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METEOROLOGICAL OFFICE

Scientific Paper No. 17

Extremes of Wind Shear

by A. F. CROSSLEY, M.A.

LONDON: HER MAJESTY'S STATIONERY OFFICE

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SUMMARY

Values of large horizontal and vertical shear are gathered from a survey of appropriate publications and are discussed with reference to the distance over which each is sustained. In the vertical, curves of extreme shear are estimated for north-west Europe and for the United States of America. Use is made of recordings of the Crawley automatic radar theodolite over a period of 12 months; these are analysed to obtain frequency levels of shear over various height intervals up to 10,000 feet, and a method is described of estimating corresponding long-term frequencies for other places, in particular for New York. In the horizontal, the data have been applied to obtain a curve of extreme shears in relation to distance over which they are measured. There is some discussion of anticyclonic shear with reference to stability criteria; although several instances are noted of anticyclonic shear apparently greater than the Coriolis parameter, in no case is the excess beyond the range of possible observational errors.

INTRODUCTION

Studies of the distribution of wind at any given time show that the vertical and horizontal shear occasionally reach large values, particularly in the neighbourhood of jet streams. For several reasons it would be useful to know the magnitude of the greatest shear that can be sustained over any specified interval, or better still to know the frequency with which the shear exceeds certain values. Physically the large shears are of interest in regard to their origin and persistence and their relationship with turbulence. They are of importance for the design and operation of supersonic aircraft, since an aircraft which passes with sufficient rapidity through a zone of shear will be subjected to an acceleration which will give the effect of a horizontal gust. Moreover rockets and missiles when passing through a layer of vertical shear are subject to a turning moment and hence to a possible deviation from the intended course.

From a survey of available material various values of large shear have been extracted and diagrams have been prepared which show the distribution of these values in relation to the range of height or distance through which they are sustained. This basic information is obtained from published diagrams and discussions of vertical cross-sections through jet streams, from special observations made during research projects, and from analyses of certain series of upper air ascents. It is seldom in meteorology that the accuracy of routine observations in the upper air can be fully guaranteed. Moreover observations which, if reliable, would constitute exceptional or extreme values, tend to be regarded with suspicion while they remain unconfirmed. The reliability of such exceptional values should whenever possible be supported by establishing their consistency with neighbouring observations or with the general meteorological conditions at the time. Even then there is a margin of error which can seldom be entirely eliminated and, in the case of shear, which involves the difference between two observations, the resulting errors may reinforce each other. For such reasons, entirely uncorroborated observations have been avoided as far as possible. Much use has however been made of the recordings of the automatic radar theodolite at Crawley, Sussex, which are unique and of high accuracy. Further it is desirable to take note of some statistical analyses of routine upper air ascents. Essenwanger, Bradford and Vaughan[1] have indeed shown that such analyses can be used successfully with the aid of certain safeguards. Although their particular method has not been applied to any of the analyses referred to in this paper, some of them included other statistical checks by which large errors were eliminated.

Most of the information discussed below refers to the upper troposphere and lower stratosphere, but there are a few examples both below and above these levels.

EXTREMES OF VERTICAL SHEAR

The vertical shear at a point is the vector $\partial \mathbf{V}/\partial z$ where $\mathbf{V}$ is the horizontal wind vector and z is height. The concern here is only with the magnitude of the shear, $|\partial \mathbf{V}/\partial z|$, and with the thickness of the shear layer. When there is only a small change of wind direction with height through the shear layer, as usually happens in jet streams except sometimes in the frontal zone, then the magnitude of the shear approximates to $\partial|\mathbf{V}|/\partial z$, the change of wind speed with height. This approximation is sufficiently accurate for the purposes of this paper when the variation of wind direction within the shear layer is within about ten degrees either side of the mean direction in the layer. In some cases the shear will be quoted as the rate of change of wind component in a given direction, for example normal to the plane of a vertical section; when the other component is small, this definition approximates to the preceding ones.

The absolute cgs unit of shear is the second^{-1}, but the knot per 1000 feet, which is commonly used in aviation practice, is adopted here for vertical shear; the equivalent unit in countries using the metric system is the metre per second per kilometre. The conversions are as follows:

$$1 \text{ kt}/1000 \text{ ft} = 1.69 \text{ m sec}^{-1}\text{km}^{-1} = 1.69 \times 10^{-3} \text{ sec}^{-1}.$$

The sources of some large values of vertical shear are described below and the values themselves are shown in Figures 1 and 2 plotted against the thickness of the shear layer. The points have been entered on these diagrams irrespective of sign, i.e. the wind speed may be increasing or decreasing as the height increases through the layer concerned. Both the sign of the shear and the height above ground are given in the text in most cases. It is to be noted that the curves of Figures 1 and 2 are not vertical profiles but show only the magnitude of the extreme shear in relation to the thickness of the layer of shear.

In practice, large shears are generally found above and below the cores of jet streams. The levels affected by the largest shears mostly occur within about 15,000 feet of the jet core, or in an absolute height range of approximately 15,000 to 45,000 feet, at least in middle latitudes. In the absence of a jet stream the only preferred height for large vertical shear is the immediate neighbourhood of the tropopause, but the magnitude of the largest shear in this case is likely to be considerably less than that associated with a well marked jet stream. To judge from published vertical cross-sections, it appears that the largest vertical shears usually occur within 100 miles either side of the axis, while at greater distances the vertical shear rapidly becomes unimportant. No shear is to be expected at the core itself, since the wind speed there is a maximum.

Large vertical shear in north-west Europe

Some observations of large shear in north-west Europe are described in the following paragraphs.

The Crawley automatic radar theodolite. The Crawley radar theodolite automatically follows the reflector suspended from the balloon and computes and plots the wind speed and direction and associated height at intervals of 7½ seconds. In this time the balloon rises on average about 150 feet, but there is considerable smoothing in the apparatus with the result that each plotted point on the record may be regarded, without much error, as a measure of the mean wind through a layer about 300 feet thick (R. Frith, unpublished). Records over a period of 12 months, including 441 ascents, have been analysed for vertical shear. The ascents reached 50,000 to 60,000 feet on most occasions and were made at 0500 and 1700 GMT daily except for several gaps when the instrument was unserviceable, sometimes for as many as ten days in succession. On each ascent the maximum shear (irrespective of sign) was extracted for each of five different thicknesses (250, 500, 1000, 2000 and 3000 metres), regardless of the absolute height of the shear layer; for example, on any one ascent, that layer 250 metres thick was selected which had the greatest shear, and the shear was measured and noted; and similarly for the other layer thicknesses. The averages and extremes of these values are plotted in Figure 1 and joined by smooth curves.

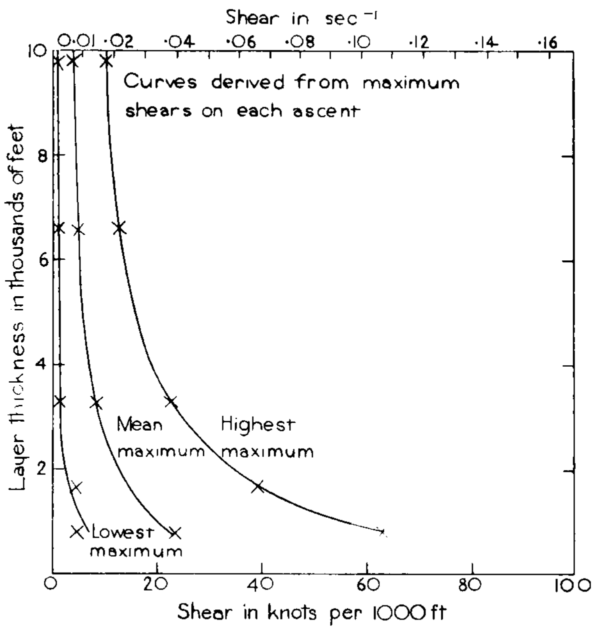

FIGURE 1. Maximum vertical shear in relation to thickness of shear layer for Crawley, June 1958–May 1959. Total number of ascents 441.

The interpretation of these curves may be illustrated, for example, by the thickness of 3280 feet (1000 metres), for which the maximum observed shear is at the rate of 23 knots/1000 feet, implying a total wind change of 76 knots in this layer; the mean of the maximum observed on each ascent is at the rate of 9 knots/1000 feet, and the least of the observed maxima is 2 knots/1000 feet. From the original data, the values of shear which are exceeded on certain percentage occasions have been obtained by graphical interpolation from integrated frequency curves and are shown in Table I. Similarly Table II gives the total wind change which is exceeded in layers of various thicknesses on certain percentage occasions; for example, on ten per cent of ascents the shear exceeds 19 knots/1000 feet over some layer

500 metres (1640 feet) thick, while over a layer 2000 feet thick the total wind change exceeds 34 knots.

