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SOME AIRCRAFT REPORTS OF HIGH-LEVEL TURBULENCE

By W. T. ROACH

In the past five years, the Meteorological Office has received about 300 reports of severe clear-air turbulence from U.K.-based civil and military aircraft flying mainly on European or Atlantic routes. A routine check is kept on the association of these reports with the relevant synoptic situations which, in most cases, are found to correspond to situations in which, from past experience, the occurrence of turbulence might be expected.

However, on some occasions the turbulence is particularly severe and widespread or possesses other features of sufficient interest to justify published comment. Previous cases have been described by Briggs[1,2] and Lennie.[3]

One problem of considerable practical importance is, given a situation in which turbulence is likely, why should the turbulence encountered be severe on some occasions rather than light or moderate? One feature which appears to be emerging from a study of severe turbulence reports is that relatively rapid changes in the large-scale flow pattern are often occurring locally — e.g. in association with a developing depression — but so far, an adequate quantitative description of development relevant to the production of turbulence has not yet emerged.

In the five cases to be described here, significant development was present, but this is not the only interesting feature discussed. In three cases, it was possible to obtain copies of the original flight recording thus enabling a more objective assessment of the reports to be made.

Gravity waves in mid-Atlantic ? On two occasions in 1967 (24 January and 2 December) reports of prolonged turbulence encounters (about 1 hour) accompanied by quasi-periodic fluctuations in height and airspeed were reported by the pilots as 'standing waves', presumably by analogy with mountain waves, although in these cases the pilots would clearly not be able to infer anything about the phase velocities of the waves with respect to the ground.

(i) 24 January 1967

Extracts from the captain's report on flight BA 600/334 from Toronto to Prestwick as follows :

'Time approx. 0500 to 0600 GMT; position from 55°N 25°W to 55°N 12°W approx.; flight level 35 000 ft; Mach 0·8; ground speed 530 kt.

During cruise in clear air, there was a very rapid fall in temperature from about − 63° to − 72°C at about 0520 GMT followed by the onset of moderate turbulence with appreciable ASI (airspeed indicator) fluctuations. It rapidly became apparent that these were systematic and we were in standing-wave conditions ... so I disengaged the height lock, advised ATC I was flying "attitude" and "rode with the wave" .... This continued for about an hour with a short break of a few minutes around 13°W* when the OAT (outside air temperature) suddenly increased to − 63°C. With the power set for Mach 0·8 level, the aircraft rose with the up-wave at up to 2000 ft/min with increasing speed to Mach 0·825 and (if not retrimmed or power readjusted) climbed 2000 ft before starting on the down-wave at up to 1500 ft/min descent with Mach No. falling to 0·78 .... The complete cycle took 4½ minutes giving a wavelength of about 40 miles and a peak-to-peak height variation of about 3500 ft.'

It seems very unlikely that this phenomenon could have been produced by aircraft behaviour alone. The aircraft recorder chart was later obtained and part of it is reproduced in Figure 1. The captain's report is largely borne out, but some extra features of interest are apparent.

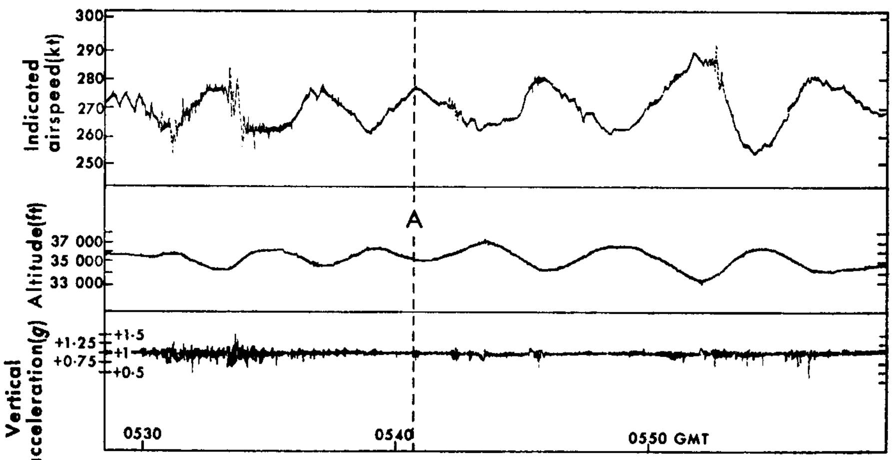

FIGURE 1—FLIGHT RECORD FROM THE RELEVANT PART OF FLIGHT BA 600/334, 24 JANUARY 1967

– – A – – Point at which heading of aircraft changed from 090° to 102°

(a) A change of aircraft heading of about 12° at 0540 GMT is accompanied by a distinct increase in wavelength.

(b) The oscillations in Mach number *(Ma)* reported by the pilot and the height oscillations in Figure 1 are in antiphase to the indicated airspeed (V_i) oscillations. This is consistent with a rough interchange between the kinetic and potential energies of the aircraft and also with the relation between V_i and Ma given by $V_i \propto Ma p^{\frac{1}{2}}$ where p is pressure.

* A break in the recorded oscillations appears near 0600 GMT. According to the navigator's log the aircraft was at about 18½°W at this time, not 13°W.

(*c*) The root-mean-square '*g*' fluctuations (vertical-acceleration trace) are about ±0·05 *g* most of the time, increasing in occasional bursts to 0·1–0·2 *g*. The '*g*' trace has no obvious relationship to the long-period oscillations. The largest event appears to have been at about 0533 GMT when a drop of about 30 kt in V_i in 15 seconds was preceded by a '*g*' spike of about +0·5 *g* (1·5 *g* on the chart).

The change in heading can be used to infer some of the properties of the wave. If it is assumed that the aircraft is crossing a system of waves with straight parallel crests and troughs then

$$\lambda_a = \frac{U\lambda_t}{|\,U\cos\theta - u\,|}$$

where λ_a = apparent wavelength observed from the aircraft
λ_t = true wavelength
θ = angle of aircraft (air) track with direction of wave propagation
U = true airspeed of aircraft
u = phase velocity of wave with respect to the air.

This gives two equations for the two wavelengths $(\lambda_a)_1$ and $(\lambda_a)_2$ observed before and after the change in heading. The latter is known and gives a third equation $\theta_1 - \theta_2 = \Delta\theta$.

A fourth equation is obtained by making the not unreasonable assumption that the frequency of the wave is likely to be close to the Brunt-Väisälä frequency $\mathcal{N} = [(g/\theta)(\partial\theta/\partial z)]^{\frac{1}{2}}$ and $\mathcal{N} = 2\pi u/\lambda_t$ giving four equations which now enable us to solve for the four unknowns λ_t, u, θ_1, θ_2.

Meteorological information and measurements made on the recorder trace give

$$\begin{aligned}(\lambda_a)_1 &= 53 \text{ km}\\ (\lambda_a)_2 &= 75 \text{ km}\\ \theta_1 - \theta_2 &= 12^\circ\\ \mathcal{N} &= 0{\cdot}013 \text{ radians/s}\\ U &= 232 \text{ m/s}\end{aligned}$$

There are two solutions depending upon the sign of $U\cos\theta$:

λ_t	u	Direction of propagation
km	*m/s*	*degrees*
30	60	055
40	80	200

Unfortunately, a continuous record of the OAT was not available, otherwise an estimate of the wave amplitude could have been made. An estimate based on the assumption that the aircraft really 'rode the wave' and thus assumed the vertical velocity of air in the wave, gives an amplitude of about 600 m, but this is unreliable as changes of pitch will in general produce aircraft rates of climb or descent relative to the air.

Synoptic situation. The aircraft was crossing in a strong anticyclonic southwest flow at 250 mb (Figure 2) and at 0545 GMT was about 800 km north-north-east of the centre of a rapidly developing depression. The data in the area is too scanty to give more than a rough idea of the atmospheric structure in the proximity of the flight track. The tephigrams of ocean weather stations (OWS) 'I' and 'J' (Figure 3) suggest that the aircraft was flying in a layer of fairly stable air just beneath the tropopause near or just

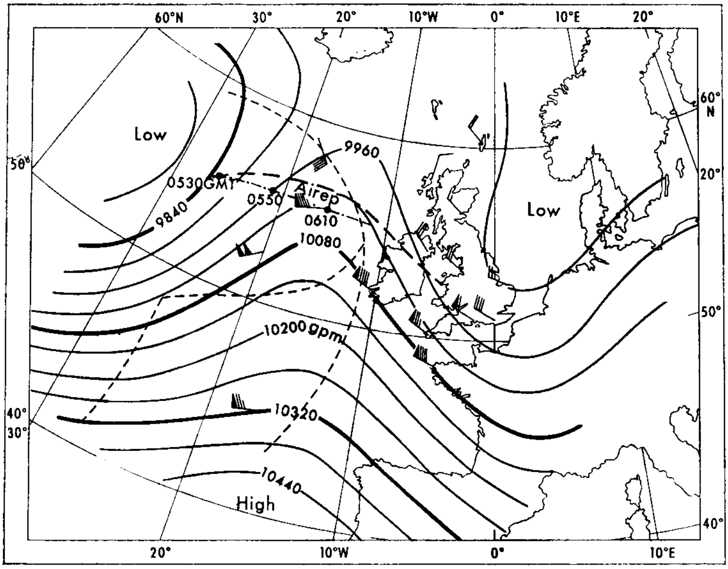

FIGURE 2—INTERPOLATED 250-mb CONTOURS FOR 0600 GMT, 24 JANUARY 1967

—·— Aircraft track during turbulent period
– – – Surface fronts at 0600 GMT
— — Wind discontinuity suggested by pilot's report and radiosonde winds

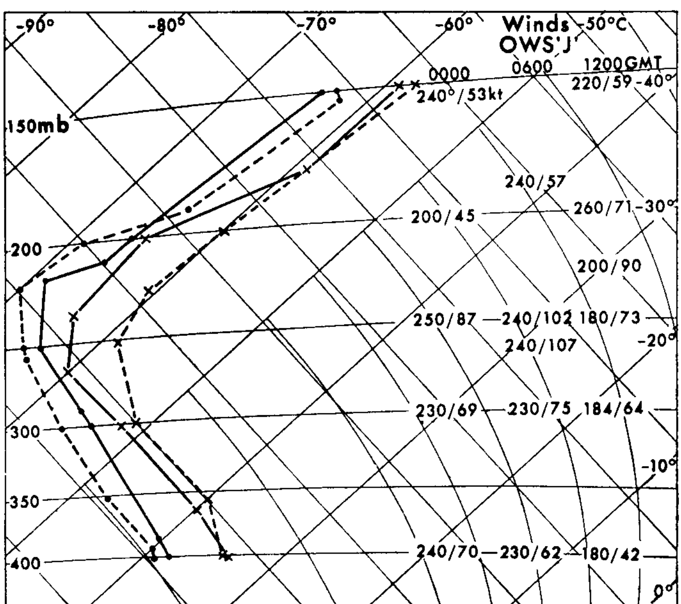

FIGURE 3—UPPER AIR TEMPERATURES FOR OWS 'I' AND 'J' AT 0000 AND 1200 GMT, 24 JANUARY 1967, AND WINDS FOR 'J' AT 0000, 0600 AND 1200 GMT

·——· OWS 'I' x——x OWS 'J' for 0000 GMT
– – · OWS 'I' x – – x OWS 'J' for 1200 GMT

above the level of maximum wind. The air immediately above the tropopause was extremely stable and contained a large negative wind shear. The sudden drop of 9 degC in the OAT at the beginning of the event strongly suggests that the aircraft entered a new air mass associated with development to the south.

