An Investigation of Extreme Low-Level Wind Shear at Selected Stations in the Conterminous United States

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ABSTRACT

The occurrence of extreme low-level wind shear at 10 stations in the conterminous United States is investigated by applying a bivariate frequency-distribution analysis to rawinsonde and pibal data. Data for Denver, Colo., received additional analysis and showed that extreme wind shears were associated with particular synoptic conditions. Many stations indicated variation of extreme shear with season. Large values of extreme wind shear were found to correlate well with mean storm tracks in the conterminous United States.

1. Introduction

Characteristics of the vertical variation of the horizontal wind component have been extensively investigated in the lowest layers of the atmosphere. Most of these studies have dealt with the general characteristics of low-level wind shear, with little emphasis on occurrences of extreme values. In recent years, the effect of wind shear on aircraft takeoff and landing has come under review (Gera, 1971; Melvin, 1970; Watson, 1969), and extreme wind-shear incidence and aircraft accidents have been shown to correlate. As early as 1964, the International Civil Aviation Organization Commission for Aeronautical Meteorology (CAeM/III) asked member states to investigate low-level wind shear conditions, with emphasis on the occurrence of extreme values, in the vicinity of aerodromes.

The results of several studies conducted at airfields and meteorological towers since 1964 have direct applicability to aircraft operations. Some of these studies can be found in two World Meteorological Organization (WMO) Technical Notes: Aeronautical Meteorology (1969) and Vertical Wind Shear in the Lowest Layers of the Atmosphere (1969). The work presented in these WMO Technical Notes emphasizes that no true climatology of low-level wind shear exists for the United States.

The work reported here provides a statistical background on the climatological aspects of extreme low-level wind shears at various points in the conterminous United States and explores the applicability of such information to aircraft operations.

2. Models of wind shear and its extremes

Three approaches may be used in modeling wind shear and its extremes. These are 1) physical models, which treat the motion equations either analytically or numerically; 2) statistical models, which treat characteristics of the population distribution of wind shear; and 3) meteorological models, which deal with meteorological conditions associated with observations of extreme wind shear. We will be concerned with the latter two. Those interested in physical modeling are referred to Taylor (1970) and Arya (1972), among others.

For statistical modeling, we must first determine the type of population distribution which applies to wind shear. Second, we must determine whether this distribution is universal. If it is, then the next step is to discover the relationship between statistics of the distribution, from which extreme values can be found, and easily measured meteorological parameters. An alternate method would be to concentrate, in a similar manner, only on the extreme value distributions. It is not known at this time whether or not the wind shear distribution is universal. In fact, the exact form of wind shear distributions in specific areas has not been conclusively determined.

Fichtl (1971), using a limited data set from Cape Canaveral, treated statistical modeling of wind shear from the similarity view of turbulent motions. His approach was to universalize certain statistical parameters by proper scaling and to associate the variation of these scaled parameters with certain external dimensionless parameters which include combinations of sensor separation, measurement height, Coriolis parameter, friction velocity, and Monin-Obukhov stability length.

Most statistical results reported so far should be considered as background material because they have

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not attempted to relate the statistics of a distribution to meteorological parameters or variables. In contrast, as we have done, they have dealt with the gross characteristics of the distribution, such as frequency of occurrence using relatively long-time series covering a wide variety of meteorological conditions.

Reports resulting from the original CAeM/III request show that individual component differences of 5 m s^{-1} in the first 30 m (the critical value established by CAeM/III, 1964) make up about 1% of the total number of occurrences. These same reports provide little information on persistence of extreme wind shear. This characteristic should be included in a working model. Kusano *et al.* (1967) cited a case of extreme wind shear persisting for 22 h, indicating that some cases are more heavily influenced by mesoscale and synoptic-scale events than, for instance, by local stability.

The object of meteorological wind shear modeling is to determine the set(s) of meteorological conditions under which extremes of wind shear exist and the extent to which these conditions influence or are associated with persistence of the extreme shear occurrence. For planning purposes, the statistical approach is probably the most useful; for operations, the meteorological approach is better because the conditions under which extreme shears may occur could be recognized by an experienced meteorologist, especially at stations where low-level wind profiles are not routinely measured.

