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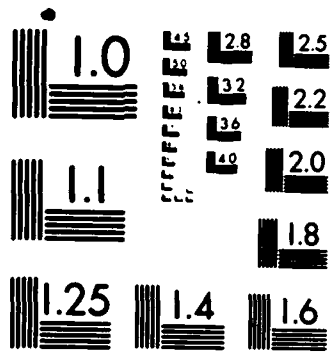

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Storm Precipitation and Wind Structure During Aircraft Strike Lightning Events

ALAN R. BOHNE
ALBERT C. CHMELA

24 May 1985

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ATMOSPHERIC SCIENCES DIVISION PROJECT 6670
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731

"This technical report has been reviewed and is approved for publication"

FOR THE COMMANDER

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A limited set of in-situ aircraft and ground-based radar data acquired during the 1981 and 1982 Joint Agency Turbulence Experiment are used to study the relationship of aircraft lightning strikes to storm precipitation, turbulence severity, and wind shear. The strikes are found to be strongly correlated with vertical drafts, predominantly downdrafts. The strikes were also well correlated with regions of strong turbulence. However, since most strong turbulence episodes were not associated with lightning, use of lightning location methods to locate hazardous turbulence within storms is considered unreliable. The strikes occurred in storm regions having radar reflectivity factor between 25 to 35 dBZ. These regions were generally on the boundaries of the dominant storm precipitation cores. Storm wind shear was frequently high in regions near aircraft strikes. The strong correlations with strong turbulence, downdraft boundaries, and precipitation core boundaries suggest that the strikes occurred in regions of charge separation.

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1. INTRODUCTION

During the spring and early summer periods of 1981 and 1982 the Air Force Geophysics Laboratory participated in the Storm Hazards Program of NASA Langley Research Center and NASA Wallops Flight Center, Virginia. The Air Force effort was termed the Joint Agency Turbulence Experiment, and was primarily directed towards developing radar techniques for detecting and classifying turbulence in storms. Radar measurements of reflectivity factor, Doppler radial velocity, and in-phase and quadrature return data were obtained with AFGL Doppler processing equipment, which was incorporated into the NASA Wallops SPANDAR radar. Estimates of turbulence severity derived from the pulse-to-pulse data were compared with the in-situ aircraft estimates of turbulence severity. Methods were developed that enabled the radar to enjoy considerable success in locating the nonhazardous and hazardous turbulence zones within the thunderstorms penetrated by the instrumented aircraft. The results of the AFGL effort are presented in the Final Report of the Joint Agency Turbulence Experiment.[1]

(Received for Publication 23 May 1985)

1. Bohne, A. R. (1985) Joint Agency Turbulence Experiment--Final Report, AFGL-TR-85-0012.

While the AFGL effort was directed towards turbulence detection, the NASA effort was directed towards studying the effects of lightning strikes to aircraft, and the general meteorological effects of lightning events on the local atmosphere. The aircraft lightning strike events were correlated with aircraft penetration altitude, temperature, precipitation, and turbulence structure. Their observations showed that lightning strikes to the aircraft occurred most frequently in the upper portions of storms, high above the freezing level. Peak strike rates were observed at altitudes between 38 to 40 kft, with ambient temperatures well below - 40°C. Relatively few strikes were obtained near the freezing level. Lightning strikes were not well correlated with regions of heavy precipitation or turbulence.

The lightning strike activity observed by the NASA aircraft may, in some cases, reflect events that were triggered by the aircraft itself. It is unlikely that the aircraft penetrated existing lightning currents, although these triggered events did appear similar to naturally occurring intracloud flashes. In addition to direct strikes there were a small number of nearby flashes, generally within a few km of the aircraft, which triggered onboard equipment but did not intercept the aircraft. Whether these were a result of modification of the local electric field by the presence of the aircraft is unknown. Thus, the observations here may reflect both natural and triggered lightning activity within the storms. The results of the NASA effort are summarized in a final report.[2]

Other researchers have investigated the occurrence of lightning in storms, with frequently differing results. These efforts were generally performed with remote UHF, VHF, or sferic measurement equipment. Generally, the results indicated that naturally occurring lightning originates in layers, usually 2 to 3 km thick and located in midlevel to upper level storm regions.[3-5] Most lightning events are mainly horizontal in extent.[3,6] They frequently originate near the

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2. Fisher, B. D., Brown, P. W., and Plumer, J. A. (1985) NASA Storm Hazards Lightning Research, Flight Safety Foundation Thirteenth Corporate Aviation Safety Seminar, 14-16 April, 1985, Dallas/Fort Worth Apt, Texas.

3. MacGorman, D. R., Taylor, W. L., and Few, A. A. (1983) Some spatial and temporal relationships between lightning and storm structure and evolution, Proceedings Addendum, Eighth Inter. Aero. and Ground Conf. on Lightning and Static Elec., Ft. Worth, Texas.

4. Fitzgerald, D. R. (1985) Thunderstorm Activity, The Handbook of Geophysics and the Space Environment, Chapter 20.2, (in press).

5. Taylor, W. L., Rust, W. D., MacGorman, D. R., and Brandes, E. A. (1983) Lightning activity observed in upper and lower portions of storms and its relationship to storm structure from VHF mapping and Doppler radar, Proceedings, Eighth Inter. Aero. and Ground Conf. on Lightning and Static Elec., Ft. Worth, Texas.

6. Proctor, D. E. (1983) Lightning and precipitation in a small multicellular thunderstorm, J. Geophys. Res. 88(No. C9):5421-5440.

precipitation cores and extend towards areas of lighter precipitation.[7-9] Occasionally, however, no clear association of lightning source regions and precipitation are observed.[10,11]

There have been a small number of observations correlating lightning activity with storm wind fields. These data were usually obtained through use of Doppler radar in addition to the traditional lightning mapping techniques. A very loose pattern emerged showing lightning sources somewhat correlated with divergent storm flows, regions of strong wind shear, and updraft and downdraft regions.[3,5,12]

The data presented here represent the storm wind, turbulence, and precipitation reflectivity factor structure during periods of aircraft lightning strike events. Since the AFGL effort was directed towards turbulence measurement, only a very limited number of lightning episodes are available for discussion. Nonetheless, a strong correlation of lightning activity is found with storm downdrafts, heavy precipitation core boundaries, and strong turbulence regions.

2. DATA ANALYSIS

The aircraft and radar data presented are storm reflectivity factor, aircraft gust measurements, and estimated turbulence severity. During operations the radar operated in two distinct scan modes. During storm penetrations the NASA Wallops SPANDAR radar tracked the NASA instrumented aircraft. In between penetrations the radar performed a general series of sector scans, sequentially elevated. The storm reflectivity data are plotted on either constant height surfaces or on track surfaces. The constant height plots were generated by traditional methods of interpolating the reflectivity data from the elevated scan sequences onto constant height surfaces, using a linear trivariate weighting function

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7. MacGorman, D. R., Few, A. A., and Teer, T. L. (1981) Layered lightning activity, J. Geophys. Res. 86(No. C10):9900-9910.

8. Ligda, M. G. H. (1956) The radar observation of lightning, J. Atmos. Terr. Phys. 9:329-346.

9. Rust, W. D., and Doviak, R. J. (1982) Radar research on thunderstorms and lightning, Nature 297:461-468.

10. Fitzgerald, D. R. (1967) Probable aircraft "triggering" of lightning in certain thunderstorms, Mon. Wea. Rev. 95(No. 12):835-842.

11. Mazur, V., Fisher, B. D., and Gerlach, J. C. (1983) Conditions conducive to lightning striking an aircraft in a thunderstorm, Proceedings, Eighth Inter. Aero. and Ground Conf. on Lightning and Static Elec., Fort Worth, Texas, pp. 90-1 - 90-7.

12. Carte, A. E., and Kidder, R. E. (1977) Lightning in relation to precipitation, J. Atmos. Terr. Phys. 39:139-148.

to determine the proper contribution to the surface grid points. These, when shown, usually represent the storm reflectivity at aircraft penetration altitude. The aircraft tracks are time adjusted to properly place them relative to the storm structure at plot time. Frequently, however, due to the rapid turnaround of the aircraft from the exit of one penetration to the start of the next penetration, a coordinated sector scan sequence was not obtained. In this instance, the storm reflectivity factor along the aircraft track surface is presented. The track surface is a planar surface defined to include the straight aircraft penetration at penetration altitude, and a parallel line at the ground, passing through the radar position. In this instance, a linear bivariate interpolation scheme was used to interpolate the radar reflectivity data to the surface grid points.

The aircraft gust data represent the three orthogonal longitudinal, latitudinal, and vertical wind components. They have not been decomposed into aircraft relative longitudinal, transverse, and vertical components. The horizontal data are used to show the horizontal storm gust structure, a composite of the relatively stationary storm wind structure, and the smaller scale turbulence structure. The vertical gust data clearly indicate the presence of significant updraft and downdraft regions. The vertical wind speed values occasionally appear to need adjustment to remove a bias that may be present in the data. This may be accomplished by averaging the trace along its full extent and assuming that the mean vertical velocity should be approximately zero, or assuming that the vertical current should be close to zero near the radar storm boundary. Both methods may themselves be inaccurate however, particularly when performed over only a portion of a storm penetration. Suggested corrections will be noted where applicable.

The aircraft turbulence severity data were obtained from analysis of the gust data. Here, however, the horizontal gust components have been transformed into aircraft relative coordinates, parallel (longitudinal) and transverse to the penetration tracks. This coordinate system was found most useful in the turbulence study.[1] The manner of obtaining the turbulence severity from the aircraft gust data is fully outlined in the Joint Agency Turbulence Experiment Final Report. Simply stated, the aircraft data were used in a structure function analysis. A segment of gust data, centered about the track location in question, served as input data to the structure function analysis. The segment was increased in size until the structure function and turbulence severity estimates, for separation distances considered to lie in the inertial subrange, became stable. That is, these quantities become essentially constant even though the data segment size was increasing. A data segment length of about 1200 m was generally found sufficient to ensure this condition was met. Larger segment lengths were not employed for it was found that with continued increase in segment length, the quasi-stationary storm wind field structures would eventually contaminate the turbulence severity estimates. In these instances the estimates were not constant, but changed continuously with increasing segment size. Thus, the turbulence severity estimates presented here are believed to represent well the turbulence environment, with relatively minor contribution from the more stationary, larger scale storm wind field.

The aircraft gust data were also employed to estimate the maximum storm wind shear near lightning strike periods. One-second gust velocity averages were formed. The maximum and minimum values, which were located within about 5 sec of lightning strike time, were used to estimate the local maximum shear value. Care was taken to ensure that the gust excursions signified a true alteration in the structure of the storm wind field, and were not simply a result of a sudden turbulent burst.

3. OBSERVATIONS

The first period for consideration occurred during penetration of a small storm located approximately 124 km to the southwest of the SPANDAR radar. The aircraft penetration altitude is 4.57 km msl. The environmental winds are light, being 21 m/sec from the southeast. Figure 1 presents the storm reflectivity factor at the penetration altitude. The aircraft passes through the northern portion of the single storm core in regions of 10 to 30 dBZ. It is seen that the nearby lightning event occurs when the aircraft was in a region near 25 dBZ. The aircraft is just beginning to exit the storm core and is approximately 4 km from the center of the core.

