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METEOROLOGICAL ASPECTS OF TURBULENCE AFFECTING AIRCRAFT AT HIGH ALTITUDE

By J. K. Bannon, B.A.

Introduction.—Atmospheric turbulence is sometimes sufficiently severe and its eddies are of the appropriate linear scale to have a noticeable effect on an aircraft, resulting in irregular accelerations of the machine known as " bumps ". At low levels, say at heights below 5,000 ft., the occurrence of such bumps has long been realized and understood; the flow of the wind over irregular country or the up-and-down currents resulting from convection are recognized as capable of causing the turbulence. At heights above the ground at which the frictional effect of the earth's surface in causing turbulence is usually negligible, say at heights above 5,000 ft., turbulence is well known to occur in association with large cumulus or cumulonimbus clouds, and this type of bumpy conditions may be found at all heights in the troposphere on occasions and can be very severe.

It was expected that as flying conditions in clear air at medium levels, about 10,000 ft., are usually smooth, flying in the upper troposphere, above 20,000 ft., would be almost invariably smooth except in the vicinity of cumulonimbus clouds. Within the last ten years, however, it has been realized that flying in the upper troposphere and lower stratosphere may be bumpy, sometimes uncomfortably so, even when no clouds are present at these levels. Such turbulence cannot be directly due to the eddies set up by the flow of the air over the ground or by ordinary surface-induced convection. It would seem that it must be caused by the relative motions of the air at different heights or in different zones in the horizontal; ordinary convectional eddies caused by layers of air becoming statically unstable may occur occasionally at these levels, when they are usually discernible by the formation of cumuliform cloud, but in the majority of cases of bumpiness the cause must be frictional.

Though attention was first drawn to this " frictional " turbulence at great heights, it seems clear that it can occur at all heights down to the surface layers, where it presumably merges into the turbulence caused by the rough surface of the earth and ordinary small-scale convection. That it has not received attention at medium heights is probably because bumpiness occurs there comparatively frequently in and near layers of cloud which are convectively unstable, so that flyers become accustomed to bumpiness at these levels and are thus not unduly surprised when it occurs in clear air. This clear-air turbulence has, in fact, been reported at medium levels on many occasions.

Attention has been concentrated on bumpiness in the upper troposphere (above 20,000 ft.) and lower stratosphere in view of its importance to high-flying aircraft which, in other respects, are usually " above the weather ". From the meteorological point of view it is in some ways an advantage to consider only the upper troposphere and lower stratosphere, as instances of pure convective turbulence are comparatively rare at these altitudes and it is possible to separate the two types of turbulence for study.

The present note sets out data on the frequency of occurrence of high-altitude turbulence, its severity, distribution with height, and other details. It also gives the results of a meteorological analysis of turbulence incidents which attempted to trace the physical causes of the turbulence, or at any rate to relate it to some physical parameter. The note also draws attention to weather situations which are most favourable for the occurrence of high-altitude turbulence. In the analysis little attempt was made to relate either the severity or the frequency (number per minute) of the bumps with the meteorological features; the occurrence of turbulence was mainly considered. Turbulence associated with cumulonimbus cloud was not considered.

Observations.—Observations available for the investigation of turbulence affecting aircraft at high altitude were in two categories, instrumental (quantitative) and non-instrumental (qualitative assessments).

A series of experimental flights was made over southern England, at the instance of the Ministry of Supply, by Spitfires from the Royal Aircraft Establishment (R.A.E.). The flights were made specifically to explore turbulence in clear air on all suitable days over the period July 1946–November 1948. The observations extended from 20,000 to 40,000 ft. and provide the largest part of the instrumental data.

By arrangement with the Ministry of Supply, British European Airways operated specially equipped Mosquito aircraft over regular airline routes in western Europe and on flights over the British Isles. The flights were planned to search for regions of clear-air turbulence and explore them instrumentally when found. The layer thus covered extended from 20,000 to 37,000 ft.

Mosquito aircraft of the Meteorological Research Flight reported turbulence qualitatively at high altitude; the flights usually reached a height of about 40,000 ft. Qualitative observations of bumps were also available from flights by Royal Air Force aircraft. A few of these were made on climbs to certain levels, but the majority were made on ordinary flights so that no details were available as to the vertical extent of the turbulent layers. Table I gives the number of flights on which turbulence was reported and other data concerning the observations.

TABLE I—NUMBER OF FLIGHTS ON WHICH HIGH-ALTITUDE TURBULENCE WAS REPORTED AND OTHER DATA

	Period	No. of flights	No. of flights with turbulence	No. of bumpy layers in the stratosphere	No. of thin bumpy layers (≤2,000 ft. thick) within 1,000 ft. of the tropopause	Layers investigated
						ft.
R.A.E. Spitfire	July 1946–Nov. 1948	206	151	28	13	20,000 to 40,000
B.E.A. Mosquito	Mar.–Dec. 1948	59	14	2	2	20,000 to 37,000
Meteorological Research Flight	Dec. 1947–Dec. 1948	55	36	13*	14	17,000 to about 40,000
R.A.F. Flights	May 1947–Dec. 1948	..	101	11	5	Above 15,000
Aldergrove aircraft flights	Jan.–Oct. 1943	299	32	8	6	20,000 to 38,000–40,000

* 10 flights.

