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Characterization of Winds Potentially Hazardous to Aircraft

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A long series of discrete vertical and horizontal wind observations from a 444-m meteorological tower in central Oklahoma have been analyzed. The characteristics of the three components of the wind in the tower layer have been determined for atmospheric scales at which potential degradation of aircraft flight quality is known to be high. Through inspection of frequency distributions and wind spectra, there is ample evidence that, in general, temporally long or spatially extensive vertical motions are virtually nonexistent. In thunderstorms and behind cold fronts much more kinetic energy is present in the horizontal wind field at scales near representative aircraft phugoid frequencies.

Nomenclature

c = wave phase speed $=\bar{u}$
f = frequency (cycles/s)
G_s = aircraft ground speed
P_a = Wave period with respect to aircraft
P_g = wave period with respect to ground $=1/f$
$S(f)$ = variance density
$\bar{u}$ = mean horizontal wind
u = aircraft headwind component
v = aircraft crosswind component
w = vertical wind component
z = height above ground
Δt = sample rate
Δx = eddy half-wavelength (of the vertical wind component)

Introduction

THE Earth's atmosphere is a fluid through which all aircraft fly and upon which all aircraft depend for flight sustaining aerodynamic lift. It is also a fluid medium which, if reacting rapidly to atmospheric forces, may cause the demise of the aircraft.

The atmosphere is constantly in motion, both horizontally with respect to the Earth's surface, and vertically. This motion is also constantly changing, both in the spatial and the temporal reference frames. Wind fluctuations have widely varying amplitudes and frequencies. The frequencies that are considered most important to pilots are those in a range from typical turbulence frequencies to those that are near the aircraft phugoid or natural frequency ($\sim 0.025\ s^{-1}$). Wind oscillations that have very short frequencies relative to a horizontally moving platform do not result in full aircraft response when penetrated. Very long waves result in such a slow change relative to this vehicle, the pilot can easily maintain full control while navigating them.

A great deal is known about the character of horizontal motions, their component magnitude, and long-wave oscillations. Many measurements have been made and new measurements are made daily world-wide. Of the vertical wind component and short-wave horizontal wind component oscillations much less is known. No routine measurements are made and relatively small quantities of data exist from measurements made in a nonroutine fashion.

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Historically, the pilot has paid much more attention to the sustained (or mean) horizontal wind behavior than the vertical wind or the wind vector fluctuations (except for speed gusts). The mean horizontal wind magnitude, mean wind direction and gusts are important in takeoff and landing operations and in-flight. But the lack of attention to the vertical wind component and the vector fluctuations to which aircraft respond has not been due to the lack of interest as much as the unavailability of information.

Community-wide interest has changed, however, following a series of aircraft accidents, most notable an accident at New York's JFK Airport in June 1975. Following this disaster and the National Transportation Safety Board investigation,[1] a number of scientific papers were published[2-4] in which flight and ground-based data collected on that day were analyzed to reconstruct the meteorological scenario. Several pertinent but more general studies have also been recently published.[5-11] Terms long used by meteorologists, and some new terms, have now become part of the vocabulary of those in the aviation community: wind shear, downdraft, downburst, microburst, and gust front. Now that pilots are becoming more aware of the character of the three-dimensional wind, they are demanding more information about updrafts and downdrafts and about changes in the wind vector, both of which may be flight hazards.[12]

In this paper, low-level (surface to 444 m) horizontal and vertical wind characteristics will be analyzed in terms of meteorological scales believed important to pilots. A general study of the vertical wind component will be emphasized since so little is known of its behavior. This will be accomplished by computing frequency distributions and deriving general characteristics from them. In addition, meteorological phenomena that produce significant wind perturbations will be identified. Several examples of these events will be investigated in detail using high-resolution vertical cross sections and spectral analyses. In this manner, one can compare the behavior of both the horizontal and vertical motion fields simultaneously when the lower atmosphere is severely perturbed.

Data

Data for this study have been obtained from a 444-m tower in central Oklahoma, instrumented at six levels with various meteorological sensors. Measurements of the wind's vertical component are obtained from R.M. Young model 1200 anemometers oriented vertically. The sensor impellor is lightweight polyethelene, which helps make the sensor respond rapidly to vertical wind changes. Horizontal wind speed and direction are measured using Bendix model 120 sensors. These sensors have somewhat slower response than the vertical speed sensors.

