

The art and science of forensic meteorology

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When weather factors into a legal dispute, meteorologists use eyewitness accounts, troves of atmospheric data, and simulated reenactments to figure out what went awry.

During a severe drought in upstate New York in the late 1800s, a Presbyterian minister, Duncan McLeod, organized a community prayer for rain. Within an hour, small clouds had formed and the temperature had begun to fall. A few hours later a severe thunderstorm moved through the region, bringing almost two inches of rain and washing out a highway bridge. Worse, though, was the bolt of lightning that hit and burned to the ground a barn owned by Phinneas Dodd.

The sole objector to the community prayer, Dodd did not believe in tampering with Mother Nature. He asked McLeod for \$5000 to replace the barn, and when McLeod refused, Dodd slapped him with a lawsuit. It was one of the first court cases involving weather and the law.¹⁻³ In the end, “the defense counsel finally persuaded the court to dismiss the action on the grounds that defendants had prayed only for rain, and that the lightning had been a gratuitous gift of God.”¹

Today forensic meteorologists are regularly called on to help attorneys understand the impact of weather on events. But rather than invoke the su-

pernatural as in *Dodd v. McLeod*, they rely on scientific methods and techniques. Forensic meteorologists answer questions such as the following: What was the weather at the time of the accident or event? Would the individuals involved have reasonably been expected to know of the impending weather? If an aircraft, ship, automobile, or other vehicle was involved, where was it and how was it moving? The underlying question is, of course, Why did the accident happen?

Weather detectives

To reconstruct weather events and their impacts on human activities, forensic meteorologists must gather pertinent information about the weather at the time and location of the event and must evaluate its veracity. Due to their economic value to the general public, weather records, including surface observations, radar and satellite data, analyses, and forecasts, are often collected by government entities and made available in depositories. Those records may be obtained free of charge or at quite a cost, depending on which country is providing them. Frequently, forensic meteorologists must also gather information concerning the location or movements of people, vehicles, buildings, or other objects and assess eyewitness observations for accuracy and relevance.

Much like other scientists, however, forensic



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meteorologists do more than simply gather and report data. They also perform hard science, research, modeling, and sometimes testing, in order to come to meteorologically sound conclusions. (For a primer on some of the physics underlying meteorology, see Hans Panofsky's article on page 38.) They often must visit the scene of an accident to examine terrain or otherwise aid the investigation into the determining factors of an event.

When weather analysis is foundational to a legal case, the forensic meteorologist may lead the way in producing a succinct, clearly illustrated report, with data summaries that can be readily understood by all parties involved. As with most scientific publications, clarity and accessibility are paramount, since there is no graceful path to retraction of a legal opinion.

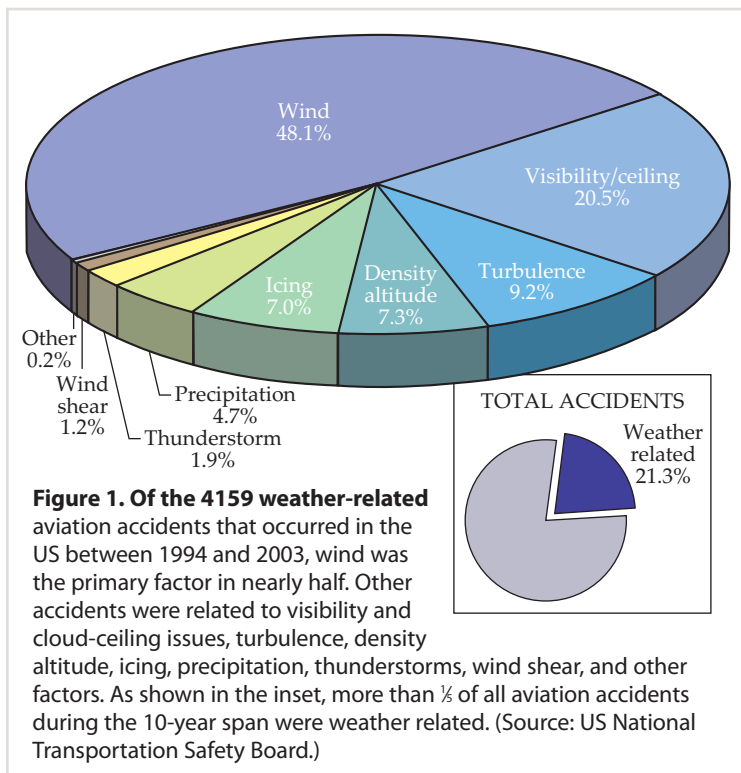
Investigations can take years; sometimes it may take a decade or longer for a case to go to trial. In many cases the attorney has the forensic meteorologist work with other experts—for example, air-traffic controllers or accident reconstructionists—to develop an integrated understanding of what happened and why. Occasionally the meteorologist is called on to reach beyond the weather to act as the general physicist for the case.

