Oklahoma Weather Phenomena That May Affect Aviation

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We report here the latest studies by the National Severe Storms Laboratory of interest to the aviation community. Of particular importance are turbulence produced by storms, low-altitude wind shear in storm outflows, and downdrafts and gust fronts. Storm turbulence has been studied extensively with the help of Doppler radar. Comparison of spatial spectra of longitudinal and transverse velocities has revealed that in severe storms the outer scale of turbulence is at least 2 km. Because of this and because measurements of spectrum widths at two different viewing angles agree, the width could prove a good indicator of storm turbulence that may affect aircraft. We report on the asymmetry of low-altitude divergent outflows produced by downbursts in Oklahoma. This has implications for the detection and quantification of these phenomena with pulsed Doppler radar. Gust front shears estimated by Doppler radar (at heights between 50–600 m) average 1.6 times the shear measured a few meters above the surface. Tall tower data show that both wind speed and wind shear increase in the lowest 90 m of the atmosphere. Thus, surface-based anemometers considerably underestimate wind shear just 100 m or so above the surface. Doppler radars located near airports may allow measurements at such low altitudes and resolve significant wind shears. Automatic methods to detect, track, and extrapolate shear produced by waves and gravity currents (downbursts) are being developed, and some results are shown.

Introduction

THE year 1985 saw the highest number of deaths due to aircraft accidents in any one year. Commercial aviation disasters in recent years have a high level of visibility because each aircraft can carry more passengers and because of increased dependence on air travel. Furthermore, due to increased cost of litigation, the direct and indirect cost of air accidents has been growing rapidly. This brings into sharper focus the need for improving safety levels in all aspects of aviation. Weather has been implicated as a hazard factor to safe flight many times.

Since 1962, U.S. aircraft have been involved in eleven fatal weather-related accidents, nine of which occurred in the area of thunderstorm rain.[1] In another accident, the aircraft flew through heavy rain without thunder. In only one case was wind shear a cause without rain being mentioned in the report. At low altitudes the aircraft is especially vulnerable because there is little time or space to recover. Therefore, avoiding thunderstorms is the safest maneuver the pilot can execute. Most rain may not have an associated hazard near the ground; moreover, there may be situations in which storm cells are far away and yet gust fronts harboring hazardous shears are crossing the runway. Thus, although warnings based on radar reflectivity could greatly enhance flight safety, there is need for other complementary information that is a more direct measure of the hazard potential. Because decisions can be made as to which instruments should be used to monitor weather near airports, it is of paramount importance to understand precisely the hazards and their evolution.

For over two decades, the National Severe Storms Laboratory has conducted observational and theoretical research concerning weather phenomena hazardous to safe flight. Although the emphasis has been on Doppler radar observations,[2] data from a tall tower, surface stations, radiosondes, and satellites have also been used, often simultaneously, to interpret various events. Even when these sensors do not detect the actual hazard due to its small size (e.g., a tornado), the hazard potential can often be determined.

Weather Factors in Aviation

Meteorological phenomena that may adversely affect flight are of four main types: convective phenomena, waves and turbulence, icing, and low visibility. In the following paragraphs, we shall dwell on only the first two types and their broad characteristics.

A considerable variety of convective phenomena depend on general synoptic conditions. Among these phenomena are the isolated thunderstorms that can easily be observed and their paths predicted.[3] In widespread convection, individual cells can be tagged and traced and attributes of severity evaluated. But it is much harder to determine the location and time of storm formation, although some significant advances in this area have been made. It has been observed with radar that storms often initiate at colliding frontal or outflow boundaries.[4,5] Also, gust fronts and stationary boundaries from prior convection can trigger storm development. Clues to storm formation have been sought in areas of boundary-layer convergence that can be quantified by analyzing Doppler radar data.[6] It is not uncommon for storms to reach maturity (reflectivity factor of 50 dBZ) in less than 10 min. There has been no comprehensive statistical evaluation of growth rates in Oklahoma storms. Our study of four Oklahoma storms showed that maximum reflectivity factor increases at about 5 dBZ/min and that updraft velocities increase as rapidly as 6.7 $m \cdot s^1/min$.[7] These values are not unusual; Browning and Atlas have used reflectivity height indicator (RHI) displays to deduce a 10-dBZ/min increase in two Oklahoma storms.[8]

A summary of storm hazards and their detection with weather radar has been given by Doviak and Lee,[9] and weather safety aspects in future civil air navigation have been discussed by Mahapatra and Zrnić.[10] We will present some new and interesting results, bearing in mind that the United States is developing a network of Doppler radars, the so-called Next Generation Weather Radars (NEXRAD),[11] which have potential for improving hazard warnings to pilots. Hail, excessive water content, shear, and turbulence

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are the weather phenomena that endanger flight, both en route and at the terminal area.

