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THE ACCURACY OF RAIN-GAUGES

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Purposes of rain-gauge comparisons.—There is considerable variation of the efficiency with which different designs of rain-gauge collect precipitation. It is the aim of rain-gauge comparisons to assess these differences of behaviour. So variable is the efficiency of rain-gauges that their design, installation and siting is strictly stipulated by the individual meteorological organizations in an attempt to unify national networks. International comparisons have been initiated by the World Meteorological Organization[1] in an attempt to provide information to unify the data from the various national networks. However, rain-gauge efficiency is not a constant quantity, but is dependent upon the nature of the precipitation and other climatic factors, both during the storm, and in the interval between the storm and the measurement of the collected water. Thus, although it is an easy matter to obtain reduction coefficients between gauge types used together over an extended period (a year is commonly adopted), these are dependent on the unique combination of climatic factors affecting the efficiency throughout the period. Poncelet[2] in Belgium has shown that such coefficients become reasonably steady only if the period is as long as five years. In using such coefficients, it must be remembered that they are validly applied only to data comparable with those from which they were derived.

It often happens that rainfall measurement is imperative in places where the conditions depart seriously from national standard conditions. When studying the water balances of forests,[3,4] it has been found necessary to measure the rainfall above the trees. Such measurements have also been made by the author in Bagley Wood, near Oxford, and for some time now records from fifteen gauges above the trees have been collected. Several kinds of wind shield and gauge have been employed: the aim of the comparison in this case has been to define the most efficient rain-gauge in this situation. The experience from this installation and from the treatment of the data has been incorporated into this paper.

Experimental methods of comparison.—

(i) *Design of the rain-gauge network.—The site* for the comparison need not be sheltered, but it should be sufficiently uniform to prevent the effects of the location of the individual gauges from obscuring the differences between the instruments themselves. In fact, an exposed site would allow of a comparison under a wider range of wind conditions, but the area is likely to be less uniform than a sheltered one. The *design of the array* of gauges should be such as to overcome location effects within the site rather than to demonstrate these as did Poncelet.[2] The account of his field comparison of rain-gauges has previously been reviewed,[5] when the value of duplicating each gauge type was discussed. Allis *et al.*[6] recognized that their comparisons suffered from a lack of replication of gauges. Replication is a precaution against any unsuspected lack of uniformity over the site; the greater the likelihood of variability, the larger should be the number of similar gauges. To reduce the replication necessary, and yet minimize the effects of site variability, the gauges could be moved every time a certain number of showers have been recorded, following the method used to overcome rainfall variability beneath trees.[7] The systematic arrangement of the compared gauges (for example, by Poncelet[2]) normally results in the differences caused by instrument design being confounded with any systematic variability across the site. The instruments therefore should be placed at random over the area,[6] the only restriction being that they must not be so closely spaced as to disturb one another's behaviour.

(ii) *Additional instrumentation.*—Various rain-gauge designs differ in the degree to which they are subject to errors caused by evaporation from the funnel or the container, splashing out of the funnel, splashing into the gauge from the ground or a wind shield, condensation in the funnel, and aerodynamic effects. According to the resources of the station, as many as possible of the primary causes of these effects should be measured, although the Belgian work illustrates how much can be done when only approximate data are available.[2]

Of the greatest value is a *rainfall recorder* on the site for assessing the rainfall intensity (mean intensity over the total record, or short-period maximal intensity), the number of showers contributing to a record (and thus the number of wetting and drying cycles to which the gauges are subject) and the time of the rain, for the purpose of synchronization with other environmental measurements. A simple *directional rain-gauge* has been found very valuable in the comparison of rain-gauges at Oxford. It serves as a useful check on the freedom of the individual gauges from anomalous location effects. The angle of incidence of the rain (a function of raindrop size and wind speed) can be computed from the directional gauge[8] to assist in interpreting the differences between gauge types. *Recording anemometers* are valuable in assessing the varying efficiency between the instruments in overcoming aerodynamic errors. While the wind speed ought to be measured at the height of the gauges on the site, some important information might be obtained in a detailed study of the wind speed around the individual instruments. Other factors associated with evaporation can be measured with a *thermohygrograph* and a *solarimeter*, while the temperature of the rain-gauge surface might also be recorded.

Treatment of data.—

(i) *Form of basic data.*—Reading the rain-gauges at intervals shorter than 24 hours increases the information yielded by the installation.[3]

Splashing and aerodynamic factors are operative only during the time of rainfall; evaporation takes place after the rainfall as well. To utilize the environmental information it is necessary to integrate the readings separately for each of these two periods. The integration may be manual, from the recorder charts, or automatic, by modifying the recording instruments. There is obviously considerable scope for ingenuity in designing a meteorological station such that the information is collected in the most relevant form, provided that the comparison of rain-gauges is sufficiently important to warrant such development. For example, the integration of the information collected during rainfall ought probably to be weighted according to the rain intensity. It is to be noted that the directional rain-gauge in fact does this. It would be of considerable assistance to the subsequent analysis of the data if as much as possible was recorded directly in a form suitable for a computer.

(ii) *Classified ratios of rain-gauge catches.*—The ratios between the total catches of different instruments over a lengthy period allow of very little interpretation of the differences unless climatically distinct seasons are compared. It is more informative to classify the data according to the climatic conditions associated with each record, and then to compare the ratios between gauge collections in each class. Poncelet[2] has demonstrated this method, and has shown that the various gauge designs conform with the relationships of the classified results. A synopsis of the classification has been given, and the limitations of the method discussed.[5]

(iii) *Correlation of relative catches.*—A better method is to adopt a multiple regression approach (first suggested by Riesbol[9]) since this allows of simultaneous variation among the environmental variables. Furthermore, the effect of interaction between the environmental variables on the relationship between gauges may be defined, and the arbitrary limits of the classes in Poncelet's method are removed. Three types of regression have been used in the treatment of the data from the gauge comparison at Oxford. They are illustrated by the following equations, where R_1 and R_2 are the catches of the compared rain-gauges (or the mean catch where replication is employed), and x_1, x_2 etc., are environmental variables:

$$R_1 - R_2 = a + bx_1 + cx_2 + dx_1x_2 \ldots \qquad \ldots (1)$$

$$R_1/R_2 = a' + b'x_1 + c'x_2 + d'x_1x_2 \ldots \qquad \ldots (2)$$

$$R_1 = A + BR_2 + CR_2x_1 + Dx_1 + ER_2x_1x_2 + Fx_1x_2 + Gx_2 \ldots \qquad \ldots (3)$$

Equation (1) reveals the relationship between the absolute differences in catch and the environment, irrespective of the size of record. This is suitable for analysing the differences between gauges due to 'end losses' caused by wetting and retention. Equation (2) is useful to interpret cumulative differences dependent on the size of the catch. Equation (3) allows of insertion of wetting differences and cumulative differences at the same time, interactions on the right-hand side involving R_2 representing cumulative effects, and those without R_2 the 'end effects.' Seventy per cent or more of the variability (expressed as the sum of squares) between the tree-top gauges at Oxford has been shown to be correlated with environmental factors by such equations. The form of the functions of the environmental factors as inserted in the regression should follow, as far as possible, the form in which they are known to affect the physical processes which govern rain-gauge efficiency. Where this is not yet known, the form of the functions should be as rational as possible.

Where the 'independent' variables are known to be highly correlated among themselves as in the case of those which condition gauge behaviour, the statistical significance attaching to each of the partial regression coefficients is considerably determined by the inclusion or exclusion of related variables. A better form of statistical analysis in this case is multivariate analysis.

Application of derived relationships.—With the improvements outlined above, the conventional method of assessing the accuracy of rain-gauges by the comparison of instruments in the field is eminently suited to climatological studies. Despite the different gauge designs employed in the different countries, such a procedure could lead to the unification of the data from the various national networks.[1] The relationships between gauges defined in terms of the prevailing climatic environment, are applicable within the range of conditions under which they are derived, and not only to the unique climatic combination of the site over a period. The relationships are thus similar to Poncelet's *Interpolation coefficients*[2] for the application of the results of gauge comparisons to areas where no comparison has been conducted, solely by reference to the climate of these areas. The regression equations are applicable to individual storms unlike simple coefficients from gauges compared for lengthy periods.

Using these field methods the causes of the differences between gauge types can be analysed, in so far as correlations can be interpreted to distinguish cause and effect. The defects and merits of the different instruments can be defined, and this would lead naturally to improved designs.

Limitations of field comparisons of rain-gauges.—It is important to point out that this method necessarily gives only the relative accuracy of each gauge. Even with the most advanced field methods and data treatment, there seems no prospect of assessing the absolute accuracy of rain-gauges in this way. For instance, the measurements of rainfall above the trees in Bagley Wood gave surprisingly consistent records and statistically reliable estimates for the mean rainfall.[10] However, since the water balance of the plantation is being assessed, it is necessary to know the absolute accuracy of these estimates; unfortunately the installation provides no information on this. Allis *et al.*[6] reached a similar conclusion from their comparisons. In other situations where the object of using rain-gauges is the assessment of the total quantity of precipitation over an area, comparative estimates of gauge efficiency are inadequate. Those people concerned with water supply, water yield, urban or rural drainage, flood prevention and forecasting, river works, and water balance studies for biological or hydrological purposes are particularly troubled by the problem of the accuracy of rain-gauges. In these fields, for adequate sampling, the gauges may have to be sited in exposed places such as on hillsides or above trees, instead of adhering to the national standards. Errors associated with such gauges may be particularly high.

The absolute accuracy of rain-gauges.—To emphasize the importance of defining the absolute errors of rain-gauges, Table I is reproduced as an example of a tentative estimation of their size.

These errors need to be quantitatively assessed for each type of gauge in relation to the prevailing conditions. There follows a consideration of some ways of achieving such an assessment.

TABLE I—APPROXIMATE ERRORS OF RAIN-GAUGES (AFTER KURTYKA[11])

Source of error	Size of error *per cent*
Evaporation	−1.0
Adhesion	−0.5
Colour	−0.5
Inclination	−0.5
Splash	1.0
Exposure (wind)	−5 to −80

(i) *Weighed lysimeters.*—The suggestion was made by Harrold and Dreibelbis[12] that constantly weighed blocks of vegetated soil are more accurate and more sensitive than rain-gauges, for the measurement of precipitation. The average annual excess of such a weighed lysimeter compared with a U.S. Weather Bureau Fergusson gauge was 4.38 inches at Coshocton, Ohio, with a mean annual precipitation of about 45 inches. Most of this difference occurred in the collection of snow or light rain. Weighed lysimeters present no aerodynamic differences from the surrounding ground. Splashing onto or off the lysimeter should not affect the accuracy of a carefully designed installation. However, weighed lysimeters are subject to evaporation and transpiration during rainfall which would produce errors in the measurement of precipitation and detract from their value as standards with which to compare rain-gauges. Weighed lysimeters record the condensation of water in and on the soil and on the vegetation. In the work of Harrold and Dreibelbis this was admittedly overestimated;[13] although the source and the quantity of this water is greatly dependent on the height and density of the vegetation,[14] it probably constitutes an error in rain-gauging. Nevertheless, in common with other ground-level gauges (see, for example, Bleasdale[15]) which are also subject to evaporation and condensation errors,[2] weighed lysimeters do minimize the Jevons' wind effect which is probably the largest source of error in rainfall measurement (see Table I).

(ii) *Stroboscopic and filming methods.*—Ideally, a standard against which conventional rain-gauges could be compared, would present no obstruction to the wind, no gains or losses by splashing, no thermal sink or store which would condense or evaporate water before measurement, and no surface which must be wetted and thus retain some unmeasured water. This could be achieved if the vertical component of the rate of fall and the quantity of water involved could be measured with a beam of light. This might be possible using a reflected stroboscopic beam with frequency scanning, measurement of the transmission, and appropriate orientation with respect to the direction of the falling raindrops.

Alternatively, electronic scanning of successive high-speed photographs of the falling raindrops might be developed to measure the quantity of rainfall.

(iii) *Simulated rainfall.*—It is conceivable that the production of uniform simulated rainfall (cf. Childs[16]) over rain-gauges in the field would be a feasible proposition for evaluating their efficiency. The true rainfall being known, the true accuracy of the gauges under measured climatic conditions could then be assessed.

(iv) *Controlled environment.*—Perhaps the most profitable way to estimate the absolute accuracy of rain-gauges would be to examine the aerodynamic effects by measuring the characteristics of air movement around gauges in a wind tunnel, and to determine the fate of raindrops theoretically. The thermodynamic relations of the gauges might be used to estimate condensation and evaporation errors. The assessment of splashing errors too might be approached fundamentally. Poncelet[17] has promised a theoretical estimation of the errors of rain-gauges which should at least reveal the possibilities of this method.

Conclusions.—Many scientists and engineers rely upon the accuracy of rain-gauges, but most have neither the time nor the facilities to estimate the absolute efficiency of gauges to sample rainfall correctly. They require information in one of two forms: either a statement of the conditions under which the various gauges function with a known and tolerable efficiency, or the corrections to be applied to rain-gauge catch according to the prevailing climate. In any event, it is a matter of considerable urgency that the absolute accuracy of rain-gauges currently in use be established, even although this involves an extensive programme of research.

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PERIODIC AND RANDOM FLUCTUATIONS OF THE WIND AT ADEN

By G. A. TUNNELL

Introduction.—Three-hourly wind observations over a seven-year period have been analysed and reveal very interesting periodic and random fluctuations in the wind in the Gulf of Aden. The record was obtained from an unobstructed cup anemometer and wind vane set up at a height of 41 feet at Khormaksar airfield on the narrow isthmus that runs 3 to 4 miles north and south connecting Aden to the mainland of Arabia. Figure 1 shows a map of the area.

