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THE TURBULENCE CLIMATOLOGY OF THE UNITED STATES BETWEEN 20,000 AND 45,000 FEET ESTIMATED FROM AIRCRAFT REPORTS AND METEOROLOGICAL DATA

By

ROY M. ENDLICH   ROBERT L. MANCUSO

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PROJECT NO. 8624
TASK NO. 862402
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Final Report

Period Covered: 10 May 1965 through 9 June 1968

June 1968

Contract Monitor: NORMAN SISSENWINE
Aerospace Instrumentation Laboratory

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Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS 01730

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ABSTRACT

The climatology of clear-air turbulence is defined herein as the likelihood that an aircraft or missile will encounter turbulent air at a given locality, altitude, and time of year. Turbulence data of three types were used in this study; these include observations by instrumented research aircraft, balloon tracks measured by FPS-16 radar, and turbulence reports made by pilots. The measurements that have been made by research aircraft show good relationships between turbulence and certain aspects of mesoscale atmospheric structure, but the data are too limited in number to permit broad generalizations. The FPS-16 tracks of rising Jimsphere and Rose balloons were obtained during studies of detailed wind profiles. We investigated their potential value in identifying turbulent layers. In general, the existing data are too noisy to serve this purpose; however, further special trials are recommended. The subjective turbulence reports from pilots collected during special five-day reporting periods comprise by far the largest volume of data available. Meteorological conditions for these periods were analyzed by computer from standard rawinsonde data and were correlated with the turbulence reports. The correlations show that the vertical vector wind shear corresponds most closely to turbulence frequency determined from the pilot reports. Little additional reduction of variance in the turbulence frequencies is achieved by including other meteorological factors. Optimum multiple regression equations between turbulence frequency and the mean and standard deviation of the vertical vector wind shear were obtained. In summer a different regression equation was found than in other seasons.

These turbulence observations taken in toto are too few to permit a direct computation of turbulence frequency; therefore an indirect method was used to obtain the turbulence climatology. This involved

applying the regression equations to existing statistics of wind shear over the United States. These wind-shear compilations, prepared almost ten years ago, appear to be of questionable reliability in the upper troposphere and stratosphere due to a large proportion of missing wind observations under conditions of high wind speeds aloft. Due to uncertainties in the regression equations and shear statistics, the deduced turbulence climatology (given by seasons for levels between approximately 20,000 and 45,000 feet) must be considered a first estimate.

Recommendations are made that an up-to-date wind-shear climatology be computed for the United States, and that consideration be given to developing a balloon-borne turbulence sensor to augment data from research aircraft and airline pilots.

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I INTRODUCTION

The purpose of this study was to develop methods for estimating the probability that an aircraft will encounter turbulent air at a given locality, altitude, and time of year. The discussion pertains to clear-air turbulence, which is perhaps more accurately described as non-storm turbulence--i.e., turbulence directly associated with convective or precipitating clouds is excluded. Since direct turbulence observations are not made routinely, one cannot now refer to an archive to obtain data for making a climatological study. Instead, an alternate method must be formulated that uses various types of fragmentary information. The general plan is as follows. On a limited number of occasions instrumented aircraft have measured turbulence as well as the associated meteorological conditions, and thus provide basic information concerning atmospheric conditions that are associated with turbulence. Next, turbulence frequencies on certain days were computed from reports of turbulent or smooth flight collected from airline pilots. These frequencies were correlated with concurrent meteorological conditions determined as well as possible from standard upper-air data, and regression equations were found. The final step was to apply the regression equations between turbulence and meteorological factors to existing climatological records of meteorological conditions, in order to obtain the estimated turbulence climatology.

Numerous difficulties, some anticipated and others not foreseen, are inherent in this indirect approach. These will be discussed in detail later. Conceptually, the simplest way to obtain a turbulence climatology would be to equip enough aircraft to directly determine the turbulence frequency at a variety of places, altitudes, and times; however, costs would be prohibitive. Another approach, which we have advocated but which is still untried, would be to develop a balloon-borne turbulence sensor to fly as part of the standard radiosonde instrument, or separately. If an inexpensive sensor proved feasible, the turbulence climatology up to the altitude limit of balloon flights (approximately 100,000 feet) could be found, and correlations could be made with meteorological factors at the same times and places. A similar idea is involved in the use of rising uninstrumented balloons tracked by high-precision radar to reveal erratic portions of the sequence of flight coordinates that would indicate turbulent layers. This subject is discussed in Sec. III. Other possible methods exist for remotely sensing turbulence using electromagnetic radiation, but their practicality is not established. Such methods are not considered in this report.

Among designers of aircraft and missiles, a strong interest in turbulence has existed for years (e.g., Loving, 1966; Houbolt, 1967). The aeronautical profession has perfected complex aircraft instrumentation that gives information on turbulence spectra, probabilities of gusts greater than certain threshold values, etc. Using this approach to determine the turbulence environment at new altitude levels, such as the stratosphere, requires that an aircraft of some sort be used as the initial probe. Generally, the number of flights made is far too low to indicate variations in the percentage of turbulent air to be expected under different weather conditions, places, altitudes and seasons. It is this climatological distribution of turbulence that is of primary interest in the present investigation.

This report does not summarize or review the voluminous literature on turbulence in the free atmosphere; however, references to pertinent papers are given at appropriate points. In Sec. II, the different data sources that we used are described, and their limitations are given. Section III is entirely devoted to a description of our attempt to identify turbulent layers from paths of Rose balloons tracked by FPS-16 radar. Section IV contains the regression equations used to obtain the estimated turbulence frequencies of Sec. V. (Examples of the climatological meteorological data used are given in the Appendix.) Recommendations are given in Sec. VI. A scientific report concerning the first year's work was issued under this project in May 1966.

II DATA SOURCES

As discussed in Scientific Report 1, data obtained by the AFCRL B-47 research aircraft (which measured turbulence intensity objectively, and also recorded concurrent winds and temperature) were carefully reviewed. In recent years data of this type have been analyzed by a number of writers including Briggs and Roach (1963), Endlich (1964), Endlich and McLean (1965), McLean (1965), and Kao and Woods (1966). From such information, it is usually possible to identify detailed "mesoscale" features of atmospheric structure that accompany turbulence. We found that the turbulent gust intensity recorded by the B-47 correlated best with vertical vector wind shear, with large directional wind shear, and with deformation in the horizontal plane. Correlations between turbulent gust intensity and these quantities were in the range from 0.5 to 0.8. The vertical and horizontal structure of the temperature field appeared to be less important. However, the mesoscale meteorological patterns that produce or accompany turbulence are not adequately depicted by standard upper-air soundings. Therefore, relationships between turbulence and meteorological factors are invariably more obscure when only standard meteorological observations are available for analysis. The correlations of this report, which relate standard meteorological data and subjective pilot reports, are much lower than the correlations mentioned above.

Instrumented gliders and aircraft have also documented the severe turbulence that occurs in certain portions of well developed mountain waves (Kuettner, 1958; Jones and Atnip, 1964). Quite recently, instrumented U-2 aircraft have explored stratospheric turbulence (Penn and Pisinski, 1967; Crooks, et al., 1967). These data apparently show that relationships exist between turbulence and mesoscale wind features similar to those found earlier in the troposphere.

Since the variability of mesoscale features is very broad while the amount of high-quality, detailed aircraft data that describe them is small, it is difficult to generalize from the aircraft data.

Another possible source of information comes from balloons tracked by FPS-16 radar. Flight tracks of Jimsphere balloons had been obtained by NASA at Cape Kennedy, Florida (Scoggins, 1965), and of Rose balloons by the Air Force at Vandenberg AFB, California, for use in measuring accurate winds and vertical wind shears over small increments of height. It was thought that if these data yielded information on turbulence, they would augment other turbulence measurements, particularly in the stratosphere. From the analysis of ten Jimsphere flights, the approach appeared feasible, as reported by Endlich and Davies (1967). As a result, a major effort was made to use the Rose series of flights from Vandenberg for turbulence studies. For the stratospheric layers of interest, this was not successful for reasons discussed further in Sec. III. However, the basic concept of detecting turbulence from erratic portions of the balloon path is still believed to be useful, and might be implemented by procedural changes described in Sec. III.

The main source of data used in this investigation is that from airline pilots, who have reported turbulence severity encountered during commercial flights under programs organized by Colson (1963, 1965, 1966) in association with the International Civil Aviation Organization. Each program was five days in length. Reporting periods were held in February 1963, December 1964, and March, June, and September 1965. These data have the major advantage that they are numerous, and give a reasonably good depiction of turbulence within the airspace over the United States during these periods. For example, in the March 1965 data, there were approximately 20,000 reports, each pertaining to a 100-mile flight segment. Turbulence of moderate intensity occurred in approximately six percent of these, while severe turbulence occurred only in 0.3 percent of the cases. The average wind patterns during this five-day period were by no means typical of average conditions in March, as can be seen from upper-air charts for this interval given by Endlich and Mancuso (1967). The same is true of other five-day periods. Therefore, one would not expect the pilot reports of turbulence for such brief periods to be representative of seasonal conditions--i.e., they do not give an approximate turbulence climatology. But by matching the turbulence reports to concurrent meteorological conditions, we wished to obtain reliable statistical relationships to use in estimating a turbulence climatology.

The principal disadvantage of the pilot reports is their subjectivity in regard to the severity of turbulence. Another difficulty is that in summer considerable turbulence included in the clear-air category is located in the vicinity of convective storms or downstream; these cases are probably an indirect result of the convective storms. Therefore, the June turbulence has different relationships to meteorological factors than found in other seasons.

Colson divided the airspace into volume elements approximately 4000 feet deep and bounded by 2-1/2 degree latitude-longitude lines, and determined the number of flights during twelve-hour periods that encountered smooth flight and turbulence in the categories light, moderate, or severe. From such tabulations furnished to us by Colson for the first two periods, and by the Federal Aviation Administration for the latter three periods, we computed the frequency of turbulence in each time period for each volume element. The concurrent meteorological conditions (i.e., wind speed and direction, vertical vector shear, temperature, lapse rate, horizontal wind shear, deformation, vorticity, divergence, and twelve-hour vector change in wind) in each volume were analyzed by computer from standard rawinsonde data at synoptic hours, as described by Endlich and Mancuso (1967). Thus a complete "turbulence report" consists of the turbulence frequency in a volume element, plus the associated wind speed, shear, etc. As the typical flight distance through a volume element is approximately 100 nautical miles, the turbulence frequencies should be interpreted as the likelihood of encountering turbulence within that distance. (This distance can be converted to an equivalent flight time by dividing it by the appropriate aircraft groundspeed.) The center of each volume element is represented by a grid point. Statistics on the length of turbulent patches are not given by these data, but sources such as Steiner (1965) and Coy (1967) indicate that in approximately 50 percent of the cases the length is less than ten miles.

To use the pilot reports in obtaining regression equations for the frequency of turbulence, a "climatology" of wind speeds, shears, etc. at each grid point was constructed from ten values of each factor during each five-day period. Then a multiple-regression computer program developed by M. Gorfinkel of SRI was used to relate the frequency (in percent) of moderate or severe turbulence to the wind speed, vertical shear, deformation, lapse rate, etc., during the period. Correlations between turbulence frequency and individual meteorological factors in December and March are given in Table I. Further details are given in Sec. IV.

The next step was to apply the regression equations to existing climatological records of pertinent meteorological factors in order to estimate the turbulence climatology over the United States. It was assumed at the beginning of this study that such climatological data would be available; determination of new climatological descriptions of the upper atmospheric structure was not contemplated. Climatological data concerning wind shear over the United States were given by Ratner (1958) in the altitude range 700 to 50 mb (10,000 to 67,000 feet) for the period 1951-1956, and relied upon subjective interpolation to compensate for missing wind observations. The amount of missing data was not presented, but as indicated below, must have been large. Further unpublished wind shear statistics mentioned by Crutcher (1963) had been compiled by S. Schamach of the National Weather Records Center for a ten-year period. These were generously made available to us by Dr. Crutcher. They are for levels between 450 and 150 mb for the period July 1948 through June 1958. The statistics are comprehensive, and obviously excellently computed and organized. The number of observations used is also given; no subjective interpolation was performed. In this compilation, there are approximately 900 possible observations at each station for each season (once a day for three months for ten years). The actual number of observations shows a drastic decrease with altitude, particularly during the winter season. For example, at Washington, D.C. (one of the better stations), 532 wind observations in summer reached the 200-mb level. In winter at 200 mb, the corresponding number is down to 300. At Ely, Nevada, the numbers of wind observations

Table I

CORRELATIONS BETWEEN THE AVERAGE PERCENTAGE FREQUENCIES OF MODERATE OR SEVERE TURBULENCE AND METEOROLOGICAL FACTORS[*]

Magnitude of Average Vertical Vector Wind Shear	Standard Deviation of Vector Wind Shear	Average Vertical Speed Shear	Standard Deviation of Speed Shear	Average Wind Speed V	Standard Deviation of W	Deformation, Vorticity, Divergence, 12-hr Change in W, Lapse Rate, and Horizontal Shear
0.34	0.12	0.28	0.16	0.20	0.16	All < 0.1

[*] Based on pilot reports for special turbulence reporting periods in December 1964 and March 1965. Each correlation is based on approximately 900 pairs.

at 200 mb in summer and winter are 256 and 115, respectively, again out of 900 possible. Thus the samples of measured winds and shears are quite small. This in itself is not of overpowering importance; the remaining samples might be representative. But from the nature of the observational method, we know that wind data are lost most frequently during conditions of high winds when elevation angles become too low to permit accurate tracking. Thus the remaining wind sample is biased towards low speeds, low shears, etc. In portraying the geographical and latitudinal variation in these statistics over the United States, the differing numbers of observations at radiosonde stations enter into the picture. Although we have looked briefly into the possibility of standardizing the statistics on the basis of the number of observations that went into each, no simple correcting procedure appears possible. In retrospect, one recalls that the present GMD-1 type of wind finding equipment was introduced at some stations in 1954, and at most others in 1960. Therefore, the number of observations obtained at each station evidently depends in part on the date of installation of this equipment.

This discussion of the observations that go into available statistics of upper winds and shears has been rather lengthy because of the importance of this matter to the present problem. The reliability of the averages and standard deviations of vertical vector shear (used later in the regression equations) is difficult to judge, and may be somewhat questionable for the present purpose. Typical patterns of the magnitude of the average vertical wind shear and the standard vector deviation of shear, as read at grid points from data at twenty-five stations given by Schamach, are shown in the Appendix. A future remedy appears to be the recomputation of such statistics using recent data, although even today a significant number of winds are missed in the critically important jet stream cases. A further important step that can be taken to obtain more accurate winds and shears from present equipment is a computer computation using all the data points measured by the GMD-1 (instead of certain points one or two minutes apart), as discussed by Danielsen and Duquet (1967).

An alternative type of climatological information might describe the number of times certain subsynoptic features that favor turbulence (such as jet streams passing through sharp troughs and ridges, jet fronts or tropopauses with strong wind shear, mountain waves, etc.) occur as a function of geographical location and time. One would also need to know the probability of turbulence associated with each meteorological feature. But such statistics are not available, and anyway, these phenomena should be reflected indirectly in means and standard deviations of winds, vertical shears and temperature lapse rates.

The wind shear data of Schamach are over 50-mb intervals below 200 mb, and then are from 200 to 175 mb, and 175 to 150 mb. Thus their average thicknesses are variable, and we wished to normalize the shear data to a 4000-foot thickness as used in analyzing the aircraft data. A well known feature of wind shears is that average values and standard deviations computed for thin layers tend to be larger than values computed over greater distance intervals (Dvoskin and Sissenwine, 1958). Factors relating shears over various intervals have been given by Essenwanger (1963) and Armendariz and Rider (1966). From the latter paper, we estimated correction factors of 0.5, 0.67, 1.0, and 1.3 for layers 1000, 2000, 4000, and 6000 feet in thickness, respectively, and interpolated for other thickness values. For example, an average shear computed over 1000 feet must be multiplied by 0.5 to normalize it to the desired 4000-foot shear.

III TURBULENCE IDENTIFICATION FROM PATHS OF RISING BALLOONS

As mentioned in the Introduction, quantitative measurements of turbulence intensity and associated winds and shear are scarce. Therefore, we investigated the applicability of data from Jimsphere and Rose balloons tracked by the highly accurate FPS-16 radar. The basic concept is simply that the balloon path will be relatively erratic in turbulent layers as compared to laminar portions of the atmosphere (Endlich and Davies, 1967). A preliminary study was made of ten Jimsphere flights from Cape Kennedy, and these appeared to indicate the existence of several turbulent layers under seemingly favorable conditions. With this encouragement, the technique was applied to Rose balloons tracked by FPS-16 radar at Vandenberg Air Force Base, California.

As discussed in the referenced paper, data processing can be done in terms of range (R), elevation angle (E), and azimuth (A), or after converting these basic measurements to coordinates towards east, north, and up (x, y, z). We choose to use the former three coordinates. Since the variations in R, E, A expected due to turbulence are a small, high-frequency component superimposed on large overall trends, for turbulence to be detected it is necessary that errors due to radar tracking and to self-induced balloon motions be relatively small. A number of Rose balloon flights had been made using two radars located side by side to obtain independent measurements of the balloon's coordinates versus time. If radar tracking errors were small, plots from the dual tracks should be essentially identical, and should unequivocably identify turbulent layers.

Computer programs were written to utilize the FPS-16 Rose data. These programs are as follows:

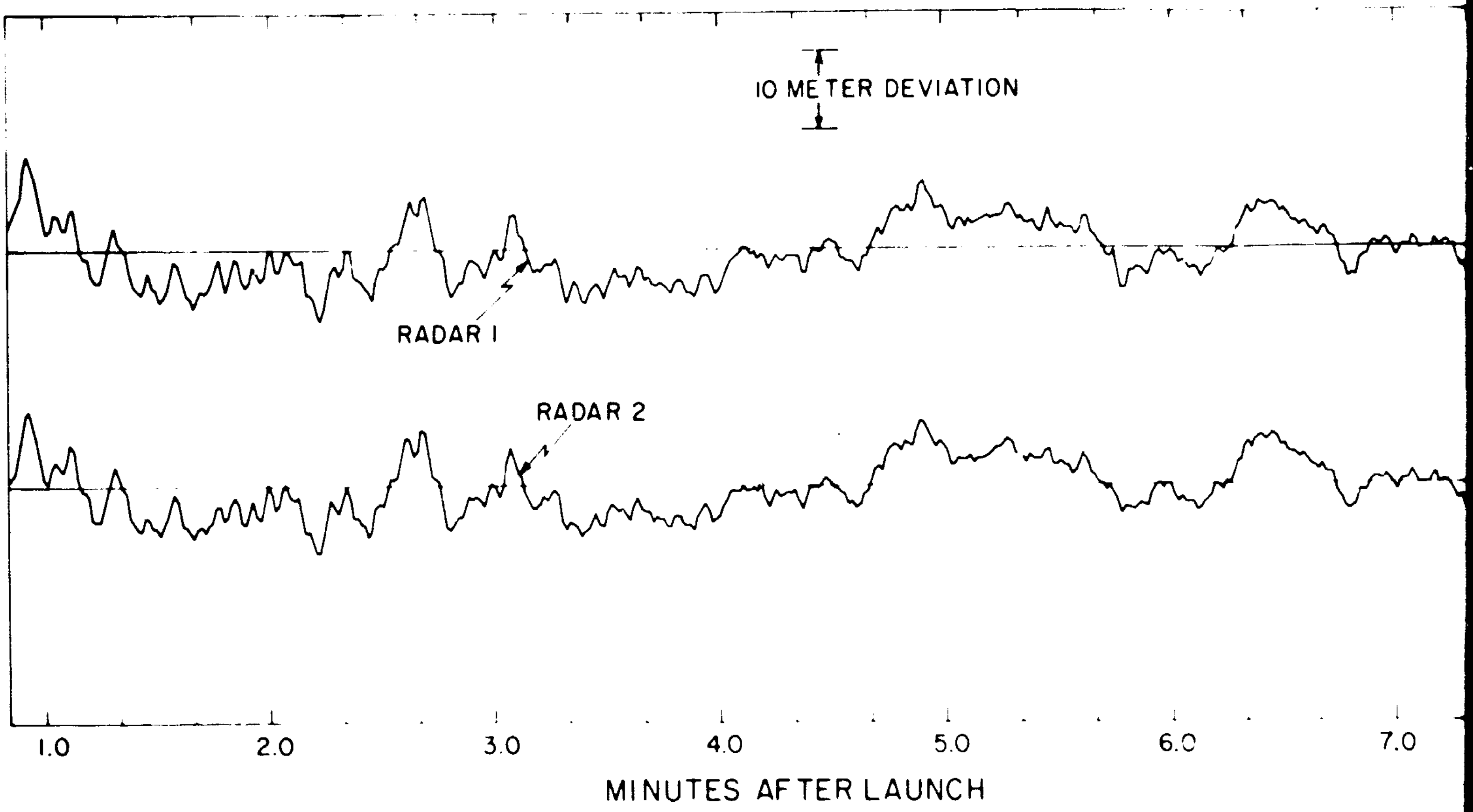
(1) The first program converts units of R, E, A to meters and radians, and averages five 0.1-second points to give points at 0.5-second intervals. (This density of information is more than adequate for the present purpose, as the balloon rises at a rate of only 4 to 5 m sec^{-1}.) The time sequence

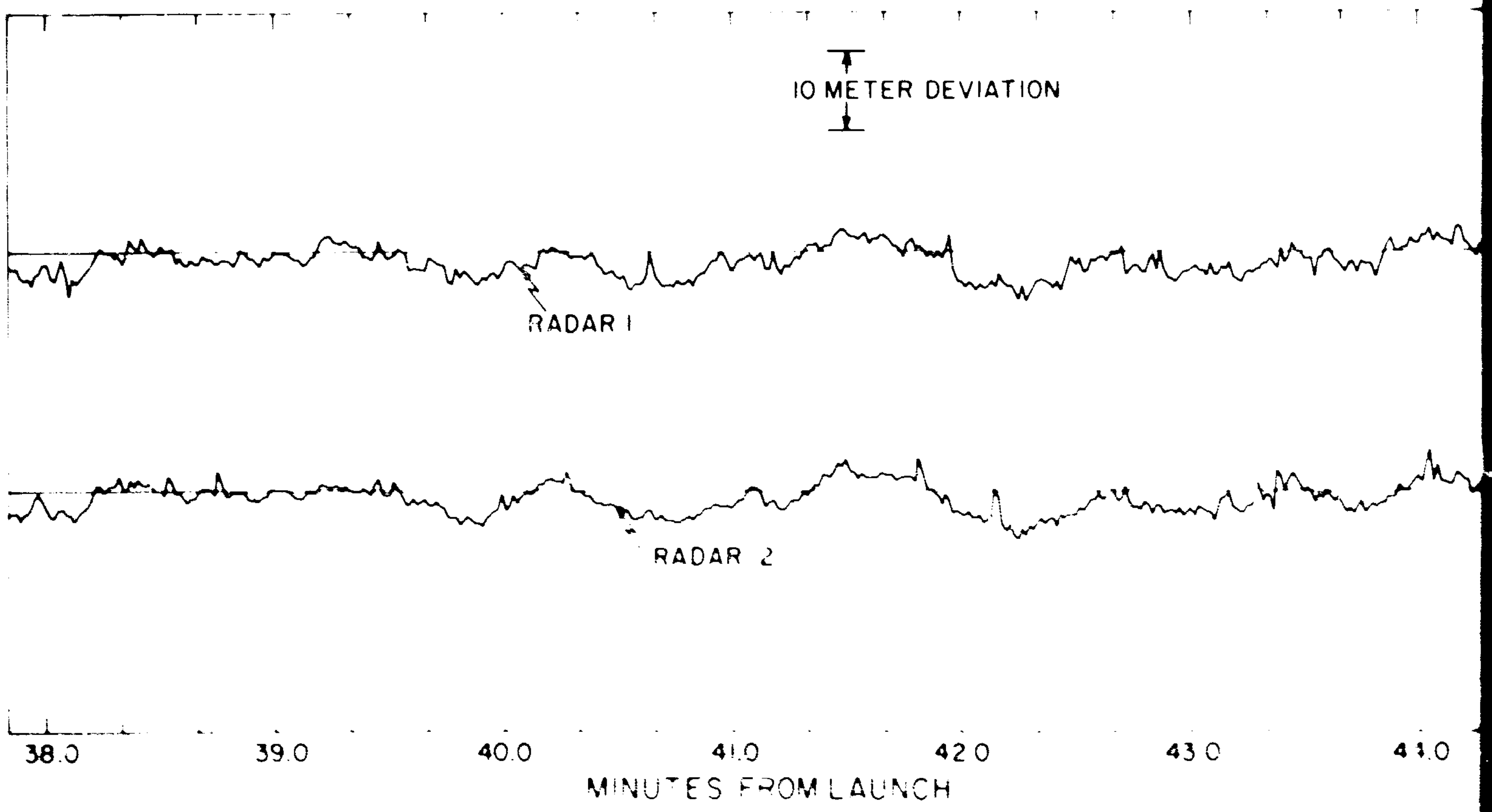
of points is then examined to isolate occasional spurious points. The relevant computation is made between adjacent points; for example, if $|R_j - R_{j-1}| > L$ (where L is approximately 50 m, the upper limit of differences in range that would be produced by a 100 m sec $^{-1}$ wind in 0.5 seconds), R_j is replaced with an interpolated point. Elevation and azimuth are treated similarly.