Measurement and assessment of turbulence.—The effect of turbulent motion of the air on an aircraft is most easily understood by considering two simple cases. First, suppose an aircraft is flying steadily and level through smooth air and suddenly meets an up-current; the aircraft will have new forces impressed on it and will accelerate upwards, i.e. there will be a bump. Similarly, if an aircraft encounters a sudden current flowing in the same direction as its flight the lift, depending on the speed of the air past the aerofoils, will be altered almost instantaneously and the aircraft will have an acceleration in the vertical. The first type of bump due to turbulent up- or down-currents is usually the more important and is the type mainly considered by aerodynamicists.

Upward or downward gusts produce much higher loads than horizontal gusts of the same magnitude. The former are therefore the more important in aircraft design.

Theory suggests that gusts of smaller dimensions than the aircraft span are unlikely to cause heavy loads, and that, at the other end of the scale, gusts which build up in 30–40 chord lengths will not produce appreciable loads. This is confirmed by measurements made from aircraft that the eddies causing bumps have dimensions of the order 50–500 ft. across. Doubtless eddies over a much wider range of dimensions occur in the atmosphere but are not detectable from aircraft.

The instrument used to measure bumpiness is an accelerometer which records the vertical accelerations experienced by the aircraft. These vertical accelerations are always interpreted by aerodynamicists in terms of vertical up- or down-currents or " gusts " ; from the measured acceleration and a knowledge of the airspeed and the aerodynamic characteristics of the aircraft it is possible to calculate a convenient parameter known as the " equivalent sharp-edge gust velocity" (see, for example, Tye [1*]). This is a calculated equivalent velocity which, if the gust were vertical, sharp-edged and of unlimited horizontal extent, would produce the acceleration experienced in the given aircraft at the same equivalent forward speed.

The Royal Aircraft Establishment experimental flights were made at an equivalent airspeed of 180 kt. and at this speed an acceleration of $0{\cdot}1g$ corresponds to an equivalent sharp-edge gust velocity of 3·6 ft./sec. The British European Airways flights were made at speeds varying between 150 and 250 kt.

An American report[2] deduces, from a comparison of pilots' estimates of the severity of bumps in thunderstorms with the measurements by accelerometers, that accelerations of $0{\cdot}4g$ or above, provided they occur every 12 sec. or less, will be considered " heavy " turbulence even by pilots of wide experience. This serves as a rough guide in assessing pilots' qualitative estimates of turbulence, though, of course, a pilot might describe bumpiness at a height of 35,000 ft. as severe which he would consider only moderate at a low altitude.

Severity of turbulence at high altitude.—The greatest acceleration measured in clear air was $0{\cdot}7g$; this was experienced by a British European Airways aircraft at 22,000–23,000 ft. over Staffordshire (at a speed of 200 kt. this corresponds to a sharp-edge gust velocity of 26 ft./sec.). This bump was, however, isolated, the general level of the accelerations being about $0{\cdot}4g$ on that occasion. Altogether in the Royal Aircraft Establishment and British European Airways flights there were only nine occasions when accelerations of $0{\cdot}4g$ or more were experienced. The frequency of these accelerations was usually less than one in 12 sec.

A few of the qualitative observations of turbulence reported it as severe, very bumpy or similar.

Jones[3] reports that accelerations up to $0{\cdot}8g$ have been observed over the Midlands in non-precipitating cumuliform cloud which did not give an echo to a 10-cm. wave-length radar set, while accelerations up to $1{\cdot}5g$ were recorded by a Spitfire flying at 180 kt. in active cumulonimbus clouds.

From the experience of these various flights reporting turbulence above 20,000 ft. it is possible to say, therefore, that severe turbulence is rare outside cumulonimbus cloud over Great Britain, and that when it occurs it is at most only comparable with that which may be experienced in a non-precipitating cumuliform cloud and is much less intense than that which may be found in active cumulonimbus cloud.

* The index numbers refer to the list of references on p. 16.

Statistics of the occurrence of high-altitude turbulence.—(*a*) *Frequencies of occurrence of turbulence within various height ranges* are given in Table II. Only observations from flights which covered the complete range of heights from 20,000 to 40,000 ft. were used in preparing this table so that the figures illustrate the true relative frequency of occurrence of turbulence in the various height bands. Over Great Britain it appears that the layers in the neighbourhood of 30,000 ft. are most liable to turbulence.

TABLE II—NUMBER OF FLIGHTS ON WHICH BUMPS OCCURRED WITHIN VARIOUS HEIGHT RANGES

Height ranges				
20,000–24,000 ft.	24,000–28,000 ft.	28,000–32,000 ft.	32,000–36,000 ft.	36,000–40,000 ft.
58	63	72	64	55

The greatest height at which bumpiness was reported was 43,000 ft. There is no information regarding turbulence at greater heights.

(*b*) *Frequencies of occurrence of turbulence within various height ranges relative to the tropopause* are given in Table III. The data were the same as those used in preparing Table II, but all flights were excluded which did not reach the tropopause. The maximum frequency at the tropopause is noteworthy; reference will be made again to this point on p. 11. The Royal Aircraft Establishment observations did not show this maximum at the tropopause, though each of the other series of observations did. Frequencies, excluding the Royal Aircraft Establishment data, are also given.

