R. & M. No. 2737
(13,316)
A.R.C. Technical Report

MINISTRY OF SUPPLY

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1953
PRICE 10*s* 6*d* NET

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Communicated by the Principal Director of Scientific Research (Air), Ministry of Supply

*Reports and Memoranda No. 2737**

June, 1950

Summary.—The British European Airways Clear-Air Gust Research Unit was formed, with the financial support of the Ministry of Supply, to investigate the problem of clear-air turbulence at high altitude over Europe. The aircraft were based at Cranfield, Bedfordshire, and flights were made of roughly 1,000 miles radius from that base. In the two years of its existence, the two PR 34 *Mosquito* aircraft employed for the purpose covered 92,300 miles of research flying between the selected limits of 15,000 ft and 37,000 ft. Statistically speaking this is a very small sample and must be borne in mind when considering the results.

Some twenty areas of turbulence (defined as giving vertical acceleration increments greater than $\pm 0 \cdot 2g$) were actually investigated, the greatest vertical gust velocity encountered being $+ 26$ ft/sec E.A.S.

The results were examined from the passenger comfort and structural aspect, and from the meteorological aspect.

The main findings are :—

Structural/Passenger Comfort.

(a) Clear-air turbulence occurs in isolated patches of widely varying thickness and horizontal extent and at widely varying altitudes ; a representative example is 50 to 100 miles long by about 3,000 ft thick. It is characterised by the lack of warning of its presence and by its short sharp hammering nature resulting from the quick succession of positive and negative gusts.

(b) The probability of meeting a gust of a given magnitude is roughly the same at any height within the range covered.

(c) The probability of meeting a gust of moderate intensity in clear air at high altitude is roughly the same as in clear air or cloud at low or moderate altitudes. Severe gusts almost certainly occur much less frequently in clear air.

(d) Extrapolation of the data may be made with reasonable assurance to gust velocities of about 36 ft/sec E.A.S., when it would be necessary to fly, on average, about 10^6 miles to meet such a gust intensity.

(e) Severe gusts are met more often in thunderstorms (as given by the U.S. Thunderstorm Project), but heavy turbulence, by their standards, is sometimes encountered in clear air.

* British European Airways R.S.D. Report No. 15, received 22nd August, 1950.

Meteorological Aspects.

(a) Analysis of the possible causes pointed to the presence of marked wind gradient in the vertical as the most likely cause. An indirect method of checking this theory has yielded promising results, confirming that wind gradient in the vertical, or more precisely, the Richardson number, is of prime importance.

(b) Evidence exists which suggests that the worst turbulence is associated with jet streams, and that turbulence often occurs near the tropopause.

(c) No other simple factor, such as terrain, geographical location, absolute wind speed, was found to yield any consistent clue to the cause of turbulence.

Recommendations to Operators.—Certain recommendations can be made at this stage to operators and particularly aircrews, although much more information is needed to establish a sound forecasting basis. These are :—

(a) Avoid flying in areas where jet streams or high horizontal thermal gradients are known to exist.

(b) Avoid flying within 2,000ft of the Tropopause.

(c) If heavy turbulence is encountered assume one is entering a jet stream and

(i) climb or descend until turbulence is reduced

and/or

(ii) fly at right-angles to the local wind direction.

(d) Should it appear that wing oscillations are being excited by the turbulence, alter speed as much as possible.

The Unit has now been disbanded, but certain reporting procedures have been initiated whereby it is hoped that information from airline operators on turbulence encountered will become available for analysis. Such information will help to provide data concerning other areas of the globe, as the results given in the report were obtained over Western Europe and do not necessarily apply elsewhere.

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1. *Introduction.*—Until only a few years ago it was assumed that flight at high altitude would be smooth, that is to say only very rarely if ever, would turbulence be encountered which would impart vertical accelerations to aircraft. It is now known, however, from wartime experience and also from post-war civil experience, that severe turbulence of this type is sometimes encountered without visual warning in clear air at high altitudes. Clearly this would have repercussions on the use of fast high-flying aircraft for passenger operations, and it was proposed by Mr. N. E. Rowe of British European Airways that an investigation of this phenomenon should be made. Accordingly in December, 1947, a contract was awarded to B.E.A. by the Ministry of Supply to cover such research work.

The aims were :—

(i) To determine the probable frequency and extent of turbulent areas in clear air and the magnitude of the associated gust velocities.

(ii) To determine the causes and characteristics of this turbulence.

(iii) To provide a basis on which a forecasting system could be founded.

Such data would make possible a critical review of existing design requirements, as at present the gust cases are based on relatively few observations at high altitude. The emergence of a reliable forecasting system would enable a pilot to prepare his flight plan so as to avoid regions where clear-air turbulence might be encountered. It might also lead to changes in design intended to alleviate the effect of such turbulence, if the latter proved severe.

When the project was initiated, little was known about the problem and in order to obtain results with the minimum outlay, a small B.E.A. Gust Research Unit comprising two aircraft, one flying crew, and a resident scientist, were based at an existing airfield with full maintenance facilities. For the same reasons the instrumentation was made as simple as possible. The flights were planned to cover the European area, where the existing organisation of B.E.A. would simplify the preparation of overseas flights, as well as being an area in which future high-speed, high-flying aircraft would operate.

Research flying proper began in April, 1948, and continued until the project was terminated at the end of January, 1950. This report gives an account of the organisation, methods and results of the investigation.

2. *Equipment and Organisation.*—2.1. *Aircraft.*—Two PR Mk. 34 *Mosquito* aircraft with Merlin 114A engines were provided by the Ministry of Supply. The communications and navigation equipment was installed by the Telecommunications Research Establishment and the Royal Aircraft Establishment at Defford and Farnborough respectively, whence the aircraft

were flown to Cranfield for modification prior to the granting of a Certificate of Airworthiness in the Special Category. In the course of this work the belly tanks were removed and the 2 × 100 gal wing drop-tanks were fixed permanently to the wings. Spare supplies of coolant and hydraulic fluid were carried in 4 gal containers fitted in the rear fuselage, as was a pack of tools and spares for use at overseas stations. The normal take-off weight was 21,500 lb, including 739 gal of fuel.

2.2. *Base.*—The aircraft and crews were based at the College of Aeronautics, Cranfield, Bedfordshire, the Flight Department of the College being responsible to British European Airways for the overhaul, maintenance and servicing of the aircraft. Spares and most of the ground equipment were provided by the R.A.F. Maintenance Units, special arrangements having been made to this end.

2.3. *Crew.*—It was found possible to recruit fully experienced Mosquito pilots from within the Corporation, but for the radio officer/navigators, outside recruitment was necessary. Initially it had been thought that one crew would have been able to deal with the 500 to 600 hr per annum which it was thought could be achieved with two aircraft. However, it became clear in the summer of 1948, when the rate of about 50 hr per month was reached for a short period, that the strain of this kind of flying was greater than imagined. The precise flying called for, the necessity to breathe oxygen for long periods, and the low pressure to which the body was exposed, coupled with the rather marginal stability characteristics of the *Mosquito,* especially at high altitude, all threw a great burden on the pilot. As no automatic pilot is fitted to *Mosquito* aircraft he could not even be released from the task of actual flying during any part of the flight. The navigator-cum-radio operator was called upon to navigate the aircraft to a most difficult flight plan which often involved wide changes in wind speed and direction with the progressive variation in height (see section 3 of this report). As GEE cover was available for only about half of each overseas voyage, great care and attention had to be given to DR navigation. In addition he had to interrupt his navigation and radio work to observe the ambient air temperature at frequent intervals. All these factors made the crew's task a very heavy one from both the physical and psychological aspects.

As a result of the pilot's illness during the winter of 1948/49 a second crew was recruited, and when it became fully operational in May, 1949, the improvement was very marked. The restriction on flying rate then switched to the aircraft, and it was very obvious that a third aircraft was really necessary to maintain a steady flying rate in face of the frequent periodic inspections, random defects, and the flow of modifications to which this type of aircraft is subject.

2.4. *Instruments.*—The fairly common technique of using the aircraft to carry recording accelerometers, the results from which are converted to the corresponding vertical gust velocities, was employed in this project. No attempt was made to measure horizontal gust velocities.

(a) The main recording accelerometer was a Peravia type XR 144. This instrument is clockwork driven and remotely controlled by electrical means. The movement of a spring-suspended mass, having a natural frequency of about 12 c.p.s. is recorded on a moving paper strip set to run at 2mm per sec. The record is obtained in the form of a series of tiny punches on waxed paper, the rate of punching being 10 per sec whilst the running time is approximately 40 min.

The acceleration range is from $+ 10g$ to $- 4g$ with a total pointer movement of 10 cm approx. A more limited range of acceleration with greater sensitivity would have been desirable, but this would have entailed a natural frequency near the wing fundamental and consequent difficulties with resonance. The damping is about 40 per cent of critical.

The running speed is too slow to show the rate of change of acceleration with time accurately and the main value of the instrument is to enable a count of peak accelerations to be made. No trouble was encountered with the two instruments of this type which were employed throughout the two years of operation.

(b) A Barnes type B recording accelerometer was provided by the R.A.E. Farnborough in order to give data concerning the rate of build-up of accelerations, as this could not be obtained satisfactorily from the Peravia instrument. However, continual trouble was experienced with the Barnes instrument which was finally replaced by a newer version of the same basic type; *viz.* :—IT 4/3. This instrument although much better than the type B was not altogether free of trouble, and the result was that few useful records were actually obtained.

(c) A Hathaway V-*g* recorder was installed at the request of R.A.E. Farnborough, and all the records from this instrument were dealt with by the R.A.E. No data derived from the V-*g* recorder have been used in the analyses contained in this report.

(d) The ambient air temperature was measured on a Meteorological Office Balanced Bridge Thermometer, Mk. Ib, which is reliable and accurate to $\frac{1}{2}$ deg C.

(e) Kent flowmeters of the 'gallons gone' type were fitted to give a reliable indication of the fuel available at any stage of a flight ; the data provided also enabled the wing loading at any time to be determined with reasonable accuracy.

The recording accelerometers were under the control of the pilot, who also noted the fuel consumed, whilst the navigator/radio operator was responsible for taking the necessary readings of air temperature.

2.5. *Radio.*—To permit full freedom of operation over Europe the following radio and radar navigation and communication equipment was installed :—

(a) VHF, type TR.1430.
(b) HF, type SCR.274N.
(c) Beam Approach, type R.1598/1599.
(d) GEE Mk II, type ARI.5083.
(e) ADF, type Marconi AD.7092.
(f) Intercommunication, Bendix 3611B.

The ADF equipment was not fitted until mid-1949, but there was no doubt that it was of the greatest assistance, especially when the aircraft was outside GEE cover, as was usual for approximately half the distance on each overseas flight.

2.6. *Customs.*—For the first year or so the normal procedure was for the aircraft, when on outward flight to an overseas station, to take off from Cranfield and land at London Airport to clear Customs. This step necessitated refuelling at London Airport as, owing to a restriction on the landing weight of *Mosquito* aircraft, full fuel could not be taken on at Cranfield. Also the overseas flight plan had to be prepared and cleared at London. A somewhat similar procedure had to be followed on return trips. The necessity of having to pass through London Airport threw a considerable strain on the crew as there was frequently a rush to get through all the necessary procedures in a reasonable time. Furthermore, having to enter the Metropolitan Control Zone at all always led to delay, especially under IFR conditions. These difficulties undoubtedly contributed to the ill-health of the pilot practically throughout the first winter, after a period of strenuous operation in the summer before. After representations had been made through the Ministry of Civil Aviation the Customs and Excise authorities provided from March, 1949, 'on call' Customs facilities at Cranfield. This arrangement worked very well and eased the strain on the crews immensely, and certainly contributed materially to the success of the project.

2.7. *Meteorological Arrangements.*—Arrangements were made with the Air Ministry to have special high-altitude forecasts supplied to the Cranfield Meteorological Office for the *Mosquito* flights. The forecasts were supplied by R.A.F. 47 Group and the arrangements proved highly satisfactory. At a later stage, jet streams were forecast by the Central Forecasting Establishment, Dunstable, and the information passed on to Cranfield via 47 Group. Such forecasts at this stage are necessarily somewhat tentative, but they nevertheless attained a considerable degree of success.

2.8. *Flying Effort.*—During the twenty-five months from January, 1948, to January, 1950, inclusive, a total of 680 hr was flown by the aircraft. Of this time some 124 hr were on test flying, positioning flights, etc. The test flying included the determination of the Position Error Correction, and the compressibility correction to the thermometer for forward speed. The accuracy of wind-finding using GEE was also checked against the radio-sonde winds. While adequate from the navigational point of view, such methods are not accurate enough to give the rate of change of wind with height. The remaining 556 hr were spent on gust research work proper, and have been termed ' voyage hours, ' (each research flight was termed a voyage). A few voyages were rendered abortive or partly so, by defects occurring whilst airborne (*e.g.*, four complete engine failures took place). The voyage times quoted are ' chock to chock ' time so that the actual time flown above the lowest altitude at which observations were made totalled approximately 320 hr. The corresponding distance flown has been determined from the navigational log and is 92,300 miles. The flying rate per month varied considerably owing to the small size of the Unit, the nature of the work, and the rather temperamental type of aircraft employed. Figs. 1 and 2 show clearly how the effort varied and especially the marked improvement due to the second crew becoming operational in May, 1949. The effect of having too small a Unit is also obvious from the erratic nature of the flying rate. Table 1 gives basic details of each voyage.

The approximate track of all voyages is given in Fig. 3, which also shows the approximate centre of each turbulent area encountered. Overseas flights were made to Lisbon, Gibraltar, Rome, Stockholm, etc., and one trip was made to Iceland where the necessary arrangements were made by British Overseas Airways Corporation.

It was necessary to seek permission from the various foreign Governments concerned to fly over their territories. The approach was made by the Ministry of Civil Aviation and it is a pleasure to be able to record that not only was this permission given, but in every case special meteorological and other facilities were made available.

3. *Flight Technique.*—3.1. At the outset so little was known about this phenomenon of clear-air turbulence—except for a vague suggestion that it might be found near the tropopause—that the programme was based on making as many sampling flights as possible over the European area. The destinations were chosen so as to cover a wide variety of terrain and weather conditions, whilst the flight plan adopted as a general routine was such as to give the maximum chance of finding any turbulence existing over the chosen route. This flight plan was of a sawtooth pattern in that the aircraft took off, climbed to about 37,000 ft, descended to 20,000 ft, climbed to 37,000 ft, and descended to 20,000 ft and so on until the destination was reached. Usually three such ' sawteeth ' would be flown on an overseas flight of normal length.

3.2. By running the Peravia accelerometer for about one minute and observing the air temperature each time the aircraft passed through 20,000 ft, 25,000 ft, 30,000 ft, etc., a sample of the state of the atmosphere at those heights was obtained. On encountering turbulence (defined as giving accelerations of at least $\pm 0{\cdot}2g$ from the $+1g$ datum) the sawtooth pattern was abandoned, and a search instituted. Turbulent areas giving bumps less than $\pm 0{\cdot}2g$ were not investigated, as they were considered of minor importance in civil aviation, and also because investigation of the more frequent cases of lower accelerations would probably have been done at the expense of the more important areas with greater turbulence.

A search consisted of determining :—

(a) The thickness of the turbulent layer.

(b) The temperature lapse rate for some thousands of feet above, through and below the layer.

(c) A sample of the turbulence in the layer.

(d) The approximate horizontal extent of the layer.

(e) The temperature gradient in the horizontal (added September, 1949—*see* section 6.3).

Partly for operational reasons and partly to increase the range of altitude covered, the upper and lower limits of the sawtooth flight plan were altered in April, 1949, to 35,000 ft and 15,000 ft respectively.

3.3. In general the flight technique proved very satisfactory, and good results attended its use, twenty cases of clear-air turbulence having been found on nineteen voyages during the period. Basic details of these ' positive ' results are given in Table 2.

4. *Results—General Comments.*—4.1. The results fell into two broad categories, *viz.*:—

(a) *Statistical* measurement of accelerations and hence analysis of gust frequencies.

(b) *Meteorological* determination of local conditions and analysis of general weather situation.

Results in the first category were derived entirely from the data obtained on each flight in the form of accelerometer recordings, and related observations of speed, height, fuel consumed, etc. On the other hand the meteorological observations from a flight consisted mainly of the temperature lapse rate and the dimensions of a given turbulent layer, coupled with general remarks from the pilot on the prevailing meteorological conditions. Subsequently more detailed information on the weather situation, upper air data, etc., became available from the Daily Weather Reports of the Meteorological Office.

Some 1 per cent to 2 per cent of the recording time was actually in thin, high cloud in which a pilot would not normally expect turbulence. For the purpose of this investigation such cloud was treated as clear air. Such clouds were all cirrus types, thin alto-stratus and thin alto-cumulus. A few observations taken in the vicinity of cumulo-nimbus clouds have been disregarded.

4.2. For the purpose of this report it is proposed to describe and discuss the two categories of results in separate sections and then go on to discuss the inter-relationship which may exist.

5. *Statistical Results.*—5.1. *Analysis of Accelerometer records.*—5.1.1. The counting of acceleration peaks is not entirely straightforward. Somtimes the trace increases steadily to its peak value and then falls steadily to the datum line, but on other occasions a smaller oscillation is superimposed on the main movement. Thus instead of rising steadily from the datum to $1 \cdot 5g$ and falling steadily to the datum again, the trace may rise to $1 \cdot 5g$, oscillate between $1 \cdot 3g$ and $1 \cdot 5g$ and then fall back to the datum. It is necessary to decide on a method of counting these superimposed oscillations.