(2) The next program smooths the R, E, and A (separately) over one-minute intervals using a triangular-shaped weighting function. Mean wind speed and direction, height, and balloon ascent rate over one-minute intervals are computed from the smoothed values (R_s, E_s, A_s). Then deviations ($R - R_s$), ($E - E_s$), and ($A - A_s$) are computed at each 0.5 second, and a plot tape is written to graph the deviations as a function of time using a California Computer Company plotter.

(3) Initially it was also planned to use an existing computer program to compute autocorrelations and spectra of the deviations, but this was not done for reasons given below.

Plotted values of ($R - R_s$) from the dual tracked flights were graphed as shown in Fig. 1. A minute in time corresponds approximately to 1000 feet in altitude. In the low levels, the plots from the two radars generally agreed well, and indicate self-induced balloon motions, and occasional turbulence in the boundary layer of the atmosphere. Such turbulence is shown in Fig. 1 for the interval from two to three minutes after launch. Gust speeds indicated by the slope of the graphs are 1 to 2 m sec $^{-1}$, signifying light turbulence. Other similar cases apparently verify the basic concept. But at longer ranges and low elevation angles, the curves of the two radars did not generally agree in their small-scale features. More than fifty Rose flights were processed, involving a fairly sizeable effort in manpower and computer costs. In this sample, no clear-cut cases of turbulence in the upper troposphere or lower stratosphere could be identified from the dual plots, although one radar or the other sometimes had an erratic path


10 METER DEVIATION
RADAR 1
RADAR 2
1.0
2.0
3.0
4.0
5.0
6.0
7.0
MINUTES AFTER LAUNCH


10 METER DEVIATION
RADAR 1
RADAR 2
38.0
39.0
40.0
41.0
42.0
43.0
44.0
MINUTES FROM LAUNCH

A

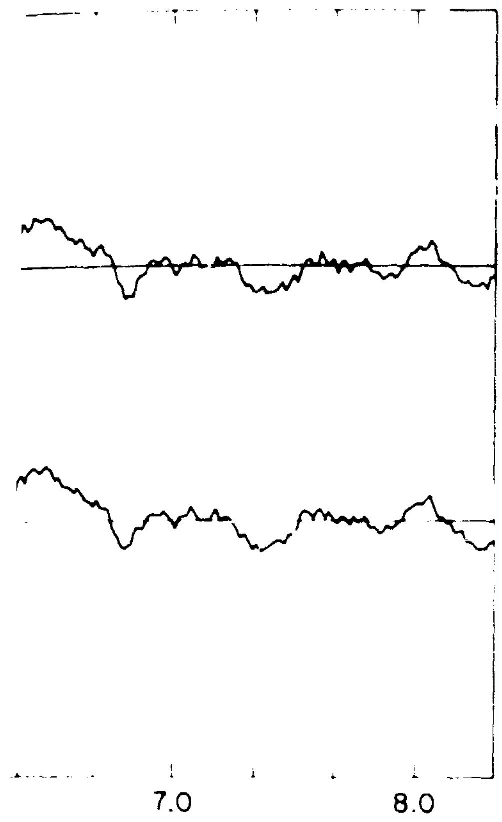


FIG. 1 GRAPHS OF RANGE DEVIATIONS MEASURED BY TWO FPS-16 RADARS TRACKING A RISING ROSE BALLOON IMMEDIATELY AFTER LAUNCH. Taken from Test 6408 at Vandenberg AFB, California, on 7 September 1966.

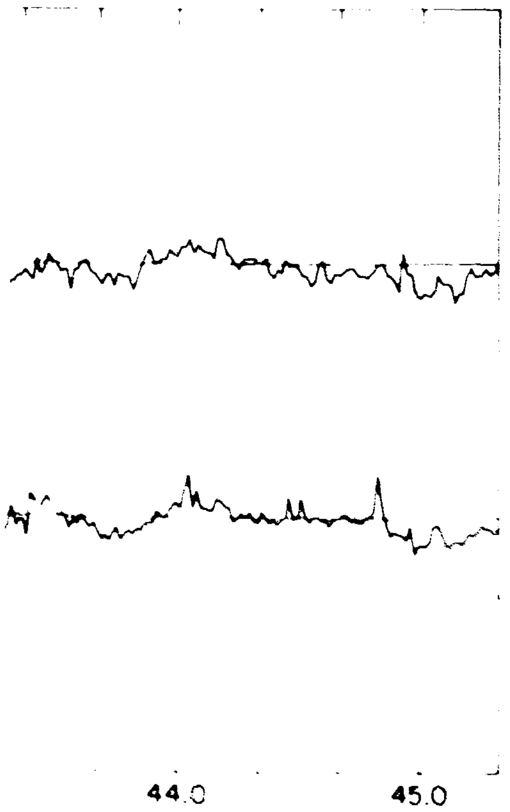


FIG. 2 GRAPHS OF RANGE DEVIATIONS MEASURED BY TWO FPS-16 RADARS TRACKING A RISING ROSE BALLOON IN THE UPPER TROPOSPHERE. Taken from Test 6408 at Vandenberg AFB, California, on 7 September 1966.

suggesting turbulence. Close agreement was not found. A typical plot (from a portion of the same flight in the upper troposphere) is shown in Fig. 2. The duplication of the two curves is obviously less than in Fig. 1.

It is our opinion that the difficulties are due to tracking uncertainties that increased with time, particularly at long ranges where signal strength was low. These uncertainties could not be removed by the editing procedure of the first computer program mentioned above. Also, operational modes of the two radars may not have been optimum or identical. Thirdly, the balloon motion may be partly aerodynamic in its detailed behavior. Differences between the motions of Rose and Jimsphere balloons have been noted by Scoggins (1967).

Unfortunately, the present study of rising Rose balloons tracked by two FPS-16 radars was not successful in isolating turbulent layers. Still we do not consider the concept discredited since the Vandenberg flights were not specifically designed to obtain measurements of turbulence. We suggest a trial based on very carefully controlled measurements where a balloon is released upstream so as to pass over the two radars at a favorable (> 20 degree) elevation angle and a relatively close range. The assistance of a search radar would probably be needed to aid the FPS-16's in locating the approaching balloon. At Vandenberg AFB, where the ocean is in the upstream direction, it might be possible to release a balloon from a helicopter. In spite of these problems, further experiments with FPS-16 tracking of rising balloons are recommended in Sec. VI.

IV REGRESSION EQUATIONS RELATING TURBULENCE FREQUENCY TO METEOROLOGICAL CONDITIONS

A. Winter, Spring, and Fall

As mentioned earlier, by far the most numerous turbulence reports available are those made by commercial and military pilots during special five-day reporting periods discussed in Sec. II. For these periods we had computed turbulence frequencies in volume elements covering the U. S. airspace between approximately 24,000 and 40,000 feet at each synoptic hour (00 and 12 GMT). Also, at the same times a number of meteorological quantities were computed from objective analyses of standard upper-air observations (see Endlich and Mancuso, 1967). The selection of quantities to be computed was made on the basis of previous experience with data from many sources, and on our estimate of what can reasonably be determined from standard rawinsondes. [Opinions on this matter differ; for example, Moore and Krishnamurti (1966) advocate somewhat different quantities than ours.] The quantities computed for each volume element included zonal and meridional wind components (or wind speed and direction), vertical vector shear and its square, vertical speed shear, temperature, lapse rate, and height. From the winds, vorticity, divergence, deformation, and horizontal shear along the flow and across the flow were computed. The values of all these quantities are, of course, subject to various errors inherent in upper-air data. Further derivatives of these fields (e.g., the Laplacian and Jacobian) were not used since we believe such terms contain an unacceptable level of uncertainty.

For a given five-day period, a "climatology" was constructed for each of the approximately 500 volume elements over the United States. This climatology was computed from the ten values of turbulence frequency and ten values of each meteorological quantity. For example, the mean vertical vector shear and standard vector deviation of shear were computed in each element. Usually about 50 volume elements had less than twenty flights during the period; these were discarded. Individual correlations of turbulence frequency with each meteorological quantity were determined for each period from approximately 450 values of each variable. Thus the sample sizes are large. Also, a multiple regression program (Gorfinkel, 1967) was used to calculate the correlation of variables with each other, the multiple correlation, and the coefficients of linear regression equations. This program also gives the standard errors in the estimate of each coefficient in a regression equation. When the individual correlations are all relatively low (less than 0.5), as in these data, the standard errors in coefficients are appreciable. If the data are separated into sub-groups, for example, on the basis of altitude, the standard errors of the coefficients enable one to judge whether differences in the coefficients are most likely real or random. It was found that most differences among subsamples (based on season and altitude) were random, except for major differences between the data for June as compared to the other periods.

In general, the turbulence frequencies (for a certain period at particular points) were related most closely to vertical vector shear, and somewhat less to the vertical speed shear. The probability density function of vertical vector shear is not known precisely, but presumably approximates a circular normal distribution. If so, its properties are well described by the vector mean and standard deviations. Also, it follows that the mean and standard deviation of the speed shear could be determined from the vector mean and standard deviation using methods given by Brooks and Carruthers (1954). Both types of statistics (for vector shear and speed shear) are given in the compilation of Schamach.

Correlations between frequencies of moderate or severe turbulence and the best climatological indicators were given in Table I. If light turbulence is included with moderate and severe, the correlations of Table I increase by amounts of approximately 0.1. Thus all correlations obtained from these data are considerably lower than those obtained using data from special research aircraft, as described in Scientific Report 1. Undoubtedly, the difficulties discussed earlier have adversely affected the correlations. Numerous trials were made using different combinations of the meteorological quantities, and a simple linear equation based on the mean and standard deviation of vector shear gave a multiple correlation as high as when additional terms were used. The relevant empirical equation for p(M), the percentage frequency of moderate or severe turbulence is

$$p(M) = C(s) + 2.0 \times \begin{bmatrix}\text{Magnitude of}\\ \text{average vertical}\\ \text{vector shear}\end{bmatrix} - 0.5 \times \begin{bmatrix}\text{Standard}\\ \text{deviation of}\\ \text{vector shear}\end{bmatrix} \tag{1}$$

where the units of vertical vector shear in the brackets are 10^{-3} sec^{-1}, and C(s) is a constant depending on season, taken as 6 in winter, and 5 in spring and fall. (These values are in accord with the average turbulence frequencies for samples of data for different seasons.) This equation has been applied to the climatological data of the Appendix to obtain estimated turbulence frequencies discussed in the next section of this report. On the dependent data, the multiple correlation is 0.36. The standard errors in the coefficients in this equation (as given by the program) are approximately one-fifth of the values given. No systematic differences among these coefficients were found when the turbulence data were sub-divided into altitude groups. Also, no diurnal differences in turbulence frequency were found.

Since climatological wind shear data are available only for the United States and perhaps a few other industrialized countries, Eq. (1) cannot be applied in other geographical areas. However, smoothed maps of mean winds and the standard vector deviation of winds are given in various sources (such as Air Force Manual SACM 105-2) for the entire northern hemisphere. In Table I we saw that turbulence frequency is related, although weakly, to these two quantities. Table II shows them to be highly correlated with each other, so that wind speed alone will specify turbulence about as well as a combination of the two. The patterns of strong winds over the United States given in SACM 105-2 compare in broad features to the turbulence frequency estimated from Eq. (1) as one would expect from the well known general association of turbulence and jet streams. The rough correspondence of turbulence frequency and average wind speed can be seen by comparing Fig. 5(c) (see Sec. V) with Fig. A-1(c), and Fig. 5(d) with Fig. A-1(f). Actually, the regions

Table II

CORRELATIONS BETWEEN METEOROLOGICAL FACTORS BASED ON OBJECTIVE ANALYSES FOR SPECIAL TURBULENCE REPORTING PERIODS IN DECEMBER 1964 AND MARCH 1965*

Meteorological Factor	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
1. Average vertical speed shear	1.0	0.73	-	-	0.54	0.59
2. Standard deviation of vertical speed shear	0.73	1.0	-	-	-	-
3. Magnitude of average vertical vector wind shear	-	-	1.0	0.17	0.40	0.43
4. Standard deviation of vector wind shear	-	-	0.17	1.0	0.24	0.26
5. Wind speed	0.54	-	0.40	0.24	1.0	0.88
6. Standard deviation of W	0.59	-	0.43	0.26	0.88	1.0

*Each correlation is based on approximately 900 pairs.

estimated to have the highest frequency of turbulence lie on the south side of the centers of the average isotachs. Nevertheless, preliminary estimates of turbulence from average wind speeds as given in U.S. Air Force Manual SACM 105-2 may be useful for certain purposes. Linear regression equations between turbulence frequency and average wind speed varied considerably among subsamples of our data. Overall, the regression equation that relates turbulence frequency to average wind speed in m sec^{-1} and that appears to give reasonable results over the United States is

$$p(M) = C(a) + 0.12 \times [\text{Average wind speed}] \qquad (2)$$

where C(a) depends on altitude and is taken as 5 percent at 400 mb, 4 percent at 300 mb, and 3 percent at 200 mb. It would be interesting to test this equation in other geographical areas, particularly Japan, where the jet stream reaches maximum speeds. However, the use of wind speeds to estimate turbulence frequency is less reliable than the use of shear statistics, as stated previously.

B. Regression Equations for Summer

Compared to pilot reports for several winter periods that are discussed above, reports from only a single five-day period (June 9-14, 1965) were available to represent summer conditions. It would be desirable to verify the present results with other summer data. As mentioned previously, associations of turbulence with meteorological quantities over the United States in June are considerably different than in winter. The mean position of maximum winds in summer is over the Great Lakes, north of the main flight routes. The vertical wind shear is generally much weaker than in winter. To a large degree the weather disturbances over the United States are convective in nature. Much of the convection occurs in areas where vertical shear in the upper troposphere is small. Even the turbulence outside convective clouds and reported by pilots as clear-air turbulence may have been indirectly of convective origin. Probably in and north of the average jet stream in summer, turbulent frequencies depend primarily on wind shear, as in the other seasons over the United States. However, the June data show negative correlations of turbulence frequencies with average vertical shear, average wind speed, and the standard vector deviation of wind. Of the quantities computed, only relative vorticity has a small positive correlation, as shown in Table III.

Table III

CORRELATIONS BETWEEN PERCENTAGE FREQUENCY OF MODERATE OR SEVERE TURBULENCE (FROM PILOT REPORTS) AND CLIMATOLOGICAL FACTORS, FOR JUNE 9-14, 1965*

Magnitude of Average Vertical Vector Wind Shear	Standard Vector Deviation of Wind Shear	Average Wind Speed	Standard Vector Deviation of Wind	Relative Vorticity
-0.20	-0.15	-0.29	-0.11	0.13

*Each correlation is based on approximately 400 pairs.

The best regression equation found, having a multiple correlation of 0.38, is

$$\begin{aligned} p(M) = 8.0 &+ 1.7 \times \underset{\text{units } 10^{-3}\ \text{sec}^{-1}}{\begin{bmatrix}\text{Magnitude of average} \\ \text{vertical vector shear}\end{bmatrix}} - 1.0 \times \underset{\text{units } 10^{-3}\ \text{sec}^{-1}}{\begin{bmatrix}\text{Standard deviation} \\ \text{of vector shear}\end{bmatrix}} \\ &- 0.5 \times \underset{\text{units m sec}^{-1}}{\begin{bmatrix}\text{Wind Speed}\end{bmatrix}} + 0.1 \times \underset{\text{units m sec}^{-1}}{\begin{bmatrix}\text{Standard deviation} \\ \text{of wind vector}\end{bmatrix}} \\ &+ 0.03 \ \underset{\text{units } 10^{-6}\ \text{sec}^{-1}}{[\text{Relative vorticity}]} \qquad (3) \end{aligned}$$

This equation is used to obtain the estimated turbulence frequencies for summer given in Sec. V. The values of mean wind speed and direction in summer, and the standard deviation of wind were taken from Air Force Manual SACM-105-2. Vorticity was computed from the mean winds. Typical examples of these fields are shown in the Appendix, in Fig. A-3. In these summer data a diurnal effect was found, such that computed turbulence frequencies at 00 GMT (evening) should be increased by 15 percent, while at 12 GMT (morning) the probabilities should be decreased by the same amounts.

C. Mountain Effects

In these regression equations, no separation was made between mountainous and non-mountainous terrain. The flight frequency is such that the majority of data pertain to non-mountainous areas. To isolate terrain effects, grid points were separated into mountainous and non-mountainous categories. Then under similar meteorological conditions, differences in turbulence probability between the two categories were found. These show that turbulence frequencies are generally higher in mountainous regions than would be indicated by a regression equation based only on synoptic parameters. This effect can be adequately represented by increasing the turbulence frequencies in mountainous areas by an appropriate amount. The mountainous regions of the United States (generally having elevations greater than 1000 m) are shown by light shading in Fig. 3. Within these areas, the turbulence frequencies given in Sec. V should be multiplied by a factor k_2, taken as 1.3 in

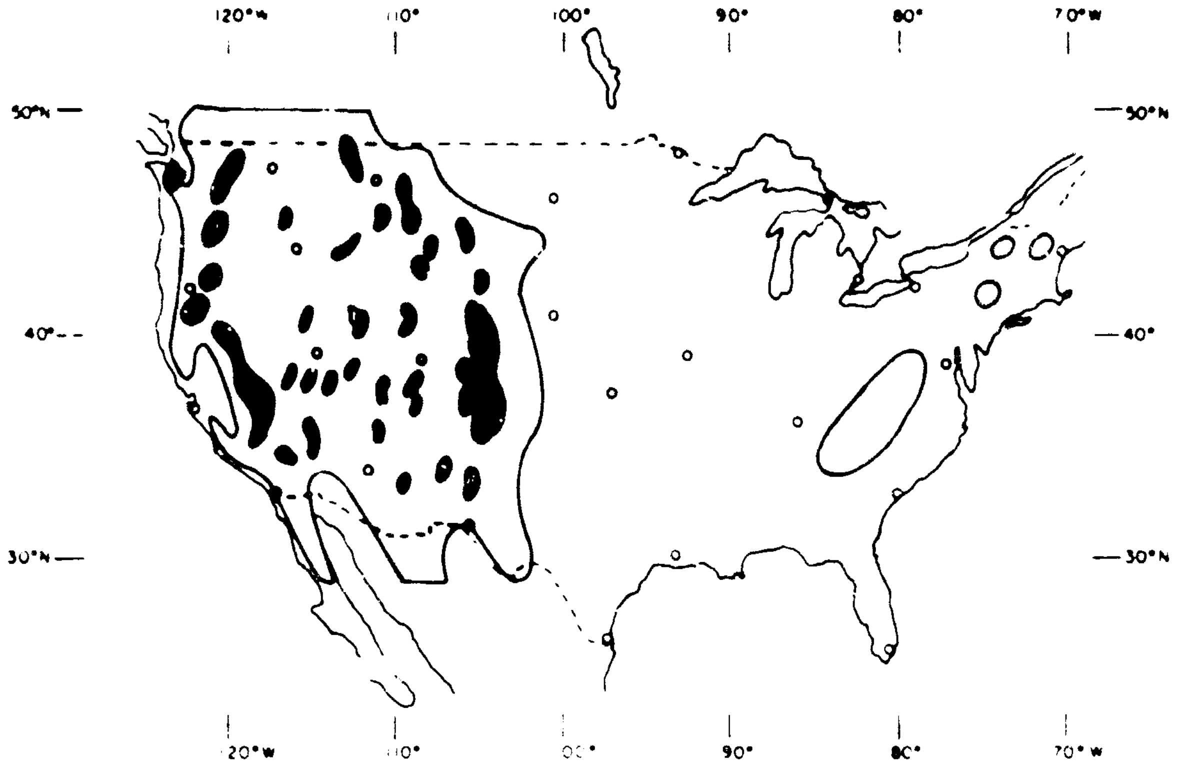


FIG. 3 MAP OF PRINCIPAL MOUNTAIN-WAVE AREAS OF THE UNITED STATES. Within the darker shading, turbulence frequencies of subsequent figures should be multiplied by k_1 to account for average mountain-wave effects. In areas of lighter shading the multiplication factor is k_2. Values of k_1 and k_2 are given in Sec. IV-C.

winter and 1.15 in spring and fall. In summer, no such correction is needed. It is known that the largest corrections should be made on the lee side of major steep-sided mountain ranges that produce prominent mountain waves. Such areas, shown in Fig. 3 by dark shading, were subjectively estimated from topographic maps of the United States, and include mountain wave regions identified by Harrison and Sowa (1966) and Foltz (1967). To account for wave activity in these areas, turbulence frequencies of Sec. V. should be multiplied by k_1, taken as 1.6 in winter and as 1.3 in spring and fall.

D. Application to Other Areas and Altitudes

If relevant wind shear statistics were available for continental areas of the mid-latitudes other than the United States, it would be reasonable, in our opinion, to apply the same regression equations in order to obtain a first estimate of turbulence frequency. Over the oceans of mid-latitudes where terrain disturbances are lacking, the regression equations probably give turbulence frequencies that are too large. According to Clodman, Morgan, and Ball (1960), turbulence over oceans is an order of magnitude less frequent than over land. However, recent data analyzed by Colson (1968) indicate that moderate or severe turbulence over oceans is about 0.7 times as frequent as over land, and that the same sort of meteorological conditions (jet streams, troughs, and ridges) are important for both. Thus, a simple correction of this magnitude might be used in applying Eq. (1) to the oceans of mid-latitudes. In polar regions, one might expect that the wintertime procedure should be applied in all seasons. Perhaps the summer regression equation could be applied in the tropics, but this also is speculative since we have no experience with aircraft turbulence data for these regions.

It must be borne in mind also that the most comprehensive turbulence data (from pilots) have been obtained in an altitude range restricted to approximately 20,000 to 40,000 feet. At lower altitudes, the regression equations might be applicable to the United States except for changes in the constant values to accommodate greater turbulence amounts due to the influences of low-level convection and terrain. In estimating turbulence frequency in the stratosphere, one is faced with the drastic reduction in available information, as noted by Mitchell (1966). However, the descriptions of U-2 measurements of turbulence in and above jet streams given by Penn and Pisinski (1967) indicate that the wind field is of predominant importance, with a possible tendency for turbulence to be associated with intermediate values of lapse rate. (The contention that stratospheric turbulence is more closely related to temperature inversions than to the wind field appears dubious to us.) Due to the apparent similarity to conditions lower down, it appears reasonable to apply the regression equations for turbulence to the lower stratosphere. We have done so in the next section, subject to the limitation of decreasing reliability of standard climatological data in the stratosphere. But for altitudes above 50,000 feet a new range of problems enters, in that future aircraft operating at these levels will be supersonic, and will be affected by turbulent eddies of longer wavelengths than are subsonic craft. Spectrum curves of turbulence show that longer wavelengths have higher energy; therefore under identical atmospheric conditions supersonic planes may encounter more turbulence than would conventional aircraft. A fairly large amount of turbulence encountered in a small number of flights made by the XB-70 aircraft (Ehrenberger, 1966) apparently supports this expectation. For this reason the present regression equations, if applied to the stratosphere, might underestimate turbulence probabilities for supersonic aircraft. This problem deserves further investigation.