Hail

Much effort was spent in research trying to devise methods for hail detection. Reflectivity factor values larger than about 55 dBZ may be caused by hail, but detection based on reflectivity factor alone is unreliable. In combination with other information such as storm top height and its divergence[12] or the position of echo top relative to weak echo region,[13] the reflectivity factor may lead to better detection of hail. An algorithm based on these premises is currently planned for NEXRAD.[14] Preliminary tests of this algorithm in Colorado produced a probability of detection of 0.6 and false alarm probability of 0.08,[15] which suggest that further improvements are warranted. Recently, it has been demonstrated that radars with two polarizations can discriminate between hail and other types of hydrometeors.[16]

At the National Severe Storms Laboratory (NSSL), we have observed that larger hail often produces radially elongated echoes behind strongly reflecting storm cores (Fig. 1). These echoes are a result of a three-body scattering process. Radar-transmitted energy is scattered by the highly reflecting region to a large portion of the ground plane centered with respect to the hydrometeors; the ground backscatters the energy (from concentric rings) to the hydrometeors, which in turn scatters it to the radar. At the time of data collection, the storm produced golfball-sized hail, which damaged a vehicle from which the University of Oklahoma storm researchers were making observations. Multiple scatter signatures associated with excessively elongated echoes, as shown in Fig. 1, are not very common, yet theory[17] predicts that they should be always evident, provided there is no interference from scatterers behind the highly reflecting region. It may be interesting to examine Doppler spectra in weaker precipitation regions behind storm cores to see if there is evidence of multiple scattering.

Turbulence

Besides causing discomfort to crew and passengers in flight, turbulence may create structural damage to aircraft and may be responsible for delays of flights. Much effort was expended in the late sixties to understand clear air turbulence (CAT).[18] However, ground-based weather radars with a 10-cm wavelength do not have sufficient sensitivity to detect CAT at en route altitudes. Only when precipitation targets are present or when there is enough backscattering in clear air within the lowest 1–2 km of the Earth's atmosphere Doppler measurements are possible.

Both sheared flow in stratified environments and convection can generate turbulence. In either case, the turbulent energy input is at larger-sized eddies, which break down into successively smaller ones until turbulent energy is converted into heat by viscosity. If the sizes of largest eddies of isotropic turbulence (i.e., scales within the inertial subrange) are larger than the radar resolution volume, then turbulence can be quantified from Doppler spectral width measurements.[19] This had led to the development of an algorithm for NEXRAD.[14] So far, there have been few radar measurements to establish how well Doppler spectral width in storms characterizes isotropic turbulence. In the next paragraph we present such evidence.

In order to check if part of spectra of turbulent scales is in the inertial subrange and to determine the outerscale, the Doppler velocities observed at vertical incidence were used to construct both longitudinal and transverse spectra. In the inertial subrange, the ratio of the transverse to the longitudinal spectral energy will be 4:3.[19] There is, however, significant filtering inherent in the radar data, and the effect of the filtering is not the same for the longitudinal and the transverse spectra. As a result, the ratio of the two filtered spectral components is somewhat larger than 4:3 and is a function of wavelength.[20]

For our calculations, mean vertical velocities from 32 range locations spaced by 150 m in height and starting at 3 km above ground were used. These velocities are functions of time, and the time scale was converted to horizontal distance by Taylor's hypothesis to compute transverse spectra along the horizontal axis. A mean wind of 20 m-s^{-1} was estimated from the radar echo motion just prior to the vertically pointing measurement. Then three transverse velocity spectra from interlaced data (each along a 6-km length) for each height were calculated, and the three were averaged. Finally, an average of spectra over the 4.8-km height interval was obtained. Longitudinal spectra are obtained by Fourier decomposition of the mean Doppler velocities along the 4.8-km vertical interval. Because it takes about 100 ms of data collection to produce one longitudinal spectrum, we can consider this spectrum to be an instantaneous sample of turbulent energy density. However, 100 spectra spaced 3 s apart were averaged over a period of 5 min to obtain a spatial average over about 6 km. The specific data used for the study were from a severe storm that passed over the Norman radar on May 17, 1980.

The longitudinal and transverse spectra are plotted in Fig. 2. From these spectra we estimate that the outer scale of turbulence is between 2.4 and 3 km. This explains why the first point at a wavelength of 4.8 km deviates considerably from the theoretical prediction. At shorter wavelengths, the transverse spectra exhibit an irregularity that we attribute to noise. Thus, only the second through the fifth points from the left on Fig. 2 are useful for comparisons. There is reasonably good agreement between the expected ratios and those measured in this particular case. This lends increased confidence to the inertial subrange assumption and provides further evidence that the inertial subrange scales can extend to lengths of a few kilometers.

When turbulence on scales as large as the resolution volume is isotropic, we expect that Doppler spectrum widths should be independent of the radar viewing angle. This has been confirmed in comparisons between simultaneous measurements with two Doppler radars separated by 40 km (Fig. 3) and having the same processing characteristics. The storm was severe and located at about the same distance (45