The actual method must depend on the use which is to be made of the peak count and it is assumed here that the main significance of small accelerations is in terms of the fatigue life of the aircraft structure. Now the number of stress cycles to failure for small stress oscillations varies only slightly with the ratio mean stress/ultimate stress provided that the ratio is small—less than 20 per cent say—and so the superimposed stress oscillations are counted as though they had occurred about the datum.

This method was adopted in the compilation of the results presented in Table 3. In practice, owing to the slow running speed of the Peravia, it was not easy to see the stress oscillation in complete detail. The technique was adopted where necessary, however, although the actual numerical effect is small.

5.1.2. Having obtained from the accelerometer records a count of acceleration peaks, the next problem is to relate them to miles flown. Further, the desired result is the gust experience of a civil aircraft which normally flies straight and level—not the actual gust experience of the *Mosquito* aircraft whose climb and descent flight plan is not representative of normal civil practice. It will be remembered that in general the recordings from the Peravia accelerometer fall into two different classes,

(i) Sample recordings around fixed heights, of magnitudes less than $\pm 0 \cdot 2g$.

(ii) Search recordings in a turbulent area, of all magnitudes.

The problem is thus to combine these two classes to enable the data to be presented as for level flight within various height bands.

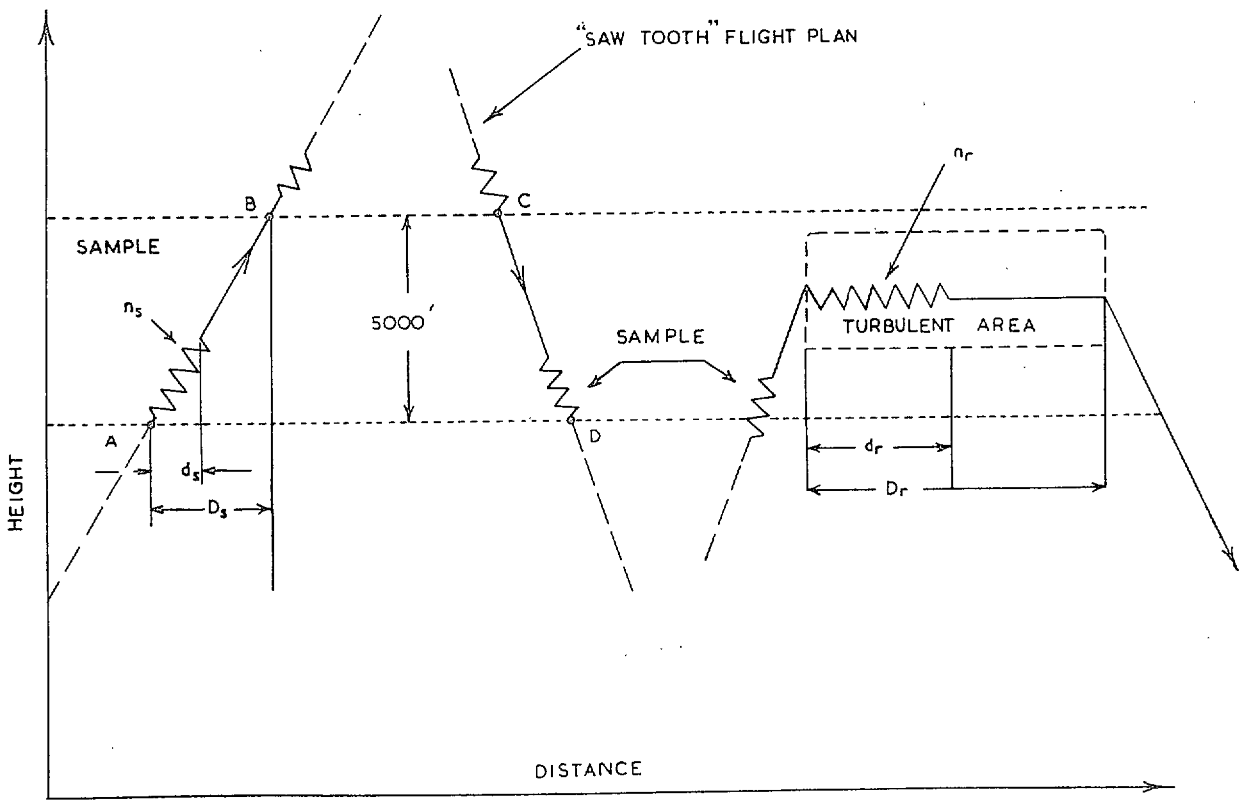
First of all the accelerations were converted to equivalent vertical gust velocities using the orthodox formula[1]

$$U_e = \frac{2\omega \, \Delta\eta}{\rho_0 K \alpha V i} \quad \ldots \quad (1)$$

It is important to note that many American reports use a definition of K which is different from that given by the British Civil Airworthiness Requirements. For a wing loading of 44 lb/ft^2 —representative of the *Mosquito*—the American value is about 1·18 whilst the British factor is about 0·7. This point must be watched in any comparisons of U.K. and U.S. gust data. All gust data in this report are based on the British definition of K.

These equivalent vertical gust velocities were then separated in various height bands of 5,000 ft thickness, *e.g.*, 20,000 to 25,000 ft, the sample at 20,000 ft being taken as representative of that layer.

A part of the typical flight plan is illustrated.



Referring to the illustration, on a given flight, *within a chosen height band,*

let n_s be number of gusts of given magnitude from a *sample* record

d_s distance covered during a sample

D_s distance flown on one 'leg' of the sawtooth flight plan (*e.g.*—AB or CD on diagram)

n_r number of gusts of given magnitude recorded in the turbulent area

d_r distance flown in turbulent area whilst accelerometer record is being taken

D_r horizontal extent of turbulent area

N equivalent number of gusts of given magnitude encountered during flight in this height band

then

$$N = \Sigma \left[n_s \times \frac{D_s}{d_s} + n_r \times \frac{D_r}{d_r} \right] \quad \ldots \quad (2)$$

This process was repeated for various gust magnitudes (both positive and negative separately) for various height bands covering the range of altitude.

The results are given in Table 3. From this table the results have been cast in such a way as to show

(a) Miles to fly to meet a gust of a given magnitude, or greater, at various altitudes (Fig. 4).

(b) Relative frequency of occurrence of gusts of various magnitudes, irrespective of altitude (Fig. 5).

5.2. *Discussion of Statistical Results.*—5.2.1. Before passing to a general discussion of the statistical results there are one or two points to be borne in mind. As reference to Table 2 shows clear air turbulence occurred in patches of various thicknesses, but averaging around 3,000 ft, and of various horizontal extents, although a representative dimension is 50 to 100 miles. It is clear, therefore, that most of the time the upper air was smooth, or at least giving less than $\pm\ 0 \cdot 2g$ accelerations, but that every now and again an area of turbulence was met which yielded accelerations of all magnitudes up to the maximum recorded in that area. Therefore, although expressing the results as ' miles to fly to meet a gust of given size ' may be convenient, one must not imagine gusts as being spaced out more or less evenly in the upper air, but rather as occurring in isolated clusters.

One might also be tempted to say that because the *Mosquito* aircraft met a turbulent region* roughly once every 5,000 miles above 15,000 ft, then that result should hold for other aircraft flying level above that altitude. This is not the case, however. It can be shown that if one assumed a turbulent region of about 2,000 ft thick and 50 miles long to exist somewhere along a given route, then the chances of the *Mosquito* meeting it when following the sawtooth flight plan were about four in ten. An aircraft flying level at some height between 15,000 ft and 35,000 ft would have only one chance in ten† of meeting such a layer.

Thus, *for the selected size of layer,* adopting such a search technique increased fourfold the *Mosquito's* chances of finding a turbulent area, or put the other way, an aircraft flying level at high altitude is likely to meet turbulent areas of these dimensions only about a quarter of the number of times the *Mosquito* did. With turbulent areas more than 50 miles in extent this fraction would get even smaller ; with areas thicker than 2,000 ft, the fraction would increase. Reference to Table 2 shows that the actual turbulent areas encountered vary widely in thickness and horizontal extent, and as a result of this variation no simple factor can be applied to the results as a whole. Furthermore, it is very unlikely that in actual operations any turbine powered aircraft will fly at constant height ; it is more likely that the aircraft will climb progressively as its weight diminishes until such time as the descent to terminal is due to begin.

The results have been presented, therefore, in Figs. 4 and 6 on the basis of miles actually flown by the *Mosquito* aircraft, and they may tend to be a little pessimistic when applied to normal civil airline operations. The degree of pessimism, however, is not significant when compared with the other factors involved.

Table 3 shows that the number of positive gusts of a given size is rather more than the number of negative ones. There was, however, a slight, though consistent, tendency for one Peravia instrument to be biased in the positive direction. Consequently no attempt has been made in Figs. 4 to 7 to separate up and down-gusts, the total number being used, irrespective of sign.

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* As defined in section 3.2.

† This assumes equal probability of the layer being anywhere between the limits of altitude—a point which is discussed later.

5.2.2. In Fig. 4 the B.E.A. results show that at around 25,000 ft one must expect to fly, *on average*, about 8 miles to meet a 4 ft/sec gust, about 60 miles to meet 8 ft/sec, about 400 miles to meet 12 ft/sec, and so on. Most results have been obtained between 20,000 ft and 30,000 ft and, therefore, it is probable that, statistically speaking, the results are most reliable between those height limits. The apparent increase in distance to be flown for heights less than 20,000 ft is possibly due to the smaller number of results available at 15,000 ft. The increase in distance at altitudes above 30,000 ft when gusts greater than 12 ft/sec are considered is also a reflection of the fewer results available. In this case it is possible that the presence of the tropopause is a factor which makes large gusts less frequent than at the lower altitudes. On the other hand the number of smaller gusts increases at higher altitudes (*i.e.*, the average distance to meet one diminishes). This is probably a genuine effect, as the crews frequently reported slight turbulence when passing through the tropopause. On the whole, however, and bearing in mind that a sample of 92,300 miles is relatively small, the variation with altitude can hardly be classed as of great significance.

5.3. *Comparison with other Gust Data.*—5.3.1. On Fig. 4 are shown some American results, as extracted from Ref. 1*. The samples chosen (numbers 5 and 7) are the only ones from Ref. 1 which are suitable for presentation in this particular form with the B.E.A. data ; the samples comprise some 65,200 miles, which is comparable with the B.E.A. coverage. The view is expressed in Ref. 1 that sample 5 is not representative of average conditions, because extremely severe turbulence was encountered during the flight. An interesting comparison is afforded between the results of flights at 5,000 ft and 10,000 ft through clear and cloudy conditions, and the purely clear air data at much higher altitude as given by the *Mosquito* aircraft. It will be observed that the 4 ft/sec and 8 ft/sec gusts are encountered more often at high altitude, whereas the 24 ft/sec gusts are met more often at the lower altitude. Intermediate gust velocities are apparently met just as often at low as at high altitude.

5.3.2. Another way of comparing the *Mosquito* and the U.S. data of Ref. 1 is given in Fig. 5, which depicts the relative frequency of occurrence† of gusts of various magnitudes, irrespective of altitude. In this figure, the *Mosquito* data have a threshold value of 4 ft/sec, whereas the U.S. data have a much lower threshold value, thus accounting for the different origins‡. The U.S. curves 'A' and 'B' are the broad limits within which fell the results of 9×10^6 miles of operation, and thus they can be regarded as a very good sample of the relative frequency of gusts to be expected over low and moderate altitudes in cloudy and clear air.

It is extremely interesting to see how the B.E.A. curve not only lies between these two limiting curves, but has the same slope at higher gust velocities. This confirms, in another way, the findings of the preceding paragraph, *i.e.*, that there is little difference between the frequencies of occurrence of gusts of moderate intensities at low altitude and at high altitude in clear air. It also suggests that one can extrapolate with fair confidence on this diagram up to gust velocities of about 36 ft/sec.

5.4. *Extrapolation to Higher Gust Velocities.*—5.4.1. We are thus led to the question of extrapolation of the B.E.A. results to higher gust velocities. Since the results of Fig. 4 show that there is little variation with altitude it is both justifiable and statistically more satisfactory to present all the B.E.A. data as a plot of miles to fly to meet a gust of given intensity versus gust velocity. This has been done in Fig. 6.

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* The American gust velocities have been made comparable with the corresponding British gust velocities, by dividing them by 0·6 approximately. This applies throughout the report.

† Defined as 'the ratio of the number of gusts equal to or greater than a given gust velocity to the total number of gusts reported.'

‡ The U.S. data, as given in the original report, has been corrected to the British gust standards and, in addition, the relative frequencies have been doubled in order to present a direct comparison with the B.E.A. results, which do not discriminate between positive and negative gusts.

Also shown on the same plot are V-g records from R.A.E. analyses[4,5], of *Constellation* and *Liberator* operations by British Overseas Airways Corporation, and samples 4, 5, 6, 7 of Ref. 1. It was not possible to re-plot, in the required form, the relative frequency polygons (curves A and B) of Ref. 1, hence the original data from the relevant samples have been employed instead.

5.4.2. It is notable that all results agree reasonably well at low and moderate gust velocities, *i.e.*, up to about 16 ft/sec. Beyond that point the B.E.A. results diverge from the others, although the latter are in reasonably good agreement with each other up to the highest gust velocities. This divergence of the purely clear air data from the remainder may well be a genuine effect, for which some support can be adduced from Fig. 7, which shows a similar difference.

5.4.3. In the R.A.E. reports[2,3], it is stated that the frequency distribution with gust intensity follows a normal error law. A curve based on this normal error law and fitted to a reasonably favourable pair of B.E.A. points is shown in Fig. 6. It is clear that this law does not fit the B.E.A. results and that it gives an unduly optimistic result when applied to higher gust velocities. For example it virtually precludes the occurrence of gusts greater than about 30 ft/sec, yet it is clear from the B.E.A. data alone that such gusts are quite likely to occur. Furthermore, in its early development trials the De Havilland *Comet* encountered some very severe turbulence[6], probably greater than 35 ft/sec vertical gust velocity, after having flown only about 6×10^4 miles above 15,000 ft. (It is of interest to note that, if the point corresponding to the *Comet* data given above is plotted in Fig. 6 it lies close to a mean line through the low and moderate altitude data). Whilst it is true that the actual magnitude of the largest gust encountered by the *Comet* is not too well defined and also that the distance flown by the aircraft has more than doubled since this episode, yet the broad conclusion does remain that the occurrence cannot be regarded as a freak.

5.4.4. In a private communication Starkey of the Structures Department, R.A.E., suggested that a ' Negative Binomial ' law might fit the B.E.A. results in a satisfactory manner*. That this is the case is clearly shown in Fig. 6.

However, the extrapolation beyond the largest observed vertical gust velocity of 26 ft/sec is seen to lie somewhat above the V-g results. No special physical significance can be attached to this extrapolated curve, although it is probable that the clear-air gust distribution will tend to lie above the V-g results. The negative binomial extrapolation may be a little optimistic, but it is a reasonable compromise to offer at this stage, at least for gust velocities up to about 36 ft/sec say.

If one accepts this suggested extrapolation it is of interest to consider what would be involved in operating a fleet of twenty aircraft of the *Comet* type. At a utilisation of 3,000 hr per annum a total distance of about 27×10^6 miles might be flown. On this basis a 36 ft/sec gust would be met, on average, once per fortnight, and a 50 ft/sec gust once in four years. These gust velocities correspond approximately to acceleration increments of $1 \cdot 5g$ and $2g$ respectively.

It is quite clear, however, that many more data are needed to present a reliable picture to the aircraft designer, and the airline operator. The *Comet* episode underlines this need.

5.5. *Comparison with Conditions in Thunderstorms.*—5.5.1. In the discussion so far consideration has been given to the frequency with which gusts are met when flying through the atmosphere as a whole, *i.e.*, through both rough and smooth air. It is interesting to examine the results from clear, turbulent air only. The weakness of this examination is that accelerometer recordings are available only for some 500 miles of turbulent air—a very small sample indeed. However, the results are portrayed in Fig. 7 and for comparison data from the U.S. Thunderstorm Project[7] are also shown together with data extracted from a paper of the Meteorological Research Committee, London—M.R.P. 484—by R. F. Jones.

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* The expression used was :—
Proportion of gusts in speed band $(x+4)$, for example, is given by the coefficient of $Z[(x/4)-1]$ in the expression $(1 \cdot 42-0 \cdot 42Z)^{-0 \cdot 326}$.

It is immediately obvious that in thunderstorms the proportion of high to low gust velocities is much greater than in clear turbulent air, also that the gusts are rather closer together. It follows also that the probability of meeting very severe gusts is much greater in thunderstorms than in clear air.

5.5.2. However, it is of great interest to note that the Thunderstorm Project has stated[7] " . . . . . if the largest gust in a group of several contiguous gusts exceeds about 15 ft/sec* and at the same time the gust frequency is greater than 8 per 3,000 ft of traverse, the Project air-crews reported the turbulence as 'heavy.' When the region under consideration is expanded to the length of one complete pass through a thunderstorm, heavy turbulence was reported for the traverse as a whole whenever the mean maximum effective gust velocity per 3,000 ft of traverse exceeded 8 ft/sec† and the frequency exceeded 4 per 3,000 ft of traverse."