V AN ESTIMATED TURBULENCE CLIMATOLOGY FOR THE UNITED STATES

The method of determining the turbulence frequencies presented in this section was described in Sec. IV. An explanation of the interpretation and use of the frequencies is as follows: The percentage frequencies p(M) given in subsequent figures pertain to the likelihood that turbulence of moderate or severe intensity (as evaluated by pilots) will be encountered during a 100-mile segment of a flight made at a particular location and altitude. The average value of p(M) over the United States is shown versus altitude in Fig. 4. If light turbulence is combined with moderate and severe to give p(T), the overall turbulence

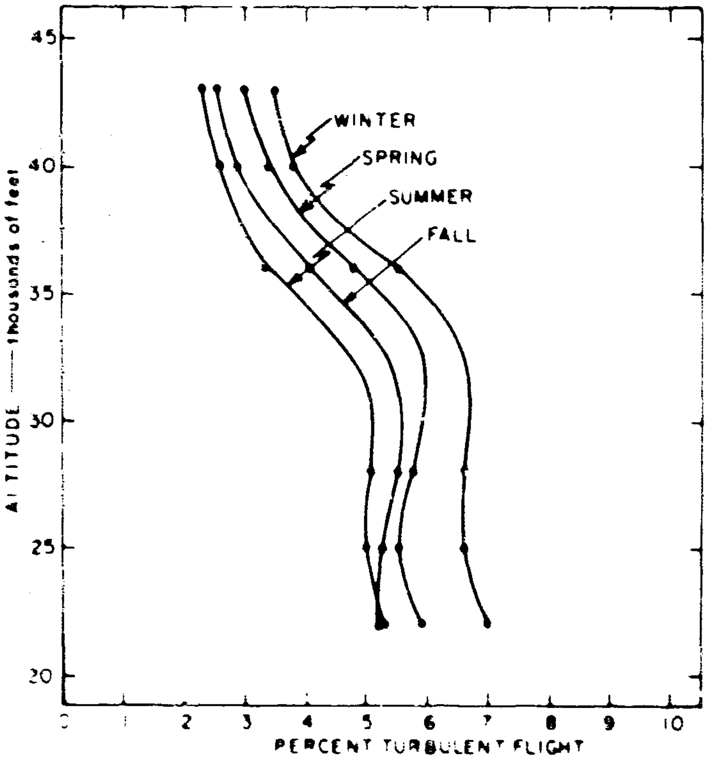


FIG. 4 CURVES OF AVERAGE TURBULENCE FREQUENCY vs. HEIGHT FOR THE UNITED STATES, DETERMINED FROM FIGS. 5 THROUGH 8

frequency (light, moderate, or severe) within 100-mile sectors, the pilot reports show that p(T) = 3.5p(M) in winter and spring, and p(T) = 4.5p(M) in summer and fall. As discussed by Endlich and Mancuso (1967), the frequency of encountering the same intensity of turbulence in a flight segment shorter than 100 miles decreases proportionately with the smaller length. Data from Steiner (1965) and Endlich (1965) indicate that the frequency of encountering moderate or severe turbulence at a given instant is less than two percent. This amount is about one-fifth of the frequency of encountering the same degree of turbulence in some portion (or possibly all) of a 100-mile segment. Thus, dividing the frequencies p(M) by five will give p(m), an estimate of the instantaneous frequency of encountering moderate or severe turbulence. Similarly, dividing p(T) by five will give p(t), the instantaneous likelihood of encountering light or greater turbulence.

In summary, the turbulence frequencies that follow may be interpreted in the following ways:

(1) The frequencies p(M) of this section pertain to the likelihood of encountering moderate or severe clear-air turbulence within a 100-mile flight segment.

(2) To obtain p(T), the frequencies of encountering light or greater turbulence within 100-mile flight segments, multiply p(M) by 3.5 in winter and spring, and by 4.5 in summer and fall.

(3) To obtain p(m), the likelihood of encountering moderate or severe turbulence at a given instant, divide p(M) by 5.

(4) Similarly, to obtain p(t), the instantaneous risk of encountering light or greater turbulence, divide p(T) by 5.

The turbulence frequencies were computed at 5-degree latitude-longitude intersections based on climatological data at the twenty-five stations whose locations are indicated by circles in Fig. 5. Frequencies are given at the midpoint of those altitude layers having wind-shear data--i.e., at 425, 375, 325, 225, 187, and 162 mb. These levels correspond to heights of approximately 22,000, 25,000, 28,000, 36,000, 40,000 and 43,000 feet respectively. No shear data were available at the 275-mb (32,000-foot) level. Charts for winter are given in Figs. 5(a) through 5(f), for spring in Figs. 6(a) through 6(f), for summer in Figs. 7(a) through 7(f), and for fall in Figs. 8(a) through 8(f). The terrain corrections indicated by Fig. 3 have not been made in Figs. 5-8; this must be done by the reader for a particular locality. Similarly, a diurnal correction (Sec. IV-B) should be made to interpret Fig. 7 to a particular time of day.

These turbulence frequencies are believed to apply to problems where turbulence frequency is needed by season, altitude, and place. They provide a rough basis for estimating the overall turbulence exposure associated with different mission profiles. Operational planning to avoid turbulence--for example, for air refueling missions--should obtain some guidance. Also, turbulence-seeking programs may be directed to areas of maximum probable exposure. Other applications of this sort will probably be found.

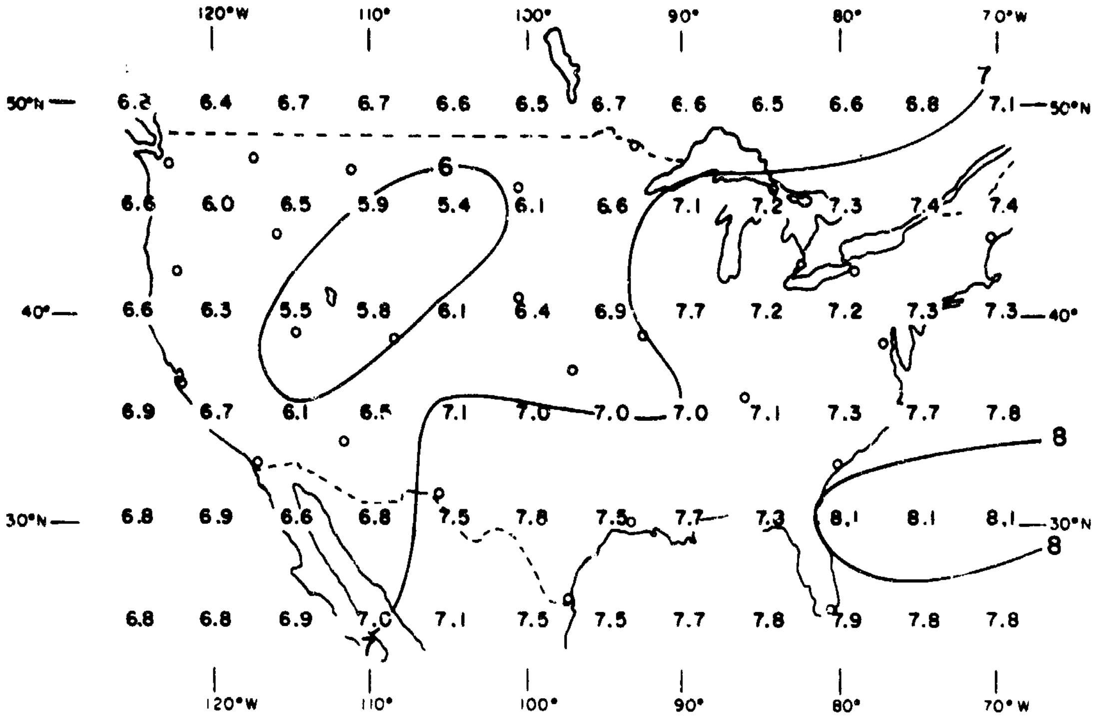


FIG. 5(a) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN WINTER, AT 425 mb (approx. 22,000 feet). Average percent turbulence = 7.0. See Sec. V for an interpretation of these frequencies.

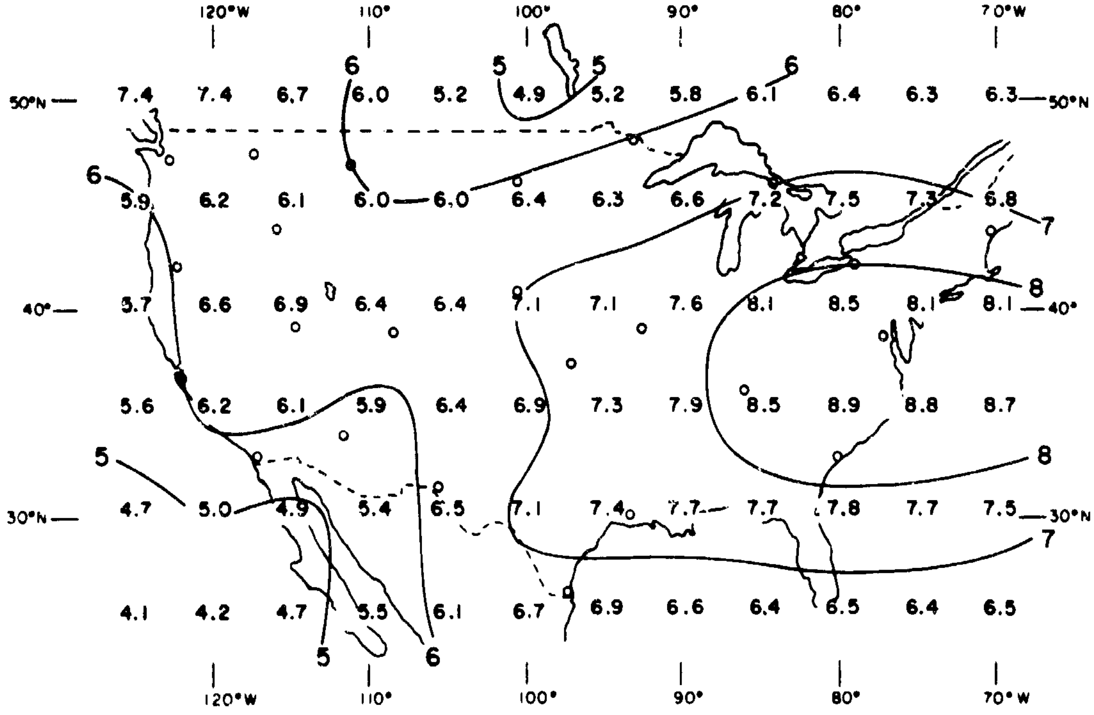


FIG. 5(b) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN WINTER, AT 375 mb (approx. 25,000 feet). Average percent turbulence = 6.6.

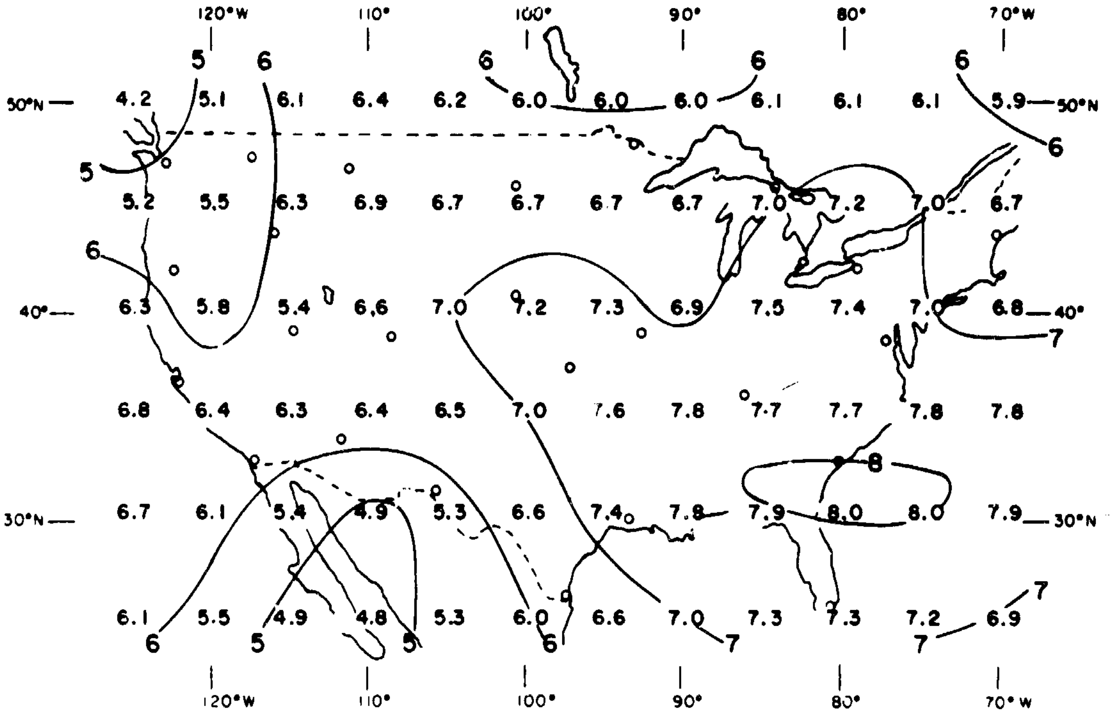


FIG. 5(c) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN WINTER, AT 325 mb (approx. 28,000 feet). Average percent turbulance = 6.6.

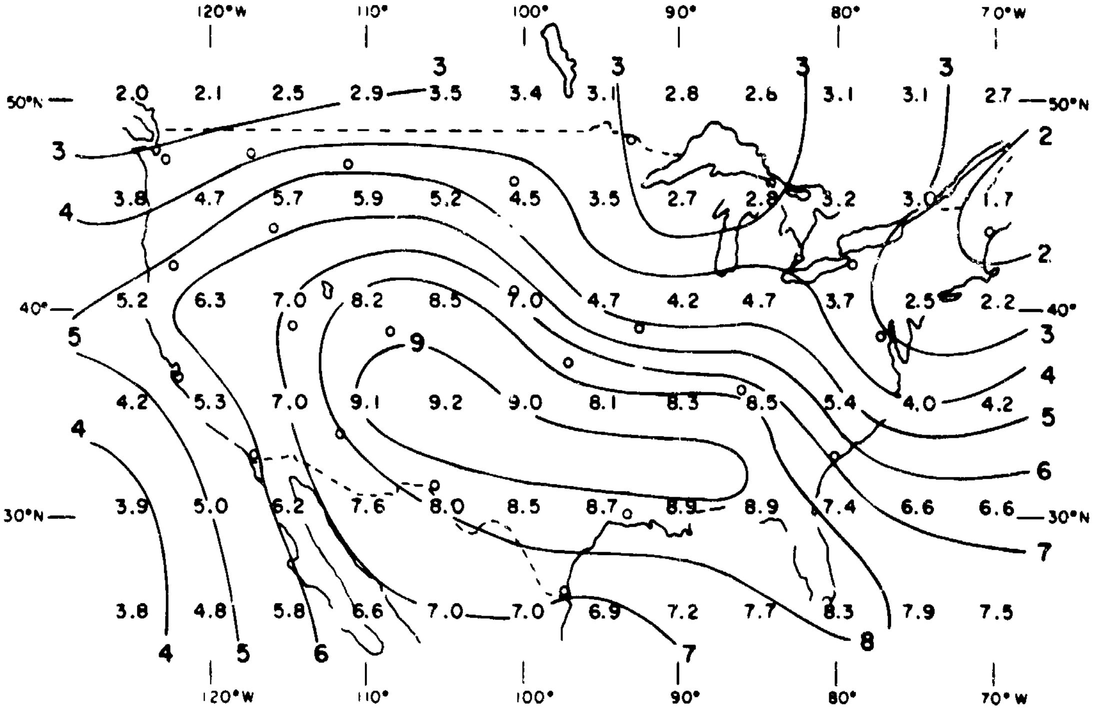


FIG. 5(d) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN WINTER, AT 225 mb (approx. 36,000 feet). Average percent turbulence = 5.5.

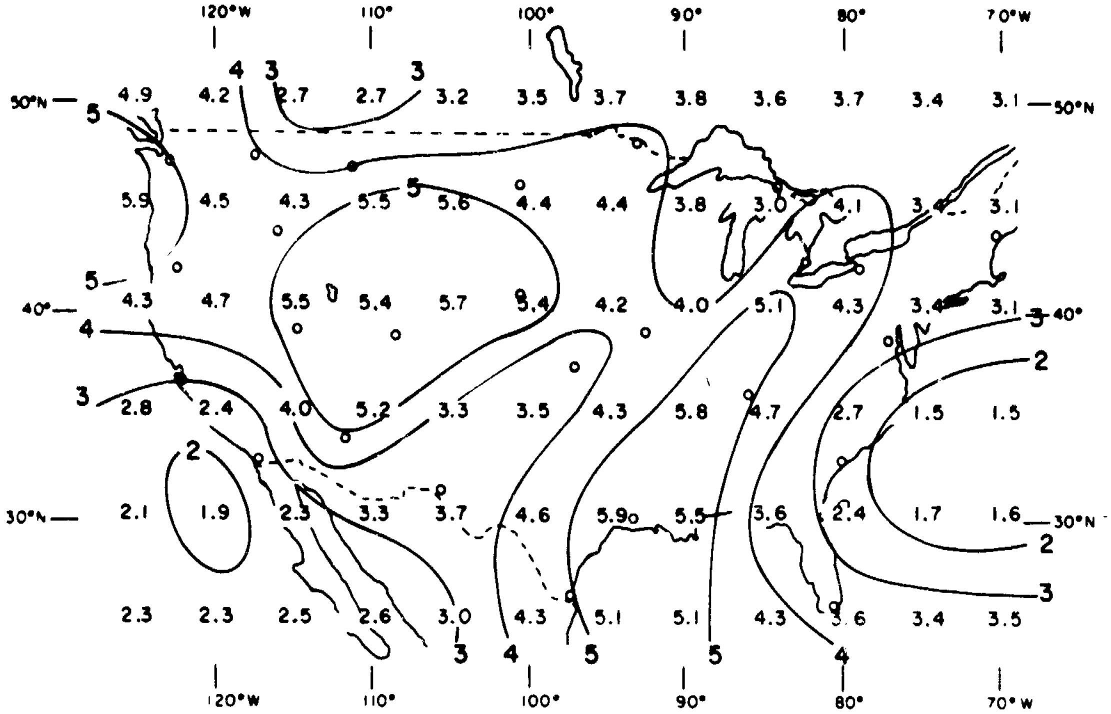


FIG. 5(e) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN WINTER, AT 187 mb (approx. 40,000 feet). Average percent turbulence = 3.8.

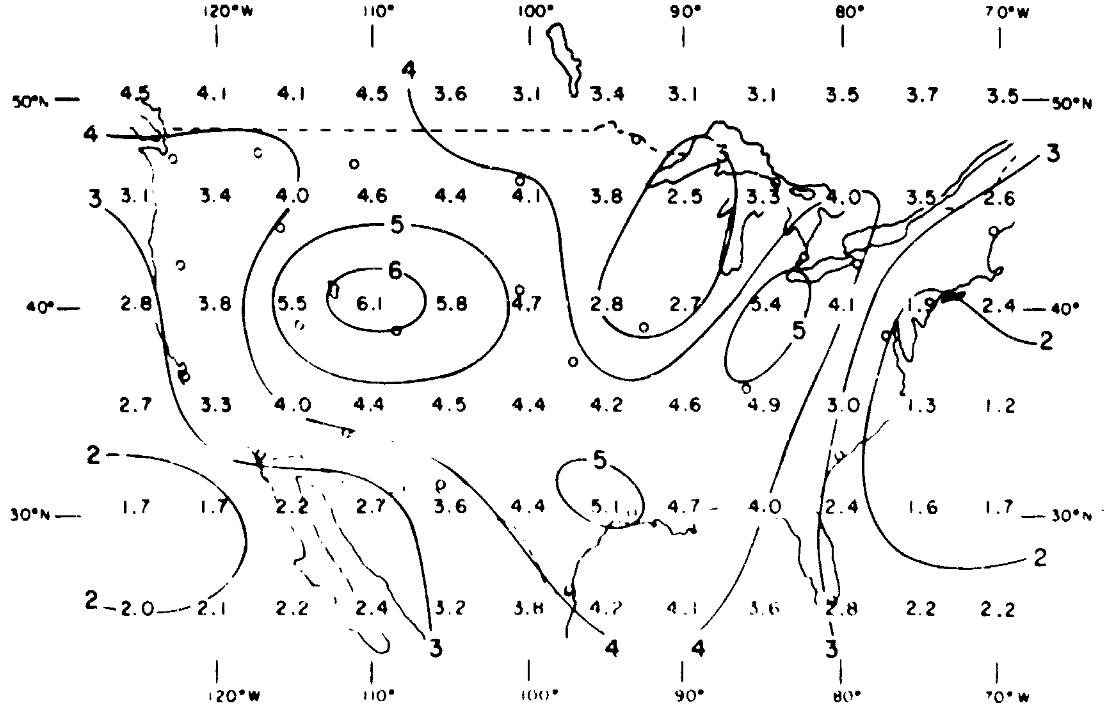


FIG. 5(f) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN WINTER, AT 162 mb (approx. 43,000 feet). Average percent turbulence 3.5.

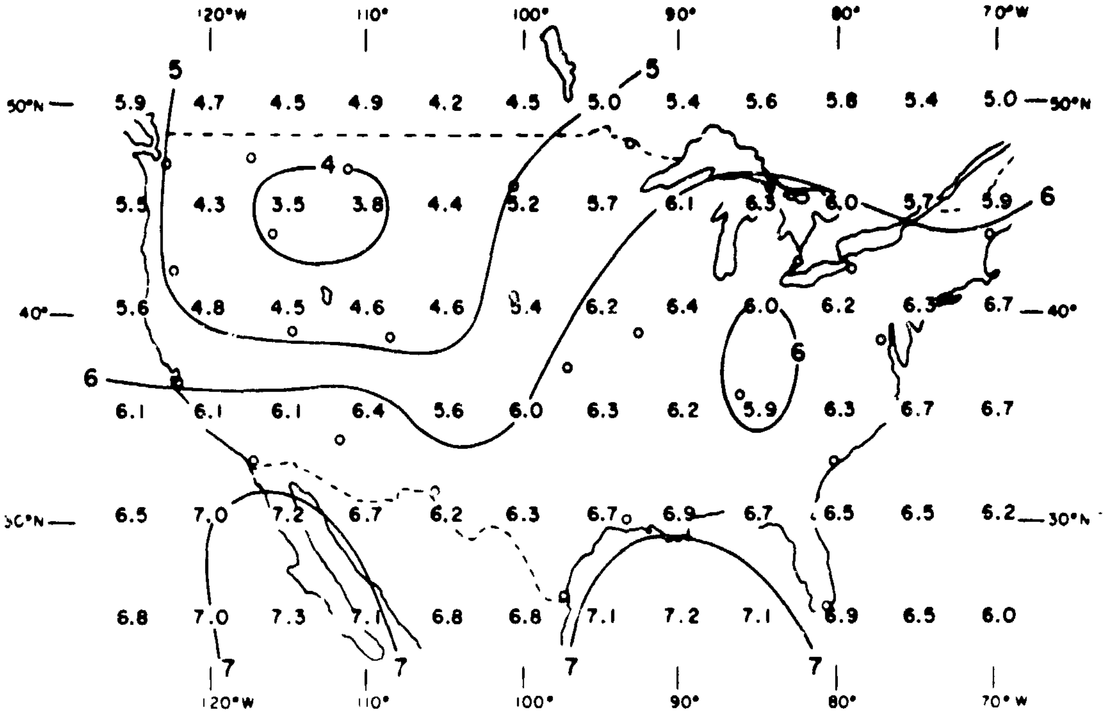


FIG. 6(a) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SPRING, AT 425 mb (approx. 22,000 feet). Average percent turbulence = 5.9. See Sec. V for an interpretation of these frequencies.

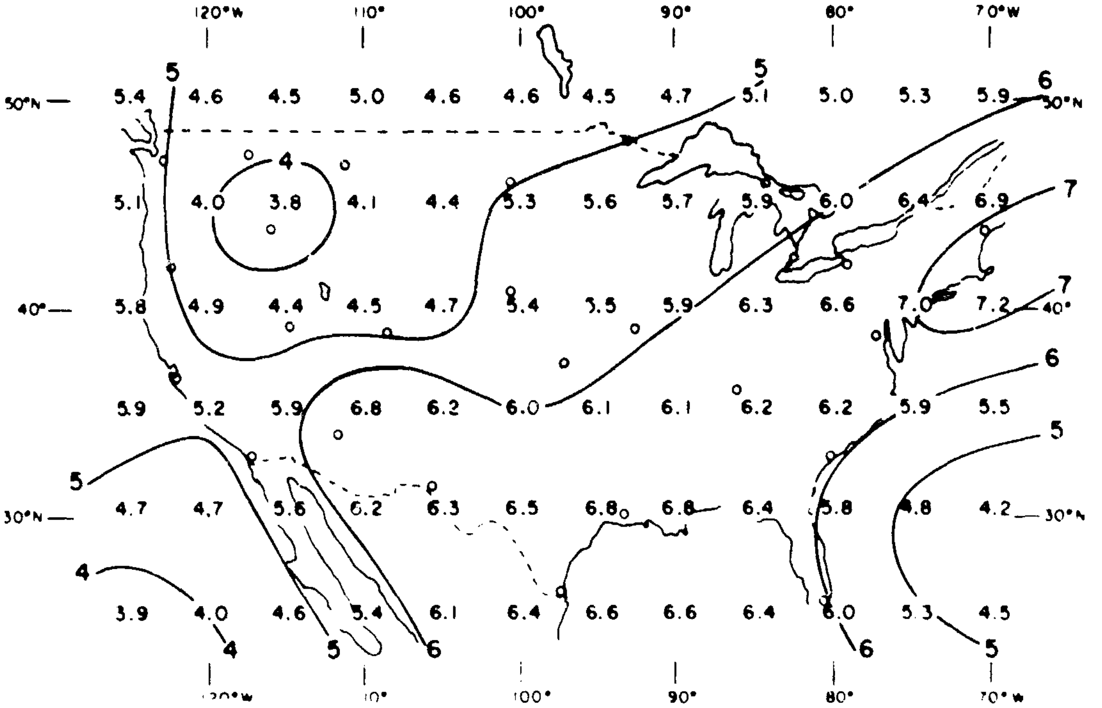


FIG. 6(b) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SPRING, AT 375 mb (approx. 25,000 feet). Average percent turbulence = 5.5.