Discussion. The suggestion that this disturbance was in some way triggered by the baroclinic instability developing to the south is plausible, although the mechanism of production is not known. The source of energy could lie in the moderate to severe turbulence created near the air-mass front encountered at the beginning of the event, in which case the wave would be propagated southwards, i.e. backwards into the northward advancing air mass of subtropical origin. Thus the second solution of our four equations is possibly the appropriate one.

There is a suggestion of a discontinuity in the wind field along a curve running east to west near 56–57°N and convex towards the north. It is conceivable that waves generated at this discontinuity and propagated southward would be focused to some extent by the curve. A curved wave-front would, of course, alter the solutions worked out for a straight wave-front, but, provided that the curvature is small, these should not be very different from the true values. Furthermore, there may be a preferred propagation of wave energy in a horizontal direction, a preference due possibly to some wave-guide effect produced by the vertical structure of the atmosphere. The fact that observations of marked wave effects of significant amplitude well away from mountains have been reported only rarely (e.g. Kuettner[4]) suggests that the right combination of conditions occurs only rarely.

(ii) 2 December 1967.

This event occurred during flight BA 561/032 from London/Heathrow Airport to Boston. No pilot report was available and most of the information was obtained from the flight record, part of which is shown in Figure 4. The aircraft entered a prolonged period of turbulence at about 1417 GMT (53°N 20°W) which continued until about 1525 (55°N 35°W). This period contained short patches of severe turbulence accompanied by marked fluctuations of height and airspeed during the periods 1443–1446, 1453–1458, and 1518–1521 (example shown in Figure 4). The amplitude of the V_i fluctuations approached the amplitude observed on 24 January, but the period was much shorter — about 25 s. Thus the possibility that this may have been some type of aerodynamic (phugoid?*) oscillation induced by the turbulence cannot be ruled out. Sympathetic oscillations can be seen in the height trace (amplitude about 45 m), and the 'g' trace (amplitude about 0·11 g). For approximately sinusoidal oscillations, the amplitude of the g-trace is about $4\pi^2 A/T^2$ where A is the amplitude of the height oscillation and T is the period. This gives $A \simeq 17$m which is much less than that indicated by the altimeter trace. There is also no quantitative correspondence between height and airspeed changes, and the latter could have been due to an aerodynamic oscillation producing fluctuations in the airflow relative to the airframe which could affect the aircraft pitot-static system.

* Longitudinal periodic fluctuation in speed.

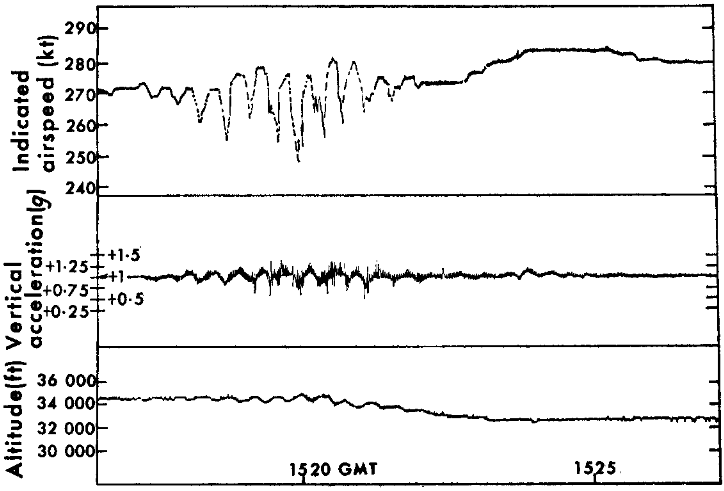

FIGURE 4—FLIGHT RECORD FROM THE RELEVANT PART OF FLIGHT BA 561/032, 2 DECEMBER 1967

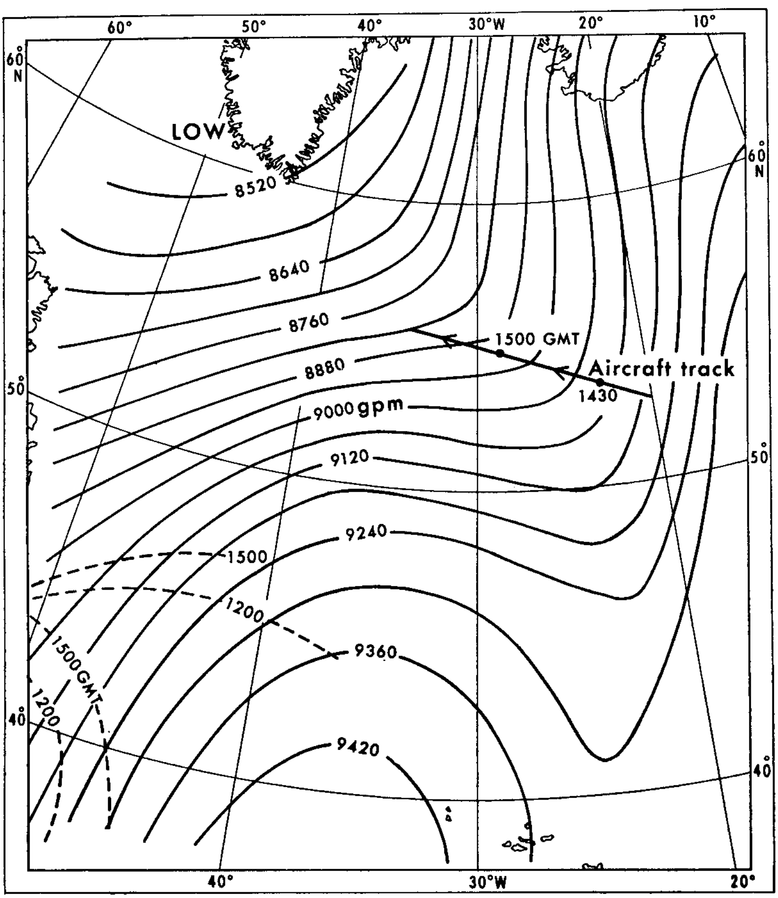

FIGURE 5—300-mb CONTOURS FOR 1200 GMT, 2 DECEMBER 1967
- - - - Surface fronts at 1200 and 1500 GMT

Synoptic situation. Figure 5 shows the 300-mb contours at 1200 GMT, about three hours before the event discussed. The aircraft track appears to run across the trough axis into the strong anticyclonic flow upwind of the trough. It would be natural to attribute the prolonged turbulence to the oblique traverse of the trough, but in fact the trough was moving north-east extremely rapidly and the aircraft winds (derived from ground track positions) indicate that the aircraft crossed the trough axis during the early part of the period of interest and was in the westerly (anticyclonic) flow after about 1440. OWS 'C' (Figure 6) reported a wind of 270° 155 kt (80 m/s) at 250 mb at 1200, and it is very likely that the aircraft was experiencing this headwind about three hours later.

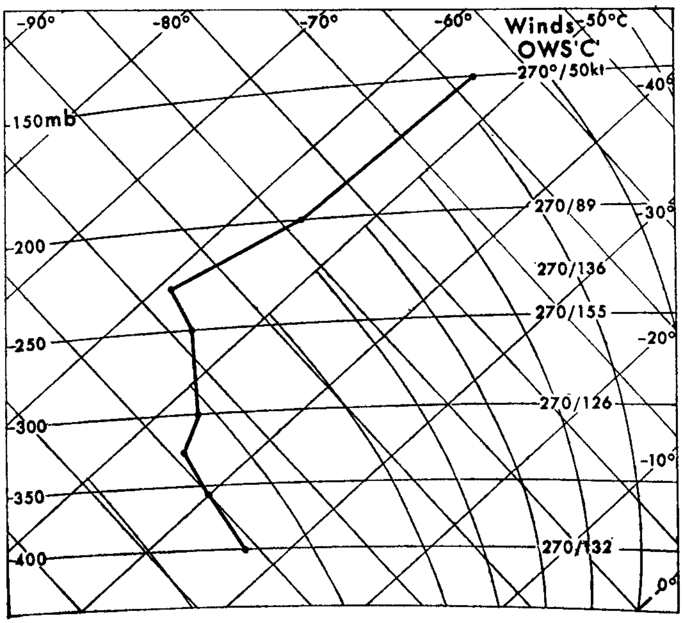

FIGURE 6—UPPER AIR TEMPERATURES AND WINDS FOR OWS 'C' AT 1200 GMT, 2 DECEMBER 1967

However, the point is not so much where the aircraft was in relation to the synoptic pattern, but that the whole area was one of very rapid change. There are, in fact, some features of this situation similar to those on 24 January, such as :

(a) The flight was in a developing upper ridge situation ahead of a deepening depression to the south-west.

(b) The aircraft was flying just beneath the tropopause.

(c) There was a strong negative vertical wind shear above the jet core.

Why severe turbulence ? Three examples are now described in which severe turbulence was encountered in 'conventional' situations — on the low-pressure side of jet cores — but the question arises as to why the turbulence was so violent in these particular cases.

(i) 5 October 1966.

The aircraft was flying at 32 000 ft (10 km) *en route* from New York to Heathrow when it encountered, with virtually no warning, a violent negative '*g*' jolt of about – 1 *g* followed by a short period of severe turbulence diminishing to moderate. This aircraft was one of the civil aircraft specially instrumented for the Civil Aviation Airworthiness Data Recording Programme (CAADRP) organized by the Air Registration Board (ARB) and the Royal Aircraft Establishment through BEA and BOAC. This turbulence encounter was picked out as a 'special event' and the ARB made available a copy of the flight record (Figure 7). This record is a good example of an occurrence of severe turbulence with only a few seconds warning, and makes a case for having seat belts at least loosely fastened during all flights.

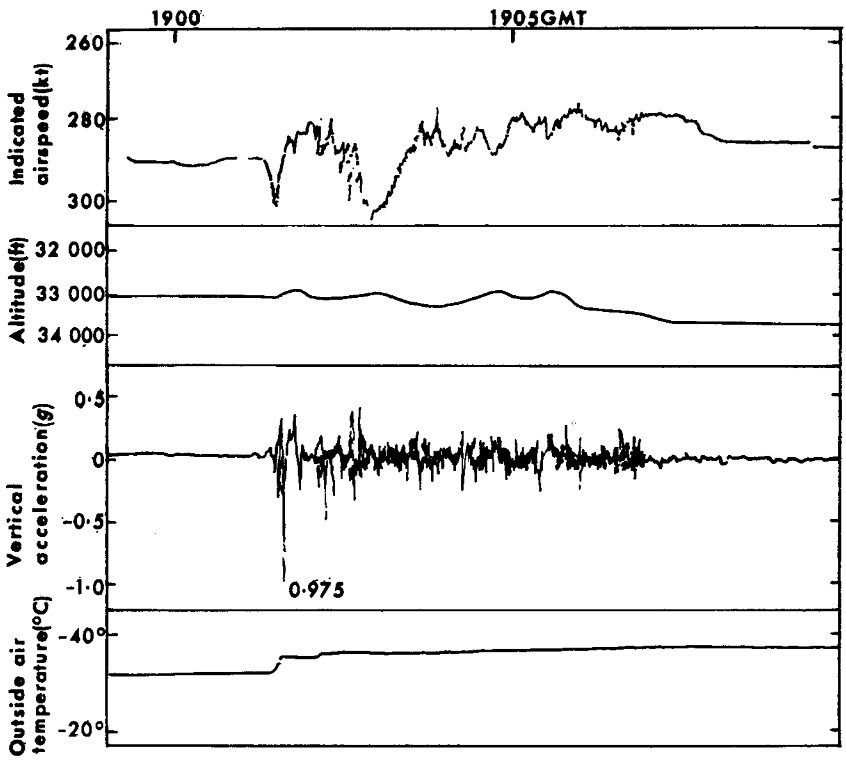

FIGURE 7—CAADRP 'SPECIAL EVENT' FLIGHT RECORD, 5 OCTOBER 1966

The turbulence was accompanied by large fluctuations in V_i (Figure 7). Of particular interest is the sudden decrease in the OAT of about 3 degC simultaneously with the initial large bump, followed by a further gradual fall of about 2 degC over the next three minutes or so, after which the aircraft climbed to 34 000 ft (10.5 km) and left the turbulence.