It is recognized that large values of low-level wind shear are associated with the low-level wind maxima (Abramovic and Glazunov, 1969; Rider and Armendariz, 1966) paralleling the observation of jet-stream-linked strong wind shears in the free atmosphere (Reiter, 1961). Strong wind shears in the boundary layer are often found in stable rather than unstable atmospheric stratification (Mashkova, 1967; Pettitt and Root, 1969; Rijkoort, 1969; Tsverava, 1967). In an apparent contradiction, Marwitz (1971) and Colmer (1971) noted strong wind-shear conditions existing in the cold air outflow of cumulonimbus; however, the cold air outflow provides for local stability in the boundary layer even though the atmosphere is unstable through a deeper layer (Zipser, 1969). Boucher *et al.* (1965), Jefferson (1966) and Sowa (1972) reported strong wind-shear occurrences in the vicinity of frontal surfaces. In Japan, Kusano *et al.* (1967) correlated strong wind shear with the following synoptic conditions: cold fronts, outbursts of winter monsoon, high pressure areas (possibly agumented by a land-sea breeze circulation), and typhoons. They noted that low visibility is unlikely to be accompanied by strong wind shear.

In summary, existing literature suggests these meteorological characteristis of strong wind shear: 1) associated with stable rather than unstable boundary-layer conditions; 2) frequently seems to be caused by changes in wind direction with height rather than with changes in wind speed with height, direction remaining constant; and 3) often found in the vicinity of frontal zones which carry with them the characteristics of stable conditions in the lowest layers and the wind direction shifts noted in 1) and 2) above.

3. Effect of wind shear on aircraft

Consider an aircraft during the critical landing operation. The aircraft is moving horizontally as it descends making the horizontal wind parameter of interest,

$$\frac{\Delta}{\Delta x}\left[\frac{\Delta \mathbf{V}}{\Delta z}\right], \quad \text{where} \quad \mathbf{V}=u\mathbf{i}+v\mathbf{j}. \tag{1}$$

The Δ is used to emphasize data acquisition restraints. Generally, the principle of horizontal homogeneity is invoked, and the operative parameter becomes $\Delta \mathbf{V}/\Delta z$, measured at one point near the landing strip. Data acquisition requirements lead to

$$\frac{\Delta \mathbf{V}}{\Delta z}=\overline{\left[\frac{\Delta \mathbf{V}}{\Delta z}\right]}+\left[\frac{\Delta \mathbf{V}}{\Delta z}\right]', \tag{2}$$

where the overbar denotes a time average and the prime a departure from the mean, or a "shear gust."

In turbulence theory, an acceptable averaging time is one in which the average of the deviations is nil. Wind shear data acquisition for aircraft operations may compromise this important criterion. Furthermore, it is possible, considering studies of vertical shear in the free atmosphere, that the correct averaging time for application to (2) would be a function of Δz (Reiter and Lester, 1967).

Some assumptions can be made that lead to an estimate of the averaging time, and Δz to be used for most major airport operations. Refinements of these estimates ultimately depend upon the aerodynamic response of a given aircraft. If an aircraft is descending at about 3 m s^{-1} with 85 m s^{-1} ground speed, and if it takes a pilot approximately 1 s to decide to correct for an approach problem, 1 s to act upon it, and still another second for the aircraft to respond, then the aircraft has traversed 9 m vertically and about 255 m horizontally. The above estimates are crude, but they give some idea of the spatial and temporal limits (i.e., $\Delta z > 9$ m and an averaging time > 3 s). These types of limits will hold even if the aircraft responds to a smaller space interval and averaging time. Furthermore operational averaging time may depend in part on the persistence of small shear layers. In addition, Burnham (1970) suggested that a pilot may not be able to distinguish between the gustiness of the horizontal wind field and a sudden wind vector change on his descent through a shear layer. Various investigators [see the two WMO Technical Notes (1969) mentioned earlier] gave results on data averaged from 5 s to 60 min. Suggestions for optimum averaging times ranged from "nearly instantaneous" to less than 4 min.

4. Method of analysis

Three questions were relevant to determing the method of analysis. First, what is the best way to present a frequency distribution of a vector field? Second, given the data set (see Section 5), how should the CAeM extreme wind-shear criterion be applied? Third, how should this criterion be applied to aircraft operations to produce results consistent with the CAeM standard format of wind shear statistics? We will take up each of these questions in turn.

a. Frequency distributions of vector fields: The bivariate frequency table

Wind shear, like wind velocity, is a vector quantity. It can be described by two scalar variables: either a direction and magnitude or x and y components. Marginal frequency distributions of either scalar variable (i.e., distribution of x components and distribution of y components) force one to view the scalar parameters as independent of one another. This may be true over very short periods of time when trends are small (Panofsky and Crutcher, 1951), but it is probably not true when wind shear components are treated in a climatological sense. Previous wind shear studies have not considered the probability that the two scalar variables are interdependent.

