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THE ESTIMATION AND VARIABILITY OF PRECIPITABLE WATER

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Introduction.—In order to improve the forecasting of cloud and to provide satisfactory quantitative forecasts of rain it is probable that the three-dimensional field of water vapour in the atmosphere will need to be defined in more detail than is possible at present from the current aerological network, especially over the Atlantic. To overcome the lack of upper air data recourse might be made to the use of estimates of water vapour based on the synoptic observations available on surface charts and further estimates based on the data available from the upper air network for previous observational hours might also be incorporated.

These possibilities were explored using precipitable water in the layer between 1000 mb and 500 mb as the parameter representing the water vapour of the lower atmosphere. Precipitable water of a column of air is defined[1] as "the depth of water (alternatively expressed as the total mass of the water) that would be obtained if all the water vapour in the column of unit area cross-section were condensed on to a horizontal plane of unit area. 'Precipitable water' is a useful measure of the water vapour content of an air column. The term is not, however, to be regarded as implying that the amount of water may, in fact, be precipitated by an actual physical process". For practical purposes the precipitable water contained in the lower troposphere can be regarded as sufficiently representative of the water vapour available for the rain processes. The layer from 1000 mb to 500 mb was chosen in preference to the layer from the surface to 500 mb, although the latter is more strictly a measure of the available moisture, as it seemed reasonable to examine the behaviour of water vapour contained between two constant-pressure surfaces rather than that contained in a layer which is of more variable depth and which is, furthermore, correlated with surface pressure.

Practical computation of precipitable water.—In the c.g.s. system of units the expressions for precipitable water[1] in centimetres and grams are numerically equal and are given by the approximate expression

$$\text{precipitable water (cm or g)} = \frac{1}{g}\int_{p_2}^{p_1} r\,dp \ ,$$

where p_1 and p_2 are the pressure in millibars at the bottom and top of the column respectively, r is the mixing ratio (g/kg) and g is the acceleration of gravity.

The precipitable water in a column 100 mb deep which has a mean mixing ratio r_m is therefore approximately equal to $r_m 100/980$ cm or $r_m(1{\cdot}02)$ millimetres: in practical calculations this can be taken as $r_m$mm, a straightforward conversion.

To compute the precipitable water between 1000 mb and 500 mb from a radiosonde ascent it is convenient to consider the layer as composed of five 100-millibar layers. A mean mixing ratio is determined for each layer by drawing the mixing ratio line which results in the areas bounded by the dew-point curve, the isobars defining the layer and the mixing ratio line itself, being equally distributed on either side of this line. Figure 1 gives an example of the construction of mean mixing ratio lines for two layers (900 to 800 mb and 600 to 500 mb) on a typical sounding. The values of mean mixing ratio for the five layers, when added together, can therefore be taken as representing the precipitable water in mm for the layer 1000–500 mb. It can be argued that some adjustment should be made to the precipitable water determined as above since the variation of humidity mixing ratio as represented on the tephigram is not a linear one (see Figure 1): in practice, however, such a refinement is generally not justified since there are appreciable errors in the observing and recording of humidity and water vapour in the atmosphere.

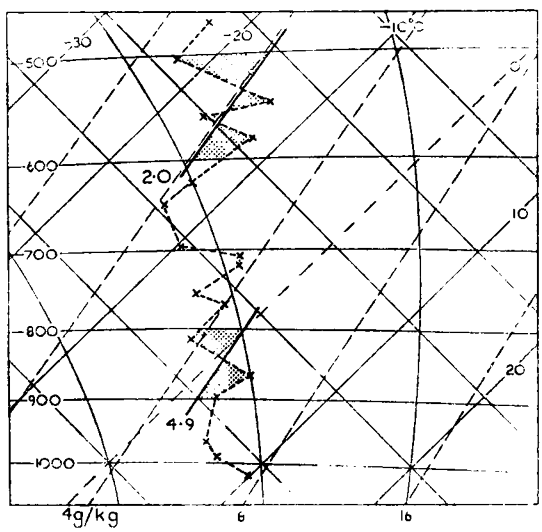

FIGURE 1—EXAMPLE SHOWING COMPUTATION OF PRECIPITABLE WATER IN THE LAYERS 900–800 MB AND 600–500 MB

x – – – x Dew-point curve

2·0 and 4·9 are the mean mixing ratios for these two layers in g/kg.

The spatial and temporal variations of precipitable water.—In devising an analysis technique for humidity it is essential to know how much the precipitable water parameter can vary in space and time. Not a great deal of work has been done on these lines, but Penn and Kunkel[2] obtained interesting statistics from an examination of mixing ratios at 1000 mb, 850 mb and 700 mb using a unique series of 168 hourly radiosonde ascents made in Massachusetts in April 1960. Autocorrelation coefficients were determined between mixing ratios over periods up to 24 hours and it was found that the correlation at the three surfaces remained above 0·80 for periods up to 4 hours, fell to between 0·65 (850 mb) and 0·40 (700 mb) over the 12-hour period and to almost negligible values over the 24-hour period. Figure 2 shows the correlation for the 700 mb mixing ratio for periods from 1 hour to 24 hours (taken from Penn and Kunkel's paper). For comparison Table I shows the correlation between values of the 1000–500 mb precipitable water parameter over periods of 12, 24 and 36 hours from the initial times 0000 GMT and 1200 GMT, using data from the three ocean weather stations 'I', 'J' and 'K' for the five months June to October, 1963: as expected the initial time from which the periods are measured had little effect.

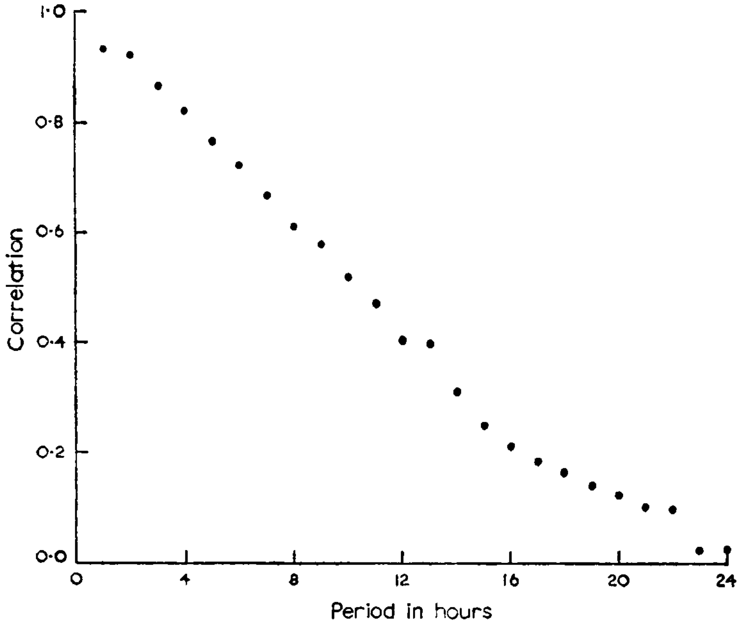

FIGURE 2—AUTOCORRELATION OF MIXING RATIO AT 700 MB OVER PERIODS FROM 1 TO 24 HOURS

After Penn and Kunkel[3]

TABLE I—AUTOCORRELATION OF 1000–500 MB PRECIPITABLE WATER FOR PERIODS OF 12, 24 AND 36 HOURS AT OCEAN WEATHER STATIONS 'I', 'J' AND 'K' IN JUNE TO OCTOBER 1963.

	Autocorrelation coefficient	
	Period starting 0000 GMT	Period starting 1200 GMT
12-hour period	0·47	0·47
24-hour period	0·26	0·23
36-hour period	0·23	0·15

It is clear therefore that the observed value of precipitable water at a place is not normally a good estimate of the value at that place 12 hours later.

To obtain rough quantitative estimates of the order of the spatial and temporal variations which could occur, the data for the radiosonde stations in the British Isles and neighbouring countries during the summer and autumn months in 1963 were also examined. Changes at a station of more than 12 mm in 12 hours were observed whilst in some synoptic situations the differences between precipitable water values at radiosonde stations gave spatial variations of the order of 1 mm per 10 nautical miles. Since the data were obtained from the normal radiosonde ascents made at intervals of 12 hours, it was not possible to determine the absolute variations over time intervals as short as one hour or over space intervals as small as 10 nautical miles. Some idea of the effect of shortening the space interval was obtained by examining those occasions when the mean 700 mb wind speed between consecutive radiosonde ascents was very weak. Only one month, June 1963, was examined but from these very limited data it was noted that a change of 10 mm in the precipitable water parameter could occur when the column, if advected with the 700 mb wind, had only moved about 50 nautical miles: this corresponds to a spatial variation of 2 mm per 10 nautical miles.

The absolute variations over small time and space intervals are therefore occasionally likely to be considerably in excess of 1 mm per hour and 2 mm per 10 nautical miles, and these variations assume considerable importance when the representativeness of individual observations in a humidity analysis is being considered.

Estimates of precipitable water from surface observations over the sea.—Since ship surface observations over the Atlantic greatly outnumber the available upper air observations, the possibility of obtaining estimates of precipitable water based on surface observations is an attractive proposition. All hours in the five-month period June to October 1963 for which a radiosonde ascent was available at the ocean weather stations 'I', 'J' and 'K', were classified into three categories representing the weather states:

(*a*) no precipitation at the time of the upper air observation or in the preceding hour,

(*b*) showery precipitation,

and (*c*) precipitation other than showers.

The surface parameters extracted for these occasions were the dry-bulb temperature, dew-point and sea temperature at the time of the upper air observation and the wind direction at the same time and also 6 hours earlier. The precipitable water (1000–500 mb) was computed from the appropriate radiosonde ascent.

Table II shows the extent to which precipitable water is correlated with the surface parameters and with the three derived parameters, the dew-point

TABLE II—CORRELATION BETWEEN PRECIPITABLE WATER (1000–500 MB LAYER) AND SPECIFIED SURFACE PARAMETERS AT 0000 AND 1200 GMT AT OCEAN WEATHER STATIONS 'I', 'J' AND 'K' IN JUNE TO OCTOBER 1963.

	0000 GMT				1200 GMT			
Surface parameters	All cases	No ppn	Shower type ppn	Other ppn	All cases	No ppn	Shower type ppn	Other ppn
Dew-point	+0·68	+0·70	+0·80	+0·66	+0·69	+0·69	+0·73	+0·67
Dew-point depression	−0·49	−0·44	−0·50	−0·42	−0·41	−0·35	−0·23	−0·38
Sea temperature	+0·40	+0·50	+0·54	+0·44	+0·46	+0·54	+0·58	+0·43
Dry-bulb temperature	+0·52	+0·58	+0·76	+0·61	+0·53	+0·59	+0·68	+0·53
Difference between dry-bulb and sea temperature	+0·42	+0·37	+0·62	+0·47	+0·33	+0·28	+0·36	+0·39
Difference between sea temperature and dew-point	−0·52	−0·44	−0·73	−0·52	−0·46	−0·37	−0·43	−0·51
Wind direction	+0·13	+0·06	+0·14	+0·14	+0·03	+0·00	+0·05	+0·09
Wind direction 6 hours earlier	+0·14	+0·08	+0·20	+0·10	+0·04	+0·00	+0·27	+0·00
Total number of cases	447	300	47	100	450	302	54	94

depression, the difference between dry-bulb and sea temperatures and the difference between sea temperature and the dew-point. The 0000 GMT data were examined independently of the 1200 GMT data and it will be noted that the surface parameter most highly correlated with the precipitable water at both observation times and for each of the three weather states is the dew-point, the correlation coefficients varying between 0·66 and 0·80. Though these coefficients might be considered rather low to form the basis of a quantitative analysis of precipitable water, comparison with Table 1 and Figure 2 shows that these coefficients are considerably higher than the autocorrelation coefficients over periods of 12 hours or more and seem likely to be higher than the autocorrelation for periods as short as 6 hours. On occasions when an upper air observation is missing at a specific synoptic hour it would appear, therefore, that an estimate based on the value of the surface dew-point and the state of the weather would probably be a better estimate than the previous observation of precipitable water for that place.

