefore that what hail there is in that area in summer, melts before reaching the surface. The 0°C isotherm in this area is then at about 10,000 ft (700 mb); if hail falling from this level melts before reaching the surface, its initial diameter cannot be greater than about 7 mm (0·3 inch) if it is composed of solid ice (specific gravity 0·9), or about 1 cm (0·4 inch) for graupel (specific gravity 0·3),[11] if indeed graupel can be as large as this. It is tentatively suggested that somewhat similar size limitations may apply also over the mid-latitude oceans in other seasons.

Equatorial regions.—*At the surface.* While the occurrence of hail in the equatorial regions is very infrequent particularly near coasts and at low levels generally where falls usually average less than one day per year, it has nevertheless been reported from many places and some quite large stones are on record. The following paragraph is based on some remarks quoted by Lemons[12] in respect of Porto Rico and the Virgin Islands which are perhaps relevant to most of the equatorial region:

Hail has occurred at San Juan only twice during a 40-year period. Favourable conditions for the formation of hail seldom occur over small tropical islands. Altogether some 30 cases of hail were reported in 10 years at stations in Porto Rico. Sixteen places reported one or more of these storms, but several of the interior stations above 500 or 1,000 feet reported from two to six each. Thus it is evident that either continentality, or elevation, or both favour somewhat greater frequency of hail. The increased frequency of thunderstorms in the interior and over the mountains in Porto Rico is much greater than that of hail, so that it is the upper air conditions more than surface conditions which limit hail frequency here.

Thus, while hail generally is rare at the surface through most of the equatorial region, it is relatively more frequent over land than over the sea, and the frequency tends to increase with both the extent of the land and its elevation.

In flight. Frost[8] describes the results of a series of flights through cumulus and cumulonimbus clouds over Malaya and Sumatra. He says that hail "gave surprisingly little trouble"; it was encountered on 7 out of a total of 87 penetrations into cumulonimbus. Although the hail on one of these occasions was described as moderate to heavy, and on another as moderate, Frost makes no further mention of damage; presumably this was insignificant or at most slight, with the corollary that the hailstones encountered were not large. The true air speed was about 170 kt; aircraft heights ranged from 10,000 to 15,000 ft; temperature (outside cloud) ranged from $+10°$ C to $-4°$ C; duration of precipitation (hail, rain or snow) from 20 to 222 sec, with a case of "moderate to heavy hail" lasting 60 sec.

The frequency of the encounters with hail in cumulonimbus reported by Frost (7 in 87 penetrations) is almost the same as that given by Byers and Braham[13] and quoted by Frost for penetrations at similar heights (10,000 and 15,000 ft) in Florida and Ohio, totalling 52 in 684. There is no lack of intense convection in the equatorial region, and clouds build up at times to the neighbourhood of the tropopause at about 55,000 ft. The absence of large hail must presumably be accounted for in terms of the precipitation mechanism of the tropical clouds, which is known to differ on many occasions from that of extratropical clouds. Since any hail in the clouds must melt before reaching the ground at sea level, the maximum size of hail aloft can again be estimated from Mason's paper[11]. The 0° C level here is at about 16,000 ft, and by extrapolation from Mason's results it is estimated that the diameter of the hailstones at that level cannot exceed about 1·5 cm (0·6 inches) for solid hail, or about 2·5 cm for graupel. This does not imply that hail or graupel of these sizes necessarily exist there.

Frost's report refers to a semi-oceanic area. The appendix contains two reports of slight damage in the tropics, one over Timor Island, and one on the route Karachi – Calcutta. There is a report (unpublished) of damage to a Britannia aircraft at 18,000 ft while on trials near Nairobi; the size of the stones was estimated from the damage as about 1 inch diameter. Another report[14] mentions damage sustained by a Viking aircraft near Kisumu; the hail was estimated as 2 – 2½ inches diameter and the duration in hail was about 3 sec, but the height is not stated.

Relationship with thunderstorms.—There is no simple connexion between the frequency of falls of hail at the ground and the frequency of thunderstorms. Sometimes hail is reported more frequently than thunderstorms, sometimes it is the other way round. The relationship is complicated by the difficulty of ensuring that every fall of hail is observed, because of the possible melting of hail before it reaches the ground, and also because hail sometimes forms in convection clouds which do not develop into a thunderstorm. The restricted area and duration of hail in any one storm could explain why many flights through thunder clouds do not encounter hail. However, the meteorological conditions required for the formation of hail do not differ in kind from those required for thunderstorms, and any thunderstorm would be expected to provide at the least a possibility of hail. In a discussion by Wichmann[15] of exploration of thunderstorms by sailplanes at a Rhône meeting in 1938, it is stated that hail was found in each storm *without exception*, and indeed up to the greatest heights reached by the gliders. The main updraught in the thundercloud as revealed by these flights was found to be concentrated in a narrow funnel whose diameter approximates to the turning circle of the gliders, that is, of order 100 metres; this funnel tapers slightly towards the top of the cloud and (as shown in a diagram) may be inclined to the vertical. Within the funnel the updraught is quite smooth, but at the edges very intense turbulence prevails which increases substantially with height. Hail occurs in the funnel and as it is carried upwards, so the stones continue to increase in size.

Presumably the greater spread of hail observed at the ground, after allowing for the drift of the cloud (see page 104) arises partly from the slope of the funnel, and partly from hail carried out sideways from the top of the funnel before falling out through the cloud. Wichmann's work implies that the hail area in an active cell may be no more than a few hundred feet across, except temporarily due to fall-out when the updraught weakens and the cell begins to decay.

It hardly seems possible at present to estimate the frequency of hail encounters in flight from the frequency of thunderstorms. Apart from uncertainties regarding the area affected by hail and its duration, any one thunderstorm consists of a variable number of cells, new ones forming while older ones decay, and it is only while in the mature stage that a cell contains hail.

Practical measures against hail damage to aircraft.—Hail of small size is liable to be encountered in association with convection cloud in all localities. In most of the tropics, where convection cloud is very frequent, it appears (see pages 106 – 107) that hail is seldom greater than 1·5 cm diameter, while elsewhere the maximum size is likely to be less than this except over the continents. It is tentatively suggested that direct protection should be provided against hail up to at least 1·5 cm diameter and specific gravity 0·9, and that any larger stones should be avoided.

It would presumably be essential for supersonic aircraft to take avoiding action against large hail. Appropriate considerations include:

(i) *Use of in-flight radar detection.* This has its difficulties arising from the high airspeeds envisaged, it being understood that avoiding action would need to be initiated at about 100 miles' distance. This method is likely to be useful only against isolated outbreaks of convection cloud. At present it is not practicable to recognize hail itself by means of airborne radar, but only the precipitation cores of cumulonimbus in which hail, if present, would be located. Hail is also known to occur, occasionally, outside the cloud in which it originates, so that it would be necessary to avoid the clouds by a few miles.