General analysis of the observations.—The monthly mean of wind at a specific hour over the seven-year period is denoted by vector $\mathbf{V}_m$. The average of the values of $\mathbf{V}_m$ for the eight three-hourly observations during each 24 hours is taken as the general monsoon wind for the month and is denoted by $\mathbf{V}_M$. The difference $\mathbf{V}_m - \mathbf{V}_M$ is considered to be a diurnal variation in the wind and is

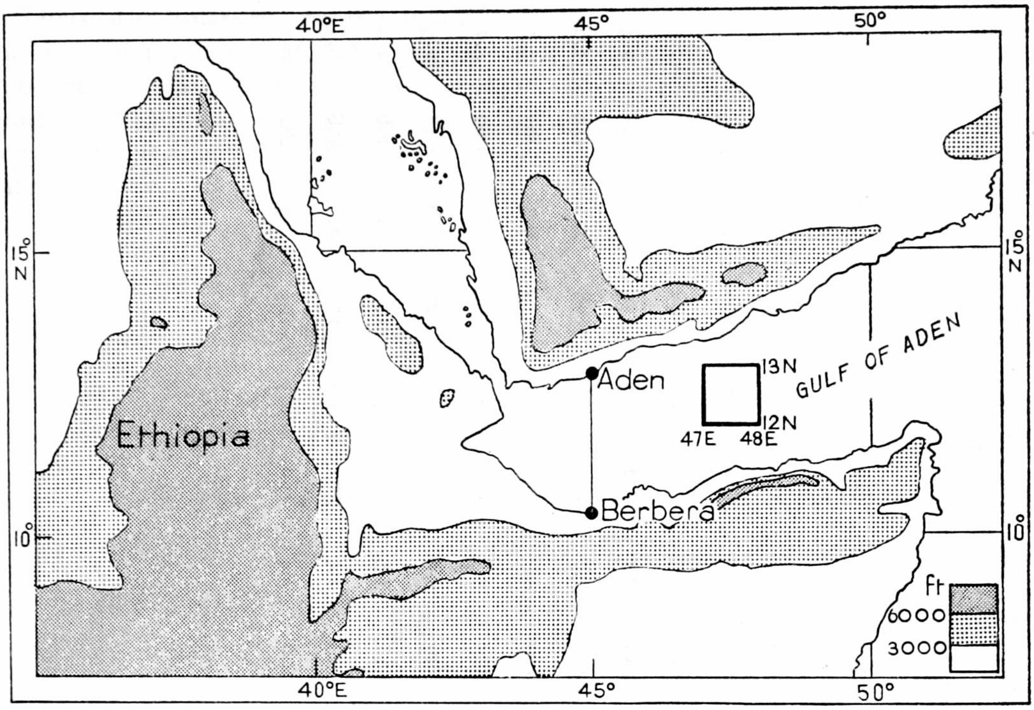


FIGURE I—MAP OF THE AREA

denoted by $\mathbf{V_d}$. If the actual wind is $\mathbf{V}$ then the difference $\mathbf{V}-\mathbf{V_m}$ is considered to be a random variation $\mathbf{V_R}$ produced either locally or from fluctuations in the general circulation by transitory systems of varying sizes.

The surface wind $\mathbf{V}$ at any time may then be taken to consist of the general monsoon wind for the month, plus a diurnal variation from the mean, plus a random variation component. Thus

$$\mathbf{V} = \mathbf{V_M} + \mathbf{V_d} + \mathbf{V_R}\,.$$

It is found convenient to resolve the various vectors into components perpendicular to and parallel to the general direction of the coastline of Arabia at Aden, so that

$$\mathbf{V} = u\mathbf{n} + v\mathbf{c}$$

where $\mathbf{c}$ is a unit vector pointing along the coast (065° from north), $\mathbf{n}$ is a unit vector pointing inland and perpendicular to $\mathbf{c}$, and u, v are the magnitudes of the components of $\mathbf{V}$ in directions of $\mathbf{n}$ and $\mathbf{c}$ respectively.

Similarly
$$\mathbf{V_m} = u_m\mathbf{n} + v_m\mathbf{c}$$
$$\mathbf{V_M} = u_M\mathbf{n} + v_M\mathbf{c}$$
$$\mathbf{V_d} = (u_m - u_M)\mathbf{n} + (v_m - v_M)\mathbf{c}$$
$$\mathbf{V_R} = (u - u_m)\mathbf{n} + (v - v_m)\mathbf{c}\,.$$

Regular variations of the wind.—Aden experiences two distinct climatic seasons: (i) that of the south-west monsoon during July and August, and (ii) the remainder of the year when the north-east monsoon predominates,[1] though there are transitional months.

Table I gives for each month the strength and direction of the monsoon winds which are remarkably constant during each of the two monsoon periods. The mean wind $\mathbf{V_M}$ during the north-east monsoon is 095° 6 metres per second, while during the south-west monsoon it is 225° 3 metres per second.

TABLE I—MONTHLY MEAN WIND AT ADEN AND THE DIURNAL VARIATION

Diurnal variation ($\mathbf{V_m}$—$\mathbf{V_M}$) for varying hours (LMT)

Month	Monthly mean wind		0000		0300		0600		0900		1200		1500		1800		2100	
	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec	deg	m/sec
Jan.	095	6.0	331	0.9	340	1.1	328	1.3	005	0.9	102	1.3	165	2.3	188	1.5	297	0.3
Feb.	096	6.1	002	0.9	344	1.1	323	1.4	005	1.0	109	1.2	171	2.6	192	1.6	341	0.5
Mar.	095	6.2	020	0.8	329	0.9	326	1.3	001	0.6	136	1.1	173	2.7	196	0.9	002	1.1
Apr.	098	5.3	342	0.9	328	1.3	320	1.5	015	0.4	142	1.7	167	2.8	172	0.8	003	1.3
May	104	3.4	350	1.1	343	0.9	327	1.7	009	0.5	145	2.2	172	2.9	173	0.7	344	1.4
June	194	1.5	043	1.8	029	1.0	354	1.5	031	0.4	211	2.7	222	3.8	158	0.7	049	2.6
July	225	2.7	056	3.2	058	2.4	038	1.2	235	1.2	240	4.7	238	5.2	113	0.5	062	4.1
Aug.	225	2.7	054	3.3	063	1.8	020	0.6	250	0.5	239	3.8	237	5.1	198	0.4	062	4.2
Sept.	164	1.5	035	2.0	037	0.9	351	1.3	320	0.3	199	2.2	211	3.4	226	0.8	045	2.5
Oct.	100	3.6	340	2.2	327	2.1	323	2.8	050	0.8	147	3.5	166	4.1	170	1.3	356	1.6
Nov.	091	5.2	342	1.6	318	2.4	315	2.4	041	1.2	129	2.4	162	3.3	176	1.7	358	0.6
Dec.	094	6.0	353	0.8	340	1.3	324	2.0	020	1.5	120	1.4	169	2.7	193	1.8	282	0.1

There are however striking seasonal changes shown in the tabulations of the diurnal variation ($\mathbf{V_d}$). During the north-east monsoon the wind increases and declines daily along an axis perpendicular to the coast, while during the south-west monsoon it increases and declines along an axis parallel to the coast. This is illustrated in Figure 2 which gives $\mathbf{V_M}$ and $\mathbf{V_d}$ for January and July.

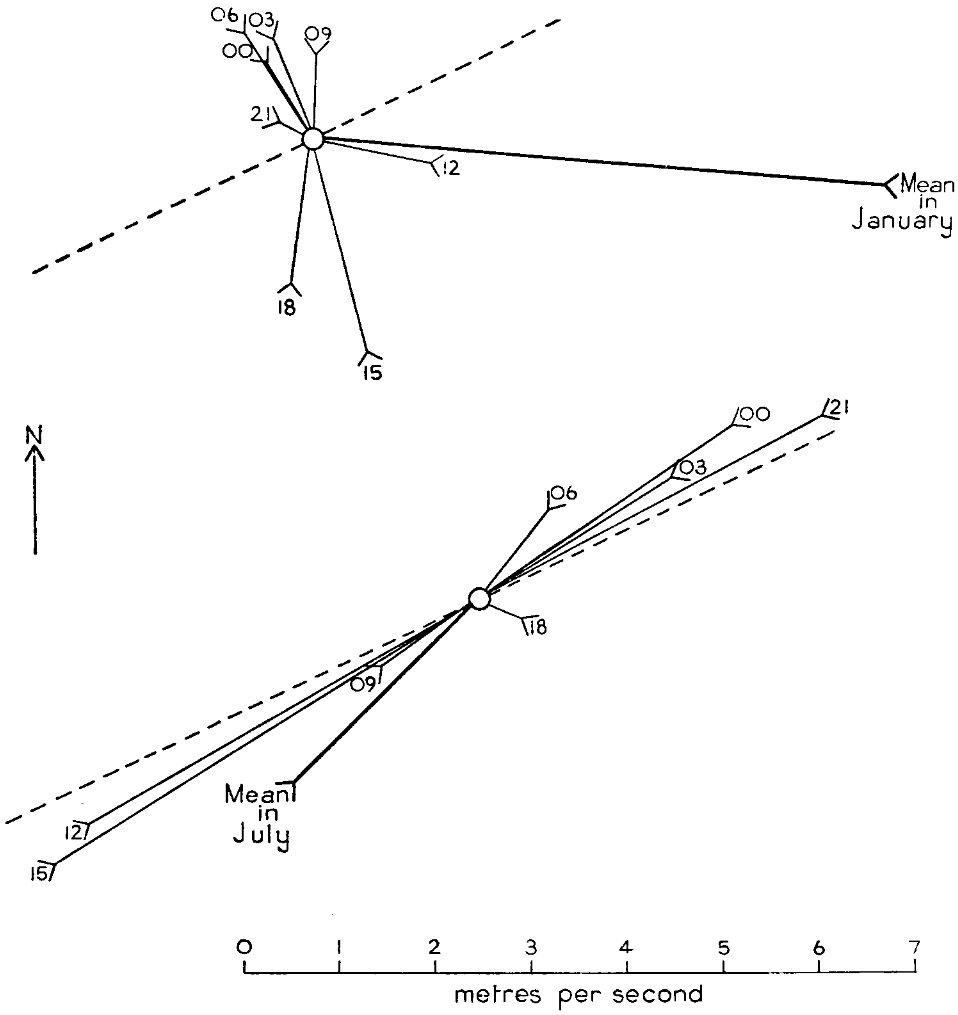


FIGURE 2—DIURNAL VARIATION ($\mathbf{V_m} - \mathbf{V_M}$) AT ADEN IN JANUARY AND JULY
Winds are drawn as vectors measured towards the station position according to the scale shown. Times of observations (LMT) are entered in the arrow tail.
— — — Coastline, ——— monthly mean wind, ——— diurnal difference from the mean.

The character of these changes is revealed more clearly by the variation in the onshore and coastwise components of $\mathbf{V_d}$. The variation of the onshore component during the day and night has the character of a sea and land breeze and varies with the inland atmospheric surface temperature, with a minimum towards dawn. Figure 3 shows the onshore component in January. Secondary maxima and minima appear frequently after midnight (local time) during the months of the north-east monsoon when the diurnal variation of either component is sufficiently small.

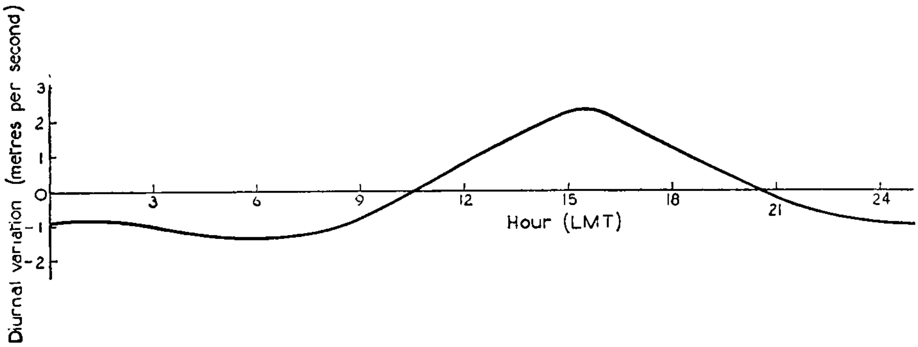


FIGURE 3—ONSHORE COMPONENT $(u_m - u_M)$ OF THE DIURNAL VARIATION AT ADEN IN JULY

During the north-east monsoon the amplitude of the mainly onshore variation of $\mathbf{V_d}$ increases with the mean daily maximum temperature, but during July and August—the months of the south-west monsoon—the predominance of the sea-breeze cycle is replaced by a mainly coastwise variation. The coastwise component $(v_m - v_M)$ of the diurnal variation in July at Aden is included in Figure 5. During July and August the coastwise component reaches its maximum from the south-west between 1200 and 1500 Local Mean Time (LMT) but its minimum is towards 2100 LMT many hours earlier than dawn which is the time of minimum temperature inland.

Harmonic analysis of the components of diurnal variation ($\mathbf{V_d}$).— The components of the diurnal variation may each be represented by first and second harmonic terms (the diurnal and semi-diurnal terms) in the form:

$$A_1 \cos \frac{\pi}{12} (h - T_{m1}) + A_2 \cos \frac{\pi}{6} (h - T_{m2})$$

where h is the hour of observation in Local Mean Time; and amplitude A_1 and time of maximum T_{m1} refer to the diurnal term while A_2 and T_{m2} refer to the semi-diurnal term.