This yardstick has been applied to one of the B.E.A. traverses in turbulent air (VR.94) and the essential results are as tabulated below. The recording from this voyage was broken down into successive lengths of 3,000 ft corresponding to about 5 or 6 sec running time.

No. of 3,000 ft length	1	2	3	4	5	6	7	8	9	10
U_{max} ft/sec (U.K.)	8	12	20	24	12	16	12	20	4	4
No. of peaks > 4 ft/sec in 3,000 ft length ..	5	10	9	11	6	8	4	7	1	2

5.5.3. It will be seen that from length numbers 3 to 8 inclusive the United States' standard for heavy turbulence has been generally exceeded. The sample given is probably the longest stretch of severe roughness which has been recorded and analysed, but others just as severe (by inspection) have been noted over shorter lengths. Following up the U.S. definition of heavy turbulence, which depends upon the length of the 'pass', it is probable that a lower standard of definition of 'heavy' turbulence would have been adopted had the distance in turbulent air been of the order of 50 or 100 miles—which is representative of clear-air turbulence—instead of the representative thunderstorm dimension, say 5 to 10 miles.

5.6. *Characteristic Features of Clear-Air Turbulence.*—5.6.1. Owing to the unsatisfactory behaviour of the Barnes accelerometer no fully reliable information on the rate of occurrence of the gusts or of how they build up, could be obtained. The crews state, however, that the bumps follow one another much faster in this clear-air turbulence than in that associated with convective type clouds. The turbulence has been described by one of the pilots as giving the feeling of 'a fast car suddenly running over a series of deep unseen ruts in a road.' His impressions of the sharp, hammering nature of this turbulence have been borne out by all other crews who have experienced it, but their feelings can neither be confirmed nor denied from the available records.

It is difficult to specify the approximate size of a turbulent area. Sometimes small accelerations ($< \pm 0{\cdot}2g$) were encountered over no more than a few miles; on other occasions turbulence was encountered over hundreds of miles. The sizes of the turbulent areas investigated in this work are given in Table 2. They vary considerably, but a representative area may be taken as 3,000 ft thick and 50 to 100 miles in horizontal extent. This area is not in general clearly defined and the severity of the turbulence at a given spot appears to change appreciably in a matter of minutes. The duration of the general turbulent region on the other hand can be several hours.

No height change takes place during a traverse, probably because positive and negative accelerations follow in succession. It is also noteworthy that on only two occasions was wing dropping reported. This suggests that the eddies usually encountered were considerably larger than the wing span of the aircraft.

* 25 ft/sec on *Mosquito* by United Kingdom standards.
† 13·3 ft/sec on *Mosquito* by United Kingdom standards.

5.7. *Effect on Fatigue of Aircraft Structure.*—No attempt has been made to analyse the results in terms of fatigue of the aircraft structure. It is preferred to leave this aspect to the specialists in such matters, especially as there is a considerable amount of controversy surrounding the best method of combining the fatigue effects due to the different frequencies and amplitudes of a representative loading spectrum.

6. *Meteorological Aspects—Basic Theory and Analysis of Aircraft Observations.*—6.1. *General.*—The major distinguishing feature of clear-air turbulence is that it gives no visible warning of its presence. As a result of horizontal eddy diffusion, an aircraft flying level would probably encounter smaller-scale turbulence before running into really severe bumps. This was the general experience of the Unit, but the warning time may be no more than two or three minutes. The corresponding diffusion in the vertical is limited in extent by buoyancy forces and for an aircraft climbing or descending the warning time might be much smaller. It is very necessary, therefore, to develop, if possible, a forecasting technique which can indicate regions in which clear-air turbulence is likely to be found.

The approach to the problem is best made in two stages :—Firstly, it is necessary to determine the immediate physical causes of turbulence, confirming if possible by experimental observations made in actual turbulent regions. Secondly, these immediate physical causes must be related to the meteorological or other conditions which generate them, thus giving a basis on which a forecast can be made. In the ensuing sections various possible causes of clear-air turbulence are discussed briefly, and it will be seen that wind gradient in the vertical (defined as $\partial V/\partial Z$) is considered the most likely cause. The theoretical background of this suggestion is given in more detail, an experimental method of measuring local wind gradient indirectly is described and the actual results discussed.

6.2. *Basic Physical Requirements for Maintenance of Turbulence.*—6.2.1. *Sources of Energy.*—Fundamentally, turbulence involves the dissipation of energy and, therefore, to maintain turbulence the rate of supply of energy must equal or exceed the rate of dissipation. Three possible sources of energy are considered :—

(a) *Thermal Instability.*—Turbulence was encountered on several occasions in clear air near cumulo-nimbus cloud. Such cases were probably associated with air movement inside the cloud. Also turbulence has on two occasions been found associated with cirrus cloud, a feature which is discussed in section 7.3.4. In the great majority of cases, however, turbulence was associated with a very stable temperature lapse rate and far removed from cloud. The possibility of thermal instability as a general cause must, therefore, be disregarded.

(b) *Atmospheric Wave Motion.*—Stationary waves are known to exist in association with mountains[8]. The wavelength is such, however, that an aircraft flying into such a disturbance would experience change of height, but not turbulence. Glider pilots have also reported[9] smooth lift in association with a cold front (*i.e.*, non-stationary) and one one occasion one of the B.E.A. *Mosquito* aircraft experienced pronounced smooth lift (1,500 to 2,000 ft/min) in clear air between 35,000 ft and 37,000 ft (*see* VR.80—Table 2). On this latter occasion the lift, initially quite smooth, petered out into rather sluggish turbulence in the stratosphere. This lends support to the hypothesis that, under certain conditions, wave motion may degenerate into turbulence. The mathematical background of atmospheric wave motion, however, has not yet been satisfactorily analysed and at present, therefore, the possible degeneration of wave motion must remain a matter for speculation.

(c) *Wind Gradient.*—If no turbulence is present, the purely viscous forces in atmospheric wind gradients are small. In practice, however, some turbulence will exist and the eddies will diffuse in the vertical and in the horizontal, tending to break down the wind gradient. The eddies can be regarded in fact as a means of dissipating energy. The underlying theory is given by Brunt [10], but a brief summary is given in the following sections for convenience.

6.2.2. *Maintenance of Turbulence.—Richardson's Criterion.*—A theoretical approach linking turbulence with vertical wind gradient was developed by Richardson [11]. It is not proposed to give his complete analysis here, but the underlying reasoning was as follows :—

If in a vertical wind gradient, some initial turbulence and hence eddy diffusion does exist, then

Rate of energy supply $\propto \left(\dfrac{\partial V}{\partial Z}\right)^2$.

But diffusion in the vertical does work against gravity, the amount of work being proportional to the thermal stability, *i.e.*, the amount by which the actual vertical temperature lapse rate differs from the lapse rate for instability.

In fact energy dissipated $\propto \left(\Gamma + \dfrac{\partial T}{\partial Z}\right)$.

Richardson states that if the rate of supply of energy exceeds the rate of dissipation, existing turbulence would tend to increase. The relation can be written[10];

$$\left(\frac{\partial V}{\partial Z}\right)^2 > \frac{g}{T}\left(\Gamma + \frac{\partial T}{\partial Z}\right) \qquad (3)$$

for turbulence to increase.

It has been pointed out by Calder[12] that when turbulence exists the eddy energy, as well as doing work against gravity, also becomes dissipated into heat and diffuses out of the turbulent region. This means in effect that to maintain appreciable turbulence the rate of energy supply must be greater than that given by Richardson. However, while equation (3) can be criticised in detail, the basic idea seems sound.

The equation makes allowance only for vertical wind gradient. It may be argued that the effect of horizontal wind gradient is also important. This may well be true, but no well-established criterion exists to take account of the additional effect. As a result, horizontal wind gradient cannot be considered except in a qualitative way.

6.2.3. *Vertical Wind Gradient.*—Richardson's approach clearly indicates that vertical wind gradient is a very important parameter in any problem of atmospheric turbulence. Realising this, every effort was made by the B.E.A. Unit to develop a means of measuring this gradient actually in turbulent regions. One suggested method involved laying vertical smoke trails and observing the relative shift with time. Another method was based on towing a trailing pitot two or three hundred feet below the aircraft and comparing the difference in total head at this pitot with that at the aircraft itself. The practical difficulties were very great, however, and it was clear that development work beyond the resources of the Unit would be involved. Consequently, neither method could be implemented whilst the Unit was in being.

Finally, an indirect approach was made using the relation between vertical wind gradient and horizontal temperature gradient. This is the familiar ' thermal wind ' equation and for the sake of clarity the background of this relationship is set out briefly below.

6.2.4. *Geostrophic and Thermal Winds.*

(a) *Geostrophic Winds.*—Any particle moving on the rotating earth experiences an apparent horizontal acceleration at right-angles to its direction of motion. If the particle is to move in a straight line, therefore, under steady conditions, this geostrophic acceleration must be balanced—usually by the pressure gradient. For balance, the relation is :—

$$\frac{1}{\rho}\frac{\partial p}{\partial s} = 2\Omega V \sin\phi \qquad (4)$$

the familiar equation for geostrophic winds[10].

(b) *Thermal Winds.*—If pressure at sea level is constant over a wide area, but a horizontal variation of temperature exists, the pressure will not be constant at a given true height above sea level. Thus, even though the geostrophic wind at sea level is zero, it is not zero at altitude, giving rise to a wind gradient in the vertical. On this basis, it is possible[10] to relate vertical wind gradient to horizontal temperature gradient as in equation (5).

$$\frac{\partial V}{\partial Z} = \frac{g}{T} \times \frac{\partial T}{\partial s} \times \frac{1}{2\Omega \sin \phi} \qquad (5)$$

This is the so-called thermal wind equation.

This relation indicates an indirect experimental means of determining the vertical wind gradient by measuring the variation of temperature in the horizontal. Observations of temperature are required at frequent intervals in a horizontal run extending over a distance of at least 50 miles. If this shows a marked temperature gradient, one would deduce the presence of a marked vertical wind gradient.

6.3. *Horizontal Temperature Traverses.*—In order to verify that the relationship given above was valid, experimental observations of the horizontal temperature gradient in both smooth and turbulent conditions were clearly needed. A number of level runs were, therefore, made in smooth air. Thermometer readings were taken every 30 sec (roughly every $2\frac{1}{2}$ miles) whilst pressure height and air speed were held constant. The results of these runs are shown in Fig. 8. Variations do take place, but they are fluctuations of $\pm$ 0·5 deg C, to $\pm$ 1·0 deg C about a mean ; there is little change of mean temperature. This confirms observations given in a paper of the Meteorological Research Committee, London—M.R.P. 402—by R. Frith.

Three runs have been made through turbulent regions and the results are shown in Fig. 9. Ideally, two runs at right-angles should be made, but in general, for operational reasons, this was not possible. The runs were, therefore, made at right-angles to the forecast or navigation wind (this would be expected to give the maximum rate of change of temperature). On all occasions a marked variation of temperature was found.

6.4. *Extent of Temperature Variation.*—6.4.1. The temperature variations shown in Fig. 9 need to be considered carefully. They extend over about 50 miles and this is a relatively short distance in terms of application of the thermal wind equation. It is reasonable to assume, however, that the relation will apply with reasonable accuracy when the extent of the variation is about 50 miles, although variations over, say, 5 miles are likely to have little significance. It is proposed, therefore, to consider the application of the thermal wind equation to the horizontal temperature traverses.

Considering first Fig. 8, it may be assumed that the wind gradients were small, certainly for VR 177 where runs at right-angles were made. (The Daily Weather Report confirms that wind gradients were small). In Fig. 9, however, this is not so. In each case, the rate of change of temperature is about 5 deg C per 50 miles which, using the thermal wind equation, corresponds to about 15 knots per 1,000 ft.

6.4.2. In each of the three cases shown in Fig. 9 the lapse rate was very stable and the thermal stability (section 6.2.2) was in fact 2 to 3 deg C per 1,000 ft. Applying the Richardson criterion for varying degrees of thermal stability gives* the following values of critical wind gradient needed to cause turbulence to increase :—

Thermal Stability	0	1	2	3	4	deg C/1,000 ft
Critical Wind Gradient	0	7·0	9·7	12·0	13·7	knots/1,000 ft

*A mean temperature of 240 deg C absolute is assumed here.

Thus, for the cases shown in Fig. 9 it would be expected on the basis of the Richardson criterion that the wind shear in the vertical would be of the order of 10 to 12 knots per 1,000 ft, which is comparable with the 15 knots per 1,000 ft derived from the thermal wind equation.

Hence, in the turbulent regions it has been shown that the observed horizontal gradient of temperature implies the existence of a high vertical wind gradient. Also that this vertical wind gradient, when coupled with the observed lapse rate, within reasonable limits of experimental accuracy, satisfies the Richardson criterion for turbulence. Since only three cases were investigated, the result must be accepted with caution, but it is at least interesting and suggestive.

The criterion for turbulence to increase is sometimes expressed as Richardson's number (Ri) defined as :—

$$Ri = \frac{g}{T}\left(\Gamma + \frac{\partial T}{\partial z}\right) \Bigg/ \left(\frac{\partial V}{\partial z}\right)^2 \qquad (6)$$

Hence, if the Richardson number is less than one, turbulence should increase. Other authorities[13] suggest that the critical value of Ri should be $0 \cdot 5$. The observations described in these paragraphs indicate that the critical value should be less than one, although a precise value cannot be given.

It is of interest to note that in one case (VR 176) a radio-sonde ascent was available corresponding closely in time and position to the turbulent area. The radio-sonde measurements showed a vertical wind gradient of only 4 to 5 knots per 1,000 ft. This is not necessarily inconsistent since the radio-sonde would, at 35,000 ft, give a mean wind over a height range of 3,000 to 4,000 ft. However, it does illustrate the inadequacy of radio-sonde data for an analysis of this sort.

7. *Meteorological Aspects—Survey of General Weather Situations.*—7.1. *General.*—The experimental results given in the preceding paragraphs represent an attempt to determine the immediate causes of clear air turbulence from purely local measurements. The results tend to confirm the earlier deductions that vertical wind gradient is the cause of clear-air turbulence, and further suggest that the Richardson criterion for turbulence is applicable.

An alternative approach to the problem is, of course, to make a detailed examination of the weather and other relevant conditions when voyages have been made and especially on those occasions when turbulence was found, using published meteological data. Bearing in mind the results of the horizontal temperature traverses it is necessary to determine whether or not turbulence tends to be linked with high vertical wind gradient—or equivalently, with high horizontal temperature gradient.

A close liaison has been maintained between the B.E.A. Unit and the Meteorological Office, London, and all results have been sent to the latter for examination. A report[17] has been published which gives an analysis of data supplied by B.E.A. (up to December, 1948), and various other agencies. The result is rather disappointing in that while certain general trends become evident, the analysis does not yield clear cut correlations which can be used for forecasting purposes. It is possible that the critical parameters are still completely unknown, but a more likely explanation is perhaps that the meteorological data are insufficiently detailed and accurate for this purpose. It is quite conceivable that localised regions can occur where conditions are significantly different from the surroundings. Such localised regions may be small enough to be missed by the radio-sonde network. In the United Kingdom stations are about 150 miles apart and ascents are made every 6 hr. Over much of Europe the intervals of time and distance are considerably greater.

It is not proposed to analyse the meteorological data in complete detail. To a certain extent this would merely duplicate work already done. Also the results are relatively few in number and their purely statistical significance is limited. In this section, therefore, the experimental results will be presented and an analysis made only of the more significant features.

7.2. *Meteorological Data Available.*—It is not practicable to give complete synoptic charts for every voyage since, apart from the sheer number of voyages involved, each covered a wide height-range and thus the preparation of representative charts would present considerable difficulty. A reduced presentation, mainly in tabular form, is, therefore, given as detailed below:—

Table 1	gives dates, times and routes for all flights made.
Table 2	gives detailed information on all flights on which turbulence was found.
Figs. 10 *to* 14	give tephigrams for all flights covered by Table 2.
Figs. 15, 17, 18	give examples of synoptic situations of particular interest.

For the benefit of those not familiar with conventional meteorological charts a brief explanation of Figs. 10 to 18 is given in Appendix I.

7.3. *Analysis of Important Meteorological Factors.*—7.3.1. *Jet Streams.*—A jet stream, fully defined in Ref. 16, is generally taken as a narrow belt of high winds (100 knots or greater) embedded in an air stream of markedly lower wind speed. An example of a jet stream as shown on a 300 mb chart is shown in Fig. 15. A vertical cross-section through a typical jet stream is shown in Fig. 16. The highest winds are concentrated in a ' jet ' and high wind-gradients occur at the boundary between warm and cold air. The jet stream is in fact associated with high horizontal temperature gradients (frontal conditions in the upper air) which lead to high wind-gradients and hence to high winds when the gradients extend over an appreciable height range.

On the basis of section 6.2.2, one would, therefore, expect to find clear-air turbulence associated with jet streams, and this is sometimes the case. Severe turbulence was twice found in a jet stream (VR 4 and VR 60). On the other hand, on more than twenty other occasions the search aircraft flew across the axis of, or near a jet stream without incident*. On VR 60, the aircraft flew out from base in smooth air and returned on reciprocal course about 30 min later to find severe turbulence, although crossing the jet stream boundary on both the outward and return trips (*see* Fig. 15). Furthermore, when making a search of the turbulent area, turbulence was found to be patchy and intermittent. This illustrates the localised nature of the phenomena. A possible explanation is that even in jet streams, where high wind-gradients are expected to occur, conditions become critical only in regions of limited extent.