TABLE I. *Values of vertical shear exceeded on certain percentage occasions, Crawley, June* 1958 *to May* 1959

Layer thickness		Per cent									
		50	40	30	20	10	5	4	3	2	1
metres	*feet*	*knots/*1000 *feet*									
250	820	17	19	21	24	30	37	39	41	45	51
500	1640	12	13	14	16	19	23	24	25	27	29
1000	3280	7	8	9	10·5	12·5	14·5	15	16	17·5	19
2000	6560	4·6	5·1	5·8	6·7	8·1	9·6	10·1	10·7	11·4	12·2
3000	9840	3·6	4·0	4·6	5·2	6·3	7·2	7·4	7·8	8·2	9·0

TABLE II. *Total change in wind speed exceeded on certain percentage occasions, Crawley, June* 1958 *to May* 1959

Layer thickness	Per cent									
	50	40	30	20	10	5	4	3	2	1
feet	*knots*									
1000	16	18	20	21	26	33	35	37	39	44
2000	22	24	27	29	34	41	43	46	49	52
4000	24	28	31	37	44	52	54	57	62	67
6000	28	32	36	43	51	61	64	68	72	77
10,000	35	39	45	51	62	71	72	77	80	88

Aerological cross-sections. (i) A vertical cross-section normal to a jet stream over the British Isles at 0500 GMT on 3 January 1943 is described by Durst and Davis.[2] The maximum wind speed of 178 knots occurred at 25,500 feet above Downham Market and the maximum vertical shear was found nearly 10,000 feet below the jet core, an increase from 57 knots at 15,000 feet to 127 knots at 17,300 feet, i.e. 30 knots/1000 feet sustained over an interval of 2300 feet. The Downham Market ascent was supported by ascents from other stations and the winds may therefore be regarded as reasonably reliable. Analysis of the ascent as given in the *Daily Aerological Record* yields a series of large positive shears over the various intervals of height, ranging from the above-mentioned value to one of nearly 9 knots/1000 feet sustained over 17,900 feet.

(ii) A vertical cross-section through a jet stream over north-west Europe at 0300 GMT on 9 November 1949 is described by Berggren.[3] The wind speed at the core at 350 mb is about 75 m sec^{-1} (146 knots). The vertical wind shear through the tropospheric front below the jet is given as about 33 m sec^{-1} km^{-1} between the 400 and 500 mb levels, equivalent to 20 knots/1000 feet over a height range of 5280 feet, the wind direction being almost normal to the section.

(iii) Vuorela[4] discusses a cross-section through a jet stream over the British Isles at 0300 GMT on 16 January 1951. The vertical shear of wind normal to the section is said to reach its greatest value, 27 m sec^{-1} km^{-1}, between 450 and 400 mb i.e. 16 knots/1000 feet sustained over 2700 feet in the frontal zone below the jet core. The jet axis was at 300 mb with maximum speed estimated at 152 knots. The Lerwick ascent, which is incorporated in the cross-section, passes through the frontal zone; from the ascent as published in the *Daily Aerological Record*, large positive values of shear are obtained over various height intervals, including the value already mentioned.

(iv) A vertical cross-section through a northerly jet stream over the British Isles on 13 November 1958 is discussed by Briggs.[5] The wind maximum exceeded 140 knots at about 300 mb and there was intense positive vertical shear in the frontal zone beneath the jet core. The Crawley ascent through this region yields some values which lie on or to the right of curve I (Figure 2) which displays the 12-month Crawley analysis, the most outstanding being an increase of 116 knots between 500 and 348 mb (14 knots/1000 feet over 8500 feet).

(v) Further information is contained in another paper by Briggs.[6] A vertical cross-section for 1200 GMT on 12 December 1958, intercepts a jet stream over England with a speed of 135 knots at the core and intense negative shear above it. The ascent at Hemsby, with the aid of a supplementary observation at 235 mb, shows a decrease of 23 knots between 32,740 and 34,010 feet, or 18 knots/1000 feet over 1270 feet. This cross-section illustrates very clearly how any analysis which depends solely on observations at standard pressure levels may give only a very inadequate picture of the distribution of vertical shear.

A statistical analysis. An analysis of frequencies of vertical shear has been given by Bannon,[7] based on routine upper air balloon ascents at Larkhill (Wiltshire). No very exceptional values were disclosed by this investigation. His Table I is derived from wind observations at fixed pressure levels; positive and negative shears are not distinguished. The largest ranges of shear tabulated are 12–14 knots/1000 feet through a height interval of about 8000 feet centred at 200 mb (about 39,000 feet), 8–10 knots/1000 feet through 7400 feet at 300 mb (30,000 feet), and 10–12 knots/1000 feet through 5300 feet at 450 mb (21,000 feet). In another analysis (Table III), Bannon gives frequencies of shears derived from wind recordings computed at one-minute intervals (in place of the three-minute interval normally used) for height intervals of 1200 feet; the largest values in this interval fall in the range 14–16 knots/1000 feet and occur at or near the base of the stratosphere. It is likely that these values are not the largest for the period sampled; for one thing, as Bannon remarks, strong winds were not properly represented above about 20,000 feet and for another the data of the first set were limited to a few fixed pressure levels, and those of the second set to the vicinity of the tropopause.

Shear over very small intervals. As the vertical or horizontal interval decreases, the corresponding shear at a given instant comes to depend more and more on the local eddy structure. Various sets of measurement of shear over small intervals made both near the ground and by recorders in aircraft are summarized in an unpublished report by Bannon and Goldie.[8] This makes it clear that the extreme shear continues to increase as the vertical or horizontal interval decreases, at least down to a few feet. A "typical" extreme value over 20 feet is given as 6 sec^{-1} or 3500 knots/1000 feet.

Extreme shear in north-west Europe. In Figure 2, values of large shear on the occasions described above for north-west Europe have been entered as crosses except for the Crawley extremes for the period June 1958 to May 1959 which have been shown simply as the curve marked I. If sufficient observations were available, the relation of extreme shear to thickness of the shear layer would be given by the envelope of the plotted points. The available points are too few for the envelope to be drawn with certainty, but other considerations help in estimating its probable position. The strongest upper wind in this region appears to be about

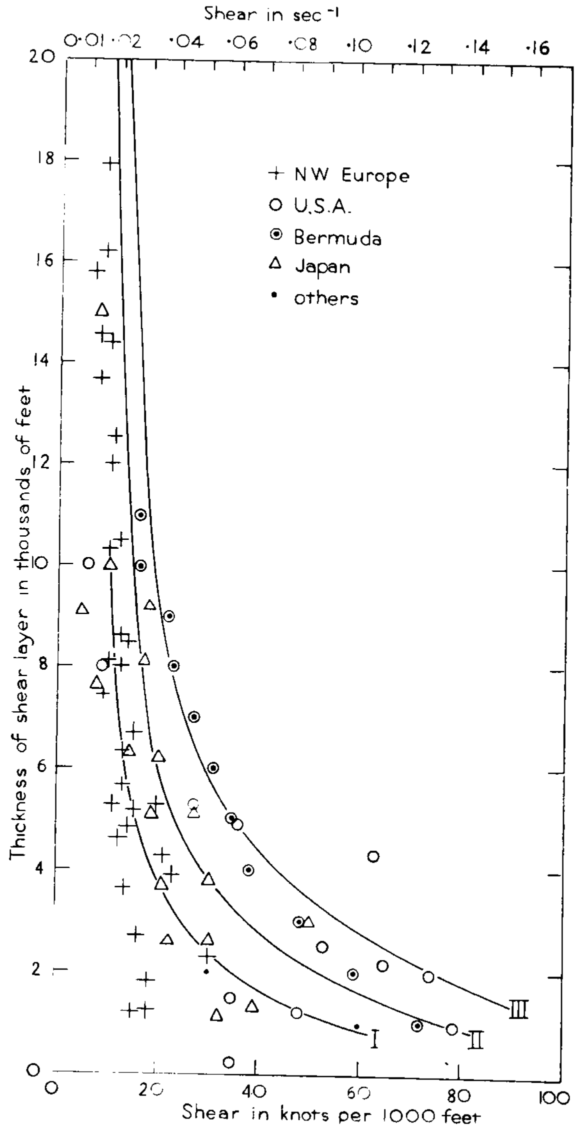

FIGURE 2. Curves of extreme vertical shear. Curve I Crawley (June 1958–May 1959), Curve II north-west Europe, Curve III United States (mainly north-eastern).

200 knots, moreover with very strong winds there is little change in direction over a wide range of height, hence the change of wind speed over an interval of say 20,000 feet cannot appreciably exceed the maximum wind at any height, that is to say the average shear over 20,000 feet cannot much exceed (if at all) a value of 10 knots/1000 feet. This fixes closely enough the upper arm of the extreme curve. Over the smallest intervals the shear can be very large and the envelope, if continued to the right, must approach the horizontal axis virtually asymptotically. For layer thicknesses between 1000 and 10,000 feet the shape of the curve has been assumed similar to that already found for Crawley. Further, because of differences in extreme wind speeds, the curve for north-west Europe would be expected to occupy a position intermediate between those for Crawley (short period) and for the United States, the latter curve being determined from the evidence presented below.