Crutcher (1957) discussed the use of the bivariate frequency distribution as applied to vector wind fields in the free atmosphere, where the two variables were the x and y components of the wind velocity. Crutcher and Baer (1962) used this approach to develop an elliptic bivariate normal distribution model of a climatological series of upper wind data.

To comply with CAeM wind shear formats, the vector wind was broken into x and y components, as in Fig. 1, and component differences between levels were then taken. All shear values were given as wind speed differences (m s^{-1}) for a known Δz. A bivariate table was constructed using the component differences as in Fig. 2.

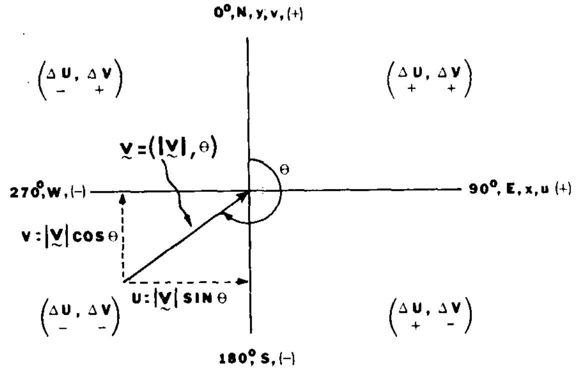

FIG. 1. The wind vector and its components. Example shown is for a southwest wind. This figure is based upon the National Climatic Center Winds Aloft Summary format.

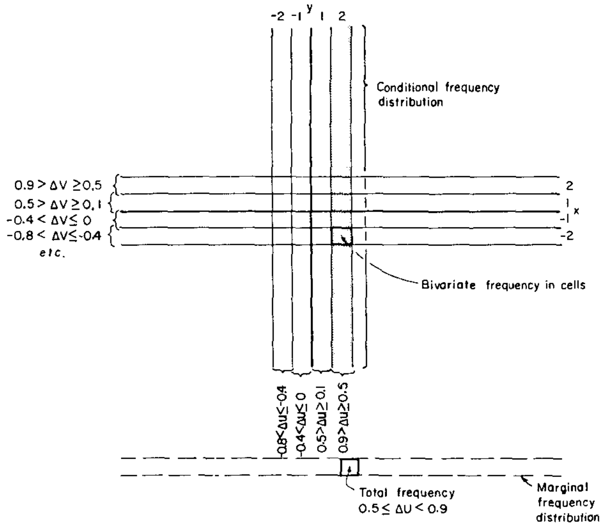

FIG. 2. Format of bivariate frequency table used as basis for this study. Bivariate classes (at top and on right side of figure) form cells representing the bivariate frequency in percent of total occurrences. Marginal frequency distributions are at bottom (for Δu, m s^{-1}) and on left-hand side (for Δv, m s^{-1}). Other information on the table includes station, month, period of observation, sample number, log of methods of observation, number of calms, layer considered, and mean shear vector in component form.

The values in the table were normalized so that

$$\int\int P(x,y)dxdy = 100,$$

where $P(x,y)$ is the percent occurrence for x, given y, or vice versa.

To find the frequency of occurrence of shear vectors originating between angles $\alpha_2 \leqslant \alpha \leqslant \alpha_1$ and having a magnitude $|\Delta\mathbf{V}|$ between $|\Delta\mathbf{V}_2| \leqslant |\Delta\mathbf{V}| \leqslant |\Delta\mathbf{V}_1|$, one needs to perform the integration

$$\int_{\alpha_1}^{\alpha_2} \int_{|\Delta\mathbf{V}_1|}^{|\Delta\mathbf{V}_2|} P(\alpha, |\Delta\mathbf{V}|) d\alpha\, d|\Delta\mathbf{V}|, \tag{4}$$

which is shown graphically in Fig. 3. In practice, the bivariate frequencies in each cell of the table are summed to give the frequency of occurrence within the desired limits. The bivariate frequency table is well suited for operational use. Airport operations personnel might want the shear vector components with respect to a certain runway alignment (i.e., alongwind and crosswind components) rather than for standard meteorological coordinates. The percent occurrence of extreme crosswind and alongwind shears can be found by using the overlay shown in Fig. 4. Marginal frequency distributions, such as those given in the two WMO Technical Notes are given by summing each row and column of the bivariate frequency table. In this study, computer roundoff errors caused Eq. (3) to be slightly different than 100.