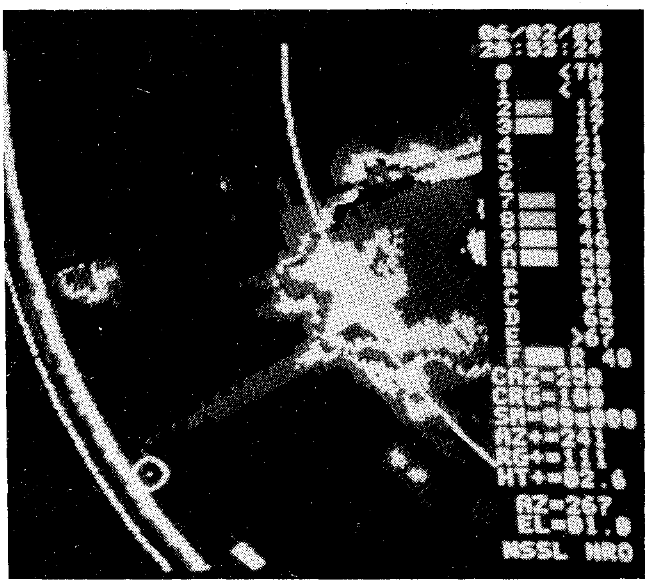


Fig. 1 Reflectivity contours of a hail-producing storm. The range marks are 40 km apart and the scale for the equivalent reflectivity factor is in dBZ. The elongated echo extending toward the cursor is produced by scattering interaction between the hail shaft and ground.

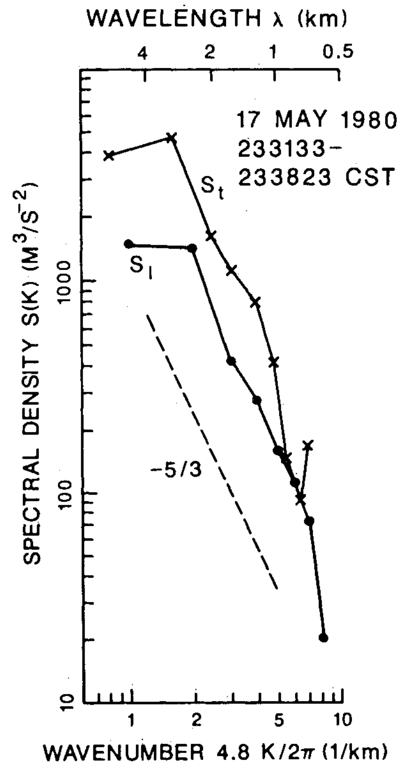


Fig. 2 Spatial spectral densities. S_t is the transverse and S_l the longitudinal spectrum. A dashed line represents the $-5/3$ law expected from isotropic turbulence in the inertial subrange.

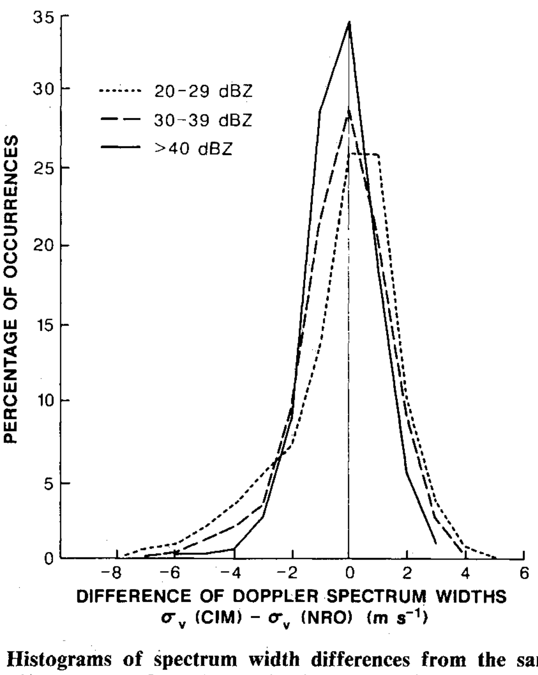


Fig. 3 Histograms of spectrum width differences from the same locations in the storm but measured with two separated radars at different aspect angles. CIM refers to the Cimarron site and NRO to the Norman site. The three curves correspond to three regions of reflectivity factor values.

km) from either radar, and the viewing angle difference (i.e., the angle between radar beams) of the two radars was 20-90 deg. Only data with reflectivity factor values larger than 20 dBZ were processed, and no shear removal was applied to isolate the turbulent component of the spectrum. Both radars measured median widths in the range of 4-5 m-s^{-1} but, for point comparisons, data were interpolated to a common rectangular grid with 1-km spacings. The mean difference is 0 m-s^{-1}, and the small deviation around 0 is most likely due to statistical uncertainty of the estimates and some contribution by shears of turbulent nonisotropic eddies. We thus expect that the vertical component of turbulent velocity that affects aircraft en route and on approach could be quantified from Doppler spectrum width measurements. To do so requires quantitative accounting of other spectral broadening mechanisms, such as shear, signal processing effects, and spectral artifacts, in order to minimize false alarm rates.