Large vertical shear in the United States of America

Radiosonde observations. (i) A critical examination of the winds in a particular jet stream over the north-eastern United States is made by Cole and Chamberlain.[9] The largest values of vertical shear considered reliable by the authors are 9 knots/1000 feet over a height interval of 8000 feet, and 6 knots/1000 feet over an interval of 10,000 feet. A value of 21 knots/1000 feet sustained over 3000 feet, as computed directly from the "rawin" reports, was considered to be unreliable. The highest reported speed in the jet core was 120 knots. It appears that the largest shears on this occasion, even including the one rejected as unreliable, are by no means exceptional, but then the jet stream itself was of only moderate intensity.

(ii) The measurement of turbulence and wind by means of a parachuted radiosonde fitted with a vertical accelerometer is described by Anderson.[10] A total of 828 soundings were made at three places in east coast states and one in Colorado. The results are discussed in regard to layers of 300 metres thickness, which was the minimum interval over which meaningful values of both vertical wind shear and lapse rate could be derived. It is stated that the largest value found for the vertical shear in any 300 metres layer was 40·0 m sec^{-1} per 300 metres, i.e. 79 knots/1000 feet over an interval of 980 feet.

Aerological cross-section. The structure of the atmosphere over parts of the United States affected by a tropical hurricane on 15 October 1954 is described by Palmén.[11] In a zonal cross-section approximately along latitude 40°N, the speed of the southerly wind exceeded 160 knots in the jet core at about 250 mb. Below the jet is a frontal zone in which the shear of wind component normal to the section is given as about 72 m sec^{-1} in a vertical distance of 1600 metres, i.e. 27 knots/1000 feet sustained over 5250 feet.

Aircraft observations. A paper in the *Air Weather Service Bulletin*[12] contains a report of an account by Bundgaard on some observations made with B-47 aircraft during a research project known as Black Sheep based on MacDill Air Force Base, Florida. In regard to vertical shear, it is stated that Tateno observatory, using the relay-sounding method described below (p 10) reports a case of a wind increase of 150 knots in 3000 feet. Previous flights by B-47 aircraft are said to have met shears which "have at times been as large as this or larger. But so far the project has found shears only up to about 30 knots per 1000 feet". The largest was a 52-knot decrease over an altitude interval of 1500 feet. This value was obtained from target winds simultaneously computed by two vertically adjacent B-47's at 40,500 feet and 42,000 feet just above and immediately to the left (looking downstream) of a 180-knot jet stream. Four other such pairs of B-47's also provided similar values at very nearly the same time in approximately the same vicinity and atmospheric layer. Since these values all formed a smooth pattern of the jet stream, this maximum value for vertical shear was considered to be quite reliable. One of the completed investigations of Project Black Sheep was concerned with measuring the small-scale structures of the upper field of motion by photographic methods following individual distinguishing features of deforming exhaust trails. Spatial variations of speed were deduced up to 3·5 knots/100 feet over vertical intervals ranging from 150 feet to 300 feet.

Statistical analyses. (i) An analysis of wind soundings made at Silver Hill, Maryland, is given by Tolefson[13]; this covers twice-daily ascents during a period of 12 months from 1 July 1953. The balloons were tracked by radio-direction-finding equipment AN/GMD-1A and the height determined from radiosonde observations of pressure and temperature. The shear is evaluated in two components, "longitudinal" and "normal", derived from the components of wind at the upper level respectively parallel and normal to the wind direction at the lower level. The longitudinal component is in general much the larger of the two and approximates to the magnitude of the vector shear the more closely as the angle between the upper and lower wind vectors diminishes. Various observations considered for one reason or another as unreliable were rejected; this admittedly introduces a bias to the extent that strong winds at high levels are not suitably represented. Tolefson's Figure 4(*a*) relates the longitudinal shear to thickness of the shear layer for a selection of results pertaining to the 10 to 15 km levels, while in the text he gives a few examples of the more severe longitudinal shears measured from the soundings. These large values are included in Figure 2, but one at least of them, representing 63 knots/1000 feet over 4300 feet, lies so far to the right of any others for a comparable layer thickness, that it appears questionable. Another of these large values (74 knots/1000 feet over 2000 feet) also appears in Tolefson's Figure 4(*a*), and curve III of Figure 2 has been drawn through it; all the other points in Tolefson's figure have values which would place them to the left of curve III, and all but one of them to the left of curve II.

For the purpose of calculating the effect of intense shear on an aircraft or missile in vertical flight, Tolefson selects a shear of 100 m sec^{-1} km^{-1} extending through a layer one kilometre thick as being representative of the more intense shears given in his Table II. This value (not shown in Figure 2) is equivalent to 59 knots/1000 feet over 3300 feet and exceeds the extreme for the United States as estimated in Figure 2. Since the actual thickness of the shear layers is not given in Tolefson's tabulated data, it is not possible to comment further on his results in detail. However, the sounding equipment used is known to overestimate the speed of strong winds (Salmela and Sissenwine[14]), and the corresponding shears consequently tend to be too large. Tolefson's results should therefore be treated with reserve.

(ii) Vaughan[15] gives an analysis for heights of 10 to 14 km at Cape Canaveral, Florida, based on routine upper wind observations over a period of seven years. Individual cases are not noted. Curves of shear against height interval are presented for several probability levels, both for the year as a whole and for the month (March) of strongest winds. In that month the 99·9 per cent probability curve for the (negative) shears above the level of maximum wind gives values which agree closely with Figure 2, curve II, from 13,000 feet down to 3000 feet, but values extrapolated for smaller intervals are less than the corresponding values of curve II. Since Cape Canaveral winds are not representative of the strongest winds in the United States, Vaughan's results are not inconsistent with Figure 2.

Shear in the higher stratosphere. (i) The information presented in this paper is concerned primarily with shear in the troposphere and lower stratosphere. There are however some observations of vertical shear at higher levels up to about 80 km, but so far these do not suggest that the shear at very high levels is any greater than that found in the proximity of jet streams.

(ii) Idealized wind profiles, based on available data, are presented by Vaughan[16] for Cape Canaveral, Florida, with special reference to heights of 60 to 80 km. The 99 per cent probability profiles indicate a peak wind at these levels of 180 m sec^{-1} (350 knots) associated with a wind shear of 0·070 sec^{-1} (41 knots/1000 feet) extending over a height interval of one kilometre above or below the peak wind. This value of the shear is intermediate between the values of curves II and III of Figure 2, for north-west Europe and the United States respectively, at the corresponding thickness.

(iii) Reisig[17] describes some observations by means of rockets up to 60 km at Cape Canaveral. The rate of ascent is about 1300 feet/sec and the effective time interval of the measurements apparently about ½ sec so that the wind profile is revealed with some of the details of gustiness, in contrast with the much more smoothed profiles obtained from the usual radiosonde measurements. Graphs are given of the vertical profiles of wind and shear for three soundings. The largest shear recorded is 0·026 m sec^{-1} per metre at a height of 52 km, equivalent to 16 knots/1000 feet. It is not stated over what height interval this applies, but from the diagram showing the wind profile this value appears to hold over about 5500 feet. For this interval the value of the shear is just half the extreme value given by curve III, Figure 2, for the United States.

Extreme shear in the United States. The extreme curve for the United States has been estimated as curve III, Figure 2. As with curve II for north-west Europe, the placing of the upper arm can be made fairly confidently from knowledge of the maximum wind speed, which appears to be about 260 knots. In consequence the vertical shear is unlikely to exceed 13 knots/1000 feet over an interval of 20,000 feet. For layer thicknesses from 5000 feet down to 2000 feet the curve is taken to be fixed by observed values, and both here and elsewhere its shape is assumed to be similar to that of curve I for Crawley.

Some further observations of large vertical shear

(i) Some comments on vertical shear in the vicinity of South Africa are given by the Union of South Africa.[18] Mention is made of an increase of 60 knots between 20,000 and 22,000 feet, just below the wind maximum of 144 knots. This value is said to be remarkably high although not exceptional for strong jets in that area. The place of the sounding is not stated, but the jet axis was thought to be to the south of Marion Island (46°S, 38°E).

(ii) Some measurements of vertical shear are quoted by Widger[19] from an unpublished report by Trefry on the results of some 30 research flights during a period of two years in Australia. Very rapid changes of wind with height were found, especially between 27,000 and 32,000 feet, and gradients were observed up to 60 knots over a vertical distance of 1000 feet.