A wide variety of weather-related court cases might require the services of a forensic meteorologist. Disputes may stem from tornadoes, hurricanes, drought, air pollution—you name it. Cases may involve murders, bombings, vehicle accidents, agricultural disputes, skiing accidents, suicides, kitesurfing accidents, weather modification, property insurance disputes, building collapses, or people slipping and falling. Weather has even been used as a defense for stealing, looting, trespassing, and other crimes.⁴ Some such defenses—the weather made me do it!—are ludicrous, but others have some merit. For example, one man used weather as a defense for driving without a license: His family's heat did not work, and he needed to get a kerosene tank for their portable heater.

Here, we present three examples from the forensic meteorology files: an ill-fated flight into a thunderstorm; an airplane landing accident during heavy rains and crosswinds; and a tornado outbreak across the southeast US. First, we offer a bit of background on aviation accidents. According to the US National Transportation Safety Board, 21.3% of all aviation accidents in the US from 1994 to 2003 were weather related. Of those, nearly half (48.1%) were due to wind; smaller fractions were due to visibility issues, turbulence, and other factors (see figure 1). Thunderstorms were the primary factor in fewer than 2% of the weather-related accidents. On 2 August 1985, however, as Delta Airlines flight 191 attempted to land at Dallas/Fort Worth International Airport (DFW), a thunderstorm led to one of the deadliest aviation accidents in history.

A microburst in Texas

The crash of flight 191 is an especially important case in the development of modern forensic meteorology. The flight, which originated in Fort Lauderdale, Florida, encountered a line of convective



storm cells just to the north of its landing site, DFW. On the final approach to landing, the aircraft flew into a microburst—a sudden, intense downdraft that can emerge from a thunderstorm. The plane subsequently crashed to the ground just short of the runway, killing 134 of the 163 people on board.

In the ensuing, prolonged bench trial, the airline's attorneys argued that the National Weather Service (NWS) and the Federal Aviation Administration (FAA) had failed to warn the flight crew of the microburst-producing storm, which they claimed was obscured from the pilots' view by other storm cells in the area. The government argued that the crew had the better vantage point of the thunderstorm, had as much if not more information than did the NWS and FAA, and therefore should not have attempted the landing.

In a first, the consulting firm Z-Axis, under the guidance of one of us (Hildebrand), was hired to create computer graphics that clearly illustrated the visibility of the thunderstorm to the pilots as they approached the airport. Prior to that, expert witnesses typically relied on transparencies, flip charts, and other low-tech means to present the facts of a case. The firm used weather radar data, knowledge of cloud-base and cloud-top altitudes, and cockpit voice recordings to reconstruct the weather conditions in the lead-up to the accident.

Still frames from three of the firm's video reconstructions are shown in figure 2. One video, constructed using ground-based radar scans recorded every six minutes by the NWS, showed the real-time evolution of the cloud cover and the aircraft flight path during the landing approach (figure 2a). A second video showed the airborne radar scans that the pilots would have seen on their cockpit display

(figure 2b). A third simulated the forward-looking view from a position just behind the aircraft (figure 2c). Each video was accompanied by a soundtrack of the crew's comments, as captured by the cockpit voice recorder.