As mentioned in section 5.4.3, severe turbulence was encountered by the *Comet* whilst flying in a jet stream. In fact one is tempted to suggest that the most severe cases usually are in jet streams, although the evidence is still very limited.

7.3.2. *Tropopause.*—There is no doubt that clear-air turbulence is often found in apparent association with the tropopause. Of the twenty cases given in Table 2, ten were within 2,000 ft of the tropopause, some above, some below. This is rather puzzling since the tropopause is normally assumed to be a region of zero vertical wind-gradient—the boundary in fact between increasing winds in the troposphere and decreasing winds in the stratosphere where the thermal wind effect is usually reversed. However, two of the horizontal temperature runs shown in Fig. 9 were just above the tropopause suggesting that under certain conditions high wind-gradients can occur near the tropopause.

The temperature structure of the tropopause is still incompletely understood. In fact the very existence of a sharp check in the temperature lapse rate has never been satisfactorily explained. It is difficult to speculate about temperature effects for this reason. It may be noted, however, that if the tropopause is sloping and the stratosphere is isothermal in the vertical, large wind-gradients can exist at and above the tropopause (on the basis of the thermal wind effect). It has been suggested that the tropopause may be discontinuous ; this also would promote temperature contrasts.

* From about March, 1949, in fact, flights were planned to cross jet streams whenever the Central Forecasting Establishment, Dunstable, notified the Unit that a jet stream was forecast within the operational range of the aircraft.

The slope of the tropopause as shown by the Upper Air Section of the Daily Weather Report is normally of the order of 1,000 to 2,000 ft per 100 miles. Above certain depressions, however, the slope is sometimes shown to be as much as 4,000 to 6,000 ft per 100 miles and this might generate wind gradients of the order of 10 knots/1,000 ft in the substratosphere. Of the ten cases mentioned above, four were in fact near a region of very steep tropopause slope. Fig. 17 shows an example of this. Table 2 shows that most cases were associated with low pressure regions or troughs although this does not necessarily result in a steep tropopause slope.

7.3.3. *Marked high or low-pressure regions in the upper air.*—If a region of marked low or high pressure exists in the upper air, the resulting circulation may bring air masses at different temperatures into proximity. Fig. 18 shows an example of an upper air depression. Table 2 shows that all but three of the cases considered were connected with upper air depressions or troughs, although sometimes the troughs were very shallow and might well be considered insignificant. United Airlines, on scheduled operations (*see* section 7.4) have found turbulence in association with upper air depressions.

7.3.4. *Thermal Instability.*—Most of the temperature lapse rates shown by Figs. 10 to 14 for all twenty cases of turbulence were stable, or very stable, tending to the isothermal. Some cases, however, showed marginal stability. Thus on VR 131 bumps were found associated with cirro-stratus cloud—this cloud is normally quite innocuous. Very curious cloud effects were noted on VR 94. To quote the pilot, 'The most remarkable feature of the cloud was a series of corrugations like teeth isolated in clear air. These teeth were 50 to 100 ft high and appeared singly or in groups of two or three. Above one or two some wispy cirrus appeared to be suspended, giving the effect of a miniature mountain with its peak immersed in wispy cloud. Marked turbulence was experienced on flying through some of those teeth . . . which appeared to be 100 to 200 ft apart.' On VR 131 the lapse rate was just unstable through the cirro-stratus and isothermal above and below. On VR 94 the lapse rate was generally stable with regions of instability over limited height bands. It may be noted that when large horizontal variation of temperature occurs, the warm air would normally over-ride the cold air—giving a stable temperature lapse rate. For this reason it is not easy to link up high wind gradient with unstable temperature lapse rate.

7.3.5. *Wind Speed.*—Wind gradient rather than wind speed is considered to be significant. However, an examination has been made of the occurrence of turbulence in relation to wind speed. Turbulence has occurred at wind speeds from 5 knots to 150 knots and 90 per cent of cases occurred below 75 knots. Having regard to the frequency with which high winds occur, the turbulence between 15,000 ft and 25,000 ft did show a tendency to become *relatively* more frequent at high wind speeds. There was no such tendency between 25,000 ft and 35,000 ft. As a forecasting aid, therefore, wind speed would be of little value, though it must be remembered that the most severe cases tend to be associated with jet streams.

7.3.6. *Polar front.*—It would be expected that the polar front would be associated with marked temperature contrasts. As shown in Table 2, however, on a number of occasions the polar front had become diffused and could not be identified with certainty. As a result no conclusions can be drawn on this point.

7.3.7. *High ground.*—It appears unlikely that the effect of high ground would extend to high altitude except through some form of wave motion. As discussed in section 6.2.1 the association of turbulence with wave motion remains speculative. Two cases of turbulence, VR 42 and VR 179, did occur near the Alps. The first case, however, was associated with a marked low-pressure region (*see* Fig. 18) and the second with a high horizontal temperature variation. The only case where apparent wave motion made itself evident was in fact VR 80. This occurred at 35,000 ft over Cranfield and there is no definite evidence relating it to high ground. The fact that except on this one occasion wave disturbances were not found does suggest that, except perhaps in a minority of cases, high ground is not important.

7.3.8. *Vertical and horizontal wind gradient.*—An attempt to correlate turbulence with vertical or horizontal wind gradient was made in Ref. 17 using normal meteorological sources of information for details of the wind gradient. The result was rather disappointing and it is not proposed to include such an analysis in this report. The wind gradients so derived are not considered sufficiently detailed or accurate for the purpose.

7.4. *Data from U.S. Airline Operator.*—United Airlines, operating DC 6 aircraft between 15,000 ft and 25,000 ft in U.S.A. have cited several cases of clear-air turbulence in an unpublished report by Harrison[14]. They have made their own meteorological analysis and report that in every case the turbulence was associated with a jet stream or a 'cold low' (a more or less vertical column of air at appreciably lower temperature than its surroundings, associated with a low-pressure region at the surface and in the upper air). They further state that the occasions were characterised by a sudden and decided change in both temperature and wind speed in the horizontal. It is of interest to note that these views are generally similar to those already put forward in this report, although United Airlines do suggest that the wind shear in the horizontal is a significant factor.

8. *Discussion of Meteorological Aspects.*—8.1. There is no doubt that further work needs to be done on clear-air turbulence from the point of view of forecasting. The results presented in this report suffer from the basic defect that they are few in number and no conclusion can, for this reason, be regarded as final. However, bearing this limitation in mind, the results presented in section 6 do suggest that the Richardson criterion, with vertical wind gradient as the major parameter, may well give a method of determining conditions which would be expected to generate turbulence.

8.2. However, even if this is in fact the case, the possibility of actually forecasting turbulence is not good. There is reason to suppose that if a very detailed mesh of high altitude reports were available, an accurate forecast could in fact be made. At the present time, however, this cannot be done. Illustrating this, it is pointed out in section 7.3.1 that turbulence can occur in limited regions of certain jet streams; but it is not yet possible to predict the position of the jet stream itself with accuracy, let alone pick out those regions of a jet stream which may generate turbulence. Again, while turbulence is often found near the tropopause, apart from a suggestion that tropopause slope is important (connected in turn with an upper air depression), no formal rules can be laid down for the forecaster. These are problems which could no doubt be solved, but at present they remain problems.

8.3. At least, however, one can say that analysis of meteorological data leads to findings not inconsistent with the idea that wind gradient in the vertical (or horizontal temperature gradient) is the basic cause of most cases of clear air turbulence. Until further information becomes available, this is probably the best basis to work on. While an accurate forecast of turbulence cannot be made as yet, it is at least possible to pick out, in a very general way, regions where it is most likely to occur.

9. *General Discussion and Recommendations.*—There are one or two points of more general interest which can now be considered.

9.1. It is probable that eddies in the atmosphere may range in size from about one foot to several hundreds of feet, until in fact they merge into the general large-scale movements of the atmosphere. Within this very wide band are those eddies or gusts which give rise to bumps felt by aircraft; and, as has already been suggested by Bannon[17], such eddies probably have a linear dimension lying roughly in the range 50 to 500 ft. Eddies smaller than 50 ft will be felt by a fast aircraft, not so much as a succession of bumps, but more as an irregular vibration. On encountering eddies much larger than 500 ft, the aircraft attitude will tend to adjust itself to the change in direction of airflow, *i.e.*, it will 'ride' eddies of this size. These remarks apply of course to present sizes of aircraft. Very much larger and faster aircraft will be sensitive to somewhat larger eddies than the normal present day aircraft. The data given in the report, however, will be applicable to aircraft of orthodox design at present envisaged.

Therefore, one can say that an aircraft employed on gust investigation 'filters' the spectrum of atmospheric turbulence and reacts only to eddies within certain limiting sizes. From the purely aeronautical aspect this is no handicap, but obviously other techniques would need to be employed were a more general investigation of atmospheric turbulence to be undertaken.

9.2. Little comment has been made on the structural implications of clear-air turbulence, but it is felt that this aspect cannot be completely disregarded. The evidence of Fig. 6, coupled with the *Comet* incident, show that large gusts may be expected in clear air, although at high altitude the frequency of occurrence is likely to be very much less than at lower altitudes where flights may pass through cumulo-nimbus cloud.

Because they are met with little or no warning, clear-air gusts will tend to be associated with the normal cruising speed of the aircraft, irrespective of the magnitude of the gusts. On the other hand, the basic gust envelope of the British Civil Airworthiness Requirements associates the largest gust velocity with a speed less than the design cruising speed. The implications of this difference on the design requirements for high-flying aircraft should be examined.

There is also a possibility that clear-air turbulence may be of a less irregular nature than the turbulence normally met, *e.g.*, in cloud. The subjective assessment of the crews appears to bear this out as all have reported on the apparent regular, hammering nature of this kind of turbulence. Inspection of the only suitable records (from the Peravia accelerometer) does not altogether confirm the crews' assessment, but this may be because the latter are more sensitive to very small accelerations than the particular instrument employed. However, the records do show here and there that for a period of two seconds or so the accelerations may occur at a sensibly constant frequency, which may be as high as 3 per sec at a speed of 350 m.p.h. Whilst this frequency is well below the wing fundamental vibration for aircraft such as the *Mosquito*, it does coincide with the natural frequency for an aircraft with a span of 130 ft[15]. The possibility of a series of eddies giving rise to accelerations at a frequency coinciding with the natural frequency of a large wing cannot be overlooked. In such circumstances the use of the normal alleviation factor which is based on the concept of single up or down gust becomes misleading, as the lag of the wing in responding to a given series of up and down impulses must be taken into account. On some occasions the effect of a given gust will be aggravated by the wing motion and sometimes it will be reduced. In this light the orthodox 'flat topped' gust conception used for design purposes is clearly unrealistic.

9.3. When this project was initiated the main problem so far as a would-be operator of high-speed high-altitude transport was concerned was that of passenger comfort. How to avoid turbulence, or, if encountered, how to mitigate its effects, were, and still are, the main problems of an operator. Complete avoidance of turbulent areas implies a fully reliable forecasting system and it will be clear from the report that not nearly enough is known at this stage to make this possible. It appears that there is more than one cause of clear-air turbulence, but it also appears that tubulence is associated with high rates of wind shear in the vertical and that jet streams are regions where such high rates can be expected to occur. Furthermore, experience shows that turbulent areas are relatively thin, although of considerable horizontal extent.

9.4. Stemming from these considerations and from the detailed discussion earlier in the report, the following precepts can be offered to operators and especially to aircrews :—

(a) Avoid flying in areas where jet streams or high thermal gradients in the horizontal are known to exist.

(b) Avoid flying within 2,000 ft of the tropopause.

(c) If heavy turbulence is encountered assume that one is entering a jet stream and
  (i) climb or descend until turbulence is reduced
    and/or
  (ii) fly at right-angles to the local wind direction.

(d) Should it appear that wing oscillations are being excited by the turbulence, alter speed as much as possible.

These simple rules are all that can be suggested at this stage, but they should help operators to deal with the worst cases of clear-air turbulence.

10. *Conclusions.*—10.1. The frequency of occurrence of clear-air turbulence at high altitude is such as to make it a significant problem from the point of view of passenger comfort. Since the turbulence can be encountered with little or no warning, further research should be directed to establishing a reliable basis for forecasting turbulent areas.

10.2. The turbulence occurs in isolated patches of which a representative size is 50 to 100 miles long by about 3,000 ft thick. It may occur over a wide range of altitude, and there is no evidence that it is associated with any particular topography or geographical position.

10.3. Gusts of low and moderate intensity occur at approximately the same frequency at high altitude in clear air as they do at low and moderate altitudes in all flight conditions. On the other hand severe gusts probably occur much less frequently in clear air at high altitude.

10.4. Since severe gusts can occur in clear air at high altitude, the possible implications on design requirements should be examined. Further, the present conception of a 'flat topped' gust for design purposes is not realistic, as in practice a turbulent region is characterised by a rapid succession of positive and negative gusts.

10.5. The available evidence suggests that clear-air turbulence occurs in regions of high vertical wind gradient (which is equivalent to a high horizontal temperature gradient) and that the Richardson criterion for turbulence is applicable.

10.6. More data are needed before a forecasting technique can be established. It has been found, however, that severe turbulence may be found in a 'jet stream' and that turbulence is frequently found near the tropopause.

10.7. The results described in the report were obtained over Western Europe. They do not necessarily apply to other parts of the world.

11. *Further Developments.*—Before the B.E.A. Gust Research Unit ceased its activities, a system of reporting to C.R.S.D., B.E.A., cases of clear-air turbulence encountered by B.O.A.C. line aircraft and by The De Havilland Aircraft Co.'s aircraft was successfully instituted. A report[18] has been issued giving an analysis of those cases reported between September, 1949 and April, 1951.

It is also understood that a world-wide reporting system through International Civil Aviation Organisation channels is to be set up, using the form employed by B.E.A. for B.O.A.C. and De Havilland Aircraft Company incidents as a basis for reporting. Analysis of all these reports is to be entrusted to the U.S. Weather Bureau, although the British Meteorological Office will also make an investigation of turbulence occurring in the European, Mediterranean and Eastern Atlantic areas.

Acknowledgments.—Many people and organisations, both at home and abroad, have contributed materially to the success of this project, and the authors, together with C.R.S.D., B.E.A., would like to express wholehearted appreciation of the efforts which have been made on behalf of this work. In particular we should like to offer our thanks to the Flight Department of the College of Aeronautics for their excellent maintenance of two rather temperamental aircraft (amply demonstrated by the fact that virtually no defect occurred whilst the aircraft were Overseas), to the Customs authorities, to the B.E.A. overseas staff and agents, the Meteorological Office, and of course to the Ministry of Supply without whose financial support this project could not have been undertaken. Above all we should like to pay tribute to the professional skill, keenness and determination shown by the crew members, Captain T. T. Thomas, D.F.C., Captain D. F. Wilson, Navigating Officer D. L. Jones, and Navigating Officer H. J. P. Bower, during the course of the project.

List of Symbols

U_e	Equivalent vertical gust velocity ft/sec E.A.S.
ω	Wing loading lb/ft^2
$\Delta\eta$	Increment in acceleration in g units
Vi	Air speed, ft/sec E.A.S.
ρ_o	Standard air density at sea level, slugs/ft^2
K	Alleviation factor $= 0 \cdot 8 - 1 \cdot 6/\omega^{3/4}$
a	Slope of lift curve (4·05 for *Mosquito*)
V	Wind speed, ft/sec
Z	Vertical axis
s	Horizontal axis
T	Ambient air temperature, deg C absolute
Γ	Adiabatic lapse rate
g	Acceleration due to gravity
Ω	Angular velocity of earth, radn/sec
ϕ	Latitude

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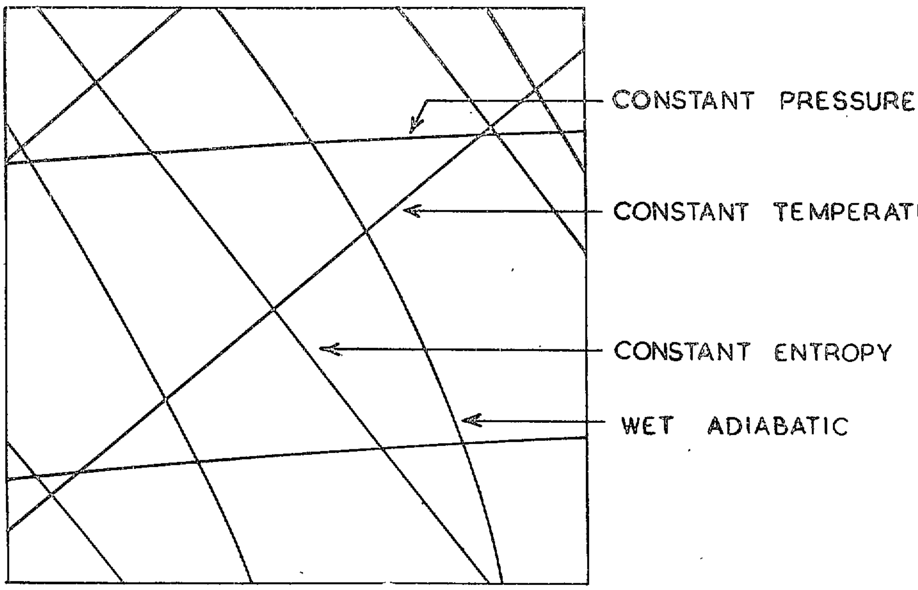
APPENDIX I

Explanatory Note on Figs. 10 *to* 18

The purpose of this Appendix is to give a brief explanation of Figs. 10 to 18, mainly for the benefit of those unfamiliar with conventional meteorological charts and diagrams.