(iii) A very exceptional instance of strong wind and shear at Bermuda on 28 March 1955 is discussed by Jordan.[20] The extreme wind was reported as 222 knots at 9000 feet with an increase of 72 knots from 8000 to 9000 feet. This remarkable wind and shear were associated with a fast-moving cold front with a large temperature inversion. It appears impossible to confirm the accuracy of these observations, but Jordan concludes that there is probably inadequate evidence to discount them on the basis of climatology, nor was there any obvious computational error, although no complete check could be made after the event on the orientation and functioning of the equipment. These values in many cases are the largest appearing on the diagram (Figure 2) for comparable layer thicknesses, but they are even more remarkable for the relatively low height above the surface at which they occurred.

(iv) Some observations of strong winds over Japan made by a relay-sounding method are described by Arakawa.[21] Balloons released at one station are tracked not only from that station but also from another station downwind, so that the balloons can be successfully followed up to great heights while the angle of elevation from the downwind station remains large enough to give accurate results. In this way, it is claimed, the most serious limitations for the measurement of the strongest known winds have been completely excluded. Details are given of the wind over Tateno on two occasions: that on 2 March 1954 from 32,000 to 42,000 feet, where the ascent terminated with a maximum speed of 292 knots; that on 6 March 1954 from 36,100 to 45,000 feet with maximum wind 230 knots at 40,000 feet. Several large values of vertical shear derived from these ascents are plotted in Figure 2, the most outstanding being 18 knots/1000 feet sustained over 9200 feet on 2 March and 27 knots/1000 feet over 5100 feet on 6 March. There are also some vertical cross-sections over Japan along 140°E which have been published by Mohri;[22] although these intercepted some quite strong jet streams with speeds in the neighbourhood of 200 knots, only moderate values of vertical shear were found (moderate, that is, in the present context). In fact the largest known shears have been found in the United States.

This unexpected limitation of the vertical shears over Japan has been similarly remarked on by Sissenwine, Mulkern and Salmela[23] who say that not only the extreme but also the mean shear is less over Japan than over the United States. Now the strong winds over southern Japan (latitude 35°N or less) are associated with the subtropical jet stream whereas the information on large shear from the United States is associated mainly with polar front jets. The subtropical jet stream differs from the polar front jet in several ways, in particular the level of the core is higher (roughly 40,000 feet compared with 30,000 feet), also the subtropical jet stream is not closely associated with a well marked tropospheric front (Sawyer[24]). For both reasons the vertical shear below the core would be less intense than in a polar front jet stream of similar speed. It must be said too, that the relay-sounding observations at Tokyo have not yet, it seems, confirmed the extremely high speeds reported from earlier observations, so that reliable measurements of shear are not available on occasions of peak winds greater than about 300 knots. At the polar front jet stream the strongest shears are often the negative ones above the core; it still remains to be seen whether this is true also for the subtropical jet stream over Japan and whether the values reached there are exceptional.

Estimated frequencies and extremes of vertical shear

A method is described here by which frequencies and extremes of wind shear at any place may be estimated from known values at some other place, provided the régimes of upper wind are similar. The method is based on the assumption that large shears are associated with strong winds—more explicitly, if the shear is proportional to the wind speed, the frequency distribution of large shear will be the same as that of strong wind, so that the shear which is exceeded with any given frequency will be proportional to the wind speed which is exceeded with the same frequency. Thus if at two comparable places the wind speeds which are exceeded on a given percentage of occasions are V_1 and V_2 respectively, and if S_1 is the vertical shear which is exceeded on the same percentage of occasions at the first place, then the corresponding value at the second place is given by the relation $S_2/S_1 = V_2/V_1$. The ratio V_2/V_1 can be obtained from known values of the mean vector wind $\bar{\mathbf{V}}$ and standard vector deviation σ on the assumption that the end-point of the wind vector $\bar{\mathbf{V}}$ has a Gaussian distribution. From world charts of isopleths of $\bar{\mathbf{V}}$ at standard pressure levels (Heastie and Stephenson[25]) and similar charts of σ (Tucker[26]) values of $\bar{\mathbf{V}}$ and σ at the chosen places are read off at the levels of strongest wind (approximately 300 mb in middle latitudes) for each of the mid-season months. The frequencies of wind speed exceeding certain values can then be obtained by means of tabulations prepared by the Rand Corporation[27] as indicated by Gloyne.[28] Table III gives an example of some figures obtained in this way.

TABLE III. *Calculation of wind speeds exceeded with certain frequencies*

			London, 300 mb					
					V in knots			
Period	$\bar{\mathbf{V}}$	σ	25	50	75	100	125	150
	kt	*kt*			*Percentage exceeding V*			
January	27	51	83·7	47·8	18·6	4·8	0·8	0·1
April	26	47	81·1	42·9	14·3	2·8	0·3	0·0
July	29	43	80·5	40·8	12·2	1·9	0·2	0·0
October	21	50	81·0	42·9	14·6	3·2	0·5	0·0
Year			81·6	43·6	14·9	3·2	0·5	0·0

From the frequencies for the year in the last row of the table, the speeds which are exceeded on certain percentage occasions are obtained by graphical interpolation. The results are shown in Table IV, together with those for New York.

TABLE IV. *Wind speeds exceeded with certain frequencies at* 300 *mb at London and New York*

					Per cent					
	50	40	30	20	10	5	4	3	2	1
					knots					
London	45	52	60	69	81	95	97	102	109	120
New York	59	68	78	90	108	123	128	134	140	152

It has been found that the assumption of a Gaussian distribution leads to an underestimate of the frequency of strong winds; comparison with observed values indicates that the speeds given for London in Table IV are too low by about five knots at frequencies of three per cent and less. A discrepancy of this order is however of little importance for a comparison between two stations.

Now the problem is how best to use the Crawley results as a basis for estimating frequencies of shear at other places. For the period June 1958 to May 1959, the mean wind speed at Crawley at 300 mb, based on the four routine observations each day, is 49 knots. Since this figure is identical with the mean speed over the nine-year period 1951–59, it may be taken that the 12 months from June 1958 to May 1959, and hence the frequencies obtained from the automatic radar theodolite, constitute a fair sample as regards vertical shear. In accordance with the hypothesis already made, it then follows that the values of shear which are exceeded on certain percentage occasions at New York can be obtained from those at Crawley (for London) simply by multiplying the latter values by 1·3, this being the constant ratio of the wind speeds at the two places for each frequency given in Table IV. The same method may be applied to other places where the régime of wind is similar, but not for example to Japan since the régime there is different, as has already been noted.

In regard to extremes of shear, values for London and New York may be regarded as fairly representative of north-west Europe and the north-eastern United States respectively. It must be emphasized that curve I for Crawley in Figure 2 is derived from a series of observations extending over a period of only 12 months and so would be expected to underestimate the values of the extremes occurring over a long period. On the other hand curve II for north-west Europe is based mainly on data gathered from a small number of meteorological

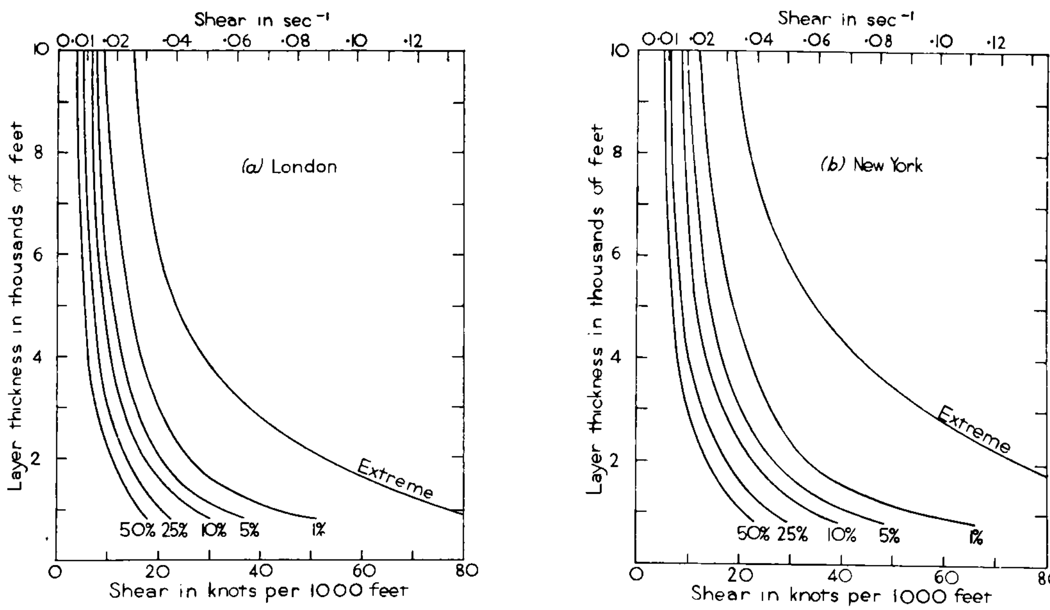

FIGURE 3. Estimated frequencies and extremes of vertical shear: (*a*) London and (*b*) New York.

situations which had been selected because of their exceptional character, and so should give a reasonable estimate of the actual extremes in that area. Similarly curve III gives comparable values for the north-eastern United States. The ratios of the extremes of curve III to those of curve II are 1·3 for layers of thickness 20,000 to 8000 feet, 1·4 for 7000 feet and 1·5 for 6000 to 1000 feet. These values are in reasonable agreement with the figure of 1·3 noted above for the ratios of wind speeds at New York and London. Although precise agreement is not to be expected, the closeness of the comparison does suggest that either of curves II or III could be used for estimating extreme shears at other places with a similar régime of wind, with the aid of a multiplying factor determined, as in the case of frequencies of shear, by the ratios of wind speeds at the two places concerned.

