The Discovery of the Downburst: T. T. Fujita's Contribution

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ABSTRACT

T. Theodore Fujita proposed the existence of a small-scale diverging wind feature that could cause damaging winds at the surface. He also proposed that it was responsible for a number of aircraft crashes when encountered on takeoff or landing. This paper describes the scientific discoveries Fujita made documenting the existence of this wind shear phenomenon that he named the downburst. It describes events that led to the remarkable reduction in aircraft accidents and saving of lives because of the discovery of the downburst. It is also intended to give the reader insight into the man himself.

1. Introduction

T. Theodore Fujita was the scientific genius behind the discovery of the convective weather phenomenon called the downburst. The subsequent research on this wind shear event and transfer of this knowledge into the aviation community have benefited the whole of society and must be considered one of the major, rapid payoff, success stories in the atmospheric sciences. There is little question that many lives have been saved from potentially deadly aircraft crashes associated with downburst wind shear. The history of the convective downburst, starting with the mysterious crashes of aircraft that no one could initially explain, to intense research and scientific understanding and, ultimately, to an engineering solution, is documented in this paper and in Serafin et al. (2000).

The purpose of this paper is to give our perspective of the role Fujita played in the discovery of the downburst, to provide some insight into Fujita's ingenious scientific techniques as well as his personality, and to indicate our present scientific understanding of downbursts. The first author was most fortunate to witness Fujita's observational discovery of the downburst and subsequent analyses. This paper draws extensively on these experiences and on previously published accounts on the discovery and the follow-up activities that led to increased aircraft safety. Among these publications are three books written by Fujita and published as research papers by the University of Chicago (Fujita 1985, 1986, 1992) and a chapter in the book *Storms* (Serafin et al. 2000). Additional insight into Fujita's work habits and personality can be obtained from Rosenfeld (1999).

2. Downburst hypothesis (Eastern Flight 66)

On 24 June 1975 Eastern Airlines Flight 66, a Boeing 727 airplane, crashed while attempting to land at New York's John F. Kennedy (JFK) International Airport killing 112 and injuring 12. While there were thunderstorms in the area, there was no understanding at

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that time of what may have caused the crash beyond speculation that it was struck by lightning. Fujita's involvement started when Homer Mouden (a safety expert with the Flight Safety Foundation), who was investigating the crash, became intrigued with the reported weather events by other aircraft landing and taking off near the accident time. Some aircraft reported little adverse weather while others experienced hazardous winds. He approached Fujita with this information with the hope that he could unravel the mystery. Fujita recalled the very small-scale damage patterns he had observed in the wake of the super outbreak of tornadoes on 3–4 April 1974 (Fujita 1974). During his numerous aerial damage surveys he not only observed the swirling pattern of downed trees associated with tornadoes but Fujita also noted strange starburst patterns of uprooted trees that indicated strong diverging winds (see Fig. 1). After analyzing the aircraft flight data recorders, pilot reports, and an airport anemometer, Fujita hypothesized that Eastern 66 had flown through a diverging wind system similar to but weaker than those he observed during his analysis of the 3–4 April 1974 starburst damage patterns. At the suggestion of his former mentor, Horace Byers, he termed this diverging wind system a downburst to capture the notion of a strong downdraft of air that burst outward on contact with the ground. Fujita defined a downburst as a strong downdraft that induces an outburst of damaging winds on or near the ground (Fujita 1978). He further subdivided downbursts into microbursts and macrobursts according to their scale of damaging winds. A damage pattern ≤ 4 km was defined as a microburst and > 4 km a macroburst (Fujita 1981, 1985).

Fujita's analysis of the weather events associated with the crash of Flight 66 is shown in Fig. 2. The analysis is an excellent example of both his creativity and insight as he carefully pieced together disparate bits of data. In Fig. 2a, he fit a few observations from a variety of sources to generate a time–space analysis of the airflow encountered by different flights including ill-fated Flight 66. He used, as a model, the airflow he inferred from damage patterns he had observed earlier. Figure 2b is a vertical time section of the descent path of Eastern Flight 902 and Fujita's analysis of the airflow encountered by the aircraft. Flight 902 aborted its attempt to land when it encountered a strong wind shear 7 min prior to the crash of Flight 66. Figure 2c is similar to Fig. 2b except for Flight 66.

Between 1976 and 1978, Fujita became involved in analyzing possible wind-shear-related accidents from all over the world. He produced at least eight analyses similar to those of Fig. 2 (Fujita 1985). Because of the lack of detailed data, such analyses were open to criticism. Accordingly, Fujita's downburst theory was met with some controversy in the scientific community (Fujita and McCarthy 1990). There were those who said Fujita had simply renamed a well-known and understood phenomena, that is, the thunderstorm downdraft and gust front. Others argued that a downdraft would weaken to an insignificant speed before reaching the ground and thus could not cause an aircraft accident (Fujita 1985). The concept of a bursting outflow was advanced by Byers and Braham (1949) based on data from the Thunderstorm Project conducted from 1946 to 1947. They noted the thunderstorm downdraft descended to the ground and then spread out horizontally similar to a fluid jet striking a flat plate. Byers and Braham also recognized that gusty surface winds, associated with the thunderstorm outflowing air, were a threat to airplanes taking off and landing, particularly soon after the downdraft reached the ground.

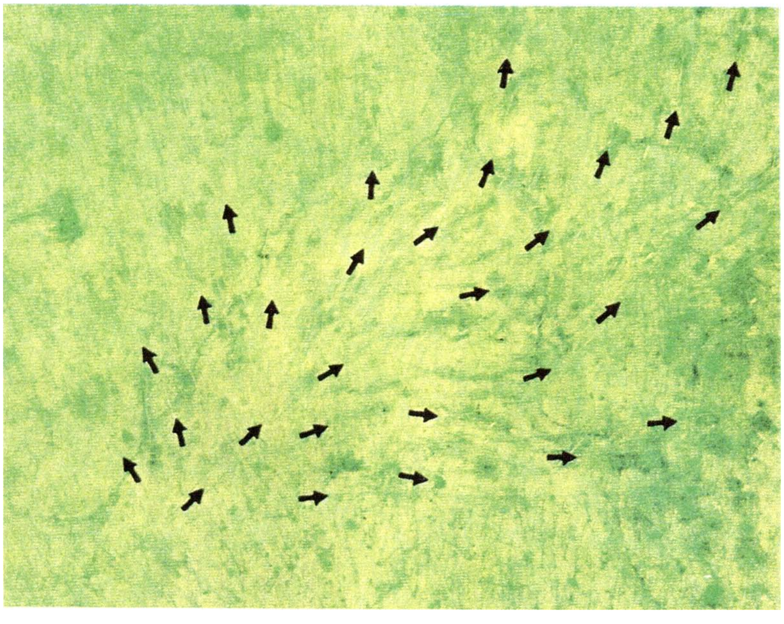

Fig. 1. Starburst pattern of uprooted trees associated with a downburst photographed by Fujita near Beckley, WV, following the superoutbreak of tornadoes on 3–4 Apr 1978. It was such damage patterns that gave Fujita the ideas for the existence of downbursts. [From Fujita (1985).]