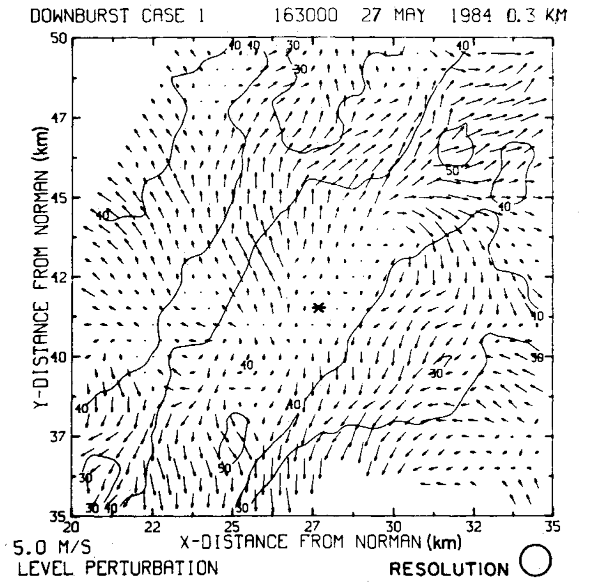


Fig. 4 Downburst of May 27, 1984. Wind vectors were obtained from radial velocities of two Doppler radars. The mean vector wind was removed from this analysis. Below the figure are indicated the interpolation (resolution) size of the analysis and the vector wind scale. Superposed on the winds are reflectivity contours in steps of 10 dBZ.

Wind Shear

Wind shear is broadly defined as a spatial or temporal gradient in wind speed and/or direction. Many types of atmospheric phenomena are capable of generating significant wind shear; among them are convective storms, synoptic fronts, thunderstorm gust fronts, jet streams, and gravity waves. Topographic factors may also induce considerable velocity variations. However, experience shows that most of the wind shear hazardous to aviation is related to storms.

A shaft of cold air descending from the core of thunderstorms is called a downdraft; when it induces damaging winds on or near the ground, it is called a downburst or a microburst,[21] depending on its horizontal scale relative to a threshold dimension of 4 km. Microbursts have been the subject of considerable study in recent years.[22] Detailed studies of microbursts have been made through dedicated programs such as the Northern Illinois Meteorological Research on Downbursts (NIMROD) and the Joint Airport Weather Study (JAWS).[23]

Spatial scales of microbursts (measured between locations of maximum approaching and receding velocities) are distributed rather homogeneously over the 1-4 km interval, though dimensions outside this interval are also found. These figures have a special significance since convective features of 1-4 km are considered most critical from the point of view of aircraft performance and safety.[24]

Eilts and Doviak[25] analyzed downbursts from spring storms in central Oklahoma and observed that these were superposed with the maximum reflectivity cores associated with heavy rain. This contrasts with the typical downburst observed during the JAWS project, which was often associated with little or no rain at the surface. The

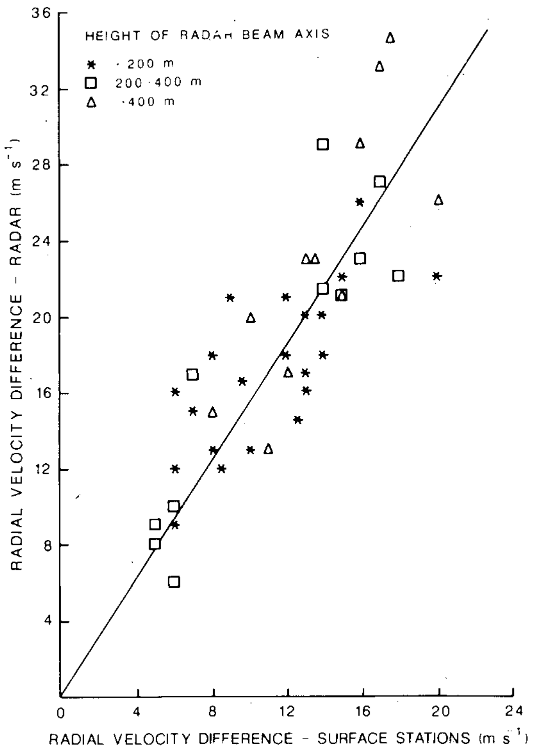


Fig. 5 Velocity difference across gust fronts as measured by Doppler radar vs velocity difference measured at the surface by anemometers. The code shows the approximate height of the Doppler radar observation. Note slight difference in scatter about the line for the different height groups.

mechanism for the initiation of the majority of JAWS microbursts was evaporative cooling, which occurred when precipitation fell into a dry, deep, and nearly adiabatic boundary layer. On the other hand, because of a lower cloud base and a more moist and slightly more stable boundary layer, it appears that mechanisms for the initiation of the observed Oklahoma downbursts are low-altitude melting and evaporation of precipitation, low-altitude precipitation loading, and evaporational cooling at midlevels due to entrainment of dry air.

