BAMS Article

Addressing the Microburst Threat to Aviation

Research-to-Operations Success Story

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ABSTRACT: Microburst wind shear has caused or contributed to a significant number of aviation accidents. Since 1943, wind shear accidents have been responsible for more than 1,400 fatalities worldwide, including over 400 deaths in the United States between 1973 and 1985. In this paper, we describe one of the more successful and societally impactful research-to-operations (R2O) programs in atmospheric science history. The remarkable R2O journey included the discovery of microburst wind shear in the late 1970s and early 1980s, the scientific efforts to understand this phenomenon and its impact on aircraft operations, the development of a wind shear training program for pilots, and the rapid development, testing, and implementation of wind shear detection systems that successfully saved lives and property. The article includes a chronological description of the wind shear research and development program, key milestones toward implementation, and the research-to-operations best practices employed for successful technology transfer.

KEYWORDS: Atmosphere; Decision support; Transportation meteorology; Wind shear; Microbursts

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The microburst story begins with the unexplained crashes of commercial airliners in the 1960s and subsequent investigations by the National Transportation Safety Board (NTSB) (see appendix for abbreviations). The NTSB findings regarding the causes of several crashes were inconclusive, but suggested that hazardous weather played a role. Professor Tetsuya (Ted) Fujita, a scientist at the University of Chicago was closely following these studies. He hypothesized that the crashes could be caused by thunderstorm wind shears of a scale and intensity not yet observed by the scientific community (Fujita 1976; Wilson and Wakimoto 2001). Prior to his discovery, there had been a long history of aircraft encounters with sudden downdraft events during approach and departure that resulted in aircraft handling problems and, in some cases, crashes. After detailed analysis of the 1975 Eastern Air Lines (EAL) 66 accident (Fujita 1976), Fujita hypothesized that a low-altitude wind shear, not yet observed or understood, might have been the cause of the crash. He termed the phenomenon a "downburst." Later, he named small-scale downbursts with a diameter ≤ 4 km "microbursts." This was the scale most dangerous to commercial aircraft. Fujita's hypothesis on the existence of downbursts was met with some skepticism in the scientific community.

In the autumn of 1976, Robert Serafin and Clifford Murino of the National Center for Atmospheric Research (NCAR) suggested to Fujita that he use NCAR's Doppler radars to verify the existence of downbursts. Serafin speculated that the Doppler radars would be able to measure winds within the storms and detect the horizontal outflow from a downburst near the ground. A scientific field program called the Northern Illinois Meteorological Research on Downbursts (NIMROD),

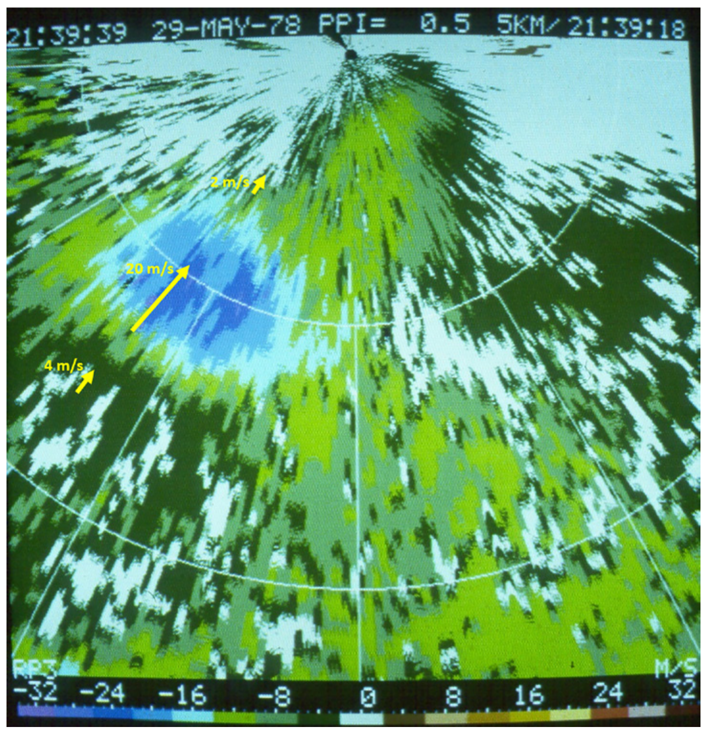

Fig. 1. Imagery from the NCAR CP-3 Doppler radar showing the "unfolded" Doppler velocity field of the first microburst observed by radar. The microburst occurred on 29 May 1978 near Yorkville, IL, 5 km from the radar. The scale at the bottom represents Doppler velocities (m s^{-1}) with negative values toward the radar and positive away. The 5- and 10-km range rings from the radar are indicated. The microburst is represented by the blue approaching velocities which reach 20–24 m s^{-1}. To facilitate interpretation, yellow arrows are drawn representing the velocities (m s^{-1}). At a range of 3–4 km from the radar there is strong convergence (from 20 to about 2 m s^{-1}) and only about 3 km further from the radar strong divergence (from 0–4 to 20 m s^{-1}).

sponsored by the National Science Foundation (NSF), was conducted in northern Illinois during the spring and summer of 1978. On 29 May 1978, Ted Fujita and NCAR scientist Jim Wilson observed a downburst on Doppler radar for the first time. The small-scale, diverging outflow, with peak winds of 24 m s^{-1} (Fig. 1), occurred so close to the radar that they felt the outflow as it moved over the radar location. During the NIMROD field campaign, approximately 50 microbursts were detected by radar, thus proving their existence.

Because of the very shallow nature (<1-km depth) of a downburst, another scientific field program was conducted, this time with the radars closer together than the configuration during NIMROD such that the detailed three-dimensional winds of a microburst could be derived. Fujita, Wilson, and NCAR scientist John McCarthy proposed the Joint Airport Weather Studies (JAWS) field project to be conducted in 1982 in the vicinity of Stapleton International Airport in Denver, Colorado (McCarthy et al. 1982). Initial funding for the project came from NSF and NCAR. The Federal Aviation Administration (FAA) expressed considerable skepticism concerning the postulated danger that microburst wind shear presented to commercial aircraft; thus, the FAA did not provide support to the JAWS project until after the 1982 Pam Am 759 accident at New Orleans International Airport. Ironically, the crash occurred during the JAWS field campaign.