TABLE II—HARMONIC COMPONENTS OF THE DIURNAL VARIATION AT ADEN

	Onshore				Coastwise			
	First harmonic		Second harmonic		First harmonic		Second harmonic	
	Amplitude	Time of maximum	Amplitude	Time of maximum	Amplitude	Time of maximum	Amplitude	Time of maximum
Month	m/sec	LMT	m/sec	LMT	m/sec	LMT	m/sec	LMT
Jan.	1.60	15.8	0.55	3.1	0.47	20.6	0.52	5.4
Feb.	1.67	15.7	0.69	2.9	0.41	18.3	0.68	5.2
Mar.	1.50	14.9	0.81	2.4	0.29*	14.7	0.61	4.6
Apr.	1.86	14.5	0.82	2.1	0.07*	9.7	0.49	4.1
May	1.93	14.2	1.08	2.0	0.21*	15.5	0.41	4.4
June	1.29	14.6	0.60	1.6	2.19	12.9	1.42	2.6
July	0.57	14.2	0.08*	2.5	4.25	12.5	1.59	2.1
Aug.	0.49	14.3	0.22	3.3	3.82	12.6	1.74	2.8
Sept.	1.30	15.2	1.11	2.3	1.96	13.0	1.10	3.3
Oct.	3.30	14.3	1.12	1.8	0.06*	19.8	0.71	4.2
Nov.	2.73	15.0	0.62	2.0	0.42	23.7	0.91	4.6
Dec.	1.98	16.0	0.65	2.2	0.57	19.5	0.73	5.0

*Not statistically significant

Table II gives the amplitudes and times of maxima for the diurnal and semi-diurnal terms of the onshore and coastwise components of the diurnal variation (V_d). All these amplitudes are significant according to the criterion for significance used by Brooks and Carruthers,[2] but some are found to be not significant when the more stringent criterion of Chapman and Bartels[3] is applied. Amplitudes that do not meet this criterion are marked by an asterisk. (The criterion of Chapman and Bartels allows for the increased probability of accidental harmonic terms when consecutive observations are not statistically independent, and makes use of the concept of the equivalent number of independent days. This concept is considered more fully later since like most climatic statistics it has a physical significance.)

The seasonal variation of amplitude, and of the time of maxima of the first harmonic terms of the diurnal variations from the mean are illustrated in Figure 4. They suggest that there are three distinct daily variations in the wind.

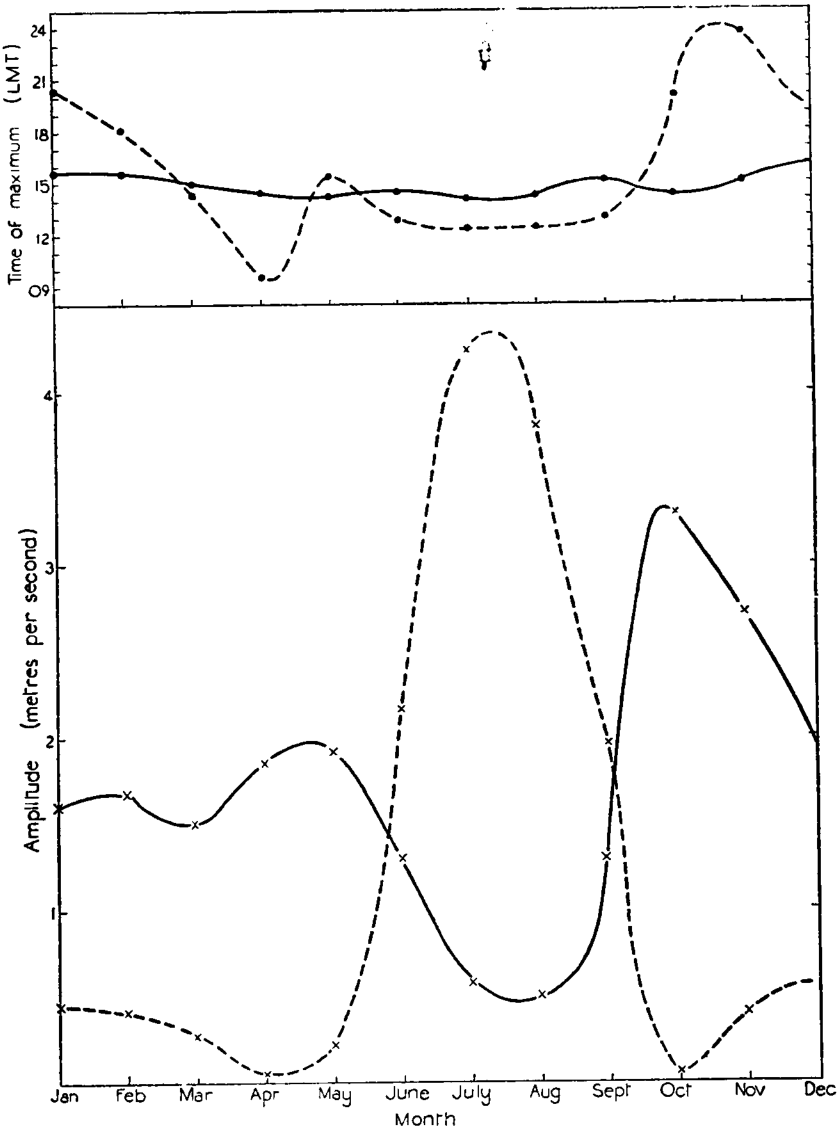


FIGURE 4—SEASONAL CHANGE IN AMPLITUDE AND TIME OF MAXIMUM OF THE FIRST HARMONIC OF THE DIURNAL VARIATION AT ADEN

.———. Time of maximum of onshore component, .– – –. time of maximum of coastwise component.

x———x Amplitude of onshore component, x– – –x amplitude of coastwise component.

(i) During the north-east monsoon, a diurnal oscillation of the component normal to the coast predominates. The time of maximum is approximately that of the maximum surface temperature inland apart from there being a small seasonal variation from just after 1400 LMT in the warmest month to 1600 LMT in the coolest.

(ii) During July and August there is a mainly coastwise variation with amplitude about twice the magnitude of the mean rate of flow ($\mathbf{V_M}$) with a constant time of maximum of about 1230 LMT two hours earlier than that of the thermal maximum inland.

(iii) During the north-east monsoon a weak daily coastwise oscillation occurs simultaneously with the predominating oscillation but disappears when the latter is at its strongest. The most striking characteristic of the coastwise oscillation is a large seasonal variation in the time of maximum which gets steadily earlier, from 0000 LMT in November to 1000 LMT in April. It then gets later but is suddenly interrupted by the strong oscillation described at (ii) above with its constant time of maximum.

Oscillation (i) is probably the normal sea breeze flowing almost perpendicular to the coast, as the geostrophic term in the wind equation at this latitude is small. The weak coastwise oscillation under (iii) above appears to be closely associated with the sea breeze. In the warmest month its time of maximum (i.e. time of weakest easterly flow) is consistent with the flow of the north-easterlies being diverted from the Gulf towards the hot interior of Arabia crossing the coast east of Aden, where the mountains are lower (see Figure 1). During the coldest months the time of maximum at midnight is consistent with a minimum in the hottest part of the day when there is a strong easterly wind towards Africa.

Oscillation (ii) above appears to be a daily variation in the south-west monsoon accentuated by the topography of the Gulf of Aden. Its time of maximum is in phase with the thermal maximum at 30 to 40°E, i.e. over northern India. (There is also a strong semi-diurnal term which produces the minimum between 1800 and 2100 LMT. See Figure 5.)

To find out whether there is a general diurnal variation in the surface atmospheric flow towards India during the south-west monsoon, the diurnal variation of the rate of flow in the direction of mean flow is derived for Habbaniya, for a 1° sea square in the Gulf of Aden and for a 5° sea square in the Arabian Sea for July and August and for January (for comparison). The results are set out in Table III which also gives details of any regular daily variation perpendicular to the direction of the mean flow (again for comparison). During July and August there is a maximum flow in the south-west monsoon at all these places within half an hour of 9.3 hours GMT. The greatest amplitudes occur at Aden, over the Gulf of Aden and at Habbaniya where the flow is concentrated by wide valleys between blocks of mountains. Southwards over the Arabian Sea towards the subtropical high the daily cycle is much less strong. However in general there is evidence of a daily fluctuation in the south-west monsoon which could be responsible for the coastwise fluctuation of the wind at Aden in July and August.

Second harmonics or semi-diurnal terms of the daily variation.— The amplitudes of the second harmonics vary as those of the first. However they never fall below a half a metre per second even when for example the

TABLE III—AMPLITUDE AND TIME OF MAXIMUM OF THE FIRST HARMONICS OF THE COMPONENTS OF THE DIURNAL VARIATION

Place	Month	Mean flow		First Harmonic: Parallel to mean flow Amplitude	First Harmonic: Parallel to mean flow Time of maximum	First Harmonic: *Perpendicular to mean flow Amplitude	First Harmonic: *Perpendicular to mean flow Time of maximum	Period	Number of observations used
		deg	m/sec	m/sec	GMT	m/sec	GMT		
Aden	July	225	2.7	4.26	9.5	0.57	11.2	1949–55	8 per day
(12°50′N, 45°01′E)	August	225	2.7	3.82	9.6	0.49	11.3	1949–55	8 per day
	January	095	6.0	0.47	17.6	1.60	12.8	1949–55	8 per day
Habbaniya	July	313	4.0	1.90	8.9	0.56	5.1	1949–56	8 per day
(33°22′N, 43°34′E)	August	316	3.2	1.69	9.4	0.18	4.0	1949–56	8 per day
	January	288	0.5	0.68	8.5	0.08	16.2	1949–56	8 per day
1-degree sea square in the Gulf of Aden	July } August }	233	4.7	2.40	9.3	0.56	4.7	1945–59	562
(12–13°N, 47–48°E)	January	077	4.7	0.20	16.4	0 45	7.4	1945–59	278
5-degree sea square in the	July	229	11.0	0.38	9.8	0.25	3.8	1945–59	669
Arabian Sea	August	229	9.2	0.53	9.1	0.07	11.2	1945–59	607
(10–15°N, 60–65°E)	January	034	5.4	0.43	9.7	0.17	0.3	1945–59	609
Berbera	July	216	7.1	3.96	5.2	5.41	14.8	1931–32	24 per day
(10°27′N, 45°02′E)	August	229	5.2	4.19	4.9	5.60	14.4	1931–32	24 per day
	January	044	2.9	2.77	3.5	3.71	12.7	1932–33	24 per day

*Onshore components for Aden and Berbera, otherwise 90° anticlockwise from mean flow.

first harmonic of the coastwise variation is zero. This is probably due to the presence of the semi-diurnal atmospheric tide which according to atmospheric pressure observations is very strong at this latitude. Theory suggests[4] that the coastwise semi-diurnal tidal oscillation should be 3 hours ahead of the onshore oscillation but there is no simple relation between the time of maximum of pressure and that of either of the wind components. Table II shows that during the north-east monsoon the second harmonic of the coastwise wind oscillation is 2 to 3 hours ahead of the onshore wind oscillation. However, there is a seasonal variation in both the time of maximum wind and its amplitude which follows those of the first harmonics, consistent with the supposition that the semi-diurnal terms during the north-east monsoon are a combination of atmospheric tide and the second harmonics of the daily variation from the mean. There is however no evidence of the atmospheric tide during the south-west monsoon.

Abnormal diurnal variation of wind at Berbera.—Table III shows that at Berbera, due south of Aden on the opposite side of the Gulf, mean winds are consistent with the north-east monsoon and south-west monsoon when they predominate but the diurnal variation $\mathbf{V}_d$ differs from that at all other locations in having a very large onshore and coastwise variation of wind, probably caused by convergence towards the large areas of intense rain over mountains to the east, south and west of Berbera, particularly over Ethiopia in July and August. During these months Figure 5 shows that there is a minimum in the coastwise flow[6] just before 1900 LMT probably associated with rain

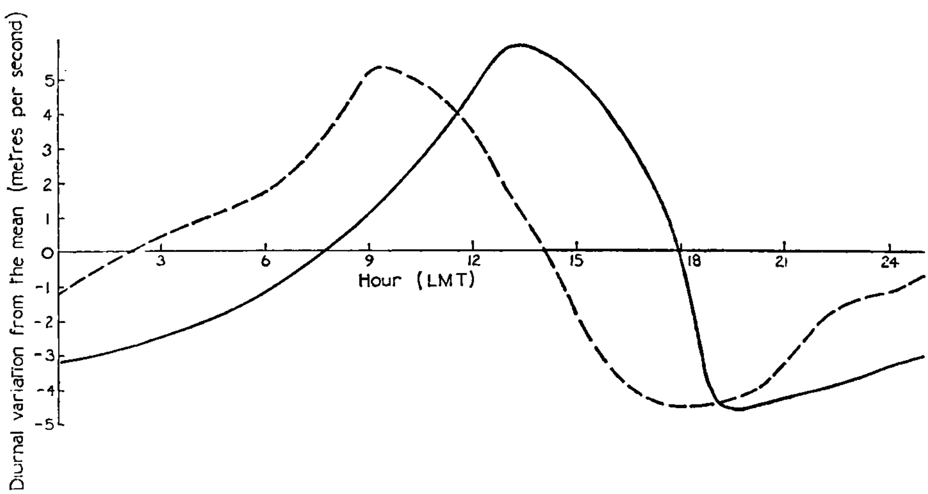


FIGURE 5—COASTWISE COMPONENT (v_m – v_M) OF THE DIURNAL VARIATION IN JULY AT ADEN AND BERBERA
——— Aden, – – – Berbera.

areas over Ethiopia to the west. This compares with a similar sharp minimum experienced just before 2000 LMT at the same time of the year at Aden. It is therefore probable that the large coastwise variation in wind at Aden during July and August is caused not only by a daily maximum in the flow of the south-west monsoon towards 1230 LMT but also to a weakening of the flow due to the Ethiopian rains towards 1900 LMT. This is confirmed by the great magnitude at this time of the variance of the coastwise random fluctuation described below (see Figure 6), and more directly by the relatively low mean wind $\mathbf{V_M}$ in July and August (see Table I).