Table 1 Vertical speed distribution at 26-m tower level, sample size 3,963,462

Vertical speed, ms^{-1}	Perturbation half-wavelength, m 1-100	101-200	201-300	301-400	401-600	601-800	801-1000	1001-1200
≤ −10.1								
−9.1 to −10								
−8.1 to −9								
−7.1 to −8								
−6.1 to −7								
−5.1 to −6								
−4.1 to −5	1							
−3.1 to −4	12	1						
−2.1 to −3	176	51	5					
−1.1 to −2	5,241	1,797	237	50	11			
1.1 to 2	31,581	12,444	2,811	857	333	65	13	7
2.1 to 3	1,819	632	64	24	5			
3.1 to 4	106	27						
4.1 to 5	7	2						
5.1 to 6								
6.1 to 7								
7.1 to 8								
8.1 to 9								
9.1 to 10								
≥10.1								

Table 2 Vertical speed distribution at 177-m tower level, sample size 3,781,594

Vertical speed, ms^{-1}	Perturbation half-wavelength, m 1-100	101-200	201-300	301-400	401-600	601-800	801-1000	1001-1200
≤ −10.1								
−9.1 to −10	1							
−8.1 to −9	1							
−7.1 to −8	9							
−6.1 to −7	14	1						
−5.1 to −6	25	2						
−4.1 to −5	50	9	2					
−3.1 to −4	143	24	6	3				
−2.1 to −3	1,852	435	82	18	8			
−1.1 to −2	28,948	10,617	3,012	1,121	489	95	37	18
1.1 to 2	40,797	17,378	6,319	3,054	1,621	563	235	101
2.1 to 3	7,710	2,473	717	291	110	25	9	2
3.1 to 4	1,089	280	66	22	6			
4.1 to 5	135	35	7	4				
5.1 to 6	24	4	1					
6.1 to 7	7	1						
7.1 to 8	6							
8.1 to 9	5							
9.1 to 10	4							
≥10.1								

Table 3 Vertical speed distribution at 444-m tower level, sample size 3,961,960

Vertical speed, ms^{-1}	Perturbation half-wavelength, m 1-100	101-200	201-300	301-400	401-600	601-800	801-1000	1001-1200
≤ −10.1	2							
−9.1 to −10	3							
−8.1 to −9	6	1						
−7.1 to −8	18	1	1					
−6.1 to −7	25	3	1					
−5.1 to −6	47	11	4					
−4.1 to −5	95	24	12	5	2			
−3.1 to −4	259	50	19	12	5	3	1	
−2.1 to −3	1,593	459	133	56	33	10	4	
−1.1 to −2	17,763	7,405	2,777	1,261	672	208	76	30
1.1 to 2	82,083	48,072	25,962	16,063	10,641	5,505	3,118	1,925
2.1 to 3	15,857	7,020	3,146	1,734	1,095	523	290	178
3.1 to 4	4,152	1,466	566	251	125	57	24	8
4.1 to 5	939	315	89	42	17	4	1	1
5.1 to 6	192	52	14	5	1			
6.1 to 7	58	10	2					
7.1 to 8	24	1	1					
8.1 to 9	13	1						
9.1 to 10	5							
≥10.1								

General Character of the Vertical Wind

Analysis Method

To describe the general character of the atmosphere's low-level vertical wind component, vertical speed data from the six tower sensor levels were arranged into trivariate frequency distributions: the three distribution variates being height z, vertical speed w, and eddy half-wavelength Δx. The whole 14-month time series was used to construct the distributions.

In the analysis, horizontal wind speed data were averaged over the depth of the tower layer, then in 1-min blocks. Thus every minute there is calculated a new 1-min average tower layer horizontal speed $\bar{u}$. This value is considereda representative atmospheric perturbation phase speed used to make a transformation from time to space. The spatial frame of reference is desired in the analysis results so that in situ data can be inspected from the aviator's perspective.

Letting Δt be the sample interval and Δx be a perturbation half-wavelength, the expression $\Delta x = \bar{u}\Delta t$ relates time and space. The hypothesis that a wave pattern is frozen as it moves past a fixed point (the Taylor frozen wave hypothesis) is assumed valid in this transformation. This is the manner in which the Δx distribution variate was determined. The other two variates were directly sensed (w) or known a priori (sensor height z).