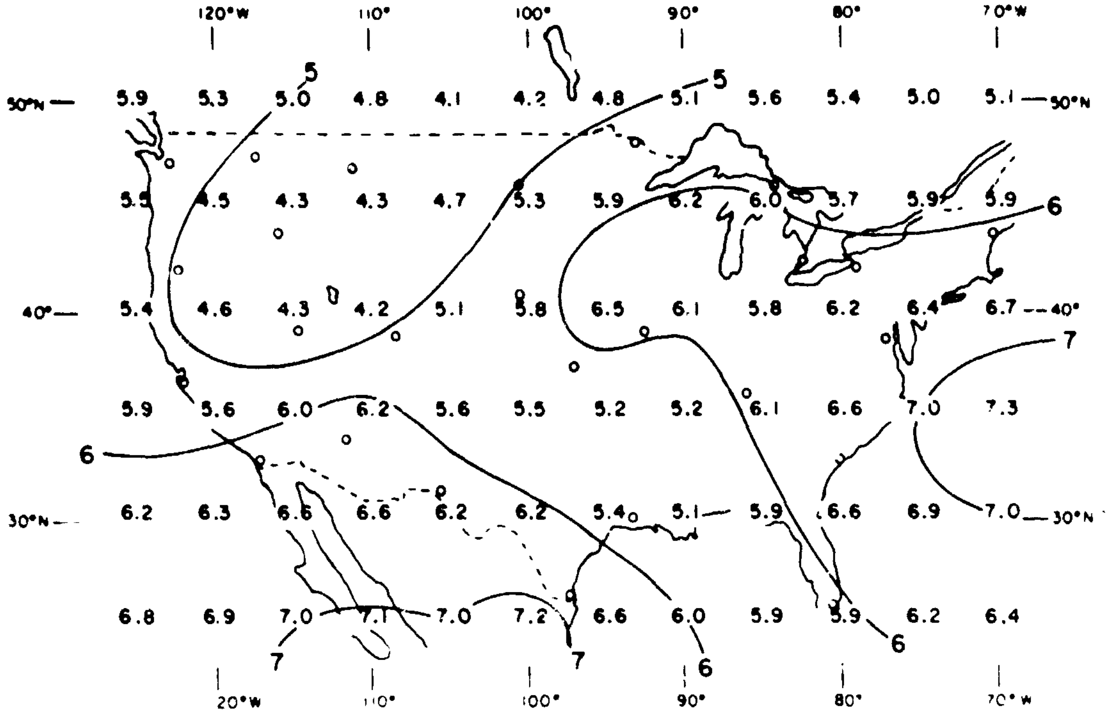


FIG. 6(c) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SPRING, AT 325 mb (approx. 28,000 feet). Average percent turbulence = 5.8.

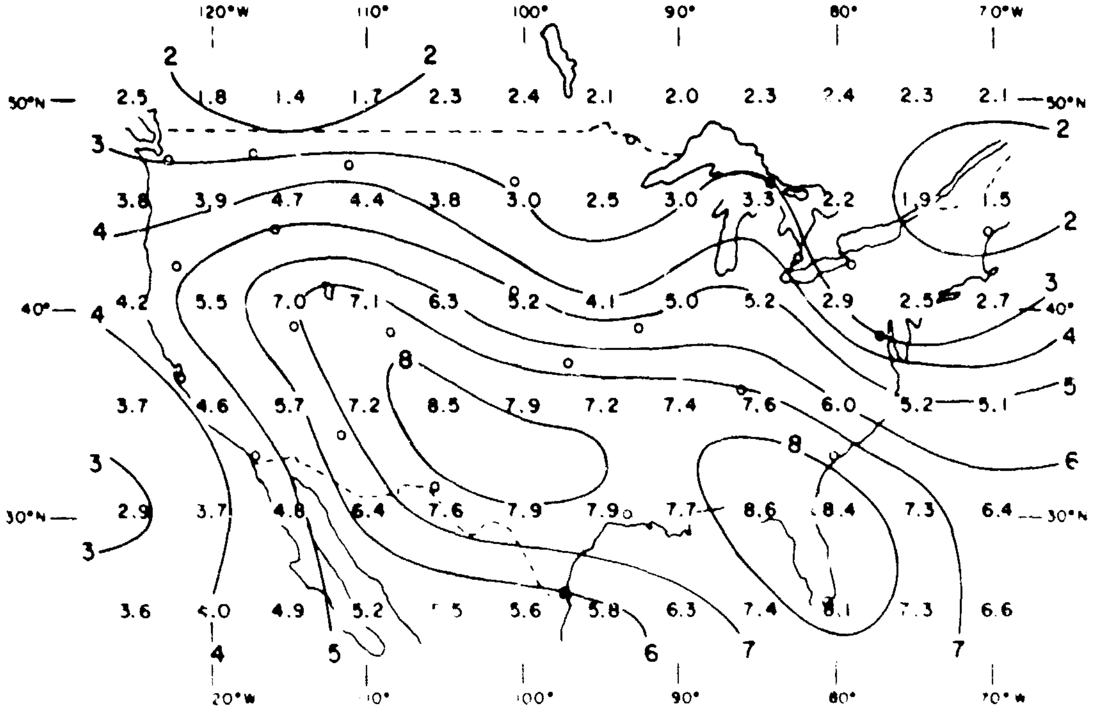


FIG. 6(d) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SPRING, AT 225 mb (approx. 36,000 feet). Average percent turbulence 4.8.

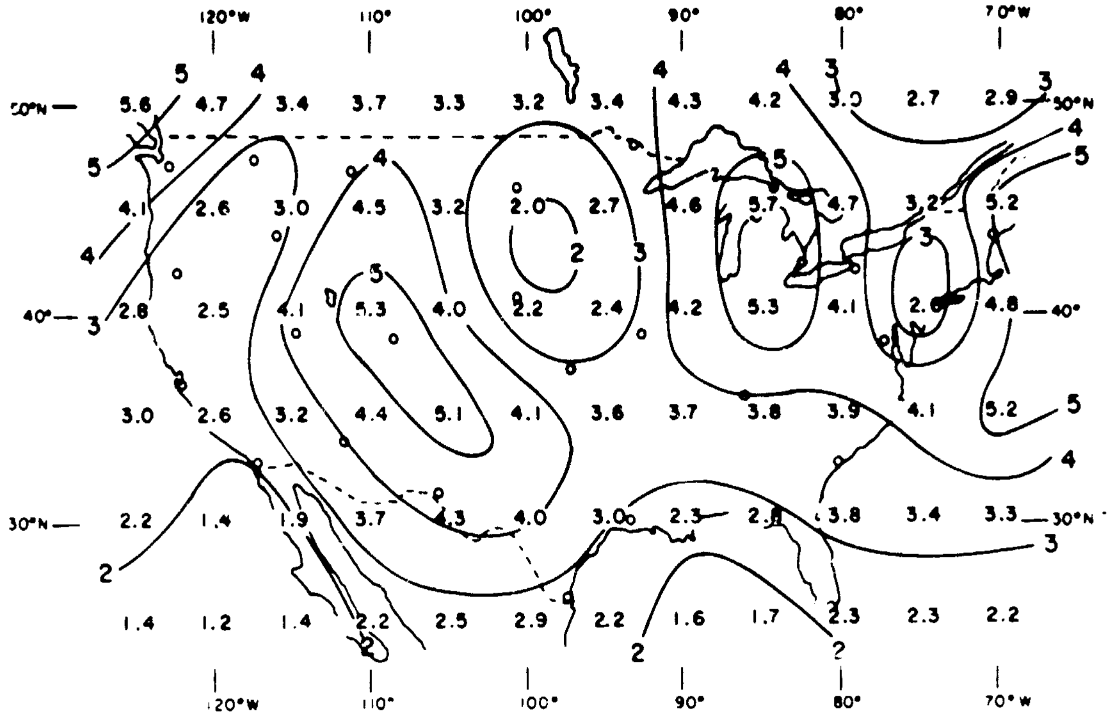


FIG. 6(e) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SPRING, AT 187 mb (approx. 40,000 feet). Average percent turbulence = 3.4.

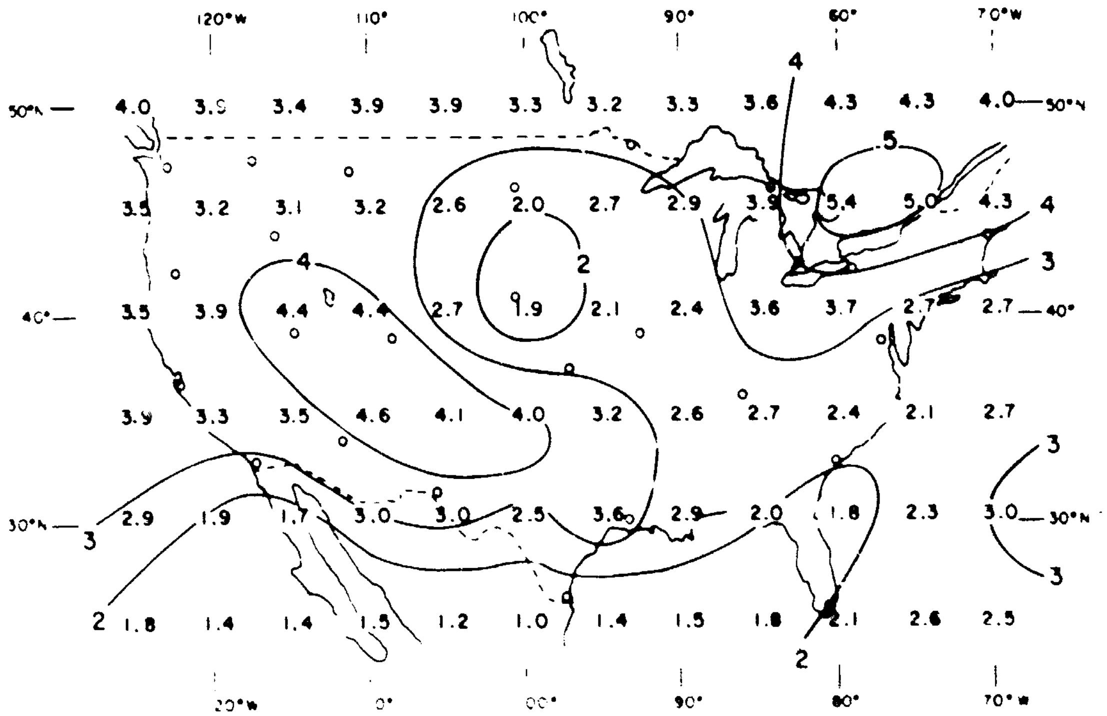


FIG. 6(f) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SPRING, AT 162 mb (approx. 43,000 feet). Average percent turbulence 3.0.

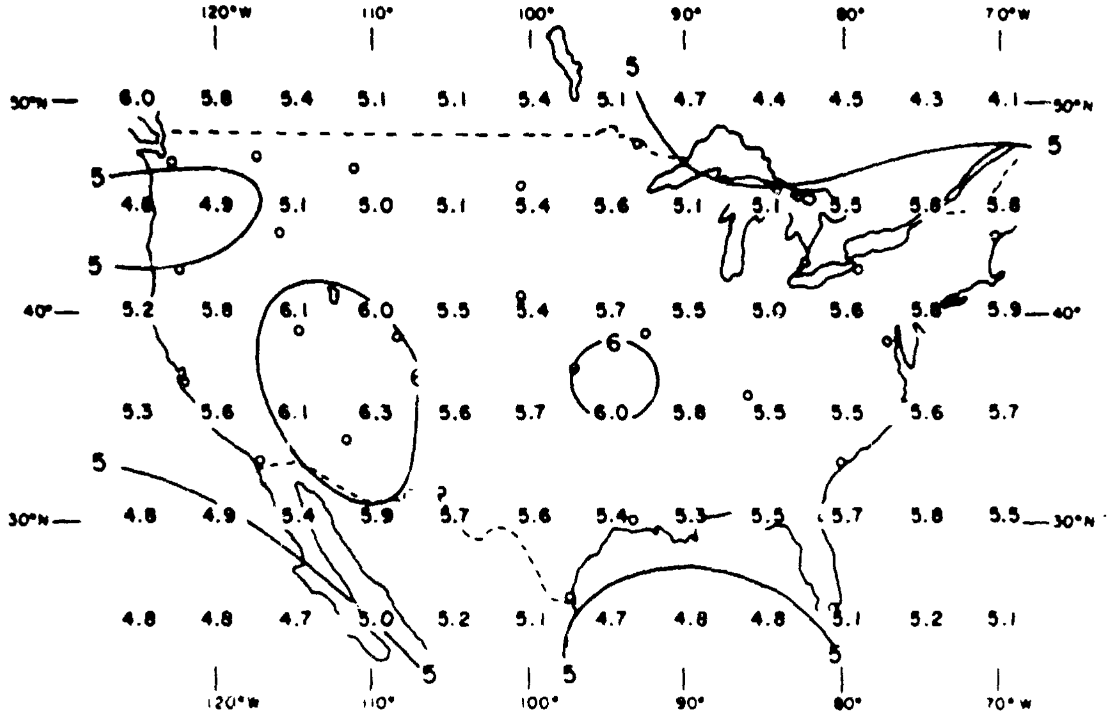


FIG. 7(a) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SUMMER, AT 425 mb (approx. 22,000 feet). Average percent turbulence = 5.3. See Sec. V for an interpretation of these frequencies.

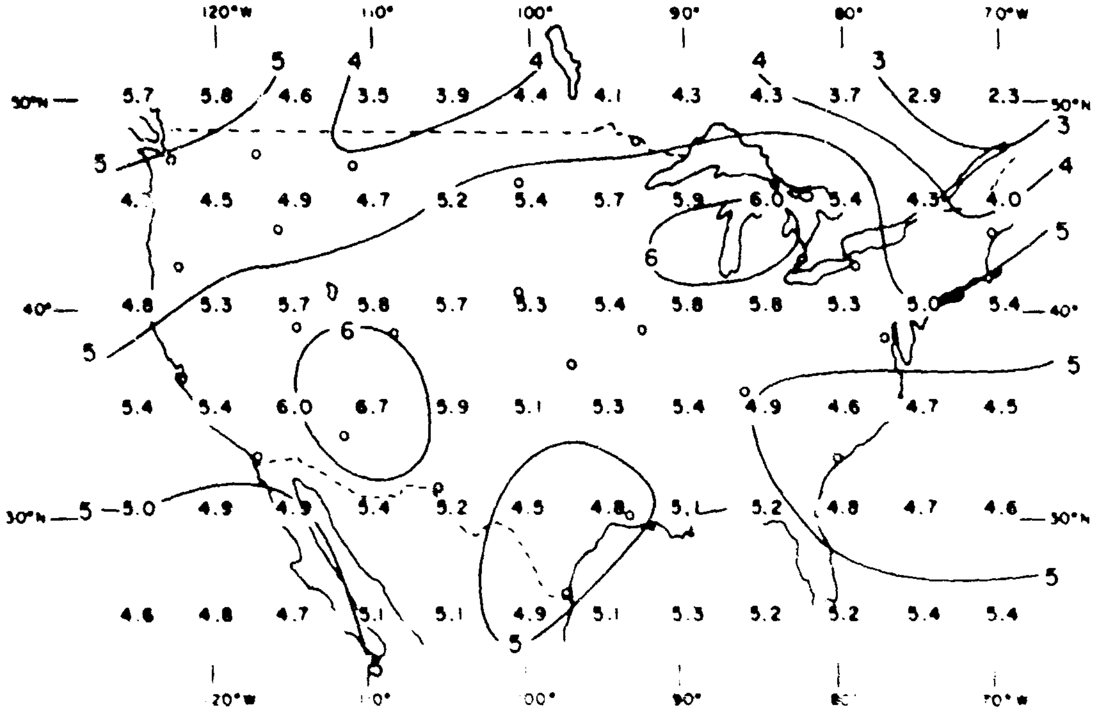


FIG. 7(b) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SUMMER, AT 375 mb (approx. 25,000 feet). Average percent turbulence 5.0.

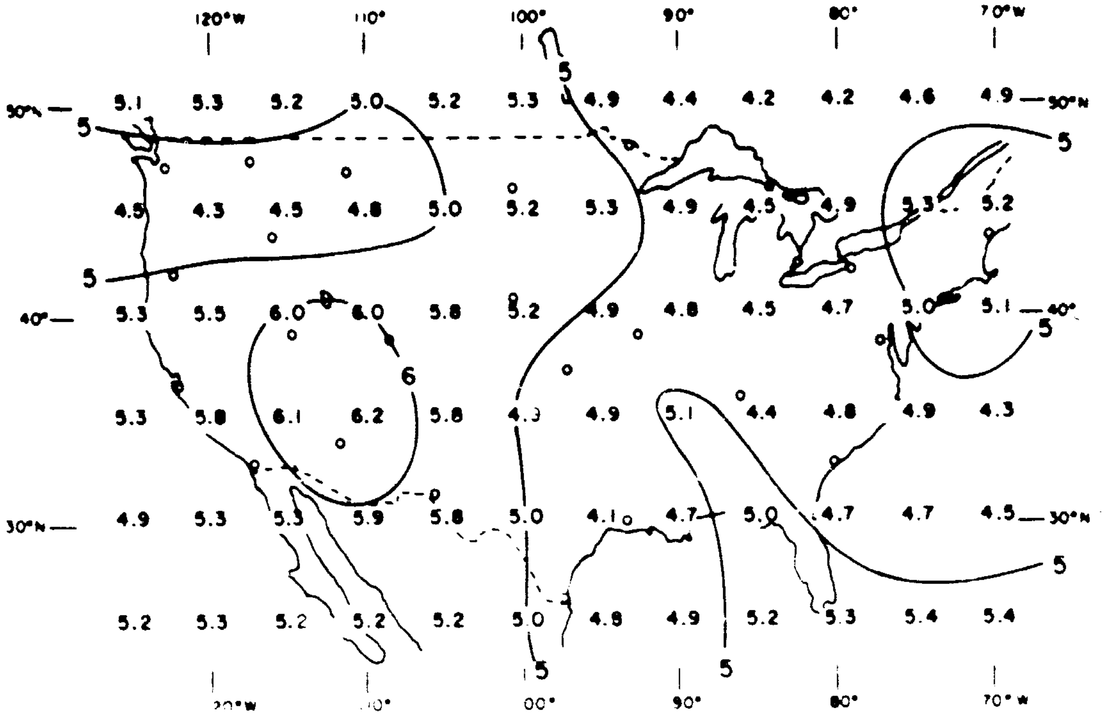


FIG. 7(c) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SUMMER, AT 325 mb (approx. 28,000 feet). Average percent turbulence = 5.1.

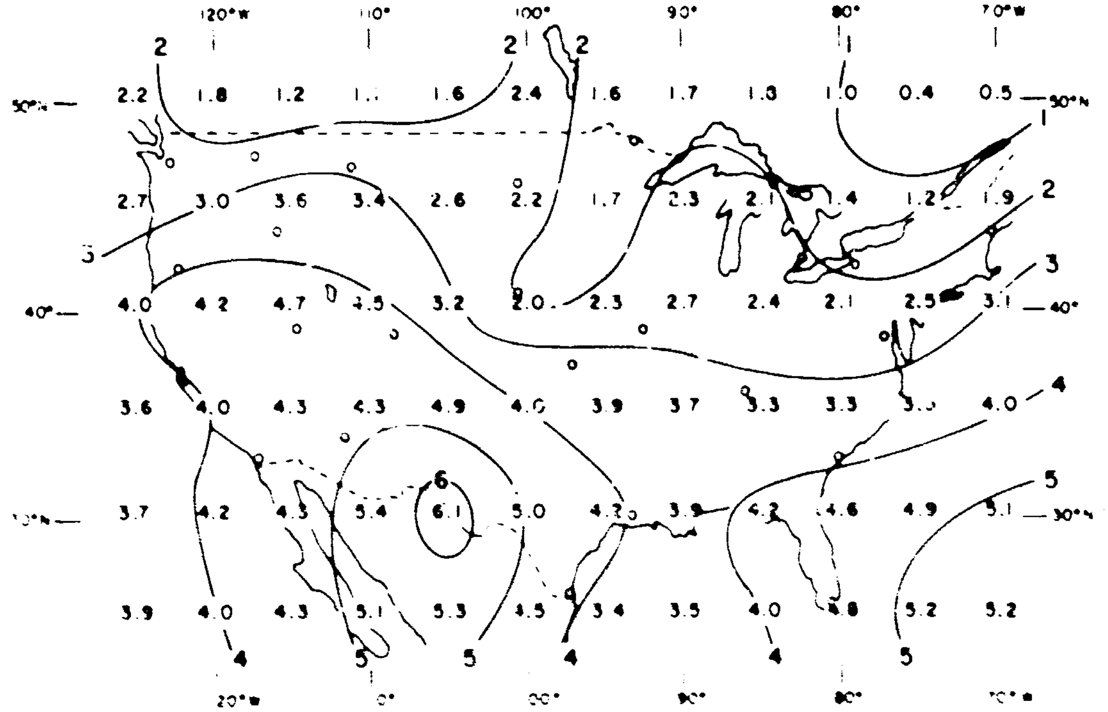


FIG. 7(d) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SUMMER, AT 225 mb (approx. 36,000 feet). Average percent turbulence = 3.3.

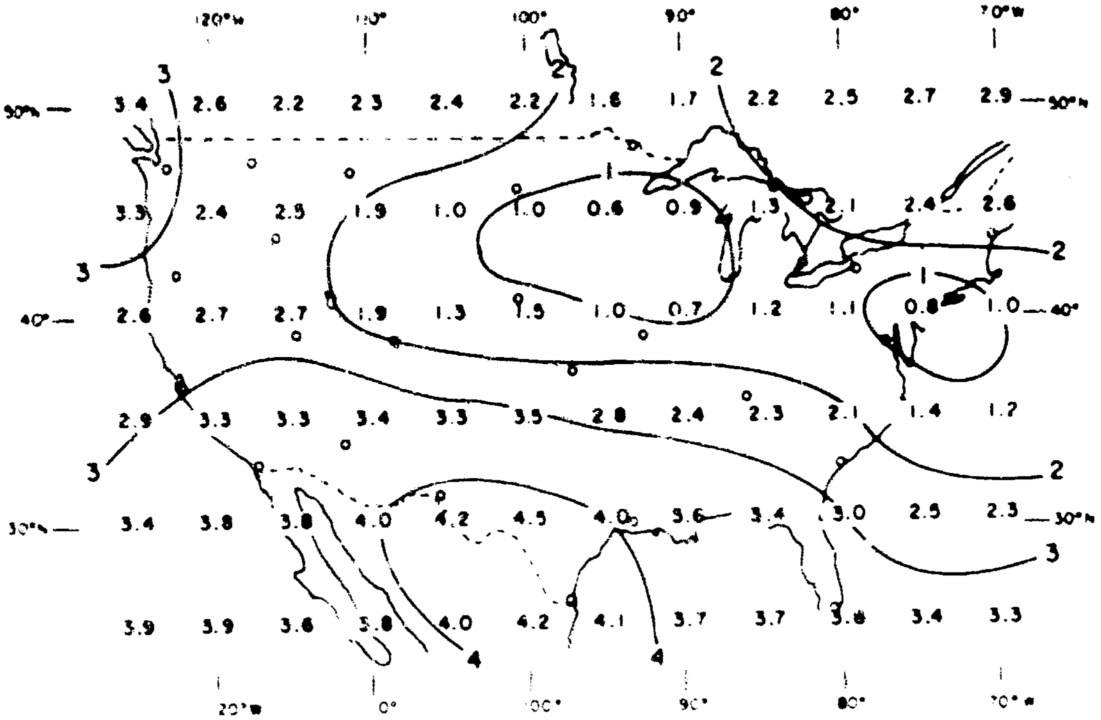


FIG. 7(e) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SUMMER, AT 187 mb (approx. 40,000 feet). Average percent turbulence = 2.6.