TABLE III—FREQUENCY OF OCCURRENCE OF BUMPS AT VARIOUS HEIGHTS RELATIVE TO THE TROPOPAUSE, EXCLUDING CASES WHEN THE TROPOPAUSE WAS NOT REACHED

	Height (feet) below tropopause					1,000 ft. below to 1,000 ft. above tropopause	Height (feet) above tropopause			
	More than 9,000	9,000–7,000	7,000–5,000	5,000–3,000	3,000–1,000		1,000–3,000	3,000–5,000	5,000–7,000	More than 7,000
Total	72	46	55	56	52	65	38	23	10	9
Excluding R. A. E. observations ..	13	8	16	18	20	36	21	9	5	3

The decrease in the number of cases of bumpiness above the tropopause is partly because some of the flights did not penetrate far into the stratosphere. An examination of those cases in which the aircraft penetrated 3,000 ft. or more into the stratosphere showed that there is a real decrease of frequency of bumpiness above the tropopause.

(*c*) *Frequencies of occurrence of various depths of bumpy layers* are given in Table IV. The same data were used as in preparing Table II. The shallow layers of less than 500-ft. thickness make up 61 per cent. of all occasions.

TABLE IV—NUMBER OF OCCASIONS OF BUMPY LAYERS OF VARIOUS DEPTHS

<500 ft.	500–1,000 ft.	1,000–3,000 ft.	3,000–6,000 ft.	> 6,000 ft.	Total
180	18	43	26	23	290

(*d*) *Seasonal variation of occurrence of turbulence.*—The only series of observations which may throw light on possible seasonal variations of high-altitude turbulence is that made by the Royal Aircraft Establishment Spitfire aircraft. Table V gives the percentage number of all flights (bumpy or smooth) made to investigate this turbulence, on which bumps were observed in various height ranges for each season separately; e.g. turbulence was experienced in the height layer 30,000–35,000 ft. on 51 per cent. of all the flights (43 in number) made in the winter season. This series of flights was not quite independent of the weather, fog or other phenomena dangerous to flying interrupting the programme on occasions. The figures in this table must therefore be treated with caution. It does appear, however, that winter is the worst season for bumpiness, and, as the worst flying weather usually occurs in this season, this conclusion is probably independent of any reserve expressed above.

TABLE V—PERCENTAGE NUMBER OF FLIGHTS IN THE VARIOUS SEASONS ON WHICH BUMPINESS OCCURRED IN VARIOUS HEIGHT RANGES: R.A.E. FLIGHTS ONLY

Height range	June–Aug.	Sept.–Nov.	Dec.–Feb.	Mar.–May
ft.		*per cent.*		
20,000–25,000	31	24	49	16
25,000–30,000	28	32	44	18
30,000–35,000	28	27	51	24
35,000–40,000	23	31	21	20
20,000–40,000	53	56	67	49
No. of flights	47	71	43	45

Upper air observations used in the meteorological analysis.—In the analysis of possible meteorological causes of high-altitude turbulence a knowledge of the wind and temperature distribution was required at the relevant levels.

In the British Isles upper air observing stations are not more than 150–250 miles apart in most cases, and many of the observations are made as frequently as every six hours. This network of observations was used to calculate the various parameters used in the investigation, interpolating in time and space where necessary. Observations of temperature made by the Meteorological Research Flight and by the British European Airways flights were used when appropriate.

Outside the British Isles upper air observations were insufficient for the analysis except over north-west Germany.

Radio-sonde observations of temperature are quite detailed and all peculiarities of the temperature distribution with height are shown. Winds, however, being measured by radar tracking of an ascending balloon, are determined as a mean over a layer approximately 3,600 ft. thick; a change in wind with height occurring in a shallow layer cannot be detected satisfactorily.

Relation between bumpiness and Richardson number.—The Richardson number is defined by

$$R_i = \frac{g}{T} \frac{\left(\frac{\partial T}{\partial z} + \Gamma\right)}{\left(\frac{\partial \mathbf{V}}{\partial z}\right)^2}$$

where $\mathbf{V}$ = horizontal wind (vector)
T = temperature (Absolute)
Γ = adiabatic lapse rate of temperature with height
z = height, measured upwards.

It is sometimes called the stability.

Originally Richardson[4] used $R_i > 1$ or < 1 as a criterion for the decrease or increase of turbulence in the atmosphere, respectively. The critical value of 1, depending on the equality of the coefficients of eddy transfer of heat and eddy transfer of momentum, has been queried (e.g. by Petterssen and Swinbank[5]); but there is little doubt that the number R_i is related to the nature of the turbulent flow, though how closely and in what manner is not known. Deacon[6] and Pasquill[7] have found close relationships between R_i and the turbulent flow near the ground.

At any rate R_i takes account of the static stability and the wind shear, both of which are important in the occurrence of turbulence and cannot be dissociated. It thus seems a suitable parameter to use in this investigation.

R_i was calculated for each occurrence of turbulence for which upper air data, as described on p. 6, were available. Values from zero to over 1,000 were noted. As pointed out on p. 6, though $\partial T/\partial z$ was probably known with fair accuracy, $\partial \mathbf{V}/\partial z$ could be determined only over a layer several thousand feet thick and thus values of R_i for shallow bumpy layers may have been too large; they would seldom be underestimates.

The smaller values of R_i are of most interest, and are liable to less error than large values, e.g. a shear of 1kt./1,000 ft. in an isothermal layer at a temperature of −40° F. gives R_i = 122, but if the shear were ½ kt./1,000 ft. or 1½ kt./1,000 ft. (an error of ½ kt./1,000 ft. in estimating the shear is quite possible) the values would be 488 and 54 respectively. Because of the very wide range in the values of R_i, $\log_{10}R_i$ has been used in the analysis. Table VI (part A) gives the percentage frequency of occurrence of various values of $\log_{10}R_i$ for the upper troposphere and lower stratosphere for bumpy occasions.