For brevity, distributions for only three of the six tower levels (26, 177, and 144 m) are presented. These are shown in Tables 1-3. Each table is a bivariate distribution in w and Δx; collectively the tables form the trivariate distribution in w, Δx, and z. Vertical speeds are divided into 1.0 ms^{-1} class intervals. The class intervals from -1.0 to $+1.0$ are not shown because the information is believed to be of little significance to the aviation problem. Perturbation half-wavelengths are divided into 100 or 200m class intervals. Distribution information in the very smallest and the very largest Δx categories is not shown because, again, it is believed of no value to the problem at hand.

Analysis Results

Inspection of the distributions in Tables 1-3 reveals several important properties of the vertical speed field:

1) In any w class interval, the vertical speed frequency generally varies directly with height above the ground at constant Δx (fix w and Δx, vary z).

2) For a given value of Δx and a given level: a) the frequency of observations decreases very rapidly as $|w|$ increases, and b) the incidence of positive vertical speeds is usually greater than the incidence of corresponding negative values; i.e., distributions have a slightly negative kurtosis and are skewed toward positive w values (fix Δx and z, vary w).

3) The incidence of large w values ($|w| \geq 2.0$ ms^{-1}) is low and virtually zero for large Δx (fix w and z, vary Δx).

The importance of properties 2a and 3 to pilots should not be overlooked. Assume a commercial jet aircraft on a typical approach path crosses the outer marker (about 10 km from the runway) at a speed of 100 ms^{-1} and touches down at about 70 ms^{-1}. In Tables 1-3, w observations that appear in the leftmost column ($\Delta x \leq 100$ m) are much too small or short-lived relative to the moving aircraft for it to respond fully to the external forces. Such spatially small updrafts and downdrafts will be sensed as turbulence, resulting in quick jolts and some roll, but probably no serious flight quality degradation. Flight quality might be seriously impaired for smaller aircraft, however, which fly slower but respond faster. Short-lived, but large amplitude w oscillations could produce upset for these aircraft.

Observe that almost all large $|w|$ observations fall in the $\Delta x < 100$ m class interval. When $|w|$ exceeds 2.0 ms^{-1} and Δx is 100 m or larger, the frequency of observations falls quickly to zero. This is in marked contrast to the vertical speed magnitudes (specifically downdrafts) and the longevity of such values deduced by Fujita[11] in an analysis of flight data recorder information from a single airline incident at Atlanta in 1979.

Character of the Wind Vector in Specific Events

Cross-Section Analysis

In the last section, the general character of the vertical wind component in the lowest 444 m of the atmosphere has been discussed using all the discrete observations from the 14-month tower record. It would be instructive, at this point, to look at the fine details of an isolated case of very strong updrafts and downdrafts to see how the tower layer flow reacts when severely perturbed. The example selected represents a worst-case situation in that never in the seven-year history of tower data collection was a more dramatic example of strong downdrafts observed (personal observation). This is the atypical factor. However, the case is representative in depicting the dissipation of the downdraft core as it approaches the ground, inasmuch as other weaker downdrafts will likely behave in a similar manner.

The case selected occurred on May 29, 1976, during a period when the tower layer was perturbed by a distant thunderstorm with a complex outflow structure.[8] Strong downdrafts occurred intermittently during two half-hour periods. One of these periods was chosen for closer inspection and the tower data machine contoured in Fig. 1. A 1975 report describes the data conditioning and contouring methodology.[5]

At about 22:08:30, the tower layer was abruptly disturbed by a very strong (>8 ms^{-1}) updraft of about 1-min duration. This was followed immediately by a series of equally strong downdrafts lasting about 6 min. Actually, the strongest downdraft was slightly less than 10 ms^{-1} at about 22:10:30. The 6-min duration of the downflow is roughly equivalent to a 2.1 km-wide pocket using the time-to-space conversion, where the speed of the front, $\bar{u}$ in the transformation, was 5