During the JAWS project, 193 microbursts were detected near Denver Stapleton Airport. The structure, evolution, and cause of microbursts were described in a series of papers (see sidebar titled "Microburst threat to aviation") following this experiment (e.g., Wilson et al. 1984; McCarthy and Wilson 1984; Fujita 1985; Srivastava 1985; Wilson 1986; Mahoney and Rodi 1987; Kessinger et al. 1988; Hjelmfelt 1988). A three-dimensional schematic of a microburst (Fig. 2) shows that the downdraft spreads outward horizontally upon striking the ground. Figure 3a shows that the time evolution of a microburst (Fig. 3; Wilson 1986) is typically only 15–20 min from initiation of the downdraft to the outburst of strong horizontal winds to dissipation of the intense wind shear. The wind shear typically attains its maximum intensity within 5 min of the downdraft reaching the ground. Figure 3b demonstrates how the microburst winds can result in an aircraft landing short of the runway. The microburst characteristics observed during JAWS made it clear that an automated detection system with a rapid update rate would be required to communicate timely warnings to pilots (McCarthy and

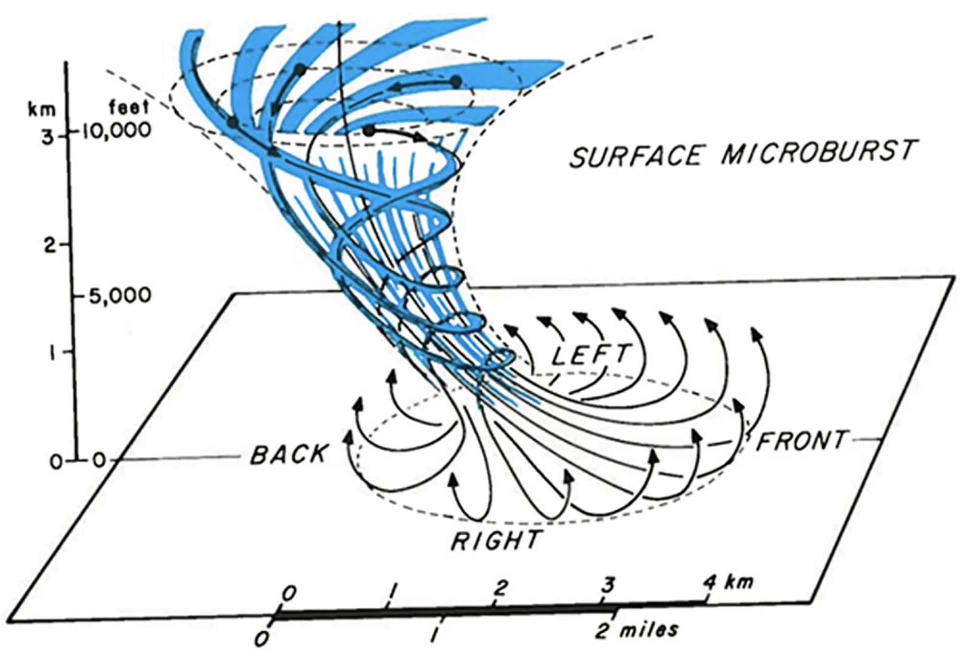

Fig. 2. Schematic view of the airflow associated with a microburst. In this case, the downdraft is rotating prior to spreading out horizontally upon striking Earth's surface (Fujita 1985).

Microburst threat to aviation

This sidebar chronicles the lethal accidents of four microburst-entrapped aircraft examined by Ted Fujita (Fujita 1985). The total number of fatalities was 499, including the flight crew, passengers, and persons on the ground. These accidents included Pan American World Airways (PAA) Flight 806 on 30 January 1974 at Pago Pago, American Samoa (Fig. SB1a), Eastern Air Lines (EAL) Flight 66 on 24 June 1975 at John F. Kennedy Airport in New York City (Fig. SB1b), PAA 759 on 9 July 1982 in Kenner, Louisiana, near the New Orleans Airport (Fig. SB1c), and Delta Air Lines (DL) 191 on 2 August 1985 at the Dallas–Fort Worth Airport in Texas (Fig. SB1d).