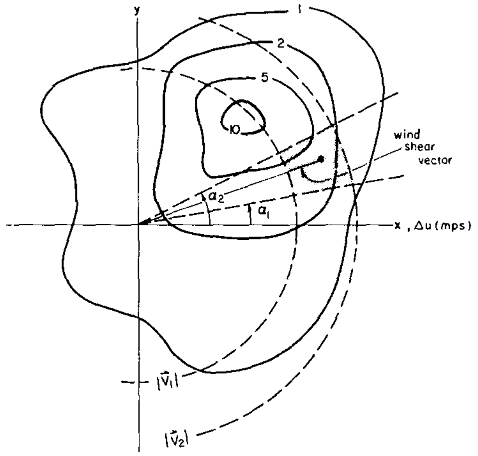

FIG. 3. Graphical depiction of integration limits for finding frequency of occurrence (sum of cell frequencies within shaded area) of wind shear vectors whose magnitude was between $|\mathbf{V}_1|$ and $|\mathbf{V}_2|$ and whose origin was between angles α_1 and α_2. Contours are in percent occurrence. Note shear vector is drawn from a point in shaded area to the origin.

b. *Criterion for extreme wind shear*

For data used in this study, the first winds aloft measurement level was 150 m above the ground making it necessary to draw a relation between the CAeM criterion of 5 m s^{-1} vector difference over the first 30 m and the results of this work.

Wind shears have traditionally been modeled by the power law relationship

$$\frac{V_2}{V_1}=\left(\frac{z_2}{z_1}\right)^n, \quad z_2>z_1. \tag{5}$$

Ekhardt and Newell (1964) report extreme wind shear conditions for military aircraft for $n\approx 0.3$. If we define $\Delta V\equiv V_2-V_1$ and $\Delta z\equiv z_2-z_1$, then using (5),

$$\Delta V=V_1\left[\left(\frac{\Delta z}{z_1}+1\right)^n-1\right]. \tag{6}$$

With the restriction that $\Delta z\gg z_1$, (6) can be reduced to

$$\Delta V\approx V_1\left[\left(\frac{\Delta z}{z_1}\right)^n-1\right]. \tag{7}$$

To give a general guideline on relating the CAeM criterion to the radiosonde measurements, the ratio

$$\frac{\Delta V_{150}}{\Delta V_{30}}=\frac{\left(\frac{150}{z_1}\right)^{0.3}-1}{\left(\frac{30}{z_1}\right)^{0.3}-1}, \tag{8}$$

was formed. The subscripts on ΔV refer to the separation distance; taking $z_1=2$ m yields $\Delta V_{150}\approx 10$ m s^{-1}.

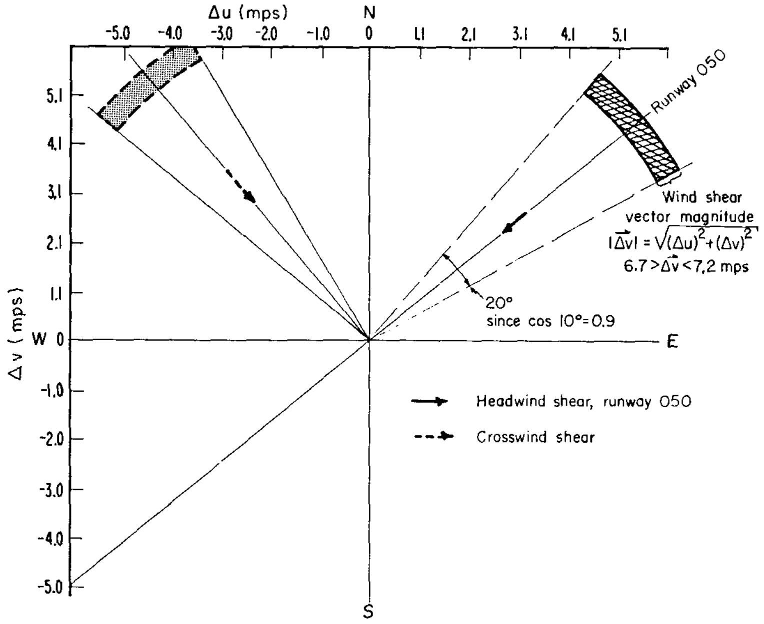

FIG. 4. Overlay scheme to be used with bivariate frequency tables to obtain percentage occurrence of wind shear along and perpendicular to a given runway. To obtain percent occurrence, add all values in shaded areas. In this case, $6.7>|\Delta\mathbf{V}|>7.2$ m s^{-1}.