There seems little reason to suggest that the correlation between precipitable water and dew-point would be markedly different at other seasons of the year but this aspect would have to be examined if it became necessary to use operationally the precipitable water fields obtained in this way. At the same time, examination of the limited data available for these five months suggests that higher correlation could be achieved by taking into account the state of the sky: subdivision of the data into categories representing the state of the sky as well as the state of the weather would therefore appear desirable, though it should be emphasized that a much greater volume of data would be required in order to achieve this greater discrimination. For interest Table III has been included to give an estimate of precipitable water in millimetres for the observed dew-point and present weather state at 0000 GMT and 1200 GMT,

TABLE III—ESTIMATED PRECIPITABLE WATER (1000–500 MB LAYER) FOR OBSERVED SURFACE DEW-POINTS AND WEATHER STATES AT 0000 AND 1200 GMT AT OCEAN WEATHER STATIONS 'I', 'J' AND 'K' IN JUNE TO OCTOBER 1963

Surface dew-point °C	Weather state: No precipitation at time of observation or during previous hour		Showery precipitation at time of observation or during previous hour		Precipitation other than showers	
	0000 GMT	1200 GMT	0000 GMT	1200 GMT	0000 GMT	1200 GMT
	millimetres					
1	4·5		5·8		6·5	
2	5·7		6·9		7·9	
3	6·9	7·6	8·1	9·0	9·3	7·2
4	8·1	8·7	9·2	9·8	10·7	8·7
5	9·3	9·9	10·3	10·6	12·1	10·2
6	10·5	11·0	11·5	11·4	13·5	11·8
7	11·7	12·1	12·6	12·3	14·9	13·3
8	12·9	13·2	13·7	13·1	16·3	14·8
9	14·1	14·3	14·9	13·9	17·6	16·4
10	15·3	15·5	16·0	14·7	19·0	17·9
11	16·5	16·6	17·1	15·5	20·4	19·4
12	17·7	17·7	18·3	16·4	21·8	20·9
13	18·8	18·8	19·4	17·2	23·2	22·5
14	20·0	20·0	20·5	18·0	24·6	24·0
15	21·2	21·1	21·7	18·8	26·0	25·5
16	22·4	22·2	22·8	19·6	27·4	27·1
17	23·6	23·3	24·0	20·5	28·8	28·6
18	24·8	24·4	25·1	21·3	30·1	30·1
19	26·0	25·6	26·2	22·1	31·5	31·6

based on the five months' data. Table IV gives the values of precipitable water assuming that the air is completely saturated at the indicated 1000 mb dew-point and with a lapse rate corresponding to the saturated adiabatic.

TABLE IV—PRECIPITABLE WATER (1000–500 MB LAYER) FOR SPECIFIED 1000 MB DEW-POINTS ASSUMING A SATURATED-ADIABATIC LAPSE RATE

Dew-point at 1000 mb (°C)	0	2	4	6	8	10	12	14	16	18	20
Precipitable water (mm)	8	10	12	14	17	20	24	29	34	40	48

Figure 3 shows a map of precipitable water for 1200 GMT on 6 June 1963; the computed values from the radiosonde ascents are given to the nearest tenth

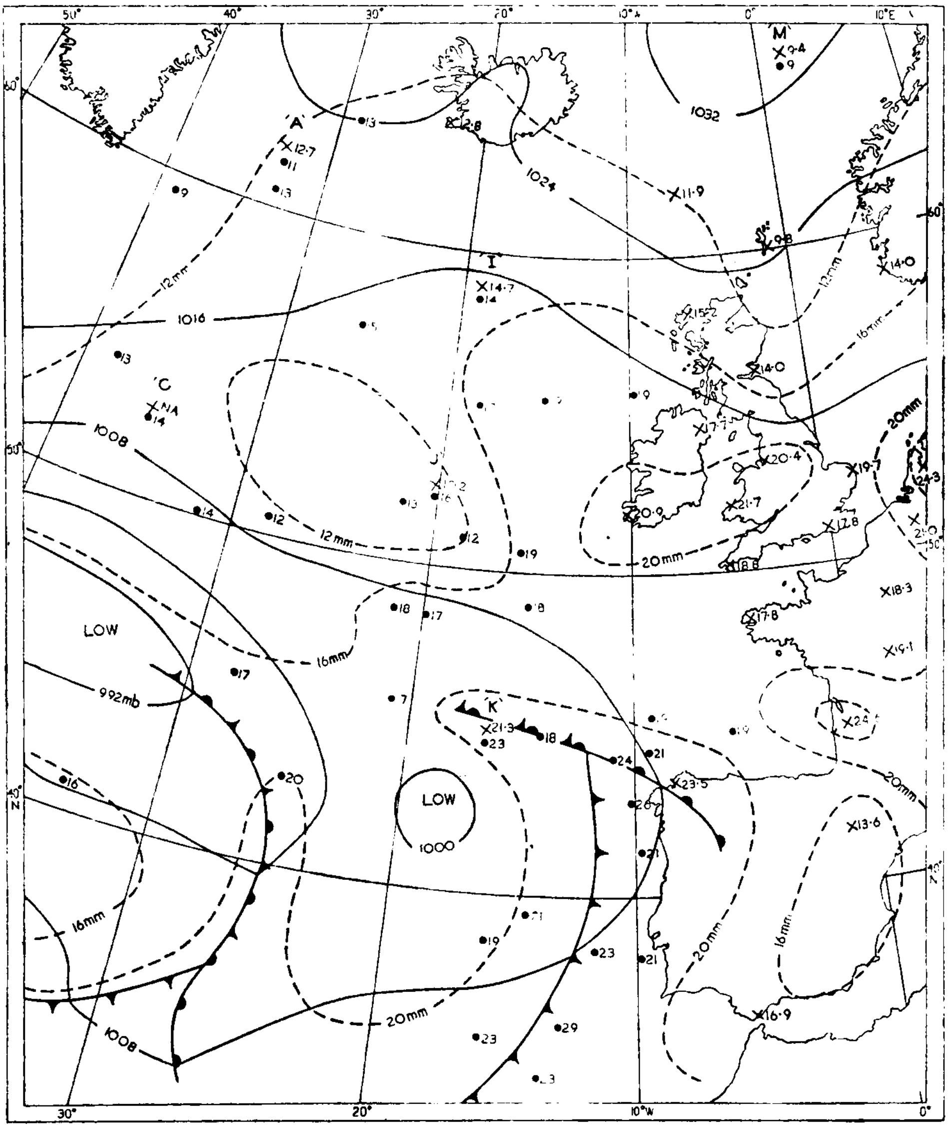

FIGURE 3—MAP OF PRECIPITABLE WATER AT 1200 GMT ON 6 JUNE 1963

——— Surface isobars at 8-mb intervals

— — — Isopleths of precipitable water at 4-mm intervals

x Values of precipitable water computed from radiosonde ascents given to the nearest tenth of a millimetre.

. Estimated values from surface ship observations given to the nearest whole millimetre.

of a millimetre and the estimates, based on surface ship observations and Table III, are given to the nearest whole millimetre. It will be noted that no 1200 GMT sounding was available for Lajes in the Azores and that the humidity data on the sounding from ocean weather station 'C' (approx 53°N, 35°W) were insufficient to permit a value of precipitable water to be computed for the layer 1000–500 mb. Extremely dry air had been carried previously from the British Isles towards ocean weather station 'J' and it will be seen that in this part of the map, the computed value is rather low compared with the estimate derived from the surface observations; for other ocean weather stations the estimates are fairly close to the computed values.

Estimates of precipitable water from the 1000–500 mb thickness.— The relationship between the 1000–500 mb precipitable water and the 1000–500 mb thickness was examined using the data for the same five months as the previous section, namely June to October 1963, for the three ocean weather stations 'I', 'J' and 'K'. Table V shows the correlation between precipitable water and thickness for all occasions at 0000 GMT and 1200 GMT as well as for the three weather state categories previously defined. The correlation is highest, 0·71, for those occasions when precipitation other than showers was occurring: for the other two weather states the correlation coefficients are lower than those obtained with some of the more significant surface parameters, e.g. dew-point and dry-bulb temperature.

TABLE V—CORRELATION BETWEEN PRECIPITABLE WATER (1000–500 MB LAYER) AND THICKNESS (1000–500 MB) AT 0000 AND 1200 GMT AT OCEAN WEATHER STATIONS 'I', 'J' AND 'K' IN JUNE TO OCTOBER 1963

	0000 GMT				1200 GMT			
	All cases	No ppn	Shower type ppn	Other ppn	All cases	No ppn	Shower type ppn	Other ppn
Correlation coefficient	+0·59	+0·57	+0·69	+0·71	+0·61	+0·60	+0·63	+0·67
Number of cases	447	300	47	100	450	302	54	94

There is, however, another aspect which should be kept in mind when considering the possible use of the thickness field in this problem. It might become necessary to use a field of precipitable water more akin to that of maximum precipitable water on the assumption that the air column involved in the rain process is completely saturated. The 1000–500 mb thickness charts could provide such a field of maximum precipitable water by using a table such as Table VI, which gives precipitable water values for specified thickness values assuming that the air column is saturated with a lapse rate following the saturated adiabatic: some adjustment could be made when the stability of the air mass is markedly different from this.

TABLE VI—PRECIPITABLE WATER (1000–500 MB LAYER) FOR AN AIR COLUMN WHICH IS SATURATED AND IN NEUTRAL EQUILIBRIUM AND WITH INDICATED THICKNESS (1000–500 MB)

1000–500 mb thickness (decametres)	510	516	522	528	534	540	546	552	558	564	570
Precipitable water (mm)	7	9	11	13	16	20	24	29	35	42	50

Conservatism of precipitable water.—In an earlier section reference was made to the observed temporal changes in precipitable water at a fixed point and to the observed spatial changes at a fixed synoptic hour. It is interesting, as well as useful, to attempt to determine what changes take place in the 1000–500 mb precipitable water parameter, following the air motion at 700 mb. By constructing 700 mb trajectories of 24-hour duration, originating at radiosonde stations in the British Isles and neighbouring sea and land areas, it is possible to compare the precipitable water at the start of the trajectory with a later 'observed' precipitable water value, whenever the trajectory passes sufficiently close to a radiosonde station. Such an experiment was carried out with data from June 1963, using British radiosonde stations as control stations for providing the 'observed' precipitable water values for comparison. Whenever one of the 700 mb trajectories constructed as above passed within 100 nautical miles of a control station the following details were noted:

(i) The time of nearest approach;

(ii) Whether the nearest approach distance was
(*a*) 50 nautical miles or less
or (*b*) between 50 and 100 nautical miles;

(iii) The period of the trajectory up to the nearest approach time in the four categories:
(*a*) up to 6 hours,
(*b*) more than 6 but not more than 12 hours,
(*c*) more than 12 but not more than 18 hours,
or (*d*) more than 18 but not more than 24 hours.

The 'observed' precipitable water value was that value obtained from the upper air ascent closest in time to the time of closest approach; in those cases, therefore, when the time of closest approach fell midway between consecutive upper air observations, there were two 'observed' values for comparison. There were also some trajectories which passed sufficiently close to more than one control station and on these occasions, as well, more than one 'observed' value was available for comparison. In all, 476 comparisons were made, giving a correlation coefficient of 0·60 between 'initial' and 'observed' precipitable water. When the restriction that the trajectory should be for not more than 12 hours duration is imposed the number of cases is 269 with a correlation coefficient of 0·63. The correlation is 0·65 (281 cases) when the occasions are restricted to those when the time of nearest approach is within 4 hours of the time of the 'observed' precipitable water, and the correlation coefficient reached 0·68 (142 cases) if this time interval is reduced to 2 hours or less. When this last restriction is coupled with the restriction that the trajectory had to pass within 50 nautical miles of the control station, the number of cases drops to 89, giving a correlation coefficient of 0·65. Bearing in mind the size of the variations in precipitable water previously discussed, namely 1 mm per hour and 2 mm per 10 nautical miles, these correlation coefficients seem high enough to support the suggestion that precipitable water is a fairly conservative parameter.

Computed values of precipitable water from the previous upper air observation time, advected with the appropriate 700 mb wind, could therefore provide, especially over the Atlantic, approximate values of precipitable water which could be utilized in the analysis.

Conclusions.—To provide satisfactory forecasts of rainfall it is important to know the distribution of moisture in considerable detail in addition to that of vertical motion. It is suggested that charts of precipitable water be used to define the moisture patterns; however, the present synoptic upper air observations are insufficient to provide the details of the smaller-scale patterns in the moisture fields and should be supplemented by estimates based on surface observations and on previous upper air observations displaced with the appropriate 700 mb winds.

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TECHNIQUES OF TEMPERATURE AND WIND SOUNDING WITH THE SKUA METEOROLOGICAL ROCKET

By R. ALMOND

History.—Firings of the first development rounds of the SKUA Meteorological Rocket commenced in March 1963. Initial failures were associated with the delayed ignition of the sustainer motor, and this trouble was rectified by October of that year. It had been planned that firings would start in the Outer Hebrides at the commencement of the International Years of the Quiet Sun period in January 1964, and with this end in view development firings were completed at this station.