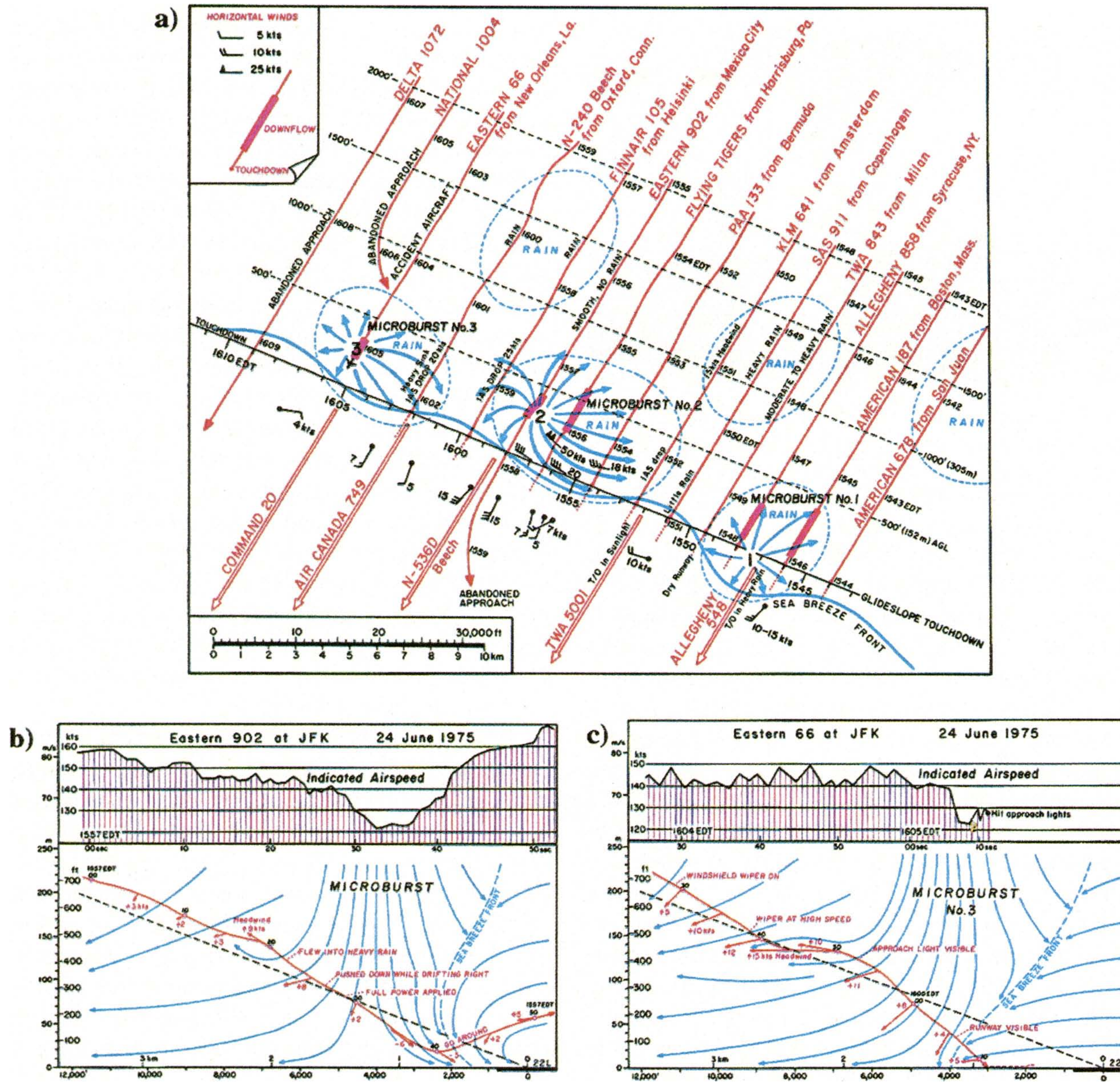

FIG. 2. Fujita's analysis of the wind events and flight paths at JFK airport on 24 Jun 1975 near the time of the crash of Eastern Flight 66. The analyses are based on reports from pilots landing near the time of the crash, flight data recorders, and an anemometer: (a) flight path vs flight time diagram for 14 landing aircraft, (b) flight path of Eastern 902 (aborted approach) and hypothesized airflow, (c) same as (b) except for Eastern Flight 66, which crashed. [From Fujita (1992).]

In the authors' opinion, in spite of the earlier work of Byers and Braham (1949), many meteorologists did not appreciate the notion that a downdraft with horizontal dimensions of order 1 km could descend almost to the ground before rapidly diverging outward as a strong horizontal wind less than a kilometer deep and only a few kilometers in horizontal dimension. In addition, it was not understood that it was the center of the diverging outflow that was of greatest danger to aircraft and not the leading edge of the outflow (gust front). Fujita's analysis of aircraft accidents illustrated this point. Fujita often mentioned the criticism and felt strongly compelled to prove the existence of a downburst. From 1975 to 1978 he embarked on an intensive program to photographically document small-scale diverging damage patterns in corn fields and forests using low-flying Cessna aircraft. These photographs and analyzed wind patterns are documented in Fujita (1978); however, direct detailed observations of the airflow were needed to quiet the critics.

FIG. 3. Fujita standing on the CP-4 antenna pedestal trailer during the MIST field program in 1986. He spent many hours at this and the other radars collecting downburst data and then many more hours analyzing the data. (Photograph by R. Wakimoto.)

In the autumn of 1976 Robert Serafin and Clifford Murino of the National Center for Atmospheric Research (NCAR) met with Fujita and suggested that he make use of the NCAR Doppler radars to verify the existence of downbursts. Serafin thought that the Doppler radars, which were proving to be highly effective in probing thunderstorms, would be able to remotely measure the winds within the parent cloud and detect the horizontal outbursting winds near the ground from a downburst as hypothesized by Fujita. This led to formulation of the first of three field programs that proved the existence of downbursts and provided a detailed description of their evolution. The data collected by these field programs showed airflow patterns that were remarkably similar to those hypothesized by Fujita in Fig. 2. Figure 3 shows Fujita with one of the NCAR C-band Doppler radars that played a major role in providing data for his downburst research.