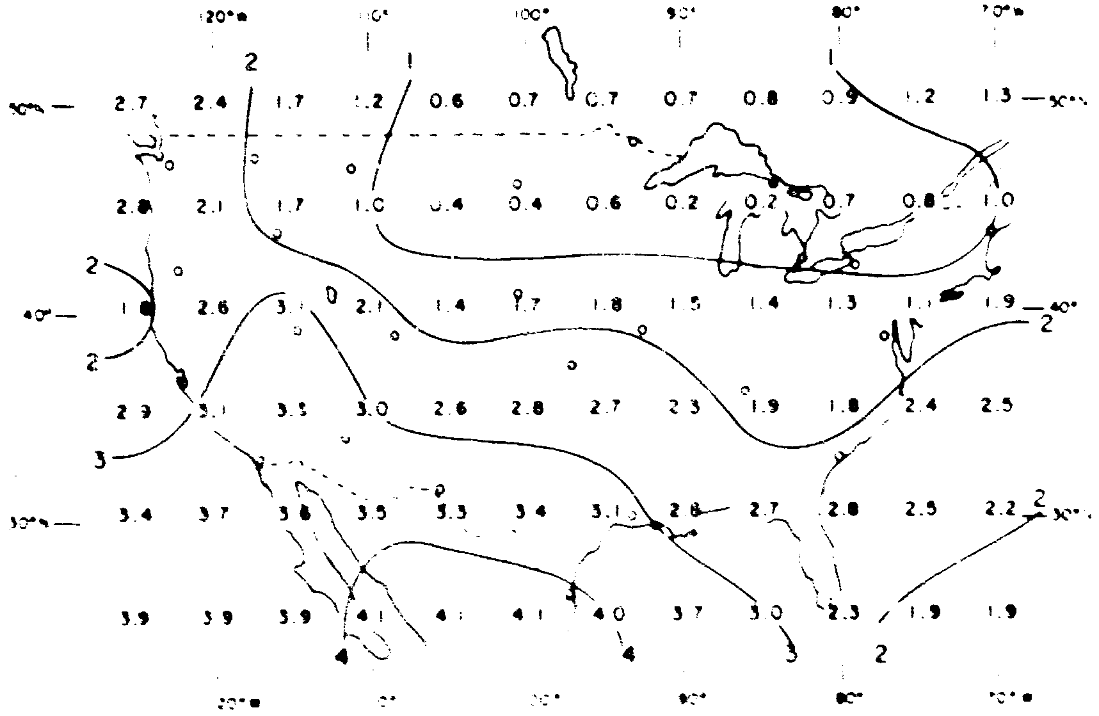


FIG. 7(f) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN SUMMER, AT 162 mb (approx. 43,000 feet). Average percent turbulence = 2.2.

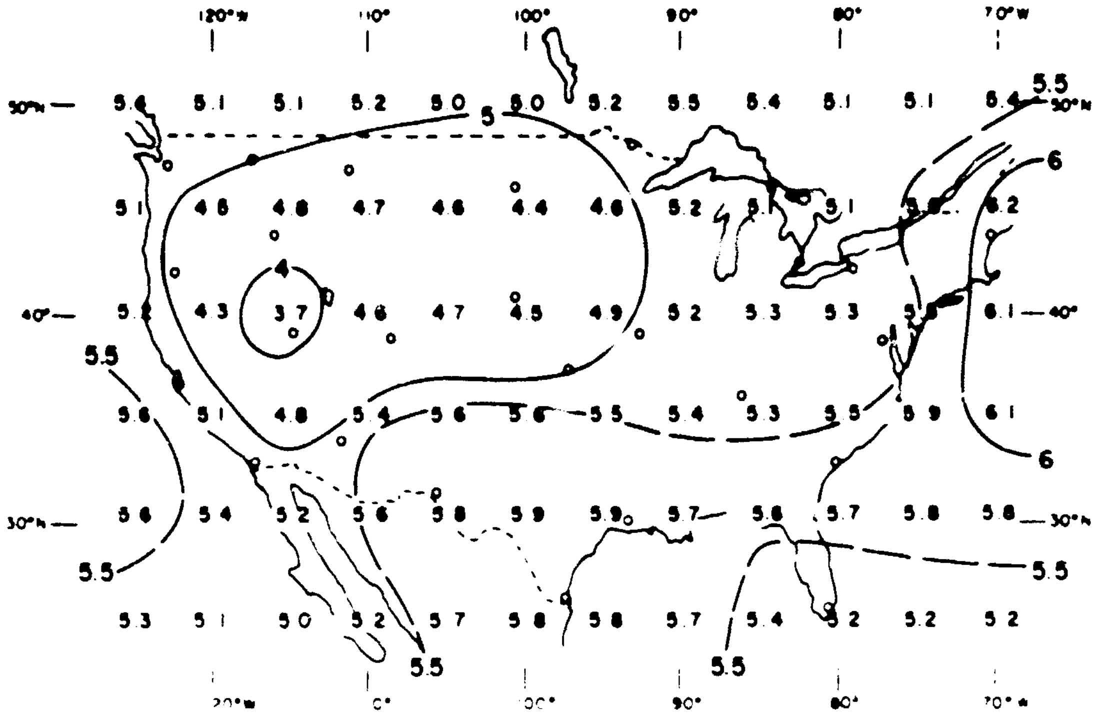


FIG. 8(a) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN FALL, AT 425 mb (approx. 22,000 feet). Average percent turbulence = 5.3. See Sec. V for an interpretation of these frequencies.

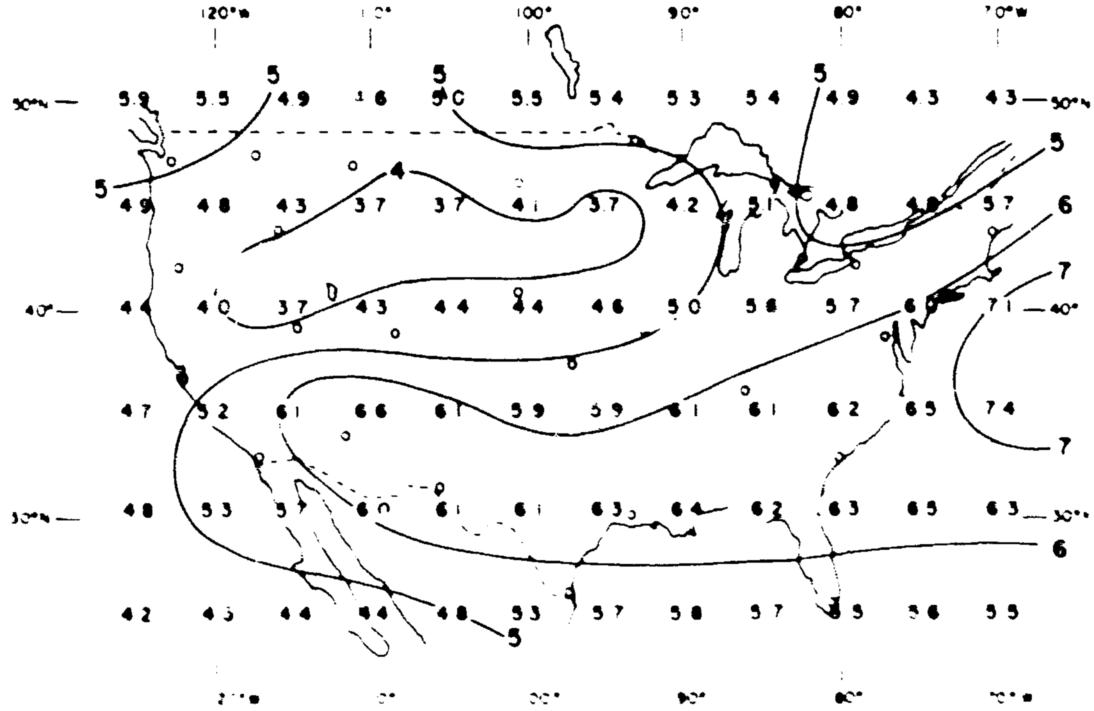


FIG. 8(b) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN FALL, AT 375 mb (approx. 25,000 feet). Average percent turbulence = 5.3.

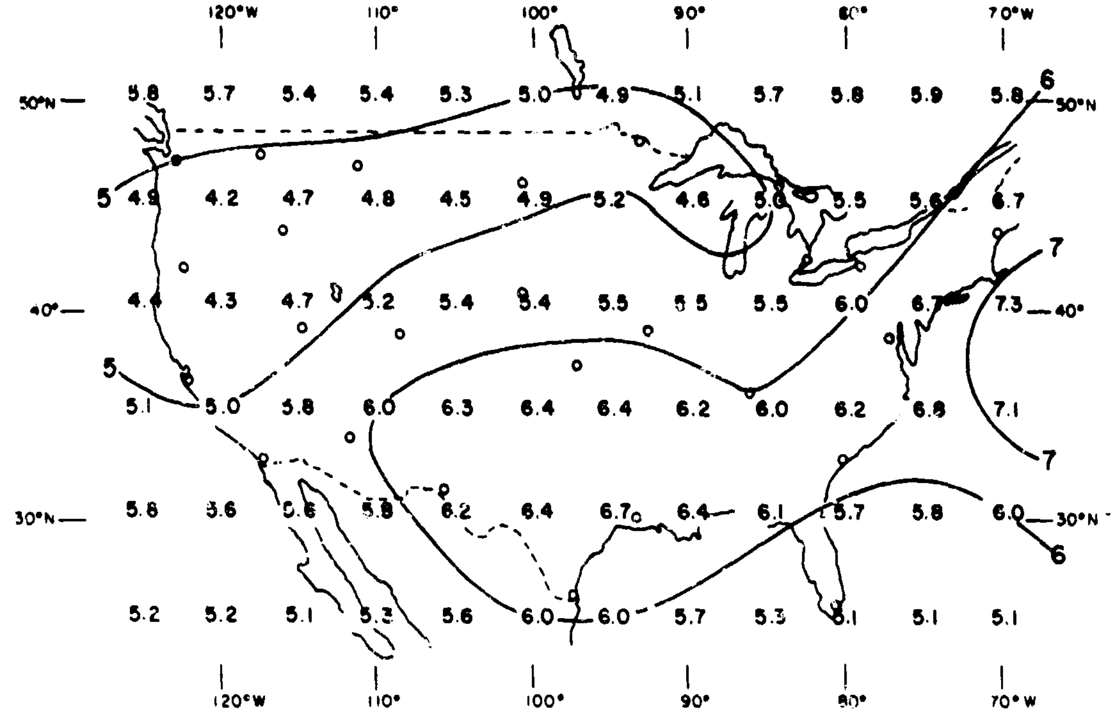


FIG. 8(c) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN FALL, AT 325 mb (approx. 26,000 feet). Average percent turbulence = 5.6.

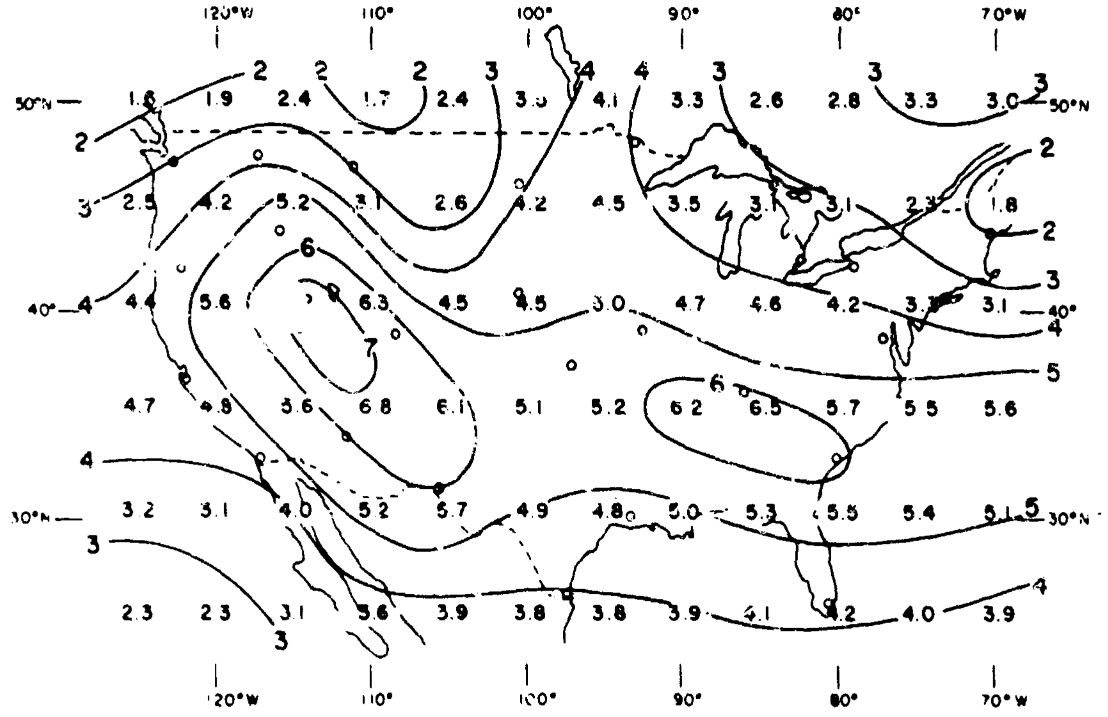


FIG. 8(d) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN FALL, AT 225 mb (approx. 36,000 feet). Average percent turbulence = 4.1.

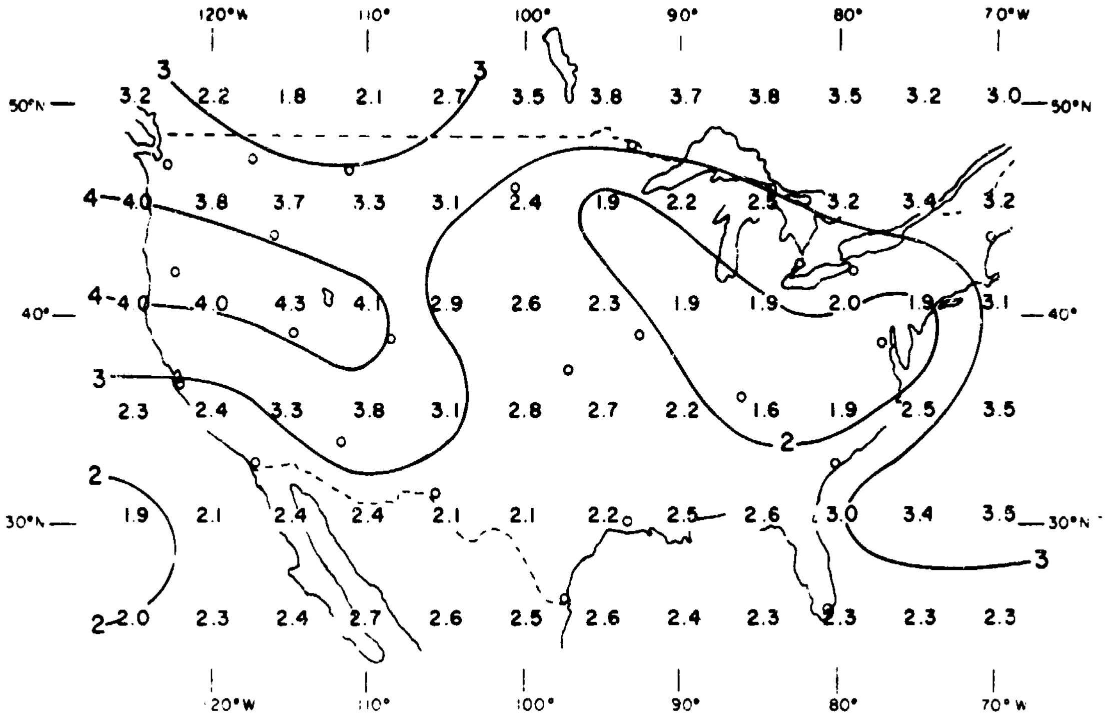


FIG. 8(e) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN FALL, AT 187 mb (approx. 40,000 feet). Average percent turbulence = 2.8.

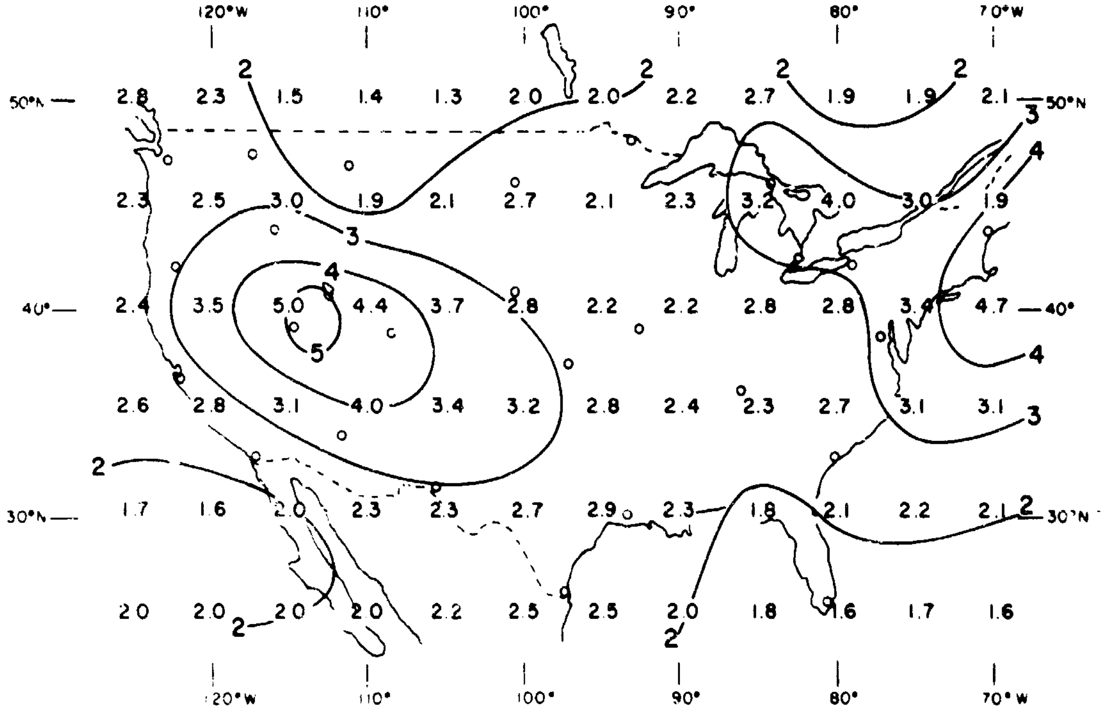


FIG. 8(f) ESTIMATED PROBABILITIES (percent) OF ENCOUNTERING TURBULENCE IN 100-MILE SECTORS OVER THE UNITED STATES IN FALL, AT 162 mb (approx. 43,000 feet). Average percent turbulence = 2.5.

VI DISCUSSION AND RECOMMENDATIONS

At this point we briefly recapitulate our view of efforts to estimate the turbulence climatology of the globe.

Flights by instrumented research aircraft provide very valuable basic knowledge about turbulence as well as statistical information for design purposes, but often cannot answer important questions such as the following:

(1) What is the three-dimensional extent of a turbulent volume?

(2) What are the special conditions in the generating region of the turbulence?

(3) How long does the turbulent area last, and how far does it travel in association with synoptic meteorological features?

(4) If the mesoscale meteorological conditions were slightly different, would the turbulence still have been present?

Lack of answers makes generalization from limited flights quite difficult. Future flight programs should attempt to obtain information concerning these matters insofar as possible.

Pilot reports have been of major importance in describing turbulence frequencies at altitudes below 40,000 feet. Since equivalent information is not available in the stratosphere, knowledge of stratospheric turbulence will tend to remain incomplete until a new generation of aircraft has been built and flown. At that point, design decisions will have already been made. Mistakes in design due to poor knowledge of turbulence may be costly.

Many people have recognized these problems, and have suggested that remote sensors on the ground, in aircraft, or satellites might be able to detect turbulence or associated mesophenomena (for example, see Reiter, 1967). Probably the stratosphere will present special difficulties if viewed from below. Efforts to develop remote sensors are being carried forward, as they should be. However, the fact that approximately 150 weather balloons rise through the atmosphere to the

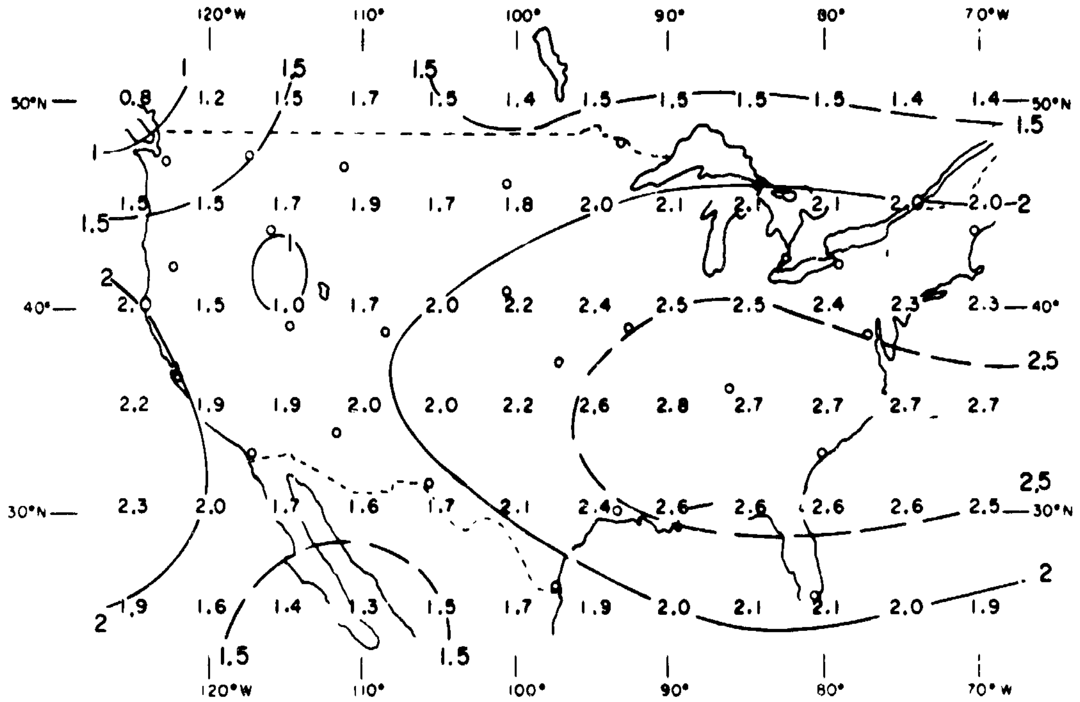
100,000-foot level in the United States every day has been ignored in regard to the possibility of their carrying direct turbulence sensors aloft. The sole exception in the United States is the very interesting work reported by Anderson (1957) using the gustsonde; since that time technology has improved greatly. Certainly on low-level towers, direct measurements of turbulence predominate over indirect sensing, and this might be taken as a partial guide for the stratosphere. Instrumental problems related to balloon-borne sensors are unknown, but might be much simpler to solve than the similarly uncertain problems of remote sensors. Development of a balloon-borne turbulence sensor should be undertaken immediately as a possible means of augmenting other types of data. Also, such a sensor might be useful prior to flights of instrumented aircraft in locating favorable atmospheric layers to be probed for turbulence.

As discussed in Sec. III, special trials are recommended to determine whether the FPS-16 Rose system can detect turbulence in the stratosphere. Of course, this can only be done at those few sites having FPS-16 radars.