Synoptic situation. The incident occurred at 1900 GMT about 100 km west of Shannon in a cyclonic south-west flow. Figures 8 *(a)* and *(b)* show the 300-mb flow seven hours before and five hours after the incident. Some development of a moderate nature occurred during this period. Warm frontogenesis occurred over western U.K. accompanied by a backing and tightening of the gradient at 300 mb ahead of the upper low. An attempt has also been made to draw tropopause contours, and these also changed during 12 hours in sympathy with warm advection over the U.K. and cold advection over the Western Approaches. The charts suggest that the tropopause was at 250 mb at the time and place of the event, i.e. only 500 m above the aircraft.

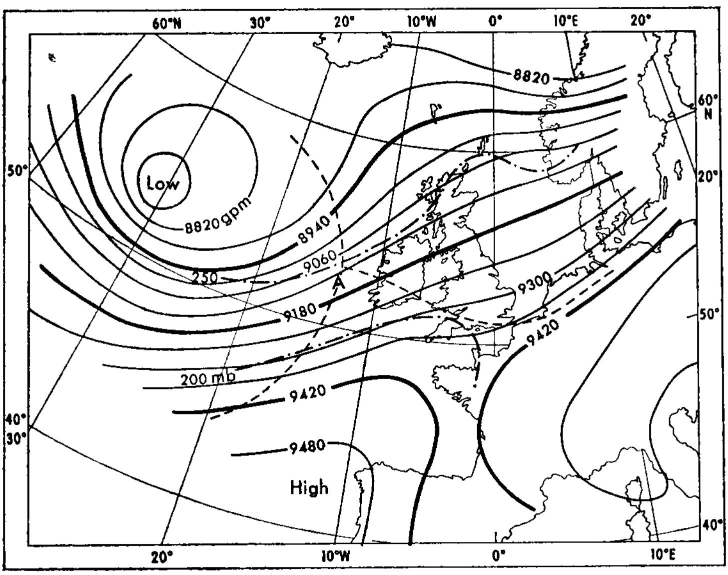

FIGURE 8 *(a)*—300-mb CONTOURS FOR 1200 GMT, 5 OCTOBER 1966

– – – – Surface fronts at 1200 GMT
·—·—· Tropopause contours (50-mb intervals)
A Position of – 0·975-*g* spike in Figure 7

Discussion. It seems likely that the turbulence occurred as the aircraft crossed the tropopause. There must have been a thin, intense (thermally) stable layer immediately above the tropopause. This layer may have contained a large localized directional wind shear resulting from a south-west flow in the stratosphere riding up over a backed and backing flow in the upper troposphere. It is possible at that time and place that dynamical processes were producing rapid tightening of the vertical wind shear near the tropopause, resulting in locally severe turbulence acting to relieve the shear as it was being produced.

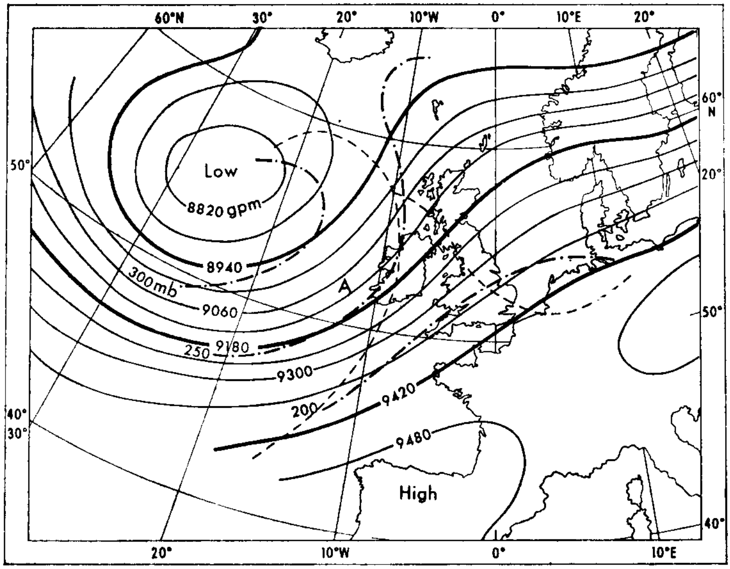

FIGURE 8 *(b)*—300-mb CONTOURS FOR 0000 GMT, 6 OCTOBER 1966

– – – – Surface fronts 0000 GMT

—·—· Tropopause contours (50-mb intervals)

A Position of – 0·975-*g* spike in Figure 7

A change in true vertical velocity of about – 15 m/s over a distance of less than 100 m would be required to produce a negative 1-*g* acceleration in a big jet clipper at 10 km altitude, and it seems likely that this can only have been produced by local breakdown of the shear layer as a whole; the aircraft may have entered the downward plunge of an internal 'wave breaker'. Also the small amplitude '*g*' oscillation of period about 10 s (i.e. about 2 km) just prior to the main event could be interpreted as a rapidly amplifying gravity wave just prior to breaking. This case was chosen as one in which study of the associated synoptic charts would not have led one to expect that turbulence would have been more than light or moderate, and conventional radiosonde data suggested that wind speeds and wind shears were nothing exceptional.

(ii) 10 February 1968.

On this day, two reports of severe or violent turbulence over the U.K. were received, and it is understood that there were several turbulence encounters on flight routes into Germany on that day, but no specific reports were received of the latter. Extracts from the U.K. reports follow.

(a) Lightning aircraft from Bristol Aeroplane Company, Warton.

'As Mach 1·3 was reached, Warton Approach passed a message from another Lightning that clear-air turbulence was encountered between 25 000 and 28 000 ft. This message was acknowledged, but flight remained smooth until reaching Mach 1.7 at 31 000 ft about 30 miles (50 km) west of Warton about 1200 GMT. The entry into turbulence was very sudden, and for several seconds the pilot could do nothing but hang on to the stick and throttles. During this period it was impossible to control the aircraft which was bucking violently in every direction. The actual deviations from the flight path were thought to be small, but the sharpness, random nature and high frequency of the bumps were disorientating. At this stage the pilot thought the aircraft might disintegrate. A determined effort was required to place the aircraft in a climb and to throttle the engine. The buffeting ceased on passing through 36 000 ft.

In approximately 1200 supersonic flights, the pilot has encountered CAT on many occasions, but the severity and extent has not caused undue concern until this particular incident.'

(b) Air Registration Board Trident aircraft flown from De Havilland, Hatfield.

'Severe turbulence was encountered at 21 500 ft over the Wash at 1140 GMT. The IAS was reduced from 330 to 270 kt and the aircraft climbed on a course of 070° magnetic, and left turbulence after about 5 minutes at 25 500 ft.'

Synoptic situation. A strongly anticyclonic westerly jet associated with a depression in the South-west Approaches was pushing slowly north against an old cold trough (Figure 9). Very large vertical and horizontal wind shears (of about 3×10^{-2} and 3×10^{-4} m/s per metre respectively) were reported on the northern boundary of the jet, and severe turbulence in these conditions is not surprising. A radiosonde cross-section (Figure 10) shows a well-marked frontal zone between the westerly jet and the relatively stagnant cold-pool air. Over Hemsby, this zone appeared to extend from 21 000 to 26 000 ft which agrees very well in time and place with the turbulent layers reported by the Trident aircraft.

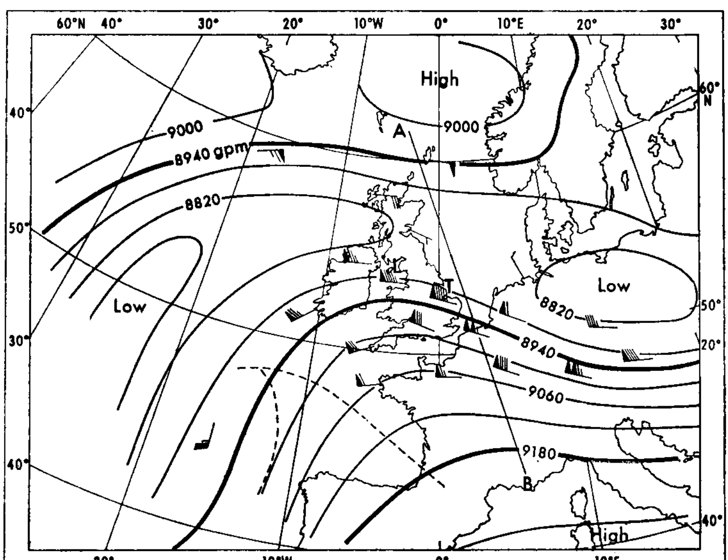

FIGURE 9—300-mb CONTOURS FOR 1200 GMT, 10 FEBRUARY 1968

- - - - Surface fronts at 1200 GMT
L and T Positions of the Lightning and Trident reports respectively
A—B Approximate line of cross-section in Figure 10

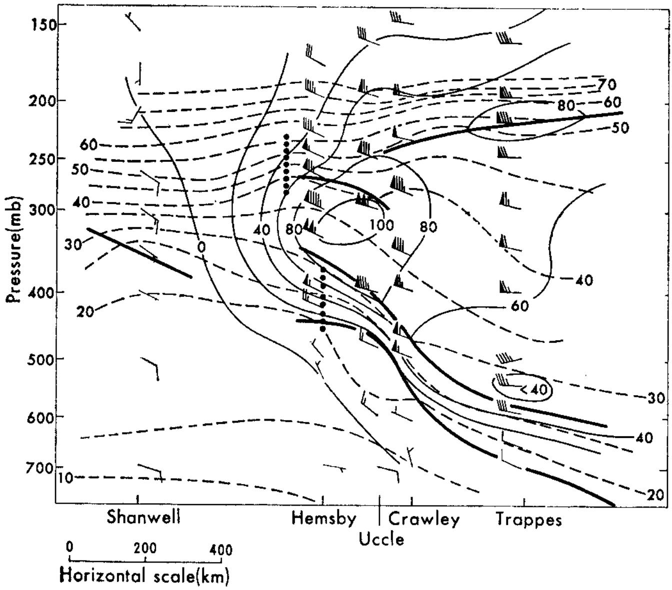

FIGURE 10—RADIOSONDE CROSS-SECTION ALONG AB IN FIGURE 9 FOR 1200 GMT, 10 FEBRUARY 1968

——— Isotachs (kt) – – – – Isentropes (°C)
. . . . Turbulent layers reported by aircrew
▬▬▬ Tropopause and frontal surfaces
(This is part of a cross-section drawn from 62½°N 4°W to 43°N 5°E.)

Discussion. In contrast to the event on 5 October ((*i*) on p. 72), the synoptic situation suggests that severe turbulence within the frontal zone would not be surprising, but the question still arises as to whether this could have been forecast. On this day, Preston issued at 0840 GMT a SIGMET of severe turbulence south of 54°N moving slowly north, but this was based on an earlier aircraft report.

We can usefully think of the frontal zone acting as a giant friction plate between the jet stream and the stagnant cold-pool air with the northward movement of the jet maintaining the pressure on the plate and therefore acting to maintain severe turbulence. Presumably decrease or cessation of this northward push would relax the pressure and decrease the turbulence.

(iii) 4 September 1967.

A Victor II aircraft of 100 Squadron, RAF, Wittering, piloted by F/Lt Bradley encountered turbulence at 1552 GMT at 40 000 ft over Liverpool. This was described as follows :

(a) Moderate 0·5 *g* then one extreme spell of clear-air turbulence +4·3 *g*.