The first signal from a payload ejected from the rocket at apogee was heard on 10 November 1963, from about 35 kilometres altitude, and the first temperature measurements from a sonde were obtained one month later on 9 December 1963, from an altitude of 42 km. Production round firings started in January 1964, and continued until March when the programme was halted because of a dramatic increase in failure rate. A further development stage covering June to November 1964, was held at the Ministry of Aviation range in Wales, and was based on deliberate spinning of the vehicle up to a maximum rate of 12 rev/second. Five good trajectories were obtained from six rounds, the failure being due to motor trouble and not to instability. This was considered good proof that the Hebrides failures attributed to a rocket instability phenomenon called 'roll yaw lock-in', i.e. destructive interaction between the roll and yaw features of the vehicle, had been overcome.

The spin feature was therefore incorporated in the rounds prepared for the second Hebrides campaign, covering the period January to April 1965. Although a few failures resulted during this period, it is felt that a very successful sounding rocket has now been developed. Photographs of the rocket launcher and the sonde are shown in Plates I–III.

The rocket vehicle.—SKUA 1 which has been used for all soundings to date, will carry a 4·5-kilogram payload to an altitude of 70 km for an 85°-elevation firing. It has a payload section volume of 8·2 decimetre^3, is 2·3 metres long and 13 centimetres in diameter, and has an all-up weight of 37 kg. The motor is a solid propellant end-burning type. Low dispersion is achieved by launching the rocket from a steel tube, 10 m long and 53 cm in diameter, using a boost rocket. The latter forms the central portion of a carriage structure and piston, on top of which the fins of the main rocket rest, under gravity only, in special wedges. The forward end of the rocket is aligned axially by a foamed-plastic sabot. The carriage has wheels which contact the inner surface of the launcher tube, and houses fins and two 2-m parachutes for guidance and safe return to ground, ensuring its usability for further firings. The boost thrust is 1800 kg for 0·2 seconds, yielding a tube exit velocity of 107 m/s. The main rocket is ignited at the same instant as the boost and burns for 30 s, after which time a height of 16·5 km and a speed of 1220 m/s have been reached. A thermal switch operates at this point, starting a delay clock with a 105-s running period, at the end of which a small rocket is fired applying thrust to a piston which separates the payload from the rocket body at a speed of 7·6 m/s having sheared the nose-cone retaining pins. This timing of 135-s from launch coincides with the 70-km apogee of the rocket.

Launcher settings to achieve effective 85°-elevation firings are determined from ballistic wind correction data. Wind structure is measured over the full burning range, i.e. 16·5 km and weighting factors are applied to the mean winds of six appropriate layers within this depth of atmosphere. This gives a total ballistic wind to which the unit wind effect of 0·598° per m/s is applied. Half the 'weighting' is taken up in the first 370 m of the 16·5 km considered.

The rocket can be 'skin-tracked' by the standard Meteorological Office wind-finding radar to a slant range of 50 km, and this is sufficient to define the trajectory and supply accurate 'laying-on' angles for parachute acquisition at apogee. Figure 1 shows trajectories for varying angles of elevation.

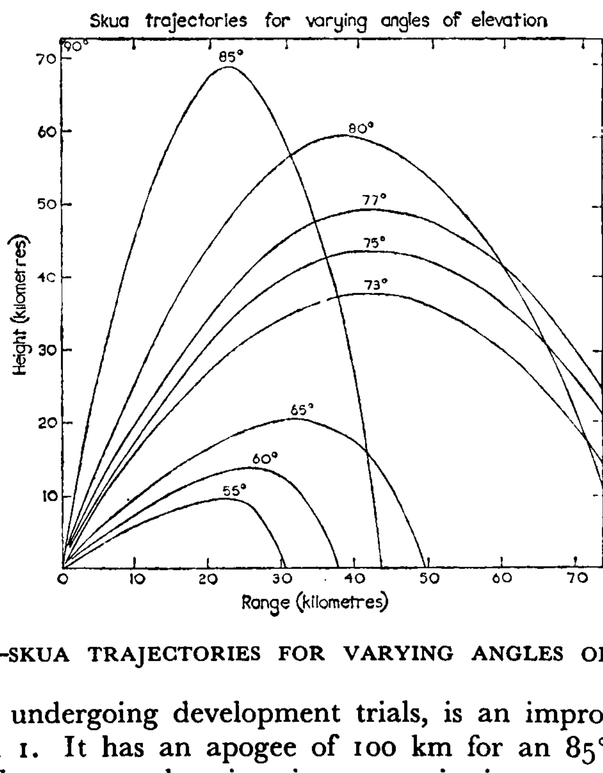

FIGURE 1—SKUA TRAJECTORIES FOR VARYING ANGLES OF ELEVATION

SKUA 2, now undergoing development trials, is an improved performance version of SKUA 1. It has an apogee of 100 km for an 85°-elevation firing, achieved by only 3 s extra burning time, necessitating a motor elongation of only 11 cm and increased all-up weight of 2 kg. The initial meteorological payload is high-altitude radar chaff (85 to 60 km) plus temperature sonde with parachute (65 to 15 km). A standard chaff load for SKUA 1 is already fully developed and tested, forming an alternative payload to the sonde.

The meteorological payload.—The meteorological payload is almost invariably the temperature-measuring sonde and parachute yielding wind/temperature/height data between 65 and 15 km. It must be capable of rocket ascent to 70 km, full deployment, and finally yield the telemetry data for at least one hour with negligible circuit temperature and voltage coefficient errors. The parachute must give reflected primary radar pulses of sufficient strength to produce automatic range, elevation, and azimuth presentation data at the ground station to at least 140-km slant range.

Sonde circuit.—A low-power (30 milliwatt) single transistor oscillator coupled to a quarter-wave aerial provides the radio frequency carrier operating at a pre-set frequency in the 27·5 to 28-megacycles/second meteorological band.

This carrier is frequency modulated with a deviation of $\pm$ 20 kc/s by an audio-frequency signal within a band 700 to 1000 c/s. The variation of the audio frequency is a measure of atmospheric temperature. This variation is produced by the temperature element which forms a variable resistance arm in a twin-T bridge oscillator.

A resistive dividing network across a stabilized voltage supply is capacitatively fed from the output of the oscillator emitter follower, yielding the correct bias and A/F signal for a variable capacity diode which produces the F/M swing of the carrier.

A two-section dry battery provides separate supplies for A/F and R/F sections, the A/F supply being stabilized by Zener diodes.

The R/F circuit has two tuning facilities, one capacitative for frequency setting, and one inductive for power matching into the quarter-wave aerial.

Construction.—The temperature element is a flat double open spiral of spiralized tungsten wire supported by plastic monofilament spokes, in an aluminized resin-bonded fabric 8·9-cm diameter ring. The wire, of diameter 13·5 microns, has a pitch of about 90 microns and a spiralized diameter of about 200 microns. This enables a resistance of 3100 ohms (at 0°C) to be mounted compactly and safely. The resulting actual length of wire is 7·72 m. The element ring is grooved on the inside to take a spring clip, which forms a resilient mount and is attached to a spring-loaded telescopic deployment shaft.

During the ascent the temperature element is held on a foamed-plastic cushion protected by an element cap which carries a cord harness and release pin. These are removed when the rocket nose-cone has separated 1 m from the sonde on parachute deployment, since the cord is attached to an eye-bolt in the apex of the nose cone.

The temperature element is then carried by its deployment shaft to a point 13 cm from the main sonde body and at the same time power is applied to the circuit. The exposed temperature element is now the lowest point of the sonde assembly as it descends by parachute. The canopy of the parachute is 4·5 m in diameter and has alternate panels of metallized and unmetallized silk making it a passive radar target. A strop between the apex of the shroud lines and the sonde suspension point houses the quarter-wave transmitter aerial.

The average parachute fall rates from different heights are given in Table I.

TABLE I—AVERAGE PARACHUTE FALL RATES

Height *kilometres*	Fall rate *metres/second*	Time elapsed *minutes*	*seconds*
70	225	zero	
65	160		10
60	125		50
55	90	1	40
50	65	2	40
40	32	6	15
20	4·5	40	
14	3·7	60	

The main circuit components are housed in an all-metal chassis and protected with a silicone rubber coating before being completely encapsulated in rigid poly-urethane foam. To prevent twisting of the strop and parachute shroud lines a small swivel link is placed between them. This is required because of the spin feature of the rocket which also necessitates the dynamic balancing of the sonde.

Temperature corrections.—Measurements were made in the National Physical Laboratory low-density wind tunnel at the required density/speed combinations, and with and without radiation, in order to determine the law governing temperature rise above the true air temperature in the falling sonde temperature element. Dynamic heating and radiation errors are complicated by the different flow régimes (free molecular, slip, and continuum) which are encountered between 70 and 20 km, and also by the fact that the temperature element seems to behave as if possessing a dimension factor intermediate between the diameter of the wire and that of the coil. The dynamic heating correction is found to be unaffected by the yaw angle, at least up to 45°, but the radiation correction increases from a minimum at incidences normal to the plane of the double spiral to a maximum at high incidence angles, being eventually cut off by the shielding effect of the temperature-element mounting ring. From a known radiation error at 50 km, errors below this level are calculated assuming the relationship :

$$\triangle T_i \propto \frac{1}{\sqrt{(V\rho)}}$$

where $\triangle T_i$ = radiation error
V = air velocity relative to sonde
ρ = air density.

Some values for radiation and dynamic heating corrections are given in Table II.

TABLE II—RADIATION AND DYNAMIC HEATING CORRECTIONS

Height *kilometres*	Radiation correction (45° incidence) *degrees C*	Dynamic heating correction (0–45° incidence, i.e. all practical angles) *degrees C*
20	1·5	0·0
50	3·5	2·1
60	6·5	7·9
65	10·0	15·3

The radiation corrections have been evaluated on the basis of an average angle of exposure of 45°, resulting from the swing of the sonde, and must include a term, not given in the table, based on the albedo of the surface beneath.

The relationship of the element with respect to free molecular flow and continuum flow was found by the wind-tunnel experiment and from this work recovery factors have been found to apply to the full adiabatic rise for air brought to rest in continuum flow. A factor of 1 is applied up to 50 km, and this increases to 1·3 at 70 km. The lag correction is considered negligible. No error could be detected during wind-tunnel measurements, when the radiation source was switched off, indicating that the lag must be less than 1 second which is the decay period of the radiation lamp. Even at the lowest pressures, equivalent to a 65-km height, it was deduced theoretically that with a fall speed of 200 m/s in a lapse of 5 degC/km the error would not exceed 0·5 degC.

The power dissipated in the temperature element is less than 0·015 milliwatts, and this is spread over 772 cm of wire, yielding a negligibly-small self-heating error. Because of the long length of wire involved, end effects are also negligible.

Height and wind data.—Data from the automatic tracking of the sonde parachute is converted to give heights and winds.

Ground equipment.—

Sonde.—A standard Meteorological Office radiosonde ground-recording equipment is used which automatically produces a graphical record of periodicity/time at a maximum sampling rate of 40 readings per minute and accuracy $\pm$ 1 periodic-time unit (i.e. $\pm$ 0·1 c/s at 1000 c/s, $\pm$ 0·05 c/s at 700 c/s).

Radar.—The standard Meteorological Office auto-follow wind-finding radar is used both to 'skin-track' the rocket for trajectory details, and to track the sonde parachute for wind/height data.

Computation.—Sonde periodicities are converted into temperatures by means of a calibration graph and all the necessary corrections applied. A common time-scale is used for the radar and rocketsonde ground equipments, enabling correlation between the two sets of data. Finally, corrected temperatures, associated with radar heights and a tie-on radiosonde pressure, are used to compute pressures and densities to the top of the ascent. The full wind structure is also computed as mentioned above.

Personnel requirement.—The firing of a SKUA round at the Royal Artillery Guided Weapons Range, South Uist, Outer Hebrides, involves three teams of personnel. The Army provides four people in the range safety roll who can be called on for each firing after rocket preparation work has been completed. Their duties are: range surveillance, launcher setting check, all safety checks, and finally giving permission to fire.

The RAF team of four is responsible for all rocket handling, preparation (apart from the payload), loading, launching, boost recovery, a certain amount of refurbishing, and assistance by one member in radar operation and maintenance. The Meteorological Office team of four is responsible for sonde preparation, ballistic wind measurement, launcher-setting calculations, radar and sonde ground equipment operation and maintenance, computation of the sounding and preparation of the 'ROCOB' message. Some of the personnel are shown in Plate IV. The Bristol Aerojet Company, who are the rocket manufacturers, have supplied trials officers throughout the development stages of the project.

Co-operation at all times has been excellent and, as our hosts, the Army have made our visits to South Uist at all times trouble free.

