NOAA Technical Report ERL 430–ESG 2

The Crash of Delta Flight 191 at Dallas–Fort Worth International Airport on 2 August 1985: Multiscale Analysis of Weather Conditions

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ABSTRACT. The third microburst-related disaster in the decade since 1976 occurred when Delta Flight 191 crashed while on the landing approach to Runway 17L at Dallas-Fort Worth International Airport (DFW) on 2 August 1985. The microburst-producing storm occurred almost in the center of a large-scale high-pressure area that extended through a deep layer of the troposphere and was interrupted only near the surface by a thermal low-pressure area in combination with a low-pressure trough that was associated with a weak frontal boundary. Large-scale forcing patterns, which were rather weak, set the stage for the event. A computer-generated analysis of the pattern of deep tropospheric forcing reveals that a high lapse rate in the lower troposphere was generated by a pattern of vertical motion that tended to stretch the atmospheric column: At levels above 500 mb the forcing was upward; at 700 mb, it was downward. The lapse rate would have been enhanced also by strong solar heating. Weak subsidence above the surface boundary layer tended to cap it and preserve relatively high dew point temperatures near DFW, while heating southwest of the area tended to produce much drier surface conditions. Furthermore, a dry layer above 700 mb provided an elevated source of potentially cold air that would fuel strong downdrafts, which, penetrating into a deep, mixed subcloud layer, found a very favorable environment in which to become severe. In these two ways the vertical thermodynamic structure of the DFW environment was a hybrid of a type of environment that favors dry microbursts and another type that favors wet microbursts. The very weak front that lingered over DFW, and resurged southward at about the time of the accident, lifted the shallow, moist surface layer, triggering a line of discrete thunderstorm cells, one of which, situated along the approach to Runway 17L, produced the microburst that brought down Delta 191. In this case, a digital flight recorder has provided data from which the highest resolution analysis of microburst winds was possible. This analysis shows that the wind field within a microburst has a very complex structure with imbedded smaller scale vortices that inflict serious control problems on a penetrating aircraft, to compound the hazard of severe wind shear.

1. INTRODUCTION

1.1 Description of the accident

Delta Flight 191, a Lockheed wide-body jet (L1011), crashed and burned on the landing approach short of runway 17L at Dallas-Fort Worth International Airport (DFW) on the afternoon of 2 August 1985 at about 2306 GMT, after having flown through a shaft of extremely heavy rain from an incipient thunderstorm. Of the 163 people onboard, only 30 survived.

The thunderstorm present near DFW at the time of the crash was one of a line of discrete cells that extended from the northwest into the DFW area ahead of a more extensive and intense complex of thunderstorms situated along the Red River. The cells within the line were isolated and small, and may have appeared less threatening than those over the Red River; nevertheless, one situated over DFW generated measured wind gusts up to 70 kt on the centerfield anemometer and produced an impressive show of lightning—all after the accident had occurred.

1.2 Purpose of this study

The main purpose is to supply sufficient analyses, from all available sources, for the National Transportation and Safety Board (NTSB) to be able to assess the role of the weather in this accident. A secondary intent is to provide a multiscale analysis of weather conditions prior to the accident for research purposes.

2. SYNOPTIC-SCALE ANALYSIS

2.1 Upper-air patterns

In the standard NMC upper-air charts for 1200 GMT (0600 LST), 2 August 1985 (Figs. 1a–1d), all levels around the Dallas-Fort Worth International Airport (DFW) are dominated by high

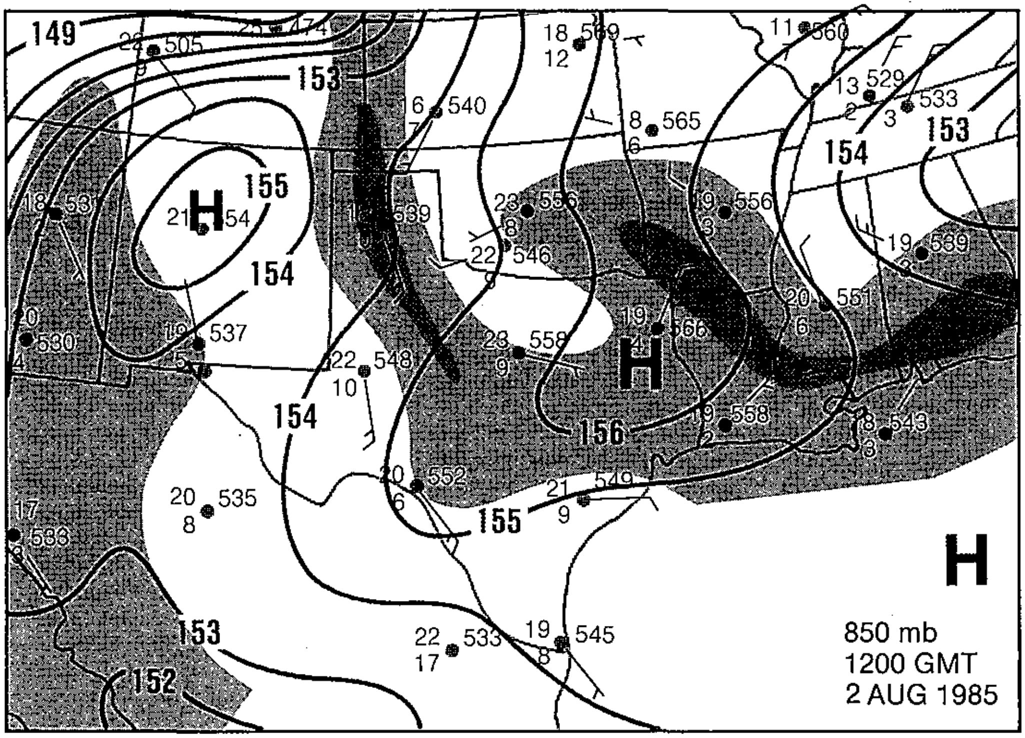


Figure 1a. An 850-mb analysis for 1200 GMT, 2 August 1985. Areas of dew point temperatures greater than 14 °C are shaded and contoured at 4 °C intervals. Height field contours are in decameters.

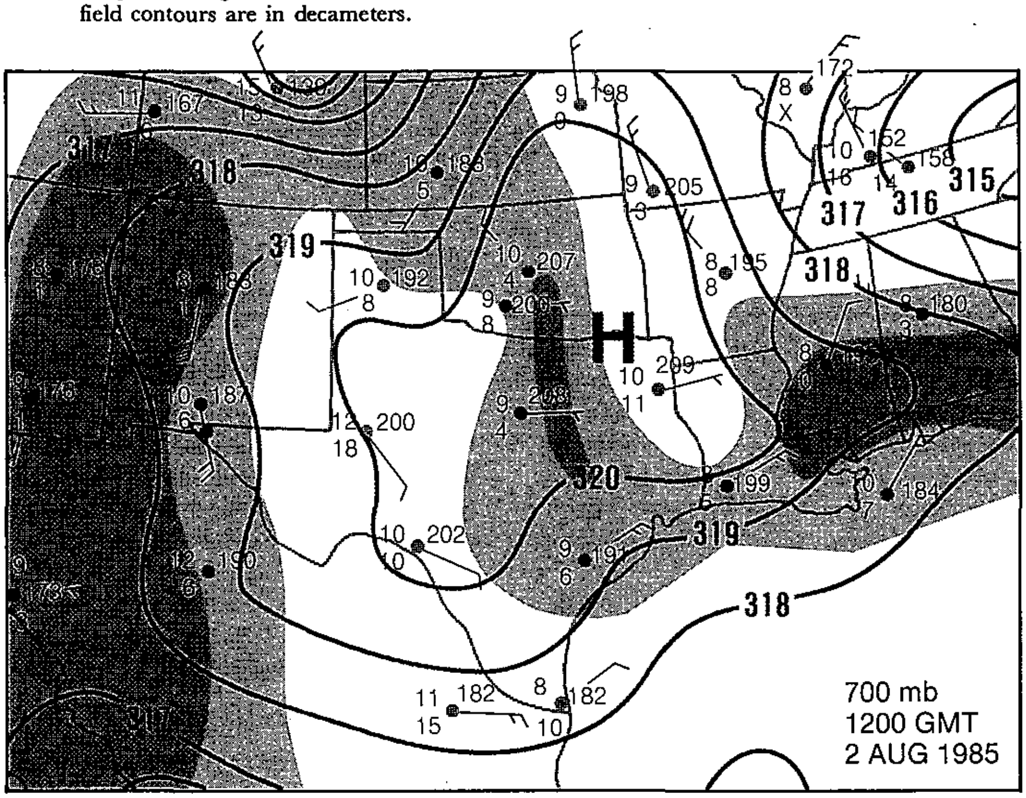


Figure 1b. A 700-mb analysis for 1200 GMT, 2 August 1985. Areas of dew point temperatures greater than 2 °C are shaded and contoured at 4 °C intervals. Height field contours are in decameters.

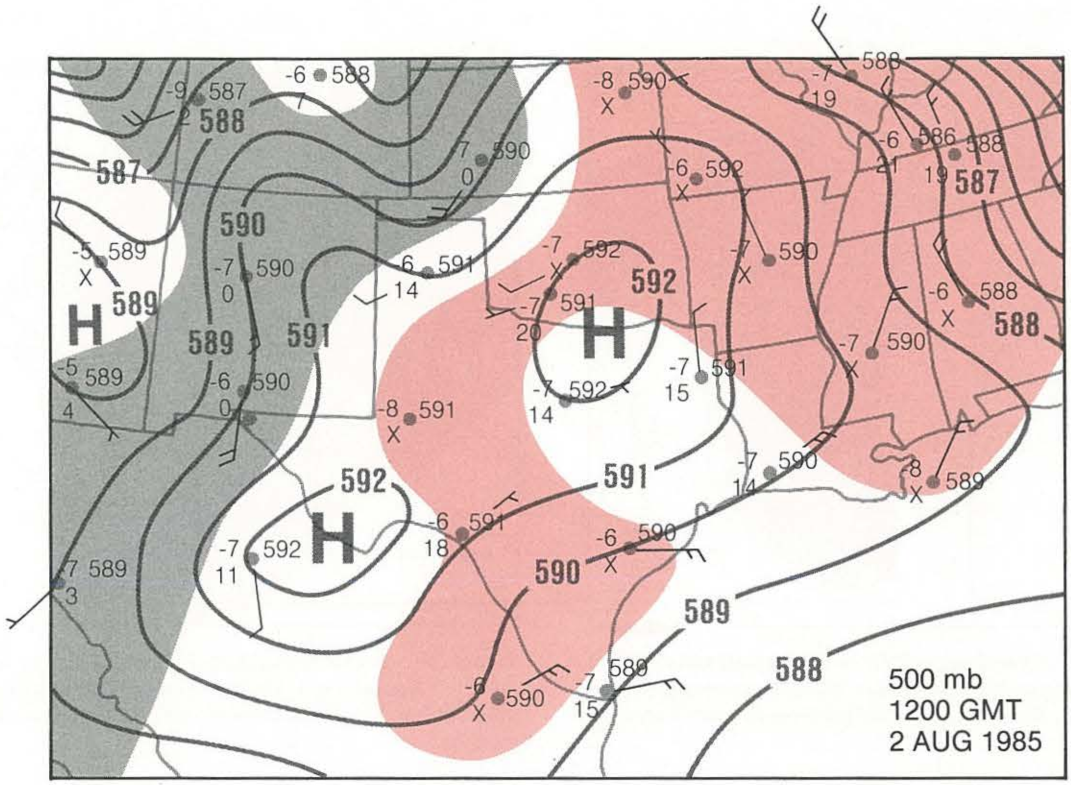


Figure 1c. A 500-mb analysis for 1200 GMT, 2 August 1985. Dry areas (dew point temperature depression $> 18\,^{\circ}C$) are shaded red; moist areas (dew point temperature depression $\leq 6\,^{\circ}C$) are shaded gray. Height field contours are in decameters.

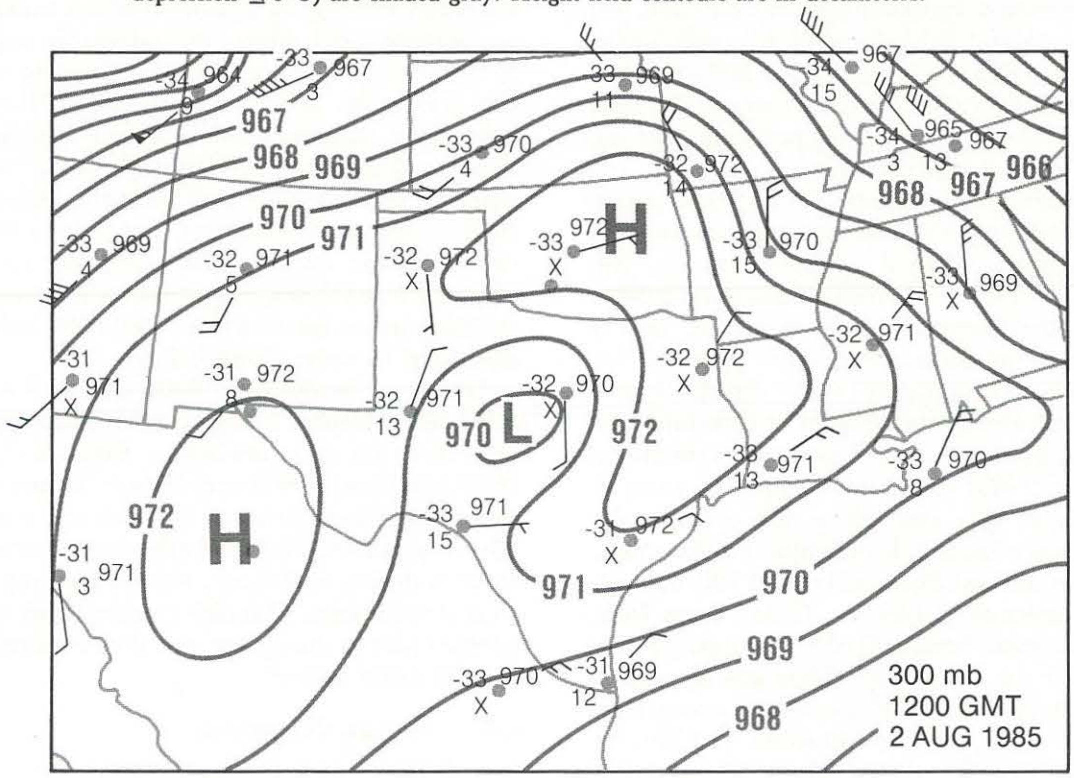


Figure 1d. A 300-mb analysis for 1200 GMT, 2 August 1985. Height field contours are in decameters.

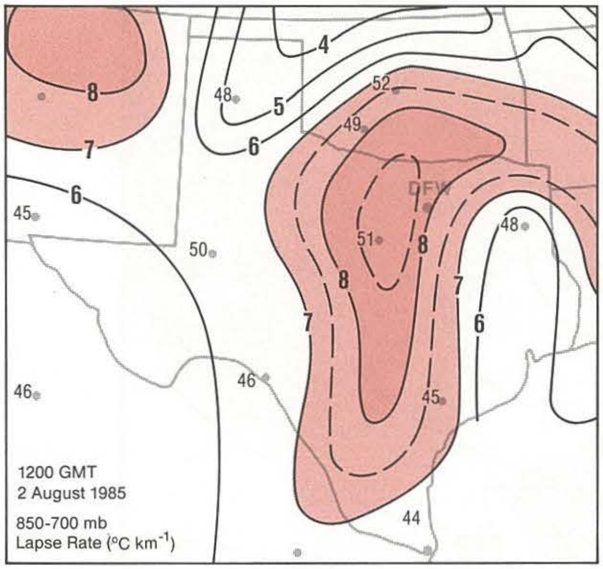


Figure 2a. An analysis of 850–700 mb lapse rates for 1200 GMT, 2 August 1985. Units are °C/km; contour intervals are 1°C/km. Small numbers are total-totals index values at stations.

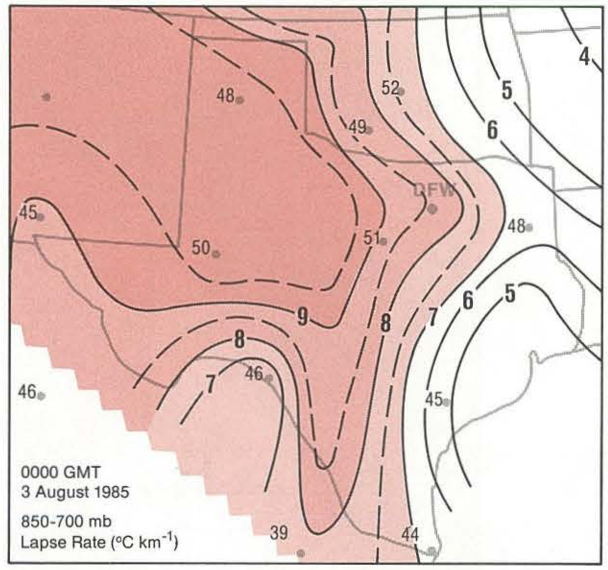


Figure 2b. An analysis of 850–700 mb lapse rates for 0000 GMT, 3 August 1985. Units are °C/km; contour intervals are 1°C/km. Small numbers are total-totals index values at stations.

pressure. Winds up to the 500-mb level are light and easterly with practically no vertical wind shear. An area of moisture between 850 and 700 mb (Figs. 1a and 1b) is located over east Texas surrounding DFW; very dry air at 500 mb is being advected over the top of this moist layer, thus setting up the environment for potentially strong downdrafts in thunderstorms.

In the classical sense, one would not expect a severe storm within this environment because of the negligible vertical wind shear in the troposphere. However, from a researcher's point of view, the thermodynamic structure of the troposphere indicates a very high potential for microbursts, as indicated by the distribution of 850–700 mb average lapse rates at 1200 GMT in Fig. 2a. A one-dimensional downdraft model by Srivastava (1985) shows that high lapse rates in the subcloud layer and heavy rain promote the development of strong downdrafts. Furthermore, experience derived from analysis of 700–500 mb thermal structure at Denver, Colo., from Joint Airport Weather Studies (JAWS) soundings suggests that lapse rates >8° C/km are associated with a high probability of microburst occurrence (Caracena et al., 1983a; Caracena and Flueck, 1987). At DFW the terrain is about 150 mb lower than Denver, so that the 850–700 mb layer there is comparable with the 700–500 mb layer at Denver.