Based on the above results, a pilot study on the wind shear environment of Denver, Colo., and the results of previous studies an extreme wind shear criterion for a 150 m separation was chosen to be $|\Delta \mathbf{V}| \geqslant 6.5$ m s^{-1}.

c. Use of the bivariate frequency table

To obtain statistics on the occurrence of extreme low-level wind shear, an overlay was constructed as in Fig. 5, and percentage occurrence was summed within the overlay corresponding to $\Delta V > 6.5$ m s^{-1} and ±45° around north, south, east and west. An example of these results for Denver is given in Fig. 6.

5. The data set and its limitations

The data set comprises wind sounding data from 10 stations chosen within the conterminous United States. Three criteria were used in the selection of a station: area representativeness, data availability (chiefly length of record), and classification by the Federal Aviation Administration as a major airport. Table 1 lists the stations chosen.

The wind sounding data (taken mostly by rawinsondes or radisondes) between the years 1956–64 were made available by the National Oceanic and Atmospheric Administration National Climatic Center (NCC). Frequency of the soundings at any one station varied from 2 to 4 soundings per day. Standard measurement levels were at the surface, 150 m above the surface, 300 m above the surface, and at the first standard level above sea level that was greater than 300 m above the surface. Therefore, the Δz of the first two layers was 150 m, while the Δz of the last layer varied from station to station. Calm winds were not included when computing shear statistics [the number of calms at each level was noted in the bivariate frequency table output (see Fig. 2)].

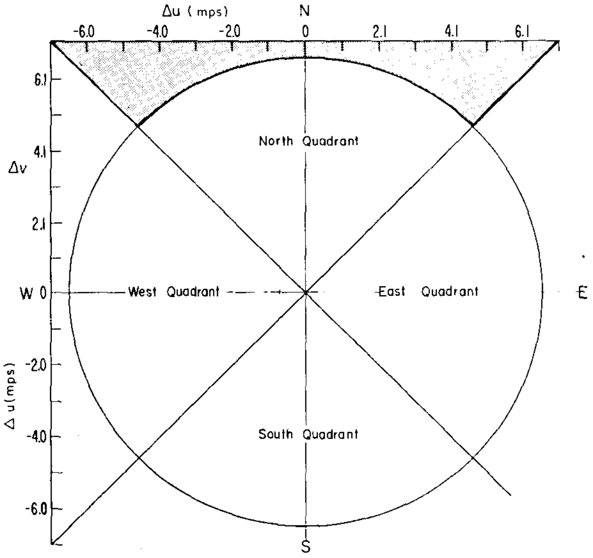

FIG. 5. Schematic of overlay used in extreme wind-shear analysis. Quadrants are as shown. Circle defines $|\Delta \mathbf{V}| \geqslant 6.5$ m s^{-1}. For example, north-quadrant percentage extreme wind shear is found by summing all cell percentages in shaded area.

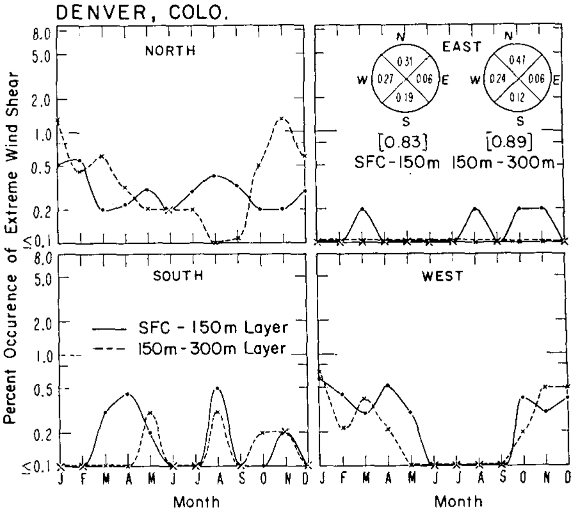

FIG. 6. Summary of extreme wind-shear (i.e., $|\Delta \mathbf{V}| \geqslant 6.5$ m s^{-1}) statistics at Denver, Colo. Results are given by quadrant; abscissa is climatological month; ordinate is percent occurrence of extreme wind shear; and circles in the upper right give values for the entire climatological year for the different quadrants. The figure in brackets below the circle gives the percent occurrence of extreme wind shear irrespective of quadrant.