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RESULTS FROM THE SKUA METEOROLOGICAL ROCKET PROGRAMME

By S. F. G. FARMER

Introduction—During the past year and a half the SKUA rocket has been used by the Meteorological Office to measure stratospheric winds and temperatures. The firing programme has been largely confined to the two winter seasons. The first operational firing campaign was held at the Royal Artillery Range on the island of South Uist in the Outer Hebrides, in January and February 1964, coinciding with the start of the International Years of the Quiet Sun. This was followed by a short series of firings made at Aberporth in the late summer of 1964, during further development work on the rocket. The third and longest firing period started in early January 1965 at West Geirinish, South Uist, and was not completed till late April. Up to the present time (August 1965) 33 successful flights have been made with nearly 90 per cent of the data recovered on these occasions.

The main features of the stratospheric wind and temperature structure have already been established by indirect methods of measurement and in more recent years by rocket soundings in the U.S.A. Meteorological Rocket Network. These features have been corroborated by the SKUA rocket soundings and in addition some light has been shed on the longitudinal variations in the winter stratospheric circulation.

The data.—The apogee of SKUA is usually about 65 or 70 kilometres. The method of temperature measurement, immersion thermometry using a very fine tungsten wire, cannot be used above this height because of the very large radiation and dynamic heating corrections. The usual method of wind measurement likewise has an upper limit of about 60 km, because the parachute fails to respond to vertical wind shears when falling at high speed. However, the whole of the stratosphere is sampled and also the lower part of the mesosphere.

At West Geirinish the stratospheric temperature minimum which occurs at about 25 km, has been found to be well defined on many occasions in mid-winter (see Figure 2). On some descents, temperatures below −80°C have been recorded. These low values are supported by the Stornoway radiosonde ascents, a temperature of −80°C or below being reported on four days during January and February this year.

Above this minimum the temperature increases to the stratopause. The mean height of this temperature maximum is 50 km, and the temperature there may sometimes exceed 0°C. The mesosphere has a small positive lapse rate, with the temperature falling towards a weakly-defined mesopause.

Analysis of the winter circulation and spring reversal.—A stormy period dominated the first two months of the year. The large day-to-day variability of the stratospheric temperatures is demonstrated by the three soundings made on 15, 18 and 20 January 1965 (see Figure 1). At the beginning of this five-day period the stratopause was unusually warm (+12°C) and situated just below 50 km. Three days later there had been a cooling of 30°C at this level, the stratopause now being situated at only 40 km. with a temperature of −17°C. Two days later it was re-established at 51 km with a temperature of 0°C. Throughout this period the winds were fairly constant in direction from about 250°, but there were large changes in speed. Similar changes had been observed in early 1964, but less comprehensively.

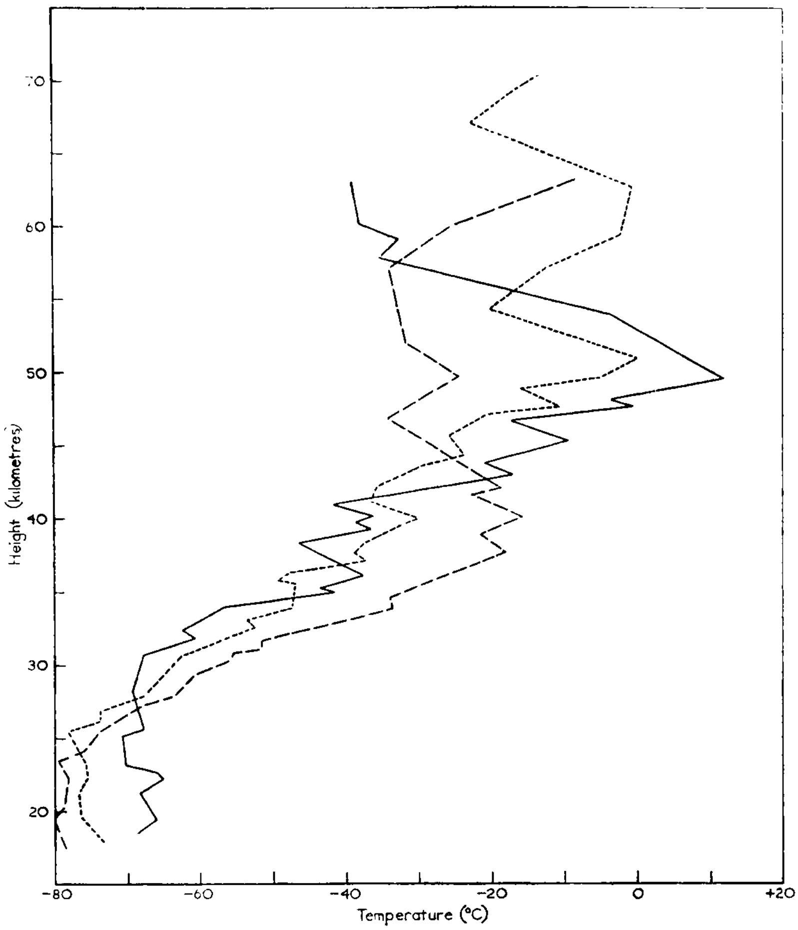


FIGURE 1—TEMPERATURE SOUNDINGS AT SOUTH UIST DURING JANUARY 1965

———— 2150 GMT on 15 January
— — — 2137 GMT on 18 January
- - - - - 1948 GMT on 20 January

An adequate description of these changes in terms of synoptic systems passing over West Geirinish has not been possible. Thermal winds calculated for 5-km thick layers have commonly been found to be reversed between successive firings. Instantaneous advective heating rates, which assume no radiative or adiabatic heating, are often an order of magnitude larger than the mean rates of change of temperature observed between soundings.

From mid-March onwards there was a much more regular change with a slow increase of temperature at all levels and a slackening of the wind. This is illustrated in the two time cross-sections (Figures 2 and 3) which have been supplemented in the lower stratosphere by data from the Stornoway radiosonde ascents.

A major stratospheric warming had its inception near the British Isles during the first week of March 1965. The rocketsonde sounding of 1 March was unusually warm at 34 km (−24°C), and on 3 and 5 March temperatures of −43°C and −32°C were recorded at 10 mb by the Stornoway midday ascent. Warming events were observed at Crawley and Berlin at about the same time. The warm centre became clearly identifiable at 10 mb on 9 March. In the next three weeks it was tracked across Europe and Asia before turning north towards the pole and weakening. The temperature of the 10 mb centre rose as high as −17°C.

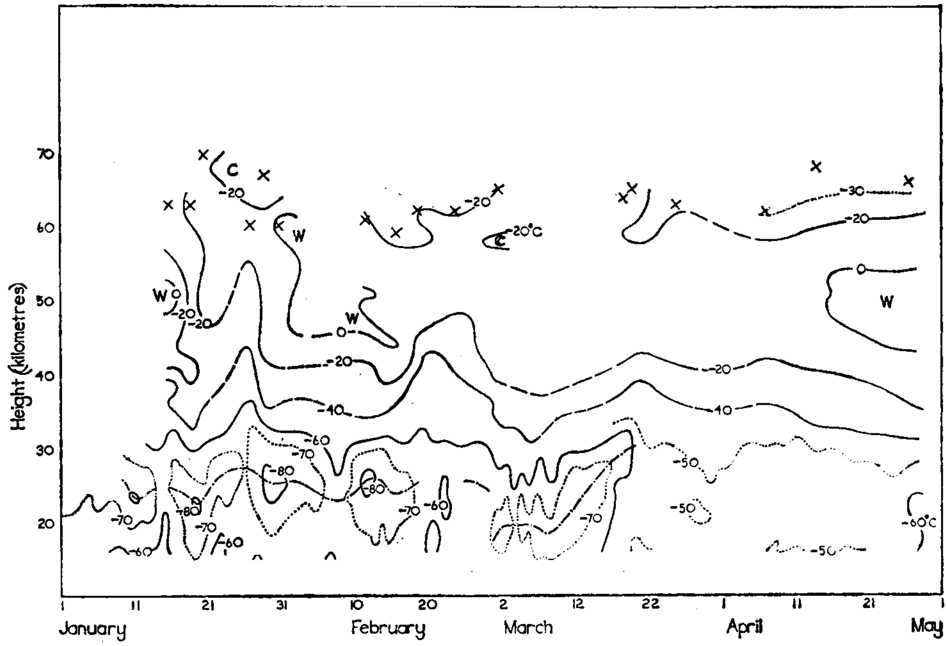


FIGURE 2—STRATOSPHERIC TEMPERATURE CROSS-SECTION FOR WEST GEIRINISH DURING WINTER AND SPRING 1965

x Upper limit of rocketsonde data
C Cold centre **W** Warm centre
— · — · Stratospheric temperature minimum

Intermediate isopleths are shown by a dotted line and pecked lines indicate where data were incomplete.

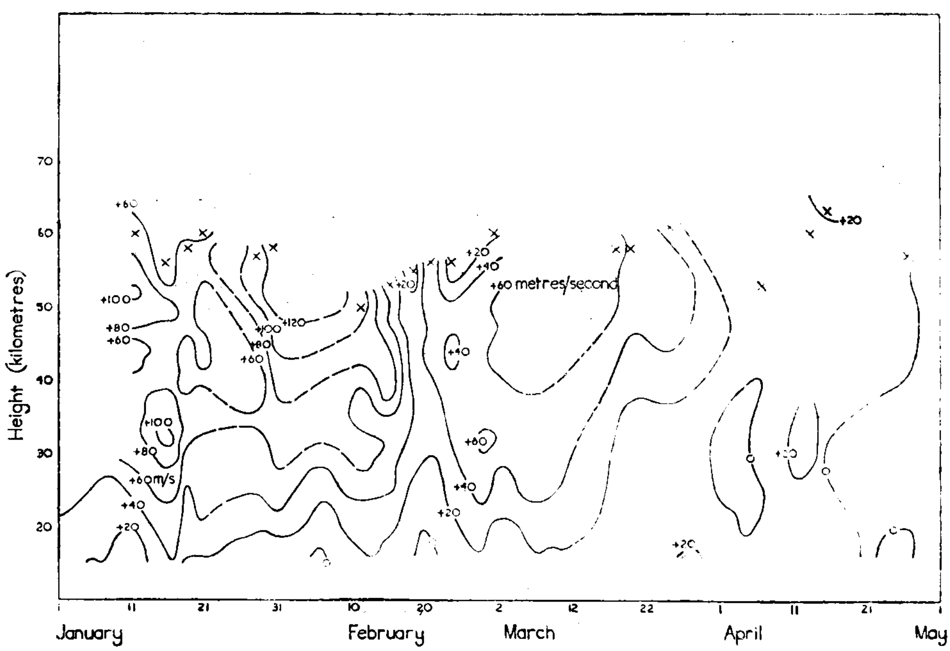
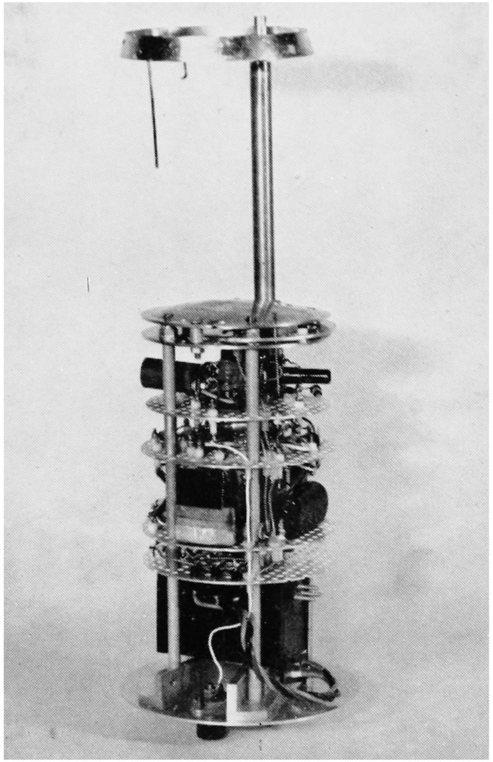
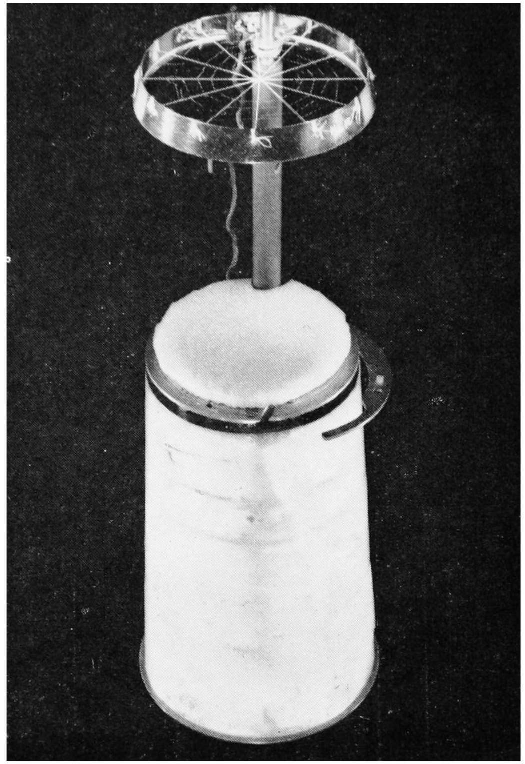