(ii) *Use of pre-flight forecasts.* These forecasts will indicate in a general way whether intense convection would affect any stage of the route. If flight is to take place through an area in which convection is expected, consideration should be given to covering both the initial climb and the transition to supersonic flight by ground-based radar, since it is in these stages that avoiding action against convection cloud will be most difficult. The radar installation would be able to give the precise distribution of precipitating convection cloud immediately before take-off and also during flight. The cruising stage will mostly be above the levels attained by hail; any convection cloud affecting this stage would tend to be isolated and not difficult to avoid except possibly in the tropics. There is no means of forecasting hail itself, but only the convection clouds in which it might occur.

(iii) *Use of flight planning to avoid the areas or times of day when large hail is most likely to occur.* In practice this would mean avoiding certain continental areas between about 1400 and 2200 hours local time in certain seasons, except where the areas concerned can be overflown at a height great enough to avoid the risk of encountering hail. As regards height, damage from hail has been sustained up to 45,000 ft (*The MATS Flyer*[1]). The upper height limit of hail, of whatever size, is likely to coincide with the limit of convection cloud, that is about 35,000 to 45,000 ft in middle latitudes, increasing to 55,000 to 60,000 ft in the tropics. On present information it is not possible to indicate with confidence how the maximum size of hail varies with height, although Table II gives some information. Also relevant is a discussion by Appleman and Lehr[16] of hail encounters by aircraft of the United States Air Force; out of 109 cases at 25,000 to 44,000 ft, they find no evidence of any decrease with height in the chance of an encounter.

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Appendix

BOAC aircraft encounters with hail

From information supplied by Mr. E. Chambers, BOAC

Sector	Position	Altitude (thousands of feet)	Time GMT	Date	Intensity	Remarks
Atlantic routes						
Shannon – New York	51°N 36°W to 50°N 41°W	10·7	0350 – 0510	3. 5.57	light	Intermittent hail in thick As. No damage
London – New York	55° 10′N 34° 41′W	10	0110 – 0210	14. 6.57	moderate	—
Shannon – Gander	—	10 to 16	0500 – 1100	29. 1.57	moderate	Intermittent hail in Sc, embedded Cu
New York – London	overhead Sydney	11·5	0100	18.11.56	moderate	Layers and towering Cu
Prestwick – Gander	55° 20′N 07° 28′W	8	2210	25.10.56	light	—
London – Prestwick	Cheshire	6·5	1720	22. 8.56	heavy	Lightning strike
Prestwick – Gander	54° 40′N 25° 40′W	10	0125	22. 7.56	light	—
Shannon – Montreal	53° 30′N 52° 30′W	10	0536	July 1956	moderate	—
Gander – Bermuda	200 mi. SW Gander	18 to 15	2240	24. 7.56	light	Thick As, embedded Cu
Keflavik – Boston	59° 40′N 44° 10′W	11	0400	25. 4.56	light	Between layers
Moncton – London	overhead Stephenville	13 to 19	0330	6. 4.56	light	8/8 As, Ac, Cu
Gander – Montreal	Moncton	12·6 to 14·4	1115	25.12.55	light	—
European routes including Mediterranean						
London – Rome	Turin	19·5	1240	10. 7.57	moderate	8/8 Cs, embedded Cb tops 37,000 ft. Slight damage to radiators
Rome – Istanbul	abeam Amendola	15·5	1650	12. 6.57	heavy	Airframe effectively de-iced by hail but no damage
Rome – London	Turin to Genoa	20·5 to 22·5	1200	19. 5.57	heavy	Flying through Cb. Hail approx. 1 in. in diameter
London – Beirut	—	15	—	16. 8.55	heavy	Line Cb tops 23,000 ft. across track. Aircraft lifted to 16,500 ft. Heavy turbulence. Considerable damage
London – Idris	—	16·0	Moonlight	7.11.57	heavy	Heavy Cu, all radiators damaged

BOAC aircraft encounters with hail (cont.)

Sector	Position	Altitude (thousands of feet)	Time GMT	Date	Intensity	Remarks
Rome – Istanbul	20 mi. WNW Araxos	13·6	0920	3.11.56	heavy	7/8 Cu, Cb from cold front. Damage to radiator intakes. Strong standing wave after front
Rome – London	Elba to abeam Pisa	19·5 to 22·5	0840	3. 9.56	heavy	8/8 Cb. Cowlings damaged and coolers deformed
Damascus – Frankfurt	Frankfurt	11 to 8	1140	15. 6.56	moderate	Slight damage on nose
London – Tripoli	40°N 08°E to 37°N 12°E	13·5 to 15·5	1900	23. 4.56	moderate	—
Cairo – Rome	100 mi. SE Caraffa	14·5	Night	27. 9.55	moderate	8/8 Ac, Cb. Slight damage to radiators
London – Beirut	15 mi. S of Athens	15	—	16. 8.55	heavy	8/8 Cb. Airframe skin damaged
Rome – London	46°N 03°E	14·5	1750	23. 6.53	light	7/8 Sc, towering Cu
Croydon – Madrid	Croydon to I.O.W.	2·2	0815	23. 1.45	light	—
Subtropical and tropical routes						
Beirut – Karachi	20 min. after take-off	10 to 16	2200	26. 4.55	moderate	8/8 Ac, Cu
Basra – Karachi	Jiwani	15·5	0630	2.12.56	light	Isolated Cb. Cb in general Ns layer
Baghdad – Beirut	Beirut	12·5	1645	19. 3.56	light	Sc and large Cu
Kano – Rome	22°N 10°E	13 to 19	2210 – 2310	13. 6.57	moderate	—
Calcutta – Bangkok	200 mi. SE Calcutta	16	—	5. 8.55	moderate	Monsoon cloud, lightning strike in vicinity of nose
Calcutta – Singapore	—	16	—	8. 6.55	—	Lightning strike on starboard side
Karachi – Calcutta	—	19·5	0945	21. 7.57	heavy	Superficial damage to propellers and wing tips
Darwin – Djakarta	Timor Is.	14·5	2017 – 2207	6. 3.57	moderate	Search radar unserviceable. In and out Cb, As. Starboard wing tip damaged. Lightning strike
Khartoum – Entebbe (returned Khartoum)	100/150 mi. S Khartoum	16	0415	27. 7.56	—	8/8 As, 6/8–8/8 Cb

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SHORT-PERIOD FLUCTUATIONS OF THE SEMIDIURNAL COMPONENT OF PRESSURE IN THE TROPICS

By R. FROST, B.A.

Most people who are interested in the problem of pressure oscillations of the earth's atmosphere have assumed either tacitly or openly that in the tropics a reasonably adequate determination of the dominant second harmonic of pressure can be made using hourly observations extending over a limited period of three or four years and that in the subtropics and temperate regions between five and ten years of hourly observations are required.