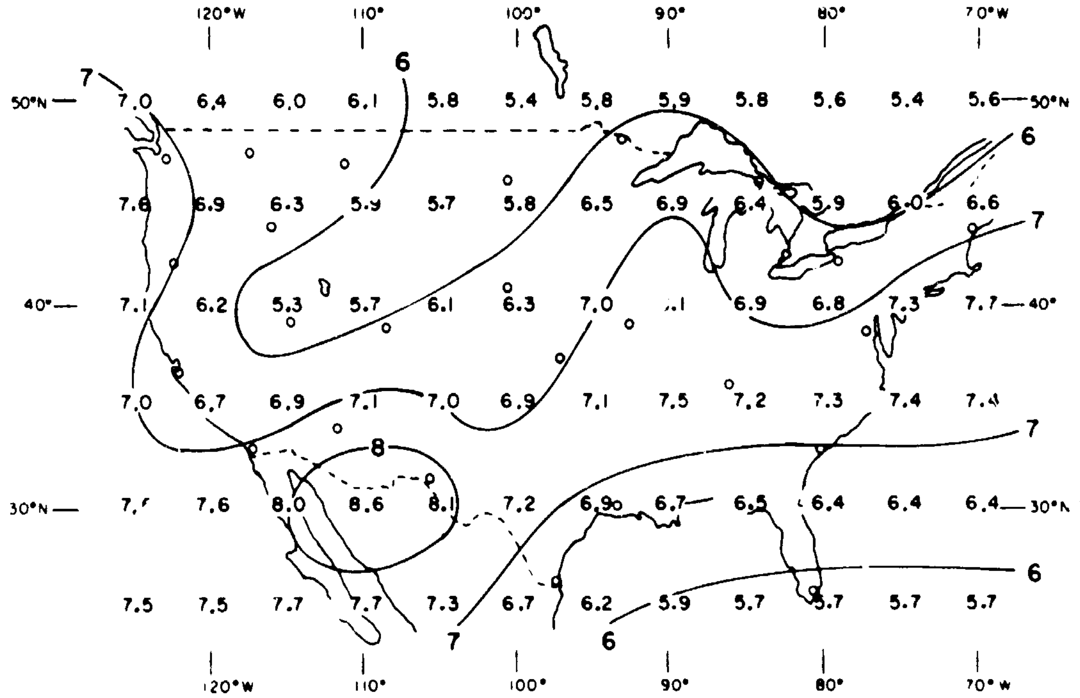
Since the presently available statistics of wind shear over the United States are based on data obtained prior to 1960 that are unrepresentative of jet-stream conditions, it would be desirable to recompute them. This is a fairly large but straightforward task that could be done from recent high-altitude wind measurements made by GMD-1 (or equivalent) equipment. Appreciable differences between the new wind-shear climatology and earlier values would dictate that the estimated turbulence frequencies of Sec. V be redetermined.

APPENDIX

SELECTED CLIMATOLOGICAL DATA FOR THE UNITED STATES

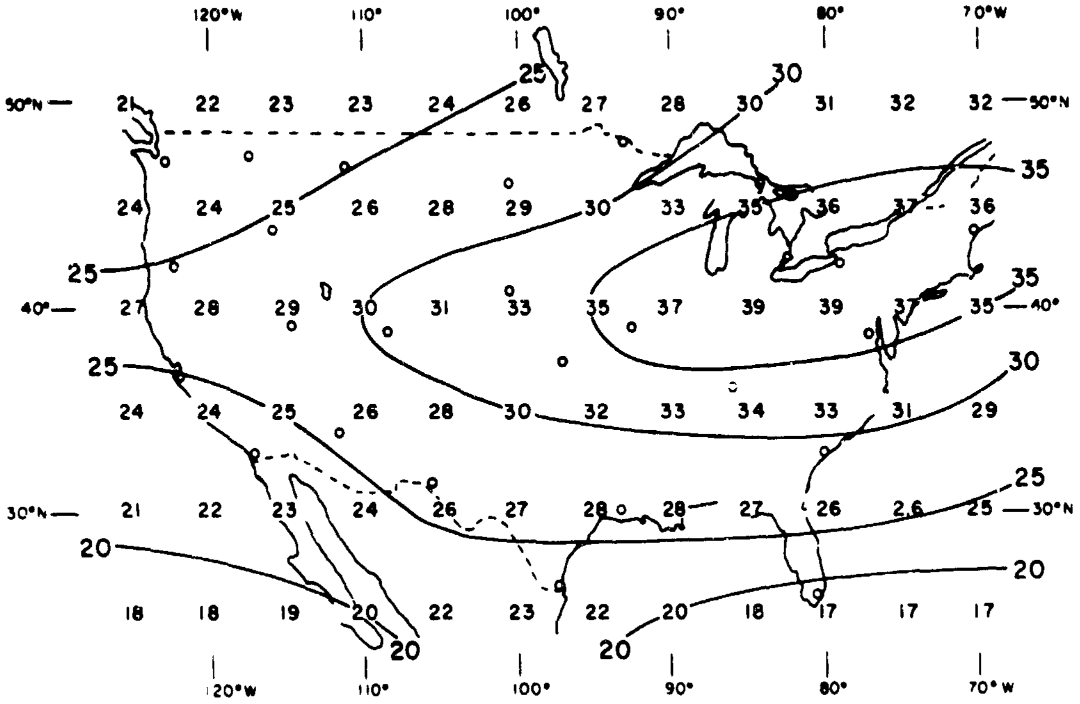


(a) Magnitude of the mean shear vector at 325 mb in winter, units 10^{-3} sec^{-1}

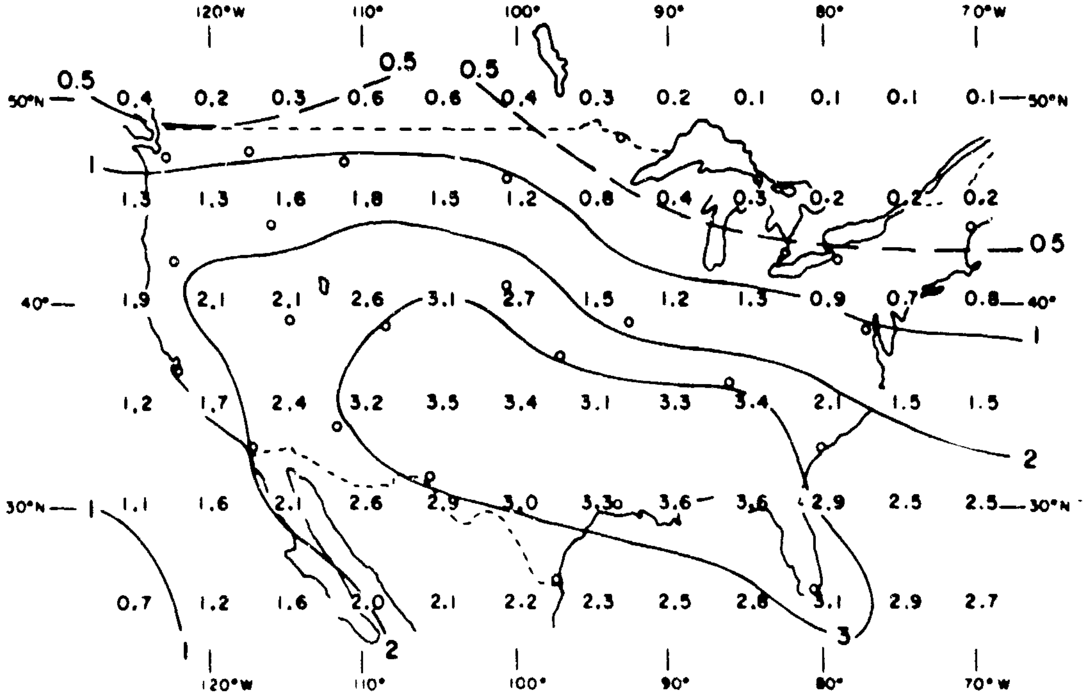


(b) Standard deviation of the shear vector at 325 mb in winter, units 10^{-3} sec^{-1}

FIG. A-1 STATISTICS ON THE VERTICAL WIND SHEAR VECTOR (normalized to a 4000-foot thickness) IN WINTER, BASED ON SCHAMACH'S DATA FOR STATIONS INDICATED BY SMALL CIRCLES, AND WIND SPEEDS FROM U.S. AIR FORCE MANUAL SACM 105-2

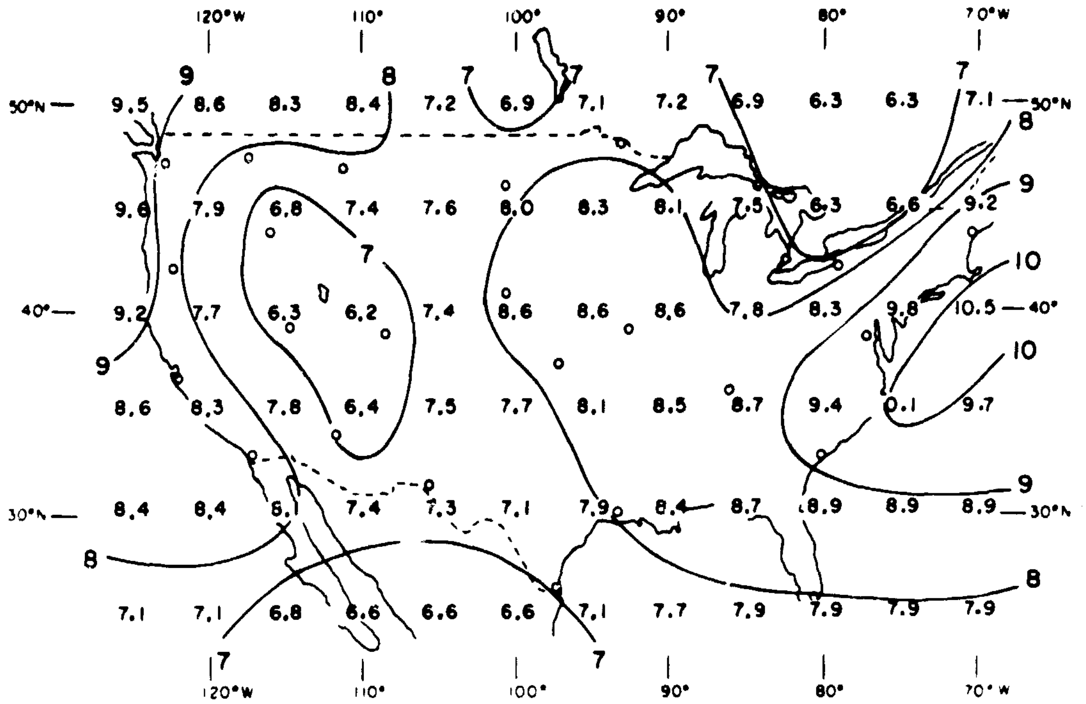


(c) Mean wind speed at 325 mb in winter, units m sec^{-1}

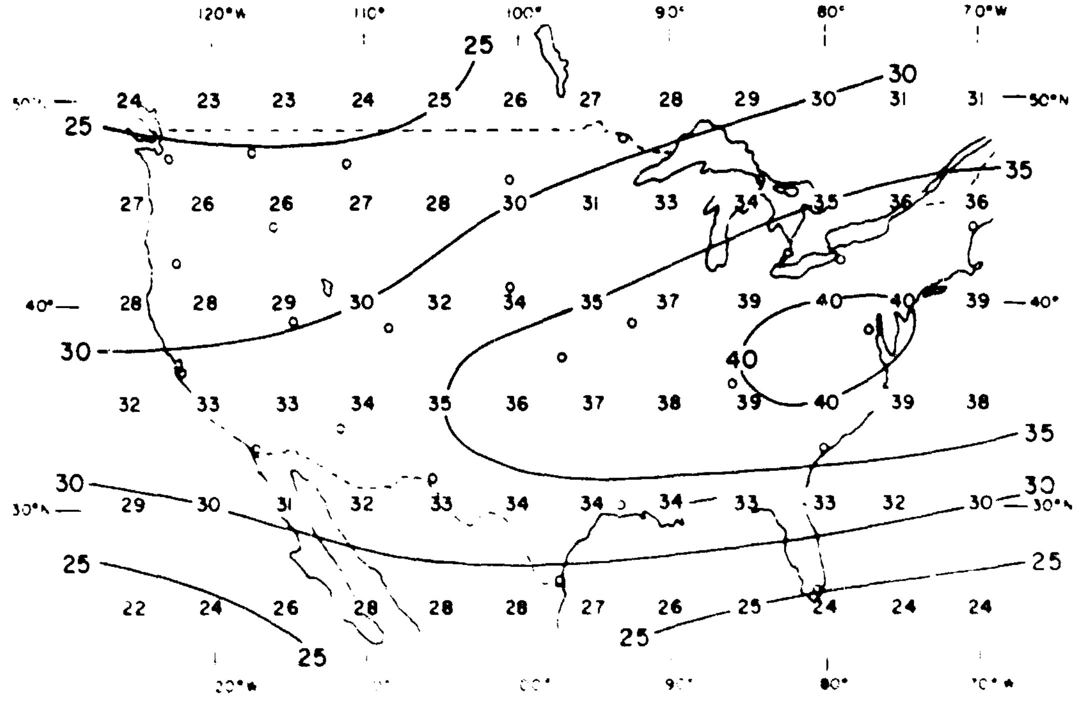


(d) Magnitude of the mean shear vector at 225 mb in winter, units 10^{-3} sec^{-1}

FIG. A-1 (Continued)

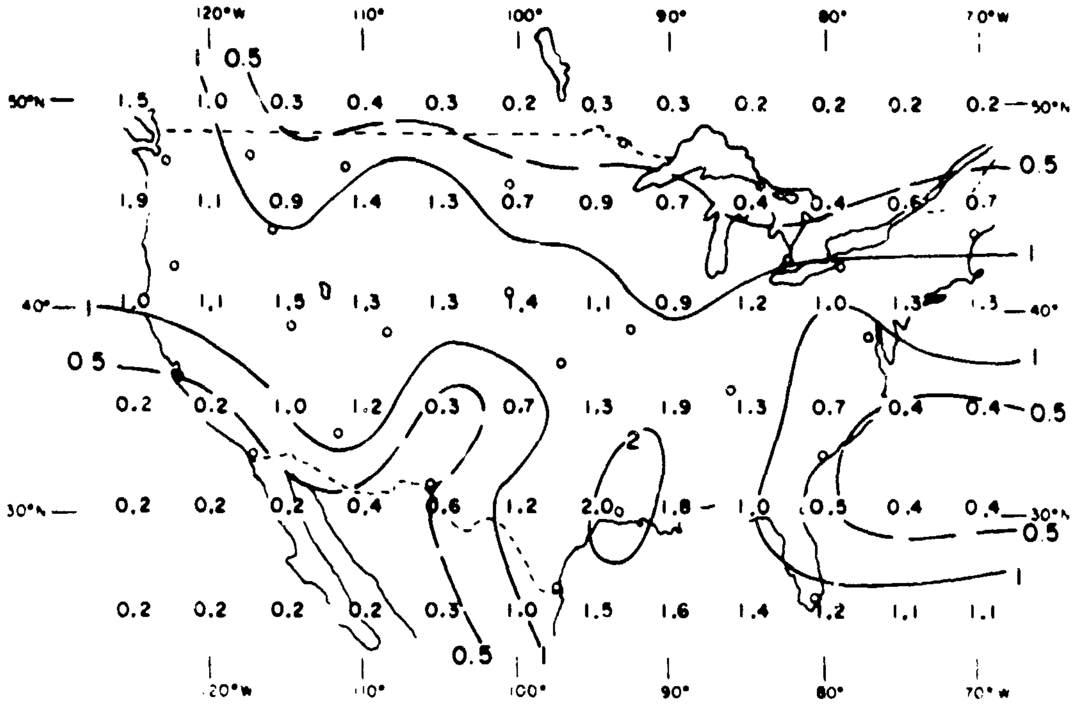


(e) Standard deviation of the shear vector at 225 mb in winter, units 10^{-3} sec^{-1}

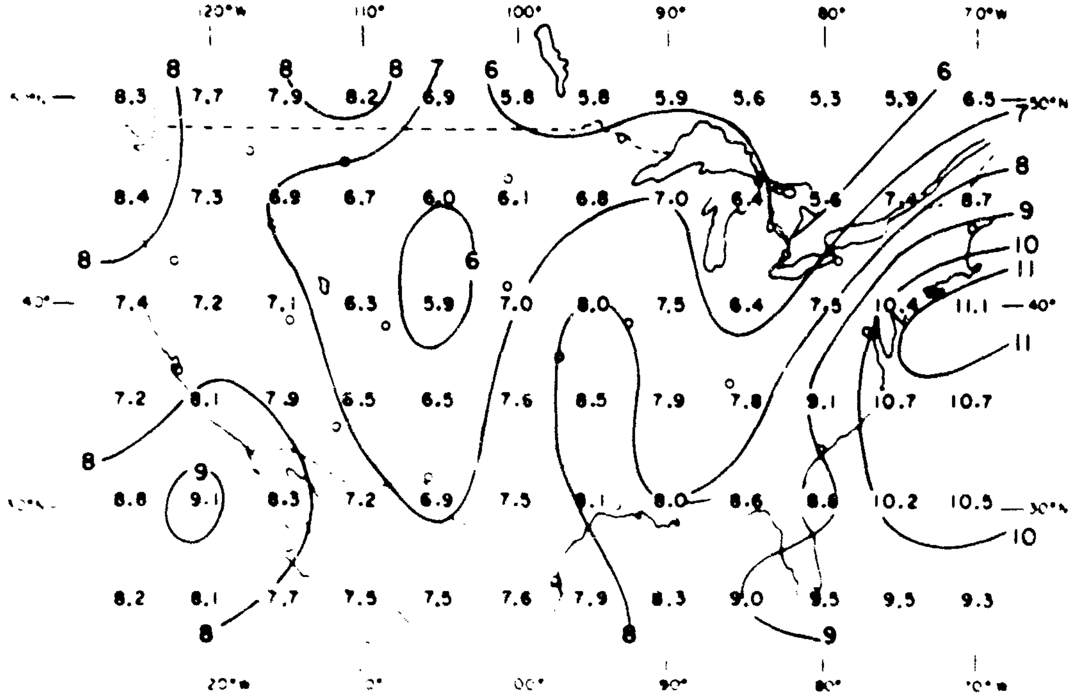


(f) Mean wind speed at 225 mb in winter, units m sec^{-1}

FIG. A-1 (Continued)

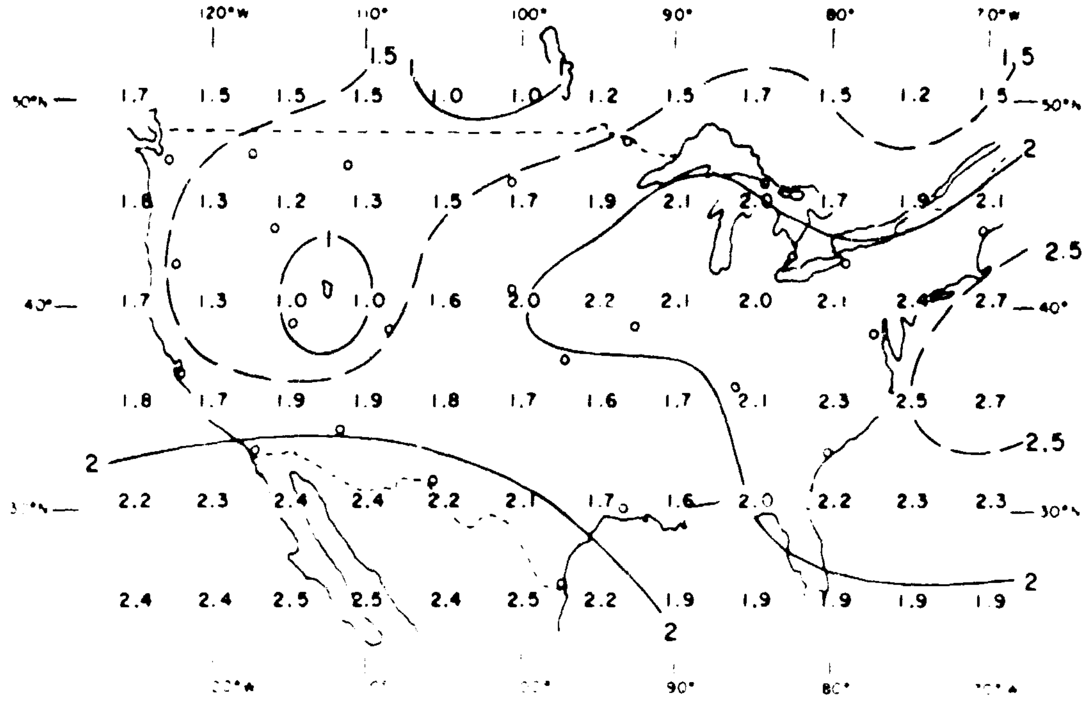


(g) Magnitude of the mean shear vector at 187 mb in winter, units 10^{-3} sec^{-1}

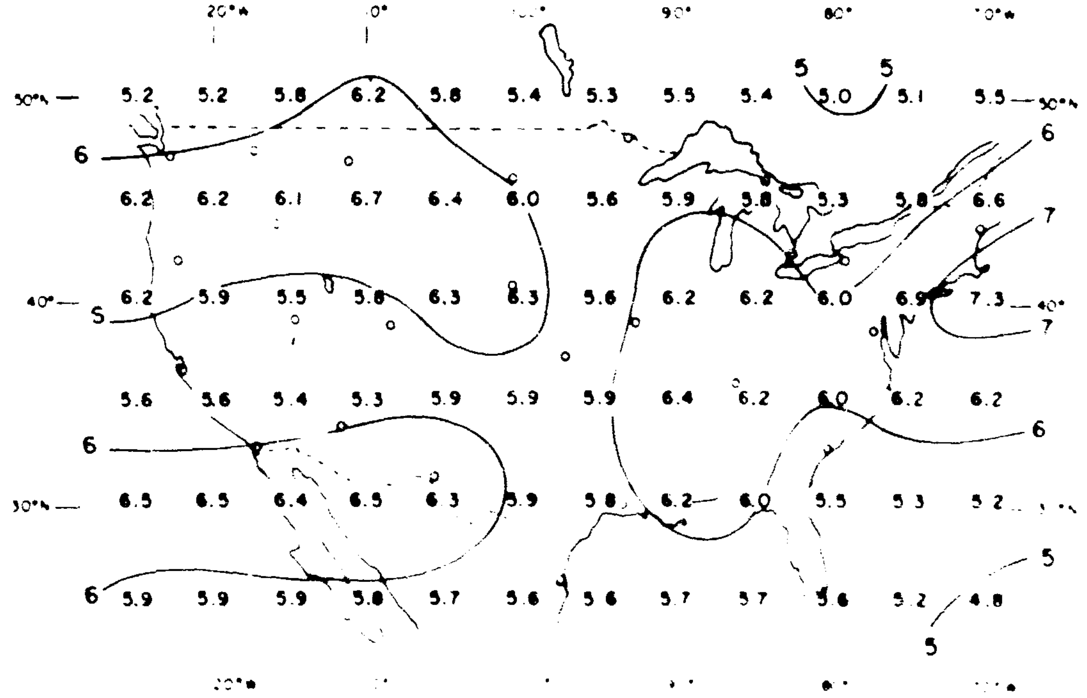


(h) Standard deviation of the shear vector at 187 mb in winter, units 10^{-3} sec^{-1}

FIG. A-1 (Concluded)

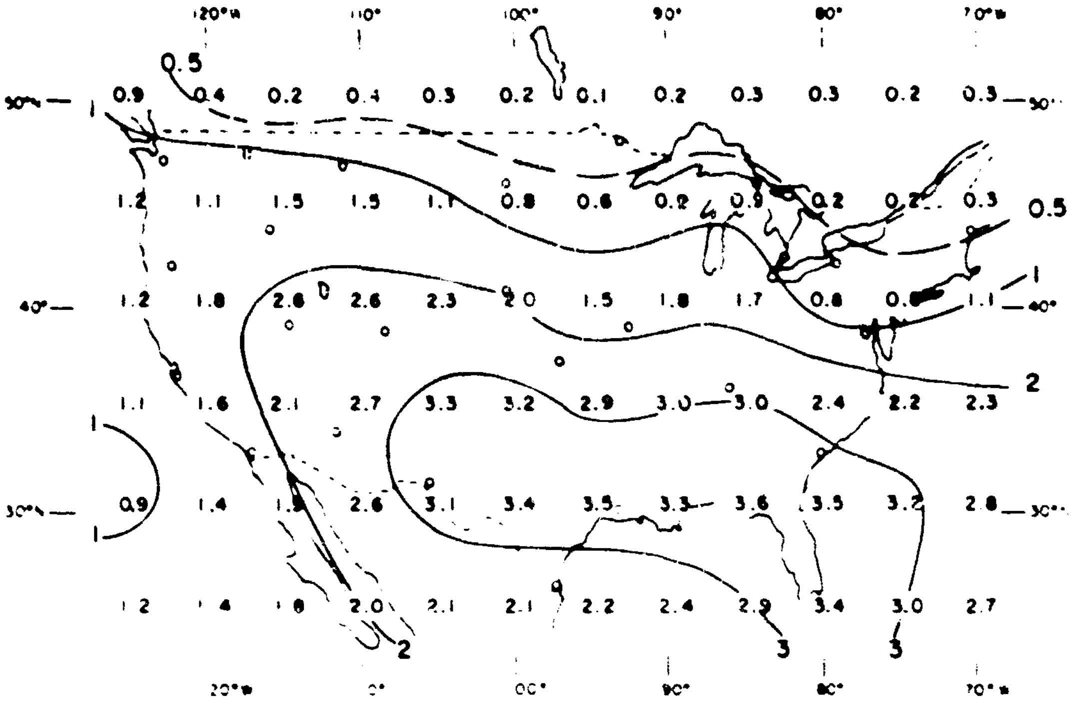


(a) Magnitude of the mean shear vector at 325 mb in spring, units 10^{-3} sec^{-1}