3. Field projects

a. NIMROD

The first field program, the Northern Illinois Meteorological Research on Downbursts (NIMROD) project, was sponsored by the National Science Foundation (NSF) and was conducted in northern Illinois during the spring and summer of 1978. It was during the planning for this experiment that the first author met Fujita. The primary issue in planning for NIMROD was the siting of the three Doppler radars [CP-3 and CP-4 from the National Center for Atmospheric Research (NCAR) and CHILL (University of Chicago/Illinois State Water Survey) from the Illinois State Water Survey]. Close spacing of the radars was required in order to determine the three-dimensional structure of the airflow within a downburst while larger spacing was desirable to increase the likelihood that a downburst would be observed. Fujita decided to go with the larger radar separation owing to the need to prove the existence of the downburst. The legs of the radar triangle were set at ~60 km. Fujita understood this would increase the likelihood of detecting a downburst while making it unlikely the radars would be able to accurately reconstruct the three-dimensional wind field. At the time this seemed the prudent approach since it was felt that the occurrence of downbursts was rare. The network of Doppler radars and mesonet stations for NIMROD is shown in Fig. 4.

This was the first time that Fujita had used Doppler radar data and he had no previous experience in the interpretation of the real-time displays of Doppler velocity. The first author, believing himself to be particularly adept at interpreting Doppler velocity images, was stunned to find that after a few short explanations about data quality, artifacts, and interpretation of the radar data, Fujita was just as good!

Shortly after the start of the field program, Fujita and the first author personally observed the first recorded microburst on Doppler radar. It was observed on the CP-3 radar at Yorkville, Illinois, on 29 May 1978. After noticing a flash of lightning southwest of the radar site the antenna was rotated to scan the area. On the first scan the Doppler velocity display showed a small bull's-eye pattern of rapidly approaching velocities centered 5 km from the radar (see Fig. 5). Within minutes, as Fujita and Wilson stood outside looking for what they saw on the radar, a strong gust

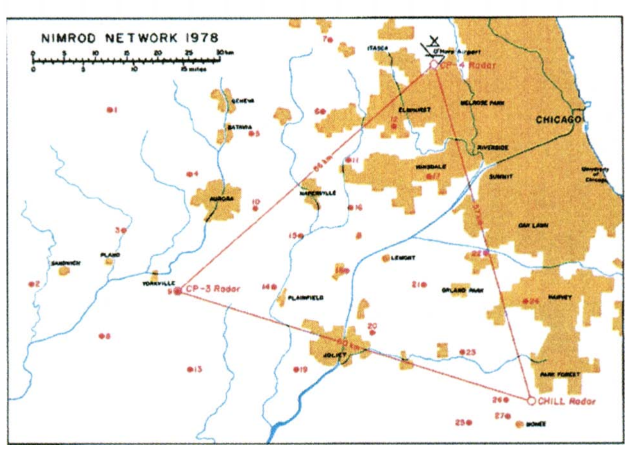

FIG. 4. Network of Doppler radars and mesonet stations established west of Chicago during Project NIMROD conducted from 19 May to 1 Jul 1978. [From Fujita (1985).]

of wind almost blew them into the adjacent farm pond. With great excitement they realized they had observed the first microburst on radar and had actually felt the diverging outflow.

Figure 6 is Fujita's analysis of the airflow associated with this microburst; it shows a downdraft a few kilometers wide that rapidly expands outward near the ground very similar to what he had earlier hypothesized. The analysis is a vertical cross section of the vertical wind speed and horizontal wind speed. The maximum horizontal velocity is 31 m s^{-1} and is located less than 100 m above the ground. This is a hand analysis of the CP-3 radar data. Since the analysis is based on only one radar, Fujita assumed that there was no cross-beam horizontal wind component. He obtained the vertical wind component by integrating the mass continuity equation from the ground upward.

Fujita rarely used computers when analyzing data, preferring to use manual analysis techniques that he had perfected early in his career. He was a master at rapidly generating colorful schematic diagrams that showed salient features of the phenomena that he was investigating. Typically he did not state the assumptions he used to prepare the analyses and seldom would anyone ask about or question the accuracy. He had a reputation of being right and few had the confidence to directly question his results. Fujita's genius was in being able to take an incomplete set of observations, intuitively fitting them to real-world phenomena, and then preparing colorful, easy to understand figures.

The large majority of his downburst work was not published in peer-reviewed journals. Rather he chose to publish in conference proceedings and via the University of Chicago Research Papers. It is likely that publication of his downburst work in refereed journals would have been an irritating, time-consuming activ-

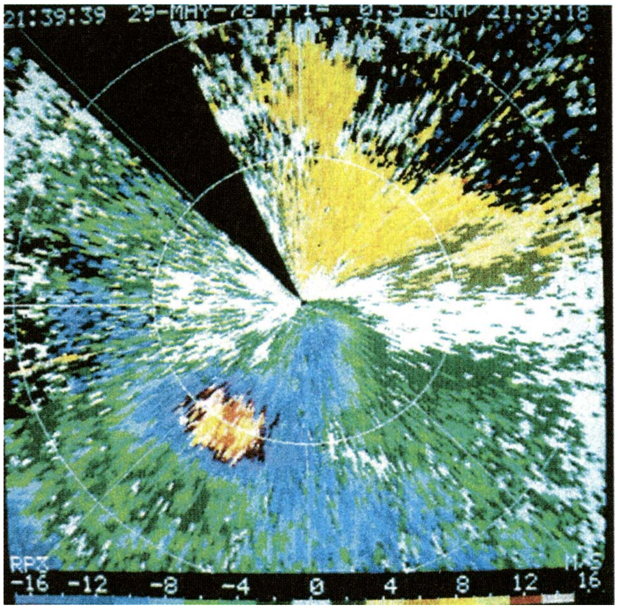

FIG. 5. CP-3 Doppler velocity display showing the wind velocities associated with the first microburst observed on Doppler radar: 29 May 1978. The small patch of red, orange, and yellow colors centered 5 km to the southwest of the radar represent winds as high as 21–27 m s^{-1} just 70 m above the ground. The white range rings are at 5-km intervals. The color bar at the bottom represents the Doppler velocities in m s^{-1}. The negative velocities indicate airflow toward the radar and positive away. However the reds, oranges, and yellows mentioned above also represent winds toward the radar; in this case the winds have exceeded the unambiguous velocity range of 17 m s^{-1}.