Out of curiosity, whilst investigating the general problem of pressure variations over Malaya[1], the present writer calculated the semidiurnal components of pressure at Changi (Singapore) for each month of each year for the decade 1948–57 in order to test this assumption. It was expected, in view of the flat and irregular distribution of pressure and the large and self-evident diurnal variations of pressure near the equator, that a few years would suffice to give a determination which, apart from slight refinements in the second decimal place, could be used with some confidence. Rather surprisingly, however, over the decade in question the mean amplitude of the second harmonic did not tend to a limit with increasing number of years but in fact after four years continued to increase almost linearly with the number of years taken to obtain the mean, which throws considerable doubt on the validity of harmonics determined from ten years' observations or less at stations outside the tropics. In view of this somewhat unexpected result it was thought that a brief review of the findings

TABLE I—YEARLY VARIATION OF AMPLITUDE (MILLIBARS) AND PHASE ANGLE OF SECOND HARMONIC

	Jan.		Feb.		March		April		May		June	
	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2
1948	1·37	149·2	1·37	141·8	1·28	144·0	1·24	146·5	1·16	150·8	1·08	147·1
1949	1·32	150·1	1·26	142·8	1·30	142·5	1·19	150·1	1·06	144·0	1·00	146·4
1950	1·13	147·8	1·20	142·9	1·22	147·6	1·22	147·4	1·06	145·8	0·99	144·8
1951	1·13	151·0	0·98	145·6	1·29	145·9	1·12	143·8	1·07	148·0	0·96	147·9
1952	1·05	140·8	1·08	135·3	1·06	138·5	1·24	145·7	1·25	150·5	1·07	152·2
1953	1·33	154·6	1·45	144·9	1·50	145·6	1·58	146·0	1·42	152·4	1·25	150·5
1954	1·31	151·0	1·48	144·9	1·64	147·5	1·52	144·5	1·35	148·1	1·15	150·0
1955	1·39	152·8	1·41	144·0	1·59	145·0	1·54	148·8	1·38	150·8	1·24	152·5
1956	1·41	149·4	1·54	145·8	1·53	145·0	1·47	149·3	1·40	152·0	1·22	152·0
1957	1·45	146·1	1·31	150·8	1·62	146·5	1·61	149·3	1·48	146·4	1·24	153·5

	July		Aug.		Sept.		Oct.		Nov.		Dec.	
	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2
1948	0·97	146·1	1·06	150·5	1·25	153·8	1·40	161·8	1·31	160·4	1·30	154·4
1949	0·97	146·5	0·97	149·6	1·05	144·6	1·20	156·6	1·25	155·8	1·24	157·7
1950	0·95	145·7	1·06	143·6	1·16	145·7	1·20	153·5	1·17	155·5	1·24	150·2
1951	0·94	141·0	0·96	141·5	1·14	144·9	1·22	154·0	1·09	152·8	1·03	148·5
1952	1·05	148·5	1·07	146·9	1·40	151·0	1·53	158·6	1·49	159·3	1·48	151·6
1953	1·21	148·5	1·24	148·7	1·32	152·3	1·45	155·9	1·48	156·2	1·50	158·4
1954	1·12	146·2	1·14	147·6	1·43	150·1	1·59	156·7	1·51	160·1	1·42	160·2
1955	1·27	146·4	1·34	145·2	1·40	151·0	1·64	156·0	1·44	159·8	1·45	153·1
1956	1·24	144·2	1·28	150·0	1·45	154·0	1·61	155·9	1·52	157·8	1·49	150·4
1957	1·15	152·2	1·30	148·9	1·40	152·5	1·62	160·1	1·59	157·8	1·50	152·5

TABLE II—VARIATION OF AMPLITUDE (MILLIBARS) AND PHASE ANGLE OF SECOND HARMONIC OVER TWO FIVE-YEAR PERIODS

	Jan.		Feb.		March		April		May		June	
	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2
1948–52	1·20	147·8	1·18	141·7	1·23	143·7	1·20	146·7	1·12	147·8	1·02	147·7
1953–57	1·38	151·0	1·44	146·0	1·58	145·9	1·54	147·6	1·41	149·7	1·22	151·7

	July		Aug.		Sept.		Oct.		Nov.		Dec.	
	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2	a_2	A_2
1948–52	0·98	145·6	1·02	146·4	1·20	148·0	1·31	156·8	1·26	156·8	1·26	152·5
1953–57	1·20	147·5	1·26	148·1	1·40	152·0	1·58	156·9	1·51	158·3	1·47	154·9

a_2 and A_2 are the amplitude and phase angle respectively of the second harmonic.

at Singapore would be of interest and possibly stimulate investigation at other stations in the tropics.

The variations in amplitude and phase of the second harmonic from month to month are exhibited in Table I for each year of the decade. Whilst as previously shown[1] the monthly means based on ten years' observations fall into a consistent pattern which bears a close relationship with the annual march of the sun, the monthly amplitudes calculated from the annual means show some rather surprising and non-random variations. These are shown even more clearly in Table III, which depicts the departures of the monthly amplitudes calculated from annual observations from those calculated from the decadal observations. From this table it can be seen that a marked discontinuity occurred between August and September 1952, the mean amplitudes before that date averaging approximately 0·12 millibar below the corresponding ten-year means and after that date averaging approximately 0·12 millibar above the corresponding ten-year means. No change of instruments or their location can be held responsible for this discontinuity.

TABLE III—MONTHLY DIFFERENCES IN MILLIBARS FOR EACH YEAR FROM THE MEAN MONTHLY AMPLITUDES FOR 1948–57 AT CHANGI (SINGAPORE)

	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957
January ...	+·08	+·03	−·16	−·16	−·24	+·04	+·02	+·10	+·12	+·16
February ...	+·06	−·05	−·11	−·33	−·23	+·14	+·17	+·10	+·23	0
March ...	−·12	−·10	−·18	−·11	−·34	+·10	+·24	+·19	+·13	+·22
April ...	−·13	−·18	−·15	−·25	−·13	+·21	+·15	+·17	+·10	+·24
May ...	−·11	−·21	−·21	−·20	−·02	+·15	+·08	+·11	+·13	+·21
June ...	−·04	−·12	−·13	−·16	−·05	+·13	+·03	+·12	+·10	+·12
July ...	−·12...	−·12	−·14	−·15	−·04	+·12	+·03	+·18	+·15	+·06
August ...	−·08	−·17	−·08	−·18	−·07	+·10	0	+·20	+·14	+·16
September ...	−·05	−·25	−·14	−·16	+·10	+·02	+·13	+·10	+·15	+·10
October ...	−·04	−·24	−·24	−·22	+·09	+·01	+·15	+·20	+·17	+·18
November ...	−·08	−·14	−·22	−·30	+·10	+·09	+·12	+·05	+·13	+·20
December ...	−·06	−·12	−·12	−·33	+·12	+·14	+·06	+·09	+·13	+·14