Figure 2 portrays the aircraft gust data during this storm penetration. The lightning event is seen to occur within 4 sec of a strong storm wind shear feature. This shear zone is relatively small in horizontal extent, occurring over a distance of roughly 800 m (about 4 sec). The estimated storm shears in the E-W and N-S directions are quite large, being about 2.8×10^{-2} sec and 2.2×10^{-2} sec, respectively.

The vertical gust trace indicates that this wind shear was coincident with a downdraft of about 6 m/sec. The aircraft was in a second small downdraft of about 5 m/sec when the nearby flash occurred. It also appears that a small, but sharp, upward air current was located in between these two downdraft regions. Although there may be a bias in the gust speed values, it is highly unlikely that any adjustment would alter the observation that the lightning event occurred when the aircraft had been in a region of moderate downdraft.

The turbulence severity estimates are presented in Figure 3. The plots indicate that the lightning event occurred when the severity was about 6 $cm^{2/3}$/sec, which would generally be considered moderate to heavy in value. The lightning

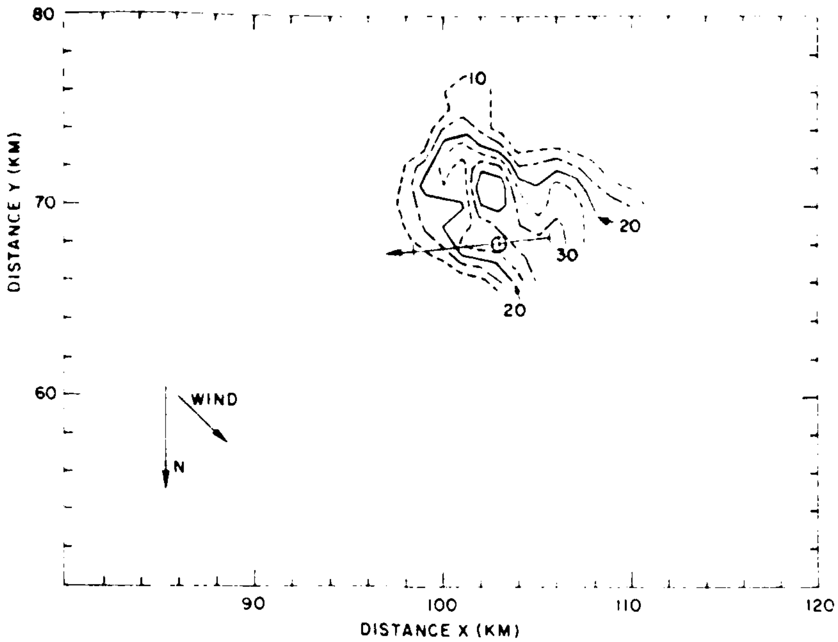

Figure 1. Contours of Reflectivity Factor for 1 July 1981 on a Constant Height Surface at Penetration Altitude of 4.57 km msl. Time is 18:17:00 GMT

event is seen to lie within about 400 m from a turbulence severity maximum of about 10 to 12 $cm^{2/3}/sec$. This value would be characterized as heavy to severe turbulence. It should also be noted that this nearby severity maximum represents the region of greatest severity along this storm track.

The next three lightning events to be presented were observed on 17 July 1982. Figures 4 and 5 depict the storm reflectivity factor on constant height surfaces during the first two and last penetrations. During these observations the storm was entering the dissipating stage, as evidenced by the decrease in maximum storm reflectivity factor, number of cores, and areal extent of the dominant storm cores, between these two periods. The maximum reflectivity factor was near 45 dBZ during the first two penetrations and had decreased to about 35 dBZ at the time of the third. The penetration altitudes were 7.8, 9.3, and 9.3 km msl, respectively. The environmental wind is out of the southwest at approximately 3.5 m/sec at these heights.

Figure 6 portrays the storm reflectivity factor structure along the track surface for the first lightning event. It is seen that the strike occurred when the aircraft was just entering the easternmost storm core. The reflectivity factor is about 25 dBZ, and the aircraft is about 4 km away from the center of this core.