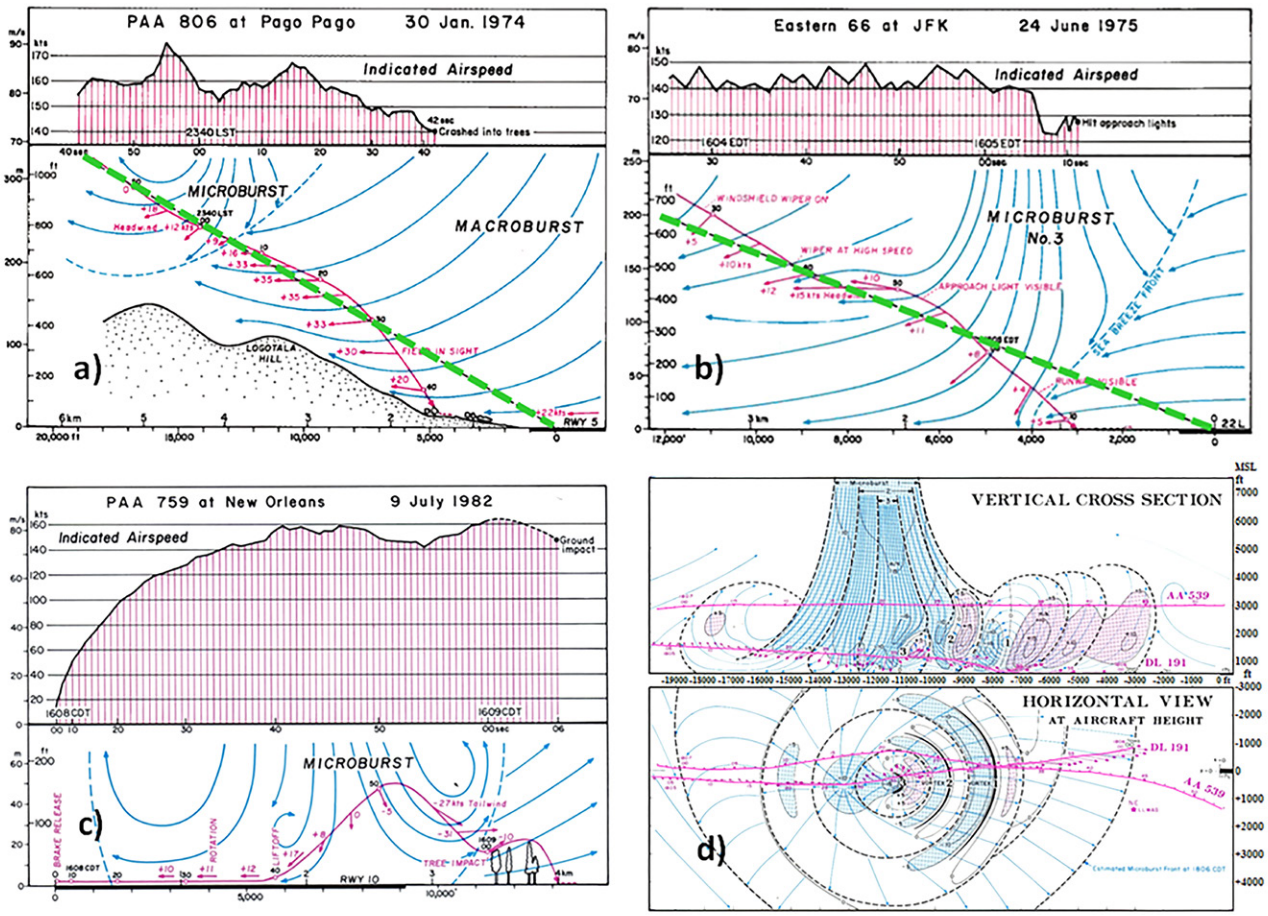

Fig. SB1. (a)–(d) Analyses of four aircraft accidents (Fujita 1985, 1986). Four vertical and one horizontal cross sections of the winds that each aircraft experienced are shown by the blue, arrowed streamlines. The position of each aircraft is shown with a solid, magenta line. In (a) and (b), the green, dotted line indicates the planned 3° glide slope route. In (a)–(c), the indicated airspeed is shown in the top panel. In (d), a horizontal cross section is shown in the bottom panel. Aircraft accidents shown are Pan American World Airways Flight 806 at Pago Pago on 30 Jan 1974 in (a), EAL Flight 66 at John F. Kennedy Airport on 24 Jun 1975 in (b), PAA 759 at the New Orleans Airport on 9 Jul 1982 in (c), and DL 191 microburst at Dallas/Fort Worth Airport on 2 Aug 1985 in (d).

Three of the four accidents occurred when the inbound aircraft passed through a microburst during descent to land (Figs. SB1a,b,d), while the fourth accident occurred during take-off (Fig. SB1c). Winds experienced by the DL191 aircraft were measured by the digital flight data recorders (DFDR). The earlier three aircraft were not equipped with a DFDR and instead the indicated airspeed (IAS) was used to estimate the wind field. The first accident analysis, PAA 806 (Fig. SB1a), showed that the aircraft first encountered a microburst while on descent at ~900 ft AGL and 18,000 ft from the runway. The initial microburst was followed by a second encounter, making it impossible to reach the runway, killing 96 on board with five survivors. During the second accident, EAL 66 (Fig. SB1b), the aircraft first encountered microburst head winds at an altitude of ~500 ft AGL while on descent for landing, followed by the downdraft at 400 ft AGL. The aircraft crashed 2,400 ft short of the runway, killing 113 people and injuring 11. The third accident, PAA 759 (Fig. SB1c), encountered the microburst while on take-off, first experiencing the head winds while on rollout followed by the downdraft once airborne. The aircraft stalled at 163 ft AGL, began descending, and hit trees before crashing and killing 152 people and injuring 9. Eight of the fatalities were killed on the ground.

The fourth accident, DL 191 (Fig. SB1d), occurred during landing when the aircraft encountered a complex, pulsing microburst that contained multiple horizontal vortices. The aircraft first encountered the microburst head winds about 3.5 miles from the runway at an altitude of ~1,500 ft. The microburst spanned a total diameter of 3 miles, and the aircraft crashed 1.5 miles short of the runway, bounced across a highway hitting a car, and then collided with several water tanks. One hundred thirty-six people were killed in the aircraft, 1 person on the ground died, and 26 people were injured.

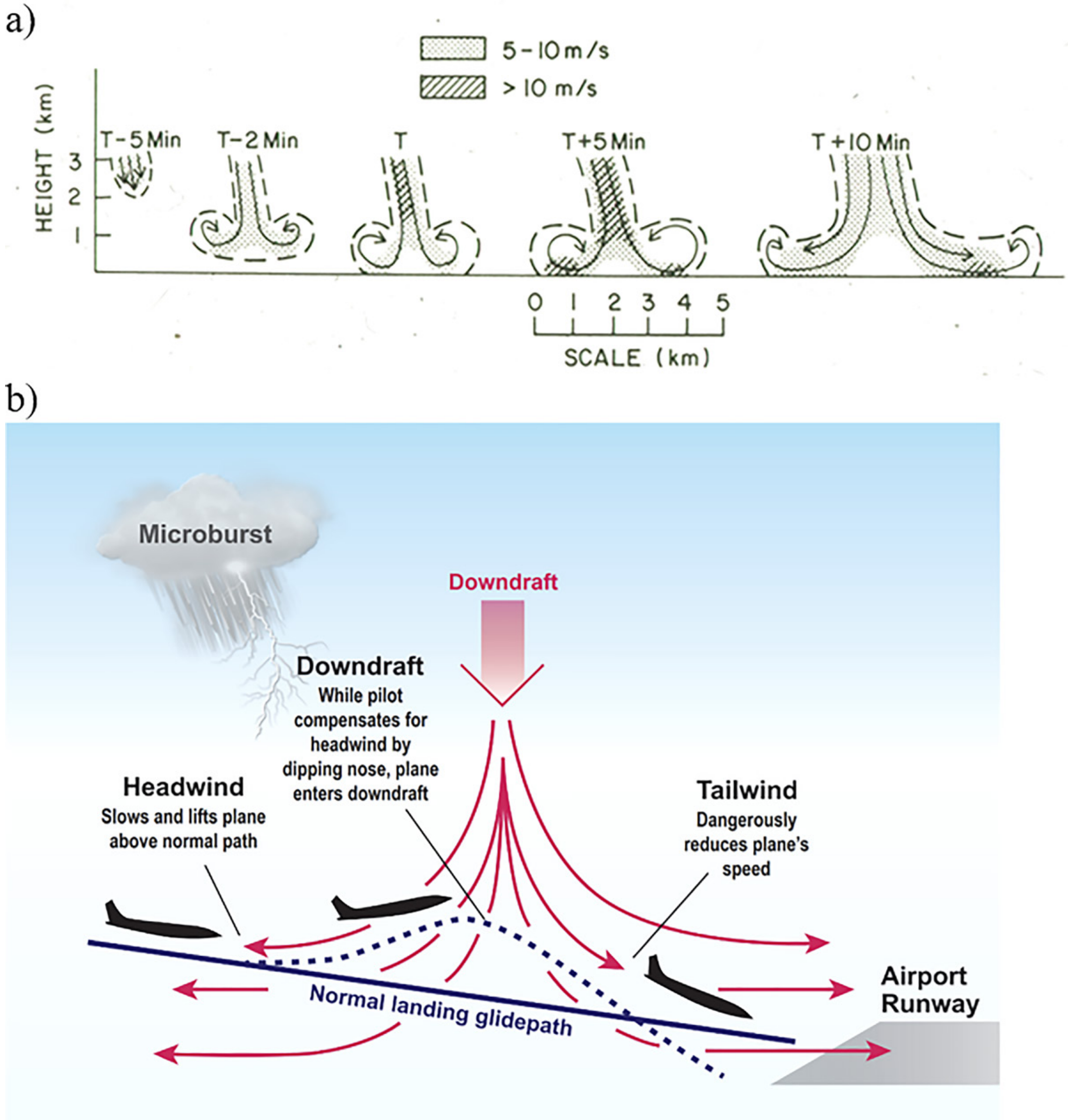

Fig. 3. Vertical cross sections of a microburst. (a) Time evolution is shown of the average microburst observed during JAWS project. "T" is the initial time of divergence at the surface. The shading denotes the vector wind speeds (Wilson et al. 1984). (b) A sequence of events shows an airplane landing short of the runway (dotted line) as it encounters the downdraft of a microburst. Note the deviation of the flight path from a normal landing glide path, a result of the changing head winds and the pilot's reactions (publications artists at MIT/LL).