Figs. 10 *to* 14.—Basically the tephigram is a plot of temperature against entropy designed to show at a glance whether the temperature lapse rate is stable or unstable.

In these figures, straight lines running diagonally upwards from left to right are lines of constant temperature in degrees Fahrenheit. Straight lines running diagonally upwards from right to left are lines of constant entropy and show the dry adiabatic lapse rate. Curved lines running diagonally from right to left indicate the wet adiabatic lapse rate. Lines running approximately horizontally are lines of constant pressure. These lines are illustrated in the sketch below :—



Thus, if the observed lapse rate lies parallel with a line of constant entropy, conditions are just unstable assuming the air is not saturated with water vapour. If the air is saturated, conditions are just unstable if the observed lapse rate lies parallel with the wet adiabatic line.

Fig. 15.—The diagram shows a jet stream as it appears on the chart for the 300 mb surface. The contours show the true height above sea level of this constant pressure surface. They are analogous to streamlines—*i.e.*, the tighter the contours, the higher the wind speed. Individual wind speeds in knots are shown in encircled figures. The jet stream itself extends from West of Portugal through the British Isles, to Southern Scandinavia.

Fig. 16.—This shows a cross-section through a jet stream, the section being taken in a plane at right-angles to the wind direction. The lines of constant wind speed show that the highest winds are concentrated in a core or ' jet ' lying between the tropopause and the front in the tropical air. Away from the centre of the jet, the wind speed drops very quickly.

Fig. 17.—Contours are lines of constant tropopause height and show a very marked low tropopause to the N.E. of Scotland.

Fig. 18.—This diagram shows an upper air depression at the 300 mb pressure surface. The closeness of the contours show that fairly high winds occurred near the centre of the depression.

TABLE 1

Basic details of all voyages

VR	Date	Time	Route	VR	Date	Time	Route
1	3.3.48	11.35	Base—Newcastle—Base	29	9.7.48	9.20	Lisbon—Base
2	8.3.48	11.40	Base—Inverness—Base	30	12.7.48	13.10	Base—Inverness—Base
3	5.4.48	13.45	Base—Edinburgh—Base	31	15.7.48	09.05	Base—Rome
4*	6.4.48	11.15	Base—Inverness—Base	32	16.7.48	09.20	Rome—Base
5	14.4.48	14.05	Base—Sheffield—Base	33	20.7.48	08.58	Base—Scotland—Base
6	16.4.48	12.05	Base—Belfast—Base	34	22.7.48	08.35	Base—Rome
7*	21.4.48	11.10	Base—Lisbon	35	23.7.48	09.15	Rome—Base
8*	22.4.48	11.00	Lisbon—Base	36	29.7.48	14.35	Base—Land's End—Base
9	6.5.48	12.10	Base—Belfast—Base	37	30.7.48	13.55	Base—Dundee—Base
10	7.5.48	13.20	Base—Cornwall—Base	38	5.8.48	09.50	Base—Dundee—Base
11	13.5.48	14.10	Base—Hebrides—Base	39	26.8.48	13.20	Base—C. de la Hague—Base
12	14.5.48	9.10	Base—Kilkenny—Base	40	3.9.48	13.10	Base—Biscay—Base
13	19.5.48	—	Abortive trip	41	6.9.48	10.10	Base—Edinburgh—Base
14	24.5.48	14.10	Base—Anglesey—Base	42*	7.9.48	10.15	Base—Rome
15	25.5.48	13.10	Base—Bay/Biscay—Base	43	8.9.48	09.00	Rome—Base
16	14.6.58	9.55	Base—Anglesey—Base	44	10.9.48	13.05	Base—S. Shields—Base
17	15.6.48	14.20	Base—Newcastle—Base	45	13.9.48	13.20	Base—N. Scotland—Base
18	21.6.48	9.50	Base—57 N 10 W—Base	46	15.9.48	—	Abortive trip
19	22.6.48	13.10	Base—Orkneys—Base	47	16.9.48	13.20	Base—49N 08W—Base
20	24.6.48	12.10	Base—Lisbon	48	17.9.48	13.15	Base—Ireland—Base
21	25.6.48	9.00	Lisbon—Base	49	20.9.48	13.00	Base—Heligoland—Base
22	29.6.48	9.50	Base—Cornwall—Base	50	21.9.48	10.20	Base—Stockholm
23	30.6.48	10.15	Base—Lisbon	51	22.9.48	09.15	Stockholm—Base
24	1.7.48	9.20	Lisbon—Base	52	20.10.48	10.15	Base—Dundee—Base
25	5.7.48	13.30	Base—N. Wales—Base	53	27.10.48	09.45	Base—Southampton—Base
26	6.7.48	9.50	Base—Copenhagen	54*	28.10.48	13.40	Base—Isle of Man—Base
27*	6.7.48	14.10	Copenhagen—Base	55	3.11.48	10.10	Base—Ireland—Base
28	8.7.48	10.00	Base—Lisbon	56	10.11.48	11.05	Base—N. Sea—Base

TABLE 1—*continued*

VR	Date	Time	Route	VR	Date	Time	Route
57	11.11.48	10.40	Base—Land's End—Base	86	12.5.49	10.20	Base—Stockholm
58	17.11.48	11.30	Base—N. Wales—Base	87	13.5.49	09.30	Stockholm—Base
59	18.11.48	14.30	Base—Lundy Island—Base	88	17.5.49	10.30	Base—Limerick—Base
60*	8.12.48	11.50	Base—Isle of Man—Base	89	20.5.49	10.00	Base—Brest—Base
61	15.12.48	14.05	Base—Isle of Man—Base	90	1.6.49	10.30	Base—Rome
62	16.12.48	11.30	Base—Paris—Base	91*	2.6.49	10.10	Rome—Base
63	23.12.48	11.30	Base—Anglesey—Base	92	7.6.49	13.30	Base—The Wash—Bash
64	19.1.49	13.50	Base—51N 04W—Base	93	9.6.49	13.40	Base–Stornoway–Aberdeen
65	21.1.49	11.25	Base—Paris—Base	94*	10.6.49	10.20	Aberdeen—Base
66	1.3.49	11.40	Base—Lorient—Base	95	14.6.49	10.50	Base—Oslo
67	4.3.49	10.50	Base—Lisbon	96	15.6.49	13.20	Base—56N 08W—Base
68	5.3.49	10.00	Lisbon—Base	97	16.6.49	11.15	Oslo—Base
69	9.3.49	11.05	Base—Paris—Base	98	17.6.49	14.35	Base—54N 04E—Base
70	11.3.49	11.25	Base—The Hague—Base	99	21.6.49	10.00	Base—Stockholm
71	15.3.49	10.55	Base—Lisbon	100	21.6.49	10.00	Base—Lisbon
72	16.3.49	10.10	Lisbon—Base	101	22.6.49	10.15	Stockholm—Base
73	17.3.49	11.30	Base—Edinburgh—Base	102	22.6.49	10.00	Lisbon—Base
74	18.3.49	10.25	Base—The Wash—Base	103	29.6.49	10.05	Base—Stockholm
75	22.3.49	13.40	Base—Prestwick—Base	104	30.6.49	10.10	Stockholm—Aberdeen
76	23.3.49	13.40	Base—Gt. Yarmouth—Base	105	1.7.49	11.30	Aberdeen—Base
77	31.3.49	15.10	Base—Cromer—Base	106*	5.7.49	09.30	Base—Lisbon
78	8.4.49	13.25	Base—Portland Bill—Base	107	6.7.49	10.00	Lisbon—Base
79	14.4.49	13.40	Base—51N 04W—Base	108	7.7.49	13.35	Base—Inverness—Base
80*	22.4.49	09.20	Local	109	12.7.49	10.05	Base—Paris—Lisbon
81*	25.4.49	12.15	Local	110	13.7.49	09.15	Lisbon—Gibraltar
82	26.4.49	09.25	Local	111	14.7.49	07.50	Gibraltar—Base
83	28.4.49	10.20	Base—56N 04W—Base	112*	14.7.49	09.55	Base—Copenhagen
84	5.5.49	10.20	Local	113	14.7.49	15.15	Copenhagen—Base
85	9.5.49	10.20	Base—Stornoway—Base	114	18.7.49	13.10	Base—Paris—Gibraltar

TABLE 1—*continued*

VR	Date	Time	Route	VR	Date	Time	Route
115	20.7.49	08.30	Gibraltar—Base	144	17.10.49	18.30	Base—Perth—Base
116	19.7.49	13.25	Base—N. England—Base	145	19.10.49	10.00	Base—Copenhagen
117	20.7.49	09.20	Base—Scillies—Base	146	20.10.49	10.00	Copenhagen—Base
118	22.7.49	21.30	Base—Land's End—Base	147	19.10.49	13.40	Base—Inverness—Base
119	22.7.49	21.30	Base—Mull of Galloway to Base	148	20.10.49	10.00	Base—Inverness—Base
120	25.7.49	10.05	Base—Lisbon	149	21.10.49	18.15	Base—Newcastle—Base
121	27.7.49	08.35	Lisbon—Paris—Base	150	25.10.49	10.00	Abortive trip
122	25.7.49	10.05	Base—Oslo	151	26.10.49	13.00	Base—Keflavik
123	26.7.49	10.40	Oslo—Renfrew	152	28.10.49	13.50	Keflavik—Base
124	27.7.49	11.10	Renfrew—Base	153	26.10.49	11.10	Base—Newcastle—Base
125	6.9.49	14.00	Base—G. Yarmouth—Base	154	27.10.49	10.00	Base—Land's End—Base
126	8.9.49	—	Abortive trip	155	1.11.49	14.15	Base—North Sea—Base
127	9.9.49	—	Abortive trip	156	4.11.49	19.00	Base—Tory Island—Base
128	12.9.49	10.25	Base—Rome	157	24.11.49	14.00	Base—Inverness—Base
129	13.9.49	09.25	Rome—Base	158	25.11.49	12.30	Base—Moorside Edge—Base
130	15.9.49	10.00	Base—Stockholm	159*	29.11.49	11.00	Base—Madrid
131*	16.9.49	10.35	Stockholm—Base	160	30.11.49	11.25	Madrid—Base
132	20.9.49	09.50	Base—Rome	161	1.12.49	11.10	Lisbon—Base
133	21.9.49	10.00	Rome—Base	162	2.12.49	10.40	Base—Edinburgh—Base
134	22.9.49	13.25	Base—Brest—Base	163	6.12.49	11.25	Base—Munster—Base
135*	23.9.49	09.25	Base—Anglesey—Base	164	12.12.49	12.00	Local
136	27.9.49	09.25	Base—Copenhagen	165	13.12.49	11.00	Base—Lisbon
137	28.9.49	10.10	Copenhagen—Base	166	14.12.49	11.10	Lisbon—Gibraltar
138*	27.9.49	09.45	Base—Gibraltar	167	20.12.49	11.15	Base—Stockholm
139	28.9.49	09.00	Gibraltar—Base	168	21.12.49	10.15	Stockholm—Base
140	29.9.49	13.00	Abortive trip	169	4.1.50	14.05	Base—Heligoland—Base
141	5.10.49	10.20	Base—Stornoway—Base	170	5.1.50	11.00	Base—Rome
142	6.10.49	13.45	Base—52N 12W—Base	171	6.1.50	11.15	Rome—Base
143	12.10.49	10.00	Base—Malin Head—Base	172	10.1.50	11.00	Base—Lisbon

TABLE 1—*continued*

VR	Date	Time	Route
173	11.1.50	10.40	Lisbon—Gibraltar
174	12.1.50	10.00	Gibraltar—Base
175	11.1.50	11.30	Base—Inverness—Base
176*	12.1.50	14.10	Local
177	13.1.50	17.00	Local
178	17.1.50	15.00	Base—Dundee—Base
179*	18.1.50	11.00	Base—Rome
180	19.1.50	11.00	Rome—Base
181	20.1.50	17.00	Base—Land's End—Base
182	24.1.50	11.00	Base—Stockholm
183	25.1.50	11.30	Stockholm—Copenhagen
184	26.1.50	16.30	Copenhagen—Base
185	24.1.50	11.30	Base—49N 08W—Base
186	25.1.50	11.00	Base—Copenhagen
187	26.1.50	12.00	Copenhagen—Base

Notes :—

(i) Time is G.M.T. at take-off. Duration of flights 2 to 3 hours.

(ii) * denotes 'positive ' voyage.

(iii) Abortive trips were generally due to failures of essential equipment.

TABLE 2

Details of 'Positive' Voyages

Ref. No. Locality Date	Position G.M.T.	Horizontal Extent	Vertical Extent (feet)	Max. Acc. Eq. Gust Vel	Tropopause (feet)	Features of High Level Chart	$\partial T/\partial Z$	$\partial V/\partial Z$	$\partial V/\partial s$	Polar Front	Remarks
VR 4 Braemar 6.4.48	57.00N 03.20W 13.20	50 miles	18,500 to 20,000	$0{\cdot}55g$ 19 ft/sec	32,000 not associated	Jet stream	Stable part isothermal	High	High	On p.f.	On jet stream boundary
VR. 7 Brest 21.4.48	48.00N 03.00W 12.25	No Search	20,000 to 30,000	$0{\cdot}35g$ 14 ft/sec	35,000 approx.	Shallow depression	Stable	No detail appears low	Normal	Doubtful	—
VR. 8 N. Spanish Coast 22.4.48	43.50N 05.55W 12.40	,,	30,000 to 35,000	$0{\cdot}3g$ 12 ft/sec	30,000 approx.	Shallow L.P. trough	Isothermal	,,	,,	,,	Tropopause
VR. 27 Heligoland 6.7.48	54.00N 07.50E 15.20	About 50 miles	32,000 to 33,500	$0{\cdot}2g$ 10 ft/sec	33,500	Moderate L.P. trough	Almost Isothermal	,,	,,	,,	Associated with tropopause
VR. 42 Genoa 7.9.48	44.33N 08.08E 12.40	About 60 miles	20,000 to 22,000	$0{\cdot}3g$ 11 ft/sec	38,000 not associated	Moderate L.P. trough deepening	Stable marginal	Moderate	Normal	Not associated	
VR. 54 Gloucester 28.10.48	52.00N 02.25W 14.30	No Search	23,500 to 26,000	$0{\cdot}2g$ 8 ft/sec	31,500 not associated	Shallow depression	Just Stable	Low	Low	Doubtful	
VR. 60 Stoke-on-Trent 8.12.48	53.00N 02.30W 13.00	About 30 miles in one direction	17,000 to 28,700	$0{\cdot}7g$ 26 ft/sec	Possible double tropopause at 28,700 and 33,000	Jet stream	Stable to very stable	Moderate	Moderate	Associated	Jet stream

$\partial T/\partial Z$ from aircraft observations ; $\partial V/\partial Z$ and $\partial V/\partial s$ from synoptic charts.

TABLE 2—*continued*

Ref. No. Locality Date	Position G.M.T.	Horizon-tal Extent	Vertical Extent (feet)	Max. Acc. Eq. Gust Vel.	Tropo-pause (feet)	Features of High Level Chart	$\partial T/\partial Z$	$\partial V/\partial Z$	$\partial V/\partial s$	Polar Front	Remarks
VR. 80 Cranfield 22.4.49	52.05N 00.20W 10.00	No Search	36,000 to ?	$0 \cdot 3g$ 15 ft/sec	34,500	Moderate L.P. trough	Iso-thermal	Moderate	Moderate	Not asso-ciated	Smooth lift (1,500 to 2,000 ft/min) found from 34,500 ft to 36,000 ft followed by turbulence
VR. 81a Cranfield 25.4.49	52.05N 00.20W 12.00	No Search	32,000 to 33,000	$0 \cdot 2g$ 11 ft/sec	33,000	Deep L.P. trough	Very Stable	Moderate to low	Low	Asso-ciated	Just below tropopause
VR. 81b Cranfield 25.4.49	52.05N 00.20W 12.20	No Search	22,500 to 23,500	$0 \cdot 2g$ 8 ft/sec	Not asso-ciated	,,	,,	Uncer-tain	Low	,,	
VR. 91 N. France 2.6.49	49.32N 02.02E 12.40	No Search	22,000 to 25,000	$0 \cdot 3g$ 11 ft/sec	30,000 steep slope	,,	Stable	Moderate	Moderate	Doubtful	
VR. 94 North Sea 10.6.49	53.00N 02.00E 12.20	60 miles by 30 miles	22,000 to 26,000	$0 \cdot 6g$ 24 ft/sec	30,000	Very shallow L.P. trough	Part stable, part unstable	Uncer-tain	Low	Doubtful	Turbulence associated with peculiar cirrus formation
VR. 106 Cranfield to Lisbon 5.7.49	On most of route Search made at 43.00N 06.30W 13.30	Brest Peninsula to Portu-gal (About 500 miles)	32,000 to 34,000	$0 \cdot 2g$ 10 ft/sec	40,000 falling to 35,000	Almost feature-less	Stable	Low	,,	Not asso-ciated	
VR. 112 Skager-rack 14.7.49	57.00N 09.00E 12.00	About 100 miles	Slight turbulence from 24,000 to 35,000	$0 \cdot 2g$ 7 ft/sec	About 35,000	Slack gradient between two depressions	Just stable	,,	,,	,,	Ahead of dense, cumulo-nimbus, possibly thermal instability

$\partial T/\partial Z$ from aircraft observations ; $\partial V/\partial Z$ and $\partial V/\partial s$ from synoptic charts.