The mean monthly amplitudes and phases calculated for the two lustra 1948–52 and 1953–57 respectively are given in Table II and show that the monthly amplitudes in the latter are almost consistently 20 per cent higher than those in the former. Since each amplitude is calculated from about 3600 observations whose standard deviation about the mean is of the order of 2 millibars, the standard deviation of each of these harmonics is approximately 0·05 millibar, so that it is very unlikely that the marked change in amplitudes can be attributable to chance. According to Simpson's empirical formula[2] the mean annual value of the amplitude at Singapore should be 1·25 millibars, whereas for the first lustrum the calculated amplitude is 1·17 millibars and for the second lustrum 1·40 millibars, whilst for the complete decade the calculated amplitude is 1·30 millibars. Now the mean annual value of the amplitude from six stations in Malaya (between 2° and 6° north of the equator) from each of which twelve to sixteen years of hourly observations were available, is 1·29 millibars, whilst the annual value of the amplitude at Djakarta (approximately 6° south of the equator) based on forty-nine years of hourly observations is 1·33 millibars[1]. It would seem, therefore, that near the equator approximately ten years' observations are required to yield reasonably adequate values of the amplitudes of the second harmonic. Unlike the amplitudes, the monthly phase angles show little evidence of any systematic variation from year to year but values of the phase angle determined for any month of the second lustrum are always higher than those of the first lustrum, the greatest difference being 4·3° or 8·6 minutes in February.

Consideration of the spatial and temporal variations in the long-period mean monthly amplitudes and phases of the second harmonic over Malaya and Singapore previously discussed[1], strongly supported the view that the second harmonic of pressure as well as the first was in some way or other connected with the solar heating, but certain features were difficult if not impossible to reconcile with the generally held resonance theory and, as an alternative hypothesis, it was suggested that the convective flux of heat in the layer from about one kilometre to the tropopause was the cause of the second harmonic. If this hypothesis is correct then it might be expected that the fluctuations in the amplitudes and in particular the marked discontinuity which occurred between August and September 1952 should be reflected in corresponding fluctuations in the temperatures of the upper troposphere over Singapore.

It is unfortunate that a consistent set of upper air temperatures is not available at Singapore for the decade under consideration but there is a striking parallelism between the fluctuations in these amplitudes and the fluctuations in the mean monthly temperatures over the same period at the 500-, 300- and 200-millibar levels at New Delhi which were discussed by Veryard and Ebdon[3] (see Figure 1 of their paper). Table IV, taken in part from Table I of their paper, shows the yearly differences from the mean annual upper air temperature at New Delhi together with the yearly differences from the ten-year mean amplitude included for purposes of comparison.

TABLE IV—COMPARISON BETWEEN YEARLY DIFFERENCES IN °F FROM MEAN ANNUAL TEMPERATURES FOR 1948–57 AT NEW DELHI AND YEARLY DIFFERENCES IN MILLIBARS FROM MEAN ANNUAL AMPLITUDES OF SECOND HARMONIC AT SINGAPORE

mb	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957
200	−4·3	−7·9	−5·0	−5·4	−1·8	+2·5	+5·0	+5·4	+3·6	+0·9
300	−3·2	−6·3	−4·3	−5·0	−1·3	+1·1	+4·0	+3·6	+3·0	+1·1
500	−2·3	−3·6	−3·4	−2·9	−1·8	+0·4	+1·3	+2·2	+2·0	+0·9
a_2	−0·6	−0·15	−0·17	−0·21	−0·07	+0·09	+0·09	+0·12	+0·13	+0·14

Whilst it is tempting to speculate on the possible cause of the apparent relationship between the changes of upper air temperature at New Delhi and the changes in the amplitude of the semidiurnal pressure wave at Singapore, the main purpose of this note is to draw attention to the remarkable variations in the amplitude of the second harmonic of the pressure variation at Singapore over the decade 1948–57, and it is considered that calculations of the amplitudes of the pressure waves at New Delhi and further data from Singapore are required before such speculation would be profitable.

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551. 508. 74

A STANDING DEW METER

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Summary.—A portable, battery-operated dew meter is described which gives a direct reading of the total water deposit on a uniform short grass surface, such as a well cut lawn.

Introduction.—The presence of free water on a short grass surface, commonly regarded as "dew", may be caused in one or more of three ways. Two of these involve condensation and Monteith[1] has proposed that they be distinguished by the names "distillation" (for upflux from the soil), and "dewfall" (for downflux from the atmosphere). The third is "guttation", the exudation of water droplets by plant root pressure. This has been estimated by Angus[2] to account for 20-25 per cent of the total water in some circumstances. Any such moisture on the blades of grass will delay the rise of temperature and the onset of evaporation stress during the day and, if the total amount can be determined, useful information may be obtained without attempting to distinguish the source.

The standing dew meter here described, when placed on dewy grass, gives an immediate measurement of the total free water on the grass blades and may be used to sample rapidly a large area. It is easily portable and is independent of mains power supply.

Description.—The instrument, shown in general appearance in Plate I, has a sensing element the electrical capacity of which changes in the presence of more or less water. It is mounted in the bottom of a carrying case about 18 inches by 3 inches by 3 inches, which also contains a detecting circuit and indicator. The element consists of an interleaved grid of $\frac{1}{32}$-inch brass strips let into a $\frac{1}{2}$-inch ebonite base, and these form the two plates of a capacitor. Each plate was made of fifteen such strips with a separation of $\frac{1}{16}$ inch. The whole was set in Araldite casting resin type 123 B, the surface of which after hardening was milled to leave the brass elements flush with the Araldite. The surface was then given three coats of Estapol plastic coating type 7008. This provided a tough, transparent, insulating skin, some five thousandths of an inch thick, impervious to water and water vapour (Plate II).

When the element is placed on the grass any water present acts as a dielectric with specific inductive capacity different from that of air; hence the capacity increases with increasing amounts of dew. The variations in the capacity of the element, which is about 1,000 pico-farads, are detected by an electrical circuit using the repeated ballistic discharge method described by Jason[3]. In this circuit a vibrator operating at frequency n repeatedly charges the capacitor C to a potential E, and then discharges it through a current meter. The mean current I, indicated by the meter is given by $I=nCE$.

The arrangement used in the present instance is detailed in Figure 1. A standard commercial 12-volt vibrator (Oak type V6712) energized by two $4\frac{1}{2}$-volt torch batteries connected in series has been found suitable, and it operates at about 100 cycles per second. Several months' use may be obtained from one pair of batteries as the daily period of operation is normally only a few minutes.