Wilson 1984). Further, microbursts can occur in very light rain as often seen in the dry, High Plains, or in very heavy rain as is often experienced in the humid, southeastern United States.

This JAWS program research resulted in three principal findings: microbursts do exist and occur frequently in the High Plains climate, they can result in deadly aircraft crashes due to the loss of lift from airspeed changes, and they can be detected with Doppler radar and anemometer networks.

What followed was a decade of intensive ground and airborne wind shear detection-system development. The effort benefited from close multidisciplinary collaboration among universities, national laboratories, airline companies, pilots, aircraft manufacturing companies, air-traffic personnel, and several government agencies. A parallel and essential component was the development of training aids for pilots, including education and the use of wind shear models in airliner simulators in which pilots could experience flying into a microburst and practice avoidance maneuvers in a safe virtual environment. Airline companies also established operational criteria for the avoidance of threatening wind shears and procured airborne wind shear alerting systems (Delnore 1994).

The decade-long research effort resulted in the following:

1) The design, procurement, and installation of FAA wind shear detection and warning systems at 45 major airports across the United States in the 1990s. In addition, wind shear warning systems were subsequently installed at several international airports.
2) The certification of airborne forward looking alerting systems in U.S. and foreign aircraft by 1996 with over 4,000 systems in service by 2004 (Allan 2004).

Most importantly, there have been no wind shear–caused commercial airline crashes in the United States in the past 25-plus years. Figure 4 shows a timeline of wind shear fatalities in the United States, research and development efforts, pilot training and implementation of the Terminal Doppler Weather Radar (TDWR), Low-Level Windshear Alert System (LLWAS), and airborne wind shear warning systems.

When the Next Generation Weather Radar (NEXRAD) program commenced in 1979 (Crum and Alberty 1993), the FAA launched studies on using NEXRAD to improve aviation safety and efficiency (Laird and Evans 1982). In 1984, the Classify, Locate, Avoid Wind Shear (CLAWS) project was conducted at Denver Stapleton Airport (McCarthy et al. 1986) where NCAR meteorologists worked side-by-side with FAA air-traffic controllers in the air traffic control (ATC) tower to document wind shear events and test the feasibility of using radar to provide wind shear alerts to pilots. The NCAR meteorologist conveyed the information on microbursts to the ATC supervisor, who then relayed the information to the appropriate controller to alert arriving and departing pilots. The successful results of the CLAWS demonstration

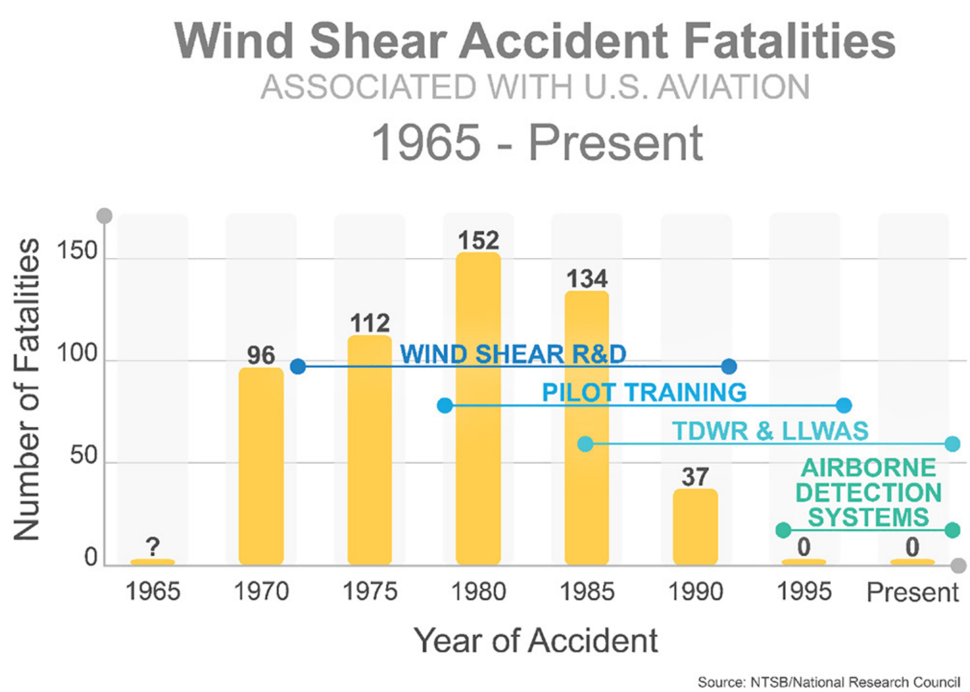

Fig. 4. Wind shear accident fatalities in the United States from 1965 to the present. There have been no documented commercial wind shear accidents in the United States since 1994. Timelines are overlaid for wind shear research and development efforts, pilot training, the design, procurement, and installation of the TDWR and LLWAS national networks, and airborne wind shear warning systems. These efforts occurred in parallel to quickly address and optimize operational microburst warning systems.

(Stevenson 1985) prompted the FAA to focus on the use of pencil-beam pulse-Doppler weather radars for microburst detection and warnings at major U.S. airports.

The FAA's goal for an operational wind shear detection system was to fully automate wind shear warnings (i.e., without human intervention) and to realize a high level of skill with a probability of detection of >90%, and a false alarm probability < 10% (FAA 1987a).[1] In the early 1980s, fully automatic detection of complex weather phenomena using pulse Doppler weather radars had not been demonstrated. There were many formidable technical challenges to achieving such an automated capability:

1) quality of radar reflectivity and Doppler radial velocity data might be compromised by ground clutter, "out-of-trip" echoes from distant storms, and ambiguities in the Doppler data;
2) fully automatic pattern recognition algorithms that could achieve the analysis capabilities of highly experienced radar meteorologists had not been demonstrated;
3) there was a lack of adequate transmitters at the likely frequency of operation for an FAA pulse-Doppler radar;
4) experimentally derived microburst characteristics existed only for a very small number of locations and climate conditions; and
5) signal processing capabilities at that time were technologically challenging.

Furthermore, the frequency of major airline accidents was so high that an operational wind shear detection solution needed to be developed, tested, and implemented at major airports across the nation as quickly as possible. To accelerate this development, the FAA decided to use a rapid prototyping process. Organizations with expertise in Doppler weather radar research as well as organizations in Doppler detection of aircraft were involved and worked together. In addition, the FAA chose to somewhat overlap operational system procurement with continued prototype system testing to better develop operational software to minimize and address operational system performance issues that would arise after deployment.