(b) Climb to 44 000 ft, no clear-air turbulence . . . . At 1608 GMT, at 40 000 ft, violent airframe vibration.

Synoptic situation. A rapidly deepening depression was centred at about 54°N 16°W at the time of the incident and was moving east at about 30 kt.

Associated with this depression was a very mobile upper flow pattern with very large vertical wind shears above and below a jet core of winds about 130 kt at 230 mb. Particularly strong shears above the jet core were reported from Long Kesh, Aughton and Hemsby; at Aughton at 1800 GMT the 200–150-mb shear was 65 kt (see Figure 11). It is also of interest to note that the maximum wind over Aughton and Hemsby increased by 80–90 kt during the periods 0600–1200 and 1200–1800 respectively. A thin layer (5–15 mb thick) of extreme stability bounding the tropopause was evident on the Long Kesh and Aughton ascents at 1200 GMT and on the Hemsby ascent 12 hours later (Figure 12). This layer would be capable of supporting vertical wind shears of up to 5×10^{-2} m/s per metre before breaking up into turbulence, although localized intensification of shear could produce localized patches of very severe turbulence in the layers. It seems very likely that the aircraft encountered extreme turbulence within this layer.

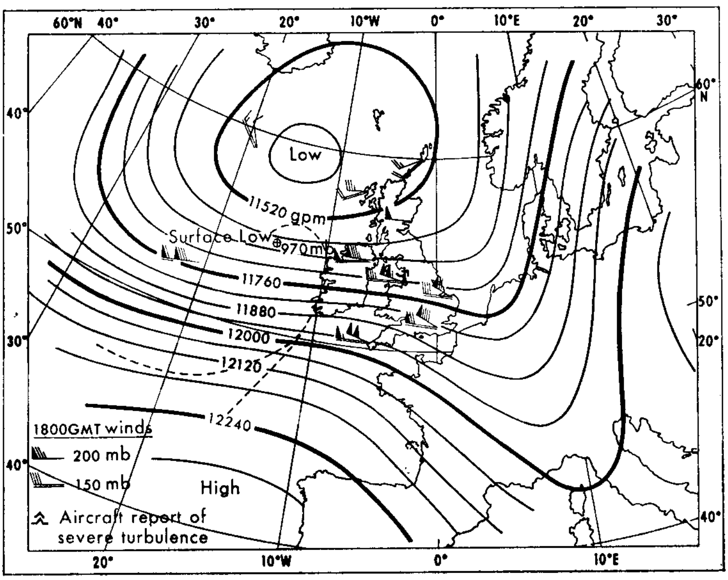

FIGURE 11—INTERPOLATED 200-mb CONTOURS FOR 1800 GMT, 4 SEPTEMBER 1967

- - - - Surface fronts at 1800 GMT

Discussion. This is perhaps the most marked example of turbulence production in a developing situation. The intensity of development is unusual and rates of kinetic energy advection averaged over 6 hours of the order of 5×10^{-2} joules/kg per second imply values several times larger over shorter periods, which in turn imply the order of magnitude of energy available for turbulent dissipation.

From an aviation point of view, it suggests that of all development areas, the upper flow ahead of a rapidly developing depression is particularly to be avoided. In practice, this area will usually be in the north-east quadrant 400–800 km from the developing surface centre.

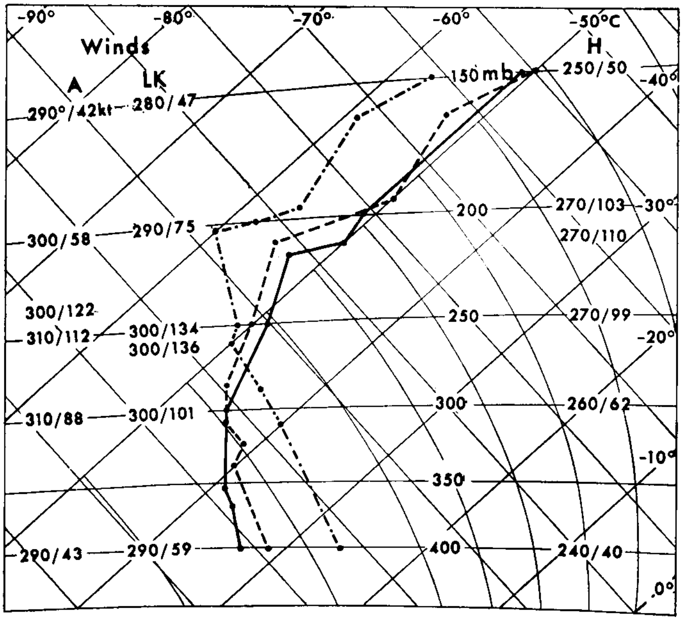

FIGURE 12—UPPER AIR TEMPERATURES AND WINDS FOR AUGHTON AND LONG KESH AT 1200 GMT, 4 SEPTEMBER 1968, AND HEMSBY AT 0000 GMT, 5 SEPTEMBER 1968

——— Aughton (A) - - - - Long Kesh (LK) —·—· Hemsby (H)

Acknowledgements. I am indebted to the Flight Data Acquisition Department of BOAC and to the Civil Aviation Airworthiness Data Recording Project for making relevant flight records available and for giving permission to publish copies of these, and to Mr B. A. Hall and Miss A. Peters of the Meteorological Office who assisted in working up the data.

REFERENCES

1. BRIGGS, J.; Widespread clear-air turbulence on 13 November 1958. *Met. Mag., London,* **90**, 1961, p. 234.
2. BRIGGS, J.; Severe clear-air turbulence near the British Isles. *Met. Mag., London,* **90**, 1961, p. 245.
3. LENNIE, J. C.; Clear-air turbulence over the North Atlantic; some notably turbulent periods. *Met. Mag., London,* **98**, 1969, p. 9.
4. KUETTNER, J.; On the possibility of soaring on travelling waves in the jet-stream. *Sailpl. Gliding, London,* **20**, 1952, p. 7.

551.524.2(41–4):551.524.36

THE VARIABILITY, WITH TIME AND LOCATION, OF SPRING AND SUMMER TEMPERATURES IN THE UNITED KINGDOM

By G. W. HURST

Introduction. This survey attempts to put into perspective the present régime of temperatures over England, Wales and much of Scotland. Many aspects of agricultural and allied disciplines relate closely to spring and summer temperature levels, and a background is presented for an appraisal of crops, or yields of honey, both geographically and over the last century or so. This follows up an earlier paper[1] on honey production and temperatures in July and August 1943–66. Throughout this paper the conventional definitions for seasons are used, with spring consisting of the months March, April and May, and summer of June, July and August, and for practical reasons temperatures are in Fahrenheit and heights in feet.

Methods of analysis. The survey has been prepared using four complementary methods of examination, with varying periods of availability of data.

(i) Period 1841–1968.
Variability over time was assessed by examination of London temperatures[2] over the last century or so. Some justification is made for the application of these data to England and Wales as a whole.

(ii) Period 1946–55.
The duration of time, in hours, with temperatures above certain levels was assessed for a number of specific localities in England, Wales, Scotland and Northern Ireland; arbitrary base temperature values of 50°F, 60°F and 70°F were chosen.

(iii) Period 1931–60.
Using mean temperature data for various regions of Great Britain, average values of accumulated temperatures in spring and summer were obtained, and an indication was made of the effect of height change to such values. Standard temperature levels of 42°F, 50°F and 60°F were considered.

(iv) Period 1931–48.
A short examination was made of the actual variability in seasonal accumulated temperatures over an 18-year period for two stations, one in south-west England and the other in the south-east Midlands.

Variability of spring and summer since 1841. In this analysis the Kew records from 1871 have been analysed with a (justified) extension to 1841 using Greenwich figures. The source of these data is *London weather.*[2] That Kew temperatures could reasonably be taken as a basis for reflecting tendencies in the nineteenth century for England and Wales as a whole, was justified by a comparison of the two sets of data since 1900. It was preferable to use Kew figures rather than Manley's for central England[3] because the Kew data had already been summarized in seasonal form.

Kew averages for both spring and summer for 1931–60 have been taken as standard (spring 49·0°F and summer 62·4°F), and for the purpose of this paper deviations from these figures of 1·0–1·9 degF have been regarded as warm or cold as the case may be, and of 2·0 degF or more as very warm or very cold. These values have been chosen arbitrarily, and have been designed to highlight extreme seasons; in the standard period 1931–60, extreme springs numbered 7 and extreme summers 6, out of the total of 30. Quintile boundaries as used by Murray,[4] for example, were not adopted. Such boundaries vary each month and are by definition chosen to give as many occasions in each extreme as in any other quintile of temperature levels, i.e. in 30 years there would be 12 extreme summers.

Temperatures at both Greenwich and Kew were compared for 1871–80, a period for which both sets of data were published in *London weather;* this comparison showed the Greenwich average temperature higher by 0·4 degF and 0·9 degF in spring and summer respectively, with no change of pattern during the 10 years. Accordingly, to be comparable, Greenwich averages for 1841–70 have been taken as 49·4°F and 63·3°F — but it is emphasized that these were not the averages for Greenwich over that period.

Finally, deviations from the 1931–60 average temperatures (reduced to MSL) for spring (48·0°F) and summer (60·4°F) for England and Wales as a whole were categorized as very warm, warm, etc. in exactly the same way as for Kew. There did not appear to be any warming at Kew compared with the country as a whole since 1901 — if anything, there is a hint of the opposite. Table I shows the frequencies of springs and summers at different temperature levels for each decade from 1841 onwards.

TABLE I—DISTRIBUTION OF SEASONS IN EACH DECADE ACCORDING TO AVERAGE TEMPERATURE LEVEL. LONDON 1841–1968, ENGLAND AND WALES 1901–68

(a) Spring

	London					England and Wales				
Decade	*VW*	*W*	*A*	*C*	*VC*	*VW*	*W*	*A*	*C*	*VC*
1841–50	1	1	4	3	1					
51–60			3	1	6					
61–70		2	3	4	1					
71–80			5	2	3					
81–90			1	4	5					
91–00	1		4	1	4					
1901–10			4	6				6	4	
11–20		2	5	2	1		2	4	3	1
21–30		1	4	5			1	4	5	
31–40		1	7	1	1		3	5	1	1
41–50	2	1	6		1	3		6		1
51–60	2	2	3	2	1	2	2	3	2	1
61–68	1		5	1	1	1		6		1
Total 1901–68	5	7	34	17	5	6	8	34	15	5
1841–1900	2	3	20	15	20					

(b) Summer

	London					England and Wales				
Decade	*VW*	*W*	*A*	*C*	*VC*	*VW*	*W*	*A*	*C*	*VC*
1841–50	1		2	4	3					
51–60	2	1	2	2	3					
61–70	1		3	3	3					
71–80		1	5	3	1					
81–90			2	3	5					
91–00	1	1	4	1	3					
1901–10			4	2	4		1	4	1	4
11–20	1		2	3	4	1		3	4	2
21–30		1	6	1	2		1	3	4	2
31–40	1	2	5	2		1	2	6	1	
41–50	1	1	6	1	1	1	2	5	2	
51–60	1	1	3	3	2		2	6		2
61–68			5	2	1			5	1	2
Total 1901–68	4	5	31	14	14	3	8	32	13	12
1841–1900	5	3	18	16	18					

Note : *VW* Very warm } departure from average > 2·0 degF. *W* Warm } departure from average 1·0 to 1·9 degF.
VC Very cold } *C* Cold }
A Average : departure from average 0 to ± 0·9 degF.

Spring. Agreement between London, and England and Wales is fairly close, with England and Wales marginally the warmer. It is very interesting to note that there have been more very warm springs in London in the 28 years since 1940 than in the 100 years before; and, perhaps even more significant, the 28 years include 8 out of the total of 17 warm or very warm springs. Cold or very cold springs have numbered 2 a decade since 1930, whereas until 1900 over half the years were cold (by recent standards).