Six type 419E deaf aid cells provide the 180-volt source used for charging the capacitor. With the vibrator and sensing element used the value of the mean current drawn from these batteries with the greatest feasible amount of

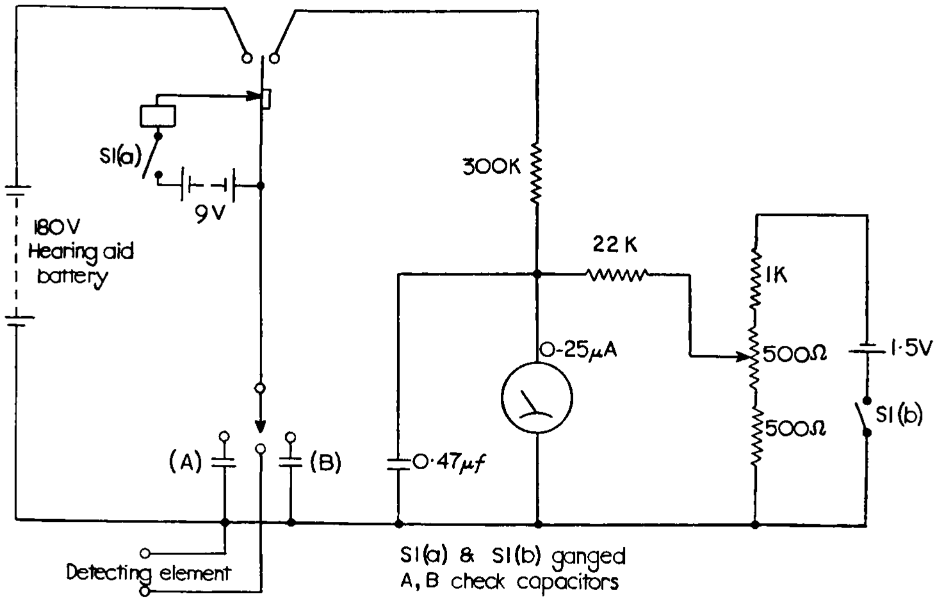

FIGURE I—CIRCUIT DIAGRAM OF STANDING DEW METER

dew is only about 20 micro-amps, and their life is virtually shelf life. A backing-off voltage derived from a single 1·5-volt cell is used to obtain a zero reading on the meter when the element is dry. A 500-ohm potentiometer acting as a voltage divider in this circuit provides a zero setting control. Two fixed capacitors are included in the circuit to give check readings at two points on the scale and thus indicate any decline in battery condition, or zero drift in the measuring circuit.

Operation.—The standing dew meter has been used to obtain comparative readings of dew deposition on a standard grass surface. A strip of fairly fine grass was mown regularly to maintain the surface as nearly uniform as possible. The dew meter was pressed firmly on to the grass, the pressure was released and then the reading on the micro-ammeter taken. A mean of several such readings on different parts of the test area was taken, the sensing element being wiped dry between successive readings with an absorbent cloth. This eliminated any error due to moisture adhering to the surface of the element.

Calibration.—This was by comparison with readings obtained by absorption of dew with previously weighed filter papers. Although the accuracy of this method has been questioned by Monteith[1] there seems to be no more suitable alternative. The continuous weighing method described by Jennings and Monteith[4] for example, provides an accurate record of the gain of moisture from the atmosphere (dewfall) but any moisture contributed by distillation or guttation would not be recorded although it would clearly affect the standing dew meter. It is also limited to a single, very small sampling area. The methods due to Duvdevani[5] and Leick[6] require the introduction of artificial dew catchers which is undesirable. It is felt that with the precautions described below the filter paper method provides a satisfactory calibration.

The procedure adopted was as follows: a plywood template was made, with five circular holes cut in it of diameter equal to that of the filter papers used, in this case Whatman No. 3 papers, 11 centimetres in diameter. The template was pegged on to the grass after dew deposition, and five previously weighed filter papers used to mop up as much dew as possible from the five exposed areas of grass. These papers were then sealed into a previously weighed boiling tube. This was repeated, without moving the template, with two further sets of five filter papers, and the three boiling tubes with wet papers weighed. The mean amount of dew absorbed by each set of five papers was then expressed in millimetres of deposition. Plotting these amounts cumulatively gave a curve tending to an asymptote. Examples of such curves are shown in Figure 2. The asymptotic value was taken as the true amount of dew on the grass. From several such tests it was estimated that the total of the three measurements was close to 98 per cent of the asymptotic value.

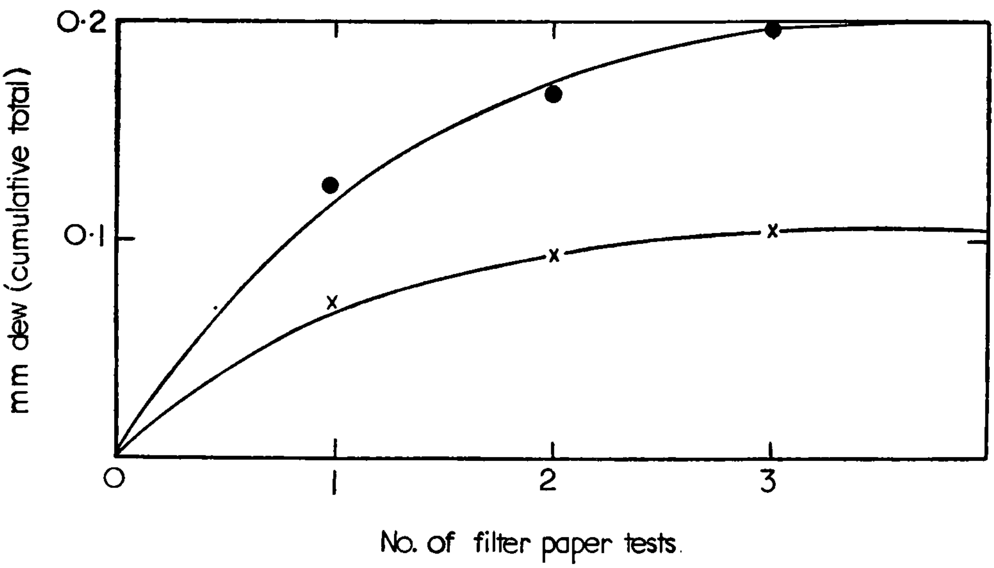

FIGURE 2—CUMULATIVE PLOT OF DEW ABSORBED BY FILTER PAPERS

The dew meter calibration obtained by this method is logarithmic and is shown in Figure 3. The overall accuracy is within ± 10 per cent of the measured value. The maximum amount of dew measured was about 0·3 millimetre and this is consistent both with results obtained by other workers and with energy balance considerations. It is clear, however, that variations in the amount of moisture contained in the blades of grass themselves and in the first few millimetres of underlying soil would cause differences in calibration. These differences have been examined by taking "dry grass" readings after the dew had evaporated and it was found that the maximum variation attributable to this was ± 5 per cent of full scale deflection.

The calibration shown was taken in a regularly mown area of short grass and does not necessarily apply to other lengths or types of grass. Some tests were carried out on longer, coarser growth on which the filter paper technique was more difficult to apply, and the resultant points showed a much greater scatter than those obtained from the short grass. However, the mean values were not inconsistent with the calibration shown in Figure 3, although it is clear that neither the instrument itself nor the method of calibration is entirely suitable for use on rough grass especially as this normally also has an irregular underlying soil surface.