In Figure 3 (*a*) are displayed the values of wind shear at London (Crawley) exceeded on certain percentage occasions, together with extremes as given by curve II, Figure 2; in Figure 3 (*b*) are shown similar values for New York, the frequency curves in this case being estimated as already explained, and the extreme curve being the same as curve III, Figure 2.

Vertical shear and horizontal temperature gradient. When the geostrophic relation holds, the vertical shear of wind is proportional to the horizontal gradient of mean temperature in the layer considered. It is desirable to verify that on the synoptic scale, the largest shears quoted are consistent with the implied temperature gradients. This point has been considered by Kochanski[29] who has discussed the variation of extreme horizontal temperature gradient with distance in the upper troposphere over North America. Among instances of large shear, he includes that of 60 knots/1000 feet quoted by Widger[19] (see p 9 above) which requires (for geostrophic conditions) a temperature gradient of 26°C per degree of latitude. By extrapolation of his curves, Kochanski concludes that temperature differences of 13°C over half a degree of latitude are feasible.

Concluding remarks regarding vertical shear. In arriving at the various estimates described above, a heterogeneous collection of observations has been used. The winds come from a variety of types of sounding; for vertical soundings the measured wind is an average over a layer the depth of which varies from about 3500 feet to a few hundred feet according to the method of observation; with aircraft observations of the types used here the wind is usually an average over a few miles or tens of miles in horizontal flight. Moreover a measure of shear derived from a vertical sounding involves an appreciable time interval between the two measurements of wind, according to the rate of ascent of the sonde and the depth of the layer over which the shear is measured. Some attempt has been made to avoid the more obvious errors of observation by restricting the material for the most part to carefully scrutinized data; moreover the construction of aerological cross-sections usually involves some subjective analysis which tends to improve the accuracy obtainable from the raw data considered in isolation. However, it is not possible to eliminate all errors. Again, in considering the effect of wind shear on the flight of aircraft, rockets or missiles, one is ideally concerned with the rate of change of wind following the aircraft, etc., and the space-time over which the wind observations are averaged should also be appropriately selected. It is impossible to do more at present than to provide a rough guide to the shears likely to be encountered, and even then the problem is to make the best use of the available information.

EXTREMES OF HORIZONTAL SHEAR

Introduction

Some measurements of large horizontal shear have been gathered from various sources and plotted in Figure 4 against the horizontal distance over which the shear is measured; the envelope of these points constitutes an estimate of the extreme shear which exists in the atmosphere as a function of distance. The shears are expressed in units of hour^{-1}; this is the same as the knot per nautical mile and is equivalent to $2 \cdot 78 \times 10^{-4}$ sec^{-1} Another commonly used unit is the metre per second per 100 kilometres, equivalent to 0·036 hour^{-1} or to 10^{-5} sec^{-1}.

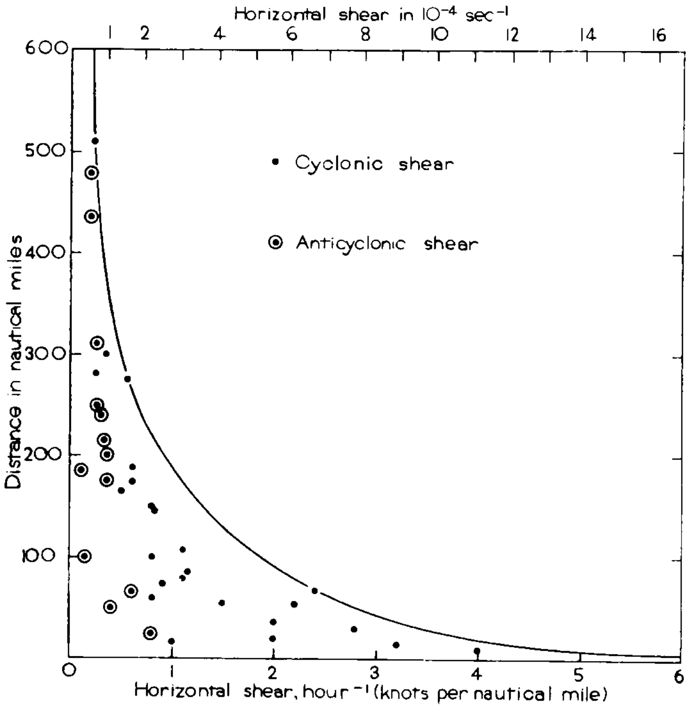

FIGURE 4. Some values of large horizontal shear with curve of estimated extremes.

From the picture given by aerological cross-sections it is evident that the largest horizontal shears usually occur at about the level of the jet core and within about 300 nautical miles either side, but when the frontal zone is well marked the largest shears may be associated with it in the neighbourhood of 400 or 500 mb. Over very short distances the shear is a concomitant of the eddy structure and large values may occur at any height, including the surface layers, wherever turbulence is present.

Theoretical considerations

(i) It might be expected that whenever in originally stable flow the horizontal shear becomes large enough, it would lead to a breakdown of the stability which in turn would limit the intensity of shear which the atmosphere could sustain in natural conditions. While stabilizing forces when present would oppose any such tendency, it seems probable that the relative effectiveness of the stabilizing and disturbing forces are related to the scale of the motion. On the synoptic scale, theoretical work (Sawyer,[30] van Mieghem[31]) indicates that the flow becomes unstable only when the shear is anticyclonic; the limiting condition then is effectively that the horizontal shear must exceed the Coriolis parameter for the latitude, or more precisely in the northern hemisphere, if

$$\frac{\partial V}{\partial n} - \frac{V}{r} > f \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $\partial V/\partial n$ is the horizontal shear, n being directed to the left of the velocity V, r is the radius of curvature of the streamlines and f is the Coriolis parameter. This is equivalent to saying that the vertical component of absolute vorticity, $\frac{V}{r} - \frac{\partial V}{\partial n} + f$, must be positive if the flow is to remain stable. If the shear is cyclonic, then the large-scale flow can in theory remain stable for lateral displacements however great the horizontal shear.

Measurements of horizontal shear on the anticyclonic (warm or equatorial) side of jet streams lend some support to these theoretical conclusions. For convenience, some values of the Coriolis parameter are given below (1 hour^{-1} = 1 knot per nautical mile):

It appears that the Coriolis value appropriate to the latitude may be attained, but

Latitude	Coriolis parameter
φ	hour^{-1}
30	0·26
40	0·37
50	0·40
60	0·46

is not generally exceeded, over distances up to three to five degrees of latitude on the warm side of the axis; however, Reiter,[32] in a detailed study of aircraft observations in the entrance region of a particular jet stream, finds a small excess over an extensive area to the south of the axis. Large though the critical value is in a given latitude it is often only moderate in comparison with the cyclonic shear on the cold side of the axis. It is again in accordance with theory that cylonic shear, much in excess of the Coriolis parameter, has been observed in the absence of turbulence.

(ii) Arakawa[33] has developed a criterion to determine whether turbulence associated with cyclonic shear will increase or decrease. The critical value of the shear is given by

$$-\frac{\partial u}{\partial y} = \Omega \sin \varphi + \frac{2u}{R} \tan \varphi \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where u is the zonal wind, y distance northwards along a meridian, Ω the earth's angular velocity, φ the latitude, and R the earth's radius. For cyclonic shear in the northern hemisphere, both sides of equation (2) are positive. If the critical value is exceeded, then the turbulent energy should increase; if the shear is less than the critical value, then the turbulence should decrease. The criterion is derived by an argument similar to that used by Richardson[34] in developing his well known criterion in relation to vertical shear—the work done by the eddy stresses is compared with the work required to maintain the turbulence against a stabilizing force which in this case is the centrifugal force acting on a displaced element of air which is assumed to conserve its absolute angular momentum. The critical value (2) in a strong zonal jet stream (u = 200 knots) is 0·30 hour^{-1} in latitude 45° and 0·37 hour^{-1} in latitude 55°. From a consideration of the evidence presented later in this paper, the critical value certainly appears to be too small; cyclonic shear up to at least 0·8 hour^{-1} in latitude 40° has been observed with negligible turbulence. Moreover, cyclonic shear greater than 0·3 or 0·4 hour^{-1} often exists in well developed jet streams and would appear to persist. In arriving at equation (2), Arakawa has assumed a certain numerical factor to be unity while admitting that this may not be justified; however, the cause of the discrepancy may lie in the assumption that turbulence is already present; if the motion originally is non-turbulent, there is no transfer of energy by the eddy stresses and the argument does not arise. The criterion may therefore have no relevance to the *initiation* of turbulence. Similar difficulties have of course been experienced with Richardson's own criterion, and are still unresolved (Reiter[32]).