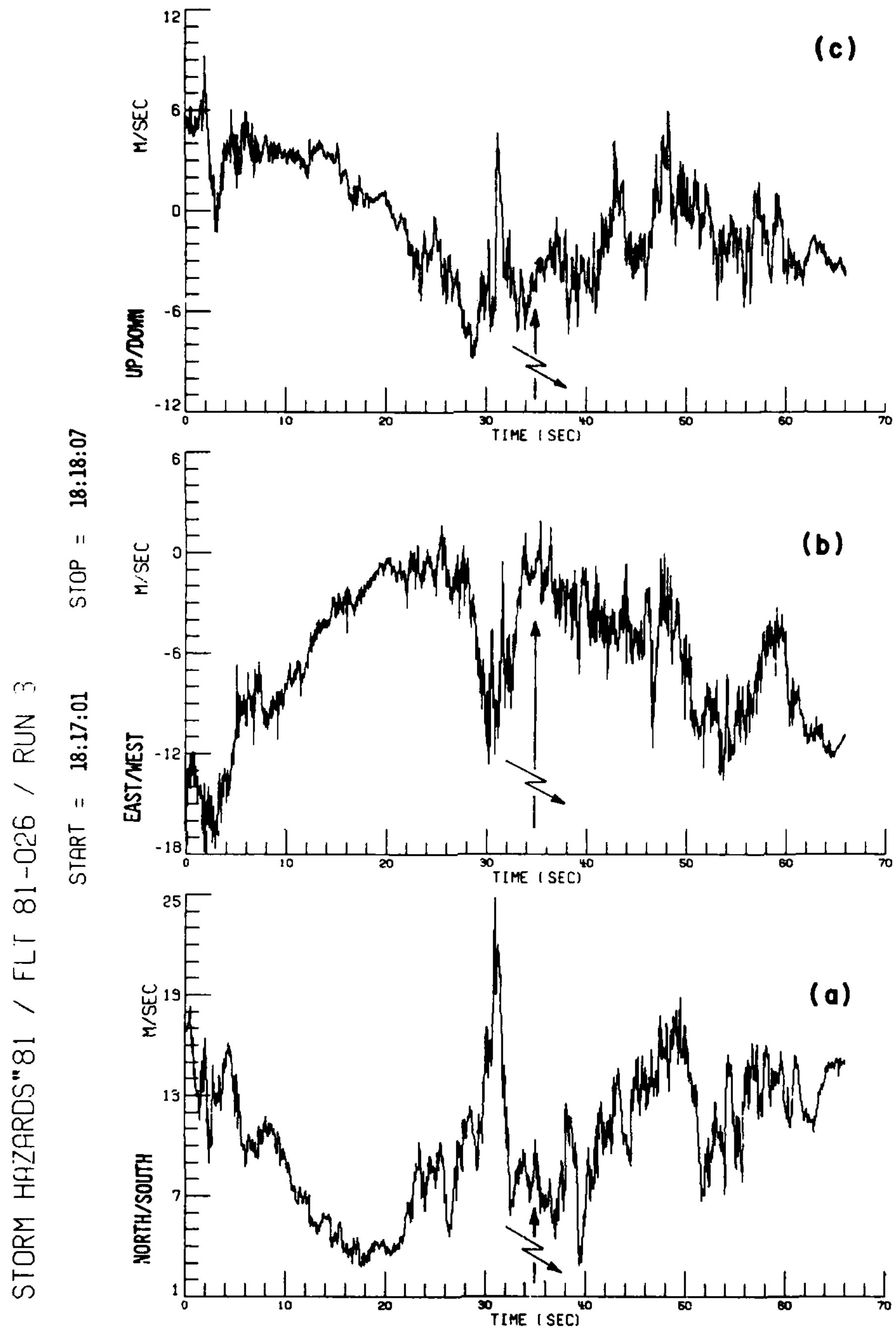

Figure 2. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 1 July 1981

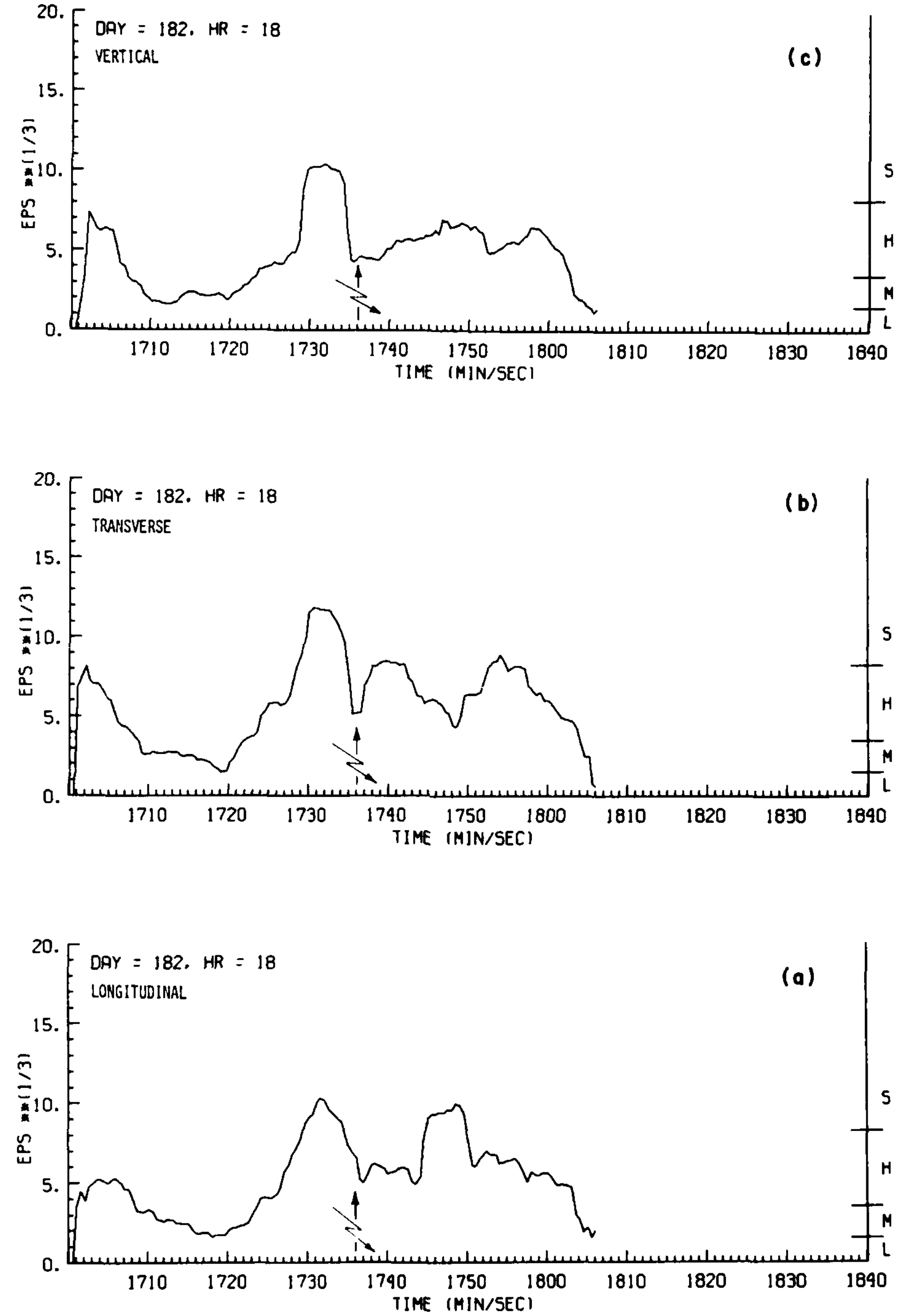

Figure 3. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 1 July 1981

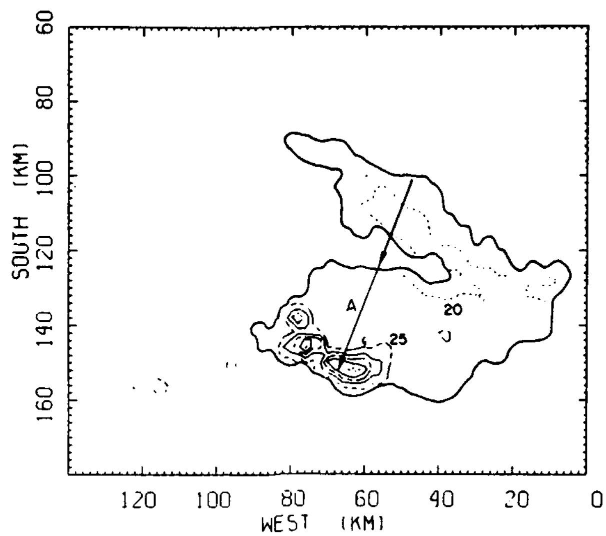

Figure 4. Contours of Reflectivity Factor for 17 July 1982 on a Constant Height Surface at an Altitude of 6.0 km msl. Time is 20:16:00 GMT

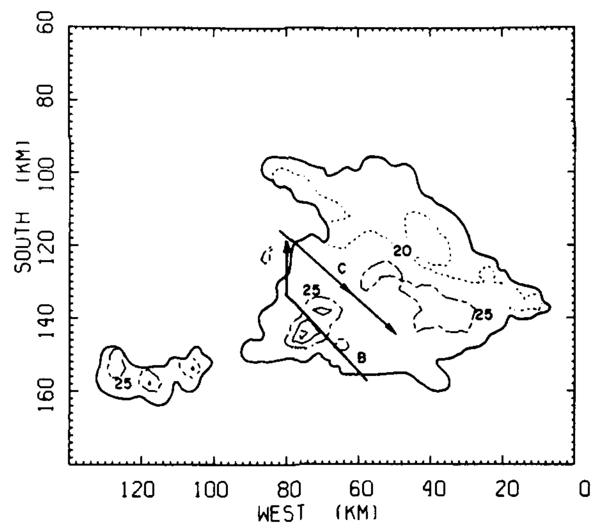

Figure 5. Contours of Reflectivity Factor for 17 July 1982 on a Constant Height Surface at an Altitude of 6.0 km msl. Time is 20:40:35 GMT

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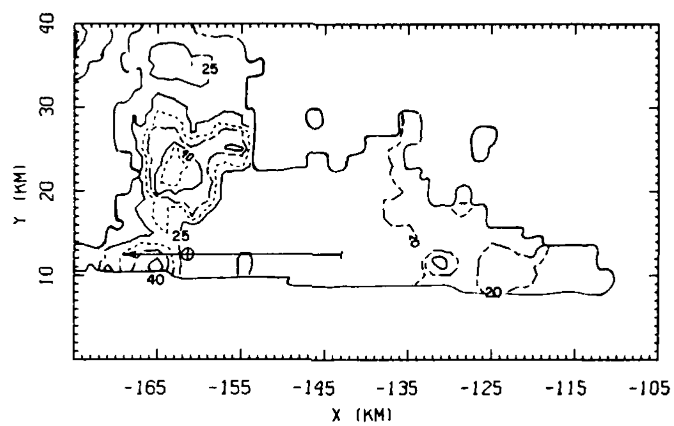

Figure 6. Contours of Reflectivity Factor for 17 July 1982 on Track Surface for Penetration A

The aircraft gust data (Figure 7) indicate that the aircraft had just entered a region of strong downdraft, with maximum vertical windspeed greater than 14 m/sec. The downdraft speed at time of strike is also greater than 14 m/sec. It is seen that this northern edge of the storm core is dominated by a downdraft region, broken into two segments of approximately 2.8 and 1.0 km width. The horizontal storm wind structure shows fairly sharp changes on scales of a few km. The smaller scale turbulence fluctuations are also seen to increase in strength in this downdraft region.

The storm wind shear estimates for the E-W and N-S directions are 4×10^{-2} sec and 3.5×10^{-2} sec, respectively. These values are indicative of strong shear, larger than that usually observed within general storm regions.

The turbulence severity estimates are presented in Figure 8. They indicate very mild turbulence away from this storm core, but increasing severity as the aircraft penetrates the 25 dBZ boundary. The three components exhibit severity values ranging from 6 to 9 $cm^{2/3}$/sec at strike time, and the lightning event is within 1200 m of the location of the severity maximum for this penetration. It is also observed that the turbulence severity is very strong throughout the entire storm core with maxima ranging from 9.5 to 14 $cm^{2/3}$/sec. These severity values indicate heavy to severe turbulence within the storm region.

The storm reflectivity factor on the track surface for the second lightning event is shown in Figure 9. Here the aircraft penetrates the northern portion of a storm core exhibiting a maximum reflectivity factor just over 35 dBZ. The lightning strike occurs at the 35 dBZ boundary as the aircraft is departing this high reflectivity region.

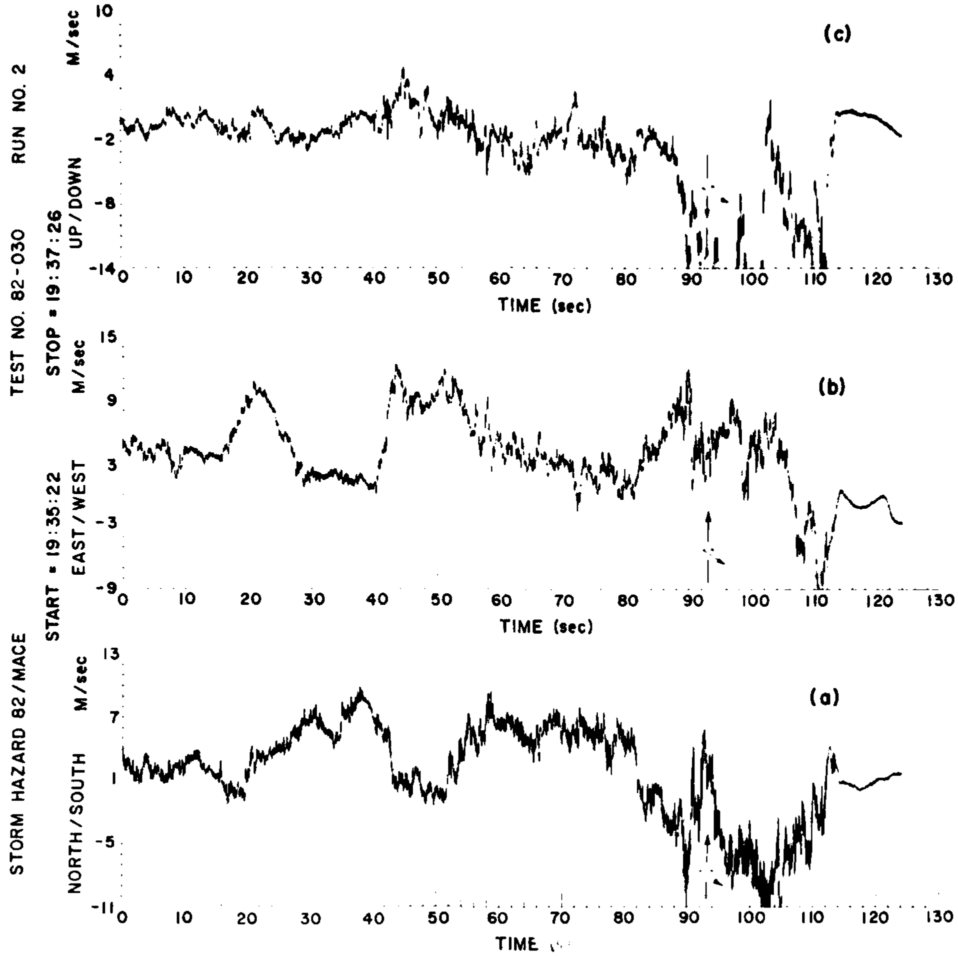

Figure 7. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 17 July 1982 for Penetration A

Figure 10 shows the lightning strike to occur in a region where the aircraft measured gusts are undergoing their most dramatic change along this penetration. The horizontal data are undergoing very strong fluctuations on a scale of 1 km or less. The vertical trace shows the aircraft is once again in a very strong downdraft at time of strike, with windspeeds in excess of 11 m/sec for both maximum downdraft and speed at time of strike. It is also noted that these strong gust fluctuations occur near the radar storm boundary. Most of the storm core is imbedded in a vertical draft structure varying from light updraft to moderate downdraft. The very strong vertical current resides on the outer boundary of the storm core. Overall, the downdraft region is roughly 3.2 km wide, with the intense portion, encountered at strike time, about 2.0 km wide.