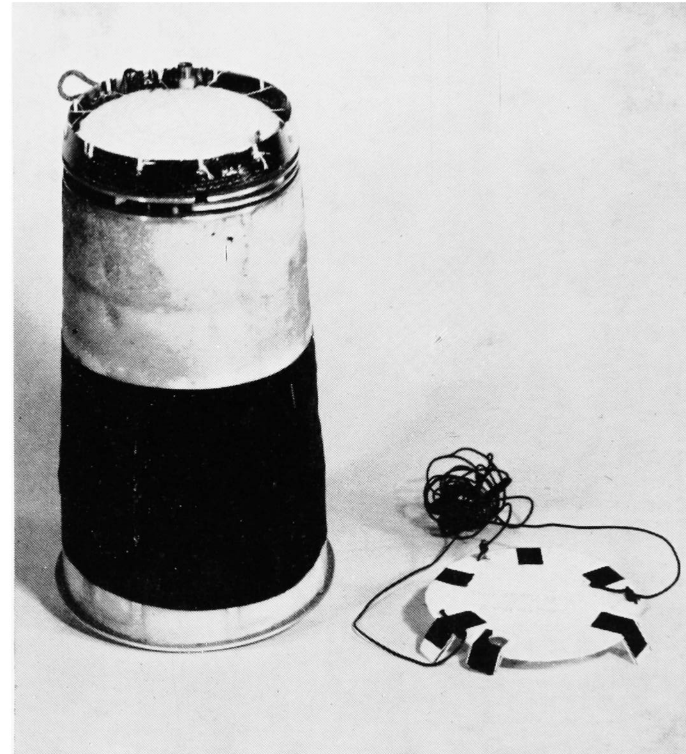
FIGURE 3—STRATOSPHERIC ZONAL WIND CROSS-SECTION FOR WEST GEIRINISH DURING WINTER AND SPRING 1965

x Upper limit of rocket wind data

Pecked lines indicate where data were incomplete.







(*a*) Before encapsulation showing disposition of circuit components and battery.

(*b*) Encapsulated with temperature element extended.

(*c*) Encapsulated with temperature element stowed for ascent.

PLATE I—ROCKETSONDE FOR THE SKUA METEOROLOGICAL ROCKET

See page 327.

PLATE II—SKUA METEOROLOGICAL ROCKET LAUNCHER VEHICLE WITH TUBE IN STOWED POSITION

PLATE III—SETTING THE TRANSMITTER FREQUENCY OF THE ROCKETSONDE

See page 327.

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PLATE IV—THE SKUA ROCKET WITH DEVELOPMENT AND LAUNCHING TEAMS

From left to right: Mr. D. N. Hoare and Mr. W. T. Fisher, Bristol Aerojet Ltd.; Mr. S. F. G. Farmer, Met. Office; Cpl. A. Mann, RAF; Mr. R. Almond and Mr. A. F. Lewis, Met. Office; Chief Technician B. Potts, S/Ac. D. White and W/O G. Brewis, RAF; Dr. R. Frith and Mr. B. Greener, Met. Office. (see p.331).

Although westerly winds still persisted in the stratosphere for the next month they became steadily weaker and temperatures at all levels showed a marked rise. A light easterly was first observed at Crawley on 26 March and at Stornoway five days later. However, even as late as 26 April, when the last SKUA sounding was made, a very light westerly was still present at the stratopause.

The autumnal reversal and the onset of the winter circulation were also observed in 1964 (see Figure 4). Four soundings were made at Aberporth. On 26 August 1964 the winds were very light up to 43 km, the radar track of the parachute unfortunately being incomplete. By 23 September the west winds were established down to 30 km. A week later the westerlies were present throughout the stratosphere, with a maximum of 37 metres/second at 51 km. The final sounding on 9 November showed westerlies in excess of 100 metres/second between 47 and 52 km.

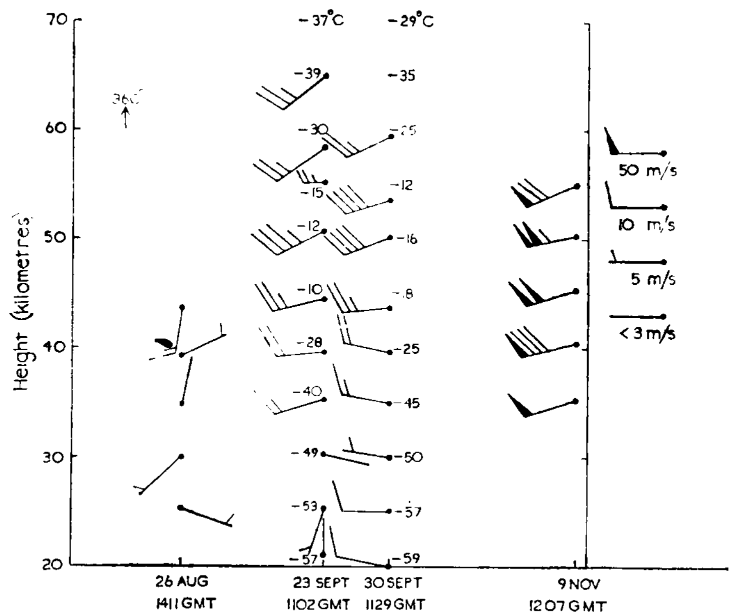

FIGURE 4—AUTUMNAL REVERSAL OF STRATOSPHERIC WINDS FOR ABERPORTH IN 1964

Temperatures are shown for the two firings in September.

The nature of the spring reversal is in marked contrast to that observed at lower latitudes,[1] where the easterly winds have first appeared above 50 km and then propagated downwards at 1 to 5 km/day. However, even at these low latitudes, easterly winds have been observed to propagate upwards from 30 km on occasions. Insufficient data are available to suggest the form of the autumnal reversal in 1964.

Longitudinal variations in the stratospheric circulation.—The monthly mean zonal wind components and temperatures have been calculated for West Geirinish (Table I). The number of soundings varies from 11 in the two January months to 4 in each of March and April 1965. Standard deviations have been quoted where there are four or more measurements available, although the sample is small for all levels.

TABLE I—MEAN MONTHLY TEMPERATURES AND ZONAL WINDS FOR WEST GEIRINISH (57°21′N, 07°23′W)

(*a*) Mean monthly temperatures

Height km	January n	$\overline{T}$	σ	T	February n	$\overline{T}$	σ	T	March n	$\overline{T}$	σ	T	April n	$\overline{T}$	σ	T
		degrees C				degrees C				degrees C				degrees C		
70	1	−14		−30				−35				−42				−49
65	3	−23		−40				−39	2	−16		−39	2	−31		−38
60	8	−15	13	−44	3	−17		−40	4	−18	2	−34	3	−22		−26
55	8	−22	12	−35	5	−8	2	−35	4	−11	4	−26	3	−7		−13
50	8	−16	14	−22	5	−10	5	−22	4	−11	4	−17	3	−1		−5
45	9	−20	11	−30	5	−14	9	−31	4	−12	3	−26	3	−7		−13
40	9	−31	10	−43	7	−31	10	−43	4	−29	10	−38	3	−20		−26
35	10	−53	13	−51	7	−45	4	−52	4	−46	11	−49	3	−33		−41
30	10	−70	6	−58	7	−65	3	−59	4	−54	4	−57	3	−47		−54

(*b*) Mean monthly zonal winds

Height km	January n	$\overline{U}$	σ	U	February n	$\overline{U}$	σ	U	March n	$\overline{U}$	σ	U	April n	$\overline{U}$	σ	U
		metres/second				metres/second				metres/second				metres/second		
60	2	+63		+59				+35	2	+27		+22	2	+11		−2
55	8	+85	27	+48	3	+24		+24	4	+51	7	+24	3	+9		+17
50	9	+88	21	+37	6	+62	27	+11	4	+55	6	+25	4	+9	6	+24
45	10	+78	21	+29	6	+65	26	+1	4	+45	10	+23	4	+10	6	+22
40	9	+68	16	+22	7	+58	19	−3	4	+39	9	+21	4	+7	7	+17
35	8	+75	10	+17	8	+54	15	0	4	+23	12	+17	4	+6	11	+13
30	9	+64	13	+10	8	+49	15	+8	4	+19	17	+13	4	+1	14	+8

n Number of observations.
σ Standard deviation (for $n \geq 4$).
$\overline{T}$ Mean monthly temperature.
$\overline{U}$ Mean monthly zonal wind.
T Temperature on first day of month at 57½°N, from proposed new COSPAR atmosphere (CIRA) (after Groves[2]).
U Zonal wind on first day of month at 57½°N, from proposed new COSPAR atmosphere (CIRA) (after Groves[2]).

These mean values have been compared with those given by Groves[2] for the first day of each month for 57½°N. These were obtained from an analysis of data obtained in the U.S. Meteorological Rocket Network and from grenade, pressure and density gauge experiments made elsewhere in the world. However the majority of measurements were made over the North American continent. Near the latitude of West Geirinish these means are strongly biased by data obtained at Fort Churchill, Canada and Fort Greely, Alaska.

In making this comparison it must be remembered that the data sample is small and that the monthly means are being compared with values for the first day of the month. Thus the difference of approximately 6°C between the two sets of values for April is merely a reflection of the warming which continues throughout that month. However, earlier in the year when the seasonal change is small, the West Geirinish temperatures are significantly warmer for all heights above 40 km. At 40 km this difference is approximately one standard deviation (10°C), and although smaller at 50 km appears to increase again above this. At 30 km, West Geirinish is much colder initially, this difference being due to the Aleutian high, which is a persistent climatological feature at 10 mb.

The difference in the zonal wind field is even more striking. In January the speeds observed at West Geirinish were very high and much more typical of the stratospheric jet core over the North American continent, where the axis has a mean latitude of about 45°N. These strong winds continue through February into March.

The reversal of the zonal wind at 40 km on 1 February suggested by Groves' model has not been observed, although a slackening of the flow occurred on 18 and 20 February, 1965. The winds at all levels were then veered north of west. A similar weakening had been observed at balloon heights on 6 February.

Conclusion.—It is quite clear that there are important longitudinal variations in the mean winter circulation at least up to the stratopause and probably above. The asymmetry of the polar vortex already shown to exist by balloon soundings at 10 mb, is still apparent at greater heights. The launching of SKUA rockets on a regular basis from West Geirinish has provided the first measurements of these differences in subpolar latitudes over the European continent.

Acknowledgements.—The author wishes to acknowledge the continued help provided by the Ministry of Aviation and Bristol Aerojet Ltd., during all the development work, and the unfailing service provided by the Commandant of the Royal Artillery Range, South Uist for the Meteorological Office during the past two years.

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551.510.53:551.557.3:551.557.5

THE ANNUAL VARIATION IN THE JET STREAM ACROSS THE GREENWICH MERIDIAN

By W. G. RITCHIE and C. J. M. AANENSEN

By considering the direction of the average winds in the middle stratosphere, the year can be divided into two parts. Thus the monthly averages given by Graystone[1] for Crawley winds to 100,000 feet and for winds at Leuchars to about 90,000 feet show that the average winds from about May to August inclusive are from an easterly quarter. Experience suggests that the winds over the Greenwich meridian from 30°N to 80°N are almost entirely easterly, particularly from mid-May to mid-August. For the remainder of the year the average winds in the middle stratosphere are predominantly westerly. The variation of wind direction from one year to another and its variation from the mean pattern are larger in the 'winter' portion of the year than they are in the 'summer' season. In fact easterly winds do occur from time to time across the Greenwich meridian even in midwinter, but mostly to the south of 50°N. The average picture however is one of westerly winds in the middle stratosphere in the portion of the year from October to March. The periods of change-over from one régime to the other are short, variable in date and occur at different times of the year at different levels.

During the course of another investigation indications were found that the position of the jet stream across the Greenwich meridian may also be bi-modal in a 12-month period and this was considered interesting enough to warrant a fuller analysis.

A series of 200 mb charts, complete in the neighbourhood of the Greenwich meridian from about 30°N to 80°N, were available for the period January 1961 to July 1964. The change in contour pattern at 200 mb is fairly slow so that extraction of data from only one chart instead of two in every 24 hours caused little if any loss of information and produced a considerable saving in effort. Only 0000 GMT charts were used.