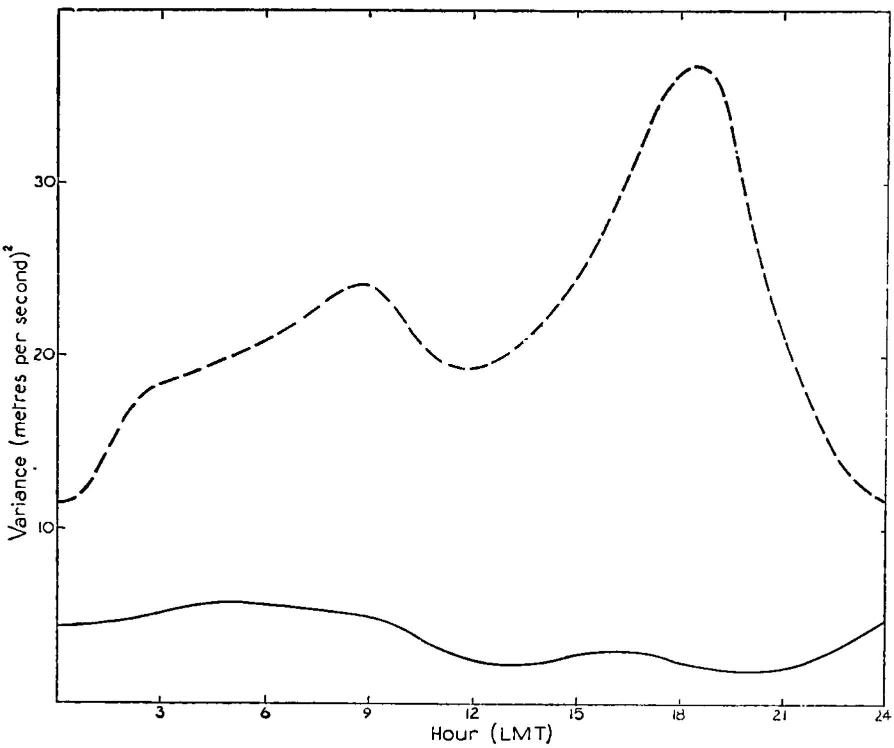


FIGURE 6—VARIANCE OF THE RANDOM FLUCTUATIONS AT ADEN
——— Onshore component in January, – – – coastwise component in July.

Random fluctuations of the wind at Aden.—This section considers the random difference of the observed wind from the monthly mean of wind at that hour i.e. $\mathbf{V}-\mathbf{V_m}$, and considers the magnitude of the onshore and coastwise components u–u_m and v–v_m. The variance (σ_n^2) of the onshore components is proportional to the energy of the onshore component of the random difference. Thus

$$\sigma_n^2 = \Sigma \frac{(u - u_m)^2}{N}$$

where N is the number of observations and similarly, for the coastwise components

$$\sigma_c^2 = \Sigma \frac{(v - v_m)^2}{N} \quad .$$

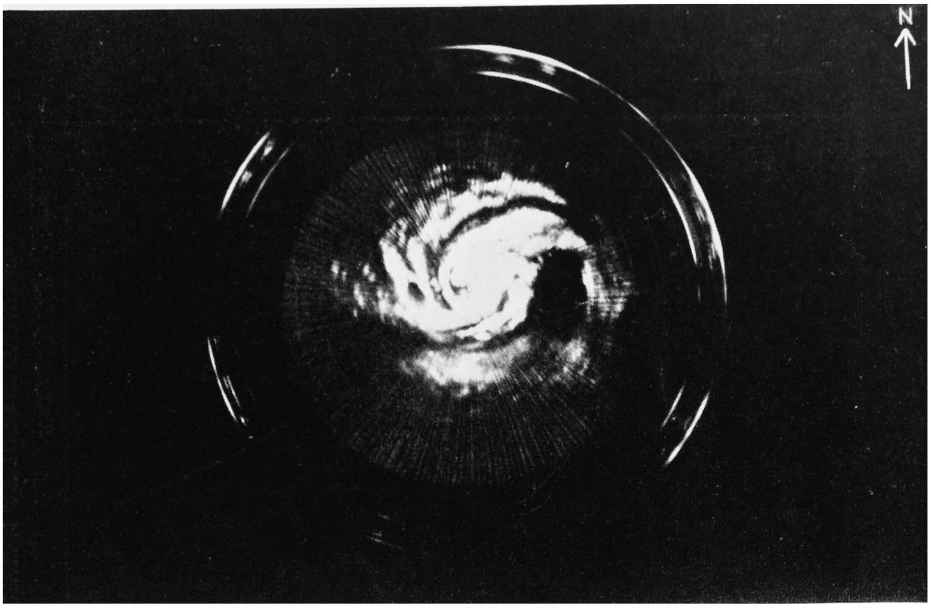
The correlation r_{nc} between the onshore and coastwise components is tabulated in Table IV along with the variance for each hour of observation.

For many hours of the day the components are statistically almost independent, but at times there is a high correlation suggesting physical association. Finally the equivalent number of independent days is used as a simple measure of the duration in time of the predominating fluctuations. Variations are from day to day and do not include microclimatic fluctuations over a few hours or

TABLE IV—VARIANCE OF AND CORRELATION BETWEEN COASTWISE AND ONSHORE RANDOM FLUCTUATIONS OF THE WIND AT ADEN, WITH THE EQUIVALENT NUMBER OF INDEPENDENT DAYS PER MONTH

	Local Mean Time																								Number of independent days per month	
	0000			0300			0600			0900			1200			1500			1800			2100				
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	Onshore component	Coastwise component
Jan.	4.5	6.7	−0.5	5.2	9.1	−0.7	5.7	8.1	−0.7	5.0	7.0	−0.4	2.5	7.3	−0.1	2.7	6.2	+0.3	2.3	4.8	+0.1	1.9	5.7	−0.2	13	8
Feb.	4.1	6.2	−0.5	4.3	7.1	−0.6	6.5	7.9	−0.6	4.3	6.7	−0.4	2.4	5.6	−0.1	2.7	4.6	+0.3	2.1	4.5	+0.3	2.4	5.0	−0.3		
Mar.	3.5	8.1	−0.5	3.7	7.8	−0.6	5.3	8.3	−0.7	3.5	7.5	−0.3	3.3	7.7	+0.1	3.6	8.0	+0.3	2.2	6.6	0.0	2.9	5.9	−0.2		
Apr.	3.3	6.7	−0.4	2.0	7.3	−0.3	4.5	7.7	−0.7	2.3	8.9	−0.5	3.8	6.4	+0.2	2.8	5.7	+0.1	2.3	5.5	−0.1	2.6	5.4	−0.1	19	11
May	2.7	6.1	−0.5	5.2	7.1	−0.4	5.1	6.3	−0.5	2.9	11.5	−0.5	3.7	14.0	−0.5	4.3	14.9	−0.4	3.2	11.6	−0.4	1.8	5.0	−0.4		
June	2.5	4.3	−0.3	4.7	10.0	−0.1	4.9	13.9	+0.1	3.0	21.9	−0.3	7.0	23.9	−0.8	7.7	21.5	−0.8	4.3	16.2	−0.5	2.9	5.8	−0.3		
July	4.4	11.8	−0.2	4.5	18.4	−0.2	3.4	20.9	0 0	3.2	24.1	−0.3	2.8	19.5	−0.6	3.3	24.5	−0.5	10.5	36.5	−0.2	4.8	21.3	0.0	16	10
Aug.	4.0	10.9	−0.1	3.7	13.7	−0.1	3.2	21.0	0.0	2.9	23.6	−0.2	6.0	26.5	−0.6	3.8	23.0	−0.6	10.7	32.4	−0.2	4.4	11.5	−0.2		
Sept.	2.5	8.6	−0.3	4.4	11.3	−0.4	5.4	11.8	−0.2	4.5	21.4	−0.4	7.3	30.0	−0.7	8.1	28.9	−0.8	6.6	20.4	−0.3	2.7	6.8	−0.3		
Oct.	4.4	5.8	−0.6	4.1	6.9	−0.4	5.3	7.1	−0.5	3.6	8.4	−0.2	3.3	7.3	+0.3	4.2	8.1	−0.2	2.8	6.2	−0.1	2.8	5.8	−0.4	20	21
Nov.	7.7	7 7	−0.7	8.2	9.5	−0.7	7.6	9.1	−0.7	3.8	5.7	−0.4	2.6	5.6	+0.4	2.8	6.0	+0.3	1.9	4.5	+0.1	3.1	4.6	−0.5		
Dec.	4.9	6.8	−0.5	6.6	7.4	−0.6	7.5	6.9	−0.6	4.5	5.7	−0.2	3.5	5.9	+0.2	2.9	4.5	+0.2	2.2	4.5	+0.1	1.7	4.9	−0.4		

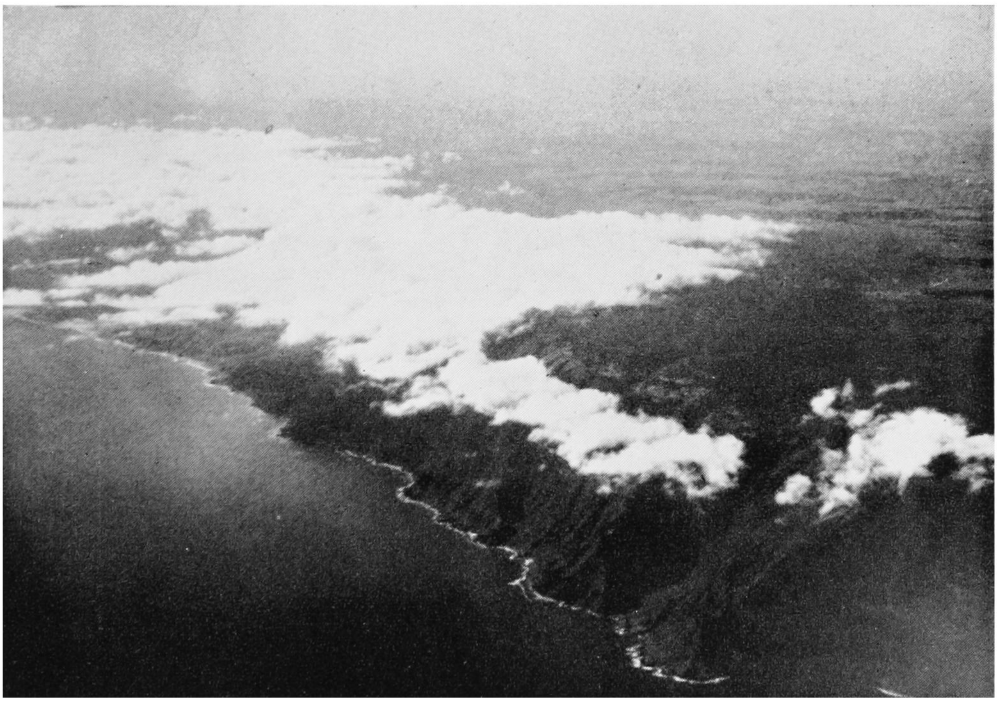
A = σ_n^2 in (metres per second)^2, B = σ_c^2, C = r_{nc}.



Photograph by R. H. Brass

PLATE I—PHOTOGRAPH OF THE PPI RADAR DISPLAY TAKEN ON BOARD THE WEATHER REPORTER AT 1100 GMT ON 14 OCTOBER 1963

The radius of the display is 75 nautical miles with range markers every 10 nautical miles, (See page 90).



Photograph by M. G. Habberley

PLATE II—CLOUD FORMING OVER THE COASTLINE BETWEEN SALALAH AND CAPE FARTAK ON THE SOUTH-EAST ARABIAN COAST ABOUT 1600 LOCAL MEAN TIME ON 23 SEPTEMBER 1963

Surface winds were light at the time and this cloud was the result of the local sea breeze.

Photograph by G. J. Jefferson

PLATE III—CLOUD FORMATION ASSOCIATED WITH A JET STREAM AT 1820 GMT ON 22 JUNE 1963

The photograph was taken looking towards a direction of 220 degrees (see p. 91).

Photograph by G. J. Jefferson

PLATE IV—CLOUD FORMATION ASSOCIATED WITH A JET STREAM AT 1820 GMT ON 22 JUNE 1963

The photograph was taken looking towards a direction of 270 degrees (see p. 92).