An analysis of 850–700 mb lapse rates for 0000 GMT, 3 August (approximately 1 hour after the accident; see Fig. 2b) shows that the maximum in the lapse rate field had moved west in response to the heating of elevated terrain, leaving a trailing maximum over the DFW area. However, analysis of denser surface data, in combination with the slowly varying 700-mb temperature and height fields (Fig. 2c), indicates that within this trailing lapse rate maximum, a surface-to-700-mb dry adiabatic environment extended over the airport—a conclusion supported by an analysis of the flight recorder data from Delta 191, which is described in more detail below.

Upper-air analyses for 0000 GMT, 3 August 1985, are presented in Figs. 3a–3d for comparison with those for 12 hours before (Figs. 1a–1d). In these analyses there is very little evolution in the upper-air pattern between morning and evening. The troposphere below 700 mb remains moist and there is drying at 500 mb, thus producing a vertical stratification of moisture that plays an important part in the generation of wet microbursts (as discussed below).

2.2 Omega diagnostics

A Q-vector analysis (see Hoskins et al., 1978; Hoskins and Pedder, 1980) performed on a microcomputer with routines developed by Barnes (1985) shows that all of Texas was in an area of

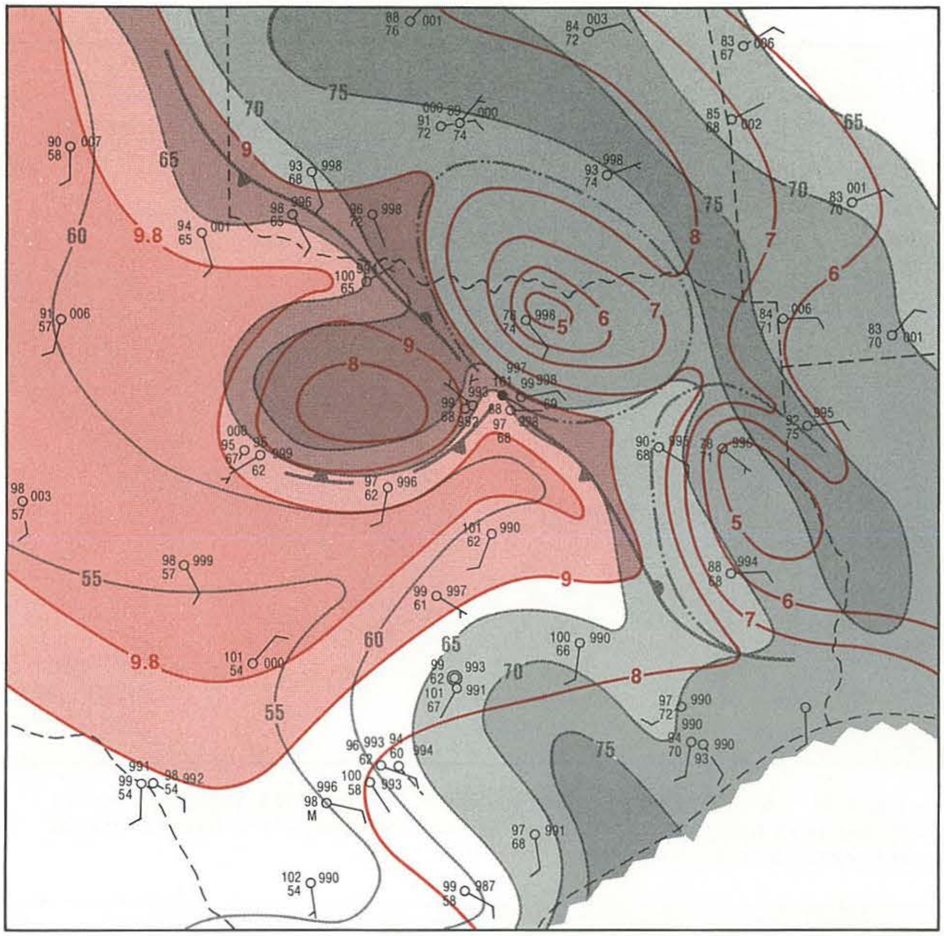


Figure 2c. A composite surface analysis of the mesoscale weather situation in the DFW area around 2300 GMT, 2 August 1985. Surface fronts and dew point analysis are in gray, and areas of moisture are shaded in progressively darker shades of gray. Lapse rates between the surface and 700 mb (°C/km) are contoured in progressively deeper shades of red. Surface temperatures and dew point temperatures are in °F.

very weak quasi-geostrophic forcing at 1200 GMT, 2 August 1985 (Figs. 4a and 4b). At 700 mb (Fig. 4a) the area surrounding DFW was dominated by weak downward forcing, whereas at 500 mb (Fig. 4b) the forcing was upward. However, the extreme northeast corner of Texas was experiencing upward forcing at both levels. Corresponding analyses for 0000 GMT, 3 August 1985, at 700 and 500 mb (Figs. 5a and 5b) show that the weak pattern of forcing changed slightly so that the area north of DFW along the Red River was experiencing upward forcing at 700 mb (Fig. 5a), and a large part of east Texas around DFW was also experiencing upward forcing at 500 mb (Fig. 5b) along with widespread, deep convection. Thus, the quasi-geostrophic forcing that was practically neutral in the morning over DFW, became weakly destabilizing by evening in the DFW area and north. Furthermore, the earlier pattern of forcing, up at 500 mb and down at 700 mb, stretched the lower tropospheric column during the day, thus increasing the lower tropospheric lapse rate—a trend reinforced by insolation.

An important effect of the weak subsidence at 700 mb during the day at DFW was that it helped preserve the low-level moisture that would fuel convection later. Warming induced by the subsidence through that level created an inversion that capped the moist boundary layer, thus preventing upward mixing as this layer heated during the day. Convection over DFW was not triggered until this surface-based moist layer was lifted mechanically by an outflow of rain-cooled air near the surface, originating from thunderstorms to the north and northeast.

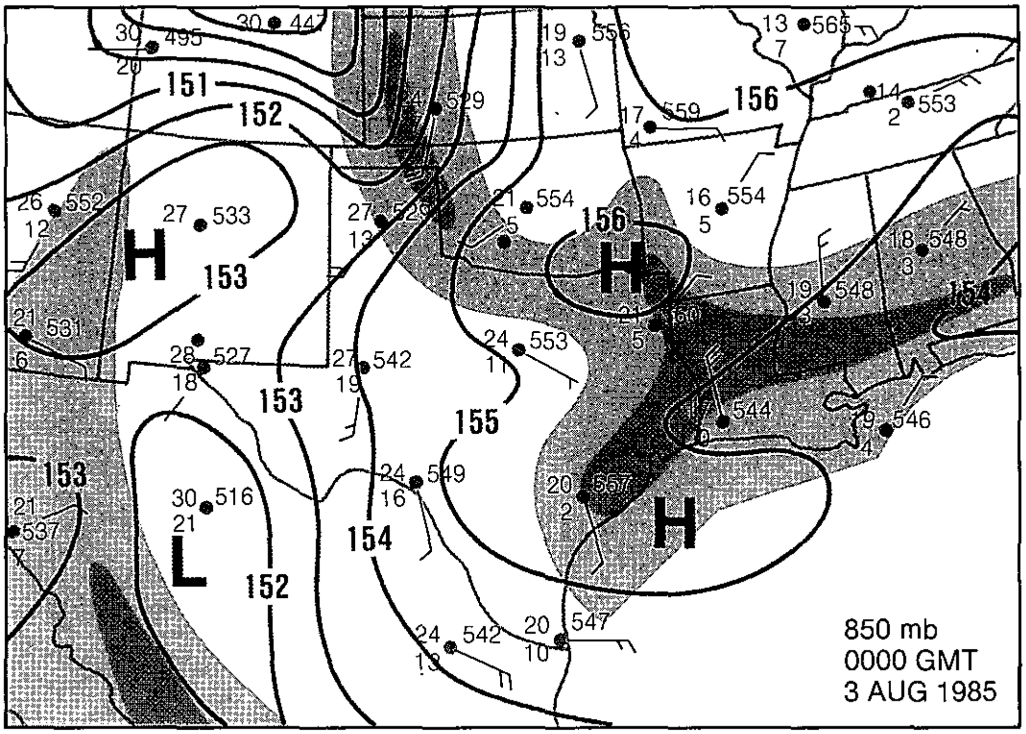


Figure 3a. An 850-mb analysis for 0000 GMT, 3 August 1985. Areas of dew point temperatures greater than 14°C are shaded and contoured at 4°C intervals. Height field contours are in decameters.

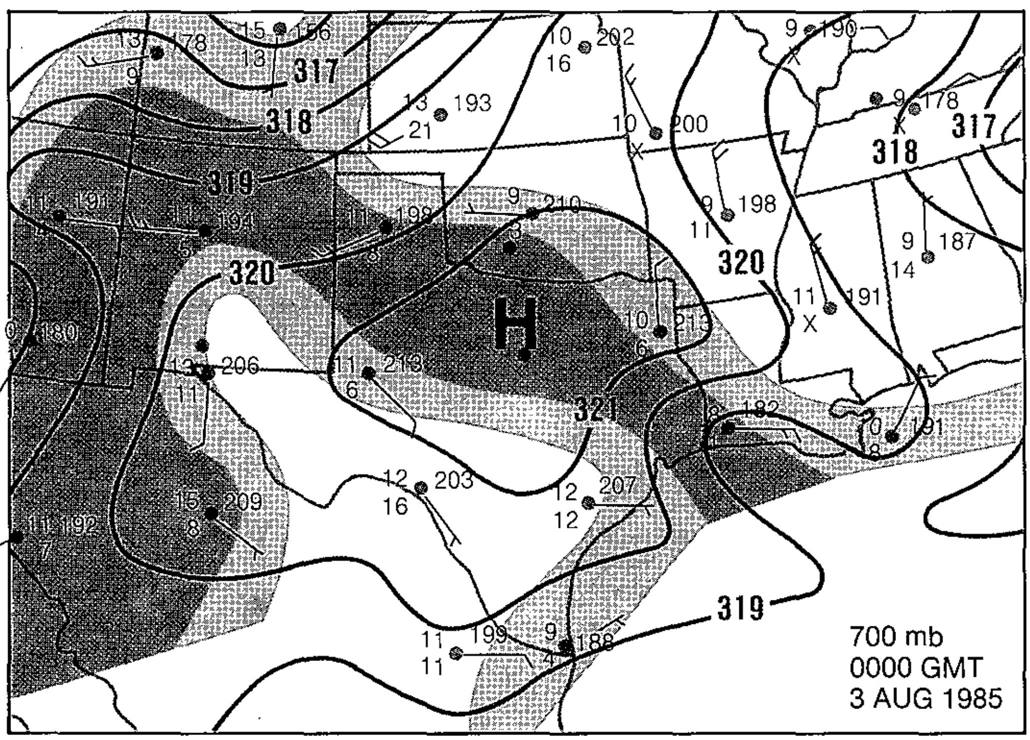


Figure 3b. A 700-mb analysis for 0000 GMT, 3 August 1985. Areas of dew point temperatures greater than 2°C are shaded and contoured at 4°C intervals. Height field contours are in decameters.

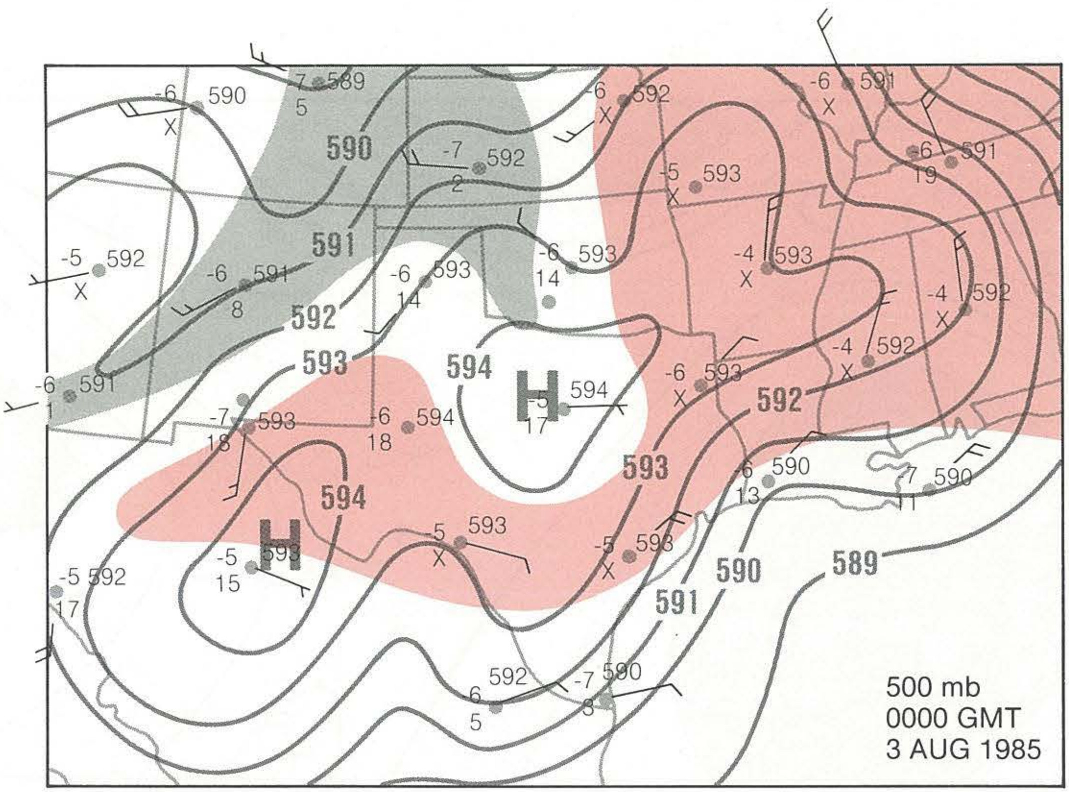


Figure 3c. A 500-mb analysis for 0000 GMT, 3 August 1985 (see Fig. 1c caption for details).

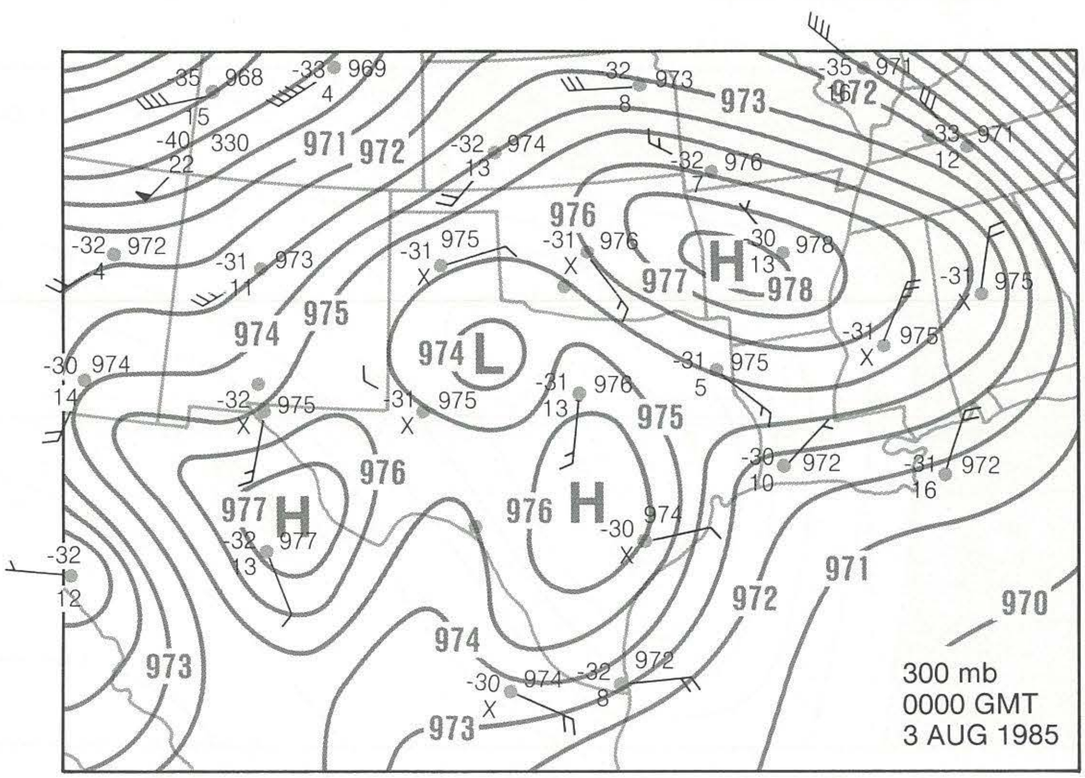


Figure 3d. A 300-mb analysis for 0000 GMT, 3 August 1985. Height field contours are in decameters.

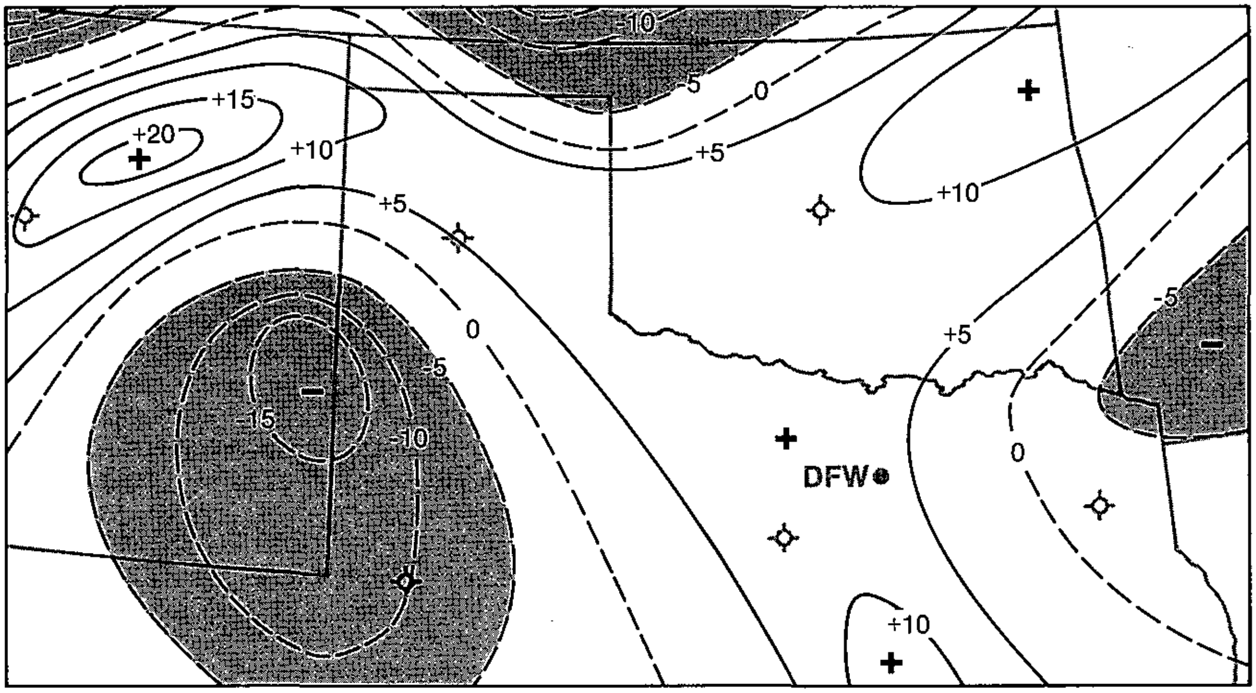


Figure 4a. A 700-mb omega diagnostic analysis (see Barnes, 1985) for 1200 GMT, 2 August 1985. Areas of divergence of Q-vectors ($10^{-18}\ 5^{-3}\ mb^{-1}$) representing upward forcing above −5 are shaded.