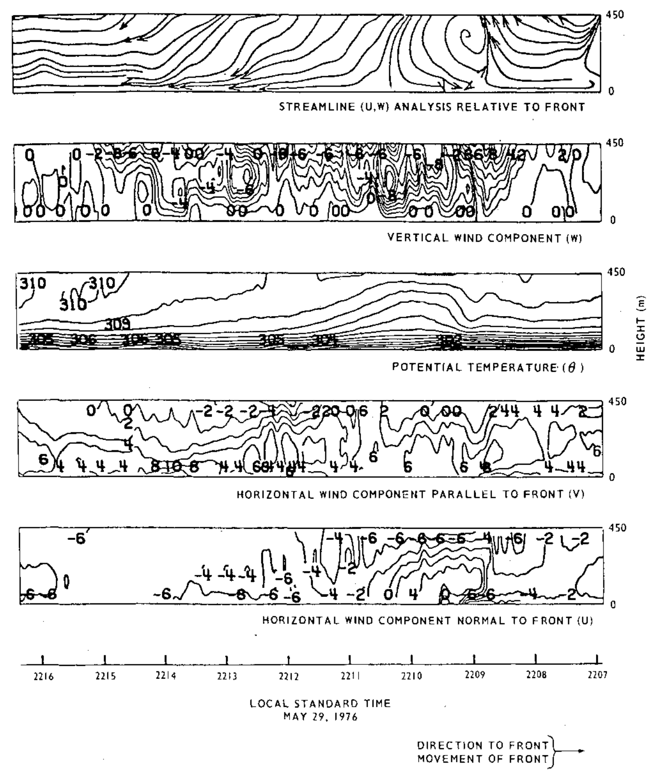

Fig. 1 Time-height cross section of Oklahoma tower wind and temperature data and appropriate u, w streamline analysis. Units are meters, kilograms, seconds, and Kelvin. Horizontal wind component normal to front (u) has been adjusted by subtracting the speed of the front (5 ms^{-1}).

ms^{-1}. During this 6 min, however, the downdraft is anything but uniform especially above 200 m. Two downdraft maxima occur at midtower levels rather than at the top of the tower. This is probably due to downdraft infusion nearby but lateral to the tower sensing plane. These downdraft pockets are coupled to distinct but lower magnitude downdrafts at the top of the tower.

The downdraft field in the upper half of the tower is so strong, it is certain any pilot would have difficulty maintaining his aircraft's intended altitude or flight path. Passenger discomfort would be severe, especially if the aircraft were to penetrate the extremely strong shear ($\partial w/\partial x$) above 300 m at about 22:09. Here the aircraft would make the transition between an 8-ms^{-1} updraft; and a 9-ms^{-1} downdraft in about 4 s aircraft time ($\partial w/\partial x \sim 0.06$ s^{-1}). But at these altitudes, a crash would not be imminent because the aircraft would eventually fly out of the zone of high perturbations or the pilot would take evasive action before too much altitude was lost.

The critical zone, however, is the layer between the surface and about 200 m. Strong downdrafts in this layer, especially below 100 m, could be very detrimental. It is clear from Fig. 1 that whatever the downdraft magnitude is in the upper half of the tower layer, it decreases sharply below 200 m. (The reader should be aware that the data sample interval in this case is 1.34 s and that there are three tower levels providing data below 100 m. Therefore fidelity of the plots is considered excellent and resolution is high.) A 3 ms^{-1} downdraft is arbitrarily chosen as the threshold between significant and insignificant downward motion. At 100 m, a 3 ms^{-1} or greater downdraft is observed four times (22:09:30, 22:10, 22:12:45, and 22:13:45). In each case, this magnitude downdraft is of short duration relative to an aircraft moving 70 ms^{-1}; the maximum duration being less than 2 s. The maximum downdraft at 100 m is about 5.5 ms^{-1} (at about 22:10). This is the time of maximum vertical shear ($\partial w/\partial z$); and Fig. 1 reveals that from 180 m to the ground, the downdraft decreases almost linearly. The streamline analysis indicates that this downdraft (microburst) spreads out into the horizontal nearly symmetrically.

It appears from Fig. 1 that the height at which downdrafts approaching the ground turn into the horizontal is about 200 m. The rate a downdraft diminishes below 200 m is dependent on the downdraft magnitude at 200 m, but in the case cited, the maximum rate is $\partial w/\partial z = 0.05$ s^{-1} (or 5 ms^{-1} per 100 m). The length of time a certain magnitude downdraft exists is short for downdrafts >3 ms^{-1}, but can be quite lengthy for smaller magnitude downdrafts. The duration of larger downdrafts is a direct function of height.