An example of wind vectors reconstructed from data of two Doppler radars that observed an Oklahoma downburst is shown in Fig. 4. The low-level outflow was associated with an elongated cell located 27 km east and 41 km north from Norman at 1630 CST on May 27, 1984. At this location, the height of the radar beam was approximately 320 m above ground level for the Norman radar and 420 m AGL for the Cimarron radar. Both data sets were interpolated to a grid with a height of 300 m. This cell was part of a line of thunderstorms that stretched east-west from the western Oklahoma border all the way to a point 120 km ENE of Norman. The maximum reflectivity of this cell was 50 dBZ, which was one of the strongest cells in the line. We see that the downburst is quite asymmetrical (the shear along the maximum shear axis is 5.5 times larger than the shear along the minimum shear axis) and could be misclassified if a single Doppler radar located along the squall line were to observe it. However, in this particular example, the high reflectivity is sufficient to alert aircraft. Other downbursts examined by Eilts and Doviak were also quite asymmetrical; the shear along the maximum shear axis was, on the average, 2.2 times the shear along the minimum shear axis.[25]

Strong wind shear may also be associated with gust fronts that are the leading edge of the mass of precipitation-cooled air, flowing first downward and then outward from the center of thunderstorms.[26,27] Gust fronts harbor both vertical and horizontal shears and, even after propagating tens of kilometers from the parent thunderstorms, they may retain shear at potentially hazardous levels. This large separation makes it unreliable to discount the presence of gust fronts merely because of the absence of thunderstorms in closer proximity.

Doppler radar offers great promise to measure shears in gust fronts void of precipitation. But, due to the nature of the instrument, measurements are usually representative of heights at beam center, so that care must be exercised when comparing these measurements with surface anemometers. Results from a recent study[28] indicate that Doppler radar estimated shears measured at heights of 50–600 m in Oklahoma gust fronts are stronger than shears measured at the surface by an average ratio of 1.6:1 (Fig. 5). Plotted in Fig. 5 are velocity differences rather than shears because it is difficult to estimate, from surface station data, the propagation speed of the gust front, which is needed to compute the distance between extreme velocities. Tower wind profiles measured during gust frontal passage confirm that winds (and shears) near the surface are weaker than winds (and shears) aloft. This is also corroborated by plots of gust front velocities with height shown by Klingle,[26] Goff et al.,[27] and by others. It is expected that frictional forces slow winds near the surface for all conditions.

The Federal Aviation Administration requirements for Doppler radar coverage in the airport area call for the lowest scan to be less than 60 m above ground level at all points within 20 km of the airport. If this requirement is met, Doppler radar should be able to detect the maximum shears produced by Oklahoma gust fronts in the airport area. It is reasonable to expect that gust fronts in other parts of the country could be similarly characterized. As far as downbursts are concerned, the relationship between shear measured at the ground and radar-derived shear has not yet been established. But because surface friction has similar effects on gust fronts and outflows, we expect shear in outflows to be smaller at or near the ground than aloft.

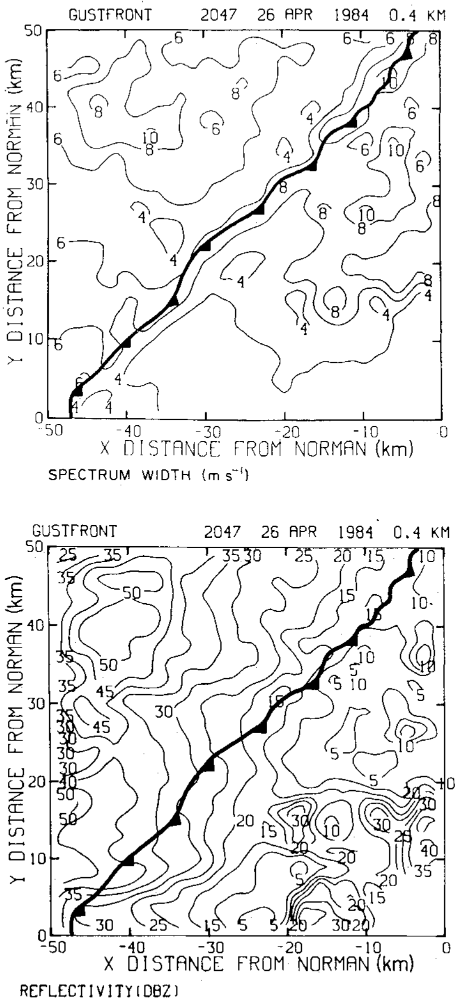
The determination that shears aloft are stronger than at the surface can be used to improve wind shear detection in areas surrounding airports, which are the areas where aircraft are most susceptible to wind shear. A ground-based sensing device, such as the Low-Level Wind Shear Alert System (LLWSAS),[29] will underestimate shears aloft. However, if shears at the ground are corrected with an appropriate factor (1.6 was found to be the average ratio of shear aloft to shear at the surface in gust fronts), the surface estimate of shear along a glide path would be more comparable to the shear aloft, where aircraft are actually flying.

Vortices are potentially hazardous because of shear associated with them. The presence of a vortex can produce as large a decrease in headwind as is found in downbursts if the flight path is tangent to the circle of maximum wind.[9] Intense circulations are often found along gust fronts, and that is one more reason to avoid them.

Strong vertical shear of horizontal wind is often present in the planetary boundary layer over large areas. Such shear by itself is not a hazard, but it may generate turbulence, and it may also be a major contributor to the Doppler spectrum width.[9] Therefore, it is important to identify and separate shear from turbulence contributions from the Doppler spectrum width so that vast regions of safe airspace are not falsely declared to be turbulent.