In addition to smoothing errors caused by time averaging of the radar data the data set was subject to two error sources. These errors resulted from improper coding and keypunching and from radar lock-on difficulty in the lower boundary layer. The latter was an especially difficult problem in built-up areas and under strong wind conditions. The Denver case study discussed below indicates that these errors were small. However, the knowledge that the errors are present suggests that caution should be used in interpreting the results.

6. Denver case study

Stapleton International Airport at Denver has been selected for an extensive field program to determine the applicability of acoustic Doppler wind-measuring techniques in an operational environment (Beran *et al.*,

TABLE 1. Stations selected for low-level wind shear analysis.

Station	Major airport
Tatoosh Island, Wash.	No
Oakland, Calif.	Yes
Salt Lake City, Utah	Yes
Carswell AFB, Tex.	No
Denver, Colo.	Yes
Topeka, Kans.	No
Athens, Ga.	No
Dayton, Ohio	Yes
Green Bay, Wisc.	No
Nantucket, Mass.	No

1973). To provide some background information for this field program, Stapleton Airport was also chosen for a more detailed examination of extreme wind-shear occurrence.

To investigate the auditing errors mentioned above, all extreme wind profiles for the first two layers were examined on a hodograph. Over a 9 year period, 176 extreme wind shears were observed in the first two layers. Of these, 41 were judged to be suspect. These 41 cases were then subjected to an audit at NCC; four were found to be mispunched and 10 were logged improperly. The 27 remaining suspect shears generally received a "questionable surface wind" comment from the auditor. It is possible that these suspect profiles reflect local winds, not uncommon in Denver. The tracking or lock-on error was investigated using the remaining 27 profiles. Of these, 13 had surface winds of less than 5 m s^{-1}, 13 had surface winds of between 5 and 7 m s^{-1}, and only one had a surface wind above 7 m s^{-1}, suggesting that lock-on errors during high surface-wind conditions were unlikely. Even if 10 of the 27 remaining cases had lock-on errors, that number represents only about 5% of the total number of extreme wind shears. It was concluded from the above analysis that the Denver statistics are relatively free of error.

The marginal distributions of u and v for each layer and for each month at Denver were checked for normality, and in general showed Gaussian characteristics. There was some deviation from normal at the extremes, an expected result from a finite (and in this case, relatively small) data sample, but overall a linear relation existed between cumulative probability and class irrespective of month or layer. This is a necessary but not sufficient requirement for modeling Denver's low-level wind shear in terms of an elliptical bivariate distribution (Crutcher and Baer, 1962). The distribution of extreme wind shear, by direction, month and level for Denver is shown in Fig. 6.

Five cases of extreme wind shear at Denver were chosen on the basis of those having the largest wind shears for the 9-year period. Table 2 summarizes some of the information about the five cases of extreme shear occurrence. The strongest shear occurrences were confined to the first two layers and the frequency of occurrence was nearly equally divided between the lowest layer and the layer just above.

A consistent pattern was apparent between the synoptic situation and the soundings associated with the cases studied. The shear always resulted from changes in wind direction rather than in wind speed. The synoptic pattern was generally one in which a weak ridge or shallow high was present near the Denver area. Clear skies generally prevailed and visibility was well above the minimum for aircraft operations (for the map time analyzed). At 500 mb, the wind field generally showed strong westerly winds either directly over Denver or over southern Wyoming. The temperature-humidity sounding showed strong radiation inversions in every case. The directional wind shift causing the shear occurred across the inversion surface. Below the inversion, the flow appeared to be the result of local circulation, with the wind having some easterly component. Most of the directional shifts in the wind profile were due to backing winds rather than veering winds.

TABLE 2. Extreme wind-shear cases chosen for synoptic analysis.