(iii) Another criterion developed by Arakawa[35] by a similar argument refers to horizontal shear in circular systems such as tropical cyclones. The critical value in this case is given as

$$\frac{\partial v}{\partial r} = \Omega \sin \varphi + \frac{2v}{r} \tan \varphi \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where r is the radius of curvature of the flow and v the wind speed at right-angles to r. As an illustration, Arakawa takes v = 50 m sec^{-1}, r = 100 km, φ = 39°N, for which equation (3) yields a shear of 3·8 hour^{-1}. On a plausible distribution of the wind speed with radial distance in a tropical cyclone, Arakawa shows that this value may be exceeded by the steep shear in the central part, outside the eye of the cyclone. Apart from the validity of the critical value (3), the suggested possible value of about 4 hour^{-1} is consistent with the curve of extremes given in Figure 4 for intervals less than about 20 nautical miles.

Some values of large horizontal shear

Aerological cross-sections. (i) Murray and Johnson[36] present some information on horizontal shear measured in a series of 60 aerological cross-sections through jet streams in the eastern Atlantic and western Europe during September 1950. The mean shear on the cold side of the jet axis amounts to 18 knots, and on the warm side 14 knots, in the first 100 statute miles, respectively 0·21 and 0·16 hour^{-1}. A large cyclonic shear at the level of the jet axis on 16 September 1950, is given as 60–70 knots per 100 miles extending over at least 200 miles, and 100 knots extending over 100 miles; these are equivalent to 0·6 hour^{-1} over 174 nautical miles and 1·15 hour^{-1} over 87 nautical miles respectively. These examples are said to refer to "two contrary jets quite near each other". The corresponding Figure 9 of Murray and Johnson[37] shows that this very large shear is associated with a change of speed of 120 knots (through a reversal in sign) in 170 miles, a shear of 0·82 hour^{-1} over 147 nautical miles.

(ii) A similar study of 62 cross-sections during January 1950 is given by Johnson.[38] The mean shear of all the cross-sections is greatest at about 100 miles either side of the core, near the points of inflexion in the horizontal wind profiles; the mean values are 0·4 $hour^{-1}$ on the cold side and 0·25 $hour^{-1}$ on the warm side. In the individual profiles, the anticyclonic shear never exceeded the cyclonic shear, and the greatest cyclonic shear was again of the order of 100 knots over 100 miles.

(iii) A vertical cross-section through a jet stream over north-west Europe at 0300 GMT on 9 November 1949 is described by Berggren.[3] The wind speed at the core is about 146 knots. The anticyclonic shear averages 9 m sec^{-1} per 100 km over a distance of 400 km, i.e. 0.33 $hour^{-1}$ over 215 nautical miles, but it is suggested that shears approaching the Coriolis value of 0·41 $hour^{-1}$ may have occurred over shorter distances. The cyclonic shear is much greater, attaining (if the observations are reliable) 60 m sec^{-1} over 100 km (2·2 $hour^{-1}$ over 54 nautical miles) more than five times the Coriolis value.

Another vertical section is given for a jet stream over Great Britain at 0900 GMT on 25 April 1949. The maximum shear on the cold side is again about 60 m sec^{-1} over 100 km.

(iv) Vuorela[4] discusses a vertical cross-section through a jet stream over the British Isles at 0300 GMT on 16 January 1951. The cyclonic shear at the level of the core (300 mb) averages 62 m sec^{-1} over 200 km, equivalent to 1·1hour^{-1} over 108 nautical miles, but from the analytical concentration of isotachs in the frontal zone at this level, Vuorela obtains a value of 41 m sec^{-1} over 100 km, or 1·5 $hour^{-1}$ over 54 nautical miles, more than three times the Coriolis value. The core speed in this example was about 150 knots. In another section for 0300 GMT, 7 November 1952, with a maximum wind about 175 knots at 350 mb, the greatest cyclonic shear is given as 41 m sec^{-1} in 305 km, or 0·5 $hour^{-1}$ over 165 nautical miles.

(v) Briggs[5] describes a cross-section through a northerly jet stream over the British Isles on 13 November 1958. The core is just west of Crawley and just below the 300 mb level at 1100 GMT with a speed of 140 knots. To the east there is a well marked trough with strong southerly winds over the North Sea; at Hemsby the southerly wind extends up to 320 mb. The horizontal shear reaches its maximum in the frontal zone near the 400 mb level, 80 knots in 29 nautical miles (2·8 $hour^{-1}$) and 160 knots in 67 nautical miles (2·4 $hour^{-1}$), the larger of these being almost seven times the Coriolis value. Equally remarkable is the large anticyclonic shear, 20 knots in 25 nautical miles (0·8 $hour^{-1}$) to the west of the core at about 350 mb and again at 500 mb; also 40 knots in 67 nautical miles (0·6 $hour^{-1}$) at 350 mb. The existence of anticyclonic shear up to twice the Coriolis value should be associated with turbulence; this was in fact confirmed by an aircraft ascent up to 300 mb just on the west side of the core. Further reports of turbulence to the east of the core are attributable to the large vertical shear which was present in the frontal zone simultaneously with the large cyclonic shear. Even with a cross-section such as this, the analysis is subject to some uncertainty arising from possible errors in the observations themselves, from their rather wide spacing and from displacement in some cases from the precise time or place of the section. Nevertheless there is little doubt that both the cyclonic and anticyclonic shears in this example are among the largest known on the synoptic scale, although their precise value may be in some doubt.

(vi) Lamb[39] and others describe the structure of jet streams over North Africa and the central Mediterranean. They find that the anticyclonic shear clearly approaches and possibly exceeds the Coriolis parameter, and give some values based directly on routine observations of upper wind which were considered reliable. Thus on 3 January 1954 at 300 mb the anticyclonic shear was 0·4 $hour^{-1}$ over 50 nautical miles, where the Coriolis parameter was 0·28 $hour^{-1}$; on 4 and 7 January 1954 at 300 mb, it was 0·2 $hour^{-1}$ over 480 nautical miles, Coriolis parameter 0·25 $hour^{-1}$; on 8 February 1954 at 270 mb, it was 0·3 $hour^{-1}$ over 240 nautical miles, Coriolis parameter 0·29 $hour^{-1}$.

(vii) Newton and Carson,[40] in a discussion of the wind field at 300 mb over North America at the beginning of August 1949, mention a cyclonic shear of 17 m sec^{-1} per 100 km between Fort Worth and Shreveport at 34,000 feet, equivalent to 0·6 $hour^{-1}$ over 190 nautical miles.

(viii) Some vertical sections crossing Japan along the meridian 140°E are described by Mohri.[22] On 9 December 1950, with an estimated jet speed of 195 knots, the calculated maximum (isentropic) wind shear south of the jet axis closely approached the critical value given by equation (1), the shear of 0·30 $hour^{-1}$ being slightly greater than the Coriolis value. On the next day the estimated jet maximum was 204 knots, and the anticyclonic shear somewhat less than the critical value.

(ix) A cross-section over the British Isles at 2100 GMT on 14 January 1951, is described by Hubert.[41] It intercepts a jet stream with maximum speed 155 knots at 250 mb above Aldergrove, and the horizontal shear amounts to 80 knots in about 100 nautical miles between the levels of 400 and 350 mb.

Traverses of jet streams by aircraft. (i) The wind profile across a jet stream over Great Britain on 18 January 1952 was determined from a series of vertical photographs on a flight at 300 mb (Hurst[42]); the individual speeds so deduced were erratic and in the published diagram the winds are averages over approximately five-mile intervals. On this basis, the core speed of 170 knots was maintained with little change over 30 nautical miles; on the cold side the speed then decreased by 40 knots in 20 nautical miles (2·0 $hour^{-1}$) and then by a further 50 knots in 60 nautical miles (0·8 $hour^{-1}$), the last two stages together giving 90 knots in 80 nautical miles (1·1 $hour^{-1}$). It was not possible to determine the shear on the warm side because of technical difficulties.

(ii) Another set of measurements of the same type was made on 1 September 1952 (Hurst[43]). The greatest measured wind at 300 mb was 112 knots, but there were gaps in the records near the core and 120 knots had been reported at Leuchars. On the cold side the wind decreased by 67 knots in 75 nautical miles (0·9 $hour^{-1}$) and on the warm side by 72 knots in 200 nautical miles (0·36 $hour^{-1}$), rather less than the Coriolis parameter of 0·43 $hour^{-1}$.