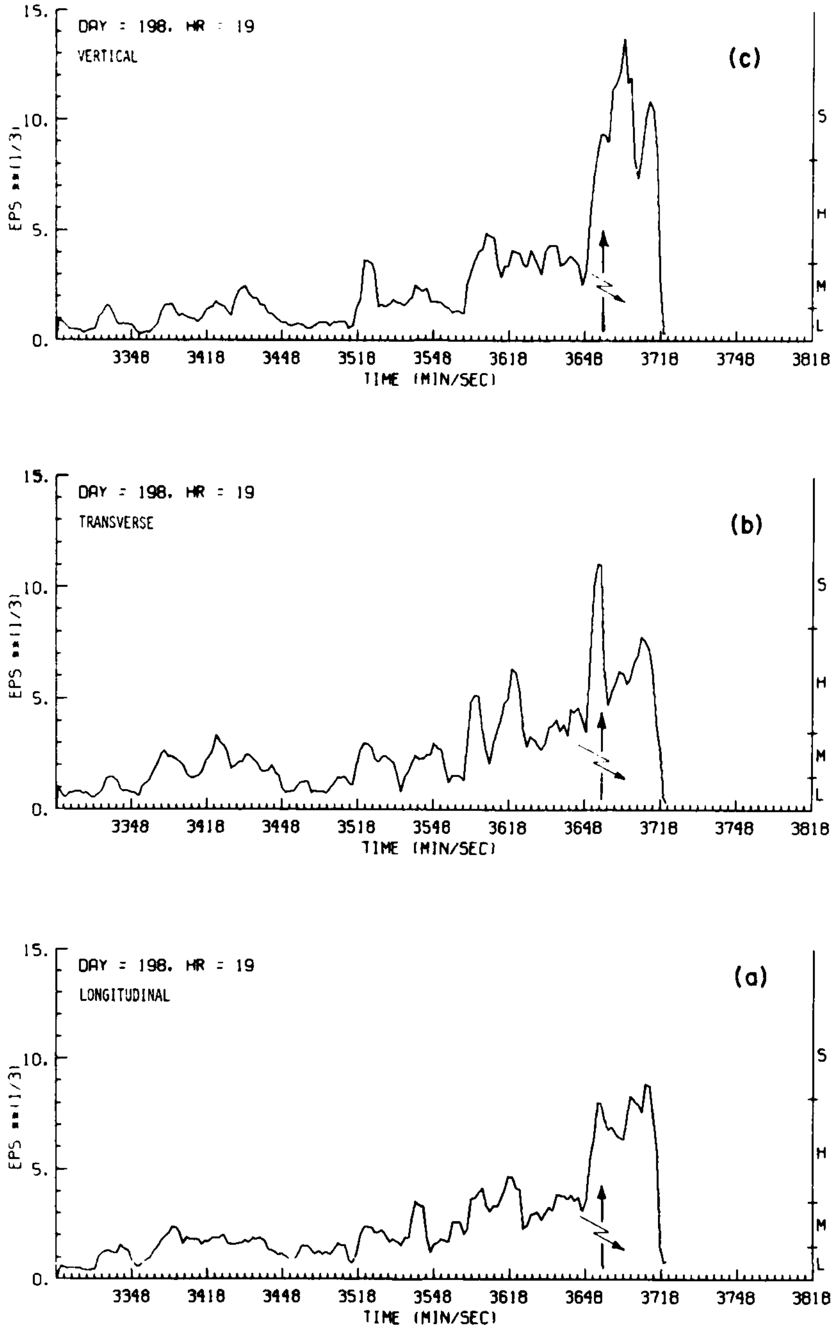

Figure 8. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 17 July 1982 for Penetration A

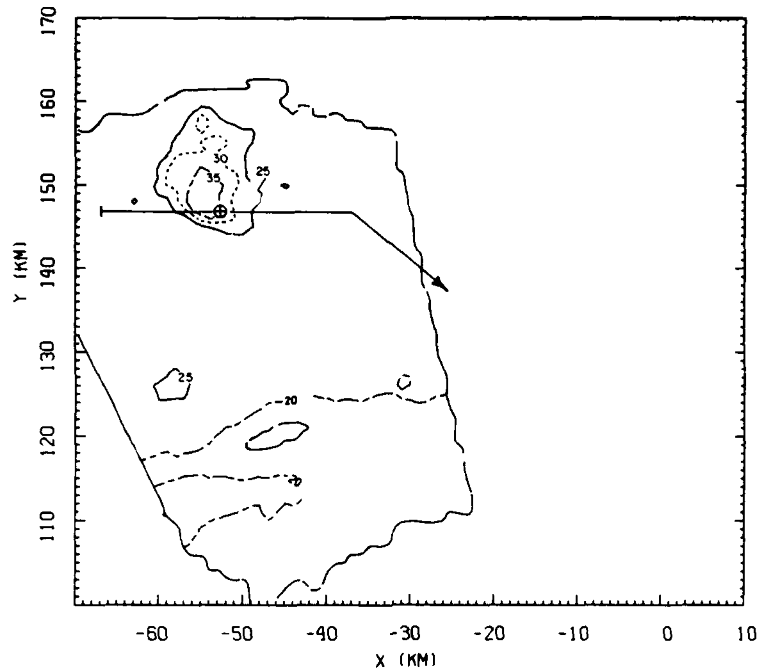

Figure 9. Contours of Reflectivity Factor for 17 July 1982 on Track Surface for Penetration B

The storm wind shear values are 1×10^{-2} sec and 1.6×10^{-2} sec for the E-W and N-S directions, respectively. Once again, these values are quite large and are representative of strong shear zones not typically observed in general storm regions.

Figure 11 shows the turbulence severity at strike time is clearly at a maximum for this entire penetration. The turbulence severity estimates range from 9.5 to 15 $cm^{2/3}/sec$, once again clearly in the range of heavy to severe turbulence. It is also noted that the severity is rather high for the entire penetration. This may be a result of precipitation induced downdraft mixing with local environmental air, resulting in the dramatic fluctuations observed on the edge of this storm.

The track surface plot of storm reflectivity factor for the third strike is shown in Figure 12. The strike occurs as the aircraft is just about to penetrate the 25 dBZ contour, which represents the northern boundary of this storm core.

Figure 13 displays the aircraft gust data. The lightning strike is seen to occur within a region where the horizontal winds are undergoing significant modification. The initial strong increase in speed in the northern component on the western side of this storm may represent environmental flow around the storm

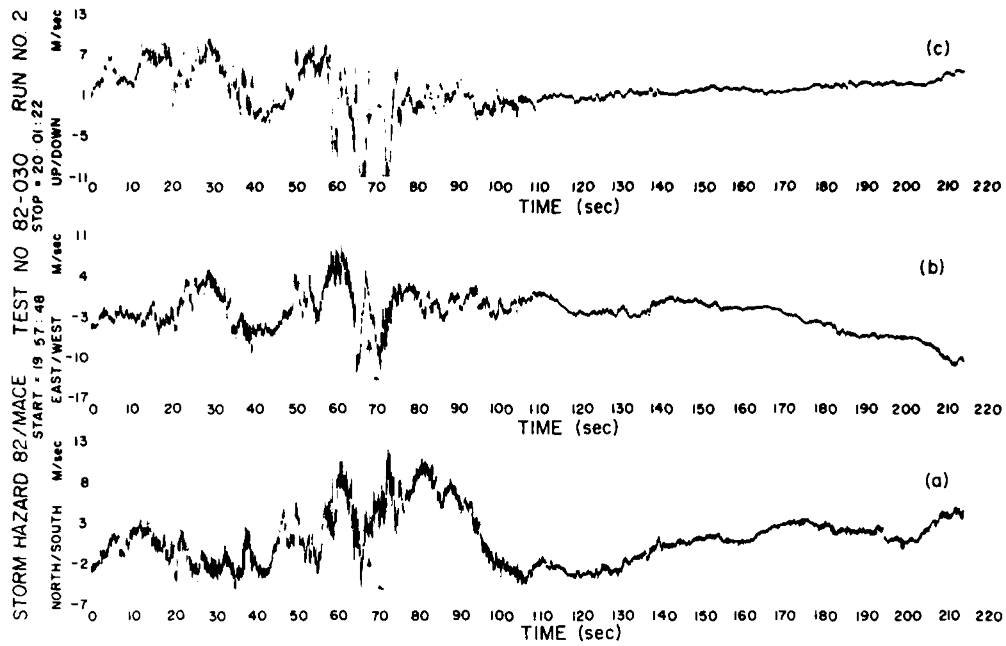

Figure 10. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 17 July 1982 for Penetration B

core, the core representing an obstacle to the oncoming air. The sudden decrease in windspeed just before the strike, adjacent to the western boundary of the 25 dBZ contour, may represent a divergent zone behind the core on the downwind side. The variation in the horizontal wind structure is more pronounced at this time than during the rest of the penetration. The vertical gust data show that the strike occurred in a region of slight upward moving air. Also note that is occurred within about 300 m of a very narrow downdraft. The downdraft region is pronounced for its sharpness, being less than 400 m in width. The maximum downward airspeed is only about 3 m/sec (assuming a bias of about 1 m/sec in the data). Finally note that the turbulent fluctuations are greater in magnitude during this period than at any other time along the aircraft track.

The estimated storm shear values for the E-W and N-S directions are effectively zero and 8.0×10^{-3} sec, respectively. These values are significantly smaller than those observed during previous strike episodes.

The turbulence severity estimates in Figure 14 show the severity to be about 5 to 9 $cm^{2/3}$/sec at lightning strike time. The strike is essentially coincident with the period of strongest severity along the entire penetration. The maximum severity values lie in the range of 6 to 11 $cm^{2/3}$/sec. Once again these values lie in the heavy to severe range.

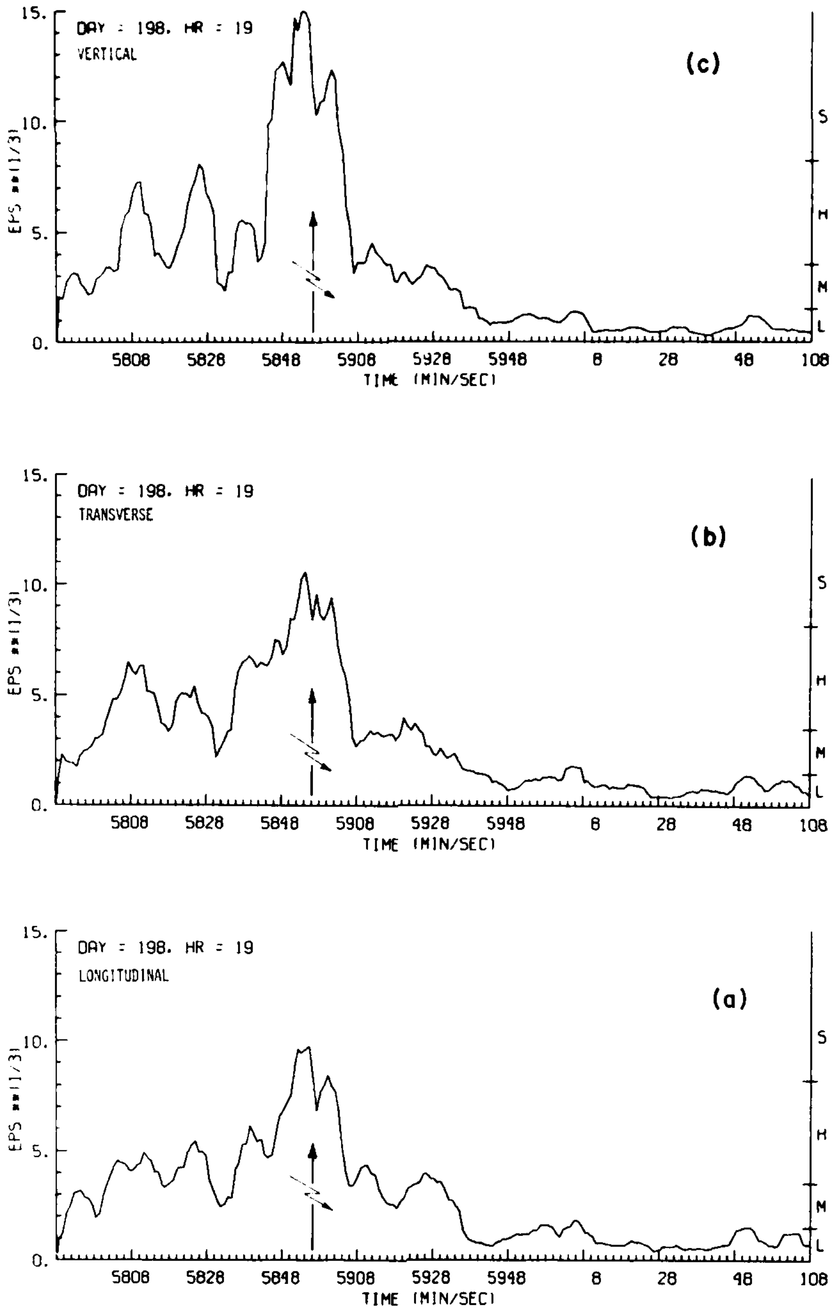

Figure 11. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 17 July 1982 for Penetration B