Together, the videos and cockpit voice recordings clearly showed that the pilots had an unobstructed view of the thunderstorm and were aware of the storm during the approach to the airport. In one cockpit exchange, for example, the first officer is heard saying, "There's lightning coming out of that one." After the captain replies, "Where?" the first officer answers, "Right ahead." Subsequent comments made it clear that once they were in the thunderstorm's rain shaft, the pilots knew they were flying through a microburst. The videos set a new standard for visual demonstrations in forensic-meteorology litigation and vastly changed the way meteorologists prepare for trial.

Crosswinds in Little Rock

Most accidents have multiple contributing factors, including not only weather but aircraft maintenance, pilot experience and training, pilot fatigue, and "get-home-itis"—the willingness to risk flying through dangerous weather conditions in a push to get home. The landing of American Airlines flight 1420 on 1 June 1999 at Little Rock National Airport (LIT) in Arkansas is a prime example.

The flight departed DFW at around 10:40pm Central Daylight Time with 145 people on board. It had been delayed for more than two hours, and the flight's crew members were nearing the end of their duty day—their maximum permitted work shift. During the delay, Little Rock's weather had started to become a safety concern: A cold front had moved eastward from northwest Arkansas toward Little Rock, and a squall line began to bear down on the Little Rock area, producing lightning, rain, and hail. Nonetheless, American Airlines dispatched the flight for takeoff with the captain's approval.

Just after 11:50pm, the aircraft touched down late, approximately halfway down its runway at LIT, and began hydroplaning. It continued past the end of the runway, struck a metal structure—an instrument landing system localizer array—passed through a chain-link security fence, skidded over a rock embankment into a flood plain, and collided with a lighting-system support structure. The captain and 10 passengers were killed. More than 100 people, including the first officer and the flight attendants, received serious or minor injuries. Only 24 passengers escaped uninjured.

One of us (Austin) was hired to help determine weather's impact on the event. The resulting analysis, based on Doppler radar data, eyewitness accounts, wind-speed recordings, and other atmospheric data, paints a picture in which weather

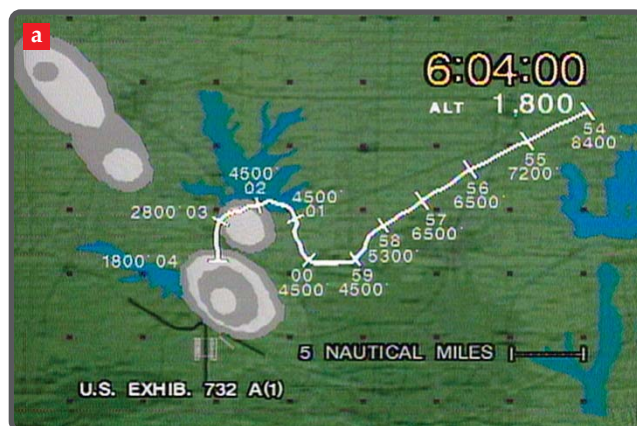


Figure 2. Still frames from three computer-generated movies re-create the weather conditions on 2 August 1985, during Delta flight 191's ill-fated approach to Dallas/Fort Worth International Airport. **(a)** A frame from a movie generated with ground-based radar data shows the location of storm clouds (gray) at 6:04:00pm and the aircraft's flight track up to that time. The white curve shows the flight track; each mark is labeled with a two-digit time stamp and the plane's altitude in feet. **(b)** A still from a second movie shows the aircraft-mounted radar

returns as they would have appeared in the cockpit display at 6:00:01pm. Here, storm clouds are represented in light green and the aircraft heading is up. **(c)** A third still frame, from a vantage point just behind the plane, illustrates that at 6:04:17pm, during the final runway approach, the pilots would have had an unobstructed view of lightning and a dark rain shaft ahead. In real life, the plane flew into the rain shaft, was knocked off course by a sudden downdraft, and crashed, killing 134 people.

Figure 3. The runway complex at Little Rock National Airport, visible at the center in these aerial photographs, was the site of the fatal landing accident of American Airlines flight 1420. Sensors captured wind speeds and directions at various locations (indicated by circles) near the airport on the night of the accident. **(a)** At 11:39:50pm, two of the sensors, depicted in red and yellow, were sounding low-level wind-shear alerts indicating the threat of dangerously sudden changes in wind speed and direction. **(b)** At 11:48:00pm, two minutes prior to the aircraft's touchdown on the runway, three sensors were sounding alerts and four were indicating crosswind speeds higher than 20 knots (kts; 1 kt = 1.9 km/h), the maximum safe value for landing under the prevailing wet conditions.