The data from this case are part of the data set used to construct the frequency distributions described in the last section.

Spectrum Analysis

Analysis Method

A one-year subset of the 14-month-long record used to construct the previously cited frequency distributions is assumed to contain a representative sample of Oklahoma weather events for the annum. To objectively identify the significant wind-weather events in this series, a machine-based data sorting technique was used. The method consists of computing temporal and spatial changes of the wind variables (wind speed, direction, and vertical motion), assigning appropriate thresholds, and retaining only those data blocks exceeding the thresholds. In this manner, 34 significant meteorological events were identified. These were divided into two groups: synoptic cold fronts (15 cases) and thunderstorm outflow gust fronts (19 cases).

For each case, a 90-min time-average tower layer wind direction was computed using data following the frontal passage. This mean value is assumed to be the direction from which the wind discontinuity is moving. It is also a good indicator of aircraft heading on approach to, or departure from, a hypothetical airport, assuming the pilot will use the appropriate runway so as to have a headwind. The mean wind direction is further used to establish the orientation of the u- and v-wind components (horizontal wind), whereby $+u$ points in the direction of frontal discontinuity movement and $+v$ is the normal component in a right-hand coordinate system. With this axis orientation, the u spectra to be computed roughly represent a transformation of headwind/tailwind data and v spectra represent a transformation of crosswind data.

Nonlinear trends in the horizontal wind data must be removed prior to computing spectra. This is accomplished by applying to the data a least-squares fit of a sixth-order polynomial. No trends were observed in the w-component data, but some series exhibited bias which was removed by subtracting the series mean w from the raw data.

Spectra were computed using a fast Fourier transform. In the spectra to be shown, only data collected at a 10 s sample rate were used. For the fast Fourier transform, the number of data points in the transformed time series is an integer power of 2 (2^n). When $n = 9$, each time series is 85.33 min long. To enhance spectral resolution, a three-point hanning filter was used.

Spectra were plotted in a manner such that the variance determined in a log frequency band in one portion of the spectrum can be compared to the variance shown in a comparable log frequency band in another portion of the spectrum. This is evident from the expression

$$\int_{f_1}^{f_2} S(f)\,\mathrm{d}f = \int_{\ell n f_1}^{\ell n f_2} f S(f)\,\mathrm{d}(\ell n f) \tag{1}$$

where f is the frequency and $S(f)$ the variance density. Spectra are plotted as $fS(f)$ against $\ell n f$.

The spectra to be analyzed are Eulerian spectra; that is, they are computed from time series data collected from in situ sensors. It is desirable to orient these data to the aircraft reference frame. To do this, a relationship between the wave periods with respect to ground and hypothetical aircraft is used:

$$P_a = cP_g/(G_s \pm c) \tag{2}$$

where P_a is the wave period with respect to a moving aircraft, P_g ($=1/f$) is the wave period with respect to the ground (or sensor), G_s is the aircraft ground speed, and c is the wave phase speed (assumed to be the mean tower layer horizontal wind speed). Only the positive part of the denominator in Eq. (2) is used.

In the spectral composites to be described, 30 of the 34 cases culled from the year-long data set had a 10 s sample rate. The remaining four cases had a 1.34 s sample rate and are not included in this analysis. The 30 cases are evenly divided between synoptic cold fronts and thunderstorm gust fronts.

Analysis Results

Cold front spectra (15 cases) for the u-, v-, and w-wind components are shown in Fig. 2c. Each plot contains three curves representing the 15-case composite maximum, mean and minimum spectral values (variance density times frequency) at the respective frequency. At the top of each chart is plotted the period with respect to a hypothetical aircraft (ground speed assumed to be 70 ms^{-1}) and with respect to the ground. The value shown for c ($=10.8$ ms^{-1}) in the legend is the average tower layer horizontal wind speed for the 15-case composite. The 15 cold fronts culled from the one-year data set are all considered strong cases characterized by sharp discontinuities in wind, temperature, and pressure. Some were dry fronts, others accompanied by stratoform rain. None, however, had associated thunderstorms. In those cases where thunderstorms were associated with a frontal passage, the event was not considered a cold front case.

