Mr.Tornado

The word tornado comes from a Spanish word, *tronado*, meaning “thunderstorm.” The Japanese word for tornadoes is *tatsumaki*, or “dragon whirls” (Kramer, 1992, p.46). To a scientist, this description, while lyrical, hardly encompasses the violent phenomenon that is a tornado.

In the 20th century, the foremost researcher of tornadoes and extreme wind was Tetsuya “Ted” Fujita, born in Japan on October 23, 1920. He was born in Kitakyushu City, on the island of Kyushu (Japan’s southwestern-most island). One would assume that his interest in severe storms came from experiencing them in the winter season on Japan’s west coast, but he actually never witnessed a live “dragon whirl” until he was almost 62 years old.

Tetsuya was the eldest child of Tomojiro (a school teacher) and Yoshie Fujita. His first name means “philosopher,” and he grew up with broad interests in mapping, geology, volcanoes and caves. He also had a talent for drawing projections of three dimensional topographs and weather visualizations. He was a practical student, and was said to have remarked upon visiting the Ao-no-domon tunnel at Yabakei, “that the monk who had dug the tunnel by hand over 30 years had wasted his time…he should have thought about it more and invented a mechanical digger, thus giving the world a tunnel and a useful machine” (Heidorn, 2007, p.2).

Fujita attended the Meiji College of Technology and graduated in 1943 with a degree in Mechanical Engineering. After graduating he was made an Assistant Professor of Physics there, teaching courses and labs.

Fujita, later in life, recalled that his father's wishes probably saved him. Fujita had been accepted at Hiroshima College