Runs of springs with similar characteristics were examined, and from 1841 to 1958 there were never two consecutive years with warm springs; 1959–61 however were all warm (1959 and 1961 very warm). Conversely, no runs of cold springs have occurred in the last 30 years. Earlier however there was a run of 4 years, 1929–32, and 1924 and 1925 were both cold; the period 1915–17 was cold, so were 1908–09 and 1899–1902. Springs from 1883–92 were continuously cold; 7 were very cold, including a run 1885–88. Earlier sequences consisted of 3 years in the 1870s, 2 years thrice in the 1860s, 2 years in the 1850s and 5 years running over the 1840s to 1850s.

Summer. London, and England and Wales figures are in close agreement, again with very slightly colder weather in London and little suggestion of any long-term change in the pattern between the two sets of data. Interestingly, the distribution of warm summers since 1841 does not vary much; indeed the only decade with two very warm summers was 1851–60. What is clear however, is the greater freedom from cold summers from the mid-1920s onwards, when cold summers averaged about 3 a decade (rather more than one of which was very cold), whereas before this, the decade average was almost 6, of which rather more than half were very cold.

The only runs of 2 or more warm summers in succession were in 1933–35 (1933 was very warm) and 1857–59 (1857 and 1859 were very warm — the latter year outstandingly so). Runs of cold summers were all too frequent in the past, but the only two since 1919 were 1962–63 and 1953–54; in the period from 1879–94 however, 13 of the 16 years were cold, and 9 very cold; 1890–92 were 3 very cold consecutive years.

Finally in this context, Table II shows the years in each decade in which both spring and summer followed a set pattern.

TABLE II—YEARS IN EACH DECADE IN WHICH THE TEMPERATURE RELATIONSHIP BETWEEN SPRING AND SUMMER FOLLOWED CERTAIN PATTERNS

Decade	Both warm	1 warm, other average	1 cold, other average	Both cold
			year	
1841–50		46		**45**, 49, 50
51–60		57, 58	52, 54, 56	51, **53**, 55, **60**
61–70	68		61, 63, 64, 70	66, 67, 69
71–80			71, 73, 80	75, **79**
81–90			82, 84, 87	81, **83**, **85**, 86, 88 89, 90
91–00	93		94, 97, 98, 00	**91**, **92**
1901–10			01, 03, 04, 07, 10	02, 08, 09
11–20		11	13, 17, 18, 19	15, 16
21–30	21		25, 27, 29, 30	22, 24
31–40	33	34, 35	32, 39	31
41–50		43, 45, 47, 49	41, 46	
51–60	**59**	52, 57	53, 54, 56, 58	51
61–68		61	63	**62**

Bold figures indicate that both seasons were very warm or very cold.

This table brings out clearly that the number of warm springs and summers (at least in relation to the 1931–60 averages) has never been high, and in 128 years, 1959 was the only really warm year. Warm, and what might be called fairly warm (i.e. one season warm, the other average), spring/summers were much more numerous between 1934 and 1957 than before or since.

It is the coldness of the years before 1931 which is striking. There have only been 3 cold spring/summers since 1925 (in 43 years) and there were 28 in the 85 years before; the 14-year period 1879–92 included 10 cold and 4 fairly cold occasions.

Duration of time with temperatures above certain levels. A number of arbitrary temperature levels were chosen, and the duration of time for which these levels were exceeded was assessed for a few widely spread localities. From information readily available in the Meteorological Office* Table III was constructed; this gives for various seasons the percentages of hours with temperatures above 50°F (i.e. 50·1°F or more), 60°F and 70°F for specified stations. In all cases the 10-year period 1946–55 was analysed.

The locations in Table III are (or were) nearly all at airfields making hourly temperature observations, so that, for example, the location of Elmdon (near Birmingham) is at least partially rural in character, and is probably tolerably representative of the central Midlands generally. Height differences between the stations are fairly considerable, and an attempt has been made to compensate for this in the yearly totals of percentages by applying the conventional compensation of +1 degF for each 300 feet of height above sea level.

In Table III *(a)*, the 11 stations are in order of the actual percentage of hours in the year with temperatures above 50°F; the range is fairly wide, from just over 64 per cent to just under 40 per cent. Geographical control is reasonably marked with the percentages at the station in Ireland and at the two in east Scotland being distinctly lower than elsewhere; Renfrew in west Scotland is, however, above several stations in England; this is probably a combination of proximity to the west coast and a measure of urbanization. The lowest ranking English stations are both in the south, but compensation for height removes these anomalies and leaves Driffield in the north and (surprisingly) Mildenhall in East Anglia as the two stations with the shortest time with temperature above 50°F in England. Variation of pattern in spring, summer and autumn is evident; in summer the change in percentage from one part of the country to another is not great, with high percentages everywhere. In autumn, however, the difference between southern England and northern Scotland, with the lower percentages, is much more manifest, and the geographical differences are still more noticeable in spring with variation from almost 60 per cent of the hours at Croydon to just over 25 per cent at Kinloss.

Contrasts are much greater in Table III *(b)*, showing the percentage of hours with temperatures above 60°F, and geographical considerations are obviously more important. After height compensation has been made, percentages at all the Scottish and Northern Ireland localities are less than

* *Climatological Memoranda* Nos. 10–13, 16–20, 35 and 39.

TABLE III—PERCENTAGE OF HOURS WITH TEMPERATURE ABOVE 50°F, 60°F AND 70°F FOR VARIOUS STATIONS AND SEASONS

(a) Above 50°F

Station	Area	Height	Spring	Summer	Autumn	Year Actual	Year Compensated*
		feet			*percentage*		
Croydon	SE. England, inland	201	59·2	99·3	74·6	64·4	66·7
Elmdon	Central Midlands, inland	319	51·0	97·0	66·6	57·8	61·7
Pembroke Dock	SW. Wales, coastal	34	38·0	97·9	70·8	55·6	56·1
Renfrew	West Scotland, inland	26	39·0	95·1	57·8	50·7	51·1
Mildenhall	East Anglia, inland	15	38·7	93·1	54·3	48·7	48·9
Driffield	East Yorkshire, inland	69	35·4	92·1	55·7	48·2	49·0
Lympne	SE. England, coastal	341	33·1	94·3	57·4	47·2	51·2
Boscombe Down	South England, inland	414	35·1	91·5	51·2	46·1	51·3
Aldergrove	North Ireland, inland	217	28·3	89·0	47·9	41·8	44·8
Turnhouse	East Scotland, inland	114	28·3	86·7	45·8	41·5	43·4
Kinloss	NE. Scotland, coastal	15	25·5	85·4	43·4	39·8	40·0

(b) Above 60°F

Station	Spring	Summer	Autumn	Year Actual	Year Compensated*	Order†
			percentage			
Croydon	9·4	54·6	15·6	19·9	21·7	1
Elmdon	5·0	39·2	9·6	13·1	15·9	6
Pembroke Dock	4·5	40·9	12·3	14·8	15·3	5
Renfrew	4·6	31·0	5·7	10·4	10·6	8
Mildenhall	9·5	51·2	16·0	19·3	19·4	2
Driffield	4·3	36·5	9·8	12·9	13·4	7
Lympne	6·1	47·2	14·2	16·8	19·8	3
Boscombe Down	6·8	43·8	11·2	15·5	19·2	4
Aldergrove	3·5	27·9	5·7	9·2	10·7	10
Turnhouse	3·2	27·4	6·7	9·3	10·2	9
Kinloss	2.7	22·7	6·7	8·1	8·2	11

(c) Above 70°F

Station	Spring	Summer	Autumn	Year Actual	Year Compensated*	Order†
			percentage			
Croydon	1·5	13·0	1·5	4·0	4·6	2
Elmdon	0·4	6·9	0·7	2·0	2·5	5
Pembroke Dock	0·4	4·8	0·2	1·4	1·4	7
Renfrew	0·4	4·0	0·1	1·1	1·1	8
Mildenhall	1·5	12·9	1·9	4·1	4·1	1
Driffield	0·4	5·5	0·6	1·6	1·7	6
Lympne	0·6	7·5	0·9	2·3	3·2	4
Boscombe Down	0·9	10·1	0·8	3·0	3·8	3
Aldergrove	0·2	3·4	0·1	0·9	1·1	9
Turnhouse	0·1	2·0	0·3	0·6	0·7	11
Kinloss	0·1	2·1	0·4	0·7	0·7	10

* Compensated for height of station. † Defined by actual percentage of year above temperature level.

Note : approximately 10 per cent = 220 hours/season
= 900 hours/year

half the Croydon value, and southern England is markedly warmer than the north. As with Table III *(a)*, variation in percentages in spring is far greater than in summer, with autumn intermediate in this respect. Variability between seasons from place to place is interesting, with spring having only a slightly lower percentage of hours than autumn at Renfrew, but a far lower percentage at Pembroke Dock. Particularly interesting are the high percentages of hours at Mildenhall in East Anglia in this table, especially in spring and autumn.

Percentages of hours with temperatures above 70°F are, of course, far lower, and differences are much increased between inland areas in southern central and eastern England on the one hand and the coastal districts in the south-west and areas in the north on the other. Interestingly, Lympne continues warm, but although coastal, it is well above the sea (and probably not much affected by sea-breezes) and also not very distant from the continent so that the effects of warm south-easterly winds might be felt. The effect of the (now) cooling breezes from the sea over coastal south Wales can be seen at Pembroke Dock, and the place with the highest number of warm hours is East Anglia. The difference between Renfrew, for example, and Mildenhall, of about the same height above the sea, is illustrated by yearly totals of 100 hours and 370 hours respectively.

If the lower threshold for a particular agricultural activity (e.g. growth of an exotic plant, or the basic working temperature for a honey bee) is 50°F then Table III shows that differences in the overall percentages over the country are not very great, except perhaps in spring. A threshold of 60°F for the activity renders the effects of geographical control much more evident. The lowest totals are in the north and in both spring and autumn percentages are low in comparison with the more favoured southern areas. Districts near the south-west coast do not do as well with the 60°F threshold as with the 50°F level. It is probably not realistic to say much on the 70°F threshold, which heavily underlines geographical effects.

Geographical variability of accumulated temperatures. Regions defined by the *Monthly Weather Report* were taken for this analysis, and five areas were considered at first :

Region 4 The Midlands (from Yorkshire down to Oxfordshire).
Region 5 South-east England (Wiltshire/Hampshire and eastwards south of the Thames).
Region 8*(a)* South-west England and Wales (southern half of Wales, and Somerset/Dorset and counties to the south-west).
Region 2 North-east England (eastern counties from Lincolnshire northwards).
Region 1 Eastern Scotland (eastern half of Scotland south of Moray Firth).

Regional average temperatures for 1931–60 were taken as standard, and accumulated temperatures were calculated by Thom's method, using monthly average temperatures and their standard deviations (quoted by Shellard[5]). A reasonably accurate assessment of accumulated temperatures is gained, but not, of course, giving exactly the same figures as would consideration of maximum and minimum daily values.

Differences between the first three regions proved slight (the south-west containing a substantial inland area to set against coastal effects) and central and southern England and Wales were therefore considered as a whole, combining regions 4, 5 and 8*(a)*. Accumulated temperatures above the conventional level of 42°F, and also above 50°F and 60°F were derived.

Height of ground was taken into account by allowing a 1 degF fall per 300 ft of height, and by computing values of accumulated temperatures for 600 ft and 1200 ft in each of the three areas. Table IV*(a)*, *(b)* and *(c)* shows average accumulated temperatures for these three areas for sea level (any possible effect of sea-breezes, etc. being ignored), 600 ft and 1200 ft, with the three different temperature bases of 42°F, 50°F and 60°F. Accumulated temperatures are given in Fahrenheit degree days. If comparable Celsius temperatures had been used the values in the table should be multiplied by 5/9 to obtain Celsius degree days.