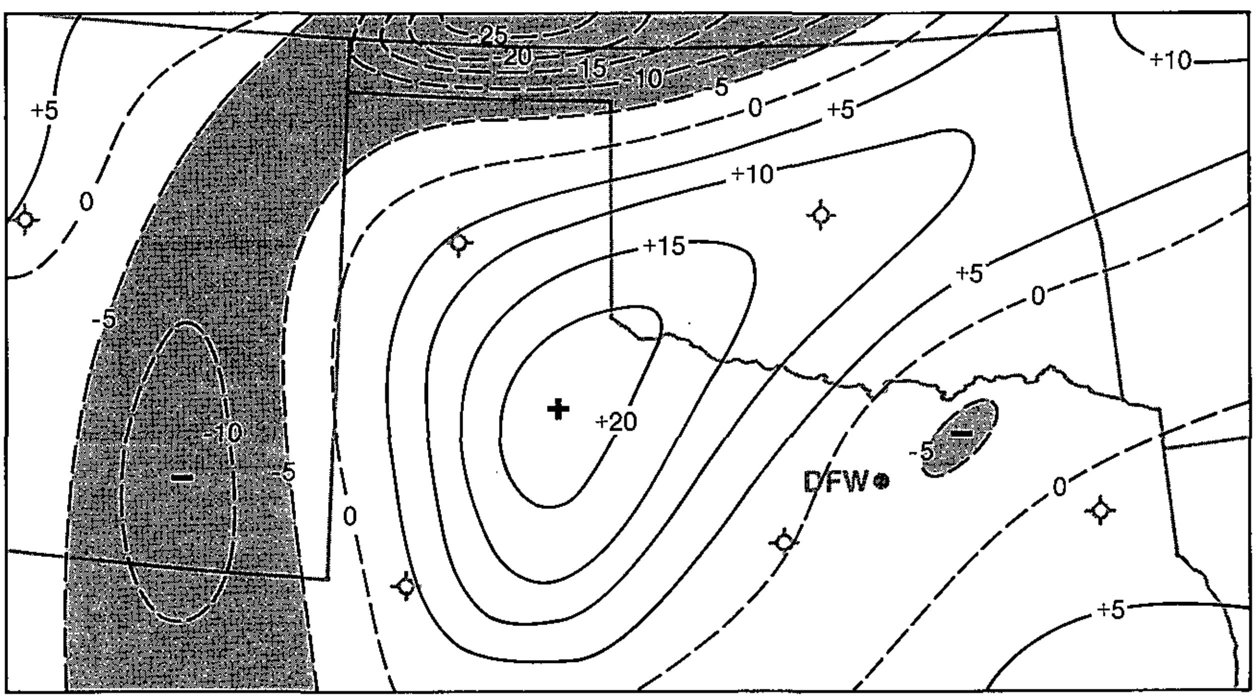


Figure 4b. A 500-mb omega diagnostic analysis for 1200 GMT, 2 August 1985 (see Fig. 4a caption for details).

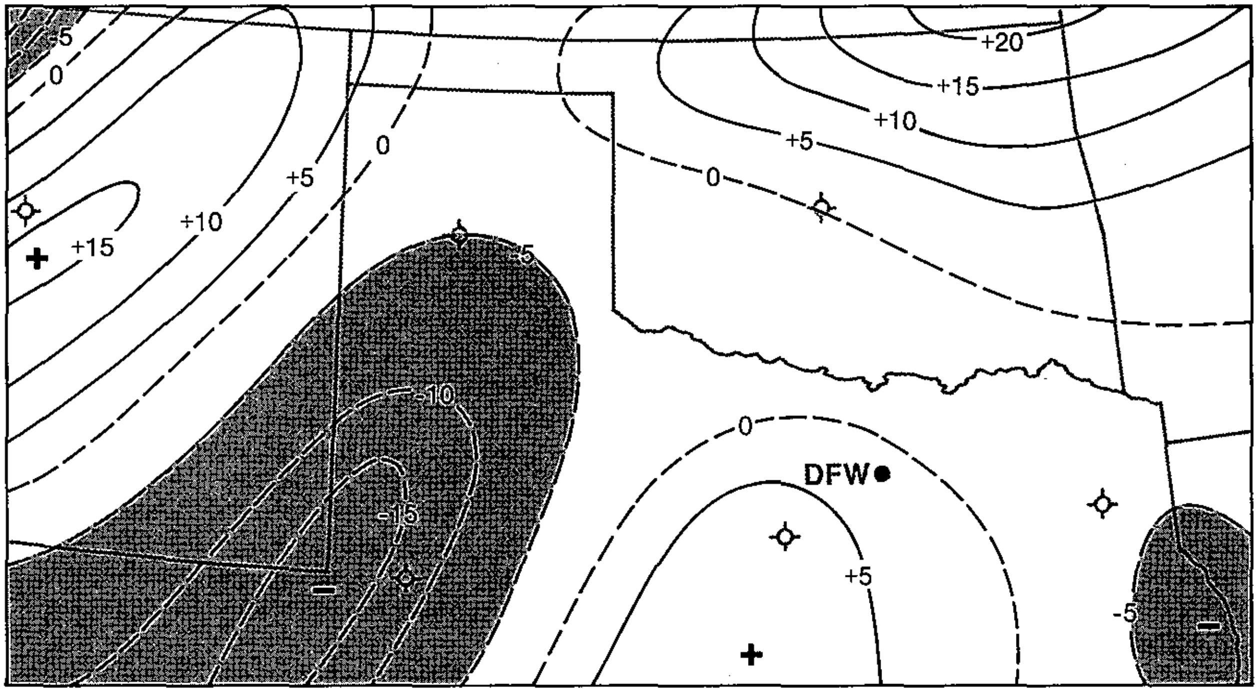


Figure 5a. A 700-mb omega diagnostic analysis for 0000 GMT, 3 August 1985 (see Fig. 4a caption for details).

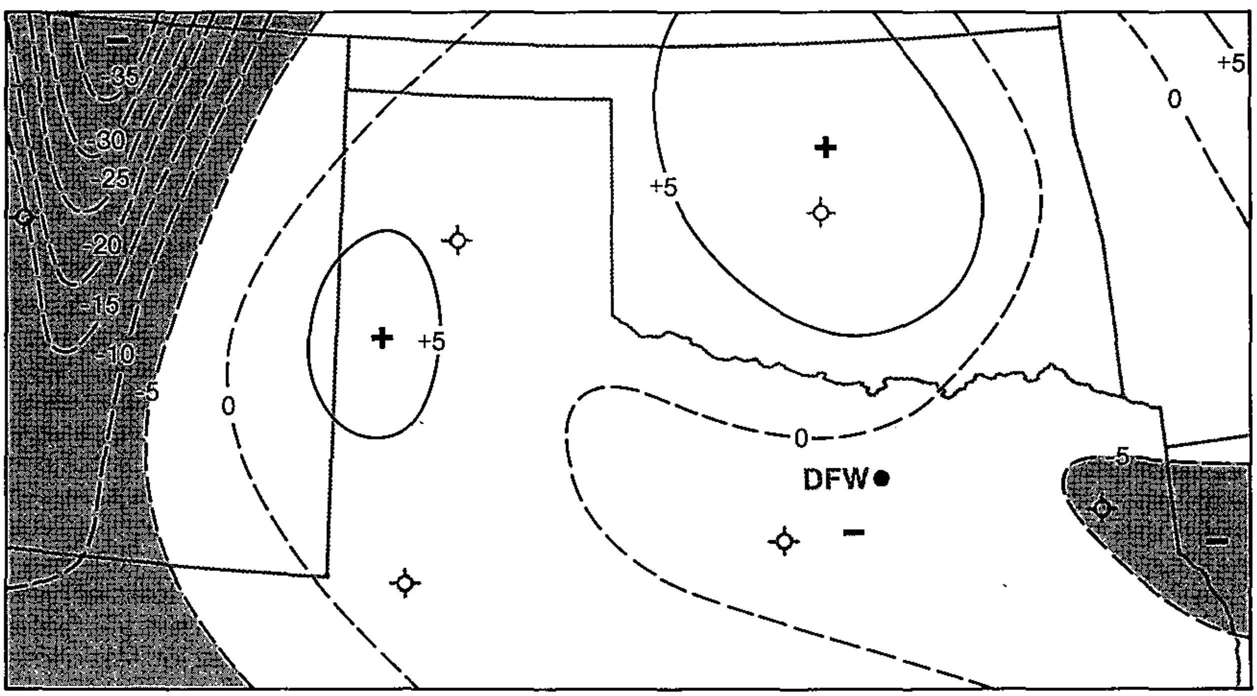


Figure 5b. A 500-mb omega diagnostic analysis for 0000 GMT, 3 August 1985 (see Fig. 4a caption for details).

2.3 Surface analysis

At 1200 GMT a weak front hung over DFW in an east-west orientation (Figs. 6a–6b). A re-analysis (Fig. 6b) of the NMC surface chart (Fig. 6a) shows multiple surges behind the leading edge of cool air. A second, stronger front located north of DFW had moved into the area overnight. These two fronts had weak thermal gradients, but were defined well by the dew point temperature field, which was marked by moisture increasing northward across each front. A third frontal surge was developing over extreme east Texas and Oklahoma, and was moving west as a cold front. Frontal positions in the re-analyzed surface maps are corroborated by thermal fields, dew point temperature fields, and troughs in the surface pressure (reduced to sea level). Note that a weak, surface low-pressure area had developed near DFW.

A series of surface analyses at 3-hour intervals (Figs. 6–10) shows that the weak, east-west oriented front near DFW held its position fairly well most of the day while the second front retreated northward as a warm front, probably as a result of the heating out of the shallower portion of the cool air mass. Meanwhile, the third frontal surge pushed westward across eastern Oklahoma, but became stationary over extreme east Texas where it spawned a mesoscale complex of thunderstorms.

At 2100 GMT (Figs. 9a–9b), the weak front over DFW had retreated slightly northwestward, leaving the airport on the intersection of the moisture gradient and a thermal ridge. A high dew point temperature of 67 °F remained over the area. Meanwhile, surface air to the rear of this front had heated considerably along the Red River Valley on the Texas-Oklahoma border and into Louisiana, while remaining very moist (with dew point temperatures in the low 70's). Extensive convection erupted in this area in response to the combination of low-level heating of the boundary layer, forcing along the third frontal surge, and upper-level forcing (revealed by the omega diagnostics).

By 0000 GMT, outflow of rain-cooled air from mesoscale thunderstorm clusters to the north, northeast, and east of DFW had produced strong thermal gradients in the surface temperature field (Fig. 10b) which pushed the front back into the DFW area from the northeast. The surface pressure field indicates that the centers of rain-cooled air were also mesohighs.

From the surface analyses in Figs. 6–10, we conclude that convection in the DFW area was forced by strong convergence in advance of the frontal surge that moved westward across the area. First, the warm front receded under strong heating; then the cold front was pushed back into the area by outflow from meso-beta-scale thunderstorm complexes to the east and northeast, in combination with a thermal low-pressure trough that formed in the area. The forced convergence in the hotter, drier air over the DFW area resulted in a line of discrete thunderstorms oriented northeast-southwest. The front, and combination of outflow boundaries, passed over the DFW area between 2100 GMT and 0000 GMT (the time is determined with more precision in the following discussions). As the front advanced toward the west, it encountered progressively drier air until no further convection was initiated.

3. REGIONAL MESOSCALE ANALYSIS

3.1 Satellite IR cloud-top imagery

The enhanced IR cloud-top imagery indicates the apparently benign conditions that existed near DFW, especially in contrast to the extensive and deep thunderstorms present north and east of the area along the Red River. Also, the imagery provides insight into the air-flow patterns in the data-sparse regions northeast of DFW.

Figure 11 shows that at 2200 GMT a band of deep convection had formed along the Oklahoma-Texas border and extended through east Texas and southwestern Louisiana and over the Gulf of Mexico. Near the time of the accident at 2300 GMT (Fig. 12), the band had grown appreciably and an arc of convection extended from the main band into the DFW area where conditions were hotter and somewhat drier. In the imagery (Fig. 12), this arc is enhanced in the range from 0° to -32°C. Because individual pixels in the imagery represent averages over 8 × 8 km areas, tops of individual cumulus towers within the arc may well have been much colder (thus higher) than indicated. The presence of an arc of convection suggests that an outflow boundary was pushing into the DFW area from the northeast. This hypothesis is developed further in Sec. 4.

The satellite imagery for 0000 GMT (Fig. 13) shows that the arc of convection grew explosively within the hour between IR images, indicating cloud-top temperatures colder than -32°C. Furthermore, reinforced outflow from the first arc of

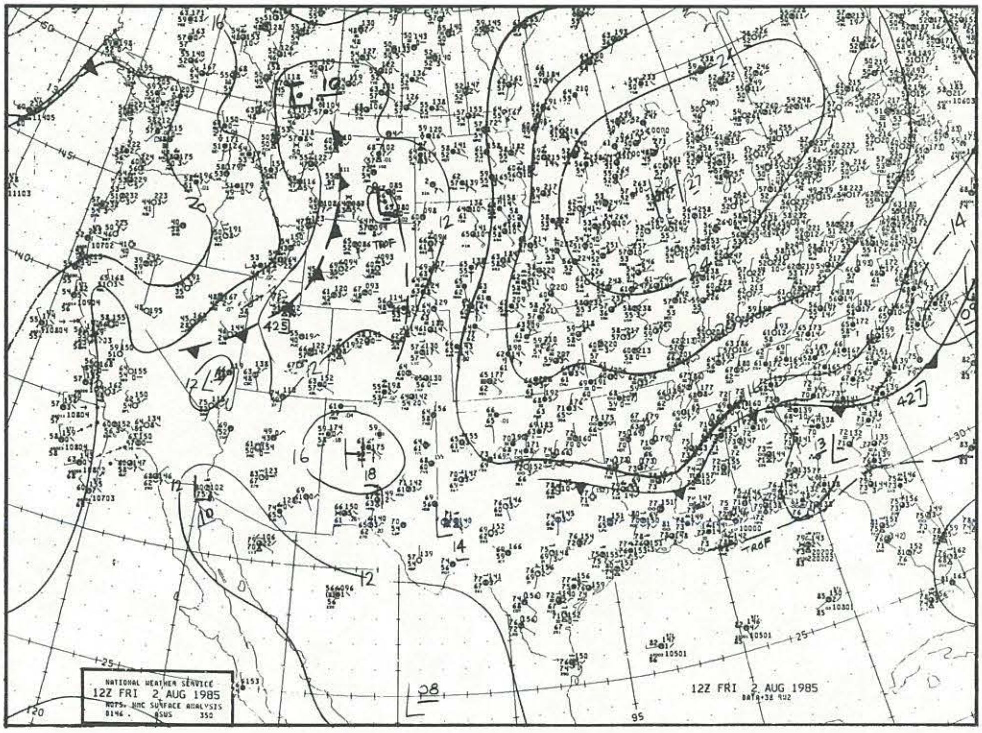


Figure 6a. NMC surface analysis for 1200 GMT, 2 August 1985.

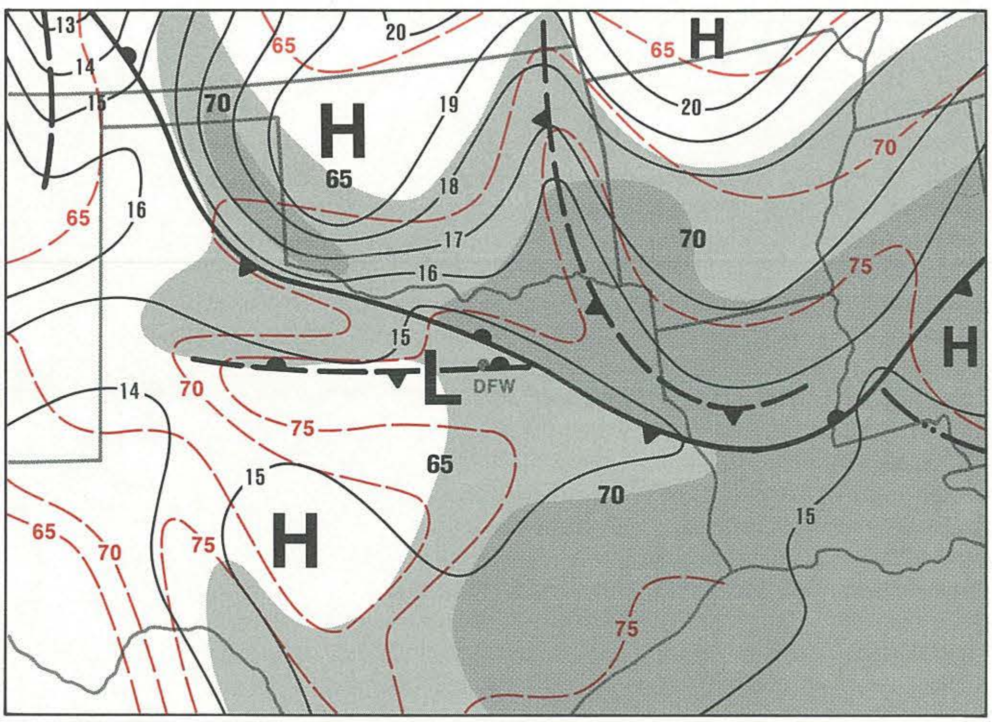


Figure 6b. Enhanced surface analysis for 1200 GMT, 2 August 1985. Light shading indicates dew point temperatures above 65 °F; dark shading indicates dew point temperatures above 70 °F. Dashed red contours are temperature isolines at 5 °F intervals. Solid black contours are reduced sea level pressure in millibars (+ 1000).