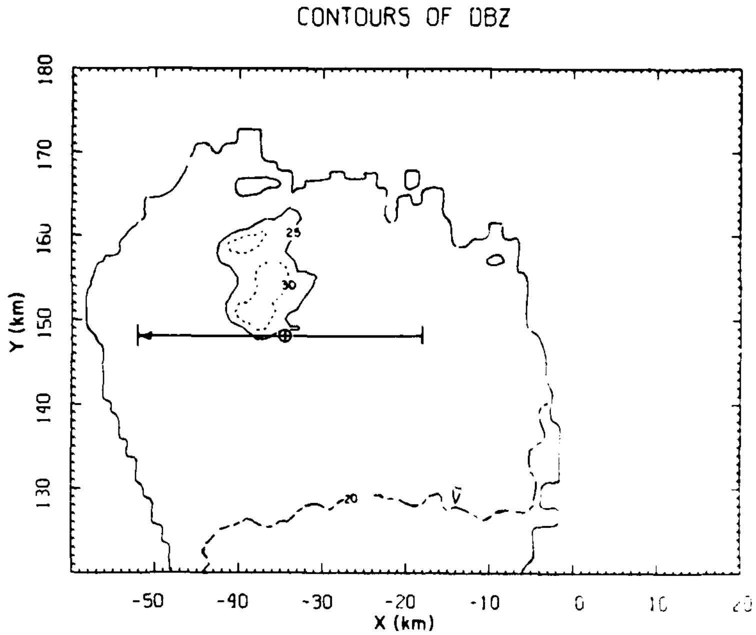

Figure 12. Contours of Reflectivity Factor for 17 July 1982 on Track Surface for Penetration C

The next penetration day for discussion is 28 July 1982. Here, an extensive line of storms, stretching about 200 km southwest to northeast, moved through the region. Figure 15 shows a constant height display of the southern portion of this line at an altitude of 3.0 km. The plan view of the aircraft track is shown to pass parallel to and along the northern side of this line. Figure 16 shows the storm structure on the track surface, which here is essentially a vertical slice (RHI surface) along an azimuth of about 251°. The penetration altitude is about 8.8 km. The strike occurs at the location of the 35 dBZ contour, within 2 km of the highest reflectivity factor for this particular storm core.

Figure 17 shows the aircraft gust data. Oddly, little significant fluctuation in the horizontal field components is observed. The changes in the horizontal components are not distinct from any other period along the penetration. The vertical trace, however, shows that the strike occurred when the aircraft was in a weak and narrow (less than 400 m wide) downdraft. More significantly, the strike occurs within 800 m of the edge of a pronounced downdraft. This downdraft is a minimum of 24 sec wide (nearly 5 km). Since most of the vertical gust for this track is downward moving, it is possible that there is a negative bias in the vertical gust data along the penetration. It is very unlikely that the indicated downward moving air could be sustained for a penetration length of roughly 40 km

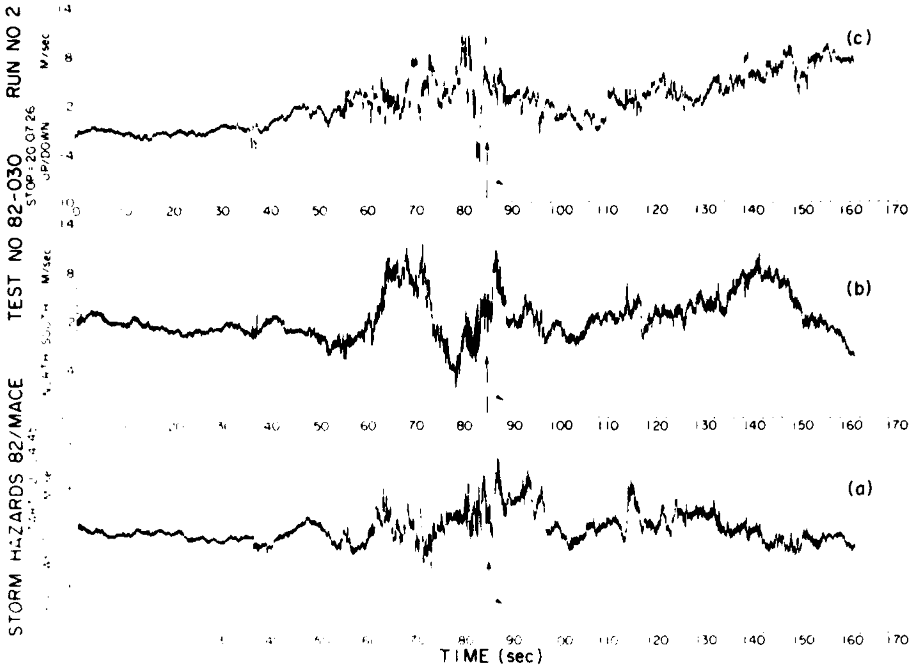

Figure 13. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 17 July 1982 for Penetration C

(200 sec) as shown here. It therefore is assumed that there is a negative bias of about 4 m/sec. Thus, the maximum downdraft speed is estimated to be about 13 m/sec.

The E-W and N-S components of storm wind shear are estimated to be negligible and 2.3×10^{-2} sec, respectively, once again indicating a strong shear zone near the lightning strike location.

Figure 18 shows the turbulence severity to range from 8 to 9 $cm^{2/3}$/sec at strike time, clearly in the heavy to severe range. The strike event is somewhat removed from the very strong severity region near 22:27:04 GMT (about 3.6 km away), where the severity would be considered extreme. This strike episode thus occurred in a highly turbulent region lying adjacent to a strong downdraft and rapidly settling precipitation core.

The next day for discussion is 30 July 1982. Here a rather dissociated system was penetrated. The constant height reflectivity plot for an altitude of 7.2 km is shown in Figure 19. The environmental wind is from the west southwest and the maximum storm reflectivity factor at this altitude is about 35 dBZ. The two strikes, which occurred at 6.9 km altitude, are shown on the track surface plot (Figure 20). They occur very close to the center of the 35 dBZ core, in a region

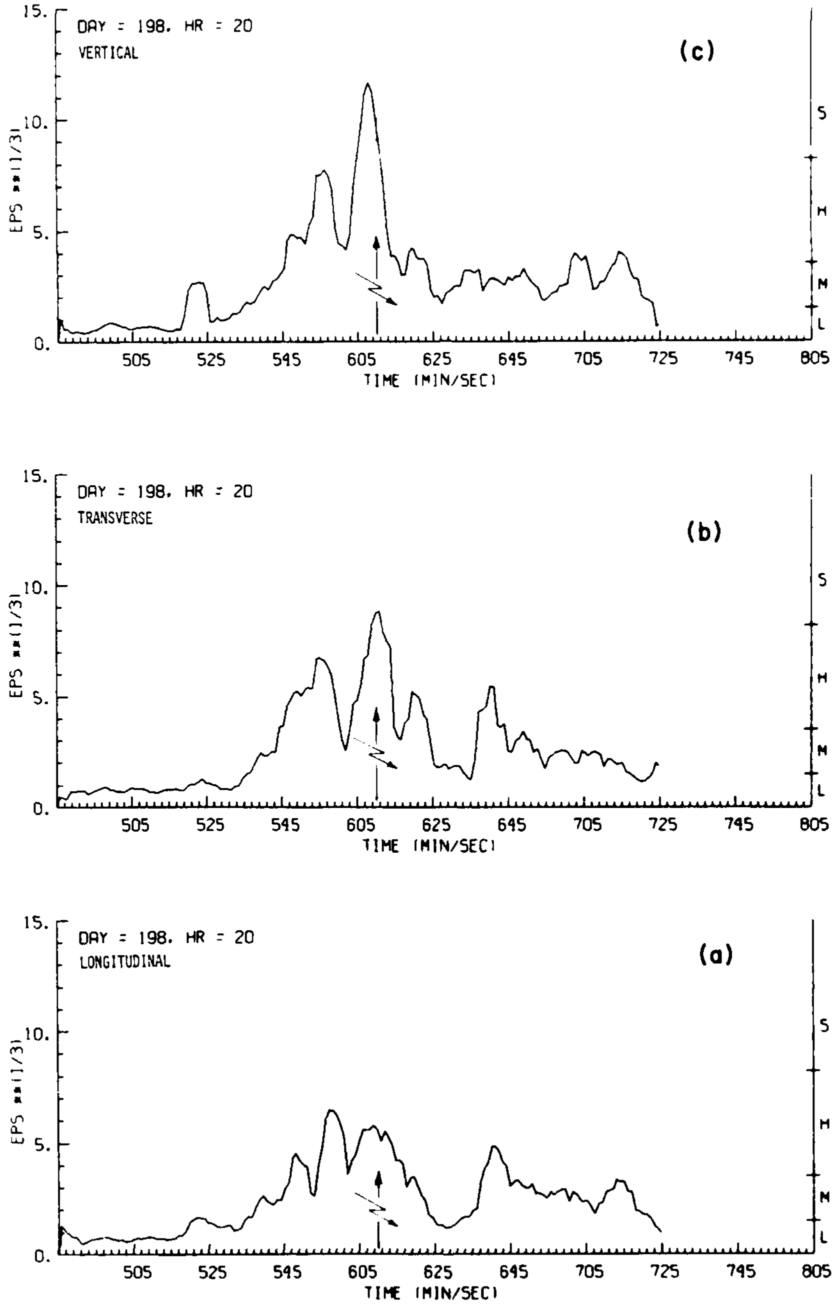

Figure 14. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 17 July 1982 for Penetration C