TABLE IV—AVERAGE VALUES OF ACCUMULATED TEMPERATURE ABOVE 42°F, 50°F AND 60°F FOR CENTRAL ENGLAND, NORTH-EAST ENGLAND AND EAST SCOTLAND AT SEA LEVEL, 600 ft AND 1200 ft

Month/ season	Sea level			600 ft			1200 ft		
	C. Eng.	NE. Eng.	E. Scot.	C. Eng.	NE. Eng.	E. Scot.	C. Eng.	NE. Eng.	E. Scot.
				Fahrenheit degree days					
(a) Above 42°F									
March	100	95	95	65	65	65	40	40	40
April	195	155	115	145	115	85	105	80	55
May	345	280	235	285	220	175	220	160	125
Spring	640	530	445	495	400	325	365	280	220
June	495	440	385	435	380	325	375	320	280
July	605	570	500	545	510	440	480	445	380
August	605	550	480	545	490	420	480	430	375
Summer	1705	1560	1365	1525	1380	1185	1335	1195	1035
Spring and summer	2345	2090	1810	2020	1780	1510	1700	1475	1255
(b) Above 50°F									
March	10	15	15	0	0	0	0	0	0
April	45	35	15	10	15	0	0	0	0
May	120	85	45	80	55	20	50	30	5
Spring	175	135	75	90	70	20	50	30	5
June	260	210	155	205	160	115	150	105	75
July	355	320	250	295	260	190	240	205	140
August	355	305	225	295	245	165	240	195	115
Summer	970	835	630	795	665	470	630	505	330
Spring and summer	1145	970	705	885	735	490	680	535	335
(c) Above 60°F									
Spring	0	0	0	0	0	0	0	0	0
June	40	25	10	20	10	0	5	0	0
July	100	70	35	65	40	15	40	20	0
August	95	65	25	60	40	5	35	20	0
Spring and summer	235	160	70	145	90	20	80	40	0

Table IV*(a)* shows that approximately the same total temperature is accumulated above 42°F at sea level in spring and summer in Scotland as at 600 ft in north-east England and at 1200 ft in central England, but that in Scotland height effects are rather more important than geography. Roughly, the total spring and summer accumulation is 30 per cent more in central England than in Scotland (but in spring, accumulation is over 40 per cent).

Totals at sea level in central England for accumulation above 50°F are just about half those above 42°F but otherwise the fractions are less than half, and in Scotland at 1200 ft, for example, the accumulation of temperatures above 50°F is just about a quarter of that above 42°F. It is interesting to consider these figures in relation to the duration of temperatures above 50°F. The percentage time above 50°F (Table III *(a)*) did not vary nearly as widely as the accumulated temperature totals, but there were distinctly lower percentages in the east of Scotland, and also in north-east England.

An important point is that the Scottish curve of diurnal variation of temperature is distinctly flatter than the English, and as Table III *(b)* showed, the duration of temperatures above 60°F was much lower in east Scotland than in southern or central England, with northern England intermediate. This is brought out in the (probably unrealistic) accumulation of temperatures above 60°F. The spring contribution is negligible, but in summer at sea level in central England the accumulation is 13 per cent of that above 42°F. Percentages are much lower elsewhere and at other heights — 4 per cent in eastern Scotland at the surface for example, and 7 per cent in north-east England at 600 ft. There is apparently practically no accumulation at all at 1200 ft in east Scotland.

In short, the quantity of heat (as rather inadequately reflected by heat sums) enjoyed in southern and central England is considerably higher than in northern England, and still more so than in eastern Scotland. This difference increases as the base temperature is increased, as higher ground is considered, and also, though less obviously, away from high summer; this effect is probably greater than it seems, as Thom's method tends to be less accurate with marginal figures.

Variability of accumulated temperatures from year to year. Seasonal totals of accumulated temperatures above 42°F have been established for two very contrasting localities: Gulval, Cornwall (50°N 5½°W, 50 ft), and Rothamsted, Herts. (52°N ½°W, 420 ft). Table V shows their variability over 18 years (1931–48) for the various seasons (Smith[6]).

TABLE V—AVERAGE, MAXIMUM AND MINIMUM ACCUMULATED TEMPERATURES ABOVE 42°F FOR ROTHAMSTED AND GULVAL

Station	Characteristic	Spring	Summer	Autumn	Winter
			Fahrenheit degree days		
Rothamsted	Average	594	1656	787	123
	Highest	814	1931	956	238
	Lowest	362	1452	647	44
	Range	452	479	309	194
	Range as per cent of mean	76·1	28·9	39·3	157·7
Gulval	Average	739	1676	1075	364
	Highest	890	1844	1289	454
	Lowest	548	1447	919	253
	Range	342	397	370	201
	Range as per cent of mean	46·3	23·7	34·4	55·2

The range as a percentage of the mean shows the greater variability inland at all seasons. In spring the frequency with which the highest Rothamsted reading exceeds the Gulval average is clearly not high, and in autumn the highest Rothamsted figure is not much greater than the Gulval lowest; in winter, the highest Rothamsted total recorded in the 18-year period is distinctly below the lowest Gulval figure. In summer, by contrast, differences are on the whole slight and, if fine and hot, Rothamsted figures can be considerably in excess of those at Gulval. Interestingly, highest values of accumulated temperature by no means always occur in the same years; in 1948 Rothamsted's highest spring value of 814 coincided with a not excessively high figure of 808 at Gulval.

In conclusion, it is emphasized that the period of analysis is relatively short, and lower totals for both Gulval and Rothamsted might be appropriate in spring and summer at least on many occasions a hundred or so years ago. If the base temperature had been taken as 50°F instead of 42°F, differences in spring, autumn and winter would have been greater, but the figures for summer would almost certainly have been reversed with higher accumulations in the Midlands than in the south-west.

Conclusions.

(i) A strong suggestion exists that in the south-east and probably also in most other parts of Great Britain, springs and summers used to be cooler many years ago, and that, in particular, warm summers were commoner in the 1930s and 1940s than before or since. Spring and summer temperatures have been far less cold since about 1930 than during the period 50 to 100 years earlier.

(ii) The percentage of hours with temperatures above 50°F varies over the United Kingdom, with distinctly smaller percentages in east Scotland and Northern Ireland than elsewhere, especially in spring. Factors like proximity to the sea and height are of considerable importance. A temperature base of 60°F greatly magnifies differences, inland southern districts being markedly warmer than other areas.

(iii) Heat accumulation above various temperature levels is considerably greater in central and southern England than in north-east England and in east Scotland, and differences are accentuated if higher ground is considered, and if the temperature base is lifted from 42°F to 50°F and especially to 60°F.

(iv) In summer, differences in accumulated temperatures above 42°F are slight between two very different places, Cornwall and the south-east Midlands, but over most of the year the south-west enjoys much higher totals of accumulated temperature. Variability is much greater away from the sea.

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REFERENCES

1. BRAZELL, J. H.; London weather. London, HMSO, 1967.
2. HURST, G. W.; Honey production and summer temperatures. *Met. Mag., London*, **96**, 1967, p. 116.
3. MANLEY, G.; The mean temperatures of Central England, 1698–1952. *Q. Jnl R. met. Soc., London*, **79**, 1953, p. 242.
4. MURRAY, R.; Persistence in monthly mean temperature in central England. *Met. Mag., London*, **96**, 1967, p. 356.
5. SHELLARD, H. C.; Averages of accumulated temperature and standard deviation of monthly mean temperature over Britain, 1921–50. *Prof. Notes met. Off., London*, No. 125, 1959.
6. SMITH, L. P.; Farming weather. London, Nelson, 1958, p. 109.

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A SHORT INVESTIGATION INTO THE RELATIONSHIP BETWEEN THE DURATION OF SUNSHINE AND TOTAL CLOUD AMOUNT

By F. B. WEBSTER

Introduction. If the percentage of sunshine expressed in terms of the possible duration and the mean cloudiness (as a percentage of complete cloud cover) over the same period are added together, the result is more than 100 per cent for most months of the year. Table I illustrates this for Valentia.[1]

TABLE I—SUNSHINE AND CLOUDINESS AT VALENTIA, 1881–1915

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
							per cent						
Sunshine	19	25	33	39	41	38	32	34	35	30	24	17	31
Cloudiness	77	76	72	68	68	71	77	73	70	72	74	78	73
Sunshine + cloudiness	96	101	105	107	109	109	109	107	105	102	98	95	104

The reason lies, in part, in the limitations of the Campbell-Stokes sunshine recorder which is not a perfect inverse recorder of cloud. Sometimes the cloud is too thin or the amount too small to prevent the sun from burning the card. During short alternating periods of sunshine and shade (such as occur when cumulus cloud is present) the burns on the recorder trace run together, giving an apparent increase in the sunshine. On the other hand, when the sun shines only through small breaks in the cloud and is mostly obscured, the observer may see relatively large areas of blue sky elsewhere and will report a mean cloudiness which is less than the mean cloudiness suggested by the sunshine recorder. In winter when the sun is low, it may fail to burn the card and, as the proportion of low sun to total daylight is greatest in these months, the discrepancy may be quite large. C. E. P. Brooks[1] made a study of the problem and produced a formula for estimating sunshine in those areas of the world where there were no sunshine recorders but where comprehensive observations of cloud were available.

The purpose of the investigation described in the present paper was to see what relationship could be established between the reported total cloud amount and type and the duration of sunshine, so as to help forecasters in describing the character of the day to the general public.

Cloud amount and sunshine. The data used were the observations from Mildenhall for the summer half of the years 1961 and 1966. The summer months were used because the public in general is more interested in them, and because of the difficulty in the winter months of the records being affected by a low sun failing to burn the card. The two years used were chosen completely at random and, apart from both having rather less sunny Aprils than usual, were unremarkable from the sunshine point of view.

The hours studied were those between which the public is likely to be most interested : 0900 and 1800 GMT. The hours were, however, curtailed in the earlier and later months, so that sunset was at least one and a half hours after the last observation used, and the complication of a low sun was avoided. The actual hours used were :

0900 to 1600 GMT	April and September
0900 to 1700 GMT	1–20 May, 21–31 August
0900 to 1800 GMT	All other occasions

This gave a total of 2992 observations.

The method used was to plot the hourly recorded sunshine against the mean cloudiness for that hour. The mean cloudiness for the hour 0900–1000 GMT was arbitrarily defined as the mean of the total cloud amount reported at the two observations at 0900 and 1000, and similarly for all other hours of the day. A trace and 7+ oktas were taken as one okta and 7 oktas respectively. A mean which included a half okta was thrown to the odd.

At first sight the method used for estimating the mean cloudiness of an hour is not particularly accurate; a number of situations can be envisaged when it might be completely misleading. In practice, however, it seemed to work quite well and the scatter in the subsequent tables was less than might have been expected.

The fact that Mildenhall is an inland station in an almost featureless terrain means that complications which might occur in certain situations at coastal or mountain stations would not be present.

Table II shows the average sunshine in minutes recorded for the various values of mean hourly cloudiness. It would not be unreasonable to describe any hour in which the sun shone for 45 minutes or more as sunny. On this basis, Table II shows that hours having a mean cloudiness of up to 5/8 would be regarded as sunny. It can also be seen that the major reduction in sunshine seems to lie between 6/8 and 7/8.