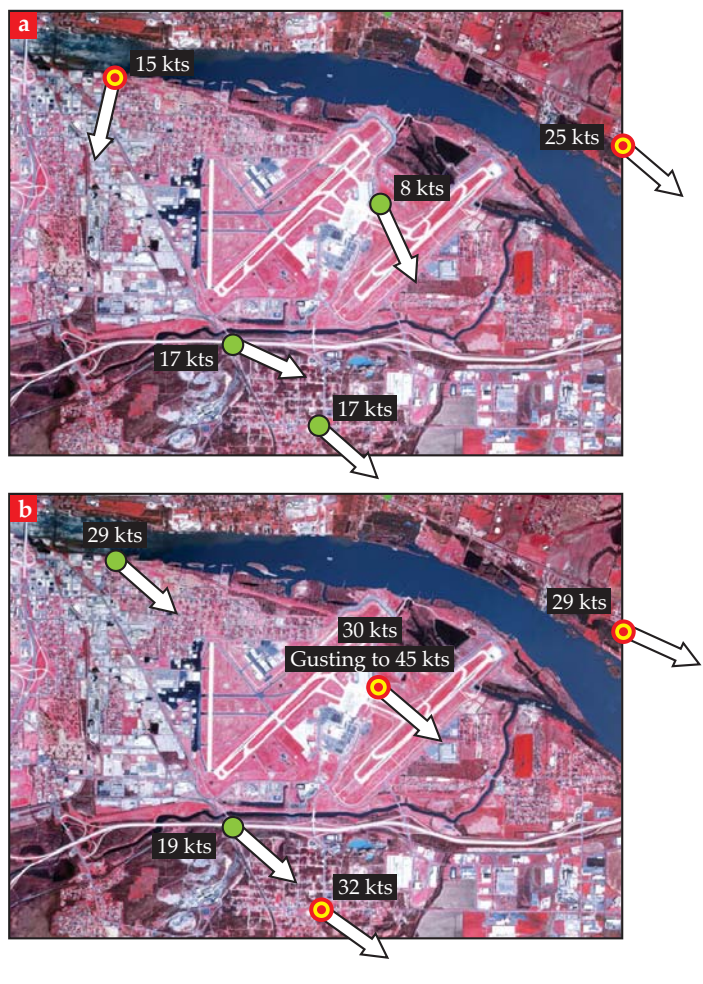
conditions at the airport deteriorated rapidly as the flight was on its final descent.

Doppler radar data generated by the NWS's Next-Generation Radar (NEXRAD) network showed that during its descent, the aircraft had skirted the east side of the long squall line of thunderstorms. Data from the National Lightning Detection Network indicated that during the crucial period between 11:46pm and 11:51pm there were 46 lightning strikes within five miles of the airport.

Eyewitness accounts tell a similar tale. Surviving passengers reported experiencing a bumpy flight, seeing lightning, and hearing rain and hail hitting the aircraft body during the descent. The first officer was recorded on the cockpit voice recorder saying, "I don't like that. . . . That's lightning," to which the captain replied, "Sure is." The captain and first officer could be heard further discussing the weather and concluding that they needed to expedite the approach and "get over there quick."

Wind sensors that had been placed at and around the airport as part of the FAA's Low Level Windshear Alert System also yielded telling evidence (see figure 3). At 11:40pm, as flight 1420 descended on its final approach to Little Rock, two of the sensors were sounding wind-shear alarms indicating dangerously sudden changes in wind speed and direction. Those alarms would have been heard by the local air-traffic control and broadcast to the pilots. By 11:48pm, two minutes prior to the aircraft's touching down, three alarms were sounding. Such alarms do not strictly rule out the possibility of a safe landing, but they do indicate conditions that could severely tax the performance capabilities of the aircraft.