The development of what became the prototype TDWR began in Boston in 1983 with experiments that used a pulse-Doppler weather radar provided by MIT/LL (Wolfson et al. 1984). Subsequently, a transportable S-band pulse-Doppler weather radar was developed by MIT/LL and tested for wind shear detection at Memphis, Tennessee, from 1984 to 1985 (Rinehart et al. 1987). As a result of the 1985 Delta 191 microburst-related accident at the Dallas/Fort Worth International Airport and the progress made thus far with the prototype wind shear detection radar, the FAA formally commenced the TDWR acquisition program in 1985 (Evans and Turnbull 1985). This radar became the prototype TDWR and was moved from Memphis International Airport to Huntsville International Airport (1986) and to Denver Stapleton Airport (1987) to acquire additional Doppler datasets on microburst events from different climatic conditions to use in developing an initial automated, artificial intelligence (AI)-based microburst pattern-recognition algorithm.

Based on the successful automatic detection of microbursts with the Memphis, Huntsville, and Denver data (Merritt 1987), the FAA conducted a formal TDWR operational demonstration at Denver's Stapleton International Airport in 1988 that was highlighted by the fully automatic detection of an 80-kt (1 kt ≈ 0.51 m s^{-1}) microburst (peak velocity differential) with automated warnings provided to four aircraft on final approach (Schlickemaier 1989). Those aircraft all received timely warnings and successfully executed the newly developed microburst escape maneuvers learned from the Windshear Training Aid (Merritt et al. 1989). The pilot of one arriving aircraft recalled a severe downdraft just after receiving the 80-kt

[1] These very stringent performance criteria arose from the concept of operational use for TDWR warnings:
- fully automated warnings to be provided in real time to pilots by ATC controllers, with
- pilots expected to automatically execute a microburst escape procedure on receipt of a microburst warning message.

microburst alert and applied full power using the microburst encounter recovery technique to escape the microburst.

In parallel with the Denver TDWR prototype testing, a competitive procurement was conducted by the FAA in 1987 and 1988 for 45 production C-band TDWR systems.[2] After the successful 1988 operational demonstration of the TDWR at Denver, the FAA awarded the production contract to the Raytheon Company with the expectation that the first deliveries of the operational TDWR would commence in 1992 (Turnbull et al. 1989). The prototype TDWR was moved to Kansas City International Airport in 1989 for testing in an operational Midwest environment, thus identifying a need for improved microburst-recognition algorithms to reduce false alarms from flocks of birds and irregular surface-wind patterns caused by strong winds blowing over irregular terrain. In 1990, the prototype TDWR moved to Orlando International Airport and was converted to C-band operation to improve ground-clutter mitigation and beamwidth reduction from 1° to ½°. The prototype TDWR served three purposes:

1) to provide an operational microburst warning service for Orlando International Airport,
2) to act as a research and development testbed for the Raytheon system developers involved with signal waveform design and processing who did not yet have an operating production TDWR for their own use, and
3) to address deficiencies with the microburst detection and warning algorithms that emerged during the Orlando meteorological and operational environment; Orlando experienced a far higher frequency of microburst activity than any of the previous prototype test environments (Fig. 5).

The high frequency of microbursts in Orlando led to frequent loss of airport arrival capacity and subsequently to major changes in the microburst alerting strategy. After the initial period of providing operational microburst alerts at Orlando, many pilots ignored or discounted microburst warnings when the visual outflow region did not appear to include their flight path, suggesting that a revised criterion for issuing warnings was needed for environments like Orlando. A new algorithm for determining when alerts should be provided to pilots was developed and tested at Orlando. This revised algorithm and associated reduction in alert frequency was better received by pilots (Evans and Bernella 1994). In addition, the FAA identified an urgent need for improved air-traffic management (ATM) support during periods of high microburst occurrence. Due to microburst detections at Orlando, arriving aircraft would often be put into holding patterns that affected wider-area operations and caused major problems in traffic management. Thus, the Jacksonville Air Route Traffic Control Center requested real-time TDWR displays to anticipate the Orlando Airport's inability to accept arrivals, and to proactively plan for holding patterns within their airspace. Another air-traffic management need identified by Orlando ATC was the ability to predict microburst impacts so that ATC could make proactive adjustments of the terminal traffic flow to minimize the likelihood for aircraft encounters of microbursts. This led to the development of two tailored forecasts:

1) short-term (0–20 min) forecasts of future storm locations that would enable the terminal controllers to recognize when microburst-producing storms were approaching the active arrival and departure runways so they could move aircraft traffic proactively to alternative runways, and
2) predictions of microburst outflow commencement and intensification (Wolfson, et al. 1994).

[2] Key technical features of the operational TDWR are a 0.55° beamwidth in both planes with a mechanically scanned dish array, ability to detect −11-dB*Z* radar reflectivity per unit volume at 50 km, ground clutter suppression of 60 dB, surface scans once per minute with volume scans up to 60° of elevation every 2.5 min (so as to detect microburst precursors such as descending reflectivity cores and rotations).

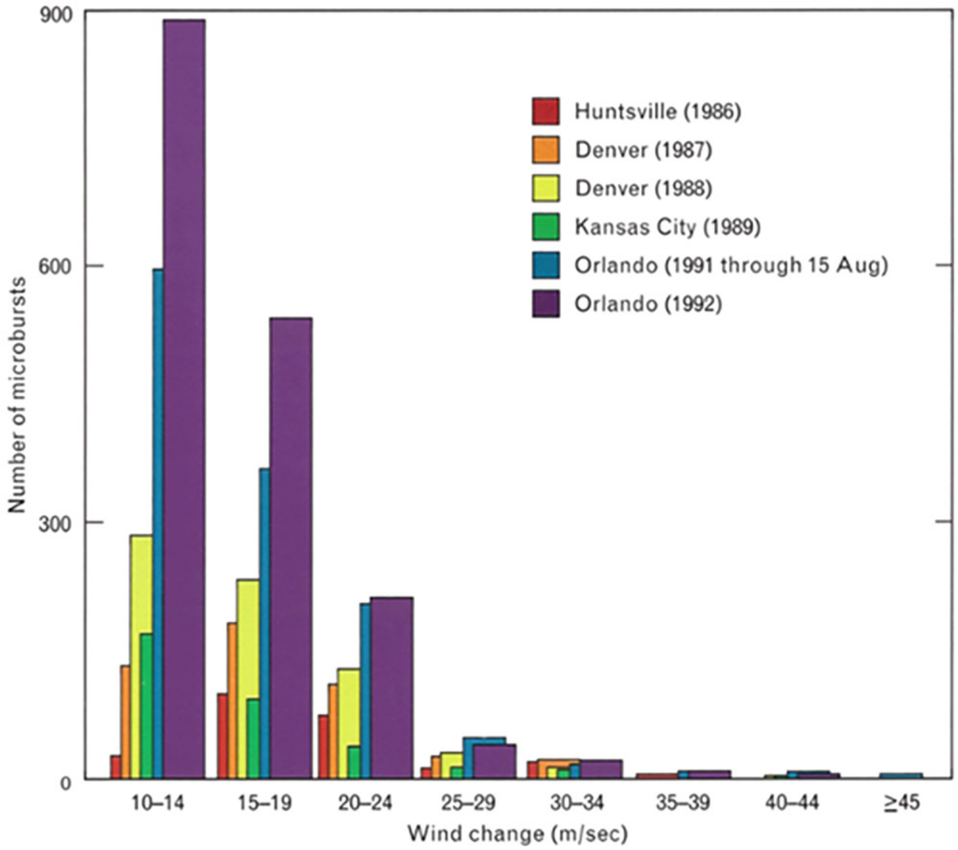

Fig. 5. Distribution of microburst strengths from various TDWR testbed sites. The total numbers of microbursts are as follows: Huntsville (1986), 236 microbursts; Denver (1987), 472 microbursts; Denver (1988), 694 microbursts; Kansas City (1989), 318 microbursts; Orlando (January–August 1991), 1,243 microbursts; and Orlando (1992), 1,663 microbursts.