TABLE 2—*continued*

Ref. No. Locality Date	Position G.M.T.	Horizontal Extent	Vertical Extent (feet)	Max. Acc. Eq. Gust Vel.	Tropopause (feet)	Features of High Level Chart	$\partial T/\partial Z$	$\partial V/\partial Z$	$\partial V/\partial s$	Polar Front	Remarks
VR. 131 N. Sea 16.9.49	54.10N 04.40E 13.00	15 miles E.W. Not known N.S.	29,500 to 33,000	$0{\cdot}4g$ 20 ft/sec	32,500	Moderate depression	Part isothermal, part just stable	Low	Low	Doubtful	Each side of the tropopause, associated with a band of cirro-stratus
VR. 135 N. Wales 22.9.49	52.35N 03.58W 10.40	Uncertain about 60 miles diameter	30,000 to 32,000	$0{\cdot}2g$ 11 ft/sec	31,000	Moderate depression	Stable part isothermal	Moderate	Moderate	Doubtful	Associated with tropopause
VR. 138 N. Spain 27.9.49	42.33N 03.45W 12.00	About 30 miles diameter	19,000 to 21,000	$0{\cdot}4g$ 14 ft/sec	About 38,000 not associated	Shallow depression	Isothermal between almost unstable layers	Low	,,	Not associated	Horizontal temperature variation found
VR. 159 N.E. Spain 29.11.49	41.45N 00.20W 13.40	No Search	At about 30,000	$0{\cdot}2g$ 8 ft/sec	About 30,000	Shallow depression	Not known	,,	Low	Doubtful	Altimeter was unserviceable
VR. 176 Cranfield 12.1.50	52.15N 00.55W 15.00	About 30 miles	35,000 to 36,000	$0{\cdot}3g$ 12 ft/sec	34,500	High pressure ridge	Isothermal	Moderate	,,	Not associated	Horizontal temperature variation found
VR. 179 Montreux 18.1.50	46.30N 07.00E 13.00	About 100 miles	27,500 to 31,000	$0{\cdot}4g$ 16 ft/sec	27,000	Moderate depression	Almost isothermal	Low	,,	Doubtful	Horizontal temperature variation found

$\partial T/\partial Z$ from aircraft observations ; $\partial V/\partial Z$ and $\partial V/\partial s$ from synoptic charts.

TABLE 3

Distance flown and number of gusts encountered in various height bands

Height feet	Distance st. ml.	Sign	Gust velocity–ft/sec E.A.S. 4–8	8–12	12–16	16–20	20–24	24–28
15 to 20,000	12,093	+	713	81	7·5	3	—	0·5
		—	415	34	11	0·5	—	—
20 to 25,000	23,426	+	1271	130	32·5	13	4	2·5
		—	1089	123	26	4·5	2	—
25 to 30,000	25,907	+	1606	159	51·5	16·3	4	2·5
		—	1093	118	22	6·5	2	—
30 to 35,000	26,494	+	2457	241	32	3·3	—	—
		—	1480	101	9	2	—	—
>35,000	4,366	+	446	34	3	—	—	—
		—	241	19	2	—	—	—
All heights	92,286	+	6493	645	126·5	35·6	8	5·5
		—	4318	395	70	13·5	4	—

Note : The fractional numbers of gusts result from the fact that the number of gusts actually recorded in a turbulent layer was corrected when the recording distance did not correspond with the horizontal extent of the layer.

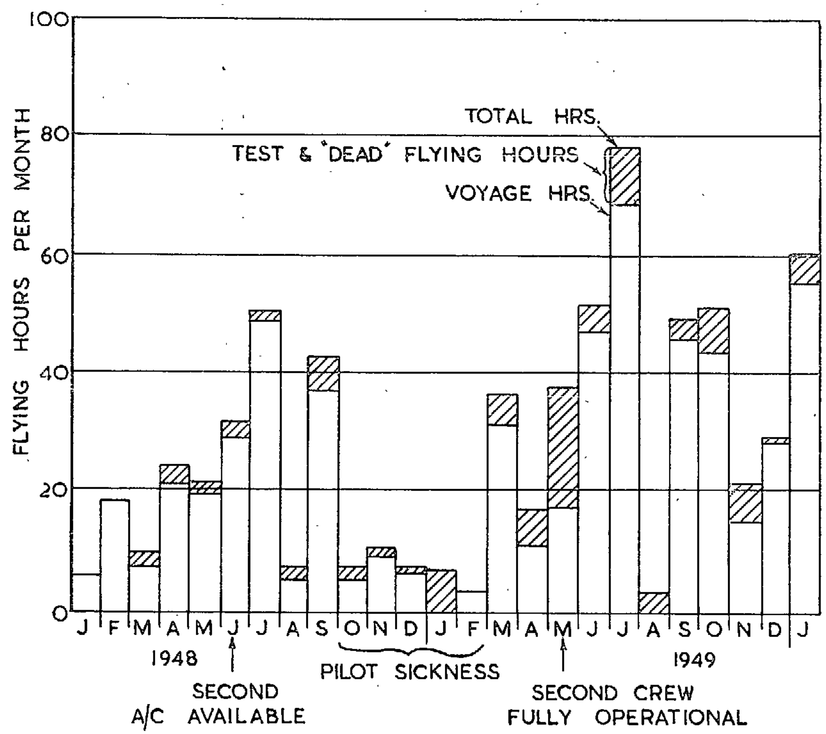


FIG. 1. Monthly flying rate.

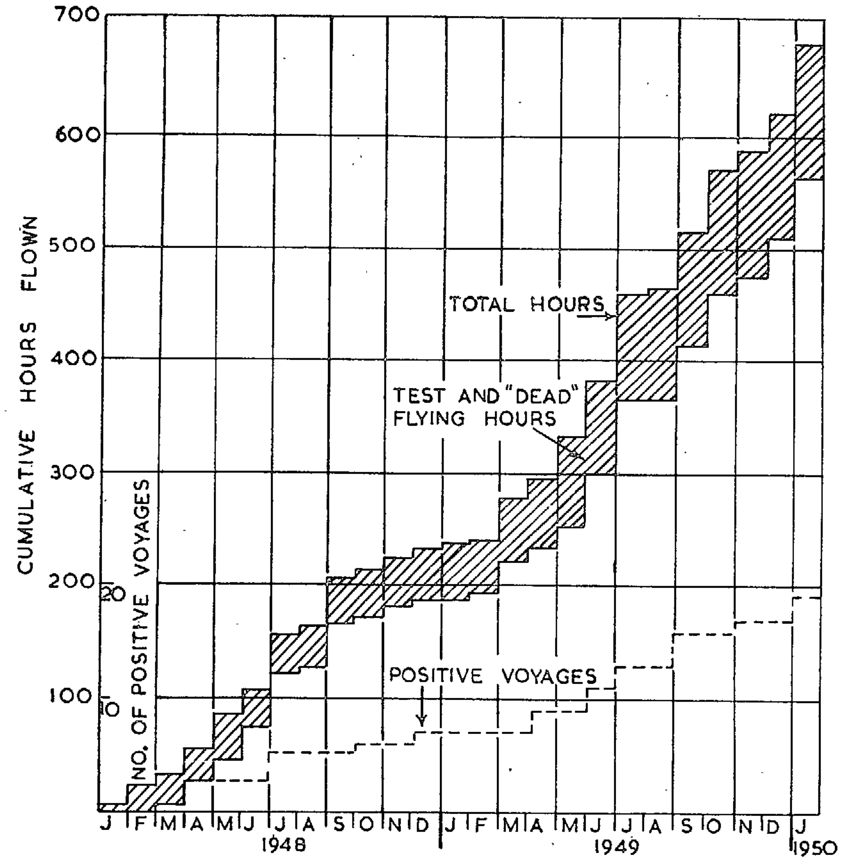


FIG. 2. Cumulative hours flown.

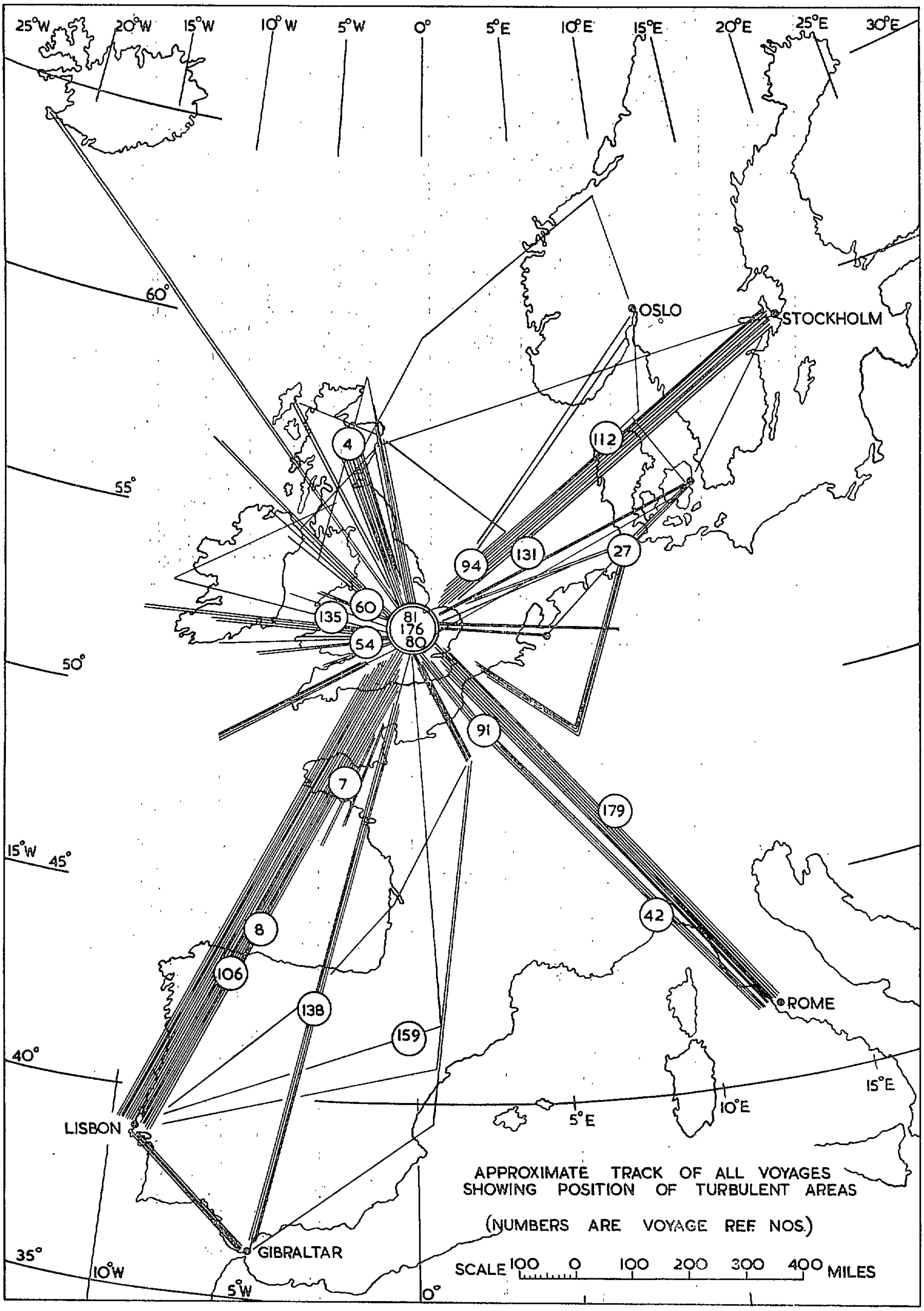


Fig. 3. B.E.A. clear-air gust research.

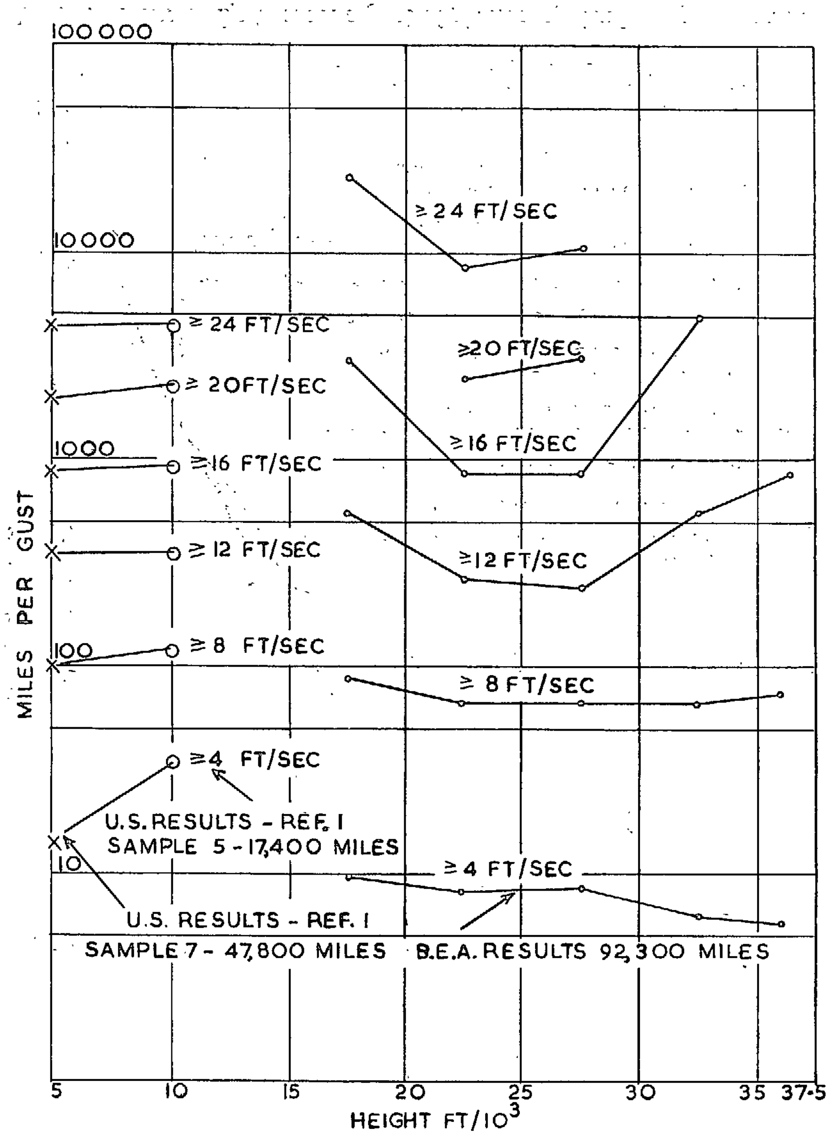


FIG. 4. Miles to fly to meet a gust of given magnitude or greater versus altitude.

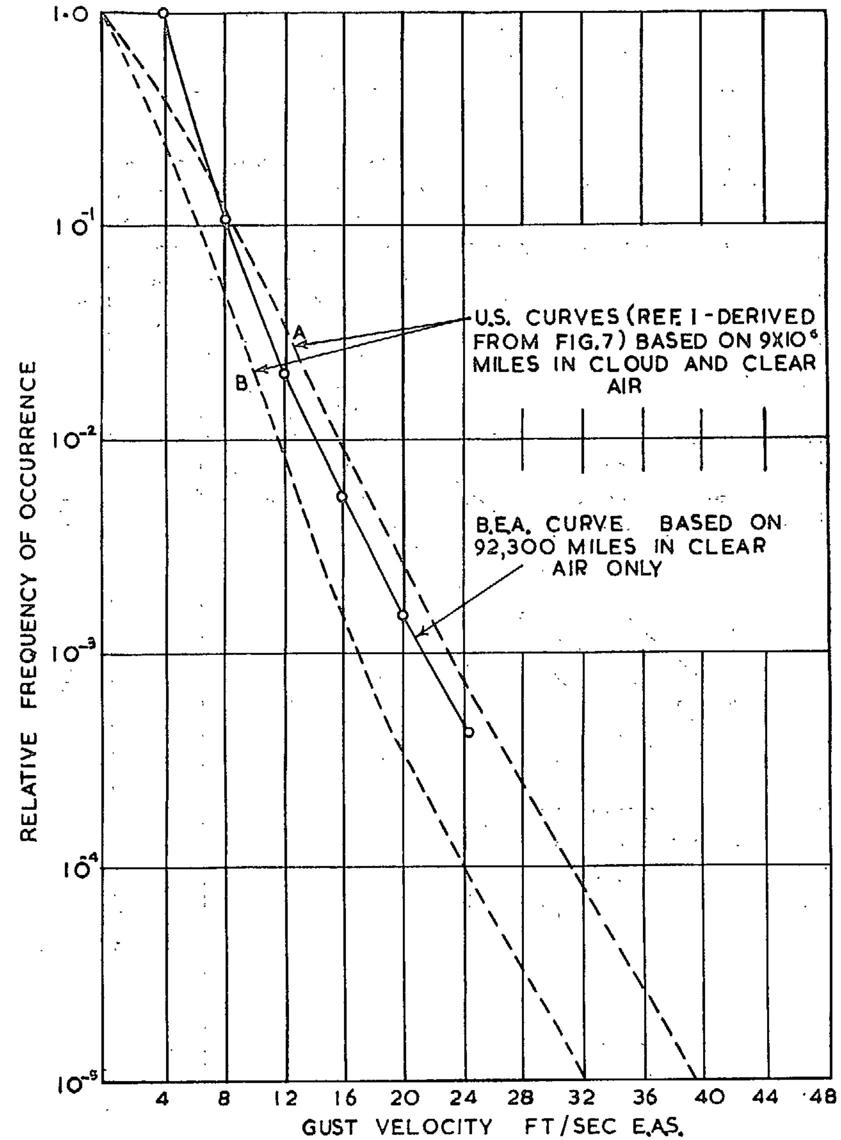


FIG. 5. Relative frequency of occurrence of gusts of various magnitudes.