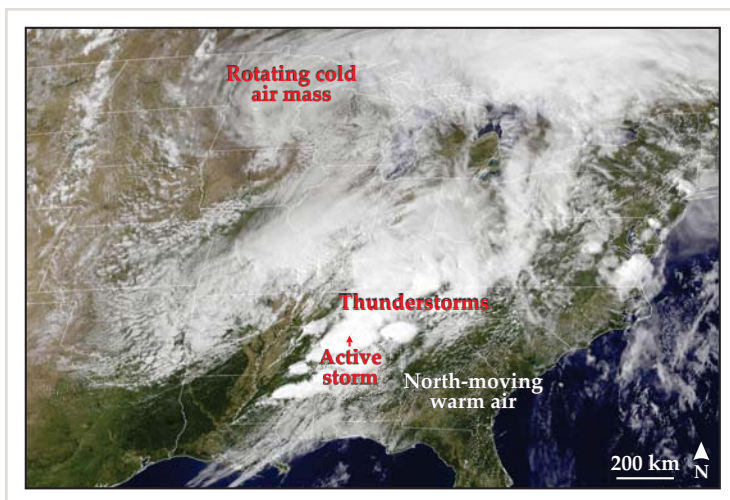
In addition to the wind-shear alarms, the sensor at the center of the runway complex reported crosswinds of 30 knots (56 km/h) with gusts up to 45 knots (83 km/h). Based on cockpit recordings, the captain was clearly aware that the maximum crosswind component for landing, an aircraft limitation set by both the particular airline and the aircraft manufacturer, was 30 knots for a dry runway and less for a wet runway. (There was some confusion between the captain and first officer as to whether the wet-runway limit was 20 or 25 knots.) On the night of the crash, rain and hail from thunderstorms had wet the runway.



The National Transportation Safety Board concluded that many factors led to the accident, including the fatigue-impaired performance of the crew, duty-time considerations, the situational stress associated with landing under adverse circumstances, and—perhaps most importantly—the decision of the flight crew to continue the landing approach despite strong crosswinds and wind shear. Also, the crew was certainly aware of the FAA guidelines recommending that aircraft maintain a safe distance of 20 miles from thunderstorms. In short, it was a case of rapidly deteriorating weather conditions being underestimated by the flight crew, American Airlines, and air-traffic control.

Twisters in Alabama

In April 2011 a massive tornado outbreak impacted seven states across the southeastern US and killed 337 people—246 in Alabama alone. The first wave of severe thunderstorms and tornadoes moved through Alabama during the early morning hours of 27 April, injuring 52 people and, luckily, killing none. Later that day a second wave brought supercells—convective storms capable of producing long-lived tornadoes and other severe weather phenomena—and injured nearly 2000 people as it moved across northern Alabama.



The outbreak was triggered by a collision between cold, relatively dry air moving southward from Canada and warm, moist air moving northward from the Gulf of Mexico (see figure 4). A jet stream traveling across the southern plains states exacerbated the situation: Flowing north and east through the middle of the two colliding air masses, it generated powerful small-scale circulations, which in turn generated lines of severe thunderstorms.

To this day, legal disputes continue over damages incurred during the outbreak. The fates of many property-insurance claims, for instance, await determination of whether the damage was caused by the straight-line winds of a thunderstorm or by the swirling winds of a tornado. (Policies that cover one kind of damage may not necessarily cover the other.) To aid in such determinations, forensic meteorologists use many types of atmospheric data, most importantly digital weather radar including NEXRAD and Terminal Doppler Weather Radar. Those data, along with surface weather observations and reports, aid the forensic meteorologist in analyzing and determining the timing, extent, duration, and strength of the events—as well as the nature of damage-producing winds.

Expertise, ethics, and empiricism

Courtrooms around the globe vary greatly in how they make use of experts and expert testimony, but they all have one thing in common: They hold testifying expert witnesses to a high standard. In the US, the *Frye* standard, embodied in Rule 702 of the *Federal Rules of Evidence*, determines the admissibility of expert testimony in federal courts. Born of the 1923 case, *Frye v. United States*,⁵ the standard states that

a witness who is qualified as an expert by knowledge, skill, experience, training, or education may testify in the form of an opinion or otherwise if:

- (a) the expert's scientific, technical, or other specialized knowledge will help the trier of fact to understand the evidence or to determine a fact in issue;

Figure 4. A satellite image of the eastern US, taken at 1:45pm Central Time on 27 April 2011, shows the weather phenomena that triggered a deadly outbreak of tornadoes across several southeastern states. A line of thunderstorms stretching from Mississippi across Alabama to northwest Georgia, North Carolina, and Tennessee was spawned when a cold, rotating air mass collided with warm air advected north from the Gulf of Mexico. Alabama suffered the storms' brunt—246 people were killed in that state alone. (Source: NASA.)