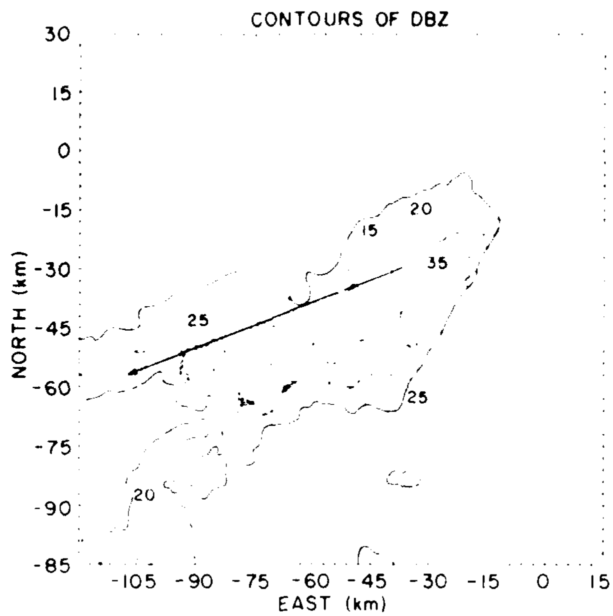

Figure 15. Contours of Reflectivity Factor for 28 July 1982 on a Constant Height Surface at an Altitude of 3.0 km msl. Time is 22:56:48 GMT

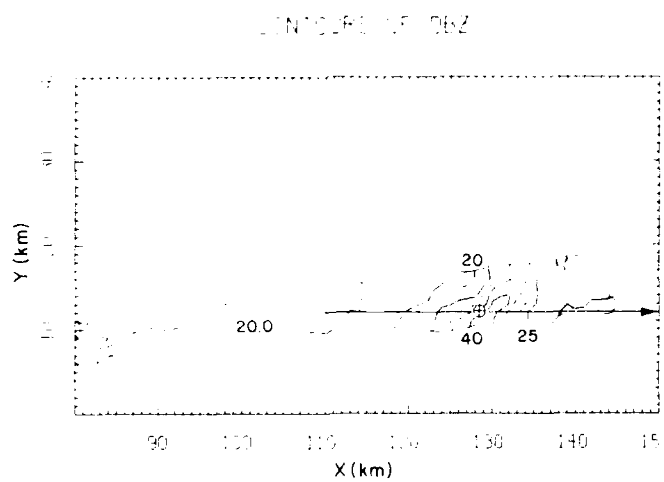

Figure 16. Contours of Reflectivity Factor for 28 July 1982 on Track Surface

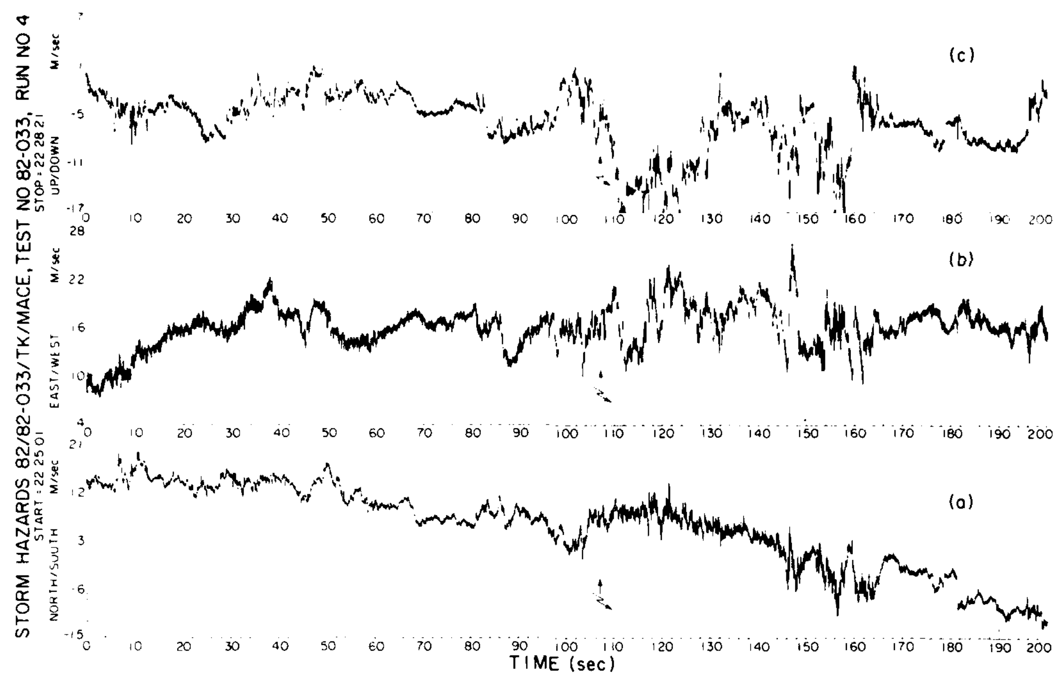

Figure 17. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 28 July 1982

of 30 to 35 dBZ. The two strikes occurred within 10 sec, or about 2 km, of one another.

The aircraft gust data, displayed in Figure 21, indicates no truly significant differences at strike times than from any other period along the penetration. The variations in the horizontal are, in fact, less severe than at other periods along the track. The only consistent feature noted is that the strikes occurred adjacent to, and within, downward moving air currents. The first strike is at a location exhibiting zero vertical air motion. The second strike occurs within a downdraft about 1 km width, and having maximum downward speed of 6 m/sec. A significant downward moving current is seen to occur about 10 sec, or 2 km, after the second strike. Similarly, a broad current of downward moving air is seen about 2 km before the first strike. This association of aircraft strike and downdraft storm region is by now a familiar pattern.

The shear components along the E-W and N-S directions are estimated to be about 2.0×10^{-3} sec and negligible for the first strike event, and 1.5×10^{-3} sec and negligible for the second strike, respectively. These values are not indicative of very strong sheared zones and may generally be considered typical of those values commonly observed in storms. They are also somewhat smaller than those observed during previous strike episodes.

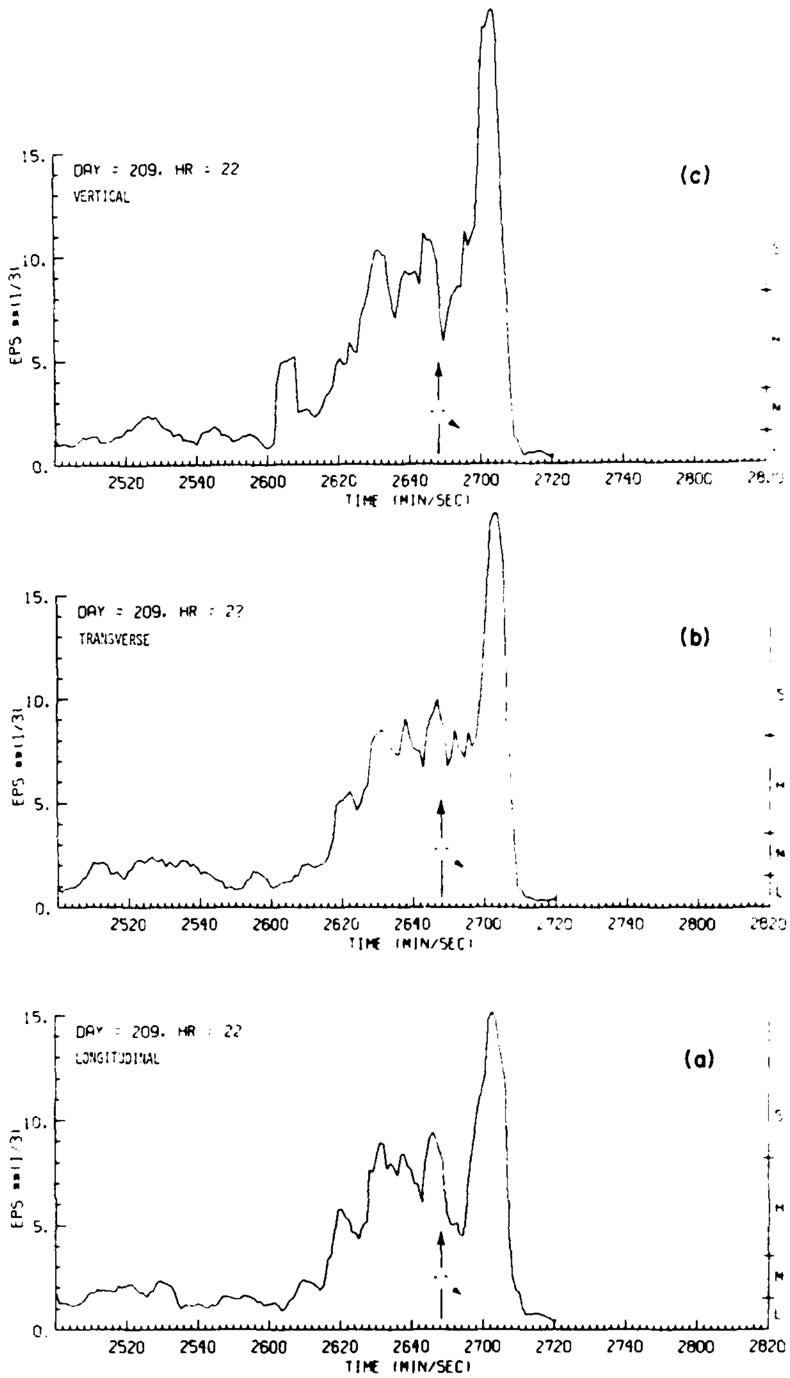

Figure 18. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 28 July 1982

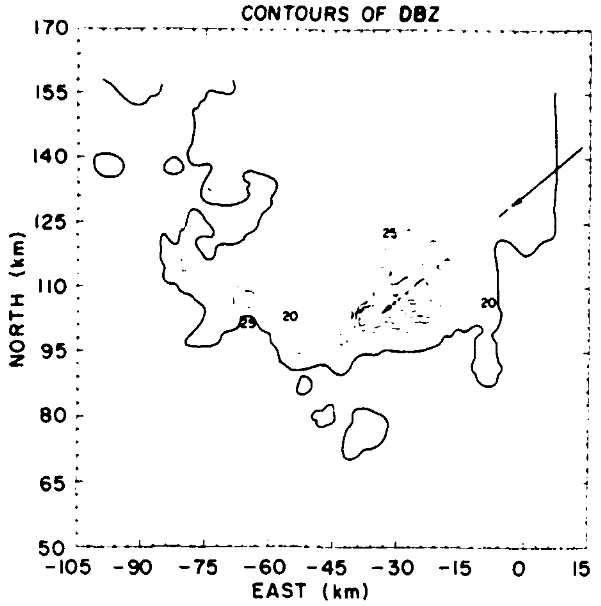

Figure 19. Contours of Reflectivity Factor for 30 July 1982 on a Constant Height Surface at an Altitude of 7.2 km msl. Time is 19:45:20 GMT