(iii) A research project[12] known as "Black Sheep" based on MacDill Air Force Base, Florida, has already been referred to on p 7. It is stated that variations in wind speed of 40 knots over 10 nautical miles (4·0 $hour^{-1}$) had been observed to the north of a jet stream at heights of about 33,000 feet or above.

(iv) Endlich[44] and others give an account of some observations made in Florida by means of aircraft of "Project Jet Stream". The greatest horizontal shear measured was 16 knots in 18 statute miles (1·0 hour^{-1}) but the authors state that they were unable to take advantage of conditions when stronger shears might have been expected.

(v) Riehl, Berry and Maynard[45] describe some results of flights through jet streams over the eastern United States. On 27 February 1953 the peak recorded wind speed was 240 knots. The profile of absolute vorticity shows zero values south of the jet axis, with a slow increase still farther south; to the north of the axis the vorticity jumps to very large values. Turbulence was negligible in spite of the extreme lateral shears. These are not given explicitly, but from the diagrams the cyclonic shear appears to be about 0·8 hour^{-1} over a distance of 150 nautical miles near latitude 40°N.

(vi) Some results of aircraft traverses of jet streams in the Middle East are reported by Harding.[46] Flights were made at constant indicated height at about the level of maximum wind, and wind speeds were deduced from a series of vertical photographs of the ground; wind averages over a number of photographic prints, corresponding with a horizontal distance of about 25 nautical miles, are used for the analysis. Supplemented by routine observations from upper-air stations, these flights yield information on the horizontal profile of the westerly jet streams in this region in winter. They are found to contain a belt of strong winds up to about 200 nautical miles in width in which there is little or no horizontal shear, while on either flank the shear appears to be of the same order as that found in jet streams over the north-east Atlantic and western Europe. Some of the largest values of shear reported by Harding are as follows:

6 February 1953, Port Said to Wadi Halfa at 40,000 feet. The jet axis was probably in the neighbourhood of Port Said. Winds averaged about 133 knots over 205 nautical miles with no appreciable shear. The cyclonic shear to the north was about 0·26 hour^{-1} over 250 nautical miles. The photographic record to the south was incomplete, but the anticyclonic shear was probably not greater than 0·15 to 0·20 hour^{-1} over a distance of 100 nautical miles.

16 January 1954, Hilla to Kuwait at 40,000 feet. Strongest winds about 160 knots with little horizontal shear over 110 nautical miles. Cyclonic shear 0·56 hour^{-1} over 275 nautical miles. Anticyclonic shear (from photographic measurements alone) at least 0·11 hour^{-1} over 185 nautical miles; with the aid of the ascent at Bahrain, 0·27 hour^{-1} over 250 nautical miles, and from Habbaniya to Bahrain 0·20 hour^{-1} over 435 nautical miles.

25 February 1954, Habbaniya to Kuwait at 37,000 feet. Strongest wind speeds averaged 169 knots over 210 nautical miles across-wind without appreciable shear. Anticyclonic shear 0·37 hour^{-1} over 175 nautical miles and 0·27 hour^{-1} over 310 nautical miles, both based in part on the routine ascent at Bahrain.

5 March 1955, Canal Zone to Wadi Halfa at 35,000 feet. Strongest speeds about 140 knots extending for 85 nautical miles across wind. A cyclonic shear of 71 knots in 36 nautical miles (2·0 hour^{-1}), determined photographically was the largest found in this series of flights.

(vii) Information on the horizontal variation of wind over great distances is given by Helliwell.[47] A series of flights between the Arctic circle and the western Mediterranean were made either in the vicinity of the tropopause at a constant pressure level ranging on different flights between 187 and 250 mb, or in the stratosphere at 140 mb. Wind was measured at intervals of about 35 miles by means of a Marconi Doppler navigator. On 26 July 1956 the flight at 227 mb (about 36,000 feet) traversed a jet stream within which the highest recorded wind speed was 125 knots. To the north the wind decreased by 100 knots in 5 degrees of latitude, a shear of 0·33 $hour^{-1}$ extending over 300 nautical miles; over about 8½ degrees of latitude (510 nautical miles) the decrease was 115 knots, a shear of 0·23 $hour^{-1}$. At 140 mb (about 46,000 feet) the profile found was generally similar but the shears were smaller.

A statistical analysis. Frequencies of values of $\partial v/\partial n - V/r$ (the function on the left-hand side of inequality (1) were prepared by Bannon[7] from routine radarwind observations at three stations in England—Larkhill, Downham Market and Liverpool. Since V/r is small except when the curvature of the streamlines is large, the function tabulated may be regarded simply as horizontal shear in nearly all cases. Frequencies are given for 450, 300 and 200 mb for the four months October 1946, January, April and June 1947 combined. The greatest range tabulated is 0·40 $hour^{-1}$ and above, the horizontal distance being about 175 nautical miles; this range includes the Coriolis value (0·42 $hour^{-1}$) but Bannon makes no distinction between cyclonic and anticyclonic shears. One would have expected to have found much larger values of (cyclonic) shear, but the actual maximum found is not stated. Bannon remarks that occasions of very strong winds are not fully represented in the analysis because of limitations of the radar equipment; the use of fixed stations and heights also limits the possibility of finding extreme values. It is noteworthy however that the values of shear of 0·40 $hour^{-1}$ or above were found mostly at 300 mb (i.e. at about jet-stream level), much less frequently at 450 mb and none at 200 mb or in the stratosphere, results which are in conformity with the general structure of jet streams.

A surface front. The structure of an exceptionally intense surface front moving southwards over the southern United States on 17/18 April 1953 is described by Sanders.[48] Values of shear are given at 1000-foot intervals up to 4000 feet. The cyclonic shear within the frontal zone is largest at 1000 feet where it amounts in one vertical section to $8{\cdot}8 \times 10^{-4}$ sec^{-1} or 3·2 $hour^{-1}$, the width of the zone being 13 nautical miles.

Shear over very short distances. As in the case of vertical shear (p 5), the horizontal shear at a given instant comes to depend more and more on the local eddy structure as the interval of distance decreases (Bannon and Goldie).[8] The magnitude of the shear may be as large as 6 sec^{-1} or $2{\cdot}2 \times 10^{4}$ $hour^{-1}$ over a distance of 20 feet.

Reliability of large values of anticylonic shear

The values of anticylonic shear given above include six which exceed the Coriolis parameter by factors ranging from 1·1 to 2·0. The reliability of these values needs to be considered. Three of them derive from traverses by aircraft of the sub-tropical jet stream reported by Harding[46] (p 19) and are based in part on the routine wind observations at Bahrain at 37,000 feet. Even with the largest of these three, the ratio (1·5) of shear to Coriolis would be reduced to unity if the change of wind speed over the leg of 175 nautical miles were too large by 21 knots, a not impossible error, while with the other two values a similar reduction would be brought about by a decrease of only 5 or 6 knots in the wind difference. There are also two large values obtained from an aerological cross-section by Briggs[6] (p 17). If the estimated wind differences over 25 and 67 nautical miles have errors respectively of 10 and 24 knots, the ratio of shear to Coriolis would be reduced from 2·0 and 1·5 respectively to unity. Such errors are again by no means impossible since the measured shears depend partly on observations from a station situated some 200 miles from the plane of the section, and partly on estimated configuration of the isotachs. Lastly there is a measurement from the Mediterranean (Lamb,[39] p 18), in which the ratio (1·4) would be reduced to unity by a reduction of only 6 knots in the wind difference which is taken from routine ascents. It appears therefore that the evidence assembled in this paper for shears in excess of the Coriolis parameter cannot be regarded as conclusive.

Extreme horizontal shear as function of distance

The curve in Figure 4 is a suggested envelope of the plotted points and constitutes an estimate of extreme shear as a function of the distance over which the shear is measured. The area of Japan where the strongest high-level winds are found is not well represented but for reasons already stated (p 10) it seems unlikely that larger values would be found there than elsewhere in the world. For distances less than about 200 nautical miles there is a striking contrast in Figure 4 between the large values of cyclonic shear and the values of the anti-cyclonic shear which are limited, with few exceptions, to the Coriolis factor.

The varied assortment of values of shear in Figure 4 are subject to various degrees of inaccuracy; these are difficult to assess especially when as in many cases the shear is determined from isopleths of speed on a vertical cross-section. Wind observations themselves are always smoothed to some extent both temporally and spatially, a process which usually leads to an underestimate of the instantaneous shear between two points, but the construction of a cross-section may yield inferential values greater than those obtainable directly from the observations. Synoptic observations are appropriate to large distances, but considerable refinements are possible when the same data are used in the construction of vertical sections.