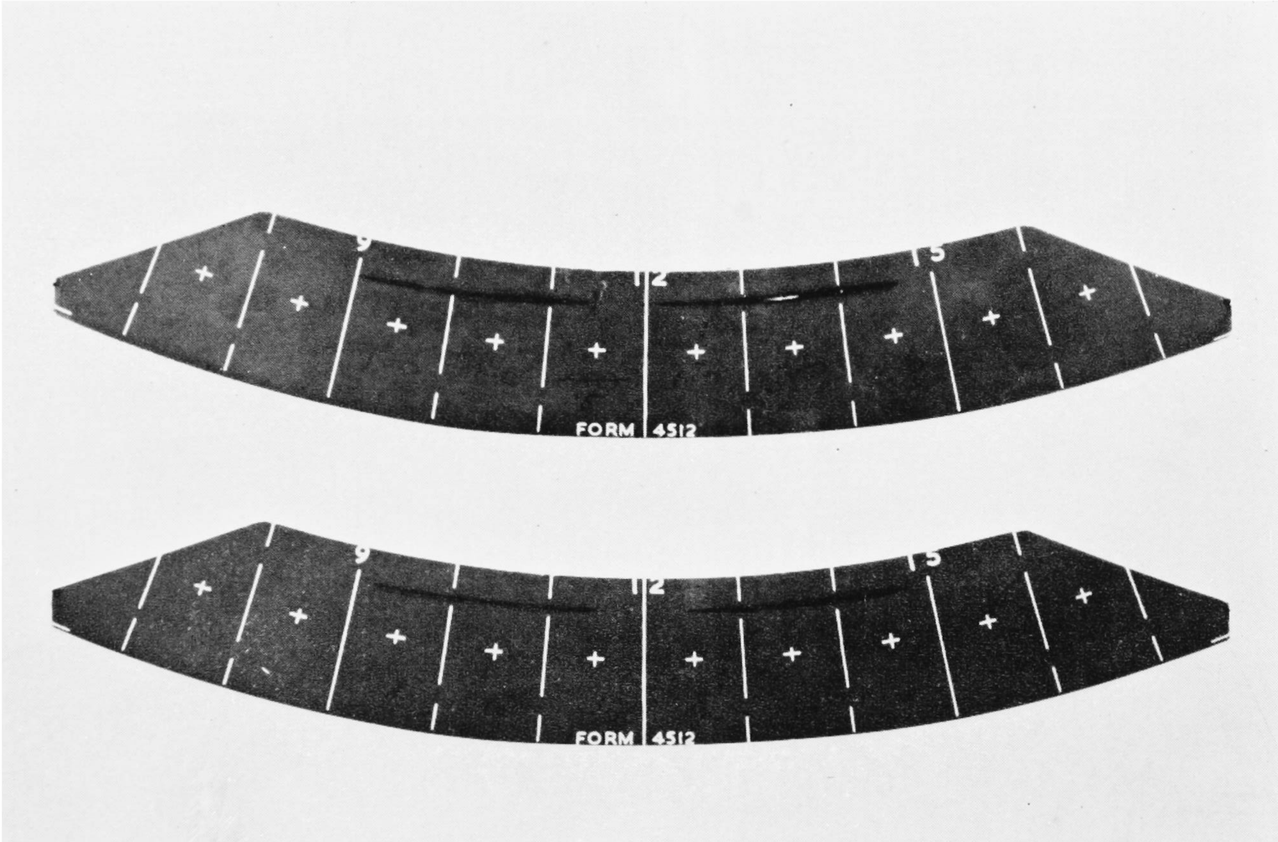


PLATE V—SUNSHINE CARDS FOR 10 JANUARY 1963

Manchester Weather Centre above, Manchester College of Science and Technology below, (see page 91).

less. For non-overlapping samples of N consecutive observations at a fixed hour with a standard deviation of σ, the standard deviation σ_a of the averages of the samples is

$$\sigma_a = \sigma / \sqrt{N_1} \quad ,$$

where N_1 is the number of independent observations equivalent to the N actual observations.

If all consecutive observations are independent then $N = N_1$ but if fluctuations tend to persist longer than a day then $N_1 < N$. The greater the duration of the predominating fluctuations the smaller will be N_1. In the present work samples contain the observations at a fixed hour for all days of the month, and from the samples the equivalent number of independent days per month is derived. Since the number of years is small, a mean is taken of values derived from four observational hours.

At the surface the air tends to flow mainly along the Gulf of Aden (Figure 1) rather than up over the mountain rim. This is confirmed not only by the direction of the mean wind but also by the upper air wet-bulb and dry-bulb temperatures below 20,000 feet which exhibit subsidence (anticyclonic subsidence during the north-east monsoon and orographic subsidence during the south-west monsoon). Any extensive atmospheric exchanges over the mountain rim north and south of the Gulf would need forces sufficient to overcome the high stability of the atmosphere. Large-scale fluctuations of the monsoon winds are therefore more likely to affect coastwise flow along the Gulf than onshore flow. Transient fluctuations produced by local variations on the scale of land and sea breezes would however affect both coastwise and onshore components of the random fluctuation ($\mathbf{V_R}$).

Thus in Table IV the energy of the coastwise component of random fluctuation, represented by the variance (σ_c^2), is frequently almost twice as great as that for the onshore component. In addition, the duration of coastwise fluctuation is greater because the equivalent number of independent days per month is about half the number for onshore fluctuations (except in October). Finally there is high negative correlation between coastwise and onshore fluctuations at night during the north-east monsoon particularly towards dawn, but during the day in the south-west monsoon. Abnormally strong nocturnal winds are thus associated with a weak north-east monsoon, and strong sea breezes with a weak south-west monsoon. In contrast, sea breezes during the north-east monsoon and nocturnal winds during the south-west monsoon are statistically less associated with and at times independent of the strength of the monsoon winds.

In the late afternoon and evening during the south-west monsoon when the random fluctuations are exceptionally high, there is low correlation between onshore and coastwise fluctuations. This low correlation suggests that it is unlikely that the random fluctuations are produced by local sea-breeze effects. Figure 6 shows the daily variation of the variance of the coastwise component of the random fluctuation in July. The maximum occurs about the time of the minima of the coastwise component of the diurnal variation ($\mathbf{V_d}$) at Berbera and Aden in July (Figure 5), i.e. at the time of weakening in the general south-west monsoon wind. The random fluctuation is therefore not of local origin but may be linked with a large-scale feature such as the formation of storm centres over Ethiopia. For comparison the variance of the onshore component in January is also shown in Figure 6 and shows the relative steadiness of the wind in January and the low energy of any random fluctuation.

Conclusions.—The periodic variation of wind at Aden is controlled largely by climatic systems on a continental scale like the Indian south-west monsoon, the north-east monsoon, and the rains of East Africa. Flow associated with these is constrained by topography to flow along the Gulf of Aden. Periodic fluctuations from systems on the scale of sea breezes are also experienced causing variations normal to the coastline. It is also apparent that the climatic controls that cause the periodic variations also closely control the magnitude and duration of random fluctuations of wind.

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551.515.4:551.553.11:551.558.1

THE SEA BREEZE AND INLAND CONVECTION—AN EXAMPLE OF THEIR INTERRELATION

By J. FINDLATER

Introduction.—Cumulus and cumulonimbus often appear to develop at random overland in unstable airstreams. This analysis however shows an example of convective storms which developed in association with meso-scale features readily identifiable some hours before the first development of showers and thunderstorms. Some detailed observations in a sea-breeze convergence zone are described also.

Analysis of surface charts.—The synoptic chart for 0600 GMT on 12 June 1963 revealed a light westerly airstream over most of England with a minor trough just discernible in the isobars from the Wash to Hampshire. On the 0900 GMT chart isobars drawn at half-millibar intervals showed consistent distortions near the trough. The whole of southern, central and eastern England was free of low and medium cloud but large amounts of thin cirrus lay over the western half of the country in association with a slow-moving occlusion which was orientated north to south over the Irish Sea. Sea fog in the English Channel affected the southernmost parts of the south coast but strong surface heating and generally light winds precluded any advance inland.

Surface winds reported at 0900 GMT were mostly of about 5 knots from variable directions. A streamline analysis of the surface wind field revealed two well marked convergence zones, one associated with the weak isobaric trough and the other with the onset of the sea breeze from the south coast over parts of West Sussex. Figure 1(*a*) shows these features as they appeared at 0900 GMT. Subsequent hourly charts were also analysed by streamlines for convergence zones and the amount of convection cloud, and a selection of the resulting analyses is shown in Figures 1(*b*)–(*d*).*

*Errata—in Figures 1, 2 and 3, 50°N should read 51°N.

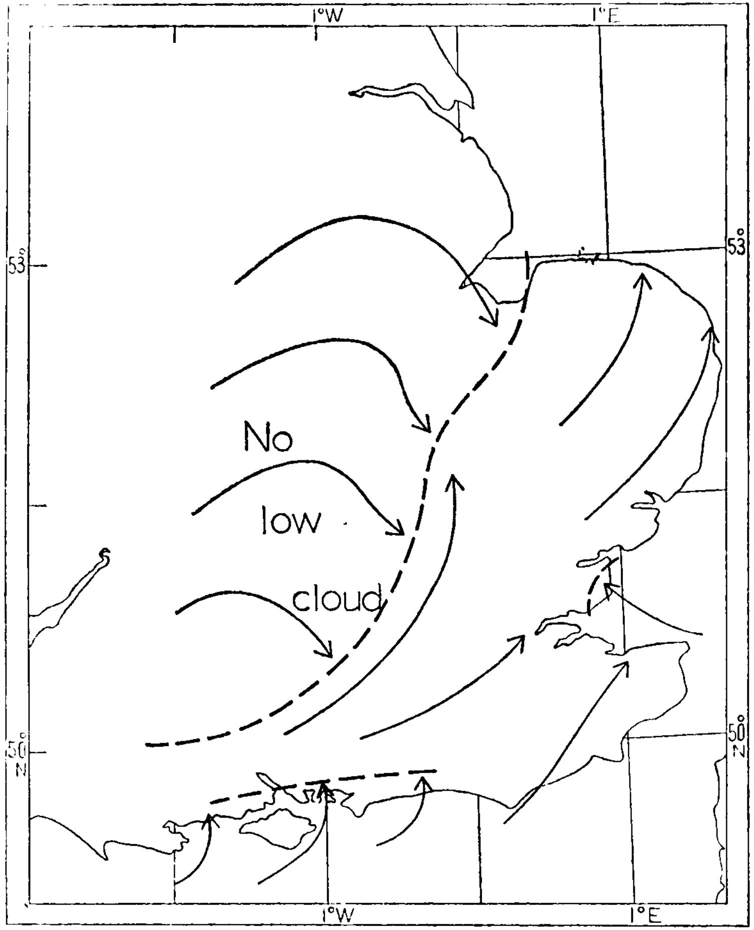

FIGURE 1 (*a*)—STREAMLINES AND CONVERGENCE ZONES AT 0900 GMT, 12 JUNE 1963
Arrowed lines are streamlines, — — — convergence zones.

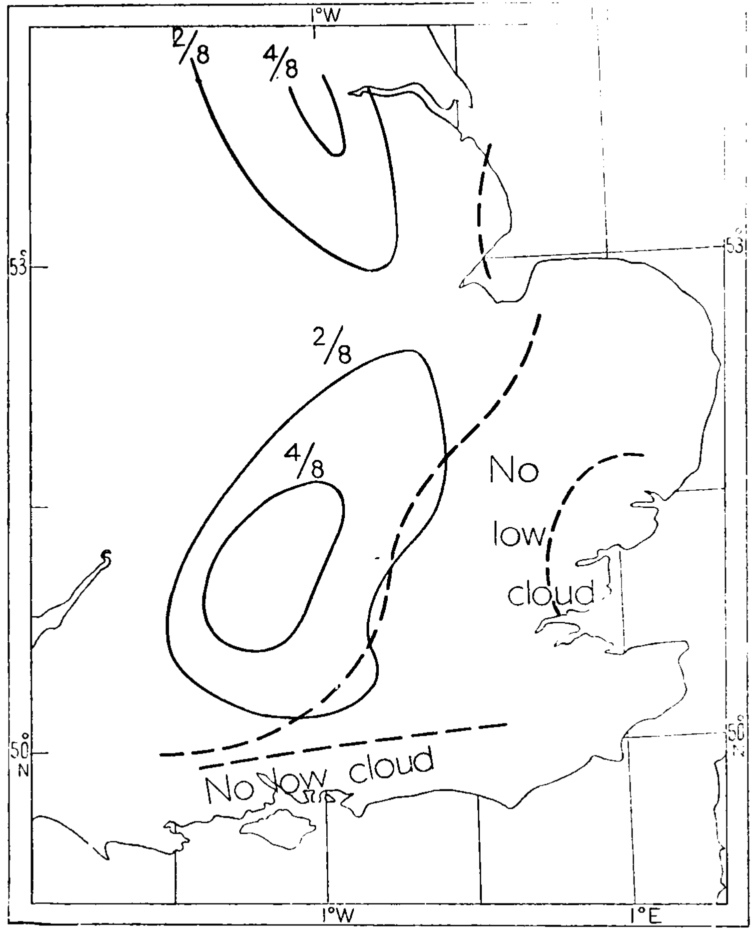

FIGURE 1 (*b*)—CONVERGENCE ZONES AND AMOUNTS OF CUMULUS AT 1100 GMT, 12 JUNE 1963
— — — Convergence zones, ——— isopleths of cloud amount.