Example of the Effects of Turbulence and Shear

We will now discuss briefly the case of a storm that occurred on April 26, 1984. The storm produced a strong gust front. Ahead of this front, very turbulent winds disrupted flights to and from the Will Rogers Airport in Oklahoma City. TWA flight 163 encountered severe turbulence on approach and had to be diverted to Tulsa. Subsequent flights also had to be diverted to Tulsa and Lubbock for safety



a) b)

Fig. 6 a) Doppler spectrum width field for the gust front of April 26, 1984, at 2047 CST. The drawn gust front curve was automatically detected from radial velocity data. b) Contours of effective reflectivity factor field for the same date and time.

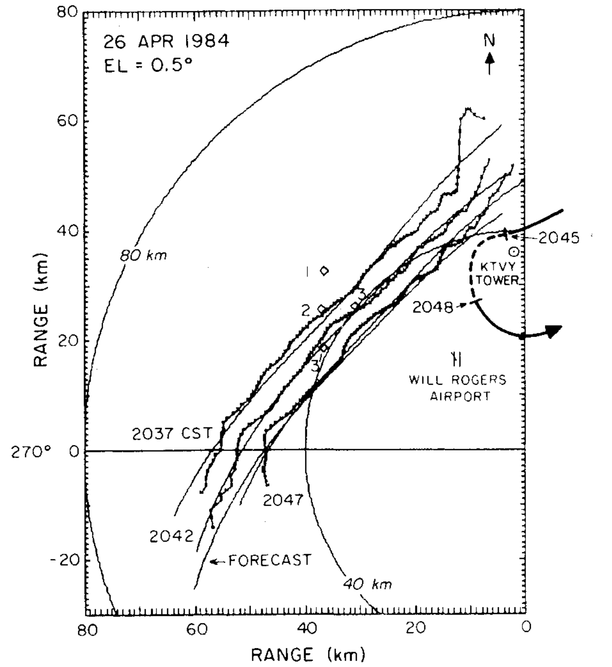


Fig. 7 Gust front positions and aircraft flight path. The rugged curves are locations of maximum radial shear of radial wind. Smooth curves are second-order least-square fits; the extrapolated or forecast position is also shown. The dashed portion of the aircraft path is at 1.3 km above ground, where turbulence occurred. The time interval of turbulence encounter is also indicated.

reasons. At the time TWA flight 163 made its approach, the reflectivity display indicated a line of heavy thunderstorms whose leading edge (12-dBZ contour) was about 10 km NW of the airport. Maximum reflectivity values near the ground were in excess of 55 dBZ; reflectivities aloft exceeded 60 dBZ. Radar reflectivities at low levels ahead of the front were weak (< 10 dBZ) and did not result from raindrops, but rather from refractive index fluctuations and discrete particles or insects caught up in the gusty wind.

A meteorological feature prominent in the velocity display was a long (80-km) convergent boundary (gust front). Strong southerly winds ahead of the gust front apparently identified a low-level jet associated with the storm system. Winds were gusting up to 15 m-s^{-1} at the surface and were 25-30 m-s^{-1} at the highest level (444 m) of the KTVY instrumented tower. Doppler velocities confirm that strong flow extended to the aircraft altitude (2 km and beyond).

A Doppler display (Fig. 6a) shows large spectral widths both ahead and behind the front. The storm outflow was rather shallow (< 1 km) and could be seen clearly only at this lowest elevation (0.5 deg, about 0.4 km high at a range of 40 km). Also immediately behind the front, regions of weak reflectivity cells (15 dBZ) were present (Fig. 6b). It is clear from Fig. 6b that strong ground clutter contamination is expected at ranges less than 20 km; at a further range and within the environmental flow, the reflectivity factor contours (10-15 dBZ) are much smoother, signal-to-noise ratios are larger than 16 dBZ, and therefore there is little contamination of Doppler spectrum width by either noise or ground clutter. From the available information, we have reconstructed the flight path of the aircraft (Fig. 7), as well as the time of turbulence encounter, which began 24 km N of Will Rogers Airport in the vicinity of the KTVY tower at an altitude of 1.3 km above ground. The aircraft stayed only 3 min at this altitude before climbing up and returning to Tulsa. The plotted trajectory is based on aircraft heading and speed and its position 10 min before turbulence encounter; also, the time of turbulence encounter to the nearest minute reported by the pilot and the corresponding increase in vertical acceleration were utilized. Therefore, an uncertainty of a few kilometers is inevitable. Obviously, the aircraft was dangerously close to the frontal discontinuity. Thus, the horizontal shear of the winds in the low-level jet ahead of the front might have caused the turbulence.

From the spectrum width display (Fig. 6a), we see that σ_v have a minimum of 4-5 m-s^{-1} 30 km W of the radar. At this location, the wind in advance of the gust front was blowing transverse to the beam and did not change direction at low altitudes (< 1 km); thus, we attribute these widths to strong turbulence and not to the shear of laminar flow. Spectrum widths at 30 km NNW and 30 km SSW were considerably larger; as a matter of fact, there is a gradual increase to about 9 m-s^{-1} on both south and north sides of the maximum (to the west) in the ambient air. We determined that about 6 m-s^{-1} is caused by the vertical shear of horizontal wind whose height profile was recorded by the instrumented 450-m (KTVY) tower. If we assume that turbulence was homogeneous and isotropic, it would have broadened the spectra from the NNW by 5 m-s^{-1} (i.e., the value measured to the west). Thus, about 7.8 m-s^{-1} is due to turbulence and shear, which leaves an rms of 4.4 m-s^{-1} unexplained. Contamination by ground clutter is the most likely cause of the additional broadening. The bias of the width by ground clutter is most severe in regions where mean velocities are most removed from the zero velocity which, on this day, was to the north or south of the radar.