TABLE II—AVERAGE SUNSHINE ASSOCIATED WITH VARIOUS VALUES OF MEAN HOURLY CLOUDINESS, APRIL–SEPTEMBER IN 1961 AND 1966

Mean hourly cloudiness	0	1/8	2/8	3/8	4/8	5/8	6/8	7/8	8/8
Average sunshine (recorded in minutes)	60	59	59	57	54	49	40	19	1

Figure 1 shows the percentage occurrences of various periods of sunshine when cloud amounts were 0–2/8 (Beaufort letter b), 3/8–5/8 (Beaufort letter bc), 6/8–7/8, and 8/8. In the partly cloudy ranges (3/8–5/8) there was no sunshine on less than 1 per cent of occasions, and less than 0·4 of an hour was recorded on only 5 per cent of occasions. On the other hand, 0·8 h or more was recorded

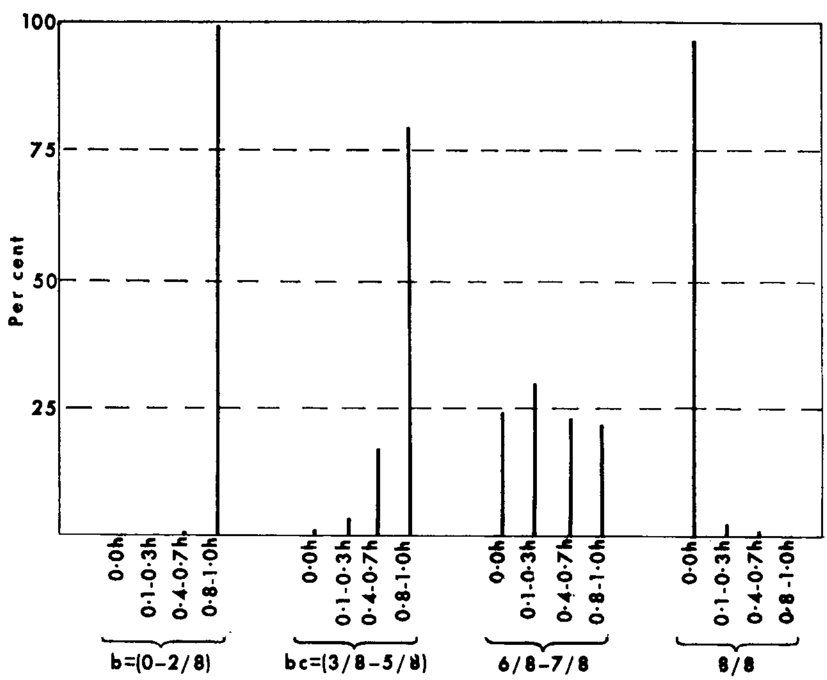

FIGURE 1—PERCENTAGE OCCURRENCE OF VARIOUS PERIODS OF SUNSHINE WHEN CLOUD AMOUNTS WERE 0–2/8, 3/8–5/8, 6/8–7/8, AND 8/8

on nearly 80 per cent of the occasions investigated. Hours with a mean cloudiness of 6/8 to 7/8 were more or less evenly divided. On 25 per cent of the occasions no sunshine was recorded; less than 0·4 h was recorded on 55 per cent of occasions, but 0·8 h or more was recorded 21 per cent of the time. It was thought that this wide variation in the sunshine recorded was probably due more to the type of cloud obscuring the sun than to any random variations in the cloud cover between two observations.

Cloud type and sunshine. In order to see what effect different types of cloud had on the sunshine recorded, the mean cloudiness calculated as above was ascribed arbitrarily to the predominating type of cloud. The following criteria were used to decide which of the various cloud types reported contributed most to the obscuration of the sun :

(i) Only those cloud groups included in a synoptic observation and which would be plotted on a chart were used, i.e. clouds belonging to the types specified for the code groups[2] for low-level cloud (C_L), middle-level cloud (C_M) and high-level cloud (C_H) as described by the World Meteorological Organization (WMO).

(ii) That type of cloud having the largest reported amount was judged to contribute most to the obscuration of the sun and was designated as the 'main' type. If the same type was reported at different levels, the individual amounts were added together to obtain the total amount for that type. It was accepted that on the few occasions when this method was used, the total amount for the type could be greater than that which actually occurred.

(iii) If two different types had the same reported amount, the lower cloud was taken as the main type.

(iv) If the main type changed from one observation to the next, the main type in the later observation was used, unless the cloud decreased to nil, when the last main type was used.

The clouds were classified into broad classes as follows :

A	Convective low cloud	WMO types C_L 1, 2, 3 and 9
B	Stratiform low cloud	WMO types C_L 4, 5, 6 and 7
C	Middle-level cloud	All WMO types C_M
D	High-level cloud	All WMO types C_H

WMO type C_L 8 was regarded as class *A* or *B* depending on whether the cumulus or stratocumulus predominated according to the criteria (i) to (iv) stated above. Fog was regarded as class *B* when it was thick enough to obscure the sky, but was disregarded otherwise. Sky obscured was counted as eight oktas in calculating the mean cloudiness.

For a mean cloudiness of up to 4/8 there was little difference between the various classes, and the amounts of sunshine corresponded fairly closely to the values given in Table II. The few occasions of sunshine that occurred with a mean cloudiness of 8/8 were equally distributed between all classes. The most, 0·6 h, was recorded when class *D* (cirriform cloud) predominated. Figure 2 shows the average sunshine recorded for the four classes with a mean hourly cloudiness of 5/8, 6/8, 7/8. It is evident that, for the same mean cloudiness, more sunshine occurred with classes *A* and *D* than with classes *B* and *C*.

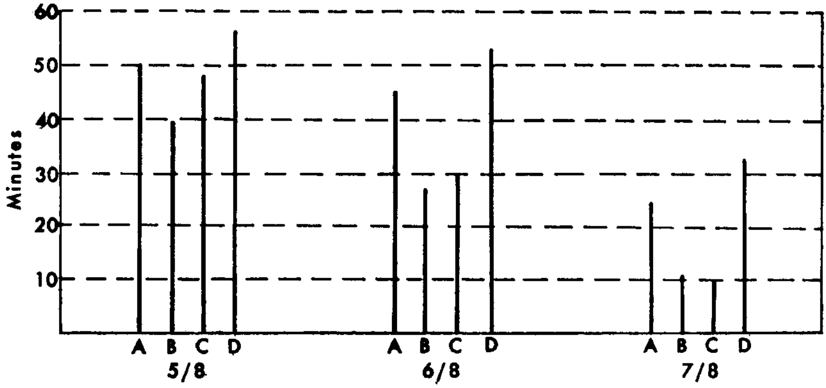

FIGURE 2—AVERAGE HOURLY DURATION OF SUNSHINE RECORDED FOR FOUR CLASSES OF CLOUD COVER WITH A MEAN HOURLY CLOUDINESS OF 5/8, 6/8 AND 7/8

Moreover, for classes *B* and *C* the sum of the percentage cloud amount and the percentage sunshine is rather nearer 100 per cent (only slightly over 100 per cent for a mean cloudiness of 7/8) than is the case for classes *A* and *D*.

There are a number of possible reasons for the greater amounts of sunshine with classes *A* and *D*, but the amount for class *D* (cirriform cloud) is perhaps not unexpected. This cloud is usually dense only in patches and it is normally only during the transition of cirrostratus into altostratus that it becomes thick enough to obscure the sun to any extent. The reason for the amount of sunshine for class *A* is not quite so clear. It is surprising to find that an almost total cover of basically cumuliform cloud gives, on average, such a significant amount of sunshine. Apart from the difficulties of measuring by the Campbell-Stokes recorder the short bursts of sunshine which are a feature of cumulus skies, the probable reason for the increase in sunshine recorded with this class of cloud is that the method of estimating total cloud cover allows the sides of cumulus clouds, especially those towards the horizon, to contribute as much or more to the final estimate than the actual base. It is, of course, the amount of cloud in the immediate direction of the sun which affects the sunshine received.

In view of the almost complete absence of sunshine when the mean cloudiness was 8/8 there was a suspicion, when compiling the results, that if 7+ oktas had been taken as 8/8, instead of as 7/8, the average sunshine for a mean cloudiness of 7/8 would have been even higher than it was. It seemed that with any significant breaks at all some sunshine was likely. It was noticed, too, on many occasions that whenever a large total cloud amount was made up of several small cloud masses at different levels there was usually a significant amount of sunshine recorded.

Discussion. This investigation treats only part of a large and complex problem. The total amount of cloud is not the only factor which decides the amount of sunshine received at any one place. There is no simple relationship between breaks in a cloud mass and the resultant sunshine. An important factor is the position of frequently occurring cloud formations in relation to the sun and the observing station, e.g. cloud formations confined to the land in the afternoon will not interfere with sunshine at a station on a south-facing coastline, but will decrease the sunshine received on a north-facing coastline. High ground near a station may also affect the local relationship between cloud and sunshine. Nevertheless it is suggested that this investigation of the relationship between cloud and sunshine at Mildenhall may serve as a general guide for meteorologists forecasting for an inland area in flat surroundings.

REFERENCES

1. BROOKS, C. E. P.; The relation between the duration of bright sunshine registered by a Campbell-Stokes sunshine recorder and the estimated amount of cloud. *Prof. Notes met. Off., London*, No. 53, 1929.
2. London, Meteorological Office. Cloud types for observers. London, HMSO, 1962.

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A FURTHER NOTE ON THE HEAVY RAINFALL OF 10 JULY 1968

By P. R. S. SALTER

Introduction. In a previous article by Salter[1] on the rainfall of 10 July 1968 an approximate rainfall map was indicated in Figure 1. It should be pointed out that the isohyets in that diagram were drawn according to the observations available on a day-to-day basis from the relatively sparse network of synoptic stations. These were the only rainfall data available to the author at the time of writing the original article. A detailed rainfall map for the rainfall of the 24 hours ending 0900 GMT on 11 July 1968, based on the observations from the dense network of rainfall stations, is now submitted.

The rainfall. The accompanying diagram illustrates the total rainfall for the 24 hours ending 0900 GMT, 11 July 1968, for south-west and central England. Falls of 100 mm or more occurred in several areas of England and helped to create flood conditions from the rivers draining these particular areas.

The first region was an area high up in the Quantock Hills (Somerset) just east of Crowcombe which is itself over 400 ft above MSL. A second region was the small area between Stanton Harcourt (Oxford) and Cumnor (Berks.) on either side of the River Thames. Another part which received at least 100 mm was a narrow strip from Shipston-on-Stour (Warwick) to Dowdeswell (Gloucester) which is about 4 miles east of Cheltenham. This strip showed that there the heaviest rainfall occurred on the north-west side of the Cotswolds. Also receiving 100 mm was the area of Lincolnshire west of Alford enclosing South Thoresby and Old Bolingbroke.

Two further areas of high rainfall remained to be noted. In the Peterborough area 100 mm fell in a zone from near Raunds (Northants.) to just south of Fosdyke (Lincs.) and there was a very narrow strip which had over 125 mm between Fletton and Whittlesey extending for several miles to the north-east and to the south-west. Severe flooding occurred south of Peterborough in the Alconbury villages of Huntingdonshire.