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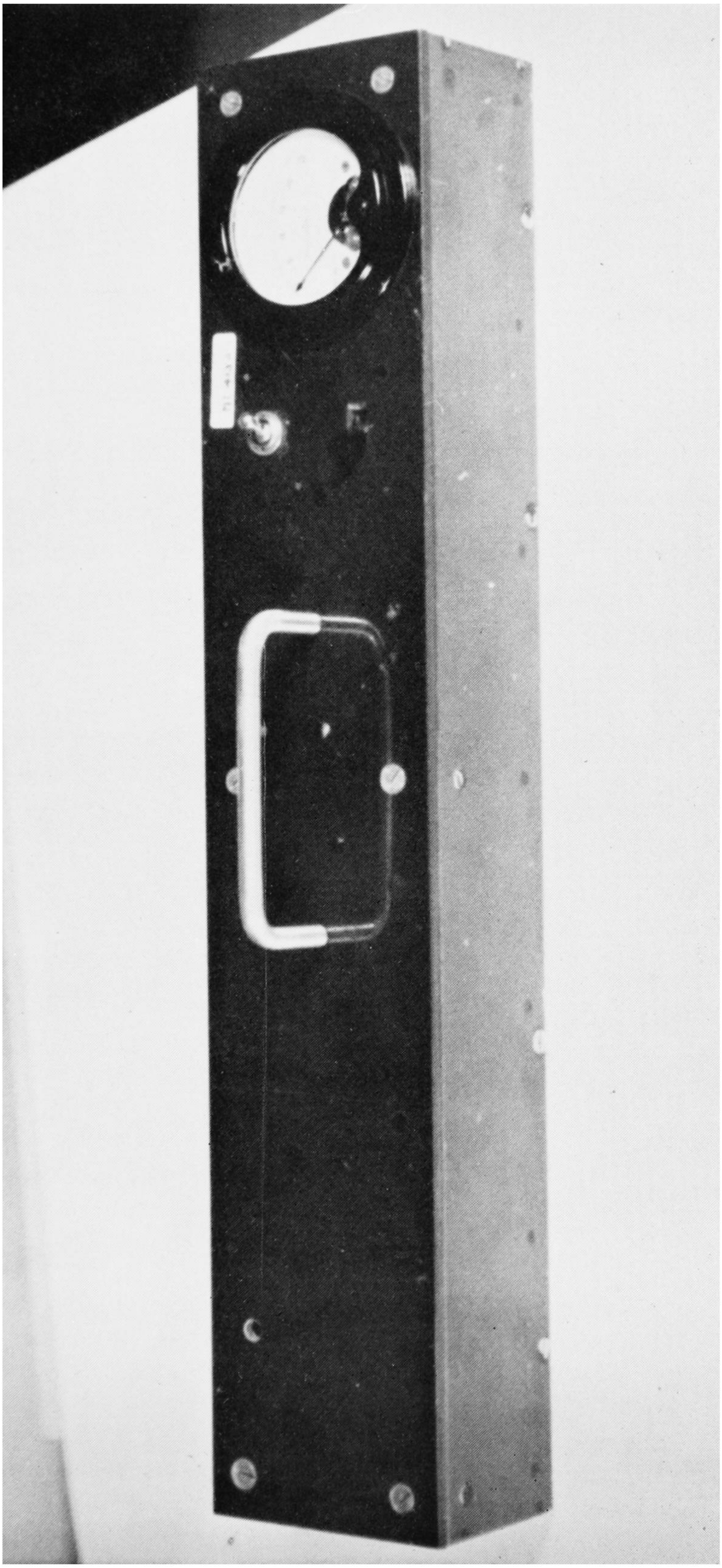

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PLATE I—GENERAL APPEARANCE OF STANDING DEW METER

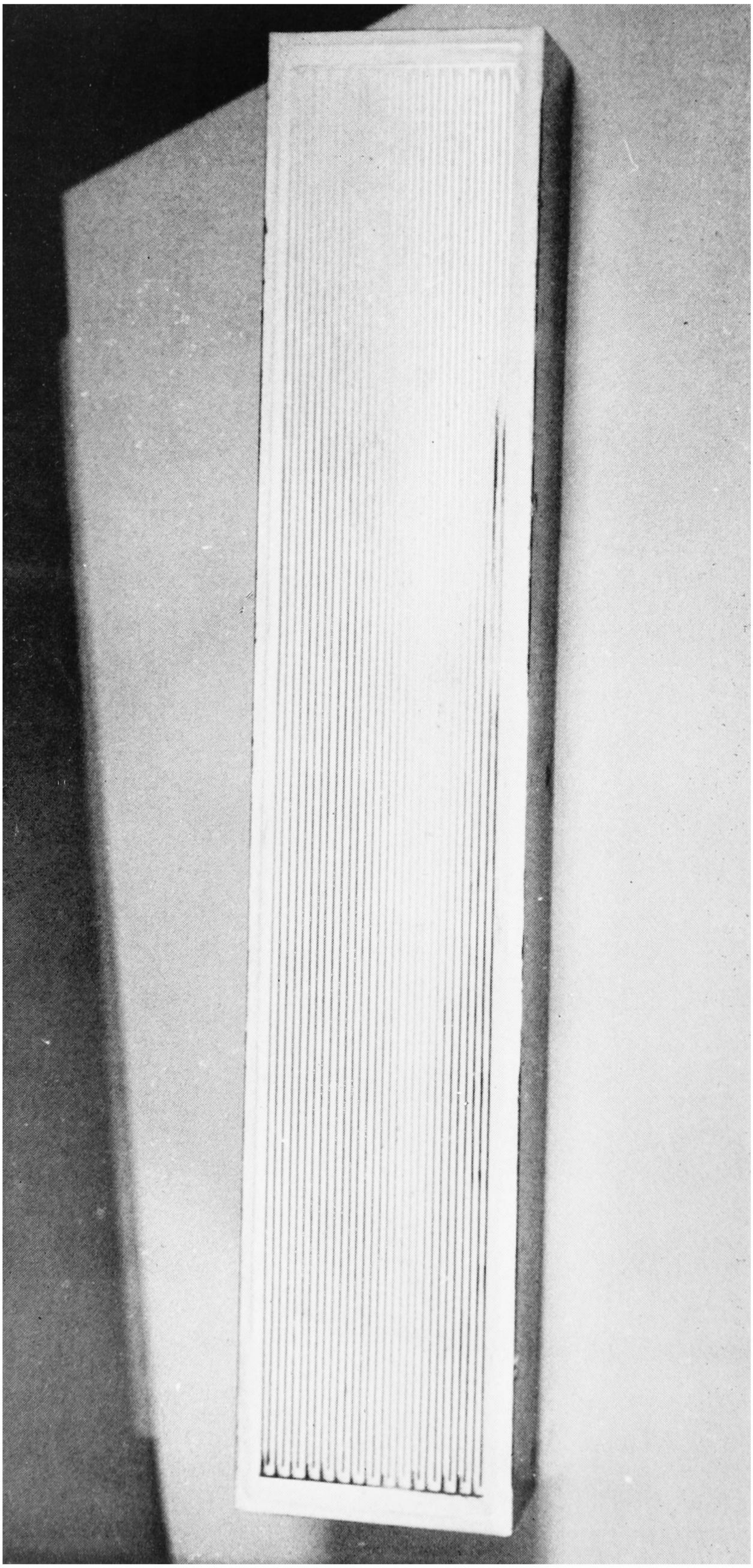

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PLATE II—SURFACE OF DETECTOR ELEMENT