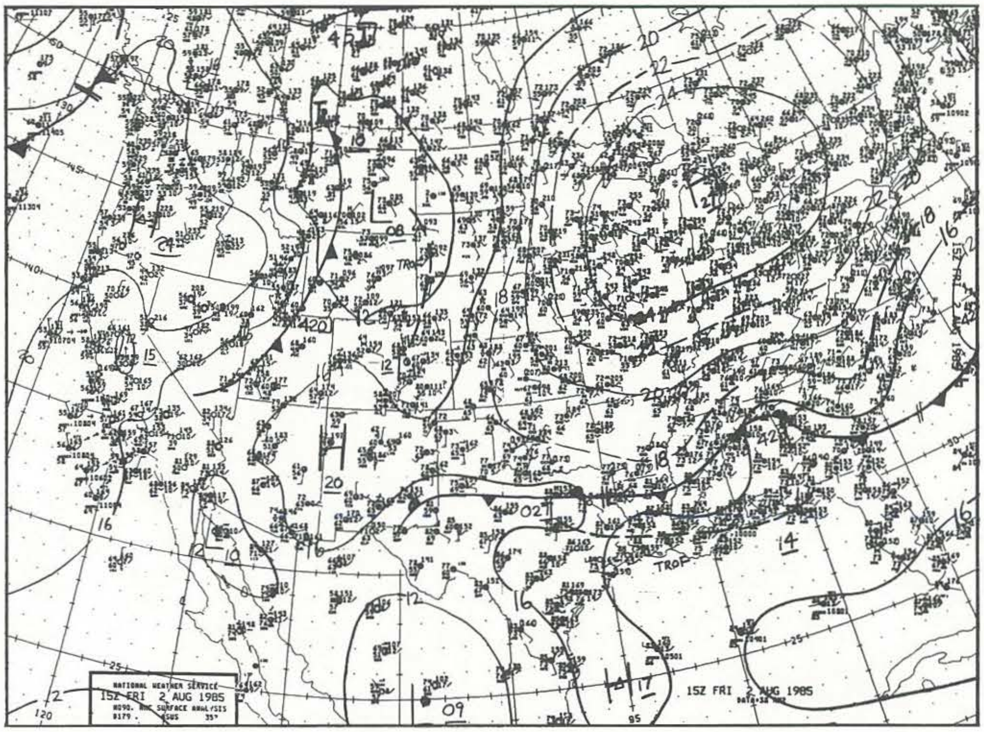


Figure 7a. NMC surface analysis for 1500 GMT, 2 August 1985.

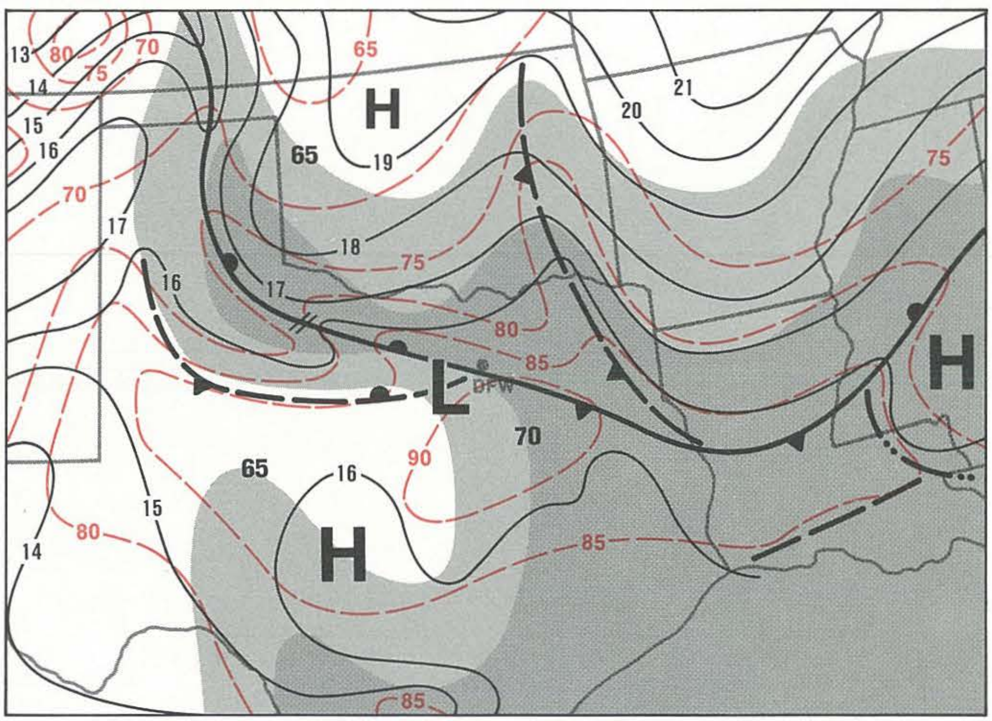


Figure 7b. Enhanced surface analysis for 1500 GMT, 2 August 1985, with temperature and dew point temperature analysis as described in Fig. 6b caption.

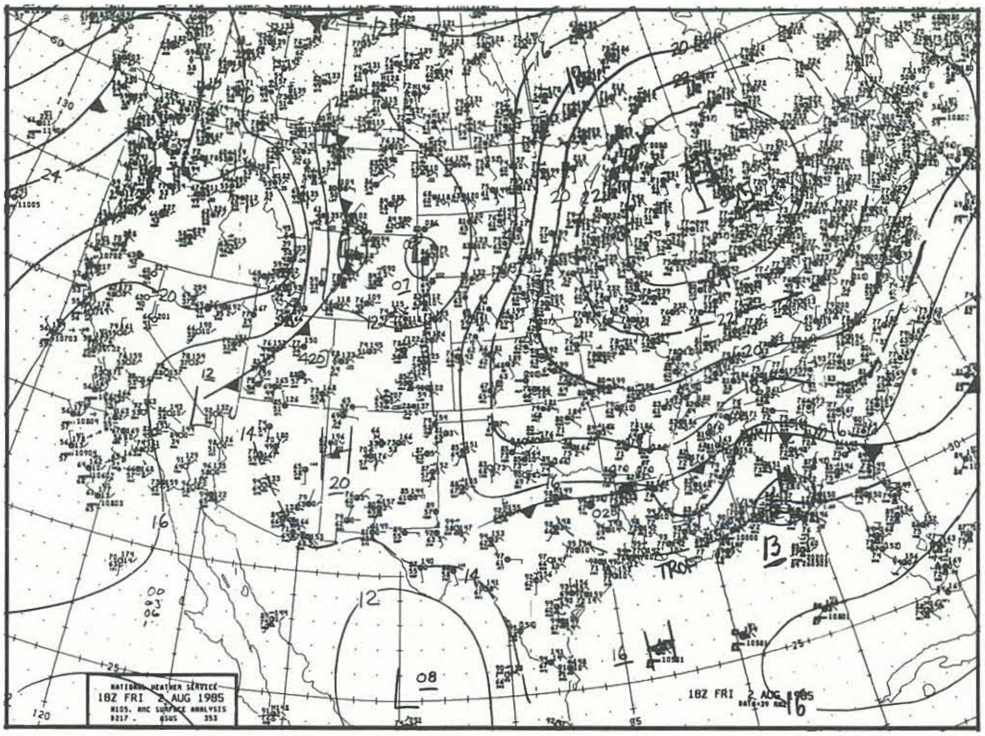


Figure 8a. NMC surface analysis for 1800 GMT, 2 August 1985.

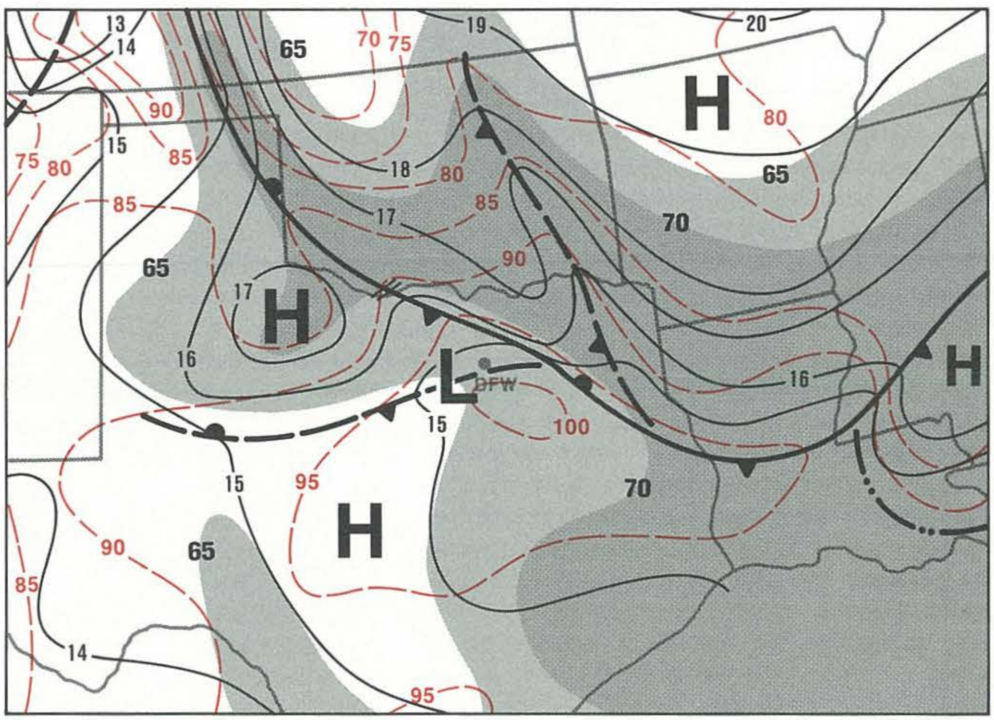


Figure 8b. Enhanced surface analysis for 1800 GMT, 2 August 1985, with temperature and dew point temperature analysis as described in Fig. 6b caption.

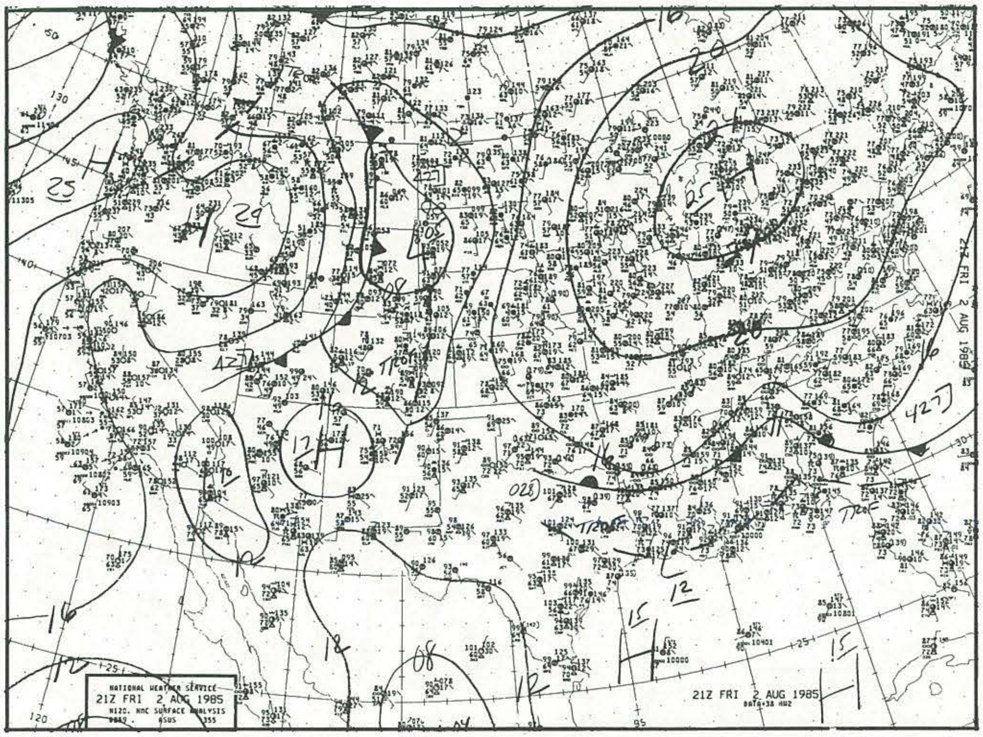


Figure 9a. NMC surface analysis for 2100 GMT, 2 August 1985.

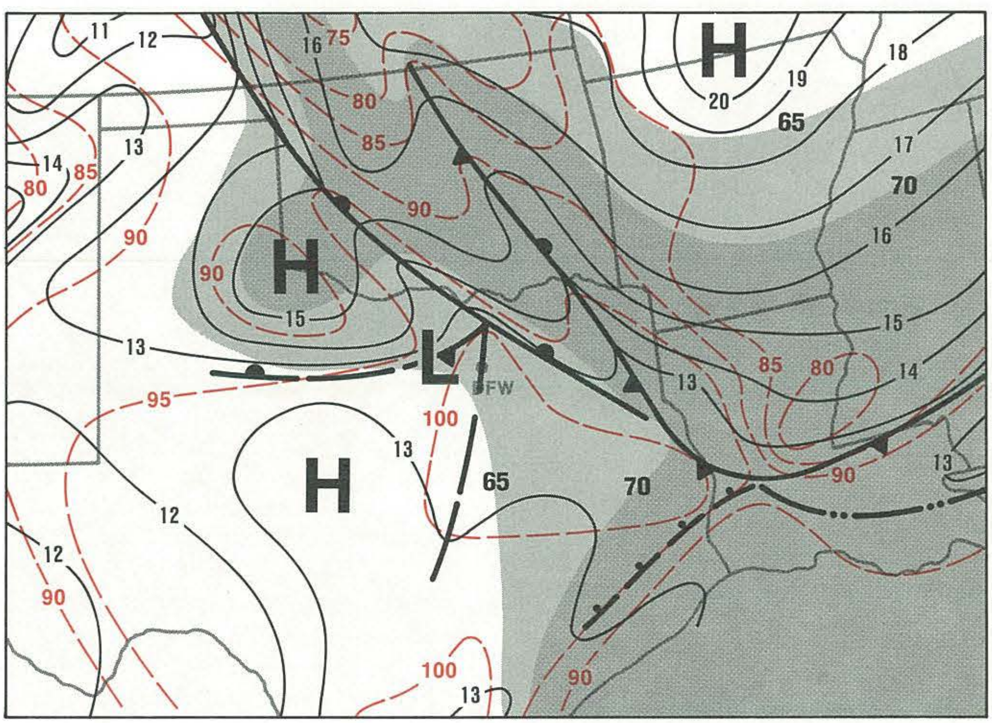


Figure 9b. Enhanced surface analysis for 2100 GMT, 2 August 1985, with temperature and dew point temperature analysis as described in Fig 6b caption.

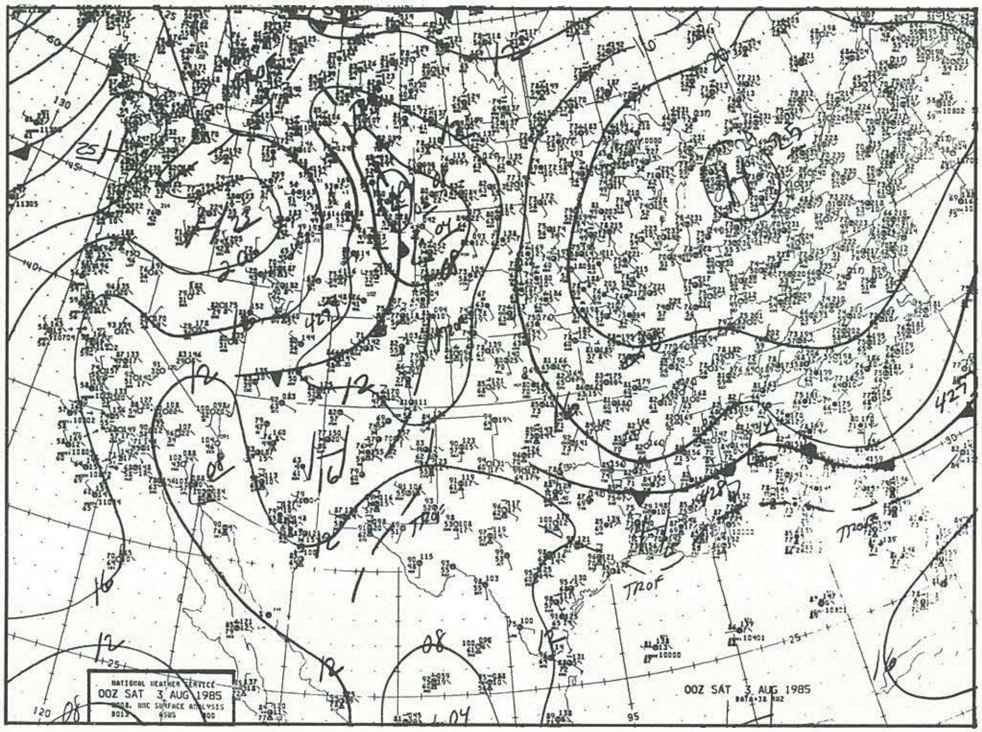


Figure 10a. NMC surface analysis for 0000 GMT, 3 August 1985.