In order to determine whether the frequency distribution of $\log_{10}R_i$ on bumpy occasions was abnormal in any way it was necessary to compare it with the

TABLE VI—PERCENTAGE FREQUENCY OF OCCURRENCE OF VARIOUS RANGES OF $\log_{10} R_i$

A. Bumpy occasions. B. All occasions at Larkhill

		$\log_{10} R_i$: −1·0 to −0·5	−0·5 to 0·0	0·0 to 0·5	0·5 to 1·0	1·0 to 1·5	1·5 to 2·0	2·0 to 2·5	2·5 to 3·0	3·0 and above	No. of obs.	Mean $\log_{10} R_i$
		percentage frequency										
A	Upper troposphere	1·3	7·4	21·1	27·4	24·1	7·0	5·0	1·7	5·0	299	0·97
	Lower stratosphere	..	..	6·5	27·4	27·4	16·1	12·9	3·2	6·5	62	1·43
B	Upper troposphere	0·3	1·7	11·8	27·2	28·6	19·4	7·6	2·3	1·1	941	1·20
	Lower stratosphere	0·0	0·4	6·1	19·4	26·0	26·0	13·0	7·8	1·3	231	1·46

usual or normal frequency distribution of $\log_{10}R_i$ for all occasions. The normal frequency was obtained in the following way: from the wind and temperature observations at Larkhill for the months October 1946, January, April and June 1947, the values of R_i were computed for the levels 450 mb. (approximately 20,500 ft.), 300 mb. (approximately 30,000 ft.) and 200 mb. (approximately 38,500 ft.); for this, wind observations to the nearest knot in speed and nearest degree in direction were used. The resulting frequencies of occurrence of various ranges of $\log_{10}R_i$ showed no large variation with season or with height in the same domain, troposphere or stratosphere; they were accordingly grouped together and are given in Table VI (part B) in the form of percentages. The comparison of the occasions of bumpiness with the normal is given in Table VII which shows the ratio of the frequencies of occurrence (percentages) of various ranges of $\log_{10}R_i$ on bumpy occasions to the normal frequency. In the upper troposphere it is apparent that small values of R_i occur considerably more frequently with bumps than normally, and large values less frequently. In the lower stratosphere there is a slight tendency for small values of R_i to occur more frequently on bumpy occasions than normally, but it is perhaps doubtful if this result is real.

TABLE VII—RATIO OF PERCENTAGE FREQUENCIES OF VARIOUS $\log_{10}R_i$, BUMPY OCCASIONS TO NORMAL

	$\log_{10}R_i$: -1·0 to -0·5	-0·5 to 0·0	0·0 to 0·5	0·5 to 1·0	1·0 to 1·5	1·5 to 2·0	2·0 to 2·5	2·5 to 3·0	3·0 and above
Upper troposphere	4·3	4·4	1·8	1·0	0·84	0·36	0·66	0·74	4·5
Lower stratosphere	..	0·0	1·1	1·4	1·1	0·62	1·0	0·41	5·0

The peculiar increase in the ratio for values of $\log_{10}R_i$ greater than 3 may not be significant. The normal frequencies were evaluated from wind observations given to the nearest degree in direction, while those for the bumpy occasions were deduced from winds to the nearest 10 degrees; thus wind shears, very small or zero as given by the latter observations, may, in fact, have been appreciable. An idea of the effect on the frequency distribution may be obtained as follows. If two consecutive wind observations were the same then R_i through the layer between would be infinite; in the analysis it was taken as 1,000. If the wind direction is considered to the nearest degree, however, it is easily seen that the mean difference (in degrees) between two observations both the same when given to the nearest 10 degrees is about 3°; this is also about the median of the random distribution. In every case, therefore, where R_i was infinite a new value of R_i was computed assuming a difference of 3° in direction between consecutive wind observations from which $\partial\mathbf{V}/\partial z$ was evaluated. These "corrections" cannot be claimed to be accurate, for some of the true corrections would be smaller and others larger than 3°. However, it should illustrate the inaccuracy in Table VII for large values of R_i arising from the rough (nearest 10 degree) wind directions. Table VIII shows the results of this modification on Table VII; it seems likely that the values of the ratio for $\log_{10}R_i = 3$ or over, in Table VII, are without significance.

TABLE VIII—MODIFIED FORM OF TABLE VII ALLOWING FOR MORE ACCURATE WIND DIRECTIONS

	$\log_{10}R_i$: -1·0 to -0·5	-0·5 to 0·0	0·0 to 0·5	0·5 to 1·0	1·0 to 1·5	1·5 to 2·0	2·0 to 2·5	2·5 to 3·0	3·0 and above
Upper troposphere	4·3	4·4	1·8	1·0	0·87	0·45	0·75	1·0	0·9
Lower stratosphere	..	0·0	1·1	1·4	1·1	0·62	1·4	0·61	0·0

As emphasized previously, R_i cannot be estimated accurately over shallow layers; it may be, therefore, that unavoidable errors have occurred in the analysis which have masked significant results. Accordingly, those cases where bumpiness occurred through a thick layer, thickness 4,000 ft. or more, were considered separately; the evaluation of R_i for these layers cannot be subject to great error. Table IX corresponding to Table VII, gives the ratio of the percentage frequencies of various $\log_{10}R_i$, bumpy occasions to normal, for these deep layers. It is seen that in essentials it does not differ from Table VII; the figures for the lower stratosphere may not be reliable, as the number of observations is so small.