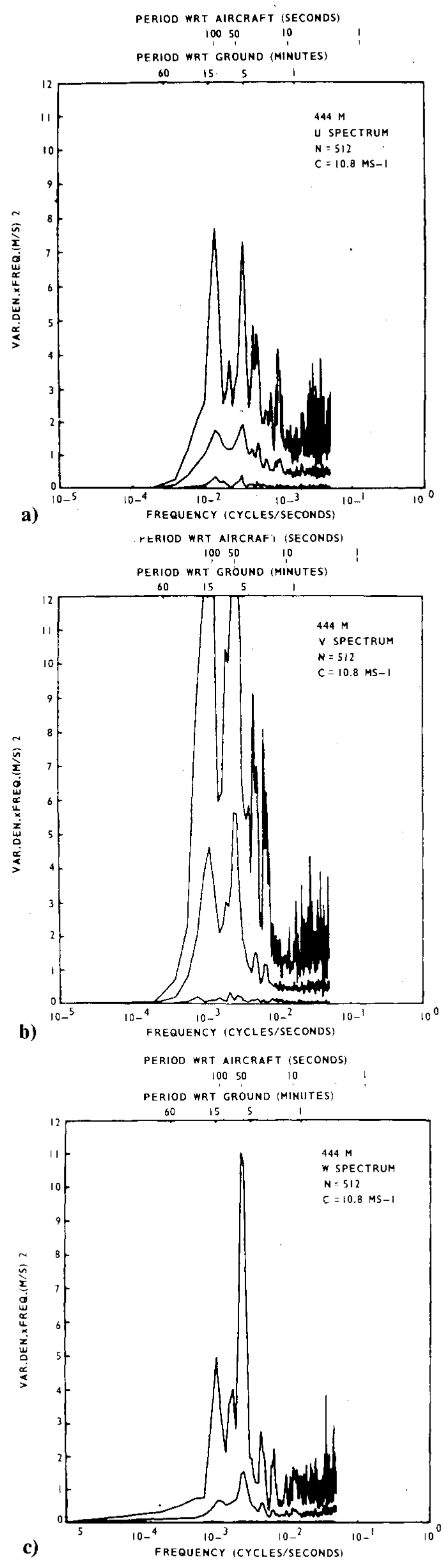

Fig. 2 a) *u*-component spectrum, b) *v*-component spectrum, c) *w*-component spectrum for cold front cases. Off-scale peaks in b are 17.9 and 16.5 $m^2\ s^{-2}$, respectively. In each plot the top curve is the 15-case maximum, the middle curve is the composite mean, and the lower curve is the 15-case minimum.