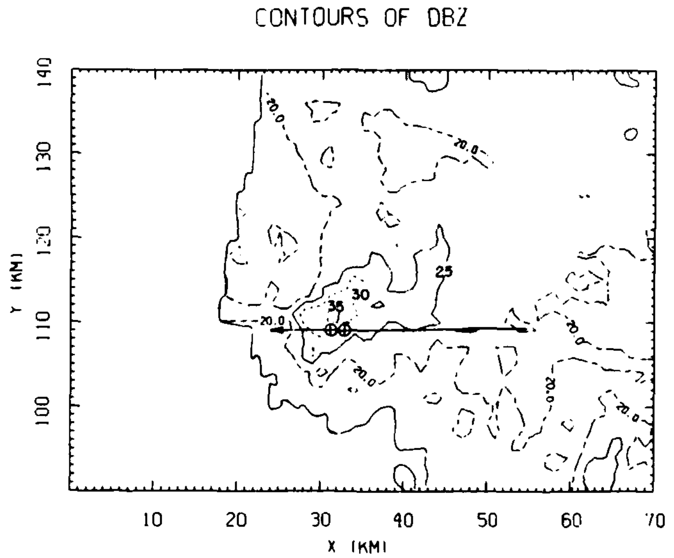

Figure 20. Contours of Reflectivity Factor for 30 July 1982 on Track Surface

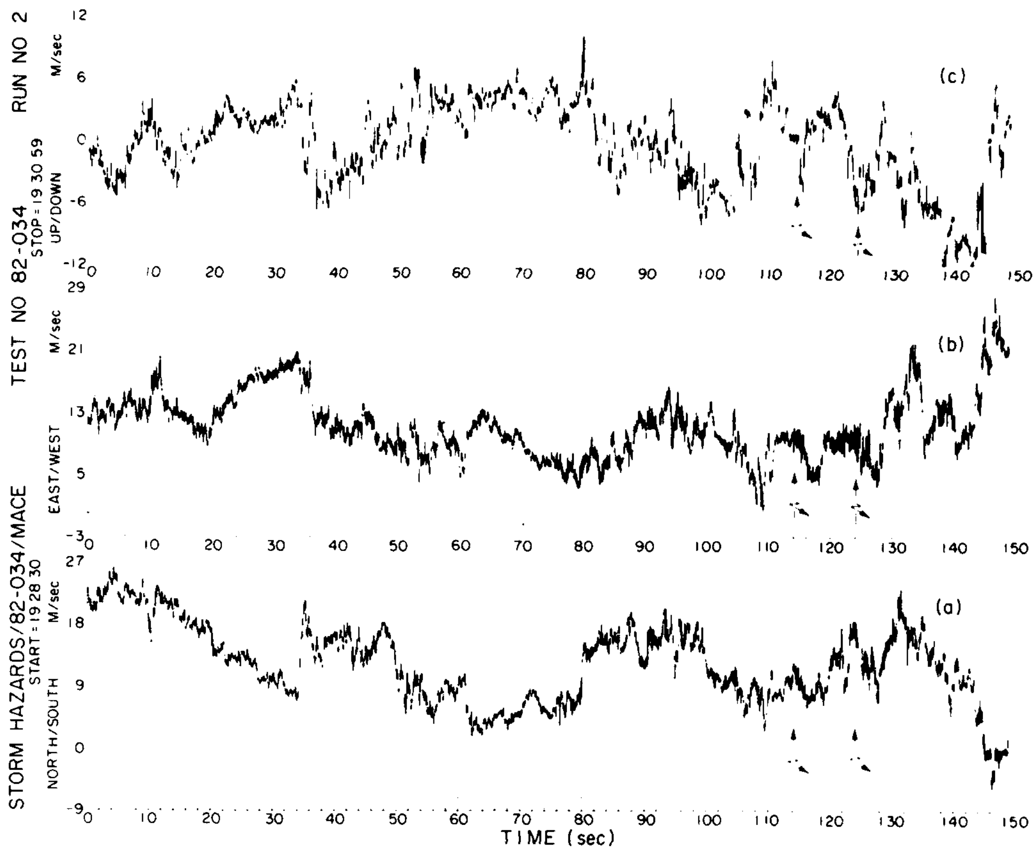

Figure 21. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 30 July 1982

The turbulence severity, displayed in Figure 22, indicates that the first strike occurred in severity of about 3 to 6 $cm^{2/3}$/sec, and the second strike was in somewhat heavier turbulence, with severity values in the range of 5 to 10 $cm^{2/3}$/sec. These severity episodes are not truly distinct from other periods observed along the track. Nonetheless, the severity at strike times still generally lie in the moderate to heavy range.

The last period to be discussed occurred during penetration of a long line of storms to the southwest of the SPANDAR radar. Figure 23 shows the reflectivity factor on a constant height surface at an altitude of 7.19 km msl. The maximum reflectivity factor is just over 30 dBZ, and the strike occurred at the 30 dBZ boundary at an altitude of 7.0 km.

The gust data, presented in Figure 24, shows the horizontal wind components exhibited considerable variation all along the penetration track. The variations near lightning strike time are not significantly different from any other period.

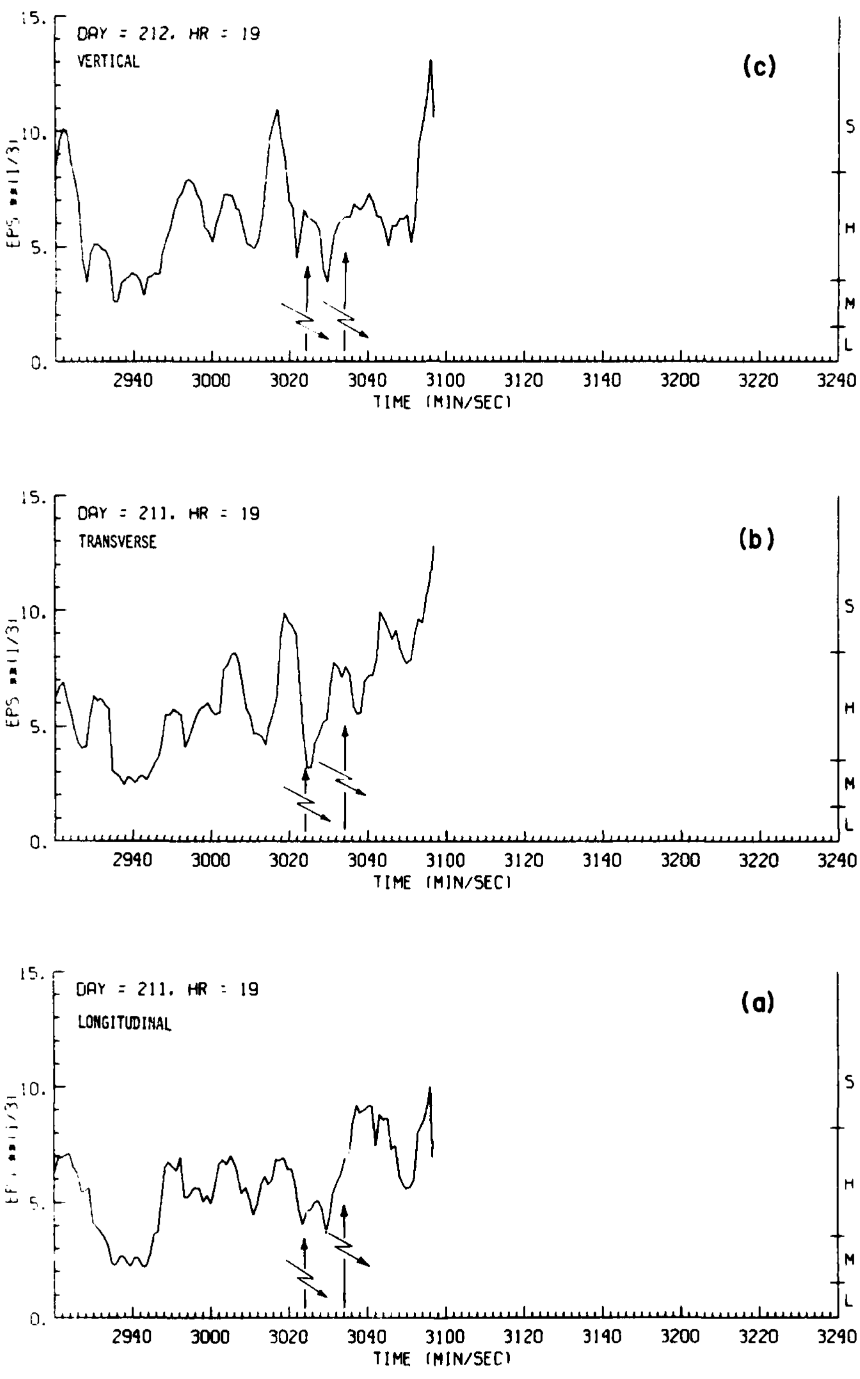

Figure 22. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 30 July 1982

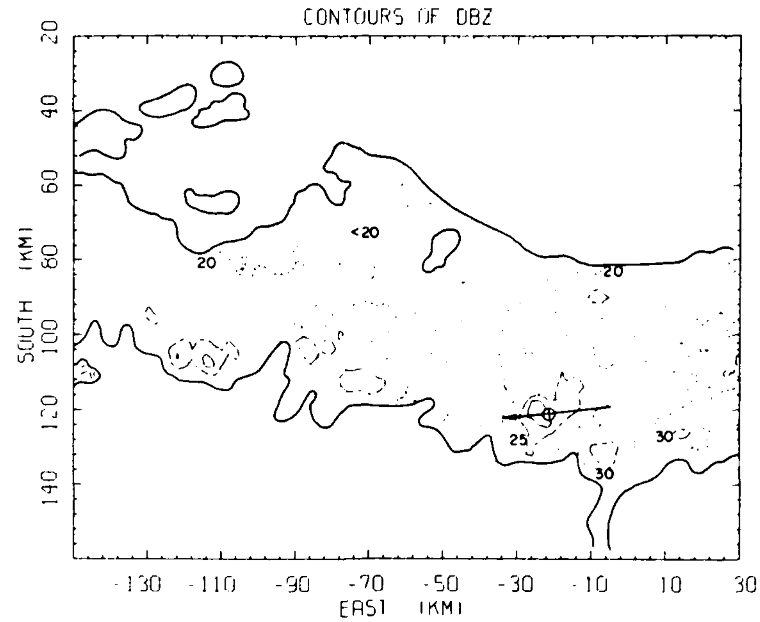

Figure 23. Contours of Reflectivity Factor for 31 July 1982 on Constant Height Surface at an Altitude of 7.19 km msl. Time is 20:14:52 GMT

What is significant, however, is that the aircraft is once again in a region of downward moving air. The downdraft is about 2 km wide, has a maximum downward speed of about 6 m/sec, and lies at the boundary of the precipitation core. The estimated E-W and N-S storm shear components are 1.75×10^{-2} sec for both directions and are indicative of a strongly sheared environment.

The turbulence severity values at strike time are 5 to 8 $cm^{2/3}/sec$, in the range of moderate to heavy turbulence severity (Figure 25). The strike occurred during, or near (10 sec, or about 2 km), peaks in turbulence severity. Although these peaks are not distinct from those observed in other portions of the track, they do represent strong turbulence episodes.