The strongest winds at the 200 mb level correspond to the main jet streams (whose cores may often be at somewhat lower heights). The strongest gradient of contour height across the Greenwich meridian on the 200 mb chart could therefore be assumed for the purpose of this investigation to show the position and direction of the main jet stream. The latitude at which the maximum gradient occurred and the direction, to the nearest 10 degrees, of the wind on the meridian were then extracted from each of the midnight charts. A maximum was not rejected because the associated jet core did not reach the value required by a strict definition of a jet stream.

The average number of occasions of wind maxima per month was obtained for each two degrees of latitude from 36°N to 69°N and, without sub-division, for latitudes north of 69°N and south of 36°N. The resultant figures are given in Table I and for latitudes 36°N to 69°N are shown graphically in Figure 1.

TABLE I—AVERAGE NUMBER OF OCCURRENCES OF WIND MAXIMA PER MONTH FOR LATITUDE BANDS STATED

Latitude degrees north	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
70 and above	7·3	7·0	2·3	2·5	1·3	2·0	1·5	0·0	3·7	2·3	2·0	4·3
68 – 69	2·0	0·7	0·7	0·0	0·3	0·0	0·3	0·0	0·3	2·0	0·0	1·0
66 – 67	1·5	1·7	0·7	0·5	0·3	0·5	0·0	0·3	2·0	2·7	1·7	4·3
64 – 65	1·7	1·5	0·3	0·0	0·3	0·0	0·3	0·0	1·0	2·3	0·7	0·7
62 – 63	1·0	1·0	1·5	0·7	0·3	0·3	0·3	0·7	1·3	1·0	0·7	1·7
60 – 61	1·5	1·5	2·0	0·5	0·0	1·0	1·0	0·3	2·0	2·7	1·3	1·3
58 – 59	0·0	1·3	1·3	0·3	0·3	0·5	2·0	0·3	1·0	0·7	0·7	0·0
56 – 57	2·0	1·3	1·0	1·0	0·5	2·7	1·5	2·0	2·3	4·0	2·0	1·7
54 – 55	0·5	0·5	0·3	1·5	0·7	2·5	2·0	2·3	1·7	1·0	0·7	1·0
52 – 53	0·5	0·7	1·3	1·3	1·5	1·3	3·3	4·0	2·3	1·7	1·0	1·0
50 – 51	2·0	1·3	1·5	1·3	5·3	4·0	4·0	5·3	3·3	3·0	1·3	3·3
48 – 49	0·5	0·7	0·5	0·7	2·0	1·7	1·5	3·3	2·7	0·7	0·7	1·0
46 – 47	1·5	1·0	1·5	1·5	3·7	1·3	2·0	3·7	1·0	2·0	2·7	0·0
44 – 45	1·5	1·3	1·7	1·0	3·0	1·0	1·7	2·3	0·0	1·3	2·3	1·3
42 – 43	2·5	1·3	3·3	2·3	1·3	0·7	3·7	3·0	1·0	1·0	3·0	1·0
40 – 41	0·5	0·5	1·5	1·5	1·0	1·3	3·0	1·3	2·0	1·0	1·3	1·3
38 – 39	0·7	0·5	0·3	1·7	1·3	1·0	2·0	0·3	1·3	0·0	0·0	0·3
36 – 37	2·3	2·0	3·0	1·7	1·0	1·0	2·0	0·3	1·3	0·7	0·7	1·0
35 and below	6·7	9·0	11·0	11·3	8·0	9·7	1·5	0·7	3·7	1·3	8·3	9·0

These averages are somewhat irregular in detail probably because of the small number of years for which data were to hand. Nevertheless, they show two predominant forms. In the months of May to October there is a major peak of occurrences at middle latitudes (about 50°N). For the months of November to April the highest peak is no longer in the middle latitudes; the distribution of the jet is much more uniform, with the highest peak north of 65°N or south of 45°N. On the basis of these figures one can say that the annual variation of the latitudinal displacement of the jet stream on the Greenwich meridian follows a 'two-season' pattern. It is of interest to note that this division of the average latitudinal pattern through the year is very similar to the seasonal variation of the average winds in the middle stratosphere. Of course this investigation does not establish any causal relationship between the jet stream and the stratospheric winds.

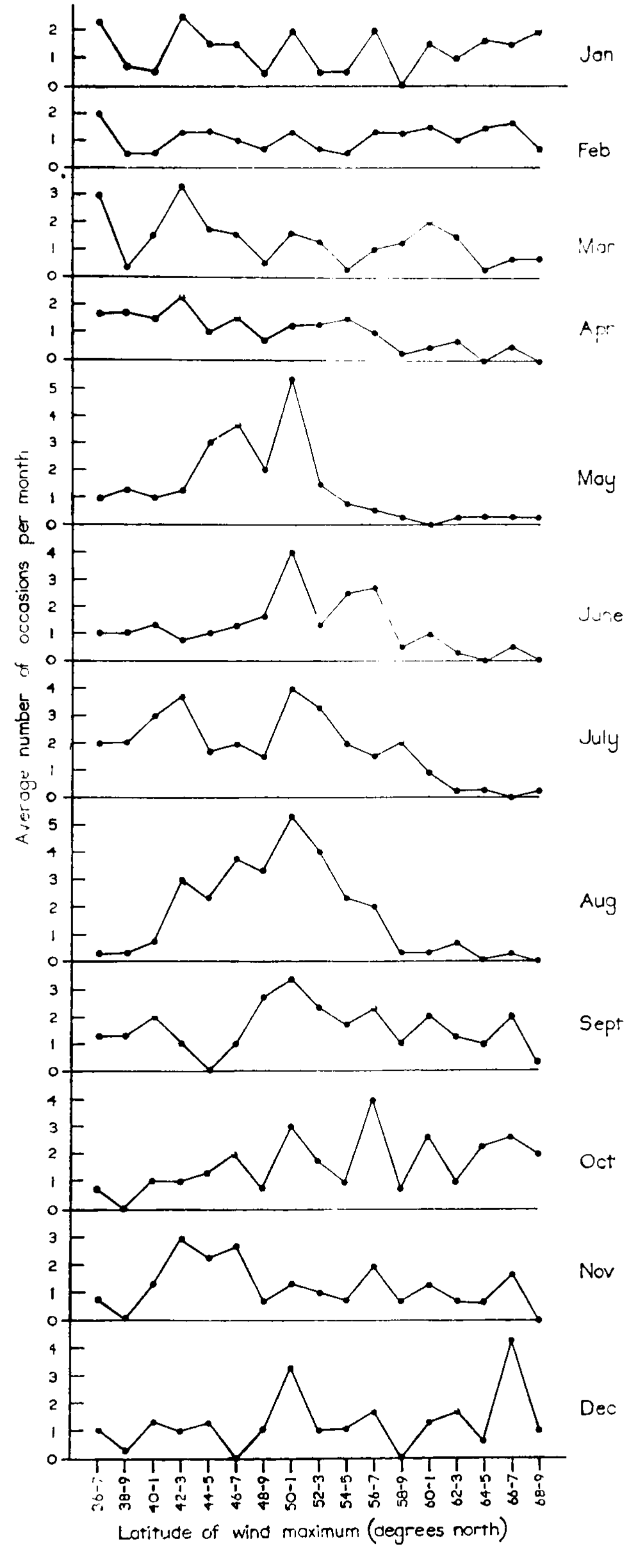

FIGURE 1—MONTHLY FREQUENCY DISTRIBUTION OF LATITUDE OF JET STREAM AT THE GREENWICH MERIDIAN

In Figure 2 are shown monthly graphs of the average distribution of the direction of the jet streams as they cross the Greenwich meridian. In these

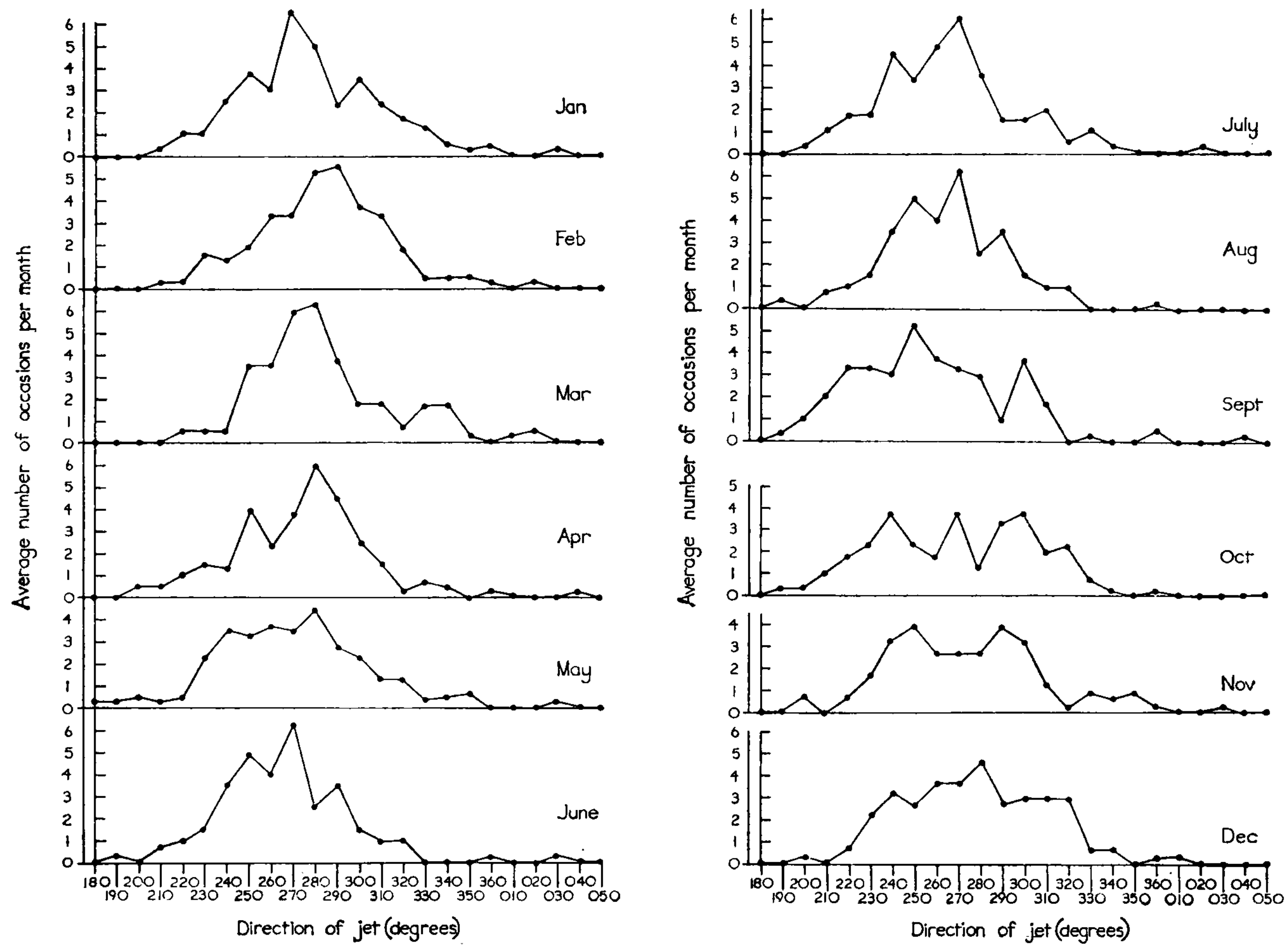

FIGURE 2—MONTHLY FREQUENCY DISTRIBUTION OF DIRECTION OF JET STREAM AT THE GREENWICH MERIDIAN

graphs there are no signs of any notable seasonal variations. The direction of the jet stream only rarely has an easterly component. For the year as a whole the mean direction is 267° with 50 per cent of occasions being within the limits 245° and 290°. Ninety per cent of occasions are between 220° and 320°.

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551.509.322.7:311.214:629.13

THE EFFECTS ON EQUIVALENT HEADWINDS AND FLIGHT TIMES OF ERRORS IN FORECASTING WIND DIRECTION AND WIND SPEED

By G. A. HOWKINS, M.B.E., B.Sc. and I. H. CHUTER, B.Sc.

Computation of equivalent headwind.—The equivalent headwind over a route may be defined[1] as that wind which, blowing uniformly along the track of the aircraft in a direction opposed to the direction of flight, would result in the same duration of flight as required by the actual system of winds.

The equivalent headwind is commonly used in flight planning and may be derived as follows.