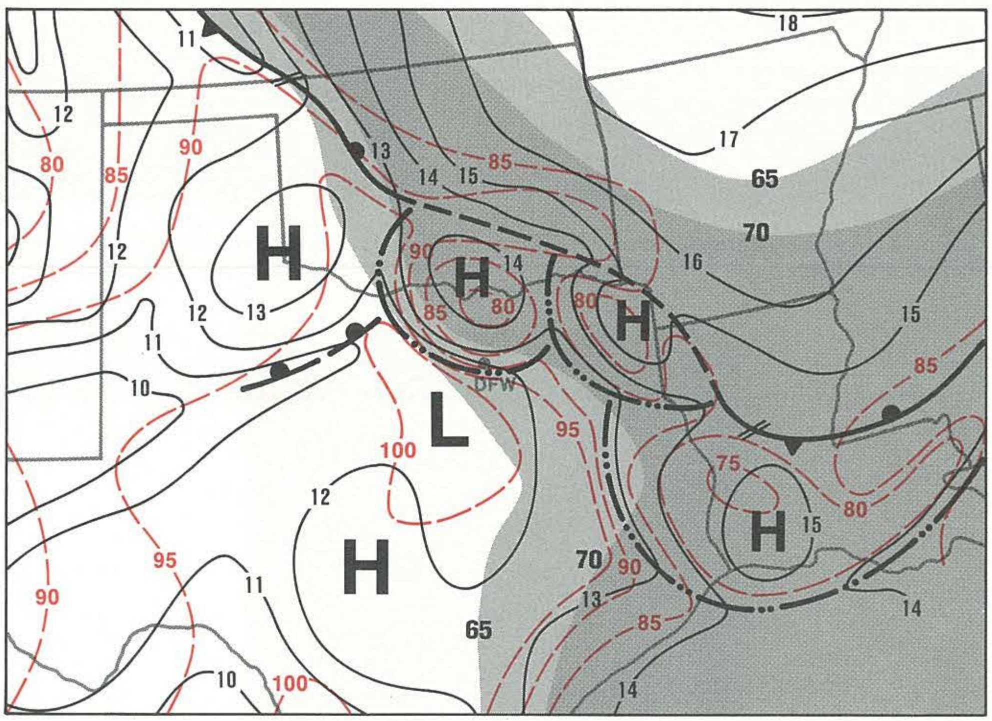


Figure 10b. Enhanced surface analysis for 0000 GMT, 3 August 1985, with temperature and dew point temperature analysis as described in Fig. 6b caption.

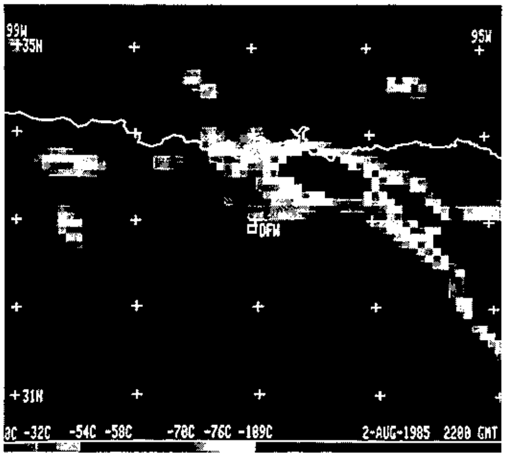


Figure 11. Enhanced cloud-top IR imagery from GOES for 2200 GMT, 2 August 1985.

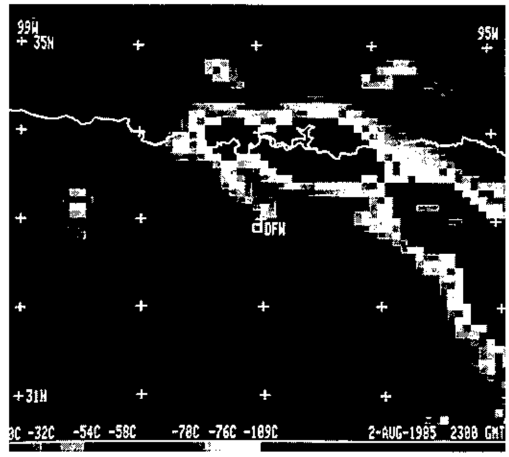


Figure 12. Enhanced cloud-top IR imagery from GOES for 2300 GMT, 2 August 1985.

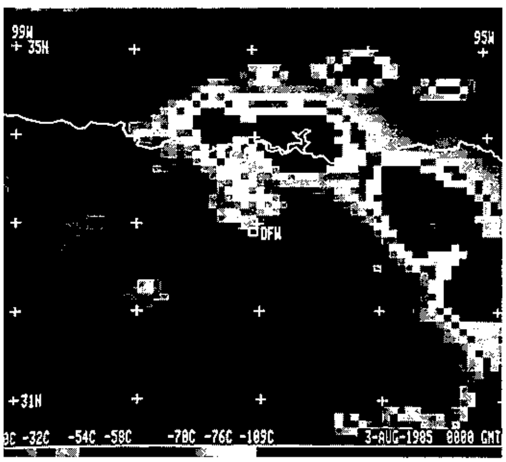


Figure 13. Enhanced cloud-top IR imagery from GOES for 0000 GMT, 3 August 1985.

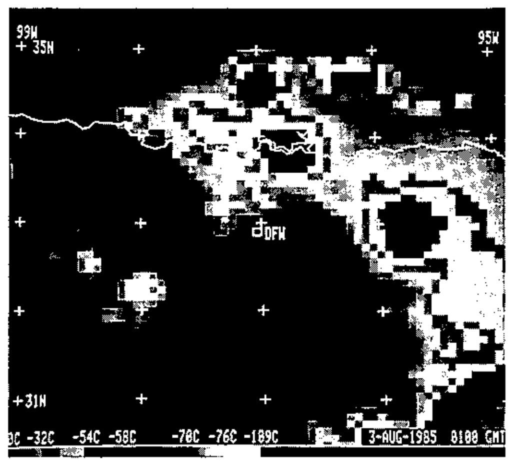


Figure 14. Enhanced cloud-top IR imagery from GOES for 0100 GMT, 3 August 1985.

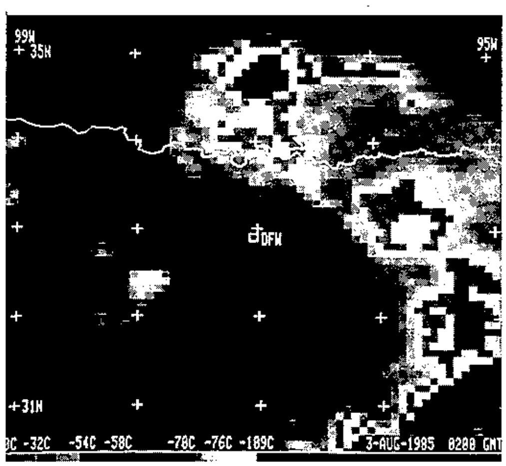


Figure 15. Enhanced cloud-top IR imagery from GOES for 0200 GMT, 3 August 1985.

convection produced a second arc of convection, which appears on the same image southwest of the parent arc. An hour later (Fig. 14), convection in the DFW area was rapidly dissipating; it was gone by 0200 GMT (Fig. 15), but note that at 0200, deep convection continued to propagate north of the Red River into more moist air.

At the time of the accident (Fig. 12), convection along the Red River must have appeared visually much more impressive than the much weaker arc of convection that extended into the north-DFW area. In this respect, weather conditions at DFW at the time of the accident were similar to those at New Orleans International Airport on 9 August 1982 when Pan American Flight 759 penetrated a lethal microburst (see Caracena et al., 1983b; Fujita, 1983). At New Orleans, a line of showers hung over the east end of the airport and produced two microbursts while a much more impressive thunderstorm was advancing into the area from the south. At the time of the accident, pilots and New Orleans tower personnel were much more concerned about the thunderstorm to the south than the showers over the east end of the New Orleans airport. Analogously, at DFW, the arc-line of cells was triggered in the drier air by outflow from much more impressive thunderstorms that formed in the moister air north and east of the area. Cells in the arc-line, although much less impressive visually (and on radar, as discussed next), moved into an environment that may have been much more favorable for microburst generation.

3.2 Radar echoes

Stephenville radar provided a series of echo depictions showing the evolution of the line of thunderstorms that is seen on satellite imagery propagating southwestward over the north DFW area (Fig. 16). The first cell of this line formed about 20 km north-northeast of DFW and appears on the 2243 GMT radar depiction (Fig. 16a). As time advanced, the line of echoes progressively filled in north-northwestward from this cell. At about 2252 GMT, a new cell appeared south-southwest of the original cell near DFW, and grew rapidly along the approach to runways 17R and 17L (Fig. 16c).

The radar depiction closest to the time of the accident, at 2304 GMT (Fig. 16f), indicates a very small area of Video Integrator Processor (VIP) level 4 close to the left landing approach. At this time a Lear Jet, about 1 minute ahead of Delta 191, was going through extremely heavy rain and experiencing rapid loss in airspeed, and a high descent rate. Delta 191 entered this same rain shaft, and, from the aircraft behind it (American Airlines Flight 539), was seen to disappear into the rain shaft, just at the time that an eyewitness on the ground witnessing the same event also saw a lightning discharge in that area of the storm.

Because of the distance from the radar to DFW (about 140 km) the beam width of a WSR-57 (2 deg. at half power) is about 4.9 km across and, therefore, tends to paint a weaker echo than would actually be seen at closer range. This reduction of apparent reflected power is due to the lack of beam filling from a target. (In this case the target, an incipient rain shaft, was approximately one-fifth the size of the beam.) Another consequence of the broad beam is that it enlarges the appearance of the area of echo by about the same amount on each side across the beam and catches part of the reflectivity overhang in the maturing cell.

The Captain on another aircraft trailing Delta 191 (Capt. W.H. Ohmsieder, Delta Flight 1067) scanned the cell that Delta 191 flew through and reported seeing a solid red echo with a narrow reflectivity gradient around it on his onboard color radar. He also reported seeing a green hook echo, that he believes was a downburst signature, protruding over the airport ahead of this cell. In Sec. 4.3.5 we discuss this feature in more detail.

3.3 Lightning

Uncalibrated lightning data were furnished for this study by the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma. DFW is located at about 265 km from the lightning detector array, and the detection efficiency at this range is expected to be about 70%. Further, the lightning detector counts only cloud-to-ground strokes, which means that cloud-to-cloud lightning officially observed at 2302 GMT (prior to the accident) would not be counted by the detector.

A lightning strike was observed on the NSSL detector during a 5-minute period ending at 2250 GMT (about 15 minutes before the accident) in the first cell north-northeast of DFW. The data show no further lightning strikes in the immediate area until the 5-minute period ending 2315 GMT, when the record shows five lightning strikes within 20 km north-northeast of DFW. After this time, lightning activity decreased.

The lightning data agree with surface observa-

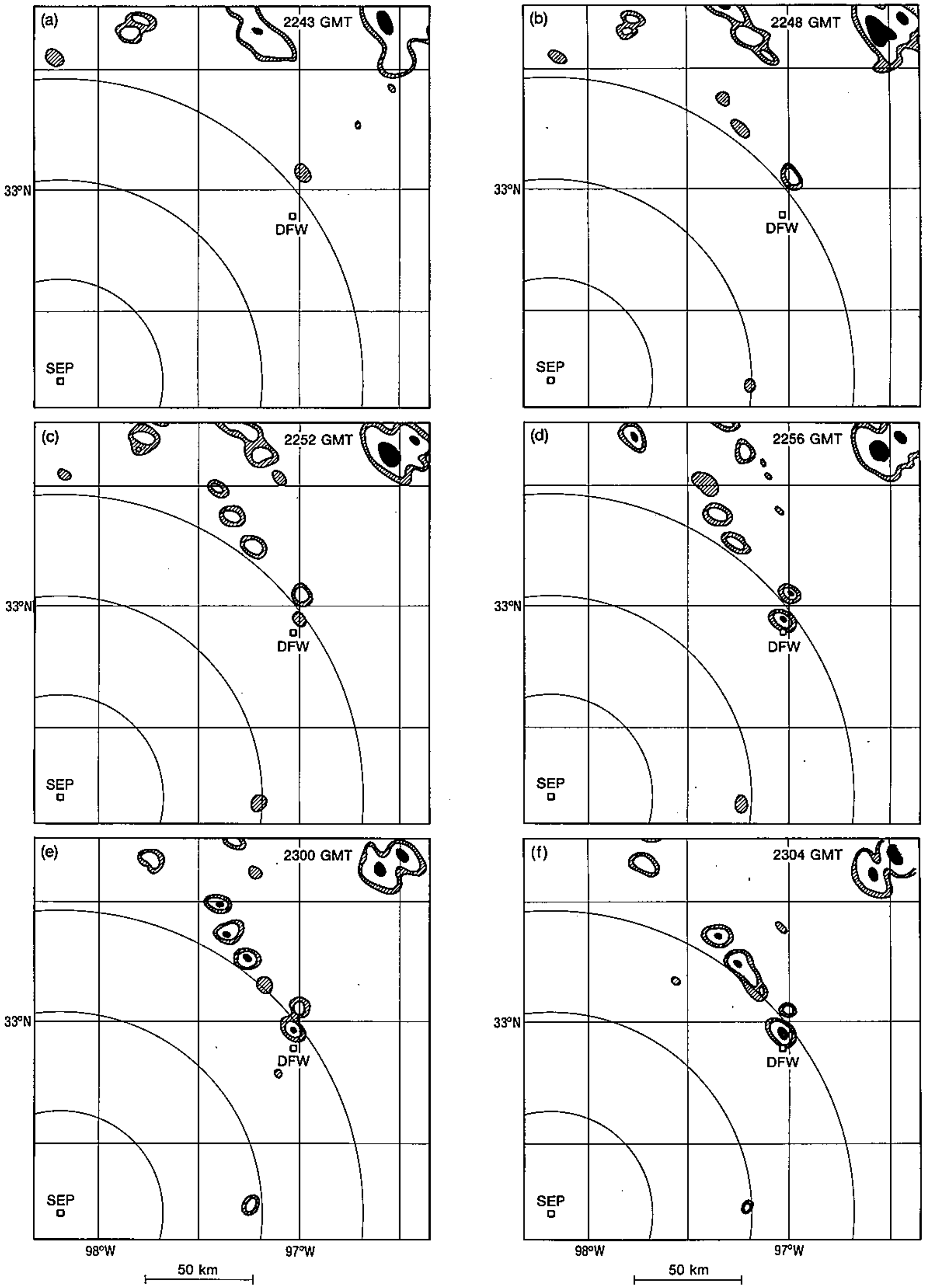


Figure 16. Stephenville radar depictions for 2 August 1985 (WSR-57, 10-cm radar with an elevation angle of 0.4°). Contours range from VIP level 2 to VIP level 5. (a) 2243 GMT; (b) 2248 GMT; (c) 2252 GMT; (d) 2256 GMT; (e) 2300 GMT; (f) 2304 GMT.

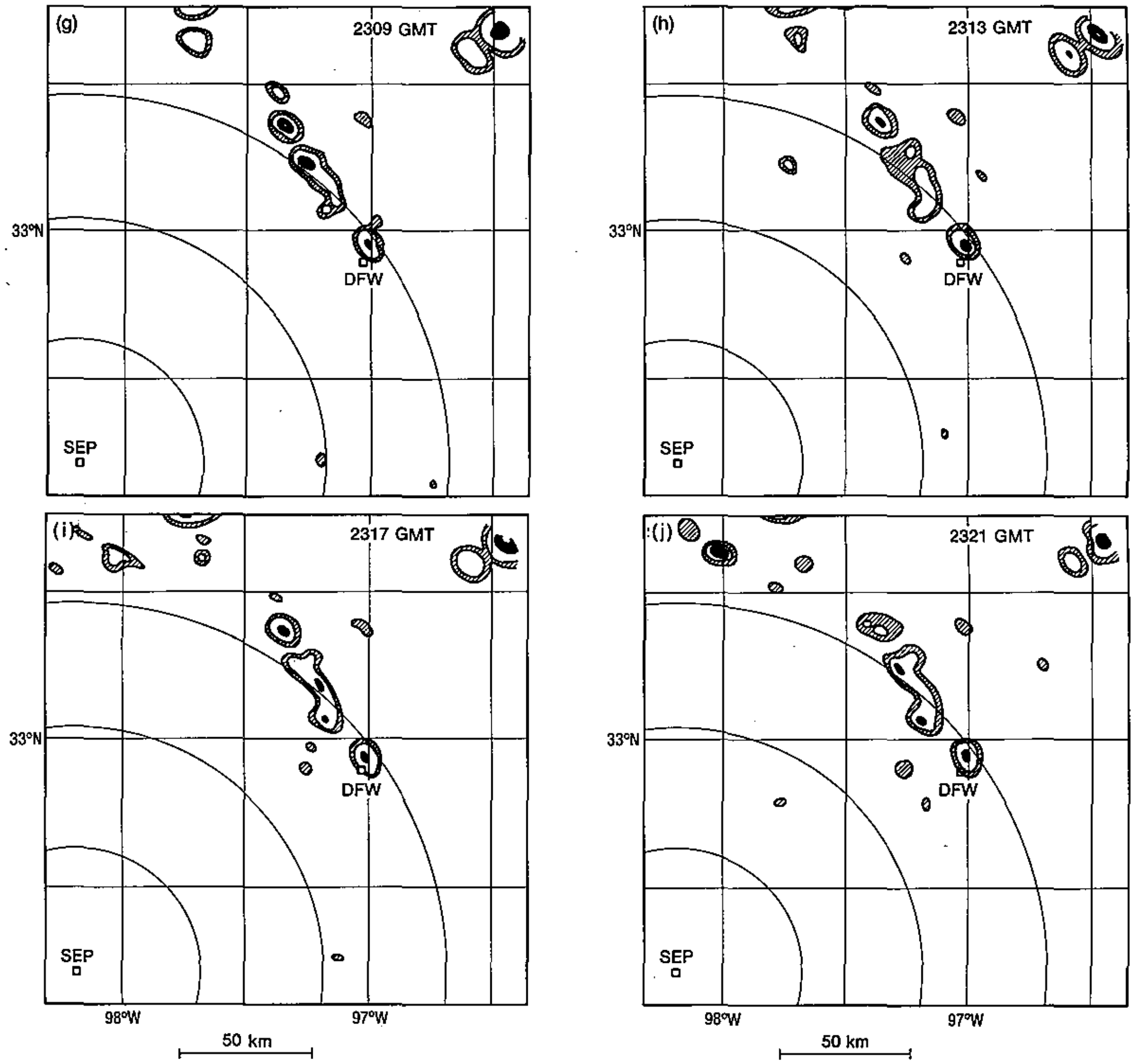


Figure 16 (continued). (g) 2309 GMT; (h) 2313 GMT; (i) 2317 GMT; (j) 2321 GMT.

tions taken at roughly 10-min intervals, beginning at 2251 GMT, when the observer's report indicates a cumulonimbus to the north-northeast and towering cumulus to the northeast, south, west, and north. At this time, the second cell, through which Delta 191 would fly, had just begun to register on Stephenville radar (Fig. 16c). The first cell (carried on the observation as a cumulonimbus) had registered some lightning on the NSSL detector.