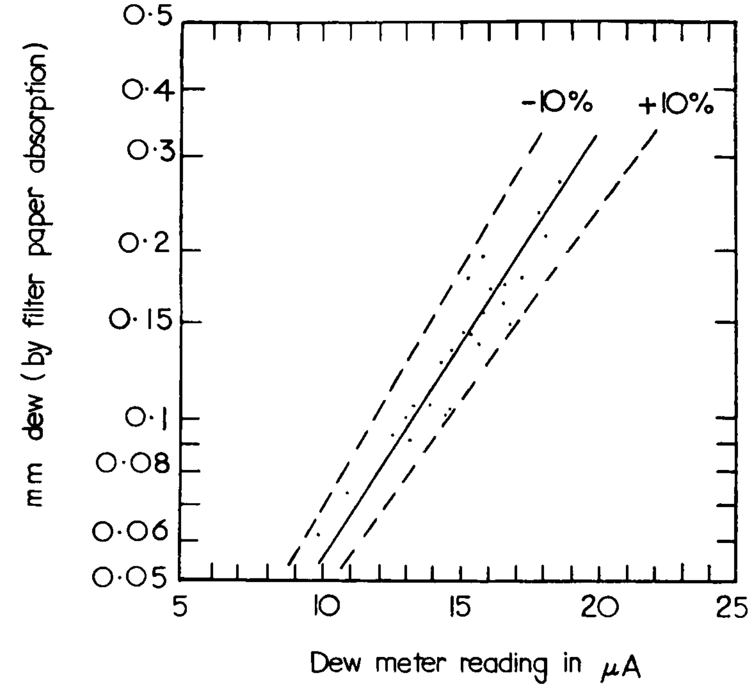

FIGURE 3—CALIBRATION OF STANDING DEW METER ON A SHORT GRASS SURFACE

Conclusions.—The standing dew meter described, which is simple and direct to operate, gives an estimate of the amount of dew (including guttation and distillation) on short grass with an accuracy of ± 10 per cent. In most cases, this will be sufficiently accurate for obtaining comparative records of the amount of dew forming each night on a well cut lawn, or similar surface.

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NUMERICAL FORECASTS MADE WITH TWO- AND THREE-PARAMETER MODELS

By E. KNIGHTING, B.Sc.

Introduction.—The first prolonged experiments in numerical prediction of the pressure field carried out by the Meteorological Office were made in 1959 and have been reported at length in a *Scientific Paper.*[1] The experiments proceeded from the Sawyer-Bushby forecasting equations[2] and used both conventional and objective analyses to provide the initial data. The level of success of the 24-hour forecasts was similar to that of the conventionally produced forecasts, except that at 1000 and 500 millibars the root mean square contour height error was significantly larger for the numerical forecasts. A series of experiments using a stream function at the mid-tropospheric level to compute the winds was carried out in 1959[3] and it was shown that this modification significantly reduced the contour height errors. An extended test of both these models was started in the spring of 1960 and computations were carried out for 43 cases on a daily basis, excluding week-ends.

Models and data

(i) The stream-function model chosen was that which assumed the wind field at 600 millibars to be given by a stream function obtained from the contour height field through the balance equation. The thermal wind field was derived from the thickness field by the ordinary geostrophic assumption and the system of equations closed by using the thickness equation derived from the first law of thermodynamics, allowance being made for the heating of relatively cold air over the sea[3].

(ii) The three-level model assumed geostrophic balance, with the wind shear and stability in the upper half of the troposphere differing from those in the lower half[4].

(iii) Forecasts were also made using the Sawyer – Bushby model as described in *Scientific Paper No.* 5[1].

(iv) The initial data required to carry out the first and third experiments were the 1000- and 500-millibar contour heights at specified geographical points over an area covering most of the North Atlantic Ocean and Europe; objective analysis schemes were available for the computation of such data.

The three-level model required, additionally, data at 200 millibars; since an objective analysis scheme had not then been developed for this level and since the objective analysis schemes were undergoing revision to remove some faults in the region of deep depressions, the initial data was obtained from the conventionally analysed upper air charts, referring to 0001 GMT, of the Central Forecasting Office (C.F.O.), Dunstable. This method of obtaining the data is slow and would not be acceptable if the forecasts were to be made on an operational basis.

TABLE I—MEAN STATISTICS FOR 24-HOUR FORECASTS, FEBRUARY – MAY 1960

Model	1000 millibars				500 millibars				1000–500 millibars				200 millibars				500–200 millibars			
	a	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
	m	*kt*			*m*	*kt*			*m*	*kt*			*m*	*kt*			*m*	*kt*		
1. Stream-function	69	25	0·54	0·65	74	27	0·64	0·75	54	28	0·67	0·57	109	40	0·59	0·71	79	25	0·40	0·11
2. Three-level	60	23	0·56	0·69	61	25	0·68	0·78	52	29	0·65	0·56	73	29	0·67	0·77	47	25	0·56	0·28
	55	21	0·56	0·69	57	24	0·69	0·79	49	27	0·65	0·58	69	28	0·67	0·78	45	25	0·54	0·28
3. Sawyer–Bushby	71	26	0·51	0·65	65	28	0·64	0·76	52	29	0·67	0·56								
4. C.F.O.	48	19	0·63	0·71	63	25	0·65	0·76	49	23	0·64	0·58	74	26	0·65	0·77	48	20	0·50	0·27
	45	18	0·61	0·72	61	23	0·65	0·76	47	22	0·63	0·60	71	25	0·63	0·77	47	20	0·49	0·28
5. Persistence	56	21		0·64	79	30		0·63	61	27		0·43	96	33		0·61	50	21		0·24
	53	20		0·61	76	29		0·63	59	26		0·45	91	32		0·62	48	21		0·25

a: Root mean square contour height error.
b: Root mean square wind error.
c: Correlation coefficient between forecast and actual 24-hour contour height changes.
d: Stretch vector correlation coefficient.
The results for models 1 and 3 and the results given in the upper rows for models 2, 4 and 5 are for 43 cases. The results in the lower rows are for 55 cases, made up of 43 cases and another 12 cases.

Results.—Verification statistics were computed over an inner area of 16×12 points, as described by Knighting and others[1], for the numerical forecasts, the conventional C.F.O. forecasts and forecasts of persistence; they are summarized in Table I for the 43 cases. Table I also gives the statistical results for 55 cases, including the 43 cases already quoted, in order to indicate the stability of the statistics.

Before discussing the relative merits of the forecasts as indicated by the mean statistics of Table I it is interesting to compare them with the corresponding results for the Sawyer – Bushby model, C.F.O. and persistence forecasts obtained for a similar period in 1959. These results, given by Knighting and others[1], are reproduced in Table II.