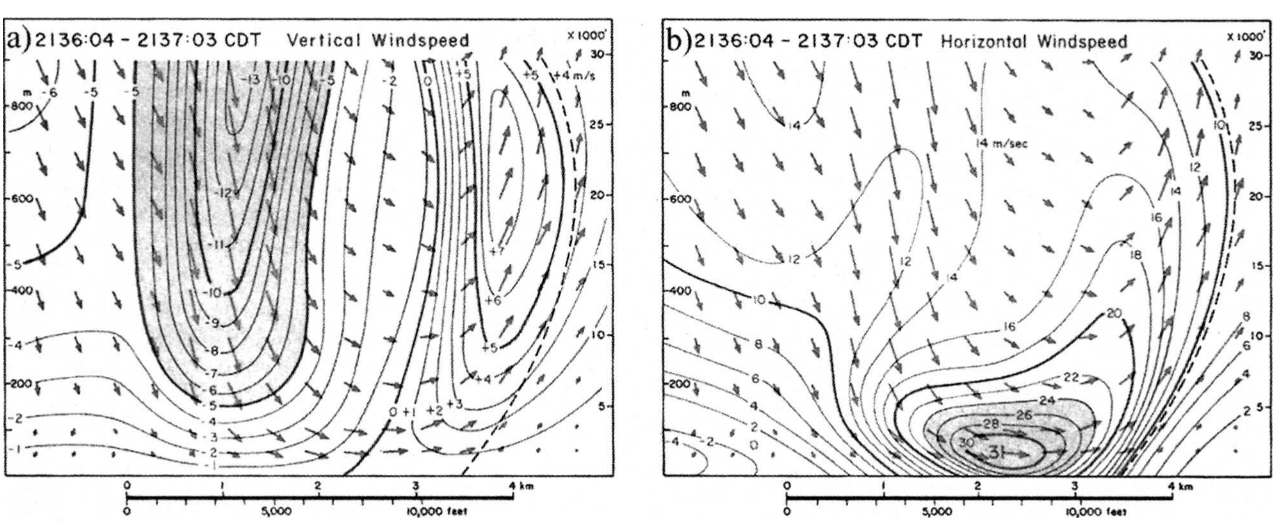

FIG. 6. Fujita's single-Doppler analysis of the airflow, in a vertical cross sections along a radar radial, in the center of the microburst in Fig. 5: (a) vertical wind speeds and (b) horizontal wind speeds. [From Fujita (1992).]

ity for Fujita. He probably realized reviewers would have questioned his unorthodox analysis procedures and heavy use of unstated assumptions.

Figure 7 is an example of dual-Doppler analyses that Fujita prepared manually. On the particular day of these analyses, 25 June 1978, the elevation drive motor for CP-3 failed. Following the failure a remarkable series of weather events occurred. The decision was made to first point the antenna at a 3.5° elevation angle and scan continuously. Fortunately, a high time resolution dataset was obtained of the full evolution of a bow echo. Fujita had earlier used this name to describe a radar reflectivity feature that took on a bow shape and was often associated with strong surface winds. Fujita generated the vectors in Fig. 7 by graphically combining the radial velocities from the CHILL and CP-3 radars. It was clear that a reflectivity notch or "trench" developed rearward of where the echo bowed outward. Fujita reasoned that this trench was the result of drying associated with the downdraft. Two F1 tornadoes formed where the winds burst outward in the bow, precisely where the strongest horizontal shear occurred. Based on these analyses, Fujita revised his earlier hypothesis (Fujita 1978) that the bow echo produced the downburst to hypothesizing that the downburst produced the bow echo. A more complete discussion on bow echoes is provided in a companion article in this issue (Weisman 2001). Fujita's bow-echo work has led to forecasters alerting for downburst-induced damaging winds when a bow echo is observed on the radar.

Later on this same day the antenna was pointed vertically while, remarkably, two hailstorms propagated over the radar site. Figure 8 is (another manual dual-Doppler analysis) a time–height analysis of the reflectivity and storm-relative wind flow patterns from the first hailstorm. The CHILL radar executed a sequence of plan position indicator scans at a variety of elevation angles over CP-3 making it possible to obtain a dual-Doppler analysis in a vertical plane directly over the site. A time history of these analyses (Fig. 8) shows airflow patterns very similar to those obtained of a hailstorm by Browning et al. (1976).

Typically Fujita was able to prepare dual-Doppler analyses in a fraction of the time required by those doing traditional dual-Doppler analyses with computers. Fujita's analyses, to a large extent, were based on photographs of the radar scope and computer printouts of the reflectivity and velocity data for each data gate. The images were obtained by his graduate students and research staff photographing each sweep of the radar from a color monitor. The number of slides taken of the radar scope numbered into the thousands. He had an uncanny ability to quickly scan through these slides and pick out the salient features and time periods. While Fig. 7 (and also Fig. 11) shows dual-Doppler analyses, the large majority of his analyses were based on a single-Doppler radar.

Approximately 50 microbursts were detected by the radars and anemometers during the NIMROD experiment, thus proving the existence of downbursts and their surprisingly high frequency of occurrence. However, because of the shallow nature of the intense outflow winds, and the 60-km spacing of the radars, it was not possible to obtain dual-Doppler analysis of the low-level kinematic structure.

b. JAWS

Many of the major findings of NIMROD were presented by Fujita at the 19th Conference on Radar Meteorology in Miami, Florida. During the conference on 18 April 1980, Fujita, Serafin, Wilson, and John McCarthy sat around the dinner table and planned a comprehensive field project that would lead to a better understanding of the structure, evolution, and cause of microbursts over the high plains. This experiment came to be known as the Joint Airport Wind Shear (JAWS) Project. JAWS was conducted from 15 May to 13 August 1982 in the Denver, Colorado, area where a high frequency of microbursts, particularly those associated with low or weak radar reflectivities, were expected (Fujita referred to these events as dry microbursts). NCAR's three Doppler radars were laid

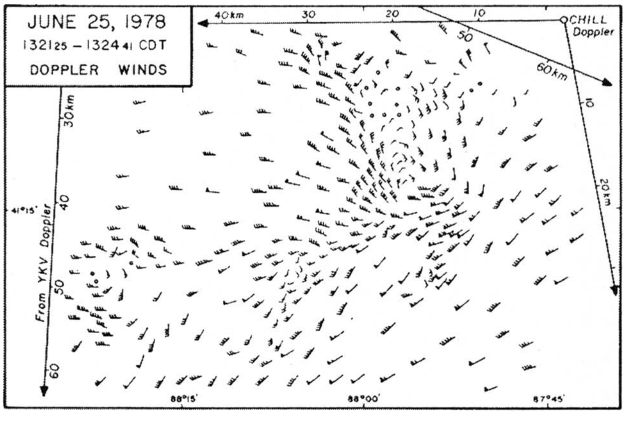

FIG. 7. Dual-Doppler analysis prepared manually by Fujita of a bow echo that occurred during NIMROD. Analysis of data from this case resulted in Fujita revising his earlier model of the evolution of bow echoes. One barb represents 5 m s^{-1} and a flag 25 m s^{-1}. [From Fujita (1979).]