The 2305 GMT special observation indicates that thunder began at 2302 GMT. The storm was "north-northeast and overhead moving south" with "occasional lightning cloud to cloud." This is about the same time that the crew onboard Delta Flight 963, the aircraft four ahead of Delta Flight 191, reported seeing a bowl-shaped "overhang" protruding below the overcast, which they flew around and briefly penetrated as they realigned their flight path on the approach to runway 17L. As they moved back onto the flight path, they abruptly encountered heavy rain and lost sight of the runway for a couple of seconds until they flew out of the rainshaft. During this landing, they experienced some difficulty in maintaining proper airspeed. Further, they report having seen numerous cloud-to-ground strokes of lightning. The aircraft (AA351) two ahead of Delta 191 reported 20 kt of wind shear at 2500 ft but made no mention of lightning.

3.4 Analysis of sounding data

3.4.1. The Stephenville sounding

The sounding nearest to DFW (Fig. 17a), taken at Stephenville (SEP), shows moderate to high potential for microbursts both in morning and evening. In looking at the sounding for 1200 GMT, 2 August 1985, one should anticipate the effects of diurnal heating, which acts to destroy the nocturnal inversion near the surface by the time convection is beginning to become active. This sounding shows a dry adiabatic (or "mixed") layer extending between the levels 850 and 700 mb, and one may anticipate that the mixed layer would extend from the surface to about 750 mb by the afternoon. Thus, from the morning sounding at SEP, we could anticipate a mixed layer about 8000 ft thick later in the day, which would indicate a potential for downbursts. The SEP sounding released at 2300 GMT, 2 August (Fig. 17b), confirms this expectation. At DFW, however, the mixed layer was somewhat deeper and the lapse rate was pushed to dry adiabatic, thus increasing the potential for microbursts.

3.4.2 The reconstructed DFW sounding

The reconstructed sounding for DFW is presented in Fig. 17c. The maximum surface temperature of 103°F for the day, and maximum 700-mb temperature of 50.2°F (10.1°C) imply a nearly dry adiabatic lapse rate in the surface-to-700-mb layer—a depth of about 10,000 ft. A surface dew point temperature of 65°F at DFW is moist in absolute terms, but is relatively dry because of the hot temperature. Further, note the dry air layer above 700 mb at SEP which, from the synoptic upper-air charts presented earlier, should be drier over DFW.

The reconstructed DFW sounding resembles other soundings taken in the Denver, Colo., area on days with a high frequency of microbursts. For example, compare this sounding with that taken at Denver on the morning of 15 July 1982 during the JAWS Project (Fig. 17d). The DFW sounding has the same kind of vertical thermodynamic structure but at a level in the atmosphere that is lower by about 200 mb; however, the surface pressure at Denver was lower than that at DFW by about 150 mb. The result was that the dry adiabatic mixed layer at DFW on the afternoon of the accident was about 3 km thick, compared with a layer about 4 km thick at Denver. Offsetting the shallower mixed layer is the much higher precipitable water vapor in the DFW sounding. Rain can be expected to be heavier in the DFW environment (Fig. 17c) than in the Denver microburst situation (Fig. 17d). The result is that rain loading and evaporative cooling would have played a much stronger part in the DFW microburst than in the typical dry Denver microburst. Further, the enhanced negative buoyancy in the DFW microburst offset the effects of the shallower mixed layer and thereby produced a microburst that was stronger than the typical Denver microburst.

For completeness, the DFW microburst sounding (Fig. 17c) is compared with a wet microburst sounding (Fig. 17e) that was released at the field observing site of the Florida Area Cumulus Experiment (FACE) at 1500 GMT, 1 July 1975, 3 hours before the microburst struck the very spot (Caracena and Maier, 1987). The most important common feature of the DFW and FACE microburst soundings is the elevated dry layer of potentially cool air at around 500 mb that could have acted as a source of cold downdraft parcels. An elevated dry layer was also noted as a potential source of the microburst that precipitated the crash of Pan American Flight 759 at New Orleans International Airport on 9 July 1982 (Caracena et al., 1983b)

3.4.3 Expected downdrafts at DFW

The negative buoyant potential energy in the DFW downdraft has been estimated from the reconstructed DFW sounding (Fig. 17c), using a modified form of Foster's technique (Foster, 1958). Foster suggested that downdraft buoyancy may be computed from the average equivalent potential temperature of a parcel which is assumed to be a half-and-half mixture of updraft air and saturated environmental air between the 700- and 500-mb levels. Downdraft velocity is computed from the area of negative buoyancy from the point where the downdraft parcel sinks under its own weight (the level of free sink) to the surface along a moist adiabat. Our calculation allows for both a higher source region for downdrafts (and associated level of free sink) and a portion of unsaturated descent. For the DFW afternoon sounding, a computed average for the potentially coldest layer indicates a level of free sink for the mixed parcel at 450 mb. Further, the analysis shows that the entire layer 700-450 mb had about the same mixed-parcel properties.

Had mixed parcels from this source region

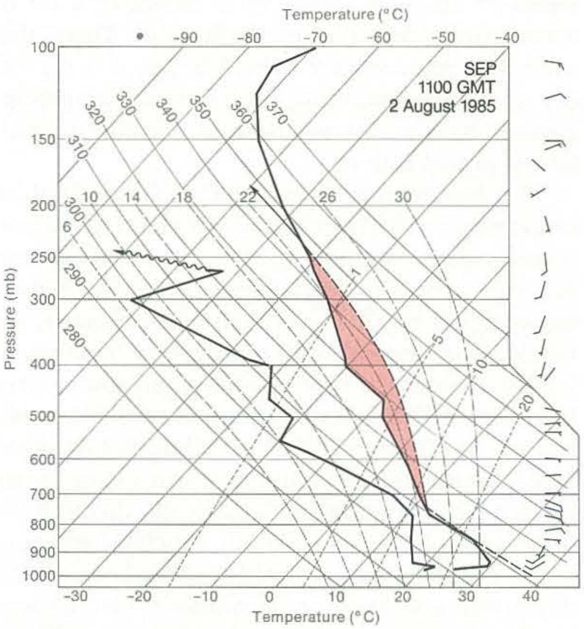


Figure 17a. Skew-T/log-P plot of the 1200 GMT sounding released at 1100 GMT, 2 August 1985, at Stephenville (SEP). Positive area in updraft is shaded red.

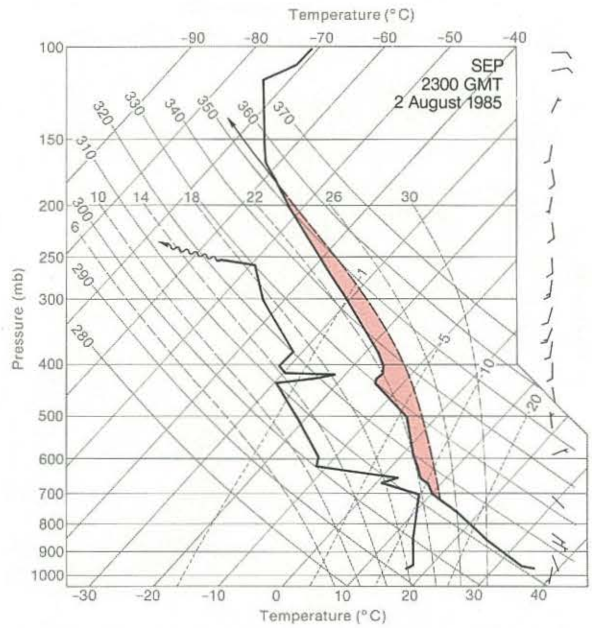


Figure 17b. Skew-T/log-P plot of the sounding released at 2300 GMT, 2 August 1985, at Stephenville. Positive area in updraft is shaded red.

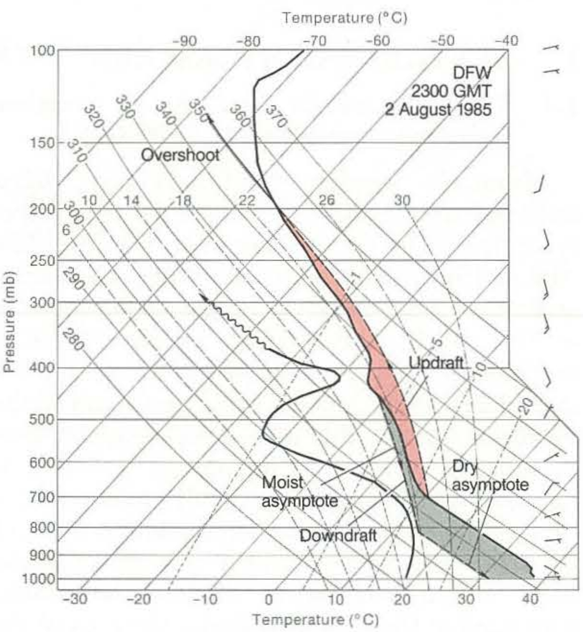


Figure 17c. Skew-T/log-P plot of a sounding for DFW, constructed from Delta 191's onboard instrumentation data and the Stephenville sounding. Positive area in updraft is shaded red; negative area in downdraft is shaded gray.

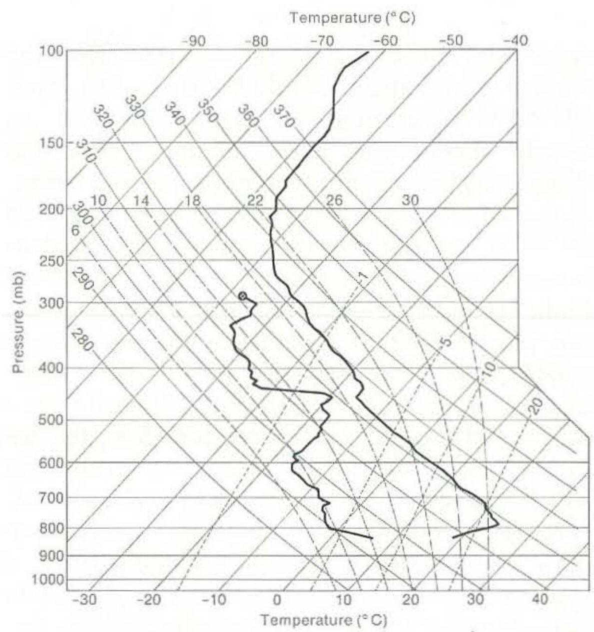


Figure 17d. Skew-T/log-P plot of the 1200 GMT Denver sounding for 15 July 1982.

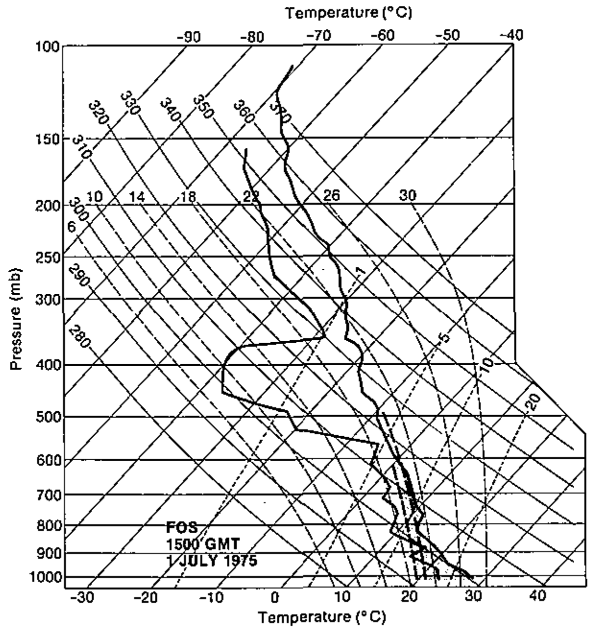


Figure 17e. Skew-T/log-P plot of the 1500 GMT sounding released from the field observing site of the FACE project on 1 July 1975, just 3 hours before a wet microburst struck the same spot.

descended moist adiabatically to the surface, the surface temperature would have dipped to about 70°F (21°C) during the storm. However, an hourly observation, taken as the storm was dissipating but still producing brisk surface wind, indicates that the surface temperature was then 88°F (31.1°C). This temperature is almost identical to the coldest temperature recorded on the flight recorder of Delta 191 as it penetrated the microburst. Thus, we model the thermodynamic trajectory of the downdraft parcel on the sounding plot as a curve (dashed in Fig. 17c) that begins at the 450-mb level and descends along the indicated moist adiabat to the 810-mb level, from which it descends dry adiabatically to the surface. Integrating the negative buoyancy acceleration between the level of free sink and the surface, it is possible to estimate the kinetic energy that could have developed in a storm downdraft within this environment. The result is a maximum speed of about 35 m/s which is very close to the peak gust recorded on the center field anemometer during the storm (70 kt).

Although the DFW microburst sounding in Fig. 17c resembles typical dry microburst soundings taken in the Denver area (see Fig. 17d; see also Brown et al., 1982; Wakimoto, 1985), in terms of absolute moisture it indicates a lot of water available for rain production. Thus, this sounding represents a hybrid between a typical dry microburst sounding (with virtually no precipitation) and a wet microburst sounding (with heavy precipitation.)

This hybrid type of downburst is initiated by evaporation within a parcel of wet cloud air, which mixes with a dry environment at upper levels and subsequently falls into a deep, dry, mixed layer below cloud level. In such an environment, we would expect downbursts to originate from penetrative downdrafts entering the cloud somewhere below the 450-mb level (about 21,000 ft), as described by Emanuel (1981). Falling below cloud base, this downdraft would continue to accelerate while descending moist adiabatically through the upper part of the dry adiabatic subcloud environment, thus widening the cold contrast between the downdraft and its hot environment. On the way to the surface, smaller rain drops would be evaporated in the downdraft, leaving larger drops, more resistant to evaporation; finally, the downdraft would continue to descend along a temperature curve that approaches a dry adiabat.

4. SYNTHESIS OF STORM ANALYSES

4.1 Local mesoscale analysis of weather situation near DFW at 2300 GMT

Mesoscale weather conditions have been analyzed from hourly data for 2300 GMT and synoptic data for the area around DFW (Fig. 18). The positions of the stationary fronts have been established from the larger scale analyses depicted in Figs. 6–10. Radar echoes in Fig. 18 (from Stephenville) appear to lie along the main front (solid line), which had retreated previously to the northeast but, by this time, had advanced back into the DFW area. As mentioned in Sec. 2.3, the ebbing of the front is probably attributable to the heating out of the shallow leading portion of the cool airmass, whereas the resurgence of the front is attributable to surface mesohighs generated to the northeast under the area of the thunderstorm complex, in combination with a decrease of surface pressure in the DFW area. In the mesoscale analysis, the surface data are insufficient to resolve the complex structure of front and mesoscale high-pressure boundaries, but an interpretation of these features has been rendered that is based on the merger of both surface and radar data.

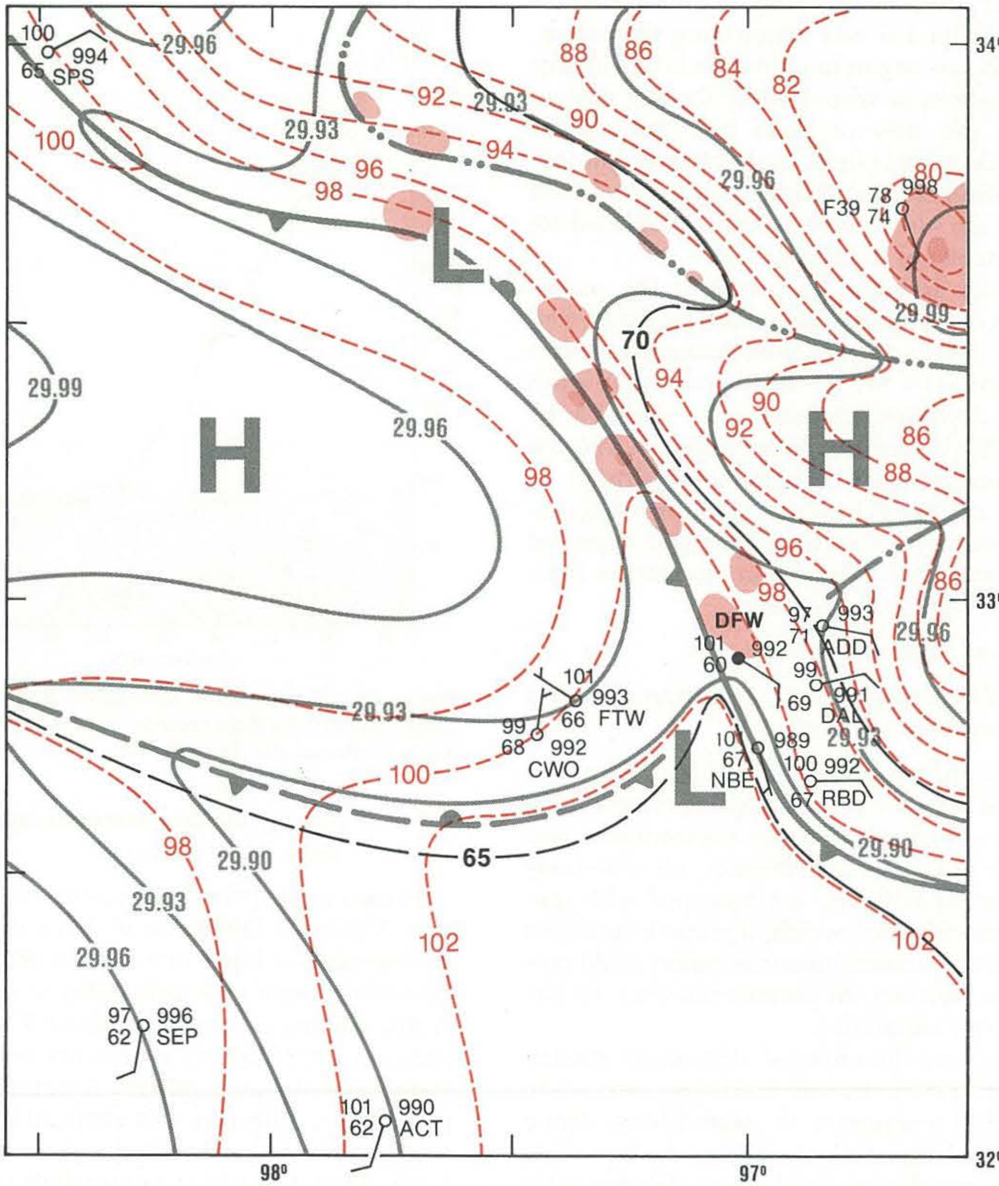


Figure 18. Mesoscale analysis of the weather situation in the vicinity of DFW at 2300 GMT. Dashed red contours are temperature in °F. Gray contours are altimeter settings in inches of mercury. Red shaded areas are echos above VIP level 2; darker red cores are echos above VIP level 3. Dashed black contours are dew point temperature in °F.