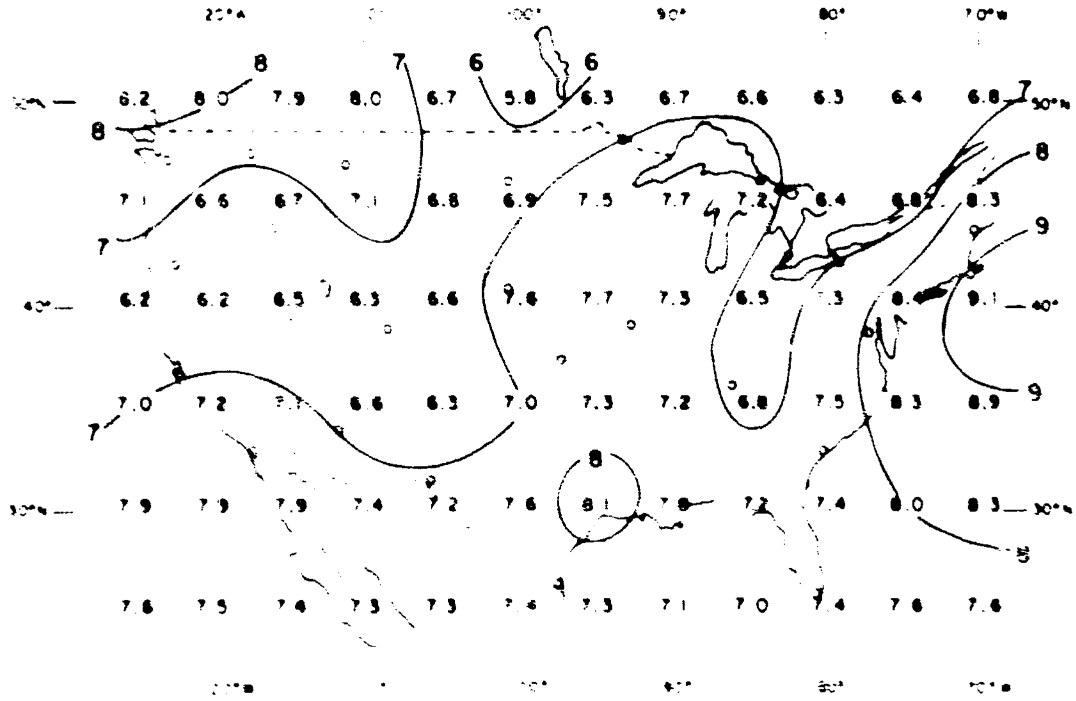


(b) Standard deviation of the shear vector at 325 mb in spring, units 10^{-3} sec^{-1}

FIG A-2 STATISTICS ON THE VERTICAL WIND SHEAR VECTOR (normalized to a 4000-foot thickness) IN SPRING BASED ON SCHAMACH'S DATA FOR STATIONS INDICATED BY SMALL CIRCLES

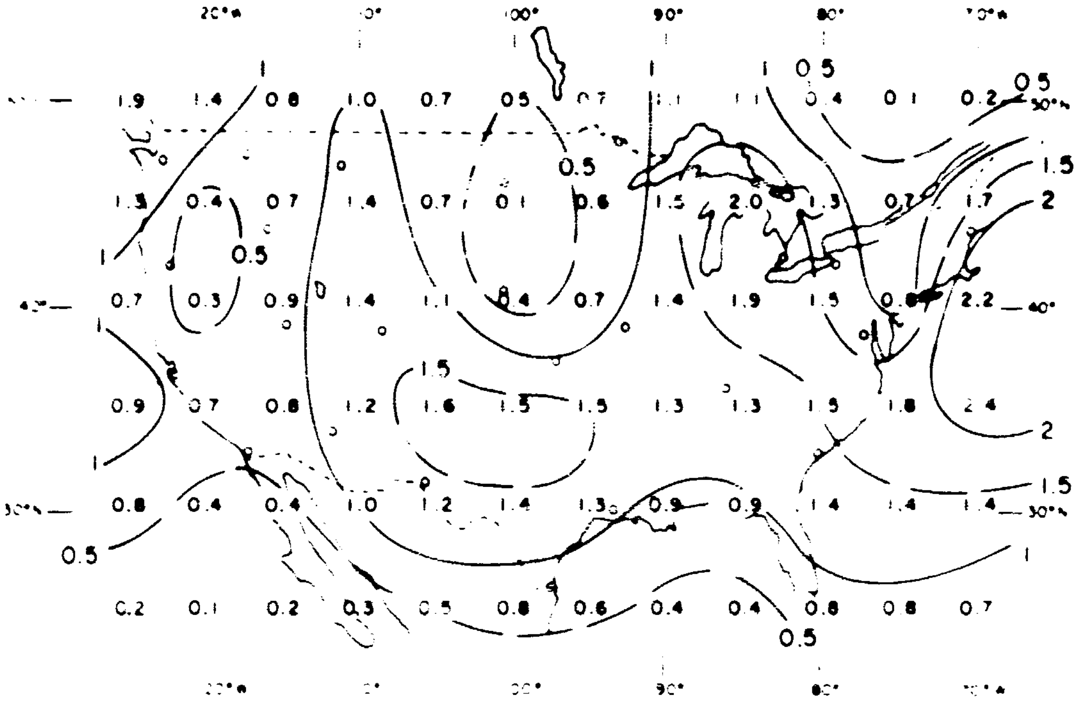


(c) Magnitude of the mean shear vector at 225 mb in spring, units 10^{-3} sec^{-1}

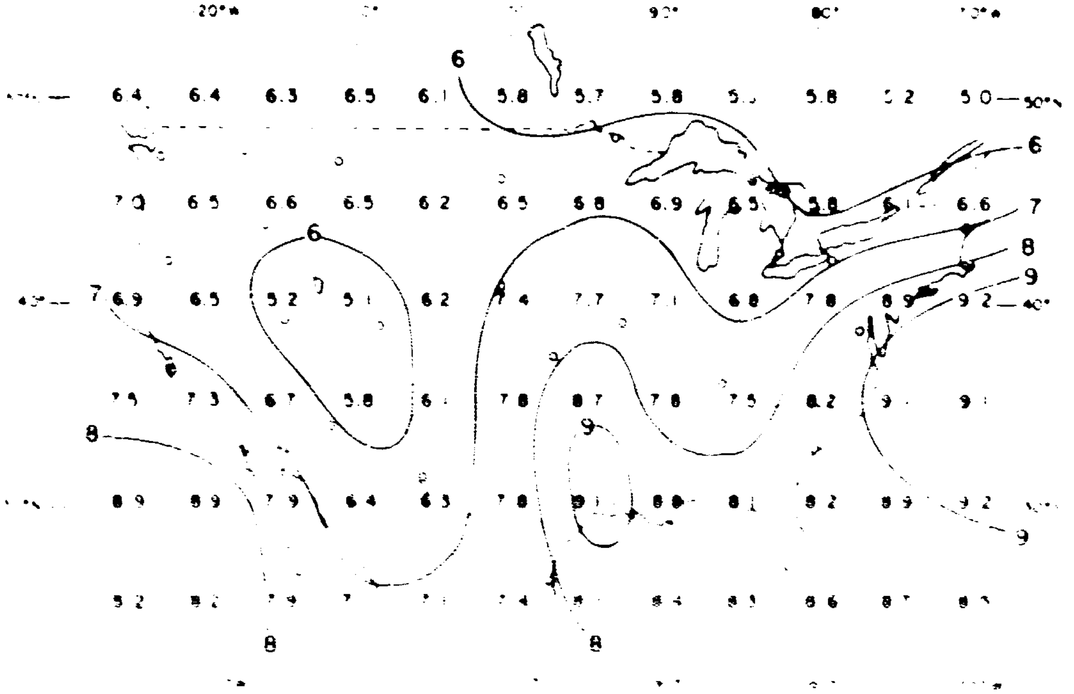


(d) Standard deviation of the shear vector at 225 mb in spring, units 10^{-3} sec^{-1}

FIG. A-2 (Continued)

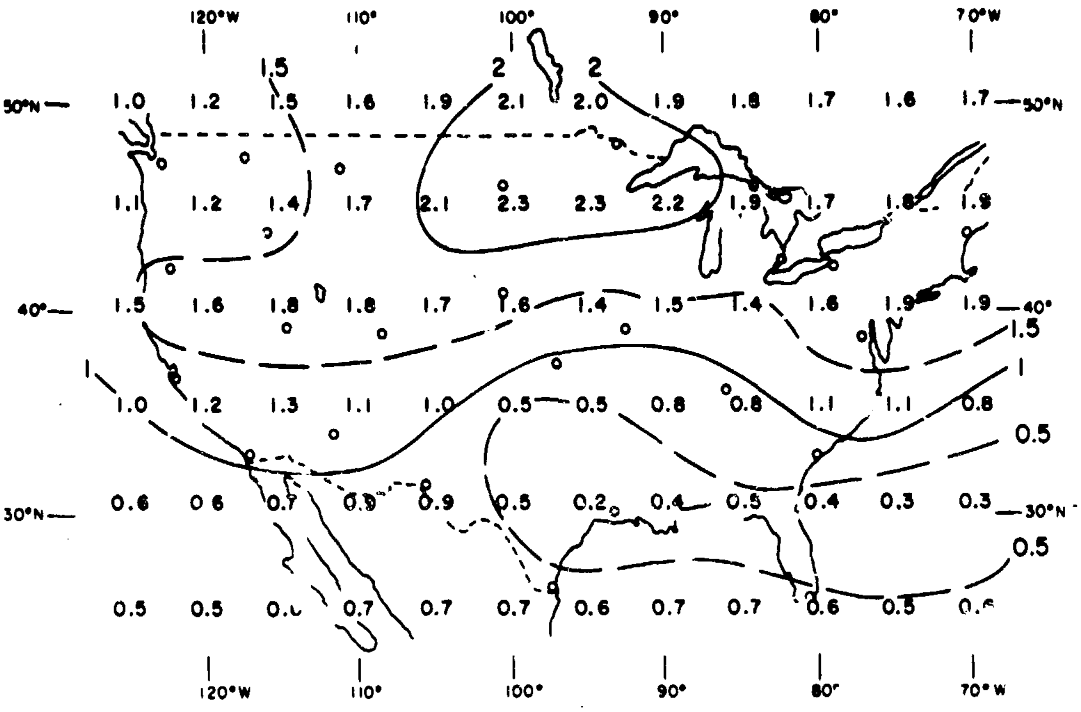


(a) Magnitude of the mean shear vector at 187 mb in spring, units 10^{-3} sec^{-1}

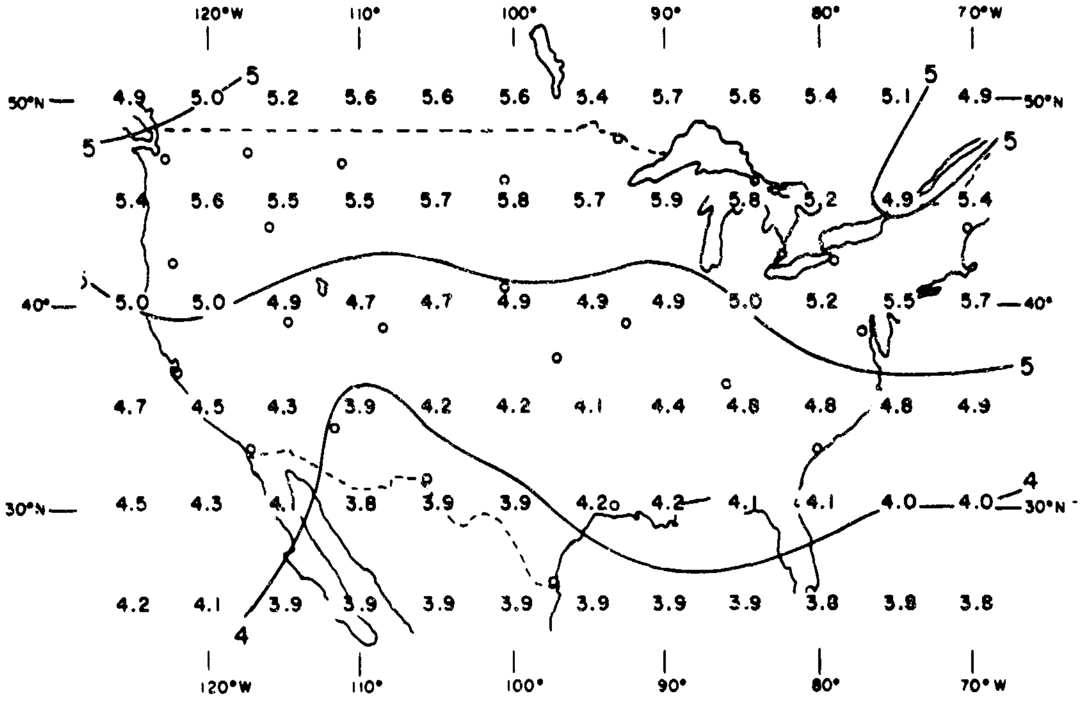


(b) Standard deviation of the shear vector at 187 mb in spring, units 10^{-3} sec^{-1}

FIG. A.2 Concluded

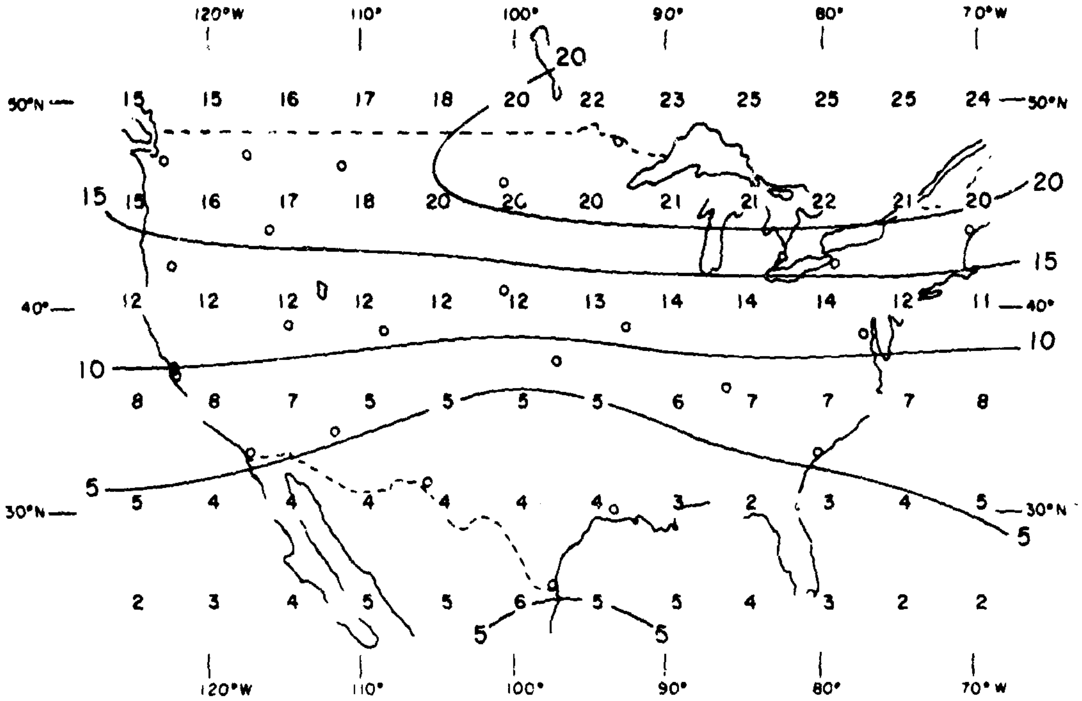


(a) Magnitude of the mean shear vector at 325 mb in summer, units 10^{-3} sec^{-1}

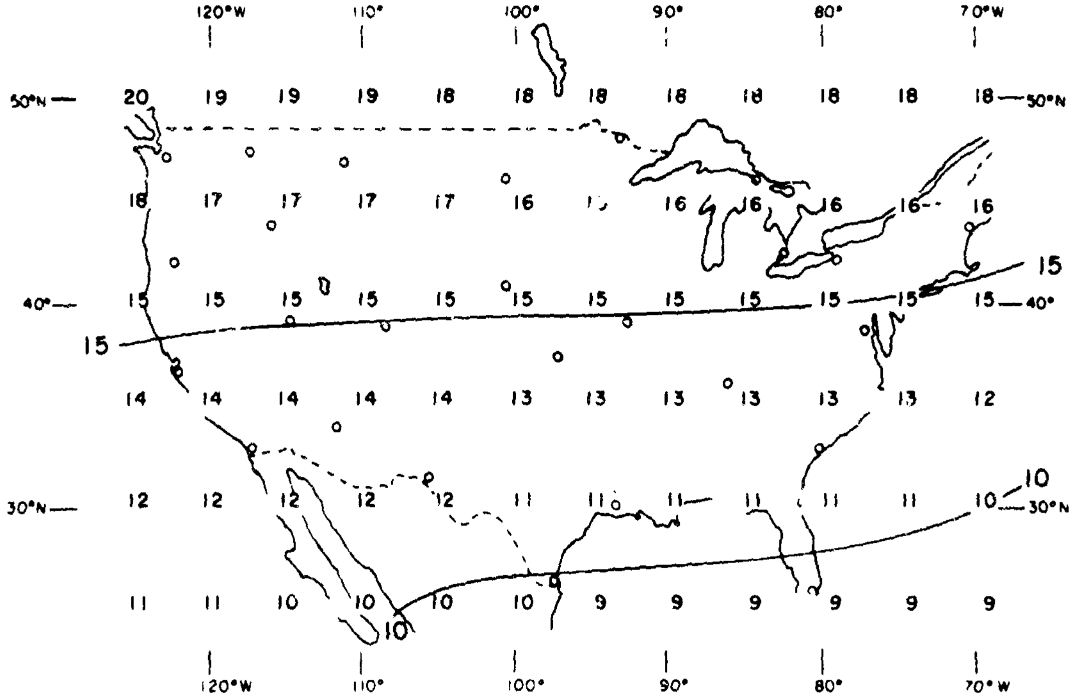


(b) Standard deviation of the shear vector at 325 mb in summer, units 10^{-3} sec^{-1}

FIG. A-3 STATISTICS ON THE VERTICAL WIND SHEAR VECTOR (normalized to a 4000-foot thickness) IN SUMMER, BASED ON SCHAMACH'S DATA FOR STATIONS INDICATED BY SMALL CIRCLES, AND WIND SPEEDS FROM U.S. AIR FORCE MANUAL SACM 105-2

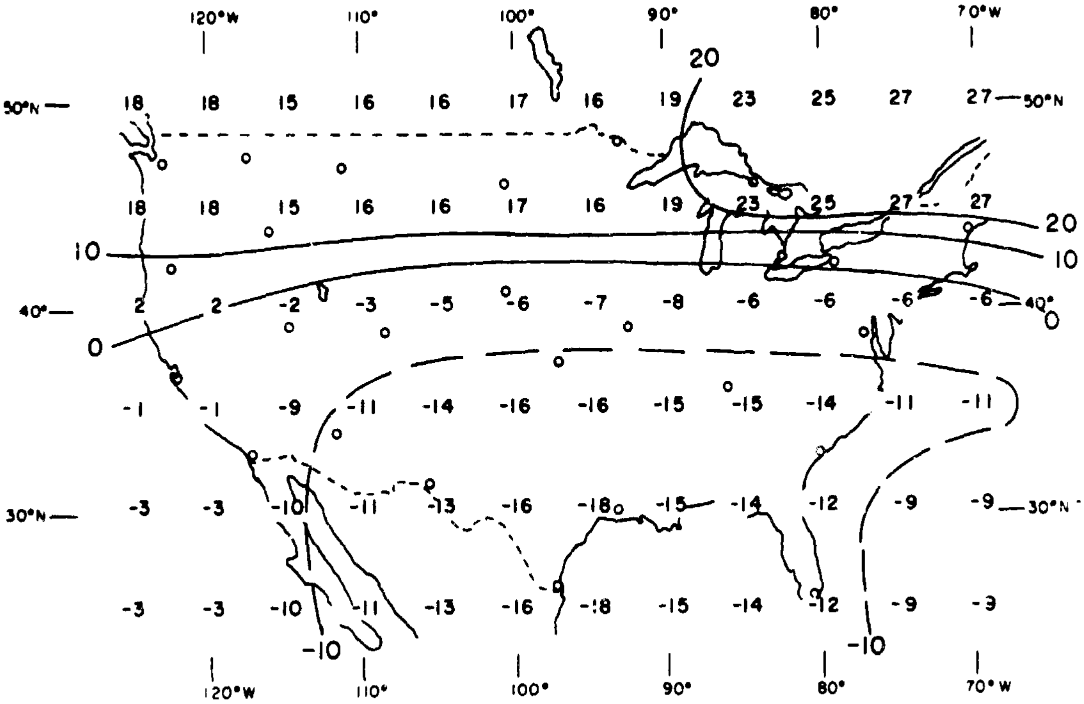


(c) Mean wind speed at 325 mb in summer, units m sec^{-1}

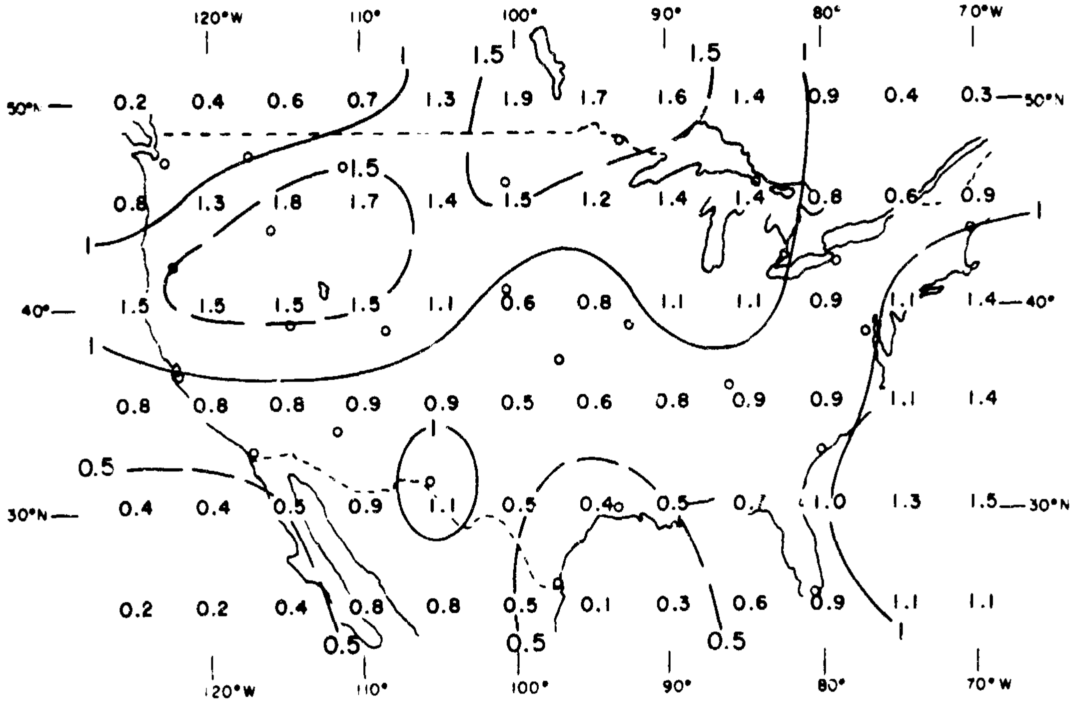


(d) Standard deviation of the wind vector at 325 mb in summer, units m sec^{-1}

FIG. A-3 (Continued)