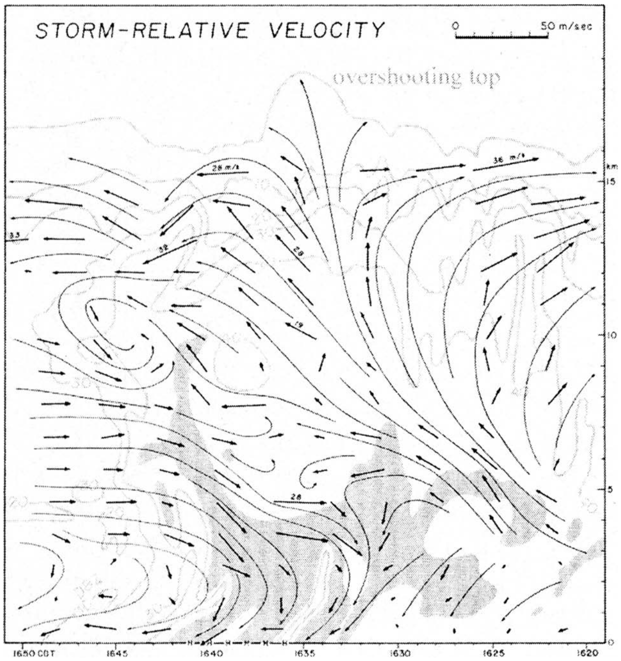

FIG. 8. Time–height analysis of the reflectivity and dual-Doppler winds as a hailstorm passes over CP-3 while pointed vertically. The dual-Doppler storm-relative winds and streamlines were prepared by Fujita from manual analysis of the CP-3 and CHILL radar data from NIMROD [From Wilson and Fujita (1979).]

out in a much tighter network than for NIMROD. With a spacing of 15–28 km between radars it was expected that the three-dimensional wind field of the life cycle of a microburst could be captured.

Fujita was very active in locating the radars and in participating in the field program. However, he generally worked independent of the other scientists. Typically he did not participate in the planning of daily activities, coordinating radar scanning, and coordinating aircraft flights. He left those activities to the other investigators. He often chose to drive around in the open country, photographing the clouds and microbursts that were often visible as blowing dust. He would also station a photographer at each radar and instruct them to take pictures at coordinated times in the direction the radar was scanning, so that he could combine cloud photogrammetry with dual-Doppler analyses. These photographs were critical in documenting the benign appearance of the parent clouds (with pendant virga shafts) that could produce damaging microburst winds (Fujita 1985).

Figure 9 is one of Fujita's single-Doppler analyses of a low reflectivity microburst, or dry microburst as Fujita referred to them. The reflectivity of the parent cloud is only 17 dBZ. This case nicely illustrates how an apparently innocuous looking convective cloud as observed by radar or seen visually can be a significant danger to aviation. Fujita named this the Rit Carbone microburst since it occurred in the vicinity of Stapleton Airport and caused a commercial airplane upon which Carbone was a passenger to abort its landing when it encountered severe windshear. A following airplane also aborted its landing. Fujita often named weather features he studied. Some examples include the flat tire microburst, ring of dust microburst, spearhead echo, and giant anteater clouds.

Occasionally Fujita would visit one of the radars and dictate its scanning mode (he was particularly fond of the CP-3 site). This was the case on 12 June 1982—the day Mr. Tornado observed his first tornado. Fujita was at CP-3 directing its scanning mode and taking coordinated photographs. Present with Fujita at the radar were Rita Roberts, an NCAR scientist, and Cathy Jirak, the radar technician. Figure 10 is a photograph taken by Jirak of this historic occasion of both Roberts and Fujita observing their first tornado. The following events were related to the authors by Roberts:

> A visually impressive line of cumulus clouds was developing to the east. It was fortuitous that the line of clouds was illuminated by the sun descending low in the sky to the west and clear skies elsewhere. Prior to the formation of the tornado, Fujita would run out the trailer door, look at the clouds and then come back making a slicing motion with his hands and say "RHIs here and here" and then he would run out

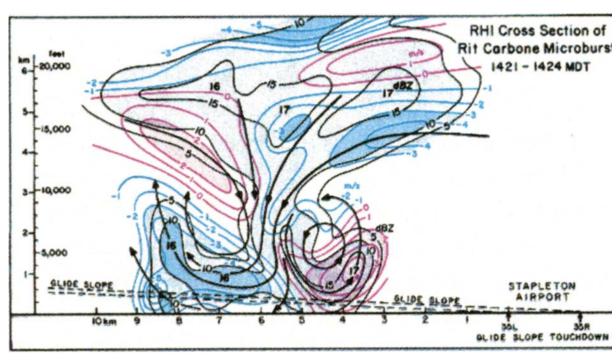

FIG. 9. Fujita's single-Doppler analysis of a "dry microburst" that caused two commercial airlines to abort their landings while landing at Denver's Stapleton airport. NCAR scientist Richard Carbone was on one of the aircraft; thus, Fujita named it the Rit Carbone microburst. The black contours are radar reflectivity factor and the red contours are receding Doppler velocities and blue approaching. Streamlines are the heavy black lines.

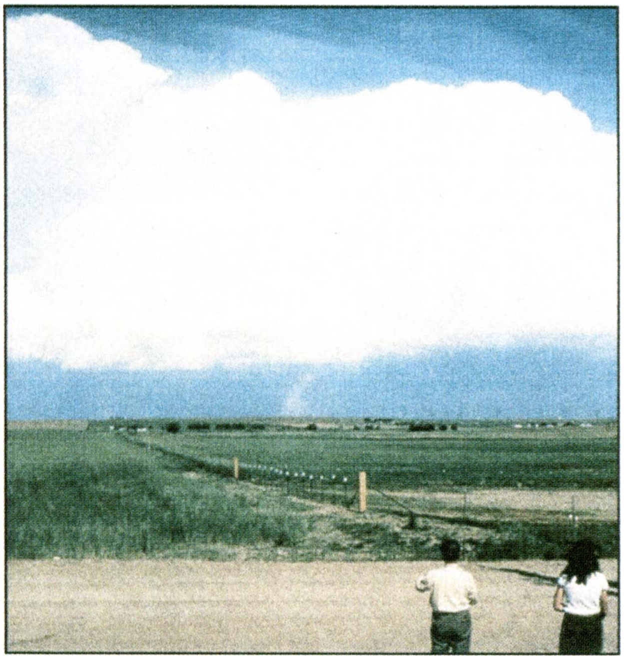

FIG. 10. Fujita observing his first tornado on 12 Jun 1982 from the CP-3 radar site during JAWS. (Photograph by C. Jirak.)

> to photograph the clouds, synchronizing every photo with specific time intervals on his watch. The tornado was perfectly illuminated for photographing. Fujita was in his element taking pictures every few seconds and constantly checking his watch. During the tornado everyone stood outside watching while the radar happily chugged away collecting RHI data of the tornadic storm. Fujita turned toward Roberts after the tornado dissipated and with a big grin said now his licence plate would no longer be TF0000. He would now have to change it to TF0001, reflecting his first tornado sighting.

Fujita documented a total of 186 downbursts that occurred during the JAWS experiment. Fujita left the three-dimensional analysis of the time evolution of the kinematic field to the other scientists in the project (Hjelmfelt 1987, 1988; Wilson et al. 1984; Lee et al. 1992, etc). His presentations documenting the occurrence of intense microburst winds from innocuous high-based clouds over Colorado stunned the scientists and led to numerous investigations of the forcing mechanisms of the intense downdrafts.[1] Srivastava (1985, 1987) and Proctor (1989) concluded that when the subcloud environmental lapse rate was approximately equal to the dry-adiabatic rate, the rates of evaporation placed little restriction on the magnitude of the downdraft. Even in light precipitation, strong downdrafts may be generated. These results have been confirmed by numerous accounts of microbursts associated with virga shafts from weakly precipitating systems (e.g., McCarthy and Serafin 1984; Mahoney and Rodi 1987). Wilson et al. (1984) and Hjelmfelt (1988) showed that the strongest microburst during JAWS was associated with only a 25-dBZ echo at a height of 500 m above ground level.