In Fig. 7, we show three consecutive positions of the gust front that was detected by an automatic algorithm based on maximum radial shear[30]; least-squares fitted curves are also drawn. These can be used to project (as in Fig. 7) the front's position ahead in time, so that controllers know when this hazard will arrive at the airport. Even if the front is weak, the information about the arrival of wind shift is very valuable because it gives air-traffic controllers time to reorganize the flight pattern of incoming aircraft prior to the change of runways.

Conclusion

We have presented some recent examples of convective phenomena, as well as turbulence, that may adversely affect aviation. In the United States since 1962, there have been ten fatal accidents in which aircraft flew through or near heavy precipitation. Therefore, avoidance of convective storm cells is the best possible maneuver for any aircraft.[31] Cells with significant water content or hail can be routinely identified by large (>40-dBZ) values of their effective reflectivity factor. Moreover, it is shown that extreme hail produces three body scattering signatures on radar displays. But there are occasions when significant turbulence and/or wind shear may occur at a considerable distance from, or even in the absence of, strong reflectivity cores. Although data are limited to one case study, it has been shown that, within thunderstorms, turbulent eddies of sizes up to about 3 km are isotropic and therefore the intensity of turbulence affecting aircraft can be quantified by measurements of Doppler spectrum width. This is further corroborated by the fact that spectrum widths measured by two spaced radars agree to within 2 $m \cdot s^{-1}$. However, laminar shear, which is not as significant a hazard to aviation, produces significant broadening of the spectrum width. This distinction needs to be recognized in order not to restrict falsely vast areas of airspace.

An example of turbulence encountered by a passenger flight was shown to illustrate a potential utility of the Doppler weather radar. Although the presence of a very strong gust front and severe turbulence was evident in real time on NSSL's Doppler radar displays in advance of its encounter with a commercial aircraft, there was no mechanism to communicate this information to pilots. In the near future, when Doppler radars (NEXRAD) become integrated in a national network, such information will become routinely available but will be useful to pilots only if adequate communication lines are in service. We can envision a scenario in which flight plans are continuously upgraded with current weather information so that unnecessary delays (or detours) are avoided while at the same time the number of weather-related accidents are reduced.

Wind shear produced by storm downdrafts has been implicated in a number of aircraft accidents at low altitude. We report that downbursts in Oklahoma severe storms are most often colocated with the maximum reflectivity core. They are often asymmetric, with the maximum shear in one direction as much as 5.5 times larger than the shear along another direction. Detection and quantification of these phenomena with a pulsed Doppler radar will therefore be aspect-dependent.

Doppler radar offers great promise to measure shears in gust fronts, as well as to track them automatically. Due to the nature of the instrument, measurements are representative of heights at beam center. Our experience indicates that radar-estimated shears at heights between 50 and 600 m in Oklahoma gust fronts are stronger on average by 1.6 times than shear measured at the surface.

Acknowledgments

The data on which we have based our study have results from a laboratory-wide effort that required the unselfish dedication of numerous individuals. Information from flight recorders on the TWA 163 was provided by Mr. J.B. Young, Manager for Meteorology at TWA. Joan Kimpel drafted the figures. This study was sponsored by Federal Aviation Administration Grant DTFA01-80Y-10524.

References

[1]Rudich, R. D., "Weather-Involved U.S. Air Carrier Accidents 1962-1984: A Compendium and Brief Summary," AIAA Paper 86-0327, 1986.

[2]Zrnic', D. S. and Lee, J. T., "Pulsed Doppler Radar Detects Weather Hazards to Aviation," *Journal of Aircraft,* Vol. 19, Feb. 1982, pp. 183-190.

[3]Crane, R. K., "Automatic Cell Detection and Tracking," *IEEE Transactions on Geoscience Electronics,* Vol. GE-17, No. 4, 1979, pp. 250-259.

[4]Rabin, R., Koscielny, A. J., and Ziegler, D. E., "Doppler Radar Analysis of a Frontal Zone Prior to Convective Development," *Proceedings of the Nowcasting II Symposium,* Norrkoping, Sweden, European Space Agency Rept. SP-208, 1984, pp. 187-191.

[5]Wilson, J. W. and Carbone, R., "Nowcasting with Doppler Radar: The Forecaster-Computer Relationship," *Proceedings of the Nowcasting II Symposium,* Norrkoping, Sweden, European Space Agency Rept. SP-208, 1984, pp. 177-186.

[6]Koscielny, A. J., Doviak, R. J., and Rabin, R., "Statistical Considerations in the Estimation of Divergence from Single-Doppler Radar and Application to Prestorm Boundary-Layer Observations," *Journal of Applied Meteorology,* Vol. 21, 1981, pp. 197-210.