Time (GMT)	Date	$\lvert\Delta \mathbf{V}\rvert$ (m s^{-1})	Layer
1200	1 Feb 61	11.1	Sfc–150 m
0600	12 Oct 62	12.0	150 m–300 m
1800	20 Nov 62	11.0	150 m–300 m
0600	28 Nov 62	12.0	150 m–300 m
0600	13 May 63	11.1	Sfc–150 m

7. Results and conclusions

Table 3 summarizes the results from all stations studied with respect to the total percentages of extreme wind shear. Four out of 10 stations showed little difference between the extreme shear in the surface to 150 m layer and in the 150 to 300 m layer; one station showed a larger percentage of extreme shear in the higher rather than the lower layer. These results suggest that extremes of wind shear do not always fit boundary-layer models which predict stronger shears in the lowest layer (as was the case for 5 of the 10 stations). The highest frequency of extreme shear was shared by Athens, Ga., and Nantucket, Mass., while the lowest frequency was at Oakland, Calif.

The results of the literature review, the seasonal march of extreme wind-shear occurrence, and the fact that extreme shears are not necessarily confined to the lowest layer allow one to speculate that the major portion of extreme shear occurrence is closely tied to synoptic (or large mesoscale) conditions (where many present boundary-layer concepts break down). This is further demonstrated in Figs. 7 and 8 which present the total percentage occurrence of extreme wind shear for the 10 stations, with the major mean cyclone tracks over the conterminous United States superimposed. The correlation between high incidence of extreme wind shear and passage of cyclonic storms is evident in both layers. The occurrence of extreme wind shears shows large variation with season at almost all stations, with

TABLE 3. Total percentage of occurrence of extreme wind shear

Station	Surface to 150 m layer	150 to 300 m layer
Oakland, Calif.	0.35	0.28
Tatoosh Island, Wash.	2.07	1.37
Green Bay, Wisc.	2.30	2.29
Nantucket, Mass.	4.65	2.32
Salt Lake City, Utah	0.89	0.55
Denver, Colo.	0.83	0.89
Topeka, Kans.	3.55	3.38
Carswell AFB, Tex.	3.05	0.76
Dayton, Ohio	2.05	3.09
Athens, Ga.	4.64	2.11

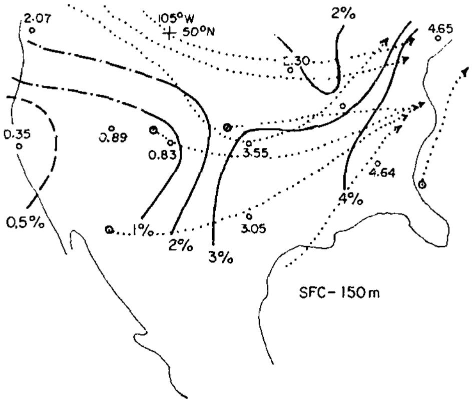

FIG. 7. Total annual percentage of extreme wind shears for the 10 stations analyzed. Dotted arrows are mean cyclone tracks (circle denotes origin of cyclone track) for the conterminous United States. Layer considered is surface to 150 m. The dash-dotted line denotes uncertainty due to mountainous terrain.

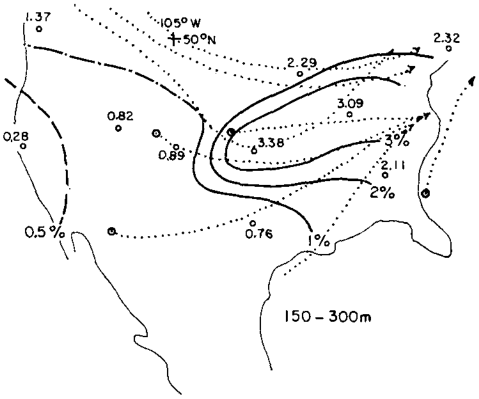

FIG. 8. As in Fig. 7 except for layer 150 to 300 m.

the greater percentage of extreme shears occurring in late fall through early spring. The lowest percentage occurrence is found from late spring through late summer.

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REFERENCES

Abramovic, K. G., and V. G. Glazunov, 1969: Wind shear in the lower atmosphere. WMO Tech. Note No. 93, 195–202.

Aeronautical Meteorology, 1969: WMO Tech. Note No. 95.

Arya, S. P. S., 1972: The critical condition for the maintenance of turbulence in stratified flows. *Quart. J. Roy. Meteor. Soc.*, **98**, 264–273.

Beran, D. W., B. C. Willmarth, F. D. Carsey and F. F. Hall, Jr., 1973: An acoustic Doppler wind measuring system. *J. Acoust. Soc. Amer.*, **55**, 334–338.