Numerical simulations by Proctor (1989) and in situ measurements by Wakimoto et al. (1994) have shown that particles in the form of snowflakes are most effective in producing microbursts. The sublimation of these particles are particularly effective for three reasons: 1) the numerous low-density, snow particles readily sublimate, with much of the snow content depleted before melting to rain; 2) the latent heat of sublimation is greater than the latent heat of either evaporation or melting; and 3) the cooling from sublimation takes place at a relatively high altitude within the deep adiabatic layer, allowing the downdraft to accelerate through a deep column. This revelation of the extreme sensitivity of downdraft speed to the microphysics of the precipitation particles can be ultimately traced back to Fujita's insightful photo documentation of these virga microbursts.

c. MIST

The third field project, called the Microburst and Severe Thunderstorm (MIST) project, was conducted near Huntsville, Alabama, during the summer of 1986. The purpose was to study downbursts in a humid environment. Cloud bases over this region of the United States were lower and the effect of precipitation loading, effectively ignored for virga microbursts, played a more important but not well-understood role. The parent clouds for these types of microbursts were typically thunderstorms.

During MIST the three NCAR Doppler radars were laid out in a triangle with a spacing along the legs of 13–25 km. Unfortunately, it was a drought year in the southeast United States; nevertheless several excellent downburst cases were obtained. The most extensively analyzed case, called the Monrovia microburst, occurred on 20 July 1986 (Fujita 1992) and is arguably one of the best documented examples of a single-cell thunderstorm since the Thunderstorm Project (Byers

[1]It should be noted that Braham (1952), Krumm (1954), and Brown et al. (1982) had earlier noted that high-based light rainshowers in the high plains could produce strong winds.

and Braham 1949). Fujita's analysis of this case is yet another example of his genius in making use of a variety of datasets. It was also typical of the independent manner in which he participated in field experiments.

On this particular day Fujita had chosen to fly on the NOAA (National Oceanic and Atmospheric Administrations) P-3 that was participating in the project. With minimal coordination from scientists at the MIST operations center, Fujita directed the P-3 to fly some distance from the radar network to collect data independent of the other observing facilities. After hearing radio reports of potential thunderstorm activity from the operations center, Fujita then instructed the pilots to fly toward the center of the triple-Doppler network. The vectoring of the aircraft toward the MIST network coincided with the rapid development of a deep convective cloud. Fujita became very excited about this storm and began to take a sequence of photographs from the airplane. At the same time the radars began to scan the growing convective tower. The series of photographs combined with the kinematic structure reconstructed from multi-Doppler syntheses produced a unique dataset. CP-2 was a dual-polarization radar; that is, it transmitted both horizontally and vertically polarized signals. Comparison of radar reflectivity factor from both polarizations provides information on precipitation particle type. This data provided one of the first views of the microphysical characteristics of a warm-based thunderstorm based on remote sensing techniques (Tuttle et al. 1989; Kingsmill and Wakimoto 1991). The storm also produced a significant microburst when the precipitation reached the surface.

Figure 11 is the evolution of the horizontal wind field at low levels for the Monrovia microburst that Fujita prepared from the CP-2 and CP-4 Doppler velocities. The range–height indicators (RHIs) from CP-4 revealed an artifact radar signature that Fujita and the first author named the flare echo. This artifact has the appearance of an elongated weakly reflecting echo that extends radially outward from immediately behind some intense radar echoes. This false echo is the result of three-body scattering. First, some of the radar signal is scattered by large, highly reflecting raindrops or hail downward toward the ground; second, the signal is reflected from the ground back to the same highly reflecting particles; and third, the signal is scattered by these particles back to the radar. An extensive discussion of this scattering mechanism and the properties of the signal can be obtained in Zrnic (1987) and Wilson and Reum (1988). An important property of the flare echo is that the Doppler velocity represents the vertical motion of the large particles that cause the flare echo.

Figure 12 shows the time evolution of the vertical motion of these large particles. Fujita was able to show using the flare echo data how large particles evolved from moving rapidly upward in an updraft during the developing stages of the storm to forming the leading edge of the downdraft that caused the microburst. In Fig. 13 he has overlaid the fall speed of the large particles upon corresponding reflectivity data from CP-4 and a picture taken from the P-3. He was then able to hypothesize that the constriction that was apparent in the cloud photographs at midlevels was the result of dry air, as indicated by a nearby sounding, being entrained into the cloud. This dry air then helped to strengthen the downdraft. This was later quantified by Kingsmill and Wakimoto (1991).

The results obtained from the MIST project confirmed the importance of higher water contents within the parent storm in order to produce strong downdrafts in environments that are more statically stable as reported by Srivastava (1985) and Proctor (1989). These high water contents often manifest themselves in radar reflectivity images as a prominent descending precipitation core (e.g., Roberts and Wilson 1989; Wakimoto and Bringi 1988; Kingsmill and Wakimoto 1991). The multiparameter radar measurements confirmed the importance of frozen condensate in producing these types of microbursts (Srivastava 1987; Wakimoto and Bringi 1988; Proctor 1989).

Inspired by the analyses presented by Fujita, other investigators examined the complex microphysical and thermodynamic structure within strong downdrafts in these more humid and stable environments. Wakimoto and Bringi (1988) showed microburst downdrafts that were associated with very narrow shafts of hail. It has been hypothesized that in more stable environments hail produces stronger microbursts since the downdraft is maintained only at lower elevations (i.e., the cooling effect is delayed) where it is less likely to be depleted of negative buoyancy due to compressional warming (Proctor 1989). The maintenance of the downdraft at low levels also results in intense cold pools of air near the surface. These cold pools may contribute to intense outflow winds through enhanced horizontal pressure gradient forces produced by the presence of a mesohigh. The enhancement of outflow winds by pressure forces highlights the difficulty of predicting damaging winds at the surface based on predicted downdraft speeds.