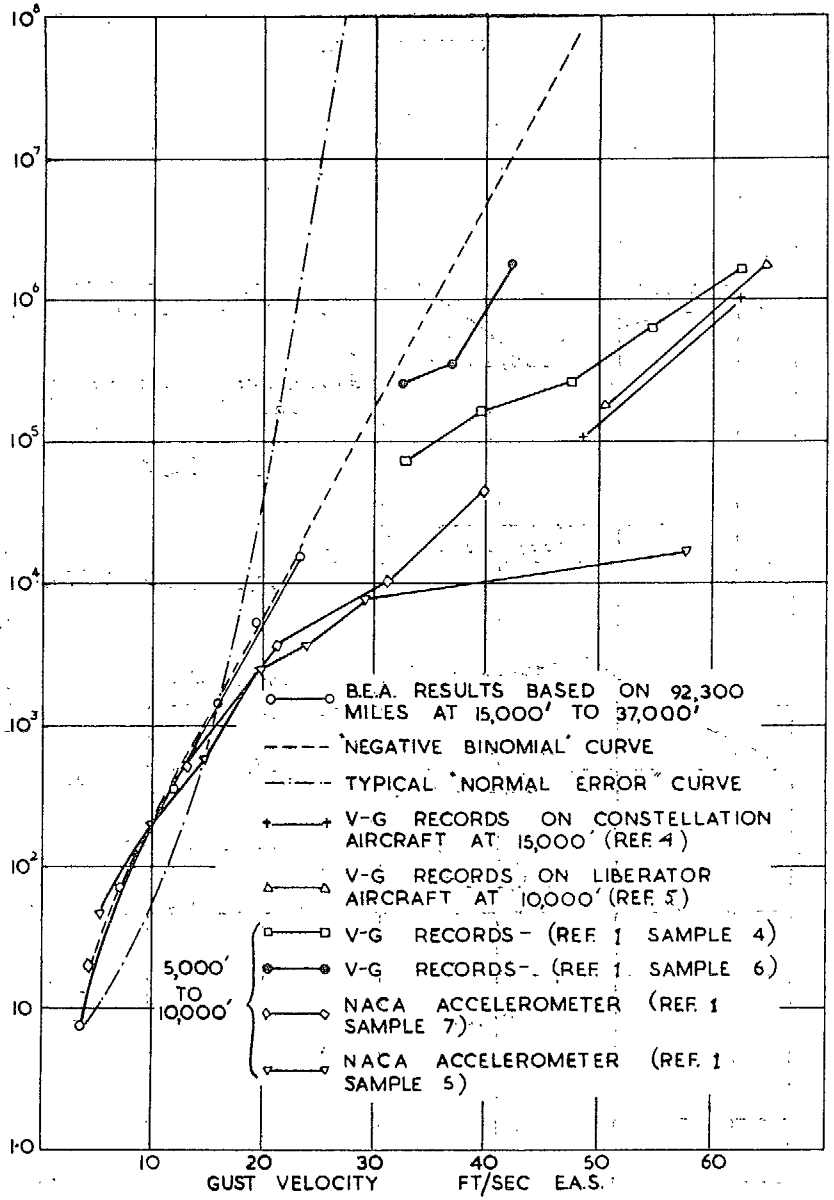


FIG. 6. Miles to fly to meet a gust of given magnitude or greater versus gust magnitude.

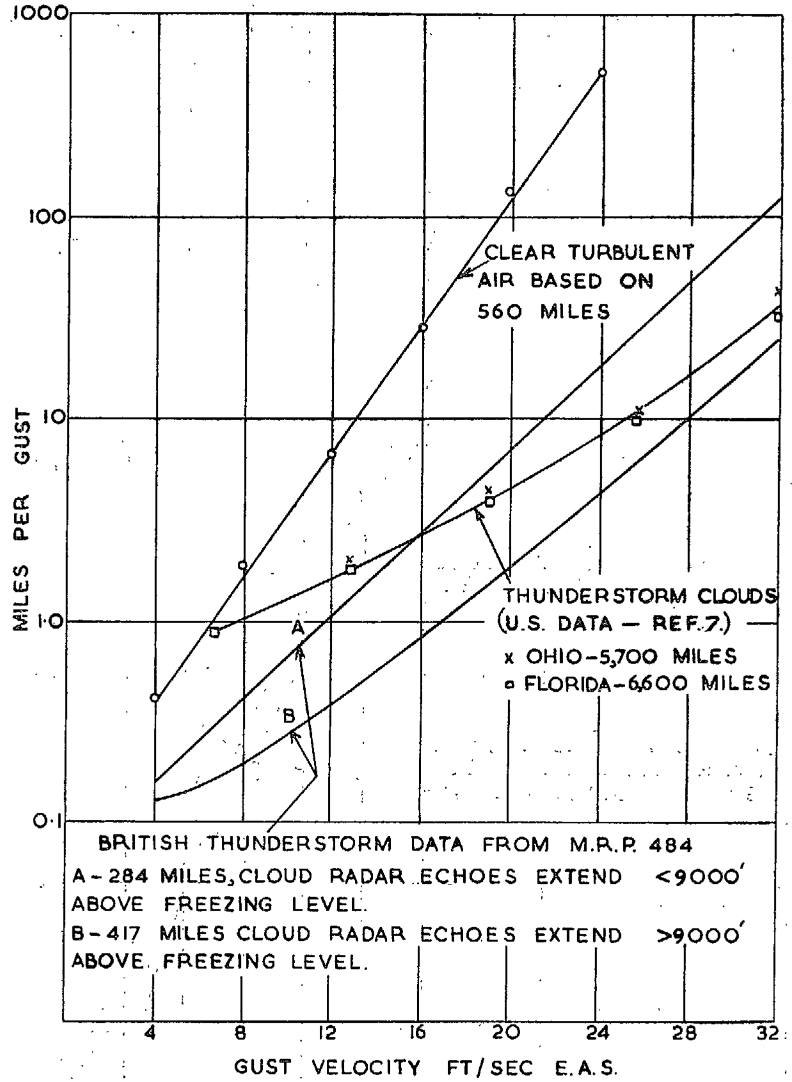


FIG. 7. Comparison of mean gust spacing in clear turbulent air and in thunderstorm clouds.

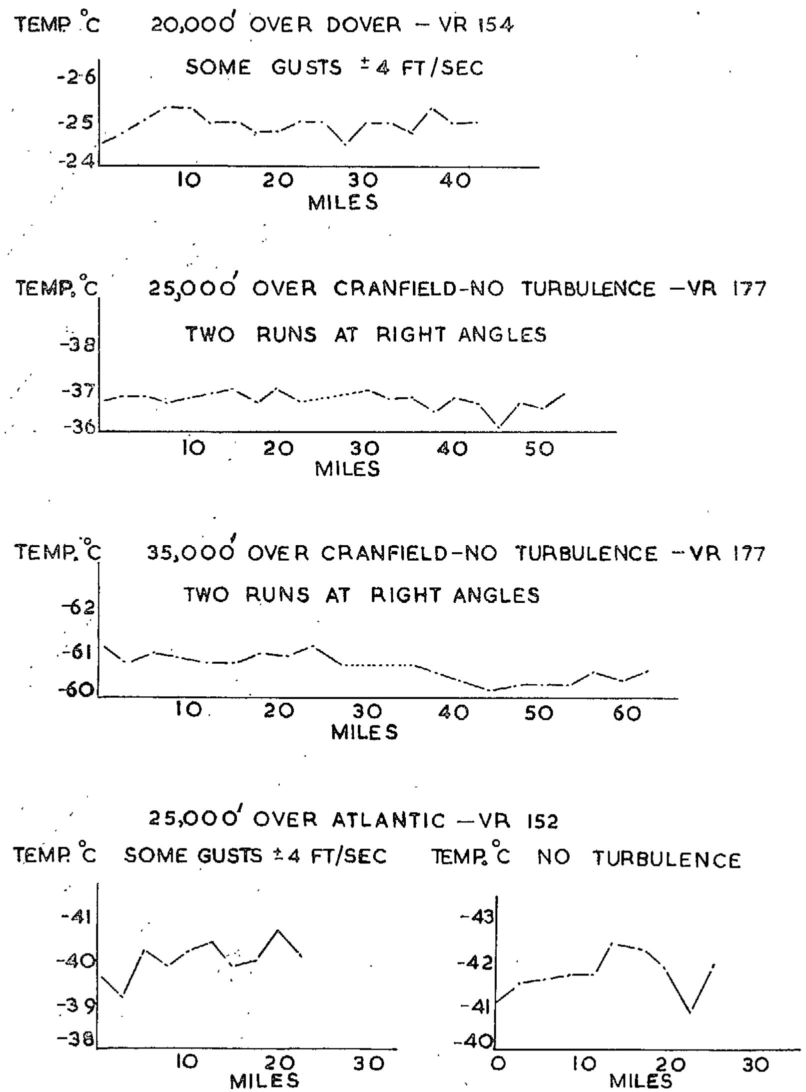


Fig. 8. Horizontal temperature, traverses in smooth air. ($\leqslant$ 4 ft/sec gusts)

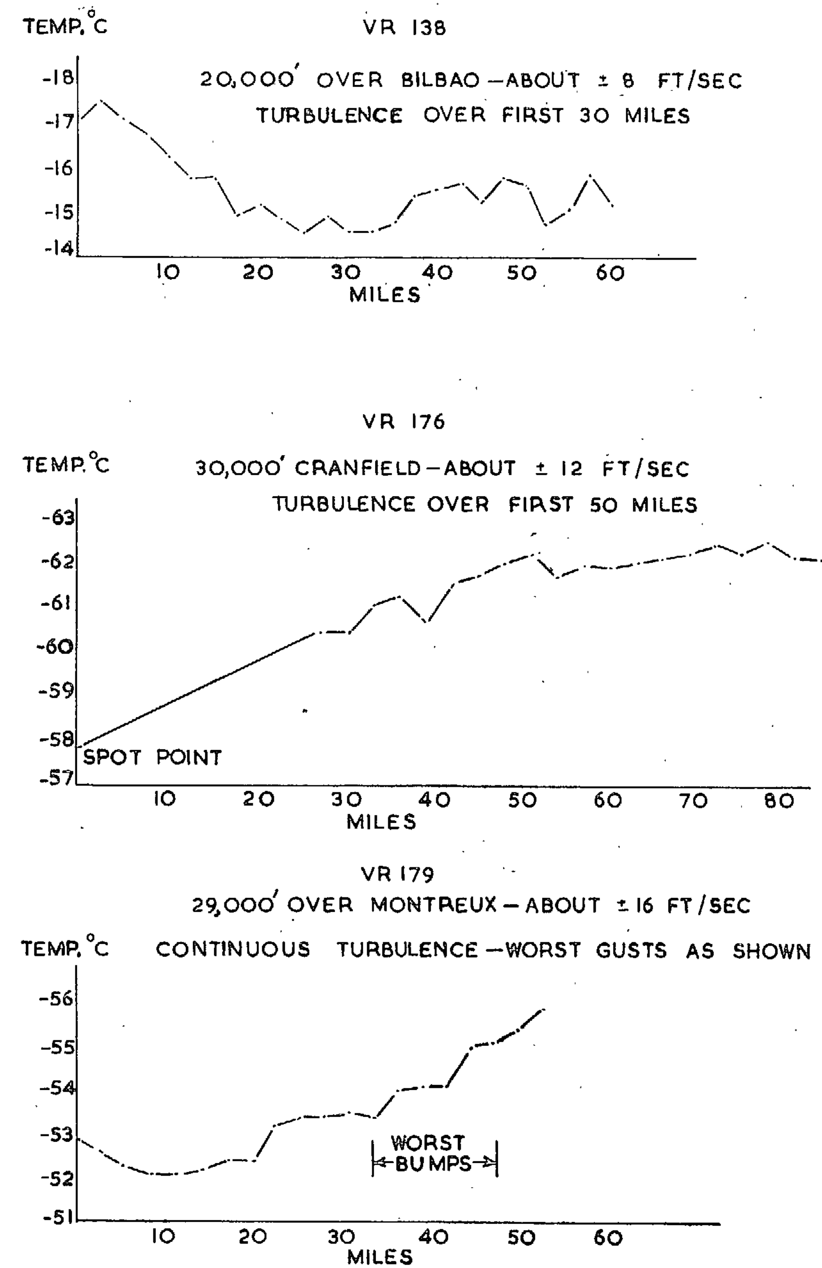
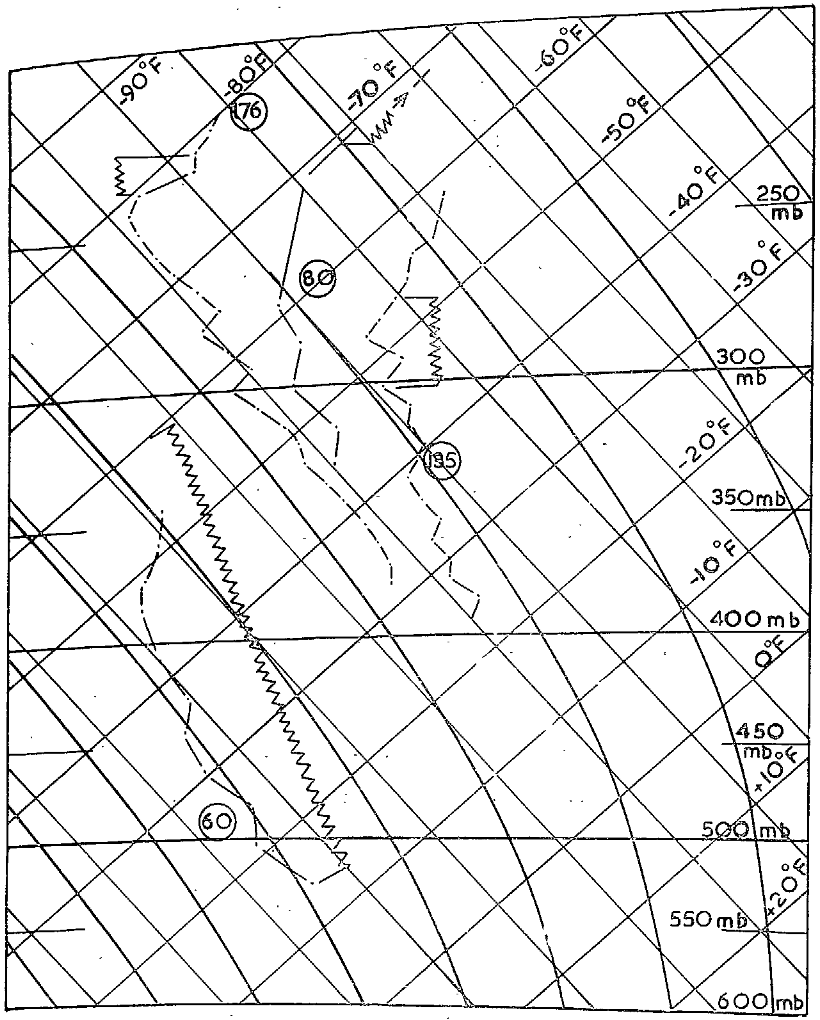
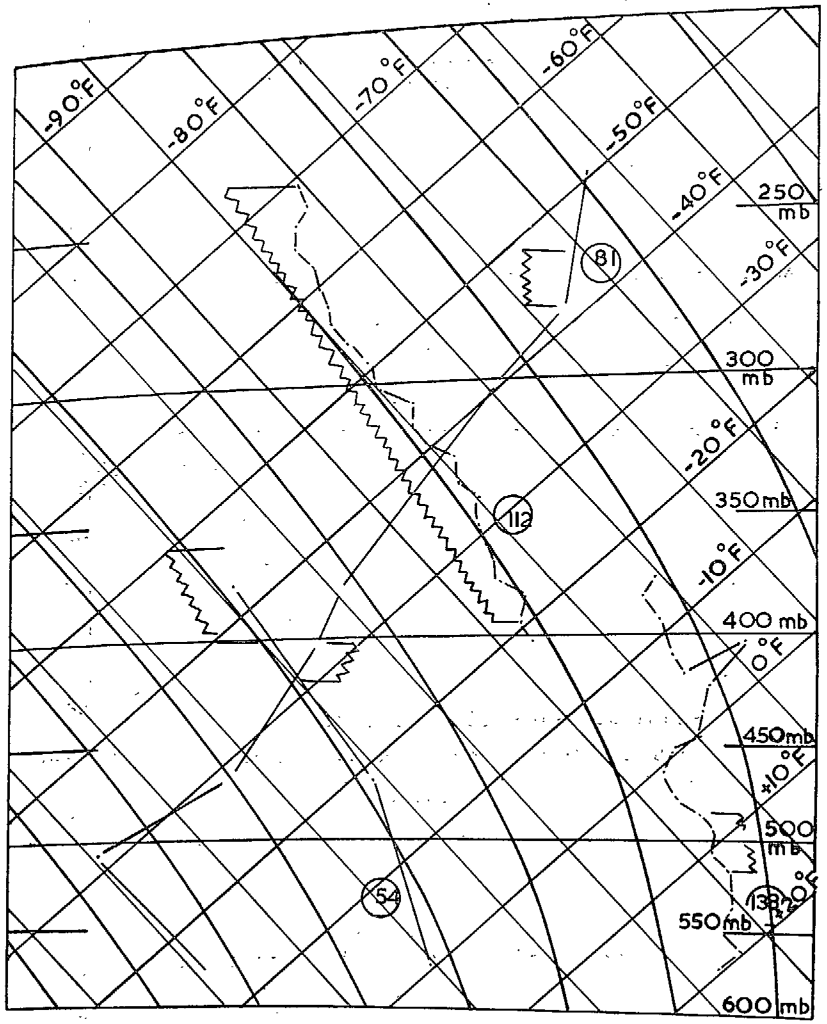


Fig. 9. Horizontal temperature traverses in turbulent air.