The main feature of the mesoscale analysis is the line of discrete echoes ahead of the parent thunderstorm complex, forming along a thermal ridge and pressure trough, in an environment that was hotter and drier than that which spawned its parent. Visually, the echoes were not as tall or as impressive as the storms over the Red River, but they were in an environment that was more conducive to strong downdrafts in thunderstorms.

4.2 Two storms near DFW

The thunderstorms in the immediate DFW area were produced by a combination of forces. A storm that formed about 20–30 minutes before the accident, approximately 20 km north-northeast of DFW, produced outflow of rain-cooled air that reinforced the larger scale frontal advance. This resulted in what was probably a more strongly forced second storm, which tapped a greater upper-level potential for strong downdrafts. At the time that Delta 191 was penetrating this storm, the cell had just begun to unload its heavy charge of precipitation, as witnessed by the fact that on approach, the crew of Delta 963 (four flights ahead of Delta 191) described precipitation falling from the storm as a bowl-shaped, downward bulge of virga surrounded by numerous cloud-to-ground strokes of lightning.

Thus, the accident happened as the parent storm was dissipating and the new cumulus congestus to the south was just maturing into a cumulonimbus (or thunderstorm) cell, from which the initial downdraft impulses were reaching the surface. This behavior is fully consistent with the observations from the Thunderstorm Project by Byers and Braham (1949) that pressure noses (impact pressure of a downdraft) usually appeared in cells that were just beginning to mature (i.e., just beginning to precipitate).

4.3 Lapse rate analyses

4.3.1 The aircraft's static air temperature as a microburst detector

The Stephenville sounding data were not available at the time of the accident, so how could anyone have known that the environment was primed for microbursts? Ironically, all wide-body jets, including L1011's, are equipped with sensors that provide data, which, if properly analyzed (e.g., with an onboard microcomputer) could provide a clear warning. At present, however, no aircraft has this capability.

Using a one-dimensional downdraft model, Srivastava (1985) showed that lapse rate is the most critical parameter in establishing strong downdrafts. In general, the higher the lapse rate and the deeper the subcloud layer supporting this lapse rate, the higher the probability of having microbursts. Another critical parameter is the concentration of water feeding into the downdraft. The form of this precipitation is also very important; the smaller the average hydrometeor size, the more efficient the evaporation and the stronger the possible downdraft.

At DFW, the thunderstorm in the path of Delta 191 was producing extremely heavy rain through a deep subcloud layer characterized by a dry adiabatic lapse rate. Thus, in this case, a critical mixture of abundant rain, and a favorable subcloud environment, combined to give a high probability of microbursts at the time that Delta 191 was approaching the thunderstorm.

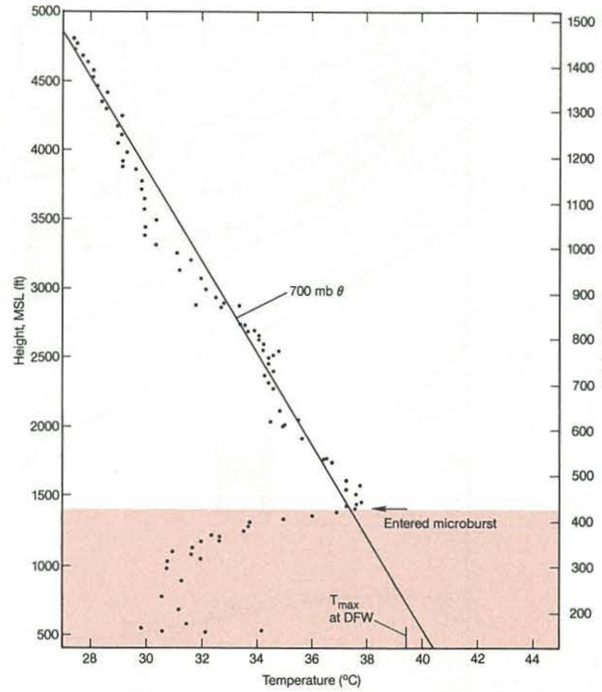


Figure 19. Temperatures determined from the static air temperature of the flight recorder onboard Delta 191. Solid line is the dry adiabat from 700 mb.

4.3.2 Sensing the environmental lapse rate with static air temperature

Brown et al. (1982), Caracena et al. (1983a), and Wakimoto (1985) found that a dry adiabatic environmental lapse rate over a deep subcloud layer indicates a high probability of microbursts. A dry adiabatic lapse rate (about 9.8°C/km, or about 5.4°F/1000 ft) represents neutral static stability of the atmosphere. A parcel of air displaced up or down in this environment from its equilibrium position will encounter no restoring force. That means that a downdraft is easy to initiate and sustain.

The static air temperature that was sensed and recorded on Delta 191's digital flight recorder has been used to obtain a lower tropospheric sounding for DFW (Figs. 17c and 19). For most of the approach from 700 mb (approximately 10,000 ft) to the surface, the change of the static air temperature with height was along a straight line, which represents a dry adiabatic lapse rate. Thus, in retrospect, Delta's own flight-recorder data showed the high potential for microbursts, although the information about how to interpret these data, and, more importantly, the means to do this, were not available to the flight crew at the time of the accident.

4.3.3 *Visual appearance of virga and rain shaft*

Once it is established that the subcloud lapse rate is dry adiabatic, then the only other factor needed to generate a microburst is precipitation. A new precipitation shaft is particularly effective in this respect because it brings down a new downdraft into a fresh, hot environment that has not been rendered more stable by substantial mixing with previous outflow. This was exactly the situation when Delta 191 was on the landing approach and flew through a new rain shaft.

Until the arrival of the aircraft three ahead of the ill-fated flight, little wind shear had been encountered at DFW. Then the flight crew on Delta Flight 963 sighted a strange bowl-shaped "overhang" extending below the base of a vigorously building cell. This downward bulge was simply a new precipitation shaft on the way to the ground. Rain not yet reaching the ground is called virga; however, unlike the virga found in more arid regions, which represents rain evaporating away before reaching the ground, this virga represented heavy rain that had not yet reached the ground. The pilot on Delta 963 prudently avoided flying under this strange cloud, and flew around it. However, as he aligned his flight path with runway 17L he flew under its edge, encountered heavy rain, and briefly lost sight of the runway.

As this rainshaft reached the surface, pilots on the ground reported sighting strange occurrences such as "water spouts," "bamboo curtain" effects, hour-glass-shaped rain shafts, and silvery precipitation shafts surrounding very dark and narrow rain shafts. There was even a report that it appeared to be "raining up." The character of the rain went rapidly from "threads" hanging from the base of the cloud to a "wall of water."

All these eyewitness accounts are consistent with the interpretation that they were seeing a microburst, beginning its impact with the ground. Rain curling back up into the cloud along the margins of the microburst was observed and documented in a series of photographs by Smith (1986, Fig. 20; also presented by Fujita, 1985). Smith's pictures show first a bulge of virga below cloud base, then an impacting rain shaft that subsequently curls up at the edges. The precipitation curl at the edge of a rain shaft and the dust curl at the base of a virga column are both visual indicators of a microburst; thus, under certain conditions, both wet and dry microbursts may be visually observed through the curl of aerosols that they raise.

4.3.4 *The temperature break as an indicator of a strong downdraft*

A deep mixed layer was revealed by the static air temperature and altimeter data from the Delta Flight 191 flight recorder (Fig. 19). The presence of a nearly dry adiabatic lapse rate over a deep layer (about 10,000 ft) in itself is indicative of a favorable environment for downbursts. The other ingredient needed to produce a strong downdraft is evaporating rain, to cool downdraft parcels at the top of the mixed layer. The greater availability of rainwater produces greater potential for evaporative cooling, and thus a stronger possible downdraft.

The static air temperature data from the flight recorder show that there was a strong temperature break at approximately 400 m associated with the rain shaft that was penetrated by Delta 191. Details of how this temperature break relates to the microburst encounter are summarized in Fig. 21. When reduced to potential temperature, the temperatures at various levels in the mixed layer prior to this break are nearly the same, and the temperature break is shown as a downward swing of the potential temperature. Note that this rapid reduction in potential temperature is apparent about 2 seconds before the downdraft is encountered, and it occurs within an updraft. A cold updraft near the surface indicates that a very strong downdraft is striking the surface nearby with sufficient force to drive a cold return flow, which is lifted against its own negative buoyancy.

4.3.5 *Visual and radar evidence for a microburst on approach to runway 17L*

The weather observer at DFW recorded a thunderstorm beginning at 2302 GMT, 3–4 minutes before the accident occurred. At this time, he observed occasional cloud-to-cloud lightning and a rainshower of unknown intensity to the north-northeast. Although the rain did not reach the observer's site until 2316 GMT, William E. Cook at the ramp control tower (NTSB Exhibits, 1985) described the shower at 2302 GMT as a solid curtain of rain, a "wall of water."

Jerry G. Bush saw Delta 191 disappear into the rain shaft and "severe" lightning strike in the area; from the flight recorder and cockpit voice recorder data, this was at about 23:05:20 GMT. Captain J.A. Coughlin, Delta Flight 963, reported

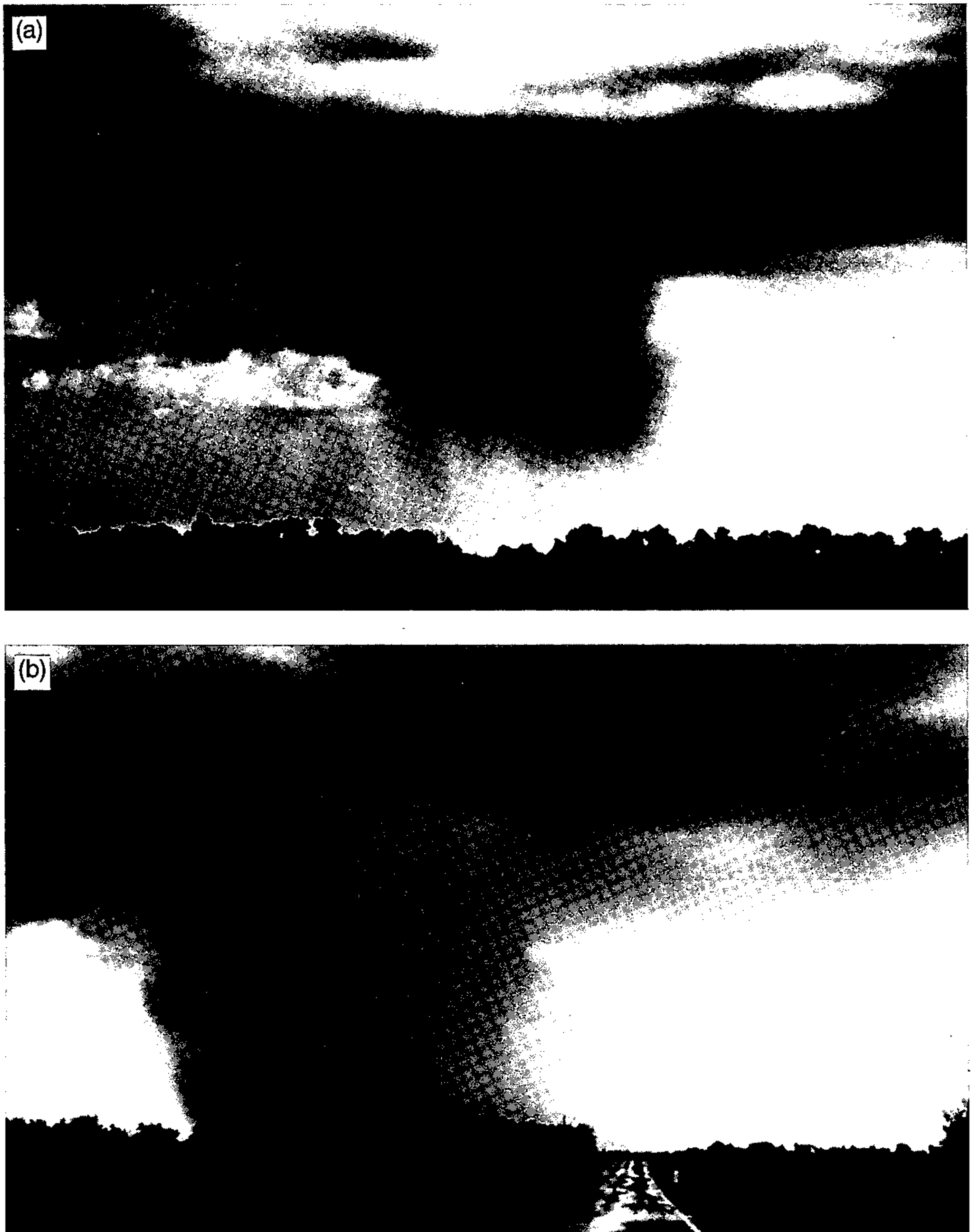
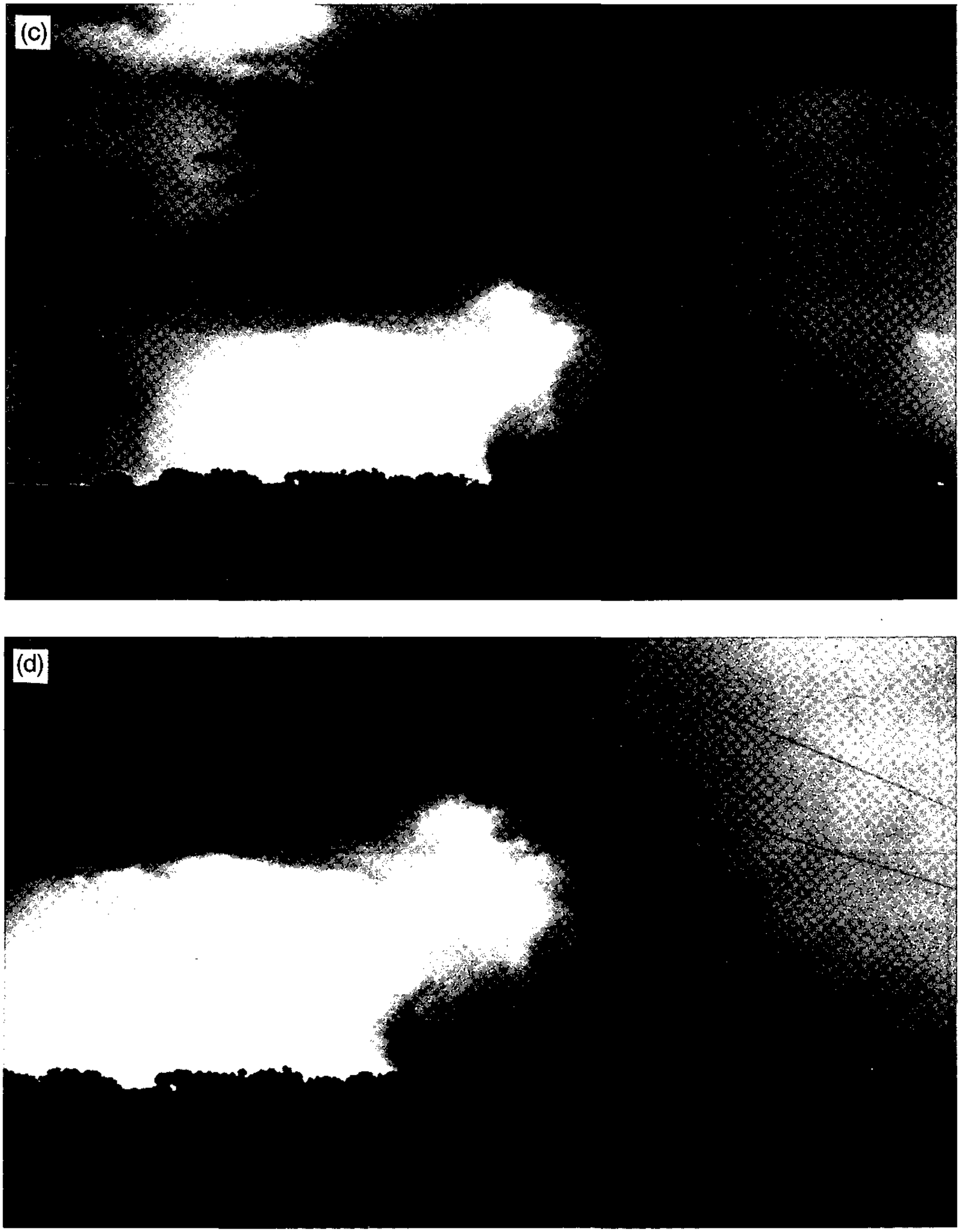


Figure 20. Photographs of a wet microburst, taken west of Wichita, Kans., at approximately 1-min intervals. (Copyright, 1986, Michael Smith.) Note in (c) - (g) that the leftward bulge at the base of the precipitation shaft becomes an upward curl.