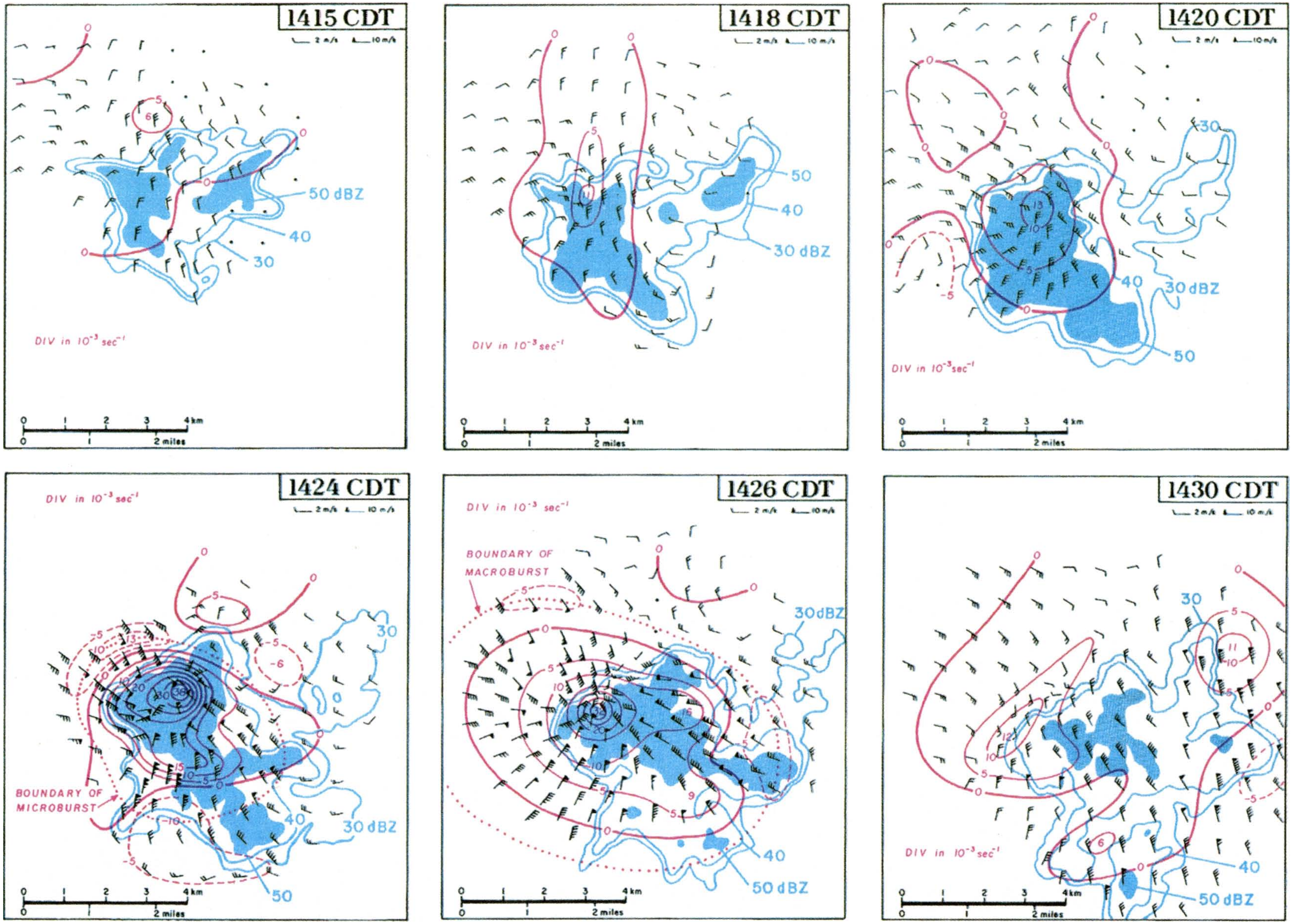

FIG. 11. Dual-Doppler winds as prepared by Fujita of the evolution of the Monrovia microburst of 20 Jul 1986 during MIST. The red contours are divergence values × 10^{-3} s^{-1} and the blue contours are radar reflectivity; solid blue represents reflectivity factors > 50 dBZ. The wind barb scale shows the speed in m s^{-1}. [From Fujita (1992).]

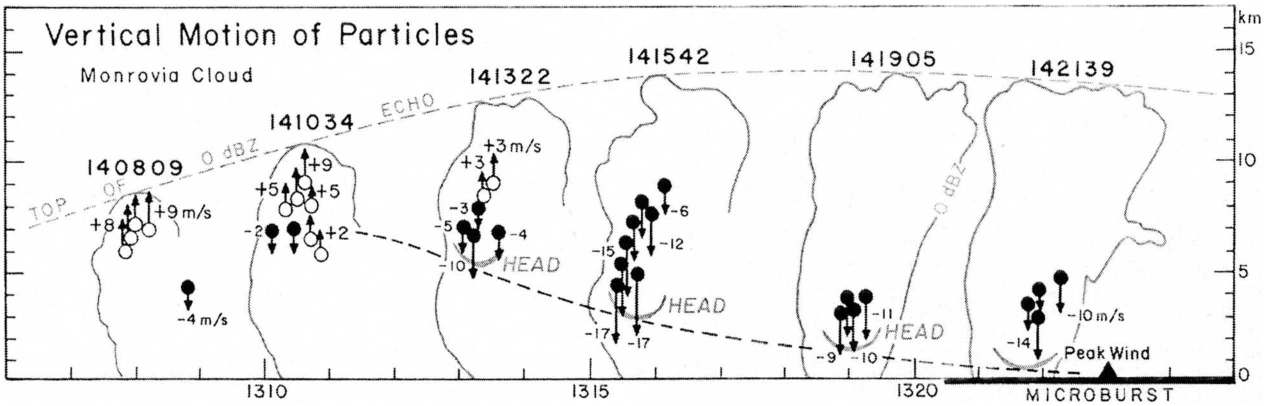

FIG. 12. Time history of the vertical motion of the largest most reflective precipitation particles during the evolution of the downburst-producing downdraft. This is a remarkable use by Fujita of a radar artifact known as the flare echo to obtain the descent of the microburst-producing downdraft. See text for further explanation. [From Fujita (1992).]

4. Present operational applications

Until 1985 the United States was experiencing a microburst-related wind shear accident on average each 18 months. After this date the next accident occurred nine years later on 2 July 1994 at Charlotte, North Carolina. This dramatic turnaround can most likely be attributed to two major efforts directed at reducing wind shear accidents: training and instrumentation. An ad hoc committee was formed to address training issues (Serafin et al. 2000). Based on knowledge gained from examining JAWS microburst data and by reviewing information learned from prior accident investigations, this committee made recommendations to (a) improve training, through the use of flight simulators with realistic wind information from actual microbursts; (b) create new training syllabi that focused on microburst avoidance; and (c) focus on new concepts that addressed flight control procedures a flight crew could take if caught in a microburst. Additionally a series of pilot training video tapes were developed by NCAR under Federal Aviation Administration (FAA) sponsorship to foster improved wind shear training. Ultimately the efforts of the ad hoc wind shear committee led to the FAA-funded Wind Shear Training Aid. This training program became the basis of both FAA-mandated and International Civil Aviation Organization–recommended wind shear training, which has been applied worldwide.