In Figure 1, the equivalent headwind $E_{\theta,v}$, due to a wind vector of speed v at angle θ to the track, is given by

$$E_{\theta,v} = BC + CD.$$

Now

$$BC = BO - CO$$
$$= A - (A^2 - v^2\sin^2\theta)^{\frac{1}{2}},$$

where A is the true airspeed,

and $CD = v\cos\theta$;

therefore $E_{\theta,v} = A - (A^2 - v^2\sin^2\theta)^{\frac{1}{2}} + v\cos\theta$ ... (1)

$$= A - A\left(1 - \frac{v^2}{A^2}\sin^2\theta\right)^{\frac{1}{2}} + v\cos\theta.$$

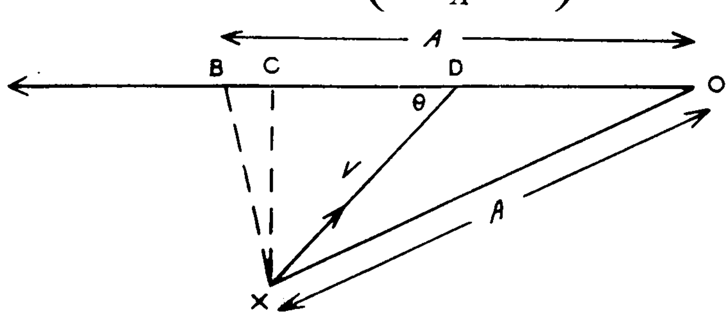

FIGURE 1—DERIVATION OF THE EQUIVALENT HEADWIND

OX is a vector with the magnitude A = true airspeed in knots and in the same direction as the aircraft heading;

XD is the wind vector, speed v knots, at angle θ to the track;

ODCB is the track to be flown, where OD represents the ground distance made good and OB = OX;

expanding the binominal:

$$E_{\theta,v}=A\left(\frac{1}{2}\frac{v^2}{A^2}\sin^2\theta-\frac{1}{8}\frac{v^4}{A^4}\sin^4\theta+\ldots\right)+v\cos\theta,$$

and since v/A rarely exceeds 0·4 for flights at 400 knots

$$E_{\theta,v}=v\cos\theta+\frac{v^2\sin^2\theta}{2A}. \qquad \ldots (2)$$

Inspection of equation (2) shows that the equivalent headwind depends mostly on the first term $v\cos\theta$. This is at a maximum when $\theta=0°$ and the equivalent headwind $E_{0°,v}$ is v. The second term is at a maximum when $\theta=90°$ and equivalent headwind $E_{90°,v}=v^2/2A$. The ratio of the two maxima is

$$\frac{E_{0°,v}\text{ (headwind)}}{E_{90°,v}\text{ (beamwind)}}=\frac{2A}{v},$$

and since v rarely exceeds 160 knots at 300 millibars and $A=400$ knots for most subsonic jet aircraft, the ratio is unlikely to exceed 5 : 1. Inspection

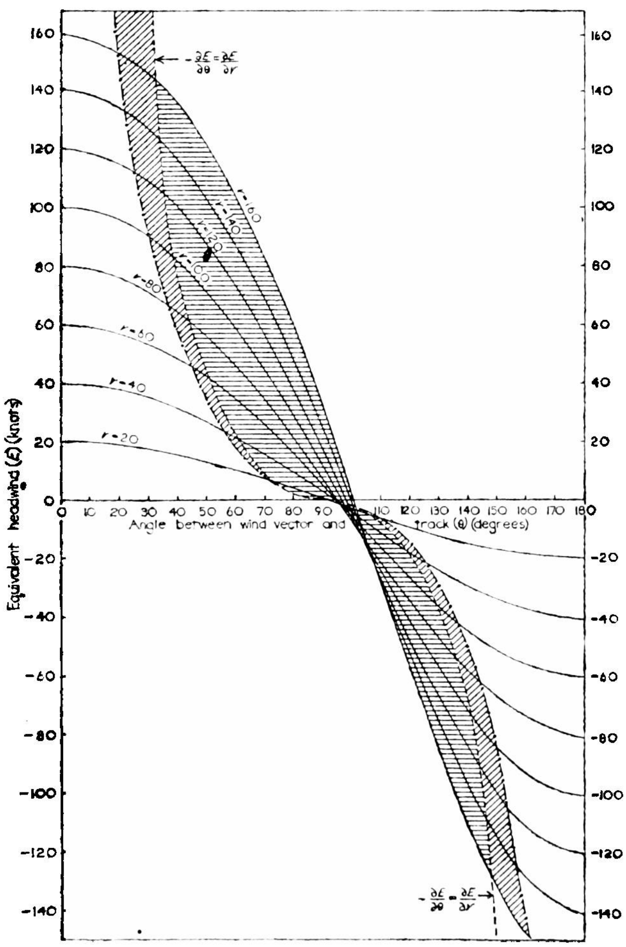

FIGURE 2—EQUIVALENT HEADWIND, E, AGAINST θ FOR SEVERAL VALUES OF v

Horizontal shading — area where errors in θ (degrees) produce greater errors in E than errors of similar magnitude in v (knots).

Diagonal shading plus horizontal shading — area where errors in θ (degrees) produce greater errors in time lost than errors of similar magnitude in v (knots).

True airspeed, A = 400 knots.

of the term $v\cos\theta$ shows that, especially for large values of v, there will be a wide range of values of θ for which the equivalent headwind is very sensitive to errors in θ.

Relative effects of error in forecasting wind speed and direction.—Current forecasting techniques lead the upper-wind forecaster to approach the problem in two steps, firstly a forecast of wind direction in terms of the contour height pattern, and secondly a forecast of wind speed in terms of the contour spacing or the isotach pattern. Zone wind forecasts are usually given to the nearest 10° and 10 knots and the forecaster thinks of the accuracy of his forecast in these terms, rather than in terms of equivalent headwind. Although the forecaster may know the tracks to be flown it is often difficult to visualize the equivalent headwind from the forecast wind. It is particularly difficult to see the relative effects of forecast errors in the wind speed and direction because the relative contributions to equivalent headwind vary with the angle between the wind vector and the track. This is readily seen from Figure 2 in which the equivalent headwind E is plotted against θ for several values of v with an assumed airspeed of 400 knots. The family of curves are intersected by a dotted curve representing the equality $-\partial E/\partial\theta = \partial E/\partial v$, where θ is in degrees and v in knots and it is apparent that for winds exceeding about 60 knots there are wide ranges of θ in which the equivalent headwind is more sensitive to errors in wind direction than to errors in wind speed.

For each value of v there is a maximum of $\partial E/\partial\theta$, this being equal to 2·8 knots per degree when v is 160 knots. These maximum values occur with θ in the range 90–110 degrees.

Time error resulting from forecast wind direction error.—The full effect on a flight of forecast errors in θ and v depends not only on the error in equivalent headwind but also on the time for which the error is experienced. Suppose a flight is crossing a strong wind belt w miles wide at an angle θ to the track (Figure 3). The distance along the track occupied by the wind belt is FG$=w\operatorname{cosec}\theta$, the ground speed while crossing it is $(A - E_{\theta,v})$ knots and the time taken to cross it is $(w\operatorname{cosec}\theta)/(A - E_{\theta,v})$. The time taken to fly

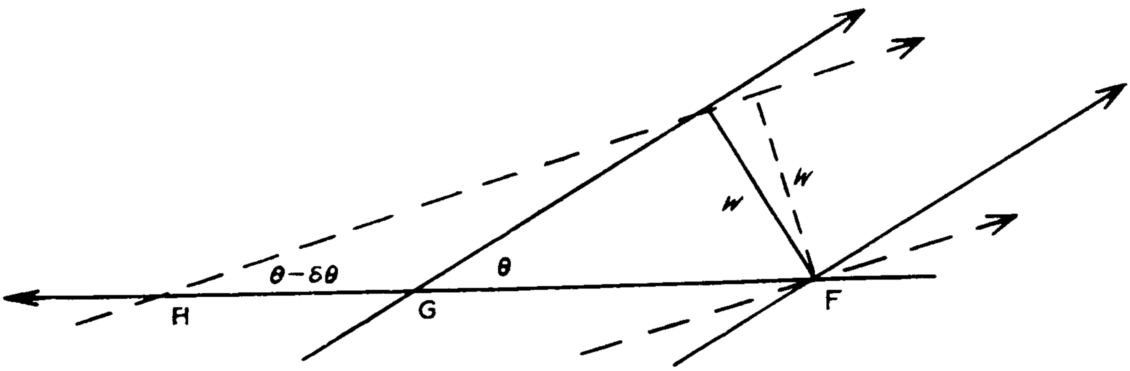

FIGURE 3—DERIVATION OF TIME ERRORS RESULTING FROM FORECAST WIND ERRORS

w = width of jet stream with forecast and experienced wind speed v,
θ = angle of jet stream to track,
$\theta - \delta\theta$ = forecast angle of jet stream to track,
FG = $w\operatorname{cosec}\theta$ = actual distance along track occupied by jet stream,
FH = $w\operatorname{cosec}(\theta - \delta\theta)$ = forecast distance along track occupied by jet stream.

the same distance in calm conditions would be $(w\text{cosec }\theta)/A$ and the time lost due to wind would be

$$(w\text{cosec}\theta)\left(\frac{1}{A - E_{\theta,v}} - \frac{1}{A}\right) \text{ which equals } \frac{E_{\theta,v}\, w\text{cosec}\,\theta}{A\,(A - E_{\theta,v})} \qquad \ldots (3)$$

Using expression (3) it can be shown that, for a wide range of θ, the total effect on a flight of a directional error $\delta\theta$ (degrees) greatly exceeds the effect of a speed error δv (knots) of the same magnitude and the ratio of the errors in terms of time lost is materially greater than the ratio of the two equivalent headwinds for θ between 20 and 50°.

In considering the full effect of an error $\delta\theta$ in terms of time lost it is necessary to examine that part of the track on which the strong wind or jet stream is forecast to occur and to compare the forecast time lost with the actual time lost over the same distance.

Using expression (3), the forecast time lost along FH in Figure 3 is

$$\frac{E_{\theta-\delta\theta}}{A\,(A - E_{\theta-\delta\theta})} \times w\text{cosec}\,(\theta - \delta\theta) \qquad \ldots (4)$$

(as it is here assumed that there is no forecast error in the wind speed v, the suffix v in $E_{(\theta-\delta\theta),v}$ is omitted for brevity).

To arrive at the actual time lost along FH, it is necessary to make some assumptions about that part of the track GH which was not affected by the jet stream. The wind speed must be less than the jet speed v because GH lies outside the jet stream and, unless the angle of the wind flow to the track is much smaller than the angle θ in the jet stream, it is reasonable to assume that the equivalent headwind along GH cannot exceed the equivalent headwind along FG. Therefore the actual time lost along FH cannot exceed the value obtained on the assumption that a jet stream (wider than w) with speed v and at angle θ to the track covered the entire distance FH. From expression (3) and the relation FH$=w$cosec $(\theta - \delta\theta)$, the actual time lost along FH is

$$\leqslant \frac{E_\theta\, w\text{cosec}\,(\theta - \delta\theta)}{A\,(A - E_\theta)}\,. \qquad \ldots (5)$$

An estimate of the minimum forecast time error is obtained by subtracting expression (5) from expression (4). For a small increment $\delta\theta$, $(A - E_\theta) \simeq (A - E_{\theta-\delta\theta})$: therefore the forecast time error is

$$\geqslant \frac{w\text{cosec}\,(\theta - \delta\theta)}{A\,(A - E_{\theta-\delta\theta})} \times (E_{\theta-\delta\theta} - E\,)\,. \qquad \ldots (6)$$

Time error resulting from forecast wind speed error.— If θ is now forecast correctly but an error $+\,\delta v$ knots (equal in magnitude to $-\,\delta\theta$ in the previous section) is made in forecasting v, then the jet stream occupies the same distance FG (in Figure 3) on both forecast and actual charts and, using expression (3), the forecast time lost along FG is

$$\frac{E_{v+\delta v}}{A\,\,(A - E_{v+\delta v})}\; w\text{cosec}\theta, \qquad \ldots (7)$$

the actual time lost along FG is

$$\frac{E_v}{A\,(A - E_v)}\; w\text{cosec}\theta\,, \qquad \ldots (8)$$

and the forecast time error along FG is obtained by subtracting expression (8) from expression (7).