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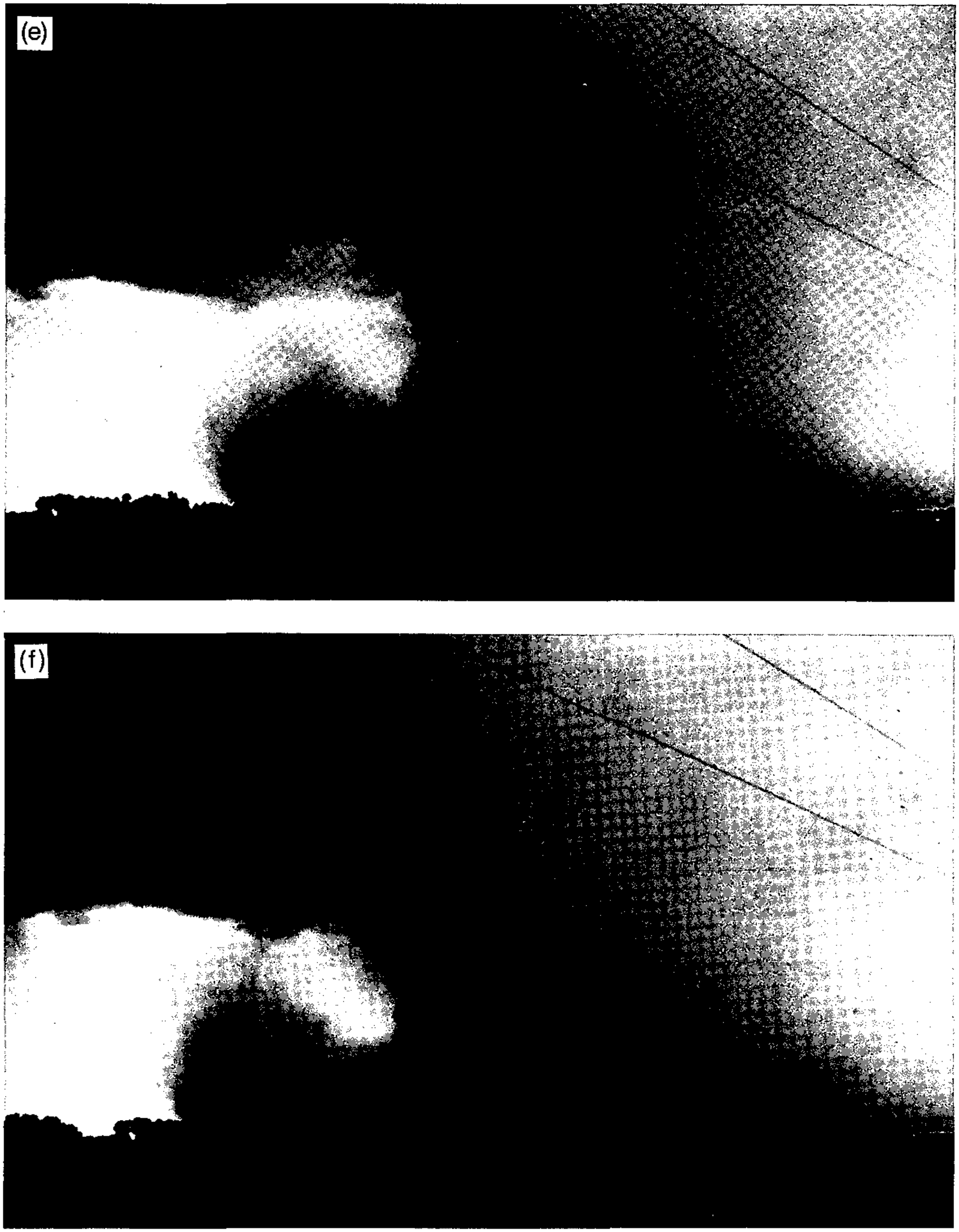

Figure 20 (continued).

Figure 20 (continued).

seeing the rain fall from the maturing cell as a bowl-shaped protuberance below cloud base, and reported numerous strikes of cloud-to-ground lightning on final approach to touchdown (about 2301–2302 GMT).

At about the time of the crash (2305–2306) Captain W.H. Ohmsieder, on Delta 1067, saw the microburst cell on the onboard color radar as a solid red contour (the highest contoured reflectivity) with no visible reflectivity gradients on a plan view scan. He notes having seen a green hook-shaped echo (the lowest contoured reflectivity) protruding from a microburst cell over DFW airport seconds before another crew member sighted the fireball produced by Delta 191. He is convinced that the green hook-shaped echo was a microburst signature—an observation supported simultaneously by eyewitnesses at the ramp control tower who report having observed what appeared to be rain moving back up toward the cloud. An upward precipitation curl on the edge of a heavy rain shaft is a good visual indicator of a microburst (Smith, 1986) and would contour as a low-reflectivity arc on an airborne radar. The spotting of rain moving up, a green hook-shaped echo, and a cold updraft (Fig. 21) all fit together neatly in indicating that a microburst was in progress.

Therefore, at the time of the crash, there was ample evidence that a microburst was occurring on the approach to runway 17L, but this evidence was scattered in bits and pieces among many observers and instrument recordings, and was not available in real time to the ill-fated crew or personnel at the surface. Now, after the fact, we see that all these bits and pieces fit into an interlocking and mutually supporting pattern. Further, all the indirect evidence is firmed into a conclusion of a definite microburst occurrence by Bach and Wingrove's (1985) analysis of the winds encountered by Delta 191.

4.4 Model of microburst and outflow affecting Delta 191

Bach and Wingrove's (1985) estimate of the wind encountered by Delta 191 on its approach to runway 17L, based on excellent flight recorder data, shows that the aircraft penetrated the main downdraft of the microburst at 550–850 ft AGL.

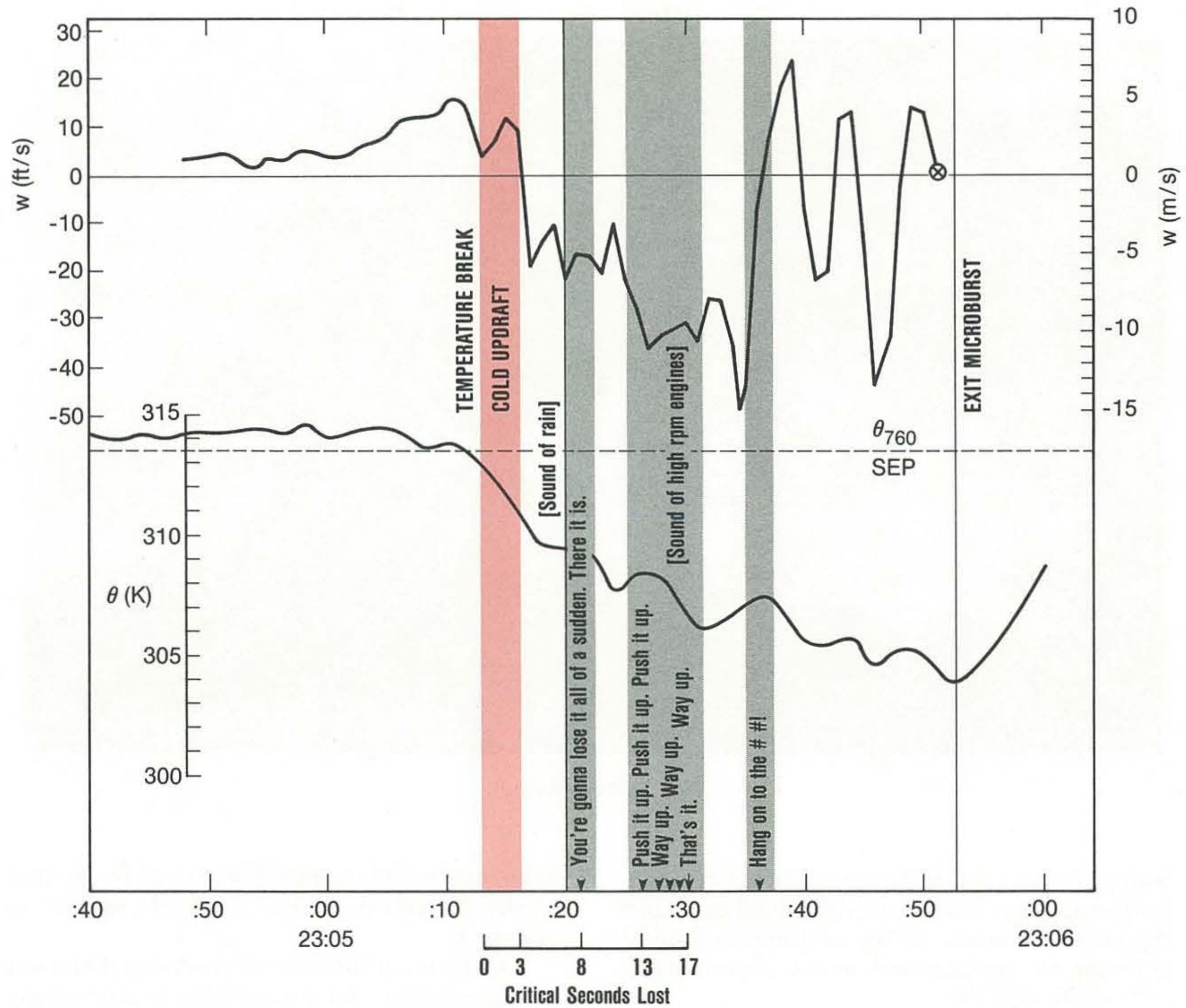

Figure 21. A time series plot of vertical wind component (w) and static air temperature (θ) from the Delta Flight 191 flight recorder together with comments from the flight crew that were recorded on the cockpit voice recorder. Wind analysis and other data were provided by Bach and Wingrove (1985).

The aircraft survived the downdraft only to crash in the outburst, or low-level outflow of strong wind, which contained not only strong tail winds but a series of three strong wind vortices, parts of vortex rings that circled the main downdraft.

A conceptual model of the microburst, based on the analysis by Bach and Wingrove, is shown in plan view and vertical cross section in Fig. 22. The overall structure is one of a large vortex ring that contains smaller scale vortices. The microburst was just reaching the surface and spreading out as Delta 191 entered it. On initial penetration, the aircraft may have flown under the smaller scale vortex rings without encountering them on the way to the downdraft core. As it continued to fly beyond the center of the microburst, it ran through a series of vortex rings in the low-level flow that produced strong vertical drafts and tailwinds. The static air temperature data indicate that the aircraft traveled outside the microburst after first ground impact (not shown); hence the last vortex ring represents the gust front or leading edge of the outflow. At the time of the accident, the entire system of outflow was very compact and the internal circulations were significant. Of particular concern are the vortex ring circulation on the margins of the descending microburst and the vortex circulation on the gust front head.

Caracena (1982) hypothesized that a microburst may be a vortex ring that descends in a thunderstorm downdraft. As this ring strikes the surface, the vortex circulation becomes concentrated because the downdraft expands the ring and stretches its vorticity. The interaction of this vortex ring and the friction-induced vorticity of opposite sign at the surface causes a strong updraft to develop on the margins of the microburst. This induced updraft may be strong enough to levitate rain drops to form an upward curl of precipitation (as documented photographically by Smith, 1986), which is chararcteristic of wet microbursts. The circulations in the head of the gust front have been well documented (see Charba, 1972; Goff, 1975).

5. SUMMARY AND CONCLUSIONS

5.1 Rapid deterioration of weather over north end of DFW

The crash of Delta Flight 191 happened after the aircraft entered a shaft of heavy rain that contained an embedded microburst. This rain shaft was just reaching the ground from a maturing thunderstorm cell. North-northeast of this cell, a second thunderstorm was dissipating. From a transcription of remarks, it is apparent that the crew members were just beginning to assess the weather situation as they were flying into the storm and felt no concern for what (in retrospect)

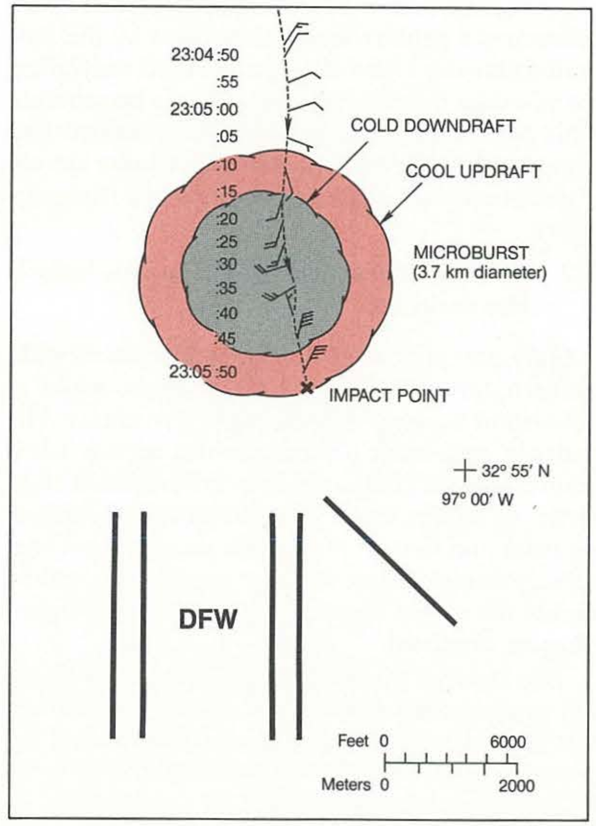

Figure 22a. A conceptual model of the horizontal airflow structure in the DFW microburst, based on the analysis of flight recorder data by Bach and Wingrove (1985). Dashed line represents the aircraft track.

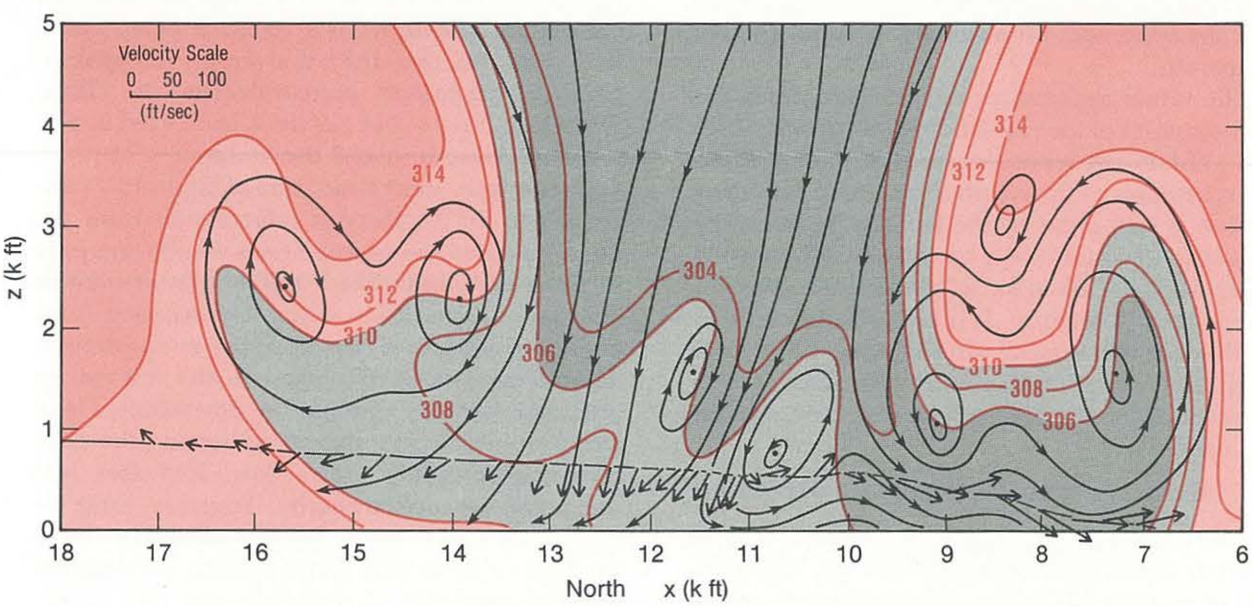

Figure 22b. A conceptual model of the vertical airflow structure in the DFW microburst, based on the analysis of flight recorder data by Bach and Wingrove (1985). Red contours are potential temperature (K); black lines are streamlines. Arrows are wind vectors (see velocity scale). Dashed line represents the aircraft track.

was a rapidly deteriorating weather situation. Furthermore, a penetration of this storm by the aircraft following Delta 191 was avoided only after the pilot was instructed by the tower to go around. This pilot testified that he had entertained the thought of going around, but he did not act on it until he received the communication from the tower.

5.2 Benign appearance of the storm before the accident

Only one pilot ahead of Delta 191 acted with concern for the weather: He tried to avoid a downward bulge of virga below the overcast. He had not seen such a phenomenon at this level before, and he compared it to an overhang that forms at higher levels. The virga bulge looked unusual and that prompted his caution, not the rapidly deteriorating weather conditions, which should have been apparent to him from the lightning he observed.

The Lear Jet pilot immediately ahead of Delta 191 probably saw a heavy rain shaft and lightning, but they gave him no apparent concern until he encountered a descending microburst. The crew in the aircraft trailing Delta 191 were unable to see the crash occur because of obscuration by heavy rain. They pulled up and went around only after they were instructed by the controllers in the tower. From these considerations, it appears that only one flight crew perceived the new storm over the approach to runway 17L to be potentially dangerous.

The visual appearance of the storm from the vantage point of aircraft landing on runways 17R and 17L did not serve as a basis for correct pilot interpretation of the weather hazards. This conclusion is supported by the fact that only one of the flight crews (and only on the basis of onboard radar displays) asked for wind shear information during the DFW storm. It is further substantiated by the fact that several aircraft were flown into a cell that, on radar from a trailing aircraft, was detected as having a very high reflectivity (solid red contour).

5.3 Evidence that the storm was dangerous

All pilot impressions to the contrary, our analysis shows that the storm over the approach end of runway 17L was a very dangerous storm and it presented the following clues that indicated danger:

- Visually the rain shaft was very concentrated.
- This showed up on aircraft radars as a solid red echo with no outer gradient colors such as yellow and green.
- The rain shaft was "hourglass-shaped" in appearance.
- It had an upward curl at its edges (rain being carried up).
- The curl appeared on an aircraft radar briefly as a green hook-shaped echo.
- The rain shaft was new, having reached the surface 3–4 minutes prior to the accident.
- The rain shaft was accompanied by frequent cloud-to-ground and cloud-to-cloud lightning, which was observed by many on the ground and in the air prior to, during, and after the accident.

Additionally, the environment was primed for downbursts over the DFW area in having a dry adiabatic lapse rate from 700 mb (about 10,000 ft MSL) to about the surface. The potential for microbursts needed only the presence of precipitation to become realized; and from a research perspective, the presence of concentrated, opaque rain shafts in this environment is a clear indicator of strong downdrafts. Further, an elevated dry layer (reflected in the Stephenville sounding), a source of potentially cool air with a high level of free sink, could act as a source of microbursts. However, although these signals of potential danger are known from a research perspective, it is doubtful that they are widely recognized among operational meteorologists or pilots. Therefore, they could not have been used in any practical sense to avoid the accident.

On the very short time scale of Delta 191's approach to DFW, there is information from the flight recorder and other sources which, analyzed in retrospect, indicates a microburst encounter about to happen. The aircraft descended from 10,000 ft MSL in a dry adiabatic environment. Thunderstorms were present in the immediate area and, before it entered the downdraft, Delta 191 flew into a cold updraft indicating the edge of a concentrated, strong downdraft that was impacting the surface nearby. Together, these ingredients point to a high probability of a microburst encounter. Again, such information was not available in real time and can be appreciated at present only from a research perspective.

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