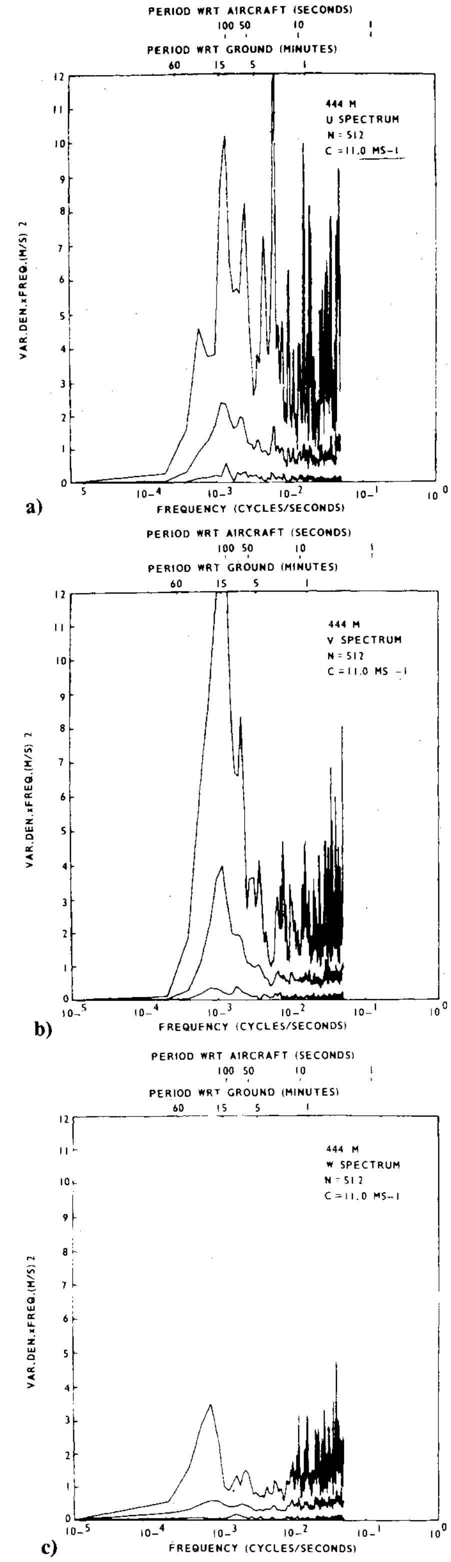

Fig. 3 Same as Fig. 2 except for thunderstorm gust front cases. Off-scale peak in b is 13.9 $m^2\ s^{-2}$.

There is considerable variation in composite cold front *u, v,* and *w* spectral maxima. However, it is clear that there is, in general, much more kinetic energy in horizontal wind component (u) spectra than in the vertical wind (w) component spectra. It is also evident that of the two horizontal wind components, the crosswind component (v) has more kinetic energy than the headwind/tailwind component (u). In both components, the mean kinetic energy curves exhibit a peak at two periods (period with respect to an aircraft moving 70 ms^{-1}): about 100 and 50 s. The shorter period peak is considered more significant since it is closer to the typical aircraft phugoid period (about 38 s for a Boeing 727). In the mean vertical speed spectrum composite, there is one significant peak at about 50 s, but it is one-fourth the magnitude of the comparable mean in the cross-wind spectrum and about 75% the magnitude of the mean in the headwind/tailwind component. There is a substantial amount of kinetic energy in horizontal wind spectra maxima at or just below the phugoid period. This is not true of the w component.

Spectra for 15 thunderstorm outflow gust fronts cases are shown in Fig. 3. As in Fig. 2, composite spectral maxima, mean, and minima are determined for the 15-case sample. In general, the thunderstorm spectra exhibit properties similar to the cold front spectra. There is much more kinetic energy associated with horizontal wind components than with the vertical wind component. This disparity is consistent with the cold front spectra but is more pronounced in the thunderstorm spectra. There is only one mesoscale peak in the thunderstorm spectra, at about a 110 s period with respect to the hypothetical aircraft with 70 ms^{-1} landing approach speed. Consequently, there is a smaller amount of kinetic energy at typical phugoid periods in all three thunderstorm composite mean spectra compared with cold front spectra. This might appear to suggest that strong cold fronts are generally more hazardous to pilots than strong thunderstorm outflows in the Oklahoma environment, if one assumes that wind oscillations near the aircraft phugoid period result in the highest potential for flight instability. Pilot experience and accident records fail to confirm this hypothesis, however.

Like the cold front composite mean spectra, thunderstorm spectra exhibit more kinetic energy in the crosswind component v than the headwind/tailwind component u. However, there is somewhat more u-component kinetic energy in the thunderstorm phenomenon than there is in the cold front u-component (spectra composite maxima and mean). Moreover, turbulence levels are higher in thunderstorms than in cold front cases.

Summary

An analysis of 14 months of meteorological tower wind observations using frequency distributions, vertical cross section and spectra has provided an in-depth study exploring, in particular, the character of the wind's vertical component. Apparently, numerous misconceptions exist regarding this little-known yet important atmospheric variable and its influence on aircraft stability in operations near airport terminals.

What has been determined in this study is that 1) vertical motions (in particular, downdrafts) of any consequence to pilots are virtually nonexistent below about 100 m; 2) strong updrafts and downdrafts are observed above 200 m, but their duration is short relative to an aircraft on typical airport approach or departure speeds; 3) there is almost always more kinetic energy in horizontal wind oscillations than in oscillations of the vertical wind; 4) airmasses following strong cold fronts appear to rival thunderstorm outflows in terms of potential hazards to aviation; 5) there is considerable kinetic energy at or near typical aircraft phugoid periods in cold front and thunderstorm cases, but usually much more kinetic energy at periods longer than the phugoid; 6) maximum up/downdrafts are about 11 ms^{-1} at 444 m, 9 ms^{-1} at 177 m, and 4 ms^{-1} at 26 m; and 7) up/downdraft magnitude is inversely proportional to horizontal spatial extent.

Acknowledgments

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