TABLE IX—RATIO OF PERCENTAGE FREQUENCIES OF VARIOUS $\log_{10}R_i$, BUMPY OCCASIONS TO NORMAL: LAYERS 4,000 ft. OR MORE IN DEPTH

	$\log_{10} R_i$									
	−1·0 to −0·5	−0·5 to 0·0	0·0 to 0·5	0·5 to 1·0	1·0 to 1·5	1·5 to 2·0	2·0 to 2·5	2·5 to 3·0	3·0 and above	No. of obs.
Upper troposphere ..	9·0	7·2	1·6	1·1	0·62	0·49	0·18	0·57	3·7	73
Lower stratosphere ..	..	0·0	3·3	2·0	1·2	0·38	0·0	0·0	0·0	10

It might be expected that in cases of more severe turbulence the association with small R_i would be more marked. Accordingly, those occasions, 25 in number, on which the Royal Aircraft Establishment flight recorded accelerations of $0\cdot3g$ or greater were analysed separately. The results were similar to those obtained for all cases of turbulence irrespective of the degree.

For the upper troposphere, in both Tables VII and IX, it is only in the cases of $R_i < 3\cdot2$, (i.e. $\log_{10} R_i < 0\cdot5$), that the frequency of occurrence of these values of R_i is appreciably greater than the normal frequency; in fact it is in the region of values of R_i where theory predicts that turbulence should be increasing that R_i appears to be important in the occurrence of bumpiness. Whether the critical value of R_i is 1 or some other figure such as $0\cdot5$ is unimportant to the argument. Since the ratios for $\log_{10}R_i > 0\cdot5$ do not appear to decrease systematically they have little significance; the fact that these ratios are mainly less than 1 is probably due to the method of analysis; if one set of ratios is greater than 1 another set must be less than 1.

Thus it seems that bumpiness in the upper troposphere, though it occurs with all values of R_i, is not related directly to R_i when R_i is greater than or equal to 10. Small values of R_i and the occurrence of bumps are definitely related as would be expected. The evidence for a similar relation in the lower stratosphere is not conclusive. It may be remarked that Durst[8] found little relation between R_i and the swing of an aerial on a radio-sonde balloon in the lower stratosphere.

Relation between bumpiness and horizontal shear.—The possible association of high-altitude turbulence with large shear of wind in the horizontal was also investigated.

In straight flow the horizontal shear is the rate of change of wind speed with distance at right angles to the wind direction. When the flow is curved, however, there is an additional term and the horizontal shear is

$$\frac{\partial \mathbf{V}}{\partial n} - \frac{\mathbf{V}}{r}$$

where $\mathbf{V}$ = horizontal wind speed, n = the horizontal direction at right angles to $\mathbf{V}$, r = radius of curvature of the stream-line, considered positive for cyclonic motion if n is measured to the right of $\mathbf{V}$.

When possible the horizontal shear was deduced from available upper wind observations for each turbulent incident. This horizontal shear was sometimes subject to considerable error because of difficulties in estimating *r*. There were many occasions when it was impossible to calculate the horizontal shear because of lack of suitable observations.

The frequencies of occurrence of various ranges of horizontal shear with bumpy conditions is given in Table X (part A); the frequencies for deep bumpy layers (4,000 ft. or more in depth) showed very similar characteristics.

TABLE X—PERCENTAGE FREQUENCY OF OCCURRENCE OF VARIOUS RANGES OF HORIZONTAL SHEAR

A. Bumpy occasions. B. All occasions over the Midlands.

		Horizontal shear (hr.$^{-1}$) 0.00 to 0.05	0.05 to 0.10	0.10 to 0.15	0.15 to 0.20	0.20 to 0.25	0.25 to 0.30	0.30 to 0.35	0.35 to 0.40	0.40 and above	No. of obs.	Mean shear
		percentage frequency										hr.$^{-1}$
A	Upper troposphere	11·3	22·0	20·2	17·1	10·4	9·0	4·1	0·9	5·0	222	0·17
	Lower stratosphere	18·2	27·2	15·9	15·9	9·1	2·3	2·3	..	9·1	44	0·14
B	Upper troposphere	39·0	31·7	14·9	7·2	2·5	1·5	1·3	0·8	1·1	637	0·08
	Lower stratosphere	59·5	19·8	10·7	3·8	0·8	3·1	0·8	1·5	0·0	131	0·06

Normal frequencies of occurrence of various ranges of horizontal shear were derived from the wind observations at Larkhill, Downham Market and Liverpool for the months October 1946, January, April, and June 1947. There was little variation in the frequencies between seasons, and accordingly they have been taken together and are given in Table X (part B). The irregularities in the stratosphere figures are presumably due to insufficient numbers of observations.

The comparison of the occasions of bumpiness with the normal is given in Table XI; because of the small number of observations the ranges of horizontal shear considered for the lower stratosphere have been doubled. There appears to be a relation, though not a marked relation, between horizontal shear and the occurrence of bumpiness. Broadly speaking the occurrence of bumpiness appears to have about the same degree of dependence on horizontal shear as it has on the Richardson number; perhaps there is more relation to the former than the latter in the lower stratosphere.

TABLE XI—RATIO OF PERCENTAGE FREQUENCIES OF VARIOUS HORIZONTAL SHEARS, BUMPY OCCASIONS TO NORMAL

	Horizontal shear (hr.$^{-1}$) 0.0 to 0.05	0.05 to 0.10	0.10 to 0.15	0.15 to 0.20	0.20 to 0.25	0.25 to 0.30	0.30 to 0.35	0.35 to 0.40	0.40 and above
Upper troposphere	0·29	0·69	1·4	2·4	4·2	6·0	3·1	1·1	4·5
Lower stratosphere	0·57		2·2		2·9		1·0		∞

There is the possibility that R_i and horizontal shear are related, and that the partial relation of bumpiness to these two factors is explained by one of them. $\text{Log}_{10}R_i$ and horizontal shear were plotted on a scatter diagram for bumpy occasions, but no relation between them could be inferred and the distribution of points appeared to be quite random. It is deduced, therefore, that the partial dependence of bumpiness on horizontal shear of the wind is independent of its partial dependence on R_i.

Relation between bumpiness and wind speed.—Wind speed tended to be above average on bumpy occasions. Without going into details of frequency distributions Table XII illustrates this sufficiently well; in it are given the mean of the winds occurring with bumpy conditions within various height ranges for the four seasons and, for comparison, the normal seasonal means for these layers. These normals are rough interpolations between means over several years of winds at Larkhill at the levels 500 mb, 300 mb. and 200 mb.; they may be underestimated in the 30,000–35,000-ft. layer as the wind very frequently reaches a maximum between 300 and 200 mb., near the tropopause. These means may be unrepresentative of strong winds above 30,000 ft.; the balloon target is carried beyond the range of the observing radar in strong winds before the height of 30,000 ft. is reached. This discrepancy will apply to both sets of data, bumpy and normal, and should not therefore affect the deductions made from them.

TABLE XII—MEAN WIND SPEEDS ON BUMPY AND NORMAL OCCASIONS FOR THE FOUR SEASONS AND FOR VARIOUS HEIGHT RANGES

Season		Height ranges 20,000–25,000 ft.	25,000–30,000 ft.	30,000–35,000 ft.	35,000–40,000 ft.
		knots			
Dec.–Feb.	Bumpy	64	69	57	54
	Normal	47	53	57	42
Mar.–May	Bumpy	57	59	75	35
	Normal	37	41	44	26
June–Aug.	Bumpy	46	44	56	49
	Normal	38	43	46	27
Sept.–Nov.	Bumpy	48	55	57	55
	Normal	44	51	55	34

Since high wind speeds are obviously associated with abnormal shear, both in the vertical and in the horizontal, the fact that high winds and bumpiness are related is not surprising in view of the theories discussed on pp. 7—10.

Bumpiness at the tropopause.—Bumpiness quite frequently occurs near the tropopause. This is shown by Table III. Durst[8] also found turbulence near the tropopause.

Bumpiness sometimes occurs in a shallow layer which appears to be directly associated with the tropopause; the numbers of such occasions are listed in Table I. Most of this bumpiness is slight and would probably pass without comment in the lower troposphere; but this is not always so.

In the majority of the cases noted by the Meteorological Research Flight the bumpiness occurred immediately at or just above the tropopause; many of the other observations were similar. Durst's observations[8] gave the same indication.

The Richardson numbers occurring with these instances of bumpiness at the tropopause indicate that stability is not an important factor in this type of turbulence. Table XIII shows this, giving the frequency distribution of various values of $\log_{10}R_i$ for shallow bumpy layers within 1,000 ft. of the tropopause and, for comparison, the frequency distribution for the 300- and 200-mb. levels together (all seasons); the 3 per cent. of bumpy occasions with $\log_{10}R_i$ between -1 and 0 arises from one observation, just below the tropopause, and is thus probably not significant.

TABLE XIII—PERCENTAGE FREQUENCY OF OCCURRENCE OF VARIOUS RANGES OF $\log_{10}R_i$ WITH BUMPINESS NEAR THE TROPOPAUSE, AND THE NORMAL FREQUENCY FOR THOSE HEIGHTS

	$\log_{10}R_i$ –1 to 0	0 to 1	1 to 2	2 to 3	3 and over	No. of obs.	Mean $\log_{10}R_i$
	percentage frequency						
Bumpy occasions ..	3	32	39	16	10	31	1·42
Normal (300 mb. and 200 mb., all seasons) ..	1	34	49	14	2	714	1·52

The suspicion remains, of course, that the many shallow bumpy layers at and just above the tropopause may be related to small values of R_i which cannot be detected because they occur over shallow layers. It seemed advisable, therefore, to investigate the wind shear at and above the tropopause as accurately as possible to see if, in fact, this region is more liable to have small Richardson numbers. Accordingly wind observations at Larkhill for the month of February 1948 were re-plotted in the neighbourhood of the tropopause, and the winds computed over 1-min. intervals, instead of 3-min. intervals as is the normal practice. From these re-computed winds it was possible to derive more accurate wind gradients than from the observations made at standard levels several thousand feet apart. Shears at two particular levels were investigated: (i) the shear between the winds during the minute in which the tropopause was reached and the following minute; and (ii) the shear between the winds observed in the first two complete minutes of observation above the tropopause. Level (i) gave an estimate of the shear immediately above the tropopause or partly across it; level (ii) gave the shear just above the tropopause in a layer about 1,200 ft. above the layer considered in (i). From these shears values of

TABLE XIV—PERCENTAGE FREQUENCY OF OCCURRENCE OF VARIOUS RANGES OF $\log_{10} R_i$ IN THE LOWER STRATOSPHERE AND NEAR THE TROPOPAUSE; LARKHILL

Level	$\log_{10}R_i$ −1·0 to −0·5	−0·5 to 0·0	0·0 to 0·5	0·5 to 1·0	1·0 to 1·5	1·5 to 2·0	2·0 to 2·5	2·5 to 3·0	3·0 and above	No. of obs.	Mean $\log_{10}R_i$
	percentage frequency										
(i) Just above or at tropopause*	..	..	9·3	24·4	39·5	20·9	4·7	1·2	..	86	1·19
(ii) Lower stratosphere*	..	2·4	11·8	18·8	30·6	24·7	5·9	3·5	2·4	85	1·30
(iii) At 300-mb. and 200-mb. levels†	0·6	1·8	8·9	24·2	29·0	22·5	6·5	4·1	2·4	169	1·29

*February 1948; †January 1947

R_i were computed. Table XIV shows the precentage frequency distribution of R_i for levels (i) and (ii) and, for comparison, the frequency distribution of the observed R_i at the standard levels, 300 and 200 mb., during the month of January 1947. Both these months, January 1947 and February 1948, were very disturbed cyclonically for part of the time and also had periods of quieter anticyclonic weather; they may be considered as fairly typical winter months. Table XIV shows no appreciable difference in the character of the frequency distributions and it is inferred, therefore, that the turbulent nature of the atmosphere, as indicated by R_i, immediately above the tropopause is in no way different from that obtained at similar heights but away from the tropopause.

The other parameter which is known to be partly related to the occurrence of bumpiness, namely horizontal shear of the wind, may be more important than stability in the vertical in these cases near the tropopause, as Table XV indicates. Since the numbeı of observations is small, the obvious deduction from the figures cannot be considered conclusive.

TABLE XV—PERCENTAGE FREQUENCY OF OCCURRENCE OF VARIOUS RANGES OF HORIZONTAL SHEAR WITH BUMPINESS NEAR THE TROPOPAUSE AND THE NORMAL FREQUENCY FOR THOSE HEIGHTS

	Horizontal shear (hr.$^{-1}$) 0·0 to 0·1	0·1 to 0·2	0·2 to 0·3	0·3 to 0·4	0·4 and above	No. of obs.	Mean
	percentage frequency						hr.$^{-1}$
Bumpy occasions	32	38	10	10	10	21	0·17
Normal (mean of troposphere and stratosphere) ..	72	21	4	2	1	768	0·08
Ratio of above	0·4	1·8	2·5	5·0	10	..	..

All the above evidence, though not entirely conclusive, does indicate that shear in the vertical is not usually the main cause of bumpiness at the tropopause and that horizontal shear is more important.

Discontinuities in temperature lapse rate.—On one occasion the British European Airways flight encountered bumpiness in a shallow inversion of temperature with height, and on six occasions the Meteorological Research Flight found it at or in an inversion, isothermal layer or sudden check in the lapse rate of temperature. These instances were apart from those noted at the tropopause. Two similar instances were noted on high-altitude aircraft flights, at Bircham Newton and Wick respectively, some years ago. The bumpiness encountered at a warm front, at 18,000 ft., by an aircraft on meteorological reconnaissance[9] was also probably in an inversion or a check in the temperature lapse rate ; on this occasion it was cloudless at this level.

The Richardson numbers for these occasions (where they could be estimated) were greater than 3·4 except in one case where it was very small in the bumpy layer (shallow) and large just above ; the mean R_i for the 7 cases for which there were observations was 10. The mean horizontal shear for the four cases for which there were observations was 0·25 hr.$^{-1}$.

It is possible that bumpiness at such thermally stable layers is often of the same nature and from the same causes as the bumpiness which occurs at the tropopause.

Two of the above cases (the British European Airways flight and the weather reconnaissance flight) were associated with fronts (occlusion and warm front respectively) though in cloudless air.

Thermally stable conditions, such as are found just above the tropopause or in layers as discussed here, would not be expected to persist in the presence of turbulence unless the turbulence does not lead to vertical mixing of the air, i.e. unless the eddies are in a horizontal plane. Aerodynamicists say, however, that horizontal gustiness can cause only slight bumps to an aircraft unless the gusts are very violent and also that the faster the aircraft the less such bumps would be felt. It is known[10] that the turbulence normally encountered below 15,000 ft. is isotropic, i.e. that the magnitude and distribution of the turbulent velocities is independent of their direction in space ; there is, however, no information on the nature of the turbulence causing bumps in thermally stable layers. It may be that on many occasions of slight turbulence in thermally stable layers the eddies are mainly in the horizontal plane. The alternative deductions are that either the turbulence is very short-lived or else the stable layer is rapidly broken down.

There is no evidence that the stability of a layer does change quickly, though it may do so, e.g. there is no evidence that the tropopause varies quickly in height, a thermally stable layer at the base of the stratosphere being broken down in a short time. Bumpiness does appear to have a certain persistence (evidence is not great as most data are from single flights) though undoubtedly it is sometimes very " patchy ".

Presence of cloud.—In the Royal Aircraft Establishment series 186 bumpy layers were observed ; of these 48 were associated with cloud over all or part of the layer, i.e. the bumpy layers were all, or partly, in cloud or were all, or partly, at the same levels as surrounding broken cloud. For the other flights 21 bumpy layers were associated with cloud. However, the Royal Aircraft Establishment flights encountered 46 layers of cloud between 20,000 and 40,000 ft. which were not associated with bumps. The Meteorological Research Flight found 14 smooth layers of high cloud and only 6 bumpy cloud layers.