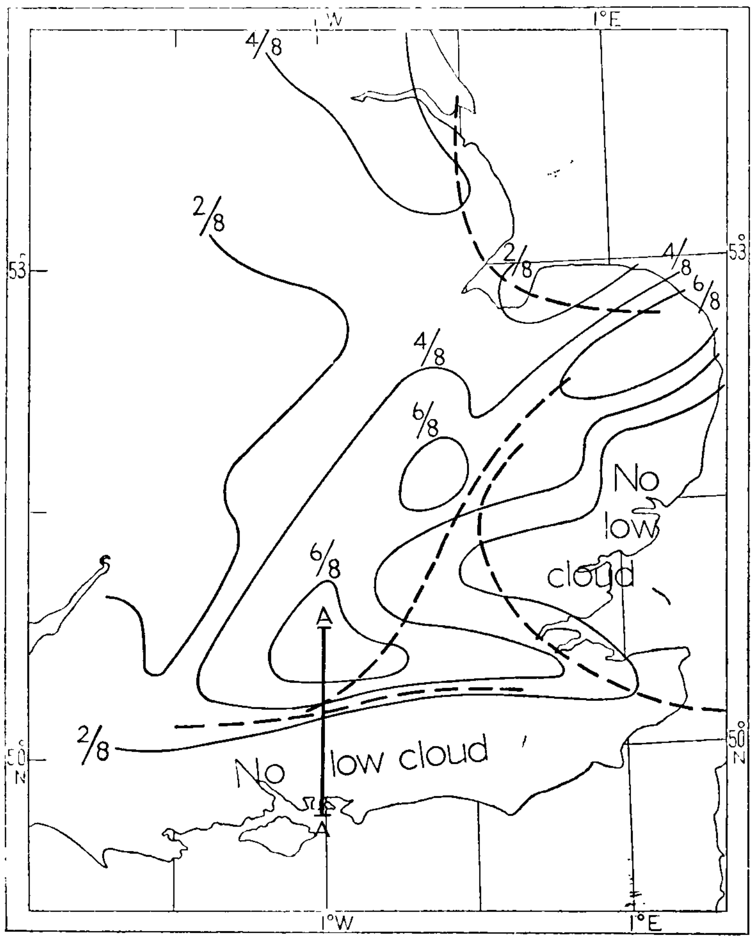

FIGURE 1(*c*)—CONVERGENCE ZONES AND AMOUNTS OF CUMULUS AT 1300 GMT, 12 JUNE 1963
— — — Convergence zones, ———— isopleths of cloud amount.
A—A is the line of cross-section shown in Figure 4.

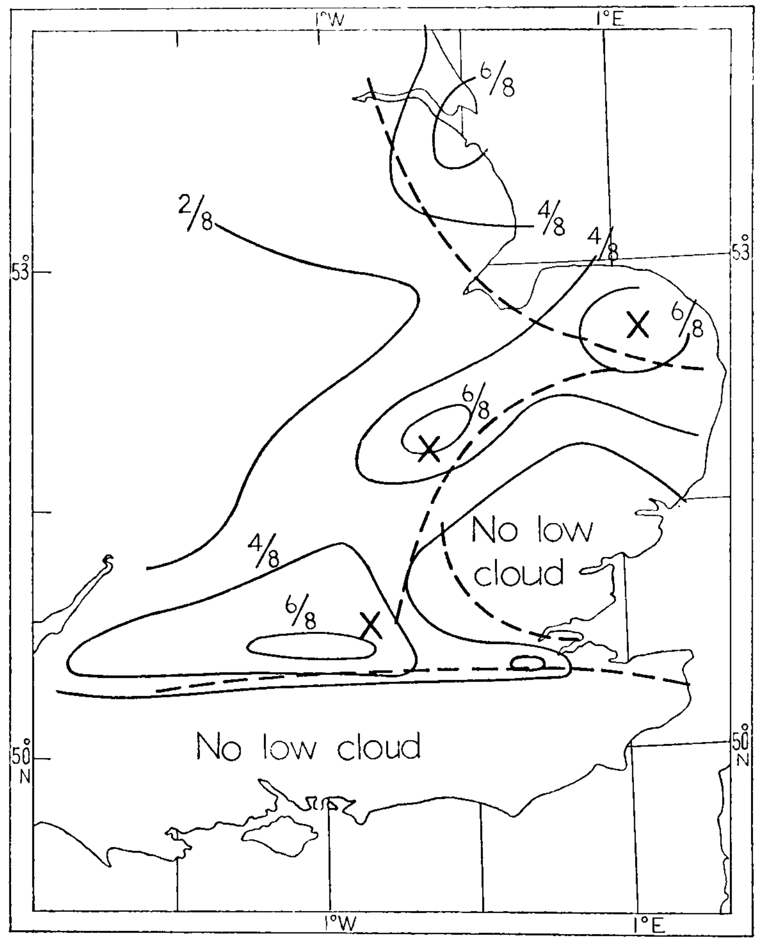

FIGURE 1(*d*)—CONVERGENCE ZONES AND AMOUNTS OF CUMULUS AND CUMULONIMBUS AT 1500 GMT, 12 JUNE 1963
— — — Convergence zones, ———— isopleths of cloud amount.
X Positions at which thunderstorms occurred at 1400 GMT.

Cumulus formed by 1000 GMT and by 1100 two distinct convection systems had become established, both of them just to the west of the main convergence zone. One centre of activity lay near Oxford and the other near Doncaster. At 1200 GMT the southernmost cloud system began extending quickly eastwards to the south of the Thames valley as sea breezes formed convergence zones which moved inland from the south coast of Hampshire and Sussex, and from the north coast of Kent. A sea breeze had also become established on the coast of Lincolnshire, parts of south Yorkshire, and most probably on the north coast of Norfolk. Figure 2 shows the pattern of isobars, streamlines and convergence zones at 1200 GMT. On this chart the relation between the surface-wind

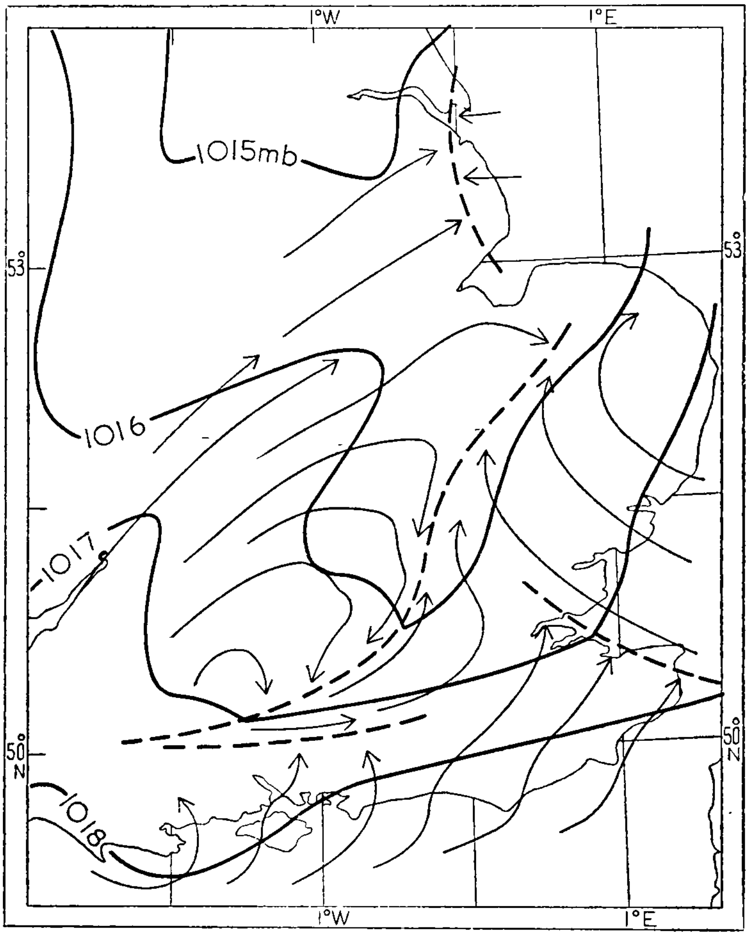

FIGURE 2—ANALYSIS OF SURFACE-WIND STREAMLINES AND ISOBARS AT 1200 GMT, 12 JUNE 1963

— — — Convergence zones, ——— isobars. Arrowed lines are streamlines.

streamlines and the isobars is of particular interest over Essex and Suffolk, and also just to the north of the convergence zone west of London. At this time also a new centre of convective activity appeared over central Norfolk—at about the same time as the sea breeze would be becoming established on the north coast of Norfolk. By 1300 GMT maximum amounts of cumulus (or cumulonimbus) south of the Wash had become organized into three areas; these were near Farnborough, Cranfield and Thetford, and one hour later thunderstorms were reported from these areas (see Figure 1 (*d*)).

It is noteworthy that in each of the three areas where convection led to thunderstorms a convergence zone due to a sea breeze closely approached the pre-existing convergence zone located on charts earlier in the day. In another area near the North Downs, where convergence zones associated with the south coast and the Thames estuary sea breezes approached each other, an isolated area of large cumulus developed at 1600 GMT. Six oktas of large cumulus were reported from Gravesend and subsequently a thunderstorm moving north affected Stansted between 1700 and 1800 GMT. During the next few hours the storms drifted northwards leaving in their wake skies clear of low cloud.

Figure 3 shows the positions of the various convergence zones at two-hourly intervals from 0900 GMT and the location of the four storm areas which developed by 1600–1700 GMT.

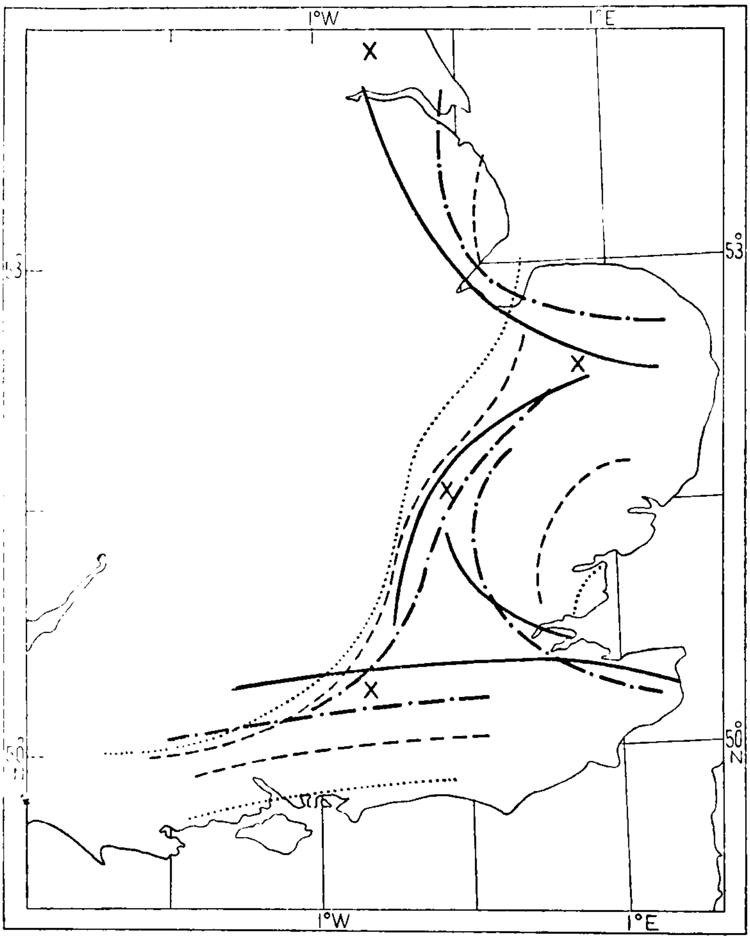

FIGURE 3—SUCCESSIVE POSITIONS OF CONVERGENCE ZONES, 12 JUNE 1963
.... 0900, – – – 1100, — · — · — 1300, ———— 1500 GMT.
X Positions of storm centres which had developed by 1600–1700 GMT.

The analysis of surface charts, of scale 1 :2 × 10^6, described in the foregoing section was carried out using only the information available from the Channel One teleprinter broadcast from the Central Forecasting Office, Bracknell.

Structure of the southern convergence zone.—From Figure 3 it is obvious that the sea air from the English Channel moved quickly inland early in the day which is much earlier than the usual time for that part of the country, e.g. Simpson[1] quotes 1645 GMT as being a normal time for the sea breeze to reach Lasham, Hampshire, during the summer of 1962 and Wallington,[2] has shown two examples of the breeze reaching Lasham at about 1730 GMT—a value which corresponds closely to general experience in that area, although much earlier arrivals have been known.

On this day it was possible to make some detailed observations in the convergence zone, although its arrival was unexpectedly early. At 1326 GMT the author, piloting a Skylark 2 glider, took off from Lasham on tow behind a powered aircraft when the surface wind was westerly at 5 knots. The sky was mostly covered by 6/8 large cumulus which was building quickly to become cumulus congestus. The aircraft and glider combination climbed to the west into thick smoke haze below a group of dark-based cumuli at a considerably lower level (2500–3000 feet) than that at which cumulus for some hours earlier had been based (4000 feet). At 2600 feet above M.S.L. the glider released from the tug aircraft which returned and landed at Lasham at 1334 GMT, by which time the surface wind had changed suddenly to southerly 10–12 knots, necessitating a change of landing run. At this time the sky at Lasham was clearing quickly from the south.