Short-term predictions of future locations of microburst producing storms could be generated by pattern-recognition algorithms operating on the TDWR precipitation product (Chornoboy et al. 1994). However, from the scientific studies of microburst dynamics (Roberts and Wilson 1989; Wolfson 1990), it was clear that operationally reliable microburst prediction would need thermodynamic information as well as pulse-Doppler weather radar data.

This consideration, plus other needs for multiple sensor inputs (e.g., joint use of pulse-Doppler weather radar together with LLWAS anemometers and storm-tracking information for storms in the conical region above the TDWR that was not scanned) led to the conversion of the TDWR prototype to an Integrated Terminal Weather System (ITWS) prototype (Evans and Ducot 1994). The ITWS prototype ingested data from the aircraft reports, surface observations, and numerical forecast models to automatically generate a vertical profile of temperature and humidity in real time which could be used in conjunction with reflectivity information from a descending storm core to forecast the strength of the surface outflow (Wolfson et al. 1994).

Operational testing at Orlando, Dallas, and Memphis (Hallowell et al. 1996) found that the microburst prediction algorithm could meet the stringent performance criteria for issuing microburst warnings only if it was restricted to forecasting that an existing weak surface divergence would increase to a level that would warrant the issuance of a microburst warning. The principal contributor to errors in forecasting microbursts that were not yet producing a surface divergence was the inability to accurately determine the temperature and humidity profiles below the descending storm core especially if there had been previous storm outflows in that area that changed the stability.

The ITWS prototype benefited from the significant improvements in real-time computer capability that took place in the 1990s. This permitted the microburst and gust-front wind shear pattern recognition algorithms to exploit major advances in image-processing technology and resulted in significant detection performance improvements, especially for gust fronts (Troxel et al. 1996).

Research to improve the technical capability of the TDWR for fully automatic detection of microbursts continued during the 2000–10 period as the Raytheon-produced TDWRs were being installed across the United States. The goal of that research was to improve the signal processing of the TDWR to address the long-standing challenges of suppressing ground clutter together with avoiding interference from storms at long range, while simultaneously reducing impacts of Doppler velocity ambiguities (Cho 2005; Cho and Chornoboy 2005).

Additionally, the new signal-processing algorithms improved the ability to reject clutter from moving scatterers (especially bird flocks) that caused false microburst alerts. These enhancements to the "front-end processing" were incorporated in the operational TDWRs by MIT/LL researchers working closely with the FAA Program Support Facility (PSF) in Oklahoma City, Oklahoma. In Fig. 6, the U.S. airports with operational pulse-Doppler weather radar microburst warning systems are shown.

The Weather Systems Processor (WSP) for Airport Surveillance Radar (ASR-9) radars was developed in parallel with TDWR using a WSP prototype system to provide wind shear protection services at airports where the benefits of a dedicated Doppler weather radar did not justify the cost. WSP prototypes operated at Kansas City International Airport and Orlando International Airport in concert with the TDWR prototype. By leveraging the concept of operation and algorithm technology developed for TDWR, the WSP was able to extend broad-area, radar-based wind shear warning capability to an additional 35 medium and large U.S. airports.

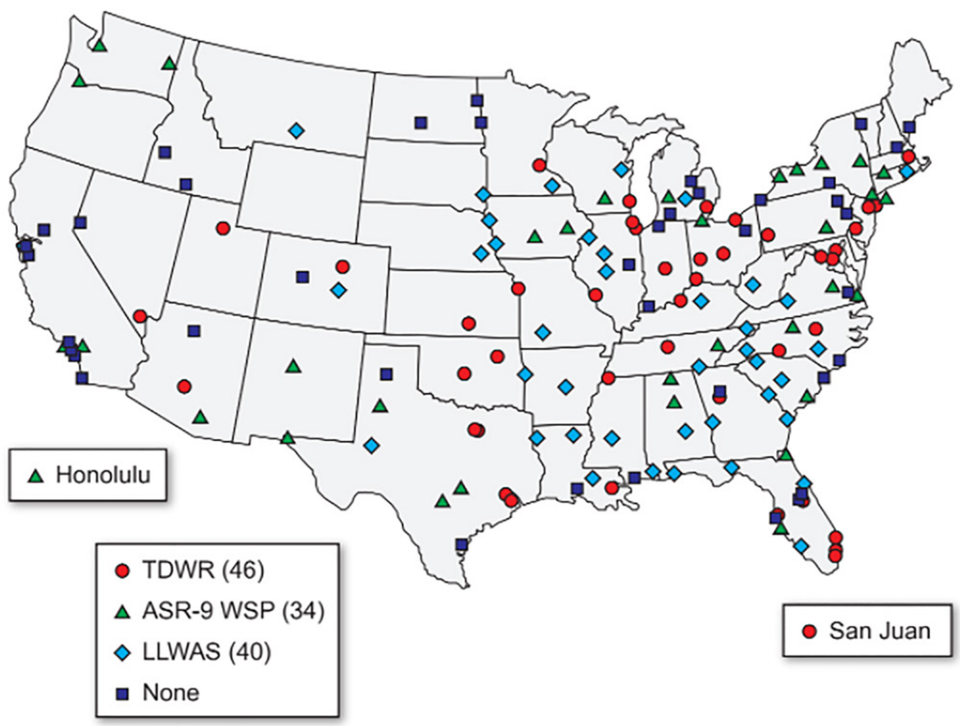

Fig. 6. Current (2022) operational pulse-Doppler weather radar airports together with air-carrier-served airports that do not have wind shear protection. The symbols indicate the wind shear protection system currently operating at each airport. Note that nine of the TDWR airports are also equipped with an integrated network-expansion LLWAS system. One major airport, Las Vegas (LAS), has a Doppler lidar (Keohan et al. 2006) in addition to a TDWR. All TDWR airports are also ITWS airports.