4. CONCLUSIONS

The data presented here detail the storm reflectivity factor, wind, and turbulence structure along aircraft storm penetrations during which lightning strikes to, or near to, the aircraft occurred. Certain persistent features were noted, and these are summarized in Tables 1 and 2. Table 1 describes the correlations of aircraft strike episodes with the storm wind and reflectivity features, while

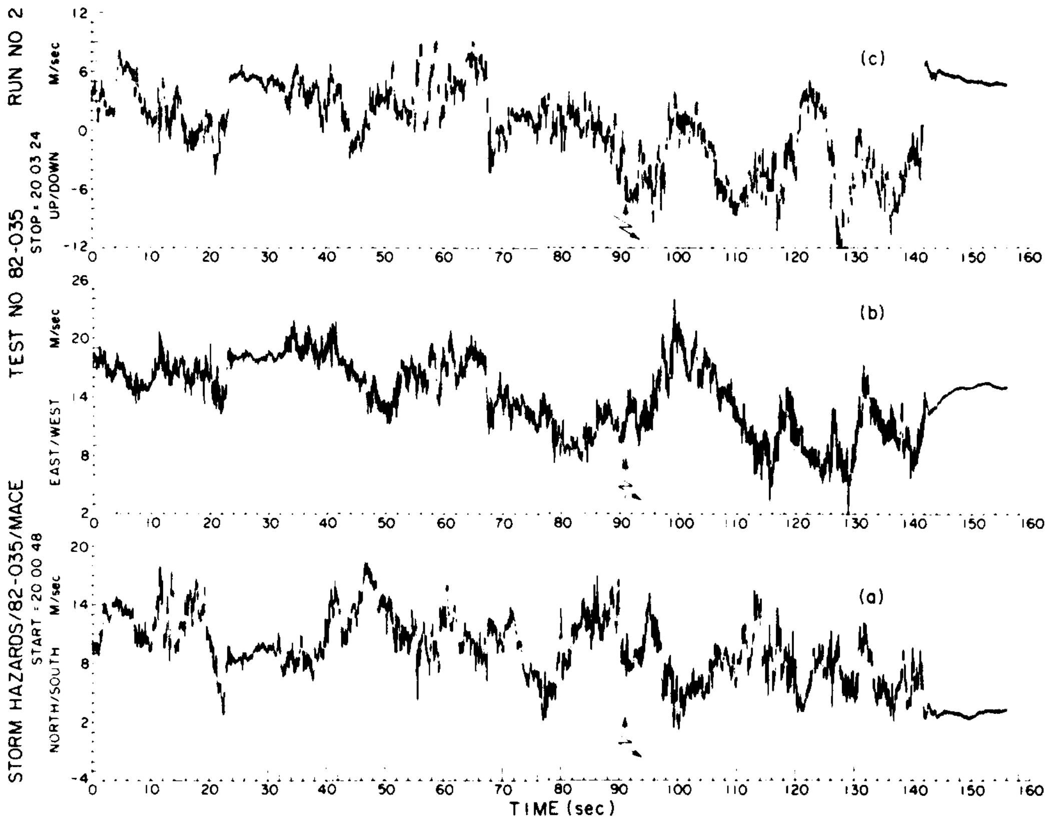

Figure 24. Aircraft Gust Data Along the (a) Longitudinal, (b) Latitudinal, and (c) Vertical Directions for 31 July 1982

Table 2 concentrates on the turbulence severity structure. The nearby nonstrike lightning episodes are indicated by the inclusion of N under the episode date.

As indicated in Table 1, all strikes occurred in storm regions where the reflectivity factor was near 25 to 35 dBZ. These episodes also occurred with the aircraft adjacent to primary precipitation cores. This suggests that charge centers are in close proximity. The strikes were also found to consistently occur when the aircraft was in a region of downward or upward moving air, or within 2 km of a significant downdraft. Table 1 shows that downdraft regions are strongly favored. The strength of the vertical currents ranged from very weak to strong. As detailed in the general discussion, the lightning episodes usually occurred near a draft edge, and not near the draft center. The association with distinct downdraft zones suggests the aircraft was near a region of charge separation. This could perhaps be verified with analysis of aircraft electric field mill data.

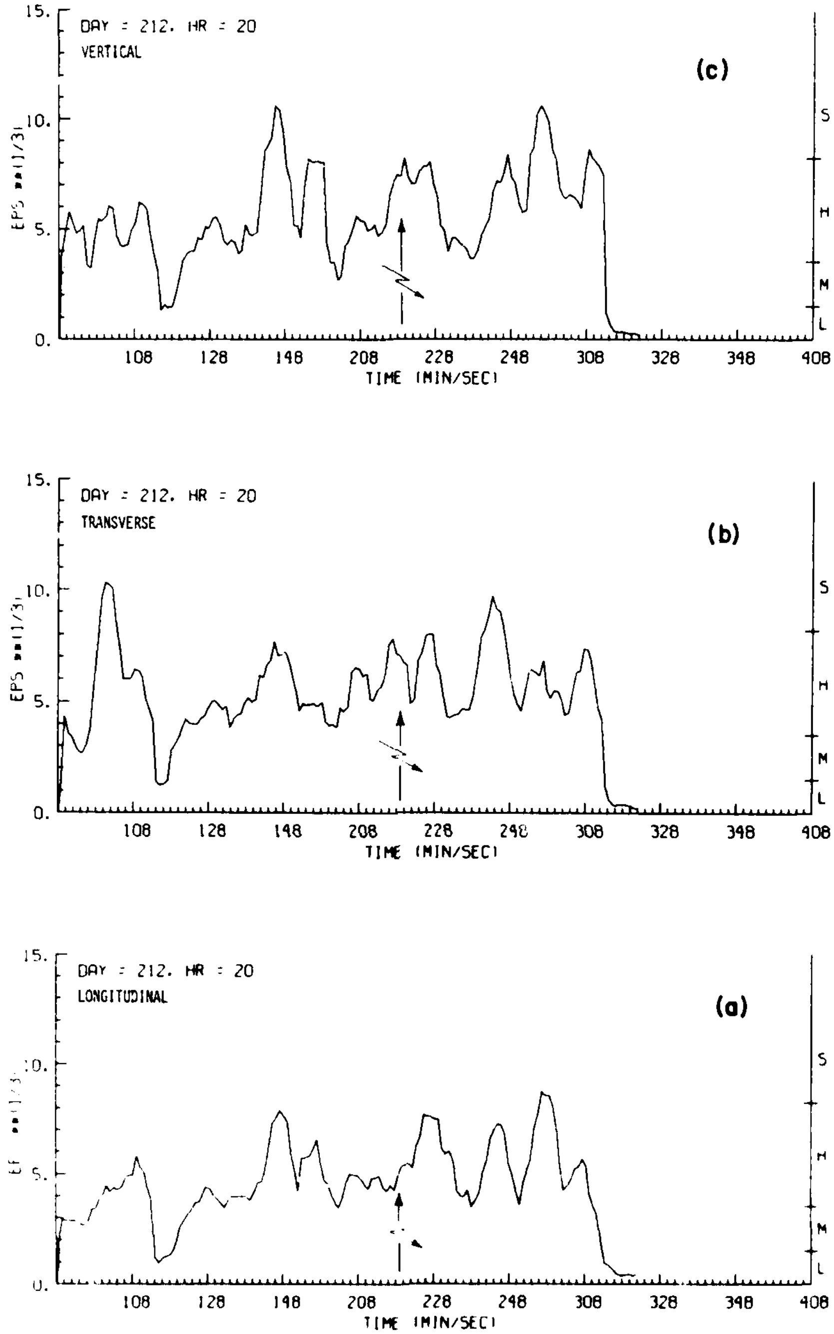

Figure 25. Estimates of Turbulence Severity for Aircraft Relative (a) Longitudinal, (b) Transverse, and (c) Vertical Directions for 31 July 1982

Table 1. Wind and Reflectivity Factor Structure

	1 July 81 N	17 July 82 A	17 July 82 B	17 July 82 C	28 July 82	30 July 82 A	30 July 82 B	31 July 82 N
Vertical Gust Data								
Character	Downdraft	Downdraft	Downdraft	Updraft	Downdraft	Downdraft	Downdraft	Downdraft
Speed at Lightning Event (ms-1)	3	> 14	> 11	3	1	0.5	5	6
Maximum Speed of Draft (ms-1)	6	> 14	> 11	7	11	0	5	7
Horizontal Shear Data								
Character	Distinct	Distinct	Distinct	Distinct	Distinct	Not Distinct	Not Distinct	Not Distinct
Shear E-W (s-1)	0.028	0.04	0.01	0	0	0.002	0.0015	0.0175
Shear N-S (s-1)	0.022	0.035	0.016	0.008	0.023	0	0	0.0175
Reflectivity Factor at Lightning Event (dBZ)	25	25	35	25	35	25	30	25

Table 2. Turbulence Severity (cm$^{2/3}$ s-1)

Character of Severity	1 July 81 N	17 July 82 A	17 July 82 B	17 July 82 C	28 July 82	30 July 82 A	30 July 82 B	31 July 82 N
	Not Distinct	Distinct	Distinct	Distinct	Not Distinct	Not Distinct	Not Distinct	Not Distinct
Vertical Component								
At Lightning Event	5	9	8	10	8	6	6	8
At Local Maximum	10	14	15	11.5	11	6.5	7	8
Time of Local Maximum Relative to Lightning (sec)	-4	6	-2	-2	-4	-1	6	0
Latitudinal Component								
At Lightning Event	5	6	9	9	9	3	8	7
At Local Maximum	12	11	10.5	9	10	10	7.5	8
Time of Local Maximum Relative to Lightning (sec)	-5	-3	-2	0	-2	-6	0	-2
Longitudinal Component								
At Lightning Event	7	7	13	5	8	4	7	5
At Local Maximum	10	8	9.5	6	10	5	10	7.5
Time of Local Maximum Relative to Lightning (sec)	-4	-3	-2	-2	-2	2	2	6

Local shear of the horizontal storm winds was often found to be most significant in a region very close to the strike location. Table 1 indicates that the shear regions were often distinctly stronger than those observed over the remainder of the penetration. There appears to exist a weak correlation of moderate to strong shear for the distinct episodes, with the nondistinct events being somewhat weaker.

The turbulence severity structure, summarized in Table 2, consistently indicates moderate to severe turbulence at strike time. Furthermore, the events generally occurred near regions of significant turbulence, of heavy to severe severity, within 2 km of the strike event. The data also indicate that the turbulence strength was essentially equal in all three orthogonal directions, suggesting the turbulence may be considered reasonably isotropic.

The correlation with significant turbulence must be tempered by the knowledge that the strike episodes were not generally in a local region where the turbulence was distinctly more severe than during the remainder of the penetration. Thus, although there is good correlation between aircraft strikes and strong turbulence for these few penetrations, observation of these and other 1981 and 1982 data demonstrates the overwhelming occurrence of strong turbulence with no associated lightning. This suggests that use of lightning locating devices are inadequate for locating the broad distribution of hazardous turbulence to be encountered within storms.

The striking correlations of strikes with precipitation cores, downdraft regions, and high turbulence severity are significant findings. It must be noted, however, that the data sample size here is extremely small. The consistency observed, nonetheless, does suggest some correlations that may be expected to occur during periods of lightning strikes to aircraft in regions of light to moderate precipitation intensity at mid to high storm levels.

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