The glider, after gaining about a hundred feet in very weak lift in the smoke haze, turned to the south and flew out of a well marked haze wall into air which was clear and with no cumulus visible to the south. The structure of cloud and haze was indicative of a sea-breeze convergence zone, whose characteristics have been described elsewhere,[2,3,4] so a return was made to the wall of haze to seek rising air. Height could be maintained in weak lift to the north of the haze wall, but none could be gained. The system was moving to the north at 5–7 knots and when repeated re-positioning failed to produce a gain of height the search was discontinued and the return flight to Lasham made through air devoid of cloud and thermals. During traverses of the convergence zone readings of airspeed and vertical velocity of the glider were noted, the latter being taken from a direct-reading variometer and also recorded on a barograph. Readings of vertical velocity have been corrected for the sinking speed of the glider at known forward airspeeds to yield smoothed values for the vertical velocity of the air in the vicinity of the convergence zone.

A cross-section through the convergence zone has been built up and is shown in Figure 4. The region to the north of the haze wall was one in which gliders had been soaring from low level up to cloud base at 4000 feet above M.S.L. until the arrival of the sea air. It can be assumed, therefore, that apart from a slight superadiabatic lapse rate close to the surface, say up to about 1000 feet above ground, the lapse rate approximated to a dry adiabatic. The convective condensational level of the surface air, marked on the cross-section as C_1, agreed well with the observed cloud base. Within the haze wall the characteristics of the rising air were different from those in thermals; a narrow belt of rising air lay on the north side of the haze wall with an equally narrow zone of sinking air on the southern side. The approximate width of these zones and the vertical velocities within them are shown in Figure 5.

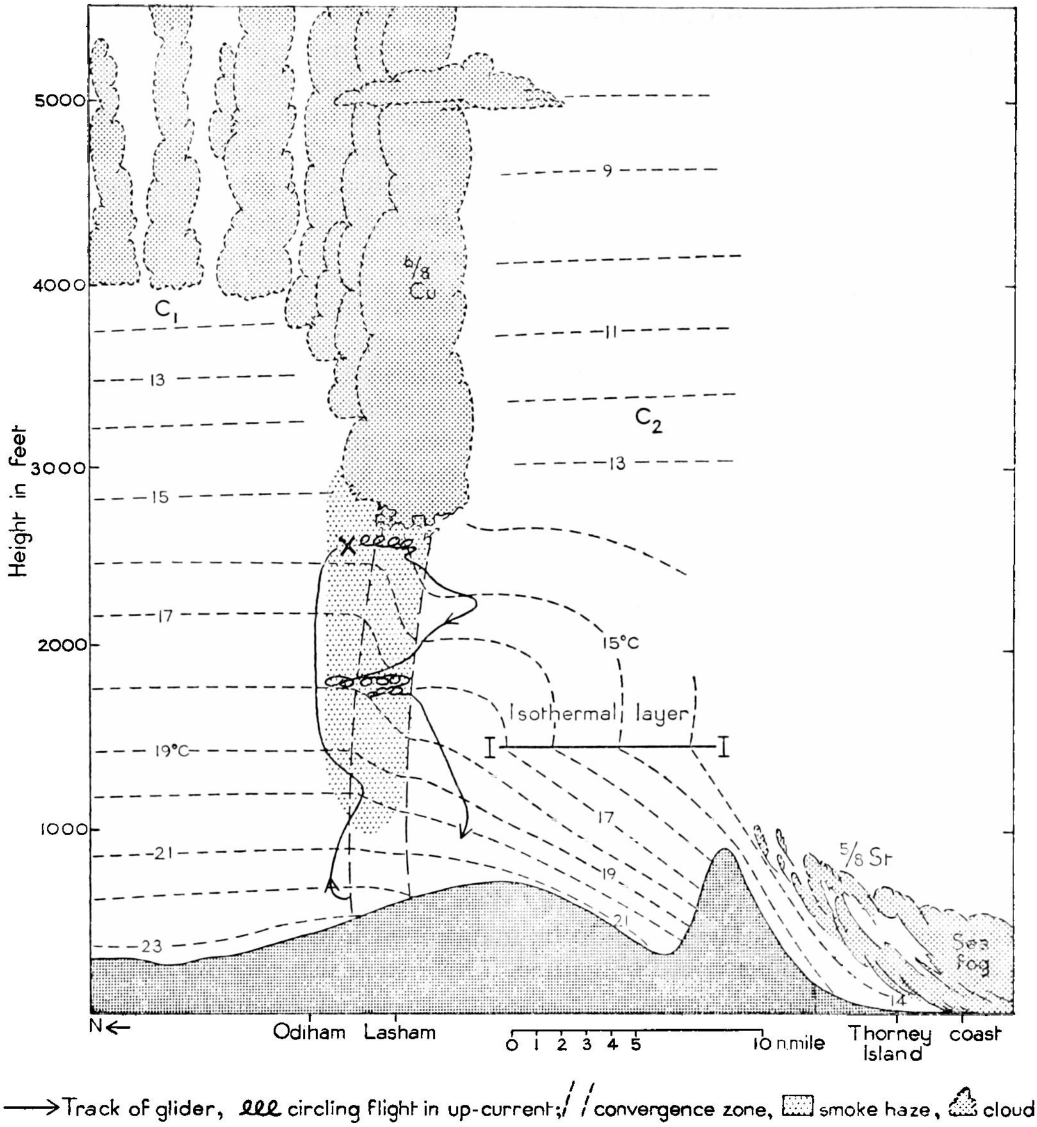

FIGURE 4—CROSS-SECTION THROUGH THE SEA-BREEZE CONVERGENCE ZONE AT APPROXIMATELY 1330 GMT, 12 JUNE 1963

The cross-section is along **A—A** in Figure 1(*c*). – – – Isotherms, **I—I** base of isothermal layer, $\mathbf{C_1}$ condensation level to north of the convergence zone, $\mathbf{C_2}$ condensation level to south of the convergence zone. **X** is point of release of glider from tug aircraft.

The distribution of temperature in the vertical to the south of the convergence zone has been deduced from reported surface temperatures and the routine sounding made at 1200 GMT from Crawley, which showed cool, sea air up to 1500 feet, an isothermal layer from 1500 to 2000 feet and a near-adiabatic lapse rate above this level. Under a cloudless sky the sea air was strongly heated by the surface to give a marked superadiabatic lapse rate in the lowest 1000 feet, but heating was insufficient to warm out the stable layer and allow the air to reach its convective condensational level marked on the cross-section at C_2. The top of the sea fog on the south coast was measured by an aircraft at 600 feet above sea level.

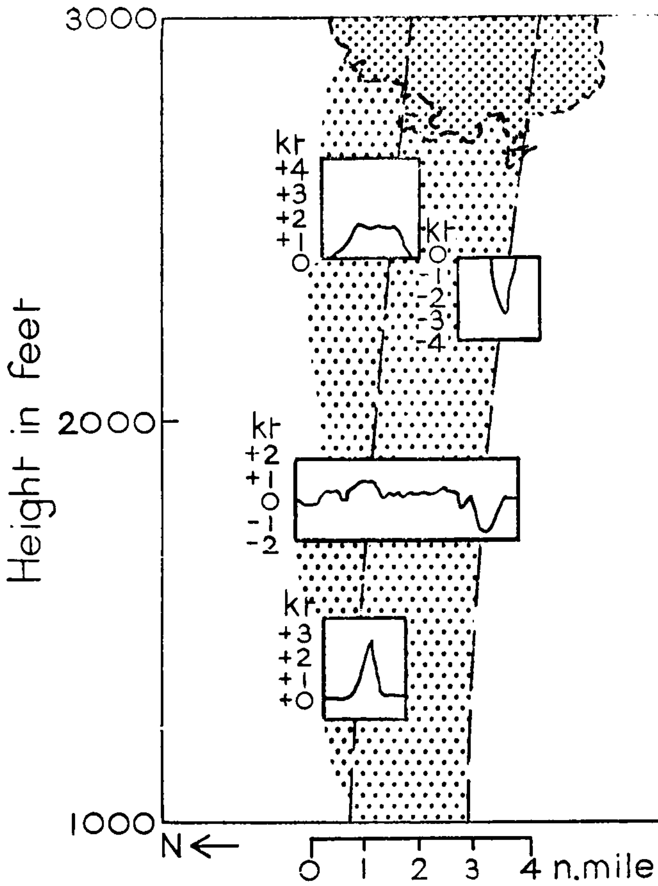

FIGURE 5—VERTICAL VELOCITIES IN THE CONVERGENCE ZONE
For legend see Figure 4.

During the afternoon at Lasham the wall of cumulus could be seen receding to the north and although general tops were estimated at about 10,000 feet a massive flat-topped cumulus extending to about 15,000 feet could be seen in the vicinity of Farnborough at 1400 GMT. This was the cloud which gave rise to the thunderstorm in association with the southern convergence zone.

Conclusions.—This analysis, and others of the same kind which have been carried out, indicate that on some occasions preferred areas for convective development can be identified early in the day by meso-scale analysis, using routine hourly reports. Once the system was recognized only abbreviated charts were required to track it from hour to hour.

The structure of the sea-breeze convergence zone from the south coast on an occasion of deep convection forms a useful addition to the series recently reported[4] and, although no new characteristic was located, the way in which the south coast sea breeze fits into the pattern of convective development overland is indicative of their interrelation.

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551.501.81:551.515.12:77

RADAR PHOTOGRAPH OF A DEEP DEPRESSION

The photograph of the PPI radar display reproduced in Plate I was taken on board the *Weather Reporter* at station 'A' (62°N, 32.7°W) at 1100 GMT on 14 October 1963. It shows the echoes from precipitation around the centre of a deep depression which passed very close to the weather ship at that time. The synoptic situation at 1200 GMT, and observations from the weather ship at other hours are shown in Figure 1.

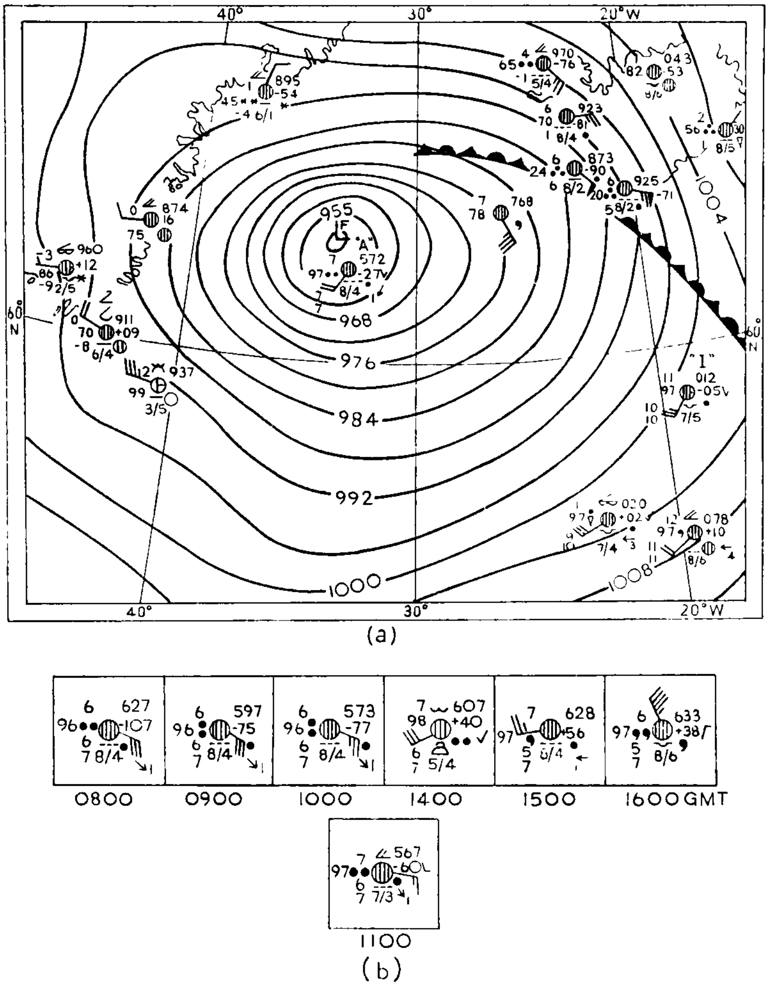

FIGURE 1—DEEP DEPRESSION NEAR WEATHER STATION 'A' ON 14 OCTOBER 1963
(*a*) Synoptic situation at 1200 GMT, (*b*) observations from *Weather Reporter* between 0800 and 1600 GMT.

The depression concerned originated as a tropical cyclone in the central Atlantic and moved northwards east of Bermuda on 11 October. Polar air masses became engaged in the circulation of the storm and its structure became generally similar to that of an extratropical storm.

Spiral bands such as are seen in Plate I are a recognized feature of the radar echoes from tropical cyclones[1] but satellite photographs also show that a spiral structure of the cloud masses is normal in an occluded depression.[2] The reason for the spiral structure is not fully understood but it has provided a valuable method of identifying depressions from satellite observations.

The photograph is of considerable interest as showing the spiral organization in the radar echoes near the centre of a deep depression. It is rather unlikely that the spiral bands are directly related to the tropical origin of the depression, but the matter must remain uncertain in the absence of further radar observations from intense, symmetrical, mature extratropical depressions.

J.S.S.

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EFFECT OF SMOKE ON RECORDED SUNSHINE

By J. E. B. RAYBOULD, B.Sc.

An interesting example of the effect of smoke on recorded sunshine occurred in Manchester on 10 January 1963. Factories and commercial firms in contolled zones, adjacent to smokeless zones, are allowed to discharge smoke and gases from their chimneys for a period of 10 minutes every 8 hours and the common practice in Manchester seems to be to exercise this right around midday. The effect of this discharge can be observed from the sunshine cards for Manchester Weather Centre and Manchester College of Science and Technology reproduced in Plate V. On this particular day the sky was cloudless and the wind easterly 6 to 8 knots, so that the loss of recorded sunshine of 0.5 hours at the Weather Centre and 0.9 at the College of Science and Technology was entirely due to smoke.