Low-Level Wind shear Alert System

In parallel with the development of the TDWR, an anemometer-based wind shear detection system was enhanced to detect microbursts. The LLWAS system was originally developed by the FAA in the 1970s to detect large-scale wind shifts (e.g., sea-breeze fronts, gust fronts, and cold and warm fronts) in response to the 1975 EAL Flight 66 wind shear accident at John F. Kennedy (JFK) Airport. The phase-1 LLWAS detection algorithm was very simple and compared the center-field wind to five other anemometers around the airport. When there was a 15-kt vector difference, it would flash the wind speed and direction information to the air-traffic controller and the controller would read the wind speed and direction information from each sensor to the pilots landing or about to depart. The pilots then would manually analyze the impact of the wind differences on their flight operations.

This simple system worked as designed for large-scale wind shear features, but the sensors were too far apart to capture small but intense wind shear events critical to aircraft, such as microbursts. In addition, wind variability within the network triggered frequent false alarms because all outlying sensors were compared to the airport center-field sensor to determine if there was wind shear within the LLWAS network. Research conducted during the 1982 JAWS field experiment demonstrated that a dense anemometer network could detect microbursts. In 1983, the FAA asked NCAR to develop an enhanced version of the LLWAS that could detect microbursts with a low false alarm rate. Between 1983 and 1988, NCAR developed and tested the enhanced LLWAS–Network Expansion (LLWAS-NE), which detected microbursts and determined their strength in terms of head wind/tail wind gains or losses aligned with the runway and the location of the event (Wilson and Gramzow 1991). The system was designed to provide alerts specific to each runway arrival or departure operation within about two nautical miles of the runway. The LLWAS-NE was designed to have the same FAA-required performance characteristics as the TDWR, that is, a probability of detection of ≥90% and a false alarm rate of ≤10% (Cole 1992). The LLWAS wind shear detection coverage area is limited by the number of sensors that make up its network. Siting anemometers around an airport and surrounding area is challenging due to land availability, land-use characteristics, and obstructions that could disrupt the wind flow and impact system performance. As an in situ sensing system, the LLWAS is effective in detecting wind shear events associated with precipitation and dry events such as low-reflectivity microbursts and terrain-inducted wind shear, respectively.

After the operational demonstration of the LLWAS-NE at Denver Stapleton Airport in 1988, LLWAS-NE was further developed to become the phase-3 LLWAS which used both anemometers and Doppler radar to detect wind shears. Testing an integrated LLWAS-NE and prototype TDWR system took place in Denver in 1990 and 1991 using NCAR's Mile High S-band Doppler radar. An independent study of the integrated system concluded that the combined system provided increased alert coverage and accuracy (Stevenson 1991). Phase-3 LLWAS systems were implemented at 40 major airports with wind shear risk. Nine major airports included a combined TDWR and LLWAS solution.

Pilot training

The FAA became very concerned by the large number of wind shear accidents in the 1980s. Likewise, all the major commercial airlines were alarmed by the high frequency of these accidents and the number of fatalities. There was significant concern that, if these tragedies were to continue, commercial aviation could face disaster. Leading the effort to review the safety concerns of these accidents were the NTSB, the FAA, and the National Aeronautics and Space Administration (NASA). Likewise, the commercial airlines were eager for solutions. NCAR and MIT/LL worked closely with the aviation industry during the 1980s to understand the impact of microbursts on aircraft performance.

The government/industry team codeveloped a training program that culminated in the Windshear Training Aid (FAA 1987b). It was designed with three goals for pilots: to teach them about wind shear, to teach them to visually recognize microbursts, and to increase the likelihood of a successful escape maneuver from a microburst event if a pilot inadvertently encountered one. The model of flight crew actions (Fig. 7) was incorporated into new and recurrent pilot training to ensure such actions are easily recalled when needed. The recommended procedures were developed for jet-transport aircraft.

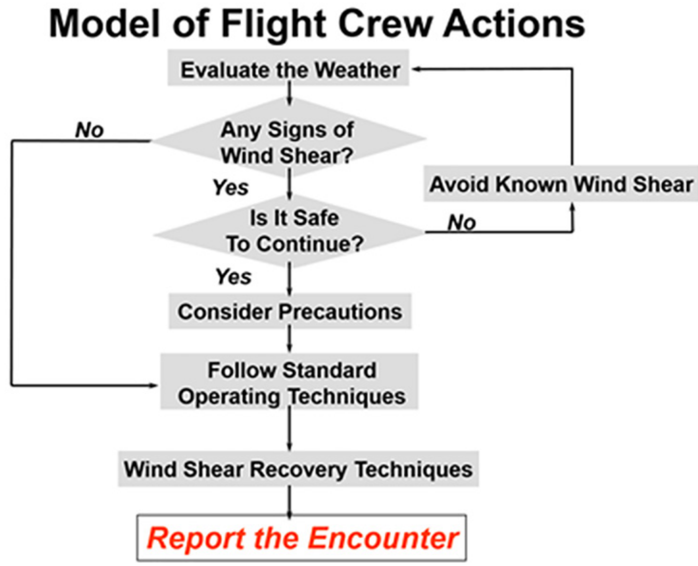

Fig. 7. Model of flight crew actions to avoid wind shear per the Windshear Training Aid (FAA 1987b).

The research indicated that pilots have difficulty recognizing microbursts from visual clues. Further, the required reaction time is short (5–15 s) for effective flight-crew coordination to address both wind shear recognition and flight recovery. After inadvertent entry into a microburst, the flight path must be controlled with pitch attitude, and reduced airspeed may have to be employed to ensure flight-path control and altitude.

The trade-off between true airspeed and altitude was counterintuitive to traditional pilot training; thus, a substantial effort was required to educate pilots on these new wind shear escape maneuvers. To support this educational effort, microburst datasets were created from digital flight data recorders of wind shear events and utilized within aircraft simulators, thus allowing pilots to test the new wind shear training procedures. The limited number of simulators available to the industry slowed the training process. Knowing that the TDWR and LLWAS wind shear detection systems would not be available operationally nationwide for several years, the industry initiated a wind shear training program as soon as possible. The International Air Safety Foundation and the International Air Transport Association played important roles in developing and promoting international training regulations. As a result, the wind shear training program became a global program focused on microburst recognition from the cockpit, avoidance, and employing microburst escape maneuvers if the aircraft unexpectedly encountered a microburst.

The wind shear training aid program was implemented across the commercial aviation industry before the full deployment of automated wind shear detection systems and led to a significant reduction in microburst accidents through improved pilot understanding of the microburst phenomena (Fig. 4).

Best practices in research to operations

Addressing the wind shear impact on aviation operations is an example of a complex scientific and technological challenge that bridged across disciplines and had a profound societal impact. The process of converting scientific knowledge into successful operational applications is challenging for a variety of reasons, including a lack of technology transfer knowledge and experience within the research community, the perceived barriers to engagement with academia within the operational community and its lack of understanding of the research community, the use of technical terminology and jargon across disciplines, and disparate motivating drivers of the participants. Given the lives at stake and negative impacts on the aviation industry of routine wind shear crashes through the 1980s, all of these issues and barriers had to be overcome quickly.