[7]Vasiloff, S., Doviak, R. J., and Istok, M. T., "Weather Radar Interlaced Scanning Strategy," *Journal of Atmospheric and Oceanic Technology,* Vol. 4, 1986, pp. 245-249.

[8]Browning, K. A. and Atlas, D., "The Initial Development of a Severe Storm as Observed by Radar," *A Family Outbreak of Severe Local Storms—A Comprehensive Study of the Storms in Oklahoma on 26 May 1963,* Part 1, edited by K. A. Browning and T. Fujita, Air Force Cambridge Research Lab Rept. AFCRL-65-695(1), 1965, Special Reports, No. 32.

[9]Doviak, R. J. and Lee, J. T., "Radar for Storm Forecasting and Weather Hazard Warning," *Journal of Aircraft,* Vol. 22, Dec. 1985, pp. 1059-1063.

[10]Mahapatra, P. R. and Zrnić, D. S., "Weather Safety Aspects in Future Civil Air Navigation," Preprints, National Technical Meeting of the Institute of Navigation, Long Beach, CA, Washington, DC, 1986.

[11]Durham, A. F., "NEXRAD: A Doppler Radar System for Weather Recognition and Forecasting," International Geoscience and Remote Sensing Symposium (IGARSS'85), *Digest,* Vol. 1, 1983, WP-5, 1.1-1.6.

[12]Witt, A. and Nelson, S. P., "The Relationship Between Upper-Level Divergent Outflow Magnitude as Measured by Doppler Radar and Hailstorm Intensity," Preprints, 22nd Conference on Radar Meteorology, Zurich, Switzerland, 1984, pp. 108-111.

[13]Lemon, L. R., "Wake Vortex Structure and Aerodynamic Origin in Severe Thunderstorms," *Journal of Atmospheric Science,* Vol. 33, 1976, pp. 678-685.

[14]NEXRAD Joint System Program Office, "Next Generation Weather Radar Algorithm Report," 1985.

[15]Holitza, F. J., Smart, J. R., McAdie, C. J., Muller, P. A., Schroeder, R. D. and Benson, T. L., "Final Report Prepared by the NEXRAD Joint System Program Office," 1984.

[16]Bringi, V. N., Seliga, T. A., and Aydin, K., "Hail Detection with a Differential Reflectivity Radar," *Science,* Vol. 225, 1984, pp. 1145-1147.

[17]Zrnić, D. S., "Three Body Scattering Produces Precipitation Signatures of Special Diagnostic Value," *Radio Science,* Vol. 22, 1987, pp. 76-86.

[18]Browning, K. A. and Wakins, C. D., "Observations of Clear Air Turbulence by High Power Radar," *Nature,* Vol. 227, 1970, pp. 260-263.

[19]Doviak, R. J. and Zrnić, D. S., *Doppler Radar and Weather Observations,* Academic Press, Orlando, FL.

[20]Brewster, K. A. and D. S. Zrnić, "Comparison of Eddy Dissipation Rates from Spatial Spectra of Doppler Velocities and Doppler Spectrum Widths," *Journal of Oceanic and Atmospheric Technology,* Vol. 3, 1986, pp 440-452.

[21]Fujita, T. T., "Tornadoes and Downbursts in the Context of Generalized Planetary Scales," *Journal of Atmospheric Science,* Vol. 38, 1981, pp. 1511-1534.

[22]McCarthy, J. and Serafin, R., "The Microburst: Hazard to Aviation," *Weatherwise,* Vol. 37, No. 3, 1984, pp. 120-127.

[23]Fujita, T. T., *The Downburst Microburst and Macroburst,"* University of Chicago Press, Chicago, IL, 1985.

[24]Elmore, K. L., McCarthy, J., Frost, W., and Chang, H. P., "A High Resolution Spatial and Temporal Multiple Doppler Analysis of a Microburst and Its Application to Aircraft Flight Simulation," *Journal of Climate and Applied Meteorology,* Vol. 25, 1986, pp. 1398–1425.

[25]Eilts, M. D. and Doviak, R. J., "Oklahoma Downbursts and Their Asymmetry," *Journal of Climate and Applied Meteorology,* Vol. 26, 1987, pp. 69–78.

[26]Klingle, D. L., "A Gust Front Case Studies Handbook," FAA Rept. FAA-PM-84/15, 1985.

[27]Goff, R. C., Lee, J. T., and Brandes, E. A., "Gust Front Analytical Study," FAA Rept. FAA-RD-77-119, 1977.

[28]Eilts, M. D., "Low Altitude Wind Shear Detection with Doppler Radar," *Journal of Applied Climate and Meteorology,* Vol. 26, 1987, pp. 96–106.

[29]Goff, R. C., "The Low-Level Wind Shear Alert System (LLWSAS)," FAA Rept. FAA-RD-80-45, 1980.

[30]Uyeda, H. and Zrnic', D. S., "Automatic Detection of Gust Fronts," *Journal of Atmospheric and Oceanic Technology,* Vol. 3, 1986, pp. 36–50.

[31]Kessler, E., "Wind Shear and Aviation Safety," *Nature,* Vol. 315, No. 6016, 1985, pp. 179–180.