If it is now assumed that the forecast error δv in zone FG does not produce an error in the adjoining zone GH, then the forecast error due to δv along FG will apply to the longer sector FH, i.e. the forecast time error along FH due to δv is

$$\frac{w\text{cosec}\theta}{A\ (A - E_{v+\delta v})} E_{v+\delta v} - \frac{w\text{cosec}\theta}{A\ (A\ -\ E_v)}\ E_v\ .$$

And, since for a small increment δv, $(A - E_v + \delta v) \simeq (A - E_v)$, the forecast time error along FH is

$$\simeq \frac{w\text{cosec}\theta}{A\ (A - E_v)} \times (E_v + \delta v - E_v)\ . \qquad \dots (9)$$

Relative time errors due to forecast errors in wind direction and wind speed.—From expressions (6) and (9), the minimum value of the ratio of the forecast time error along FH (in Figure 3) due to $-\ \delta\theta$ (v correctly forecast) to the forecast time error along FH due to an error δv knots of equal magnitude (θ correctly forecast) is given by

$$\frac{\text{Time error due to } \delta\theta}{\text{Time error due to } \delta v} \geqslant \frac{[w\text{cosec}(\theta - \delta\theta)]/A(A - E_\theta)}{(w\text{cosec}\theta)/A(A—E_v)} \times \frac{(E_{\theta - \delta\theta} - E_\theta)}{(E_{v + \delta v} - E_v)}\ ,$$

but E_θ and E_v are identical, and the expression reduces to

$$\geqslant \frac{\text{cosec}(\theta\ -\ \delta\theta)}{\text{cosec}\theta} \times \frac{(E_{\theta - \delta\theta} - E_v)}{(E_{v + \delta v}\ - E_v)}\ .$$

Therefore the ratio of the time errors due to $\delta\theta$ and δv is greater than the ratio of the corresponding errors in the equivalent headwinds by a factor of not less than cosec $(\theta - \delta\theta)$/cosecθ. Table I shows this ratio for various values of θ when $\delta\theta = 10°$ and it is apparent that the full effect of errors in θ on the time of flight must be considerably greater than the effect on equivalent headwind and must extend over wider ranges of θ than those contained within the horizontally-shaded area in Figure 2. The probable minimum extension of the area when errors are considered in terms of time lost because of errors in θ of 10° is shaded diagonally.

TABLE I—RATIO COSEC(θ – 10)/COSECθ FOR VARIOUS VALUES OF θ

θ degrees	Cosecθ	Cosec(θ – 10)/cosecθ
90	1·0000	1·02
80	1·0154	1·05
70	1·0642	1·09
60	1·1547	1·13
50	1·3045	1·19
40	1·5557	1·28
30	2·0000	1·46
20	2·924	1·97
10	5·759	∞

Some general considerations.—In addition to the effects already discussed there are also important differences in the way errors are correlated along a route, depending on the angle between the aircraft's track and the general wind direction. Consider first a broad straight flow with shear. For a route making a small angle to the general direction of flow, the equivalent headwind depends mainly on the forecast wind speed and will be very sensitive to the positioning of the strongest flow with respect to the track flown. Forecast errors will tend to be positively correlated along the track and the total error in terms of equivalent headwind is unlikely to decrease rapidly with increasing route length. In contrast, for a route normal to the flow, errors tend to be negatively correlated and the equivalent headwind errors should decrease rapidly with increasing route length. Also, when the wind is mainly beamwind the equivalent headwind is less by a factor of at least five than for a similar wind directed along the track (see page 342).

Now consider a wave pattern superimposed on the broad flow. Equivalent headwinds for a track along the general flow must decrease as the amplitude of the wave pattern increases and it has been shown that the forecast wind direction is more important than the forecast wind speed unless the wind flow is almost entirely a headwind. For a route directed along the general flow the actual positions of troughs and ridges in the wave pattern are of little importance if the route is long compared with the wavelength. For a track crossing the flow the angle θ between the track and the wind direction depends critically on the position of the pattern. If positive and negative errors in forecasting the wave pattern are equally likely then, for tracks across the mean flow, the mean error for a long series of equivalent headwind forecasts should tend towards zero but the standard deviation will be large. Any tendency to underestimate the amplitude of the wave pattern will underestimate the equivalent headwind and restrict the gross errors.

REFERENCE

1. SAWYER, J. S.; Equivalent headwinds; application of upper-air statistics to air-route planning. *Met. Rep., London*, No. 6, 1950.

SYMPOSIUM ON METEOROLOGICAL DATA-PROCESSING, BRUSSELS, 1965

A symposium on meteorological data-processing was held at the Royal Meteorological Institute, Brussels, from 2 to 5 July under the joint auspices of the World Meteorological Organization (WMO) and the International Union of Geodesy and Geophysics. The meetings had been planned to provide a forum for the discussion of the problems of providing the research meteorologist with the data which he requires for the study of the large- and medium-scale systems in the atmosphere, and to consider the steps which might be taken to ensure that the maximum value for research is obtained from the very large number of observations which are made each day.

It was clear from the discussion that these matters give particular concern at the present time because of the rapid increase in the available data, also because of the rapid changes in the technology for data-processing on electronic computers and for data storage, and because of the reorganization of the handling of synoptic data to be expected with the gradual implementation of World Weather Watch.

The programme included several speakers who aimed to outline the requirement of the research scientist for meteorological data. Professor P. A. Sheppard stressed the need to ensure that research students are aware of what data are available and relevant to their problem and Mr. J. S. Sawyer emphasized the continuing need for published series of synoptic charts among which the research scientist can browse and thus acquire the familiarity with the atmosphere needed to formulate his problems; it is difficult, if not impossible, to visualize the problems while data remain in digital form.

Other speakers described their experiences in processing meteorological data on electronic computers. These ranged from small computers in Austria and India to large installations in the U.S.A., and covered a wide range of purposes from strict climatology to numerical weather prediction. Although all reported various difficulties, particularly in respect of lack of uniformity of format of the data, it was clear that all the speakers expected that the electronic computer would in the future have a rapidly increasing importance in meteorological data-processing throughout the world.

Much discussion centred around the desirability of the very large random-access computer stores which are now becoming technically feasible. The meeting was told that stores of up to 10^{12} bits (binary digits) could now be built and that this is several times greater than the data content of the climatological records of the U.S. Weather Bureau at Asheville. Speaking from experience at Asheville, Mr. J. F. Bosen emphasized the need for permanence in the records such as is provided by some photographic methods of recording now available. He said that it was difficult to eliminate the risk of erasure of records on magnetic tape.

At a final discussion some recommendations were drafted which drew the attention of WMO to the special problems of providing data for research, and stressing in particular the need for world data centres with adequate facilities.

The success of the symposium owes much to the excellent facilities provided by the Royal Meteorological Institute of Belgium.

J. S. SAWYER

REVIEWS

Cloud structure and distributions over the tropical Pacific Ocean by J. S. Malkus and H. Riehl. 8¾ in × 10¼ in, pp. ix + 227, *illus.*, University of California Press, Berkeley and Los Angeles (distributed by Cambridge University Press, Bentley House, Euston Road, London NW1), 1964. Price £3.

This book contains a detailed record of an investigation of tropical oceanic clouds by two world authorities on the subject. The main material used was a time-lapse colour film for which frames were exposed at one-second intervals from an aircraft flying at about 8000 feet. The flights were made in July and August 1957 and covered 15,000 miles, mainly between latitudes 10 and 20 degrees north on routes between Honolulu and Guam. The whole gamut of tropical oceanic activity was experienced, from almost cloudless conditions, through undisturbed trade-wind cumulus régimes, minor disturbances, easterly waves, and small cyclonic circulations to a full-blown typhoon.

The cloud pictures on each flight were related to the three-dimensional structure of the atmosphere by various analyses of the routine synoptic surface and upper air observations, the utmost information being extracted from the all too sparse network. A good portion of the book is taken up with charts of surface isobars, low-level wind flow, shear winds in lower and upper troposphere, precipitable water, tephigrams, wind profiles, cloud and humidity cross-sections, together with tables of observational data and descriptive material. All this is a model of clear and careful analysis.

An important step in the method of analysis was to codify the appearance of the sky as shown in the cloud photographs. The authors found that 17 code figures were adequate, 5 for undisturbed trade-wind skies, 5 for weak disturbances and 7 for strong disturbances. Good agreement was obtained between the code figures allotted by different observers. To the reviewer this 'Tropical Whole Sky' code seems one of the most valuable features of the book. Several hundred cloud photographs taken near Christmas Island were examined by him and the impression was gained that with a little practice it would be possible to allot code figures satisfactorily and consistently. Photographs typical of each code figure are included in an appendix to the book, together with definitions of each type of sky. Unfortunately it is here that one of the few criticisms of an otherwise excellently produced book must be made. The quality of the reproduction of the cloud photographs leaves something to be desired, partly, no doubt, because of the change from colour to black and white, and to the fact that non-glossy paper is used. In the appendix lack of clarity is increased by the small size (less than 3 by 2 inches) of each picture. Elsewhere in the book selected photographs occupying a whole page are much more impressive. The importance of the 'Tropical Whole Sky' code is such that it could usefully be published as a separate document with large pictures, and would then greatly facilitate cloud reporting from aircraft over the tropical oceans.

The authors do not, however, stop at description; they seek to explain and elucidate what they observed. The sections dealing with the fairly common organization of cumulus clouds into lanes are particularly useful. Adjacent frames from the film could be used as stereo pairs and a measuring technique was devised to provide estimates of the position and size of individual clouds. A great many of these measurements were made and detailed charts were drawn of sections of the route where lane structure was well marked. Much the commonest mode of organization was into lines nearly parallel to the low-level streamlines. In the absence of other data, therefore, observations of cloud lanes could provide useful information on surface wind flow, though the correspondence is not exact. Less frequently observed was an organization of clouds into lines across the low-level winds. A factor thought to favour this mode was the development of the cumuli through sufficient depth to penetrate an upper layer of strong shear in the wind, the cross lines of cloud then being roughly parallel to the shear vector. On occasion both forms of organization appeared simultaneously.

Other plausible, but more speculative, relations are discussed. It was observed that almost all the rain was associated with major disturbances. Often differences between wet and dry situations are small in the conditions near the surface and the authors explain the development of large convective storms by wind flows in the upper troposphere which lead to increased anticyclonic vorticity and divergence, with compensating convergence at low levels. The need for much more numerous wind observations to elucidate such relations is stressed.

The book is one which no meteorologist dealing with tropical oceanic weather can afford to ignore. To the newcomer to the field it gives an excellent insight into how clouds develop and behave over tropical oceans and the investigator will find much material to stimulate him.

M. H. FREEMAN

Read well and remember by Owen Webster. 8 in × $5\frac{1}{4}$ in, pp. 280, Hutchinson & Co., 178–202 Great Portland Street, London W1, 1965. Price: 20*s*.

This is a book for all readers who wish to use their time profitably when they have to learn from the printed word. Most students and research workers have taught themselves a good deal about how to remember what they read using such rules as: read material more than once; write summaries; relate new knowledge to old; use mnemonics; and so on. They may even have learnt a few tricks of fast reading and skimming. But the subject of reading efficiency is not widely taught and many readers will benefit from learning the principles and putting them into practice under the author's guidance. No unusual standard of knowledge or of memory is required and the principles can be applied in any subject field or to any type of writing.

Mr. Webster has studied his subject as a student and as a lecturer, and has used his experience to communicate his ideas to readers and obtain their co-operation in carrying out his instructions. The result is a well-planned 'teach yourself' book; each chapter contains carefully chosen passages for reading, and exercises designed to stimulate as well as guide. The reader can measure his own speed of reading and his power of comprehending and remembering; and he may be impressed by his own improvement or by some of the author's forecasts of the results of exercises. Techniques of reading and studying are explained but the reader is also taught to read with a purpose and to look for the underlying philosophy of what he is reading. Besides being critical the reader must be actively involved in finding answers to his questions. Another feature of the book is the wide range of interests shown in the examples and reading lists (no doubt stemming from the author's experience in the world of books and journalism), and the encouragement given to readers to extend their reading into areas outside their own special activities.

Several books have been published in Britain recently to help writers to improve their standard. This book meets an obvious requirement in that it helps readers but it is also a useful book for writers interested in the best way of communicating ideas to readers.

W.S.G.

The amateur weather forecaster by E. S. Gates. $7\frac{3}{4}$ in $\times$ $5\frac{1}{4}$ in, pp. 93, *illus.*, George G. Harrap & Co. Ltd., 182 High Holborn, London WC1, 1965. Price: 6*s.*

At first glance this is an attractive publication with good type and clearly drawn diagrams. But both text and diagrams contain many imprecisions and errors of fact. For instance, on page 23 pressure gradient is defined and followed by the misleading statement "thus it indicates the velocity and general direction of air movements." In several respects figures 27, 28 and 30 give a false picture of a depression. There is even a lot of misinformation in Appendix II about the meaning of terms used in weather forecasts for the public.

The reviewer cannot recommend this book to any amateur weather forecaster.

R. J. OGDEN

CORRIGENDA

Meteorological Magazine, June 1965, p. 173, 'The yearly distribution of rainfall intensities', two lines below equation (1): for "i the average rate" read "$\bar{i}$ the average rate"; p.177, to Figure 3 add "the straight line is given by equation (1)"; p. 179, Figure 4, delete "the straight line is given by equation (1)".


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