The second major effort was the installation of the FAA's Terminal Doppler Weather Radar (TDWR) at 47 major airports. The TDWR is a 5-cm, 0.5° beamwidth Doppler radar. The system is highly automated and provides timely and unambiguous warnings of hazardous wind shears and microbursts. The Weather Sensors Group at the Massachusetts Institute of Technology's Lincoln Laboratory played a vital role in the science and technology of the TDWR system

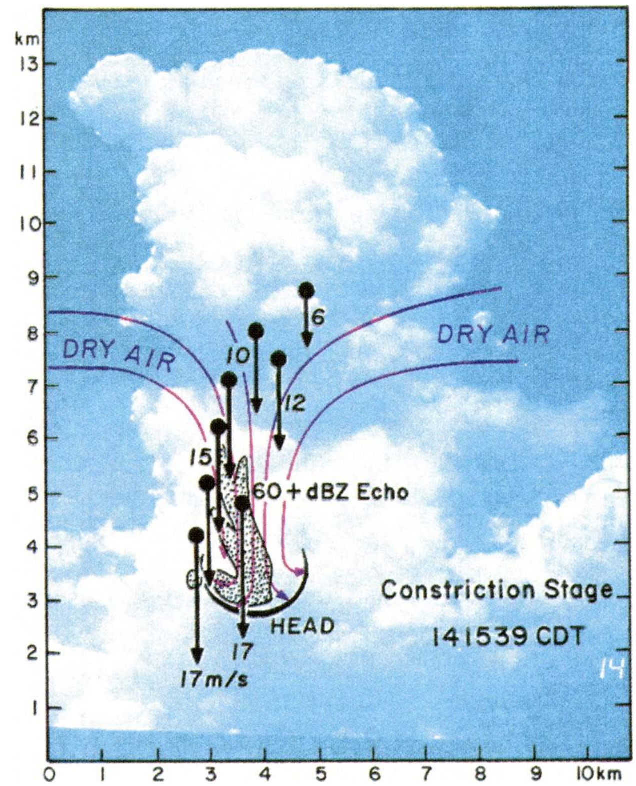

FIG. 13. Example of Fujita's skill in overlaying radar analysis on cloud photographs. In this case the particle vertical velocities from Fig. 12 at 1415 CDT and the 60 + dBZ radar echo are overlaid on a photograph taken at the same time. Based on the visual constriction in the cloud he hypothesized that dry air was being entrained into the cloud at that location [From Fujita (1992).]

FIG. 14. Fujita in early 1984 performing a photographic site survey for the FAA prototype terminal Doppler radar prior to testing at the Memphis airport. Fujita unhesitatingly trooped through the Olive Branch, MS, thick mud to help find an off-airport location for the radar. (Photograph by J. Evans.)

(Evans and Ducot 1994; Wolfson et al. 1994). Dedicated to the improvement of aviation safety, Fujita himself helped in siting the Lincoln-built prototype TDWR in preparation for automated wind shear detection testing in Memphis, Tennessee (see Fig. 14).

The prediction of microbursts is limited to a few minutes. Based on fundamental knowledge of how microbursts evolve, Roberts and Wilson (1989) showed that by using single-Doppler radar to monitor the descending precipitation core and convergence of air into the accelerating downdraft, forecasts of several minutes could be made of a microburst. Utilizing these principles the National Severe Storms Laboratory (NSSL) has developed an algorithm to assist National Weather Service forecasters to issue severe storm advisories and warnings associated with downbursts. This algorithm, called the Damaging Downburst Prediction and Detection Algorithm (Eilts 1996a), resides on the Warning Decision Support System (WDSS) also developed by NSSL (Eilts 1996b). The WDSS is a workstation used by forecasters to assess the intensity of convective storms as observed by the Weather Surveillance Radar-1988 Doppler radars (WSR-88D).

5. Concluding remarks

Many lives have been saved because of the reduction, if not elimination, of potential airline crashes caused by dangerous wind shear conditions on takeoff and landings. These saved lives are the result of training pilots on the dangers of microbursts and the installation of Doppler radars at major airports across the United States to warn pilots when microbursts are present. In the future it is critical that pilot training programs continue and that there be a progressive oversight activity to monitor the performance of the TDWRs and the operational microburst detection and forecast algorithms. Fujita is the person who was responsible for first proposing and eventually proving the existence of the downburst. There is little doubt that the downburst would have eventually been discovered without his contribution, but at what expense? The community owes a debt to Fujita's extraordinary intuition and analysis skills that led to this early discovery.

Fujita's attention was diverted elsewhere before he could provide a complete physical conceptualization of the downburst phenomenon. However, the microburst was another example in his illustrious career where he stimulated an entire research community to focus their efforts on an important research problem. In a period of only about 15 years the scientific understanding of the microburst evolved from no knowledge to a thorough understanding of the evolution of the downdraft and outflow and considerable knowledge of the forcing mechanisms of the downdraft. Specific prediction of when and where a microburst will occur is limited to a few minutes based on radar features. Longer period prediction of which cells will produce microbursts and when a microburst will occur is virtually nonexistent. Also there is very little understanding of large-scale downbursts such as bow echoes [see the discussion by Weisman (2001) in this issue]. Forecasting of downbursts requires better understanding of the organization of downdrafts on different scales and the factors controlling their evolution.

The process of educating others about the hazards of downbursts was also accelerated by Fujita's highly entertaining presentations and outstanding graphics. He also used the University of Chicago Printing Co. to publish and distribute large numbers of reports and books, which was quicker than going through traditional scientific peer-reviewed journals. To be fair, it should also be noted that Fujita's hypotheses were sometimes incorrect. During the early research on the microburst, Fujita and Caracena (1977) proposed that the microburst originated in the upper troposphere from the collapse of an overshooting cloud top. Subsequent thermodynamic and radar studies (e.g., Betts and Silva Dias 1979; Raymond et al. 1991) have argued that such a descent is highly unlikely. Such errors, however, were infrequent compared with the number of novel and correct scientific contributions to the community.

The NSF and NCAR deserve considerable credit for supporting the downburst field programs (NIMROD, JAWS, and MIST). At a time when many in the scientific community had serious doubts about Fujita's downburst hypothesis these two agencies fully supported his efforts. Fujita's scientific procedures were unorthodox and easily questioned by other scientists; however, Ronald Taylor of NSF, who monitored Fujita's grants, was willing to take a chance and support his proposals for field programs. Influential people at NCAR such as Robert Serafin, Richard Carbone, and Bill Hess strongly supported his field projects and helped make the NCAR radar, aircraft, mesonet, and sounding facilities available for the field programs. John McCarthy of NCAR played a central role in making the JAWS project happen. Indeed, one wonders if it had not been for these people willing to support Fujita's early downburst ideas, how long would it have been before its discovery and how many additional aircraft accidents would have occurred and lives lost.

Fujita played a prominent role in the scientific identification of the wind shear phenomenon that was causing aircraft crashes and in an operational solution of the problem. It also highlights his scientific attributes that are now well known to the community—uncanny insight, generation of hypothesis, preparation of creative and easy to understand analyses, and inspiring the work of other scientists.

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