The wind shear program underscores the importance of advancing science with, and for, society. However, for the effort to be successful, the program needed to include several components: strong leadership; dedication to the cause of improving aviation safety from all participants; deep stakeholder engagement from day one; appreciation for all the disciplines represented by the program participants and their critical roles in designing the solution; rapid prototyping and the use of an evolutionary system-development approach; ongoing and transparent system performance verification; and a significant education, training, and outreach component. Today, this type of research approach is called convergent research (Roco et al. 2013).

A key foundation of the wind shear program was the establishment of the LLWAS/TDWR User Group (Table 1). The user group's charge was to define the hazardous weather information needs of pilots and controllers in airport terminal areas and focus on those needs that could be met by an improved LLWAS and/or by an automated TDWR, to provide guidance for the development of the TDWR and LLWAS products and displays, and to develop procedures and terminology to disseminate the information accurately and promptly.

The group was established and tasked with ensuring that the output from the wind shear detection systems was effective, accurate, and actionable. The multidisciplinary group included scientists, software and aeronautical engineers, program managers, pilots, industry association representatives, aircraft manufacturers, FAA air-traffic and flight-standards representatives, and the NTSB. The group met several times between June 1986 and November 1991. It defined the wind shear alert messaging, update rates, performance requirements, terminology, and overall operational concept of operations.

Bringing all the stakeholders together to design the solution from the beginning was an essential contributor to the success of the wind shear program. Another important component of the program was the ongoing and independent assessment of the effectiveness of the wind shear detection system's warning service. Several studies led by the Volpe National Transportation System Center (Stevenson 1985, 1990) evaluated the warning strategy, messaging, detection accuracy, and decision-making impacts from the viewpoint of the pilots and air traffic controllers. For the system to be effective, it had to provide information that would result in swift decision making by the pilots to avoid penetrating the microbursts during takeoff and landing operations, without interfering with the primary duties of air-traffic controllers. Results from these

Table 1. TDWR–LLWAS User Group.

TDWR–LLWAS User Group	
Government agencies	**Aviation industry**
Federal Aviation Administration	Aircraft Owners and Pilots Association
FAA, Denver Stapleton Air Traffic Control Tower	Air Line Pilots Association
FAA ATCT, Douglas Municipal Airport	Air Transport Association
FAA Technical Center	Allied Pilots Association
Department of Transportation, Transportation Systems Center	Martin Marietta Corporation
National Transportation Safety Board	National Business Aircraft Association
	Boeing Commercial Airplane Company
	United Airlines
Research centers	
Langley Research Center	
National Center for Atmospheric Research	
Massachusetts Institute of Technology Lincoln Laboratory	
MITRE Corporation	

operational impact studies were used to refine the system warning strategy and thresholds. The feedback was part of an operations-to-research (O2R) feedback loop.

Pilots and airlines were somewhat unfamiliar with low-level wind shear and the term "microburst" was new to the industry. Developing the wind shear training aid in parallel with the development of the wind shear detection systems was also a best practice that saved lives until the full complement of wind shear solutions were in place.

As a result of the wind shear research, development, and implementation efforts, there has not been a commercial microburst-related accident in the United States since USAir Flight 1016 in Charlotte, North Carolina, in 1994 when the crash and ensuing fire caused 37 fatalities and seriously injured 20 others (Fig. 4).

Convening the critical stakeholders representing multiple disciplines, scientific understanding, knowledge of operational impacts, thorough testing and evaluation, training, education, and outreach formed a visionary approach for a research and development program. The convergent-science approach used to address this very complex weather hazard led to a profoundly beneficial outcome for society. The wind shear R2O program was one of the most successful and societally impactful R2O programs in atmospheric science history.

Thoughts on the future

Almost 30 years of past success must not lead to complacency. Microbursts and wind shear remain regular features of thunderstorms and therefore will continue to present serious threats to aviation. The next generation of pilots must be adequately educated and trained to understand and respond to the threat. As spatial and temporal resolution of thunderstorm models improve, these may serve to create ensembles of microburst model data for use in aircraft simulators. Next-generation aircraft must be tested in simulators to quantify their vulnerability. Next-generation traffic controllers must be trained to understand and recognize wind shear phenomena and respond effectively. Industry and government leaders must continue to place aircraft vulnerability to wind shear at the highest priority level regarding aviation safety and next-generation wind shear detection systems must be designed, developed, tested, and deployed to enhance flight safety (see sidebar titled "Studies of replacement of the TDWR by next-generation radar technology").

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Studies of replacement of the TDWR by next-generation radar technology

The production TDWRs have been a mainstay of the real-time microburst decision support at the major U.S. airports for nearly 30 years. Since 2000, there have been a number of studies of next-generation radar options including phased array radars (PAR), use of polarimetric information, and the use of lidars at locations with low-reflectivity microbursts (i.e., "dry" microbursts and challenging ground clutter environments) (Weber et al. 2021).

In addition, the question has arisen of whether there is a need for ground-based microburst detection information, considering the capabilities of airborne wind shear warning systems, the ongoing pilot training on microburst avoidance, and the increased thrust-to-weight ratio of contemporary airline jet aircraft.

Studies of the cost benefits for wind shear systems (Hallowell and Cho 2010) have shown that there still is a monetary benefit from the TDWR. However, the benefits of replacement of the TDWR by a PAR are not as clear at this time for two reasons:

1) Typical PAR designs for weather surveillance have wider beam widths than does the TDWR as well as higher sidelobes. As a consequence, a PAR may have greater difficulty in detecting surface microburst outflows in severe ground clutter environments than does the TDWR.
2) PARs should be able to do a bit better job at tracking descending storm cores, which are an input to microburst prediction algorithms. However, the principal impediment to reliable microburst prediction before there is a surface outflow from a storm has been difficulties in accurately estimating the temperature/humidity profile below the descending storm core.

A lidar has been tested at Las Vegas (LAS) since 2005 (Hannon 2004; Keohan et al. 2006) to improve the detection of low-reflectivity "dry" microburst outflows in a very challenging clutter environment. This lidar demonstrated improved detection capability for "dry" microbursts. However, the FAA has yet to make the considerable expenditure required to make the (LAS) lidar an FAA-commissioned system.

Appendix: Abbreviations

ASR-9	Airport Surveillance Radar (version 9)
ATC	Air traffic control
CLAWS	Classify, Locate, and Avoid Wind Shear
DFDR	Digital flight data recorder
FAA	Federal Aviation Administration
JAWS	Joint Airport Weather Studies
LLWAS	Low-Level Wind shear Alert System
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Weather Radar
NIMROD	Northern Illinois Meteorological Research on Downbursts
NTSB	National Transportation Safety Board
PAR	Phased-array radar
R2O	Research-to-operations
TDWR	Terminal Doppler Weather Radar
WSP	Weather System Processor

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