TEMPERATURE VARIATION SHOWN
EXTENT OF TURBULENCE SHOWN

FIG. 10. Tephigrams of positive voyages.



TEMPERATURE VARIATION SHOWN
EXTENT OF TURBULENCE SHOWN

FIG. 11. Tephigrams of positive voyages.

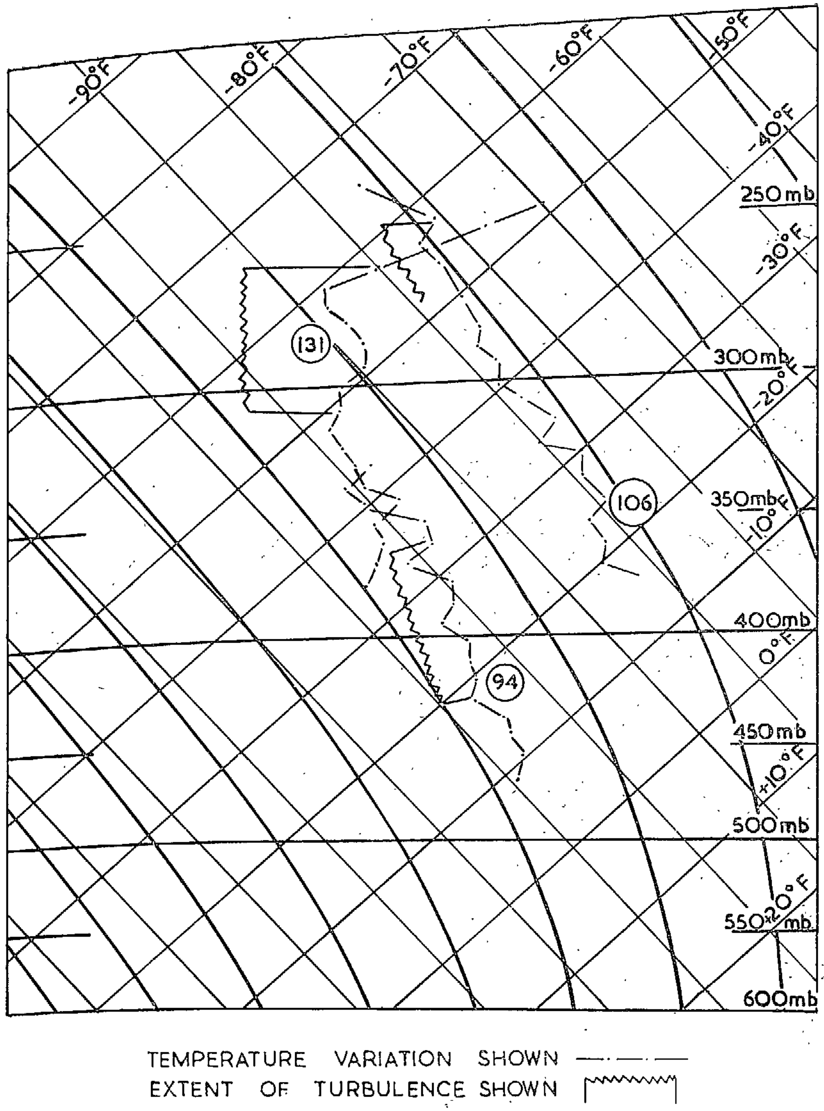


Fig. 12. Tephigrams of positive voyages.

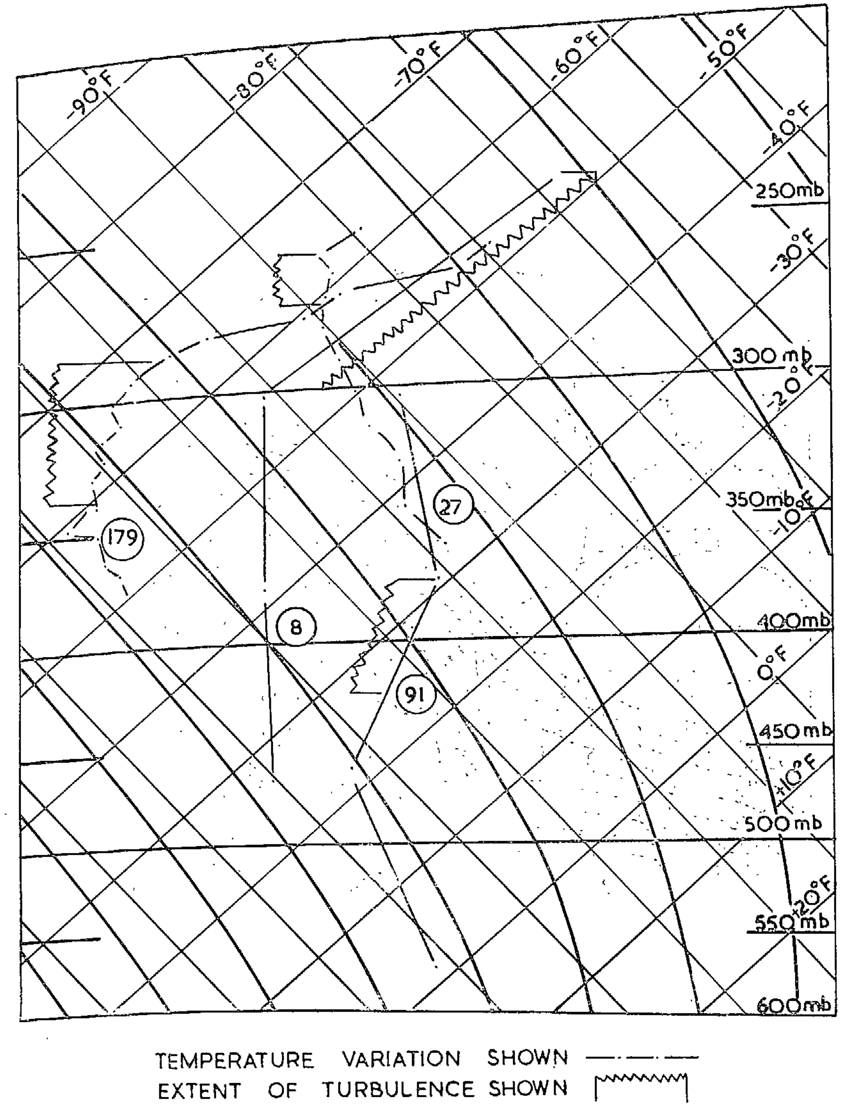
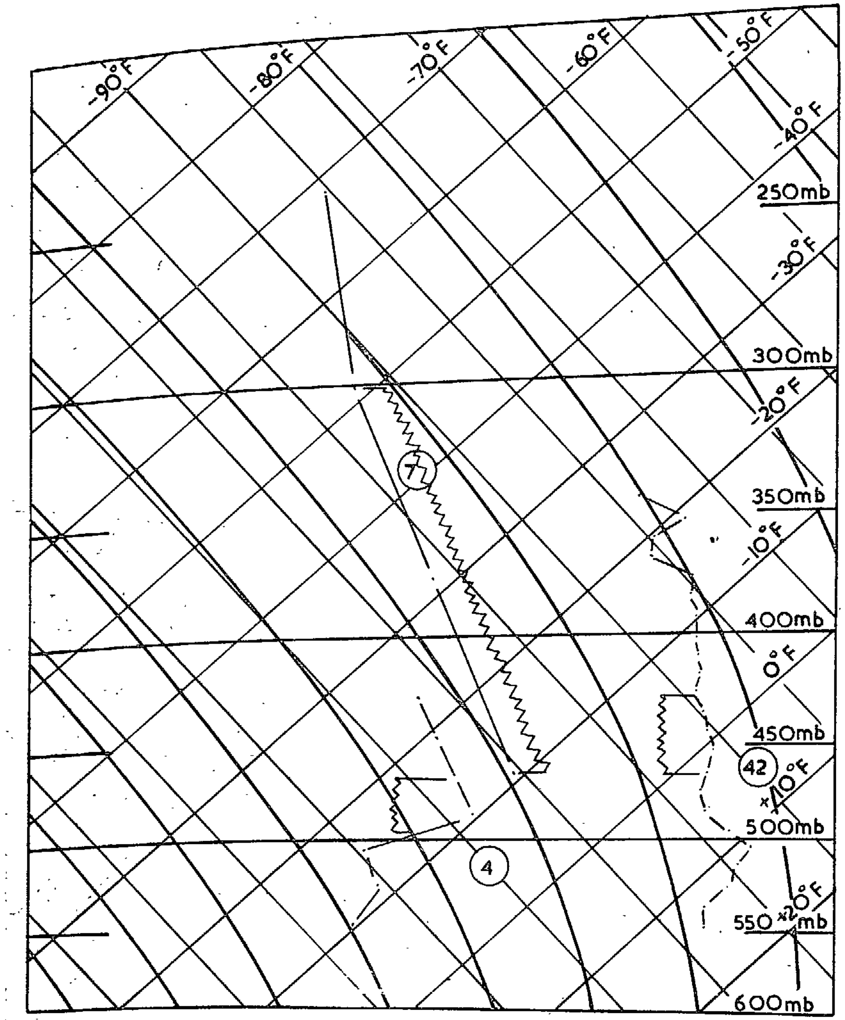


Fig. 13. Tephigrams of positive voyages.



TEMPERATURE VARIATION SHOWN

EXTENT OF TURBULENCE SHOWN

FIG. 14. Tephigrams of positive voyages.

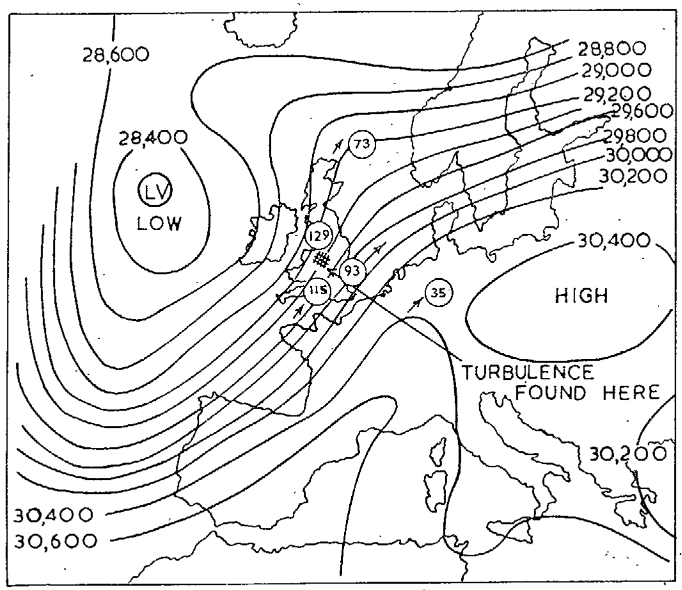


FIG. 15. Example of jet stream shown at 300 mb surface (From VR. 60).

J4282 Wt.13/680 K9 9/52 D&Co. 34/263

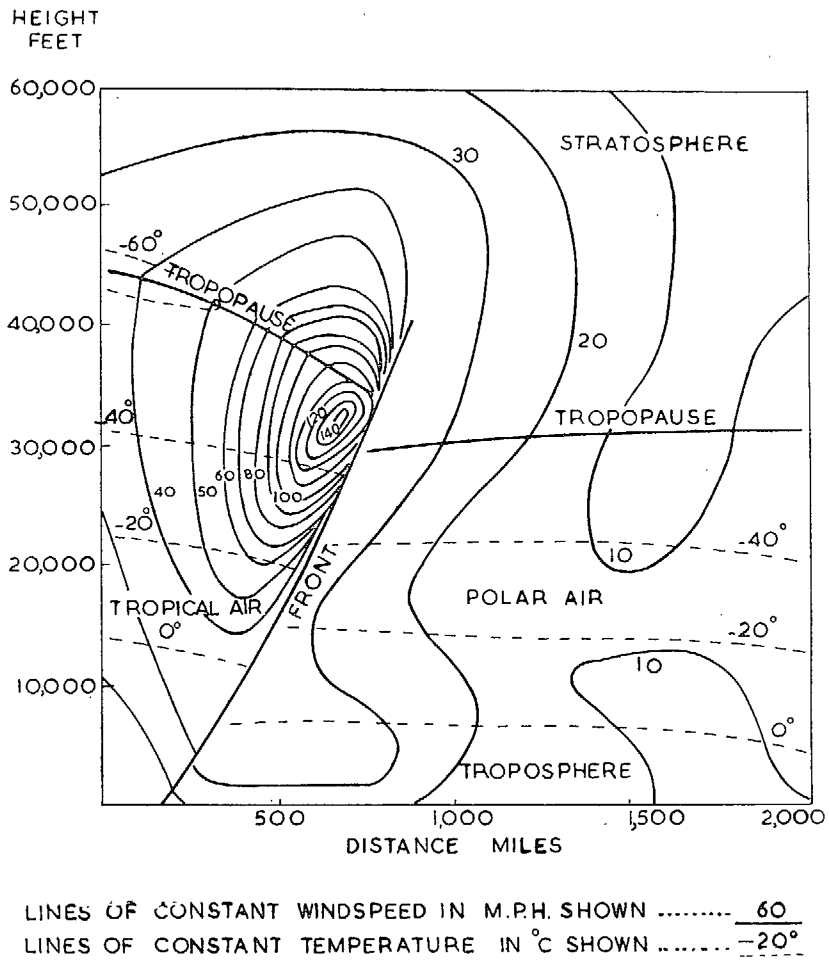


FIG. 16. Vertical cross-section through representative 'jet stream'.

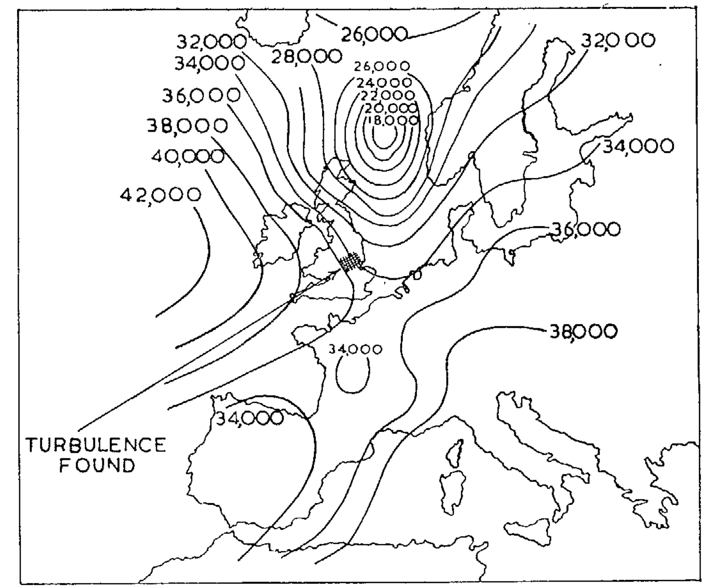


FIG. 17. A steeply sloping tropopause (From VR. 80).

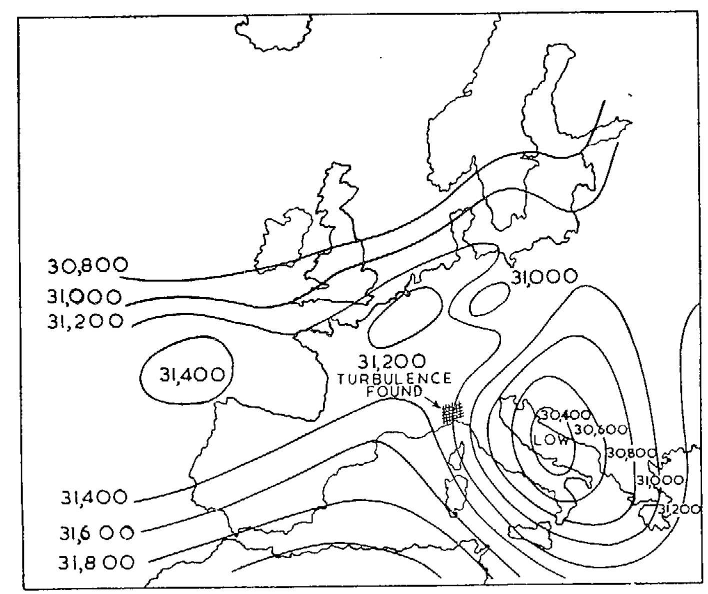


FIG. 18. Example of upper air depression shown at 300 mb surface (From VR 42).

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