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PHOTOGRAPHS OF JET-STREAM CLOUDS

By G. J. JEFFERSON, M.Sc.

It is well known that jet streams, although commonly occurring in clear air, are at times accompanied by cloud. This has been shown statistically by Sawyer and Ilett.[1] Since the neighbourhood of jet streams, especially the entrance and exit regions or where the jet is intensifying or declining, is an area of ageostrophic motion, it follows that vertical motion is common. Where the motion is upward, cloud formation will occur when the air is sufficiently moist. Schaefer[2] discusses and illustrates the cloud types which are associated with jet streams and Schaefer and Hubert[3] discuss an actual occurrence of cloud associated with a jet stream over Schenectady, New York. Frost[4,5,6] in three illustrated articles describes, from an airline captain's view-point, the types of cloud which occur with jet streams and his findings are very similar to those of Schaefer. The main features are cirrus streamers of great complexity, showing long tufted streaks and complex shear lines. The bands of cloud lie along the jet, sometimes for great distances together with cross striation and at times tufted cirrus with long streamers ('fallstreifen') beneath. Frost mentions an occasion on which a line of thin cloud associated with a jet stream was followed for 1700 miles across the Atlantic until the aircraft's track left the line of the jet core. At lower levels, lines of altocumulus along the wind direction show billow or wave formation at right angles to it.

The two accompanying photographs, which were taken at Uxbridge, Middlesex, at 1820 GMT on 22 June 1963 illustrate clouds of these types associated with a jet stream. Plate III which was taken with the camera pointing approximately in a direction of 220 degrees shows that the main banding of cloud was in a direction of about 240–060 degrees. Plate IV was taken in a direction of 270 degrees and again shows the main banding of the cloud with some signs of tufted cirrus and fallstreifen.

Figure 1 shows the maximum wind from a number of stations in north-west Europe at 1800 GMT on 22 June 1963 while Figure 2 shows the maximum winds at 0000 GMT on the 23rd. On Figure 2 the pecked line shows the analysed

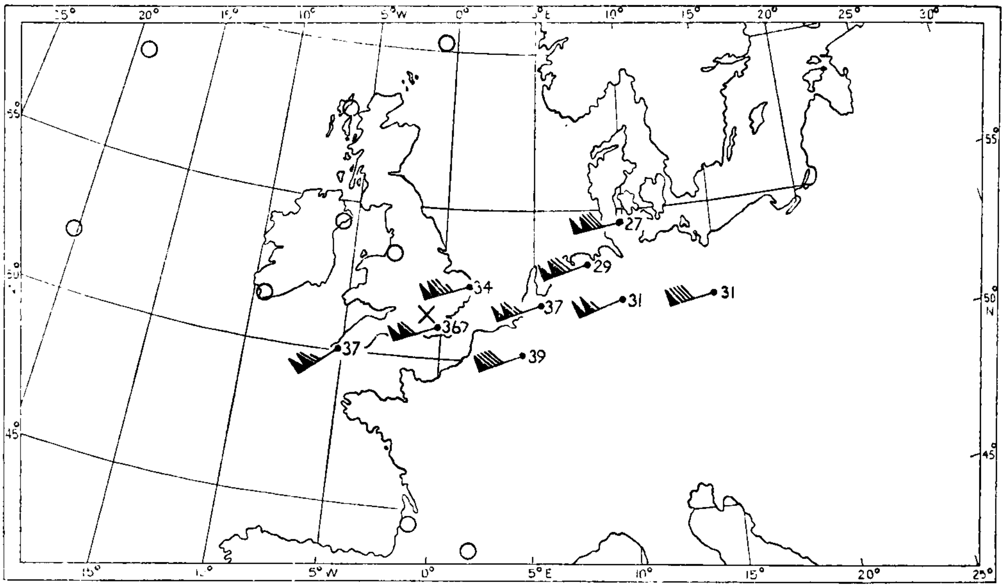

FIGURE 1—MAXIMUM WINDS OVER NORTH-WEST EUROPE AT 1800 GMT ON 22 JUNE 1963

X Position where photograph was taken.
O Stations where the maximum wind was less than 80 knots.
Figures on the right of the station circle give the height of the maximum wind in thousands of feet.

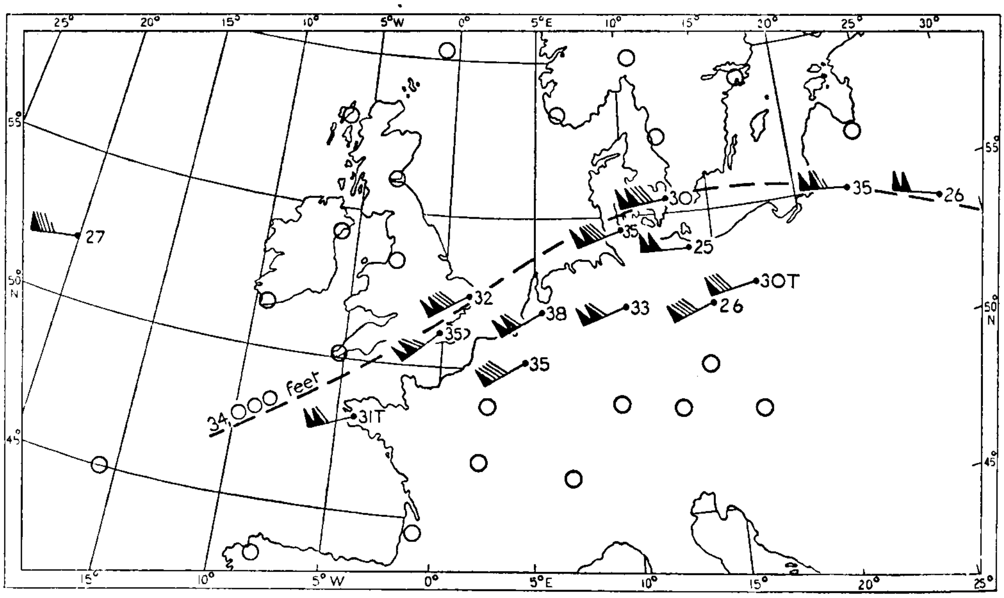

FIGURE 2—MAXIMUM WINDS AND JET-CORE POSITION OVER NORTH-WEST EUROPE AT 0000 GMT ON 23 JUNE 1963

O Stations where the maximum wind was less than 80 knots.
Figures on the right of the station circle give the height of the maximum wind in thousands of feet. T indicates that the maximum occurred at the highest point reached by the balloon.
— — — Jet-core position.

jet-core position and height taken from the working charts at London (Heathrow) Airport Meteorological Office. It can be seen that the jet core lay from the west of the English Channel across East Anglia to Copenhagen and was placed at a height of 34,000 feet. Furthermore there appears to be some increase of wind speed downwind. The place where the photographs were taken thus lay just to the warm side of a weak jet entrance, a region where some upward motion is to be expected below the level of the jet. It thus appears probable that the clouds photographed were a little below 34,000 feet.

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METEOROLOGICAL OFFICE DISCUSSION

The investigation of frontal rain by aircraft

At the first Meteorological Office discussion of the winter, held at the Royal Society of Arts on 21 October 1963, the subject was 'The investigation of frontal rain by aircraft.'

Mr. S. G. Cornford described how aircraft of the Meteorological Research Flight had flown in frontal layer cloud over southern England in winter to measure the concentration and size distribution of precipitation particles using the aluminium-foil technique. The results were used to calculate precipitation rates at heights up to 20,000 feet and showed that much of the precipitation was generated low in the cloud. On occasions when the nimbostratus extended well above the 0°C level the Bergeron process contributed less than half the rain which fell at the ground.

A novel feature was a layer 1000–2000 feet deep near the nimbostratus cloud base (which was usually at or below 2000 feet), in which the precipitation rate was several times that at the ground. The loss was too great to attribute to evaporation. The only explanation so far advanced was that raindrops shattered near the cloud base with an appreciable proportion of their water forming droplets of cloud droplet size. As it was borne upwards on the weak updraught, which must be present if rain is to be generated continuously, cloud water would be swept through by the next generation of raindrops so that they would grow and at the same time maintain a strong gradient of cloud water content in the upper side of the rainy layer. The water budget is balanced because in the presence of this gradient the updraught effects a net import of cloud water into the upper side of the layer and together with the condensing water vapour provides water for the net export of rain. As many of the raindrops shatter again much of the water begins another cycle within the layer.

Dr. Caton then explained how at the Meteorological Research Unit at Malvern he was able to measure precipitation particle concentrations and sizes at many levels in the free air by means of a vertically pointing 3-cm

Doppler radar. The measurements made so far were unreliable below 2200 feet, but above that height amongst 60 observations made on 8 days he could find nothing to support the idea of the existence of the rainy layer.

The discussion then centred on sampling errors, calibration of the aluminium-foil instrument and some of the implications of the existence of the layer.

Closing the discussion the Director-General said that there was evidence to show that the phenomenon described was a fact and no doubt practical applications would emerge. The need now was to reconcile the results of the radar and sampling techniques.

REVIEW

Tropical meteorology in Africa. Proceedings of the symposium jointly sponsored by the World Meteorological Organization and the Munitalp Foundation. Edited by D. J. Bargman. $9\frac{1}{2}$ in. × 7 in., pp. xv + 446, Munitalp Foundation, Nairobi, 1960. Price: S.F.20.

This book contains the papers presented at the symposium on Tropical Meteorology held at Nairobi in December 1959. Delay in publication, caused by the ill-health of the Editor, David J. Bargman, has not seriously detracted from its usefulness.

The symposium was attended by meteorologists from twenty-one African countries and by several well known scientists from Europe and the United States of America. The international character of the symposium as well as the quality of the main participants made this symposium an outstanding landmark in the history of meteorology in Africa. A wide field is covered by the recorded proceedings with the emphasis on practical applications both in synoptic meteorology and climatology. However, papers on various aspects of synoptic meteorology tend to dominate the book.

There are six excellent articles of a survey type on general synoptic problems including synoptic analysis and synoptic models, by N. E. La Seur and A. G. Forsdyke, and H. Flohn covers a variety of topics in five articles, for example, 'Multiple tropopause above the equatorial Pacific,' and 'The structure of the intertropical convergence zone.'

Amongst the other papers with a synoptic basis, perhaps the more interesting are 'Forecasting research in East Africa' by D. H. Johnson and H. T. Mörth, 'Generalized gradient wind equations and contour analysis in the tropics' by E. Kruger and 'Some streamlines and contours over the equator' by J. Cochemé. The contribution of Johnson and Mörth is particularly notable in emphasizing the usefulness of upper air contour charts in the equatorial zone by stressing the dynamical interpretation of contour and wind patterns, especially in relation to rainfall. Previously most meteorologists were sceptical of the value of upper air contour charts owing to the weakness of the geostrophic relationship in very low latitudes quite apart from the scarcity of reliable observations. However Johnson and Mörth give a broadly adequate theory supported by persuasive synoptic examples over Africa of their basic synoptic models, namely the Duct, the Drift and the Bridge. The papers by Johnson and Mörth, Kruger and Cochemé all highlight the necessity for an improved upper air network over Africa, and the need for more stations as well as more frequent and reliable observations.

Rainfall plays a vital role in the life of all African countries and its fundamental importance is reflected in such papers as 'On the global water vapour balance and the hydrological cycle' by J. P. Peixoto, 'The application of weather radar to hydrological problems' by V. D. Rockney, 'Cotton crop potential and rainfall expectation in Uganda' by H. L. Manning and 'Les campagnes de pluie artificielle du Nord-Cameroun' by R. Du Chaxel. These are all of a high standard.

The diversity of subjects treated at the symposium is illustrated further by papers on 'The agricultural uses of meteorological data' by E. W. Russell, 'Applications of synoptic meteorology to problems of locust control: some recent findings' by R. C. Rainey and 'The possibilities for utilization of wind power in tropical Africa' by E. W. Golding.

No doubt a case could have been made out for cutting down the size of this book of 446 pages, by drastic pruning of many papers or even by the omission of some of them. However it was probably wise to record the entire proceedings in view of the rarity of such meetings in Africa, and the need for periodical stock-taking.

R. MURRAY

LETTER TO THE EDITOR

An occurrence of 'ball lightning'

On the evening of Wednesday, 6 November 1963, at approximately 11.5 p.m., my father saw in his bedroom, in the centre of the room, a small, egg-shaped ball of brilliant light. Within the space of a few seconds, this small ball of light spread itself to form a sheet of darkish green light as wide as the room itself (approximately 12 feet). This curtain of light then moved towards my father and turned greyish colour. The whole sight then vanished as suddenly as it appeared, with a very loud bang, similar to the report from a rifle. The light was witnessed only by my father but the bang was heard by both my brother, from a neighbouring bedroom and my mother, who was downstairs in the kitchen. The bedroom light was on and it was raining at the time. We would not believe that this phenomenon had occurred if it were not for the fact that the very loud bang was heard by three people who were each in different rooms at the time.

5 *Hillside Avenue, Mapperley, Nottingham* M. F. FALKNER

[Other accounts of ball lightning appear in *Nature, London*, Vol. 198, 1963, p. 745, and *Zeitschrift für Meteorologie, Berlin*, Vol. 8, 1954, p. 27. Ed. M.M.]