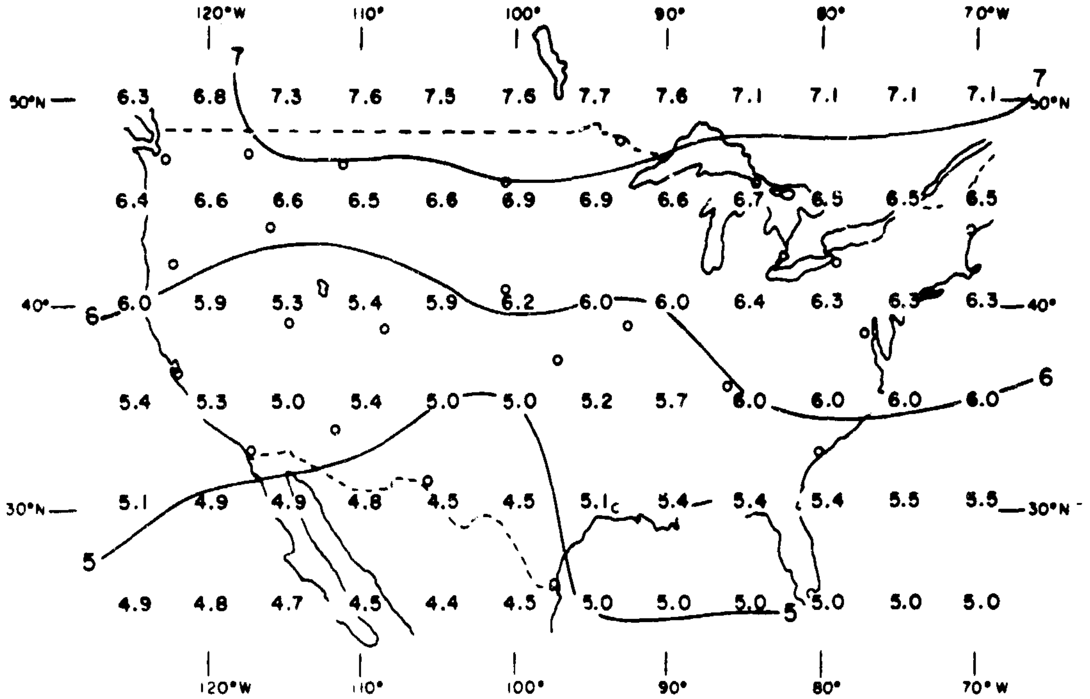


(e) Relative vorticity computed from mean winds at 325 mb in summer, units 10^{-6} sec^{-1}

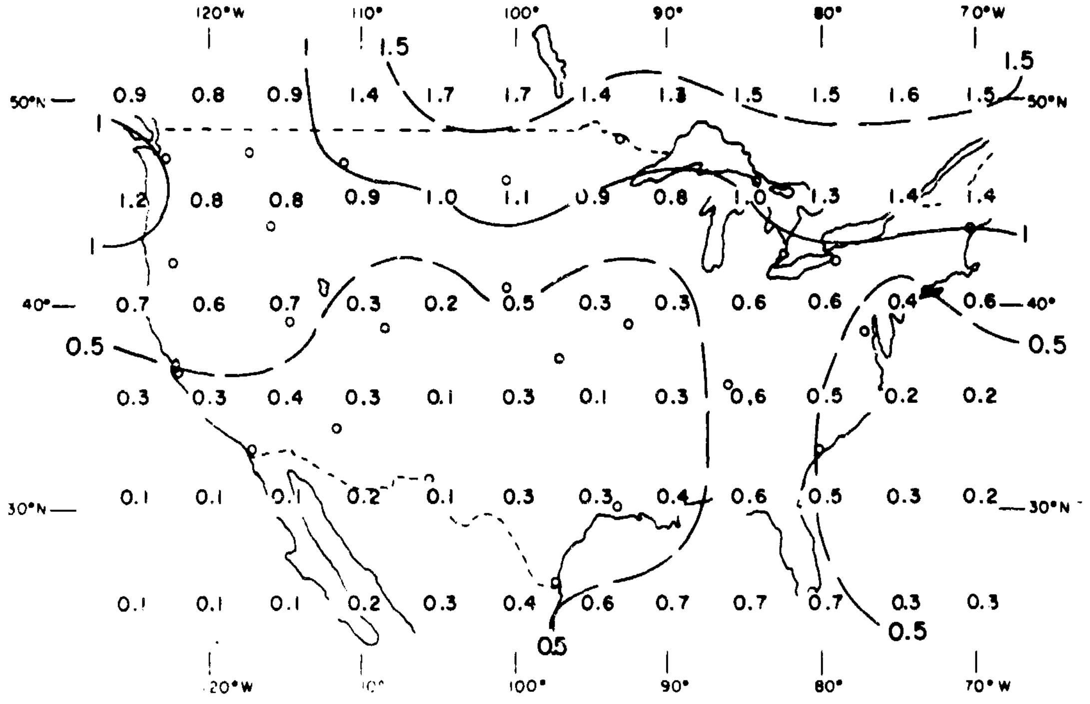


(f) Magnitude of the mean shear vector at 225 mb in summer, units 10^{-3} sec^{-1}

FIG. A-3 (Continued)

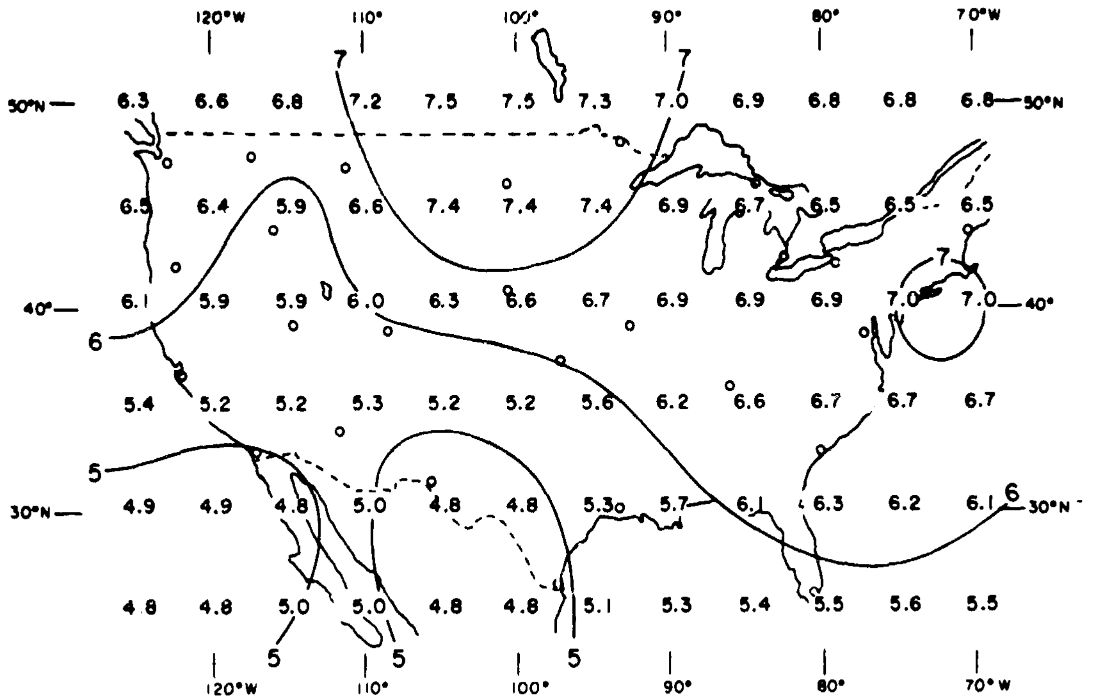


(g) Standard deviation of the shear vector at 225 mb in summer, units 10^{-3} sec^{-1}



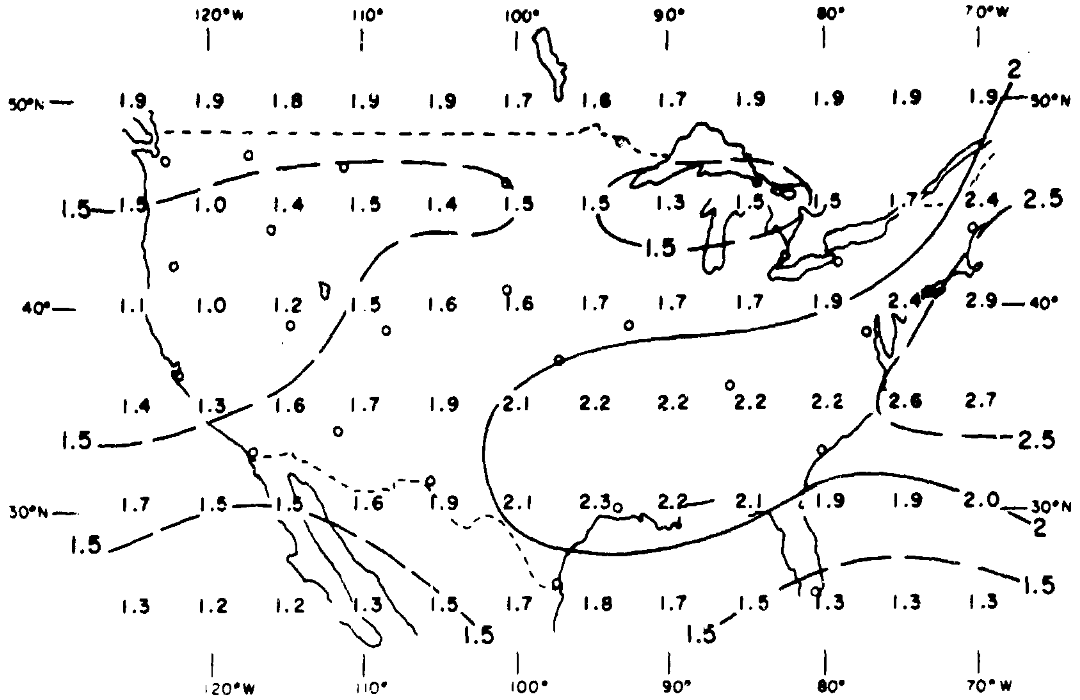
(h) Magnitude of the mean shear vector at 187 mb in summer, units 10^{-3} sec^{-1}

FIG. A-3 (Continued)

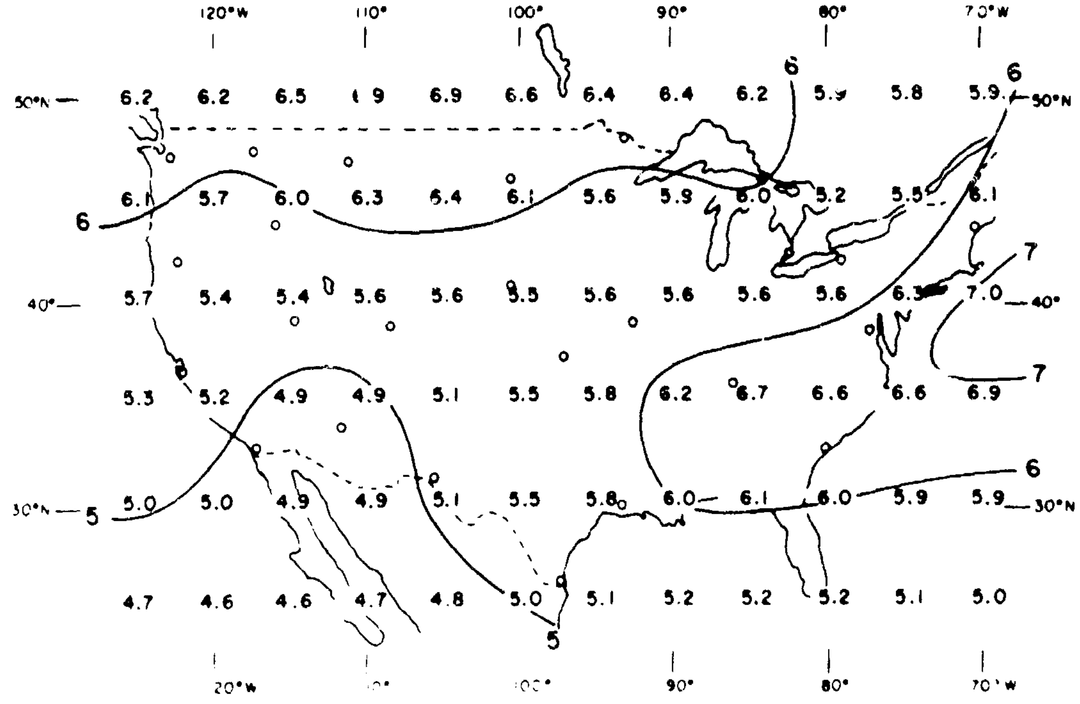


(i) Standard deviation of the shear vector at 187 mb in summer, units 10^{-3} sec^{-1}.

FIG. A-3 (Concluded)

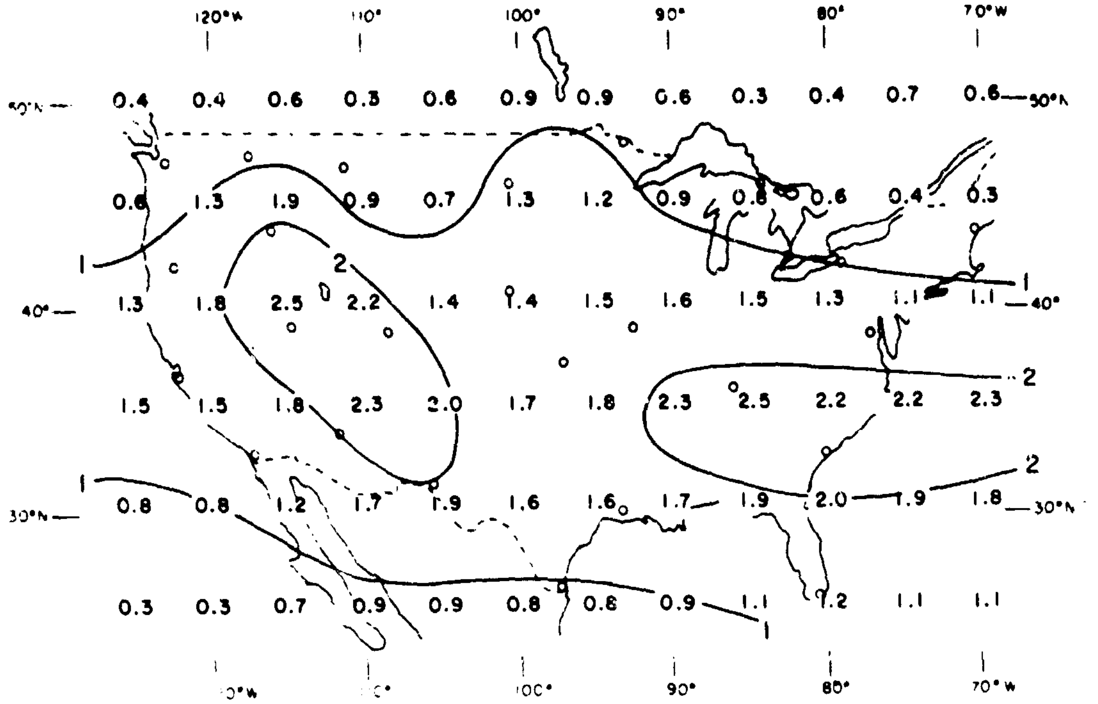


(a) Magnitude of the mean shear vector at 325 mb in fall, units 10^{-3} sec^{-1}

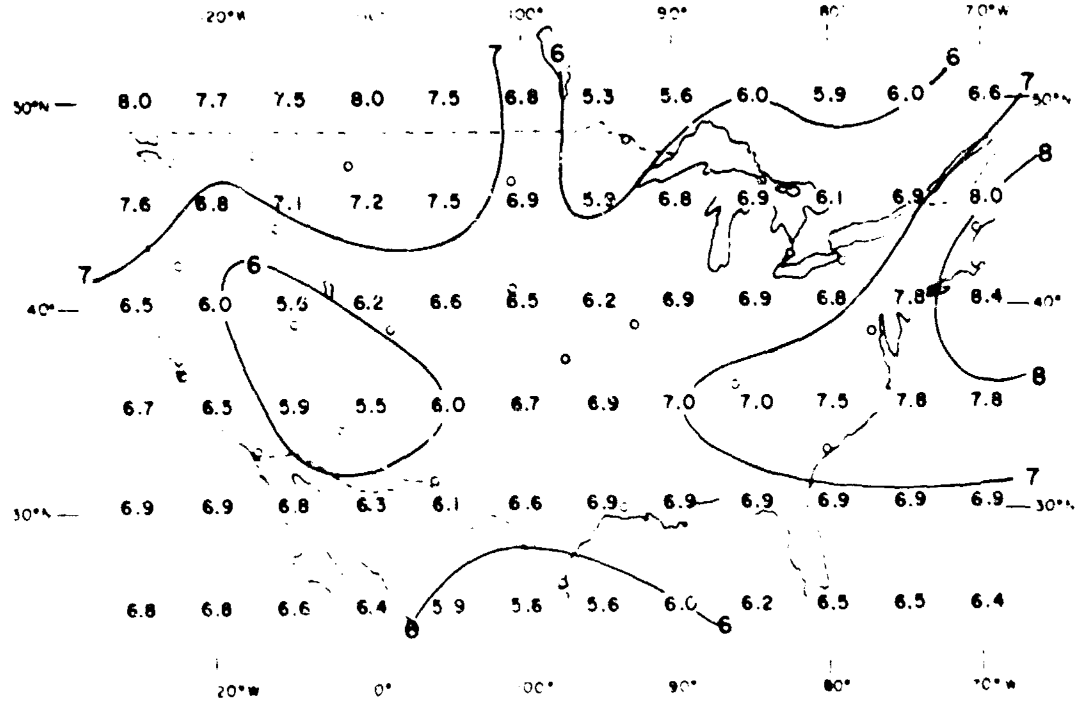


(b) Standard deviation of the shear vector at 325 mb in fall, units 10^{-3} sec^{-1}.

FIG. A-4 STATISTICS ON THE VERTICAL WIND SHEAR VECTOR (normalized to a 4000-foot thickness) IN FALL, BASED ON SCHAMACH'S DATA FOR STATIONS INDICATED BY SMALL CIRCLES

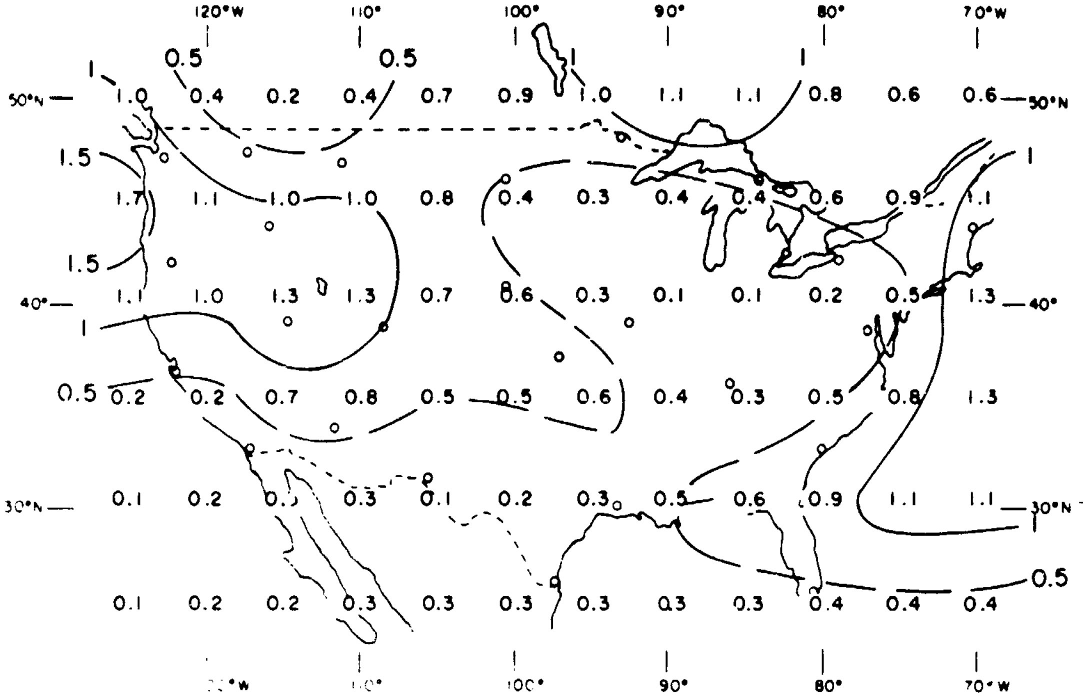


(c) Magnitude of the mean shear vector at 225 mb in fall, units 10^{-3} sec^{-1}.

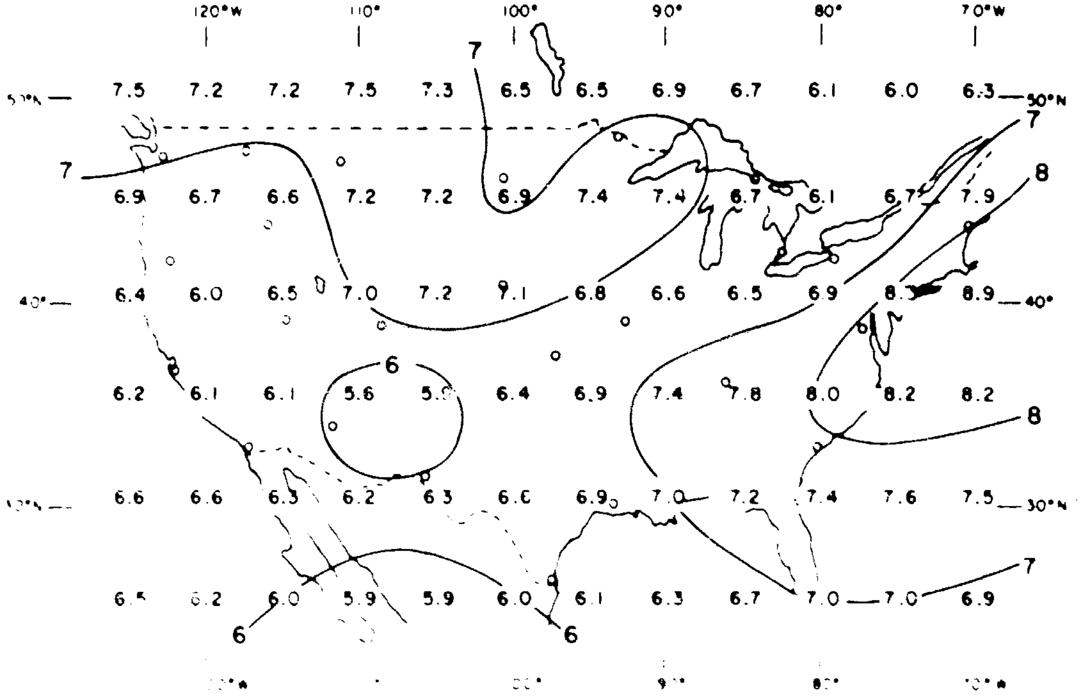


(d) Standard deviation of the shear vector at 225 mb in fall, units 10^{-3} sec^{-1}.

FIG. A-4 (Continued)



(e) Magnitude of the mean shear vector at 187 mb in fall, units 10^{-3} $\sec^{-1}$.



(f) Standard deviation of the shear vector at 187 mb in fall, units 10^{-3} $\sec^{-1}$.

FIG. A-4 (Concluded)

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13. ABSTRACT

The climatology of clear-air turbulence is defined herein as the likelihood that an aircraft or missile will encounter turbulent air at a given locality, altitude, and time of year. Turbulence data of three types were used in this study; these include observations by instrumented research aircraft, balloon tracks measured by FPS-16 radar, and turbulence reports made by pilots. The measurements that have been made by research aircraft show good relationships between turbulence and certain aspects of mesoscale atmospheric structure, but the data are too limited in number to permit broad generalizations. The FPS-16 tracks of rising Jimsphere and Rose balloons were obtained during studies of detailed wind profiles. We investigated their potential value in identifying turbulent layers. In general, the existing data are too noisy to serve this purpose; however, further special trials are recommended. The subjective turbulence reports from pilots collected during special five-day reporting periods comprise by far the largest volume of data available. Meteorological conditions for these periods were analyzed by computer from standard rawinsonde data and were correlated with the turbulence reports. The correlations show that the vertical vector wind shear corresponds most closely to turbulence frequency determined from the pilot reports. Little additional reduction of variance in the turbulence frequencies is achieved by including other meteorological factors. Optimum multiple regression equations between turbulence frequency and the mean and standard deviation of the vertical vector wind shear were obtained. In summer a different regression equation was found than in other seasons.

These turbulence observations taken in toto are too few to permit a direct computation of turbulence frequency; therefore an indirect method was used to obtain the turbulence climatology. This involved applying the regression equations to existing statistics of wind shear over the United States. These wind-shear compilations, prepared almost ten years ago, appear to be of questionable reliability in the upper troposphere and stratosphere due to a large proportion of missing wind observations under conditions of high wind speeds aloft. Due to uncertainties in the regression equations and shear statistics, the deduced turbulence climatology (given by seasons for levels between approximately 20,000 and 45,000 feet) must be considered a first estimate.

Recommendations are made that an up-to-date wind-shear climatology be computed for the United States, and that consideration be given to developing a balloon-borne turbulence sensor to augment data from research aircraft and airline pilots.

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Wind shear						
Jet stream						
Mountain waves						
Pilot reports						
Turbulent gusts						
Rose balloons						
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