- (b) the testimony is based on sufficient facts or data;
- (c) the testimony is the product of reliable principles and methods; and
- (d) the expert has reliably applied the principles and methods to the facts of the case.

Rule 702 was amended in response to the 1993 US Supreme Court case *Daubert v. Merrell Dow Pharmaceuticals Inc.* The federal court now charges trial judges with the responsibility of acting as gatekeepers who exclude unreliable testimony based on a set of *Daubert* factors: Can the theory or technique be empirically tested? Has the theory or technique been subjected to peer review and publication? What is the known potential rate of error of the technique or theory? What standards and controls govern the technique's usage, and how are they maintained? Are the techniques and methods generally accepted within the scientific community? Whereas the *Frye* standard pertains to evidence, the *Daubert* factors pertain to the credibility and admissibility of the findings of a particular expert.

The *Daubert* standard generally sets a higher bar for acceptance of expert testimony than does the *Frye* standard and is now the law in federal court and in more than half of the states. Some state jurisdictions, however, continue to use the *Frye* standard. Other states use no formal vetting standard at all.

The major ethical tasks for the forensic meteorologist are much like those for any careful scientist. The expert must render opinions based only on the facts; must have a credible train of evidence to back up every opinion, calculation, and illustration; and must carefully stay within his or her area of expertise. Finally, the expert must truthfully represent the facts and conclusions without consideration of the legal positions that litigants may take. Because bad news can be hard to swallow, that last task can be challenging for cases in which the expert's analysis produces opinions and outcomes that are not advantageous to the party that hired him or her. The expert must give the bad news, regardless of the consequences.

From one perspective, an expert witness represents the knowledge of his or her field; the expert's role is to put aside professional rivalries, personal theories, unique but unaccepted analysis techniques, and questionable data sources and simply provide specialized knowledge that will help the judge and jury understand the evidence.⁴ As Steven

Lubet, a professor at the Northwestern University School of Law, writes, "The single most important obligation of an expert witness is to approach every question with independence and objectivity."⁶

Where do I apply?

Meteorologists—unlike lawyers, certified public accountants, professional engineers, and architects—are not required to obtain a state license or professional association certification to practice. There are, however, three prominent voluntary certification programs: the American Meteorological Society's Certified Consulting Meteorologist (CCM) program, Canada's Professional Meteorologist (PMet) certification, and the UK Royal Meteorological Society's Chartered Meteorologist (CMet) program.

The CCM has been in place since 1956. It requires the expert to provide rigorous documentation of personal training, knowledge, and experience and pass a written and an oral exam. The program review process takes approximately one year to complete and is open to anyone, including meteorologists working in the private sector, government, and industry. Wrote former American Meteorological Society president Richard Reed, "Any one of sufficient experience, who is committed to raising the standards of the profession and who provides advice and services at a professional level, whether for private fee or not, should regard himself as a proper candidate for certification."⁷

The PMet certification, established in 2011, has

requirements similar to those of the CCM program, except that it requires the candidate to have worked in Canada for a period of time before qualifying. The CMet, meanwhile, is regarded as the highest qualification in the profession in the UK.

Certification, though not mandatory, is extremely important for today's forensic meteorologist. It demonstrates that the candidate has been vetted thoroughly by peers and can be trusted to provide sound and ethical services. Increasingly, clients require that a meteorologist be certified before becoming a member of the litigation team.

Are you thinking of becoming a forensic scientist? Well, one of the first things to ask yourself is, How do I like working long, intense hours; being pressured by attorneys; and presenting my opinions in front of many people who will have no clue as to what I am saying? If you have no problem with that, then forensic science may be for you.

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