TABLE II—MEAN STATISTICS FOR 24-HOUR FORECASTS, JANUARY – MAY 1959

Model	1000 millibars				500 millibars				1000-500 millibars			
	a	*b*	*c*	*d*	*a*	*b*	*c*	*d*	*a*	*b*	*c*	*d*
	m	*kt*			*m*	*kt*			*m*	*kt*		
Sawyer – Bushby	80	29	0·66	0·60	86	29	0·73	0·78	54	26	0·78	0·61
C.F.O.	63	24	0·67	0·61	79	27	0·69	0·75	64	26	0·68	0·58
Persistence	75	31		0·41	100	37		0·52	78	32		0·31

All the results are for 42 cases.

On comparing Table II with Table I it is clear that in 1960 there was more persistence of type, with the root mean square contour height and wind errors reduced and the correlation coefficients of persistence forecasts increased. In Table II it is also apparent that the 1000 – 500-millibar thickness is better forecast using the Sawyer – Bushby model than by C.F.O., and this result was repeated in the experiments carried out in the summer of 1959. In Table I the C.F.O. forecast of thickness was superior, a reversal of the former results and indicative that the conventional forecaster is relatively more successful in forecasting mean temperature changes in periods of lesser change than in periods of greater change. The differences in Tables I and II underline that forecasting systems can only be properly compared when tested over the same periods and that it is necessary to test over a large number of cases.

Returning to Table I, the figures relating to the 1000 – 500-millibar thickness forecasts are very similar for the three numerical models, because the thickness changes are dealt with in much the same way in all three. The root mean square wind errors are greater than those for the C.F.O. forecasts and also slightly greater than those for persistence. The root mean square contour height errors are similar to that of C.F.O. and less than those for persistence, while the correlation coefficients quoted are similar to those for C.F.O. and superior to those for persistence.

At the 1000- and 500-millibar levels the three-level model appears to be superior to the other two numerical models. At 500 millibars its forecasting success is equal to that of C.F.O.; at 1000 millibars its success is slightly inferior to that of persistence, which in turn is slightly inferior to that of the C.F.O. forecasts. The results of these tests at the lowest level should not be judged against persistence, because the period over which the forecasts were made was much more persistent in type than have been other periods tested in this country and elsewhere.

The Sawyer–Bushby and stream-function models, which deal with the motions of the 1000–500-millibar thickness field and at 500 millibars, imply changes in the contour fields above 500 millibars and hence are capable of predicting the 500 – 200-millibar thicknesses and the 200-millibar contour heights. The forecasts were obtained by adding the implied forecast 24-hour changes to the initial fields. The three-level model deals directly with the changes in these upper fields. The statistics given in Table I show that using the three-level model leads to forecasts which are decidedly superior to those made using the two-level stream-function model. The results corresponding to the three-level model are directly comparable with those obtained from the C.F.O. forecasts, both being superior to those corresponding to persistence. Of the numerical models tested the three-level model is the most satisfactory and yields forecasts which are comparable with those produced by C.F.O. at all levels, except perhaps near the surface, where the C.F.O. forecasts appear to be a little better.

Conclusions.—The conclusions to be drawn from the data obtained are:

(i) The three-level model gives superior forecasts to those obtained using either of the two-level models.

(ii) The forecasts made using the three-level model are as successful as those made by C.F.O. except at the lowest levels, where they are slightly inferior.

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NOTES AND NEWS

Rapid cloud development

An unusual and rapid cloud development was observed at Little Rissington, near Cheltenham, at about 1500 hours on 11 July 1960 and lasted for about eight to fourteen minutes. At this time, a deep depression was centred in the North Sea and an associated trough with heavy showers and thunderstorms affected the Cotswolds. A large cumulonimbus cloud was observed to approach the Rissington and Stow-on-the-Wold area and, while it was four to five miles to the west, its forward part protruded two to three miles sharply forwards. The base of the forward part was estimated at 4,000 to 5,000 feet and at the top was rapidly developing upwards to about 12,000 feet. The top of the main cumulonimbus cloud further west was estimated as over 20,000 feet.

At about 1500 hours the rapid vertical development in the protruding part of the cloud seemed to cease and heavy precipitation, absent before, commenced from the cloud but the precipitation did not reach the ground. Seconds later, cloud began to form in the precipitation and the cloud grew rapidly downwards. In a matter of four to five minutes the cloud base lowered from about 4,000 feet to about 200 feet above the high ground, with some fractostratus patches at tree-tops level. A photograph of the cloud structure faces p. 101.

The explanation would seem to be concerned with the breakdown of a development cell which started in the protruding part of the cloud. The interesting points are: the development cell being so far in advance of the main cloud structure and the very rapid formation and lowering of the cloud in the falling precipitation.

J. KONIECZNY

REVIEW

Frontiers of the sea, by Robert C. Cowen. 9 in. × 6 in., pp. 307, *illus.*, Messrs. Victor Gollancz Ltd., 14 Henrietta Street, Covent Garden, London, 1960. Price: 25*s*.

This book deals in a lively manner with many aspects of the science of oceanography—physical, chemical, biological, geological, and even political. The rapid developments in oceanographical research work during the last few years are adequately covered. There is little meteorology in the book, except in one chapter, "The Great Heat Engine", and this is largely devoted to an account of theories of climatic change in which the oceans play a spectacular role, for example, the glacial theory of Ewing and Donn, which assigns a key role to the self-regulating variations in the efficacy of the exchange of water between the North Atlantic and the Arctic Oceans across the sill between Greenland and Norway.

The author emphasizes that our present knowledge and understanding of ocean currents is still only rudimentary. Quasi-synoptic measurements in the Gulf Stream show that it is by no means a continuous band of warm water but a complex branching system accompanied by eddies and interspersed with counter-currents. Oceanographers need something equivalent to the meteorologists' synoptic charts if they are to gain a better understanding of the dynamics of the oceans. A start was made during the International Geophysical Year when 25 nations put 80 research ships to sea in co-ordinated survey work, and the Special Committee on Oceanographical Research (SCOR) has been appointed to promote further international co-operation in this field.

A striking example is given of the influence of climate on marine life: in the Sargasso Sea weedlike fishes and weedlike crabs exist and even one air-breathing inhabitant—the intrepid water-rider, which runs over the sea surface on six long hairy legs, using the Sargassum weed as a resting place. Climatologists of today will not be flattered by the implication on page 24 that they are statisticians who are content to extract an average picture from a mass of data. Perhaps it is some comfort to know that the author is here assessing the contribution of Maury to marine meteorology.

The book can be strongly recommended to anyone who is interested in the general science of the oceans.

F. E. LUMB

METEOROLOGICAL OFFICE NEWS

Mr. P. Auty, Assistant Scientific, has been presented with the Kenya Photographic Society's cups, awarded annually for "Portraiture" and "The five best prints".