Boucher, R. J., R. Wexler, D. Atlas and R. M. Lhermitte, 1965: Mesoscale wind structure revealed by Doppler radar. *J. Appl. Meteor.*, **4**, 590–597.

Burnham, J., 1970: A brief review of R.A.E. research on wind and gust effects relevant to landing and takeoff. Roy. Aircraft Est., Tech. Memo. Aero. 1201, 12 pp.

Commission for Aeronautical Meteorology (CAeM/III) International Civil Aviation Organization, 1964: WMO Rept. 157, Vol. 1 (abridged).

Colmer, M. J., 1971: On the character of thunderstorm gust fronts. *Proc. Intern. Conf. Atmospheric Turbulence*, 18–21 May 1971, London, England, Roy. Aero. Soc., 11 pp.

Crutcher, H. L., 1957: On the standard vector-deviation wind rose. *J. Meteor.*, **14**, 28–33.

——, and L. Baer, 1962: Computations from elliptical wind distribution statistics. *J. Appl. Meteor.*, **1**, 522–530.

Eckhardt, H. D., and J. S. Newell, 1964: Study of tactical army aircraft (TAALS). Task 1—Atmospheric studies. RCA Corp. Tech. Rept., 56 pp. [AD 433632].

Fichtl, G. H., 1971: Standard deviation of vertical two-point longitudinal velocity differences in the atmospheric boundary layer. *Boundary-Layer Meteor.*, **2**, 137–151.

Gera, J., 1971: The influence of vertical wind gradients on the longitudinal motion of airplanes. NASA-TN-D-6430, N71-34022, 19 pp.

Goldman, J. L., 1969: Analysis of wind field conditions adversely affecting vehicle operations. NASA Contractor Rept. CR-61286, N69-34881, 103 pp.

Jefferson, G. J., 1966: An incident of severe low-level elements in the study of eddy structure. *Meteor. Mag.*, **95**, 279–285.

Kusano, K., Y. Suzuki and H. Takei, 1967: Vertical wind shear in the lower layers at the Tokyo International Airport. *Geophys. Mag. Tokyo*, **33**, 239–256.

Marwitz, J. D., 1971: Severe storm types in relation to wind shear. *Preprints 7th Conf. Severe Local Storms*, Kansas City, Mo., Amer. Meteor. Soc., 240–243.

Mashkova, G. B., 1967: Wind profiles during low cloudiness at a height of less than 300 m. *Tr. Akad. Nauk SSSR Inst. Prin. Geofiz*, **10**, 39–43.

Melvin, W. W., 1970: Wind shear on the approach. *Shell Aviation News*, **393**, 16–20.

Panofsky, H., and H. Crutcher, 1951: Horizontal momentum flux due to small-scale turbulence. *J. Meteor.*, **8**, 420–421.

Pettitt, R. B., and R. G. Root, 1969: Vertical wind shear in the boundary layer. WMO Tech. Note No. 93, 1–30.

Reiter, E. R., 1961: *Jet Stream Meteorology*. The University of Chicago Press, 515 pp.

——, and P. F. Lester, 1967: The dependence of the Richardson number on scale length. Atmos. Sci. Paper No. 111, Colorado State University, 39 pp.

Rider, L. J., and M. Armendariz, 1966: Low-level jet winds at Green River, Utah. *J. Appl. Meteor.*, **5**, 733–736.

Rijkoort, R. J., 1969: Dependence of observed low-level wind shear on averaging period and lapse rate. WMO Tech. Note No. 93, 185–194.

Sowa, D. F., 1972: Turbulence plot program. *Shell Aviation News*, April, 16–19.

Taylor, P. A., 1970: A model of airflow above changes in surface heating flux, temperature and roughness for neutral and unstable conditions. *Boundary-Layer Meteor.*, **1**, 18–39.

Tsverava, V. G., 1967: Investigation of vertical wind vector shears based on observations on a 300 m meteorological tower. *Meteor. Gidrol.*, **2**, 82–84.

Vertical wind shear in the lowest layers of the atmosphere, 1969. WMO Tech. Note No. 93, 250 pp.

Watson, I. A., 1969: Report of an investigation into low-altitude wind structure for automatic landing. WMO Tech. Note No. 95, 61–96.

Zipser, E. J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. *J. Appl. Meteor.*, **8**, 799–814.