The final area to be mentioned may be described as a 'super rainfall' area consisting of parts of Wiltshire, Gloucestershire, Somerset and Devonshire. There the 100-mm isohyet extended from Malmesbury (Wilts.) to Bristol and eastwards to include Bath and southwards to Upottery (Devon). Within this area the maximum rainfall was on the hill-sides of the Chew valley where a

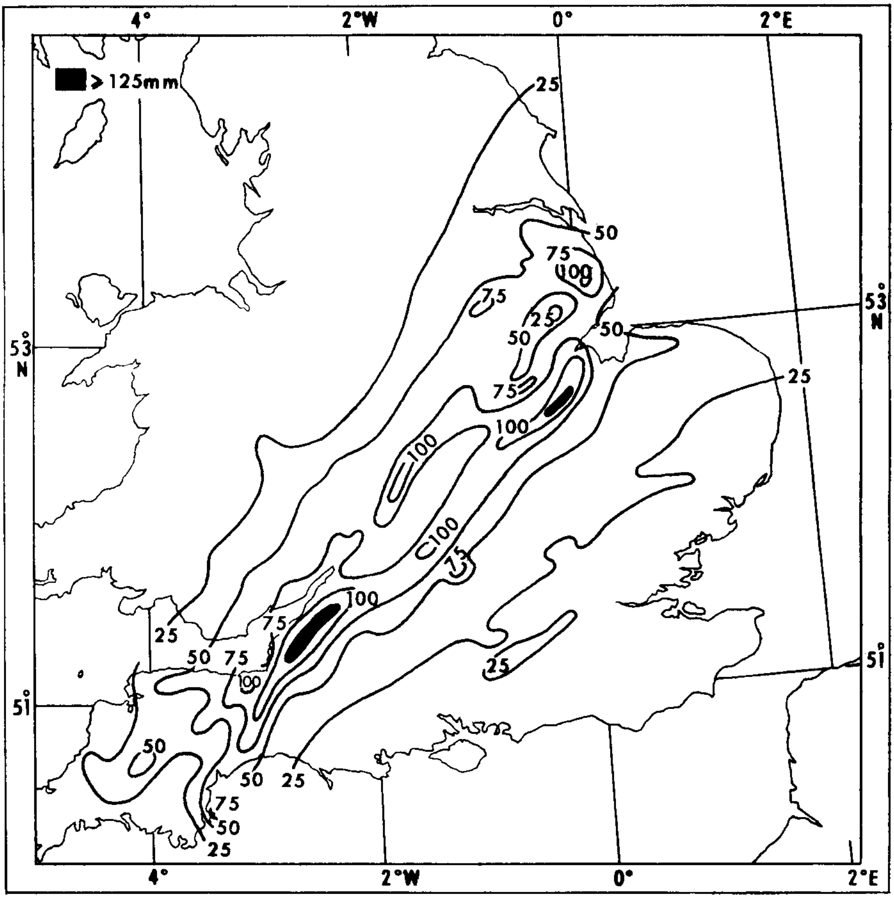

FIGURE I—RAINFALL FOR 24 HOURS ENDING 0900 GMT, 11 JULY 1968

Isopleths at 25-mm intervals

total greater than 175 mm was recorded in 24 hours. The River Chew flows from the north-east side of the Mendip Hills and joins the Bristol Avon on the north-east side of Keynsham. The exceedingly heavy rainfall in the Chew valley led very quickly to flood conditions which caused material destruction and loss of life downstream. The torrent of the River Chew helped to swell the River Avon and to flood parts of Bristol which was itself receiving heavy rainfall.

It should not be forgotten that parts of some south coast towns were flooded by substantial rainfall accompanying thunderstorms which developed near the south coast during the early hours of 10 July. Inconvenient and damaging as this was to the population there, the rainfall received was of a smaller magnitude than that which occurred in the region of the Chew Valley. In addition to the affected parts of the south coast, flooding and flood damage occurred in many towns and villages which received a rainfall substantially less than 100 mm.

It should be pointed out that this description of the heavy rainfall is intended to be brief since the object of the original article was to survey the synoptic events which led to the rain. Again the reader is reminded that the original rainfall map[1] was an approximate distribution based on reports from synoptic stations. The difference in that map, and the map of the present article, shows very clearly how much vital information is supplied by the rain-gauge network in assessing reasonably accurate rainfall distributions.

A full account of this heavy rainfall is being prepared for *British Rainfall 1968* in a study by Miss Pauline Gray.

Acknowledgements. The author is grateful to the Hydrology Branch of the Meteorological Office for kindly supplying the detailed rainfall map.

REFERENCE

1. SALTER, P. R. S.; An exceptionally heavy rainfall in July 1968. *Met. Mag., London*, 97, 1968, p. 372.

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INTERNATIONAL CONFERENCE ON CLOUD PHYSICS, TORONTO, AUGUST 1968

By J. C. DRAKE

Nearly 300 scientists attended the International Conference on Cloud Physics held at Toronto University in August. Tribute must be paid to Professor R. List, for the efficiency with which the arrangements for the conference were handled and for the organization of the social events which were thoroughly enjoyed by all. These included a reception given by the President of the University of Toronto, a banquet at Niagara Falls, sponsored by the Hydro-Electric Company of Ontario, and arrangements to attend rehearsals of the Canadian National Opera Company.

The business of the conference ranged from considering the importance of microscopic nuclei to the modification of weather on a continental scale. With such a broad field one might have expected a flood of new information and ideas, whereas in fact there were few papers that had not already appeared in the literature in one form or another. In all, about 150 contributions were submitted for the five working days, and in order to deal with this large volume of material an experimental format was introduced. The papers were divided into topics and each topic was introduced by a keynote paper that summarized present knowledge and development in the particular field. The individual papers were then surveyed by a series of lead speakers and followed by discussion from the conference floor.

This format led to severely cramped time schedules, leaving insufficient time for adequate discussion either in the body of the conference or in the 'corridors'. It is suggested that future conferences should select the material to be presented, even though this may mean breaking from the tradition that a published contribution is a ticket to attend.

Most notable among the presentations were the description of the University of California (Los Angeles) cloud tunnel with its high stability of flow that will enable investigations into water-drop problems without the use of mechanical supports, and the parametric method developed by E. K. Berry for the handling of cloud droplet growth problems. The Russian work on hail prevention was extremely impressive, but would have been even more convincing had they been less dogmatic in their statistics of success. The subject of electrification, one must conclude, is as confused as ever.

The overall impression generated by the conference is that the role of the one-man micro-physical experiment in the laboratory is rapidly diminishing, although often physically enlightening, and that much more rewarding advances in understanding weather will come through the effort now being put into the analysis of the real atmosphere.

OFFICIAL PUBLICATION

The following publication has recently been issued : *Averages of earth temperature at depths of 30 cm and 122 cm for the United Kingdom, 1931–60.*

The aim of this book is to provide earth temperature data for the use of workers in agriculture, horticulture, and the construction industries, and to aid research in climatology and other branches of geophysics. There are tables of averages and extremes of earth temperature at depths of 30 and 122 cm for many places in the United Kingdom. Monthly standard deviations and frequency tables of temperatures at a depth of 30 cm are also included for a number of places. Methods of measurement, site differences, diurnal and annual variation, variation with depth, snow and grass cover, notable winters and comparison with earlier averages are some of the subjects discussed and illustrated with diagrams. The tables are arranged in climatological districts to facilitate comparison but an alphabetical index and a map showing the position of places makes for ease of reference. Following modern practice, all figures quoted are in metric units but appropriate conversion tables are given in Appendices.

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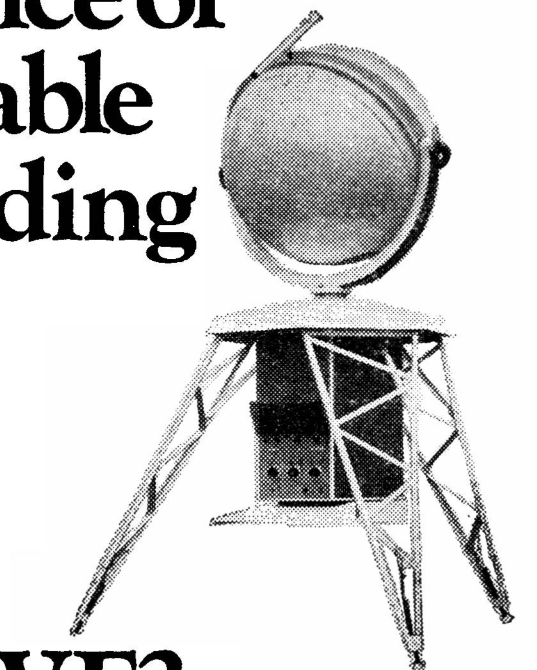

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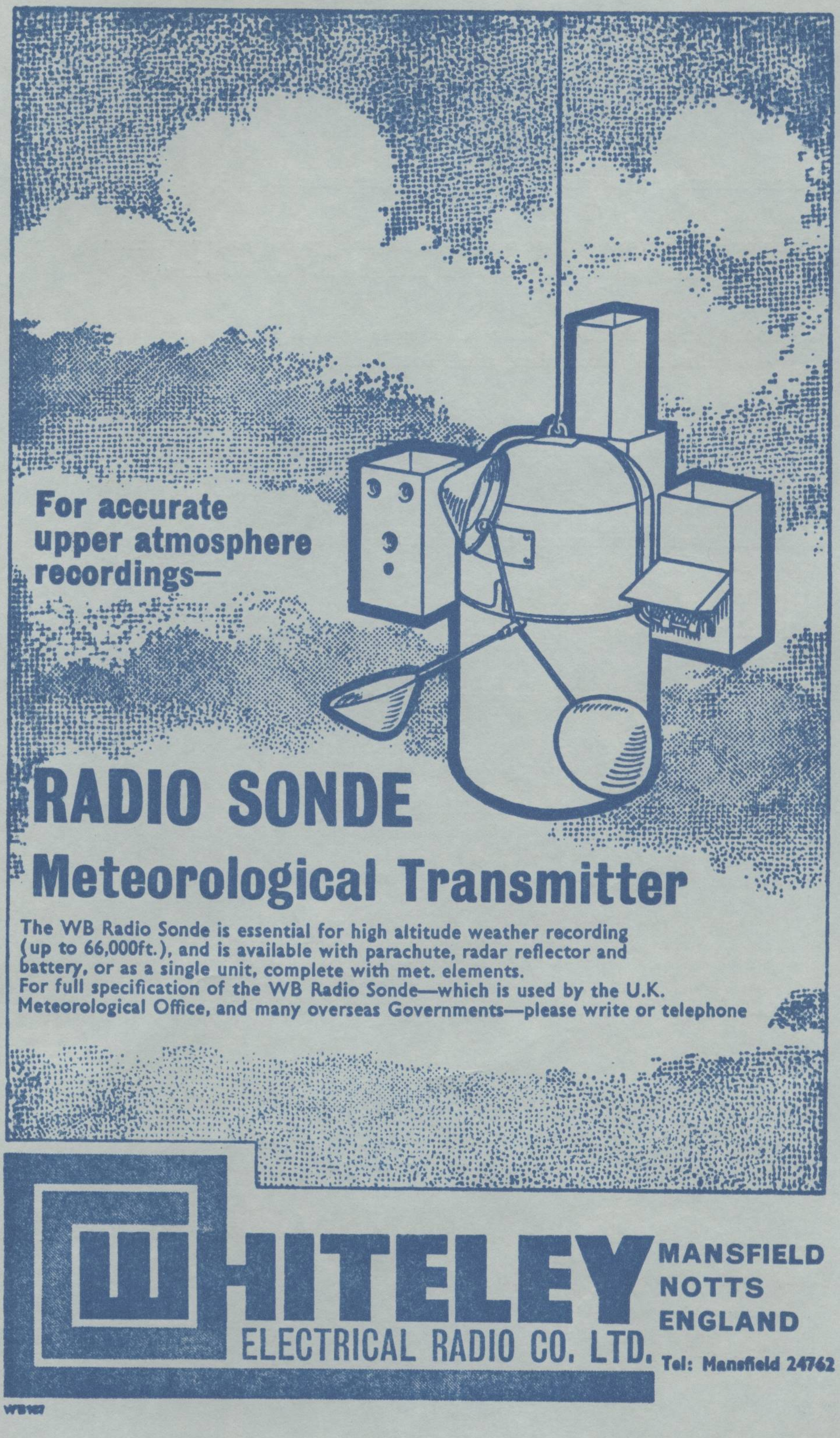
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