In no case was an observation made in cumulus or cumulonimbus cloud, though in three cases, none of them by a Royal Aircraft Establishment flight, surrounding cloud heads were of this nature when bumps were found. Usually the clouds were cirrus or frontal layer clouds (cirrostratus or altostratus) though altocumulus or cirrocumulus also occurred. At low temperatures the air can hold little water vapour and the difference between the adiabatic lapse rates of temperature of dry and moist air is therefore small ; in fact the presence of cloud can make little difference usually to the thermal static stability of the air at high levels or to the Richardson number. In only four of the cloudy cases were the lapse rates of temperature with height equal to the moist adiabatic rate ; in the others R_i was little affected.

In many cases it would seem, therefore, that the presence of cloud has little direct effect in causing bumps ; it may well be, indeed, that the cloud (particularly of the altocumulus or cirrocumulus type) is caused by the turbulent motion.

Regions of large wind shear : jet streams.—Narrow but very fast-moving streams of air embedded in a general stream of comparatively moderate speed occur in temperate latitudes in association with well marked fronts. They are known as jet streams ; Durst and Davis[11] have described their characteristics. The axis of a jet, the core of fastest-moving air, is usually at a height of 30,000–35,000 ft. and the wind velocity falls off rapidly with distance above and below the axis ; the wind velocity also decreases rapidly on either side of the jet. The neighbourhood of a jet stream in the upper atmosphere is thus likely to have large wind shear in the vertical and also in the horizontal.

Of the 296 flights on which bumpiness was observed, a total of 61 were in the neighbourhood of a jet stream. The definition of a jet stream is somewhat arbitrary, but has been taken as a well marked narrow stream attaining a speed of 80 kt. or more (usually over 100 kt.) at its maximum, which usually occurs in the range of heights of 30,000–35,000 ft. ; invariably it is connected with a marked horizontal temperature gradient associated with a front.

There is some evidence that, on occasions of jet streams when bumps do occur, the bumpy conditions have some persistence. Though the series of observations used in this investigation have very little overlap, on seven days, when a jet stream was near, high-altitude bumpy conditions were observed independently on two or more flights.

Recently (November 1949) a De Havilland Comet aircraft experienced notable bumpiness at several widely separated places on a flight which was near the axis of a marked jet stream for 1,400 miles ; the turbulence at one place was exceptionally severe.

The most marked occasion of turbulence found by the British European Airways flight occurred under, and slightly to the north-west of, the centre of a well marked south-westerly jet stream.

The existence of a jet stream may therefore be used as an indication of much greater likelihood of the occurrence of bumpy conditions in its neighbourhood at high altitudes for three reasons :—

(i) A high proportion of bumpy occasions have been found to be associated with jet streams. (61 out of 296 occasions is probably a much greater frequency than the normal frequency of occurrence of a jet stream over or near the British Isles, though no figures for the latter have been worked out.)

(ii) A jet stream is a region of large vertical shear.

(iii) A jet stream is a region of large horizontal shear.

However, there have been flights near jet streams on which no turbulence was experienced, so that it cannot be said that all jet streams give bumpy conditions. It appears likely, though the evidence is not conclusive, that notable turbulence, for example sufficient to give an acceleration of $0 \cdot 4g$ or greater to an aircraft flying at a speed of 180 kt., will occur at high altitude in temperate latitudes only in the vicinity of a jet stream. Conditions associated with cumulonimbus cloud are, of course, excepted.

Conclusions.—Turbulence, which is noticeable in an aircraft and which is not associated with cumulonimbus cloud, occurs not infrequently above a height of 20,000 ft. over the British Isles ; it is rarely severe. This turbulence occurs most frequently in the neighbourhood of the 30,000-ft. level. It has been observed as high as 43,000 ft. Turbulent layers are usually shallow (less than 1,000 ft. thick) but sometimes extend through a great depth (see p. 4).

Bumpiness at heights above 20,000 ft., and excluding cases associated with large cumulus or cumulonimbus clouds, has been shown to be related to the Richardson number (itself related to wind shear in the vertical and temperature lapse rate with height, see p. 7) and the horizontal shear of the wind (see p. 9) ; neither of these alone can explain all the occurrences of bumpiness, and from existing evidence it seems that these two possible causes of turbulence are to some extent independent.

A shallow layer of bumpiness not infrequently occurs near the tropopause and usually just in the stratosphere ; it is likely that this bumpiness is not caused by shear in the vertical (R_i is not small) and the meagre evidence points to its being due to horizontal shear. Bumpiness occurring at other checks in the lapse rate of temperature may well be of the same nature (see p. 11 and p. 13).

It seems likely that some forms of turbulence causing slight aircraft bumps have horizontal eddies ; large stability in the vertical (large R_i) is incompatible with turbulence giving rapid mixing in the vertical if the stability and the turbulence are to persist.

Well marked jet streams and their margins are regions of large shear in the vertical and in the horizontal and it is to be expected that high-altitude bumpiness will frequently occur there, and this is confirmed by observation (see p. 14).

It must be remembered that aircraft bumps are caused by turbulence of a very limited range of linear dimensions, of the order of 50–500 ft. Doubtless turbulence occurs over a very wide range of dimensions which are not detectable from an aircraft. This may be partly the explanation, for example, why a closer relation between the Richardson number and the occurrence of bumpiness has not been found. Only special conditions may be favourable for the scale of turbulence to be in the " bumpy " range. If it were possible to detect much larger eddies the relation between the occurrence of eddies and the Richardson number might be more marked. To understand all the causes of bumps it will probably be necessary to have a knowledge of atmospheric eddies over a much greater range than those detectable in the usual way from an aircraft, and the nature of such eddies (e.g. comparison of vertical and horizontal velocity components) will also have to be examined.

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