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BIBLIOGRAPHY

1. ESSENWANGER, O. M., BRADFORD, R. E. and VAUGHAN, W. W.; On verification of upper-air winds by vertical shear and extremes. *Mon. Weath. Rev., Washington, D.C.*, **89**, 1961, p. 197.

2. DURST, C. S. and DAVIS, N. E.; Jet streams and their importance to air navigation. *J. Inst. Navig. London*, **2**, 1949, p. 210.

3. BERGGREN, R.; The distribution of temperature and wind connected with active tropical air in the higher troposphere and some remarks concerning clear air turbulence at high altitude. *Tellus, Stockholm*, **4**, 1952, p. 43.

4. VUORELA, L. A.; On the air flow connected with the invasion of upper tropical air over northwest Europe. *Geophysica, Helsinki*, **4**, 1953, p. 105.

5. BRIGGS, J.; Widespread severe clear-air turbulence, 13 November 1958. *Met. Mag., London*. **90**, 1961, p. 234.

6. BRIGGS, J.; Severe clear-air turbulence near the British Isles. *Met. Mag., London*, **90**, 1961, p. 245.

7. BANNON, J. K.; Shear frequencies in the upper troposphere and lower stratosphere over England. *Met. Mag., London*, **79**, 1950, p. 161.

8. BANNON, J. K. and GOLDIE, A. H. R.; Gust gradients. 1948, (unpublished).

9. COLE, R. O. and CHAMBERLAIN, L. W.; Vertical wind shears near the core of the jet stream over the northeastern United States, August 1–2, 1958. *Mon. Weath. Rev., Washington, D.C.*, **86**, 1958, p. 319

10. ANDERSON, A. D., Free-air turbulence. *J. Met., Lancaster, Pa.*, **14**, 1957, p. 477.

11. PALMÉN, E.; Vertical circulation and release of kinetic energy during the development of hurricane Hazel into an extratropical storm. *Tellus, Stockholm*, **10**, 1958, p. 1.

12. Military Air Transport Services; Weather factors in a B-47 mission. *Air Weather Service Bulletin. Scott Air Force Base, Illinois.* September 1954, p. 18.

13. TOLEFSON, H. B.; An investigation of vertical-wind-shear intensities from balloon soundings for application to airplane- and missile-response problems. NACA Tech. Note 3732, Washington, D.C., 1956.

14. SALMELA, H. A. and SISSENWINE, N.; A note comparing 1-km vertical wind shears derived from simultaneous AN/GMD-1A and AN/GMD-2 winds-aloft observations. AFCRC-TN-59-496. GRD Res. Notes No. 22, Bedford, Mass., 1959.

15. VAUGHAN, W. W.; Investigation of the Cape Canaveral, Florida wind magnitude and wind shear characteristics in the ten to fourteen kilometre altitude region. NASA Tech. Note D-556, Washington, D.C., Jan. 1961.

16. VAUGHAN, W. W.; Idealized wind profiles applicable for the study of vehicle performance between 60 km and 80 km altitude Cape Canaveral (Atlantic Missile Range), Florida. NASA Tech. Note D.560, Washington, D.C., 1960.

17. REISIG, G. H. R.; Instantaneous and continuous wind measurements up to the higher stratosphere. *J. Met., Lancaster, Pa.*, **13**, 1956, p. 448.

18. Union of South Africa, Weather Bureau News Letter No. 117, 31 December 1958, p. 8.

19. WIDGER, W. K.; A survey of available information on the wind fields between the surface and the lower stratosphere. AFCRC Air Force Surveys in Geophysics, No. 25, Bedford, Mass., 1952.

20. JORDAN, C. L.; An instance of reported winds of 200 knots in the lower troposphere. *Bull. Amer. met. Soc., Lancaster, Pa.*, **40**, 1959, p. 410.

21. ARAKAWA, H.; The world's strongest winds as revealed by Tateno relay-method soundings. *Bull. Amer. met. Soc., Lancaster, Pa.*, **40**, 1959, p. 343.

22. MOHRI, K.; On the fields of wind and temperature over Japan and adjacent waters during winter of 1950–1951, *Tellus, Stockholm*, **5**, 1953, p. 340.

23. SISSENWINE, N., MULKERN, M. T. and SALMELA, H. A.; Design wind profiles from Japanese relay sounding data. AFCRC, Air Force Surveys in Geophysics, Bedford, Mass., No. 117, 1959.

24. SAWYER, J. S.; Jet stream features of the earth's atmosphere. *Weather, London*, **12**, 1957, p. 333.

25. HEASTIE, H. and STEPHENSON, P. M.; Upper winds over the world; Parts I and II. *Geophys. Mem., London*, **13**, No. 103, 1960.

26. TUCKER, G. B.; Upper winds over the world; Part III. *Geophys. Mem., London*, **13**, No. 105, 1960.

27. Rand Corporation; Offset circle probabilities. Air Force Project Rand R-234 Numerical Analysis Dept., Santa Monica, California, 1952.

28. GLOYNE, R. W.; Note on a tabulated function for use with two-dimensional wind distributions. *Met. Mag., London*, **88**, 1959, p. 170.

29. KOCHANSKI, A.; Horizontal temperature gradient at 200 mb and adjacent levels. *Bull. Amer. met. Soc., Lancaster, Pa.*, **37**, 1956, p. 47.

30. SAWYER, J. S.; The significance of dynamic instability in atmospheric motions. *Quart. J. R. met. Soc., London*, **75**, 1949, p. 364.

31. MIEGHEM, J. M. Van; Hydrodynamic instability. Compendium of Meteorology, Amer. met. Soc., Boston, Mass., 1951, p. 434.

32. REITER, E. R.; The detailed structure of the wind field near the jet stream. *J. Met., Lancaster, Pa.*, **18,** 1961, p. 9.

33. ARAKAWA, H.; Possible heavy turbulent exchange between the extratropical tropospheric air and the polar stratospheric air. *Tellus, Stockholm*, **3,** 1951, p. 208.

34. RICHARDSON, L. F.; The supply of energy from and to atmospheric eddies. *Proc. roy. Soc., London*, **97,** 1920, p. 354.

35. ARAKAWA, H.; Severe turbulence resulting from excessive wind-shear in tropical cyclones. *J. Met., Lancaster, Pa.*, **9,** 1952, p. 221.

36. MURRAY, R. and JOHNSON, D. H.; Structure of the upper westerlies; a study of the wind field in the eastern Atlantic and western Europe in September 1950. *Quart. J. R. met. Soc., London*, **78,** 1952, p. 186.

37. MURRAY, R. and JOHNSON, D. H.; Notes on the wind field of middle latitudes. *Met. Res. Pap., London*, No. 667, 1951. (Available in Met. Office Library, Bracknell.)

38. JOHNSON, D. H.; A further study of the upper westerlies; the structure of the wind field in the eastern North Atlantic and western Europe in January 1950. *Quart. J. R. met. Soc., London*, **79,** 1953, p. 402.

39. LAMB, H. H., FLEMING, J., HOYLE, H. D. and ROBINSON, J.; Jet streams over North Africa and the central Mediterranean in January and February, 1954. *Met. Mag., London*, **86,** 1957, p. 97.

40. NEWTON, C. W. and CARSON, J. E.; Structure of wind field and variations of vorticity in a summer situation. *Tellus, Stockholm*, **5,** 1953, p. 321.

41. HUBERT, W. E.; A case study of variations in structure and circulation about westerly jet streams over Europe. *Tellus, Stockholm*, **5,** 1953, p. 359.

42. HURST, G. W.; The profile of a jet stream observed 18 January 1952. *Quart. J.R. met. Soc., London*, **78,** 1952, p. 613.

43. HURST, G. W.; The profile of a jet stream observed 1 September 1952. *Quart. J.R. met. Soc., London*, **79,** 1953, p. 407.

44. ENDLICH, R. M., HARNEY, P., MCCLEAN, G. S., RADOS, R. M., TIBBETS, O. J., and WIDGER, W. K. Jr.; Project Jet Stream: The observation and analysis of the detailed structure of the atmosphere near the tropopause. *Bull. Amer. met. Soc. Lancaster, Pa.*, **35,** 1954, p. 143.

45. RIEHL, H., BERRY, F. A. and MAYNARD, H.; Exploration of the jet stream by aircraft during the 1952–53 winter. *J. Met., Lancaster, Pa.*, **12,** 1955, p. 26.

46. HARDING, J.; The profile of jet streams in the Middle East. *Met. Res. Pap., London*, No. 932, 1955. (Available in Met. Office Library, Bracknell.)

47. HELLIWELL, N. C.; Airborne measurements of the latitudinal variation of frost-point, temperature and wind. *Sci. Pap., met. Off., London*, No. 1, 1960.

48. SANDERS, F.; An investigation of the structure and dynamics of an intense surface frontal zone. *J. Met., Lancaster, Pa.*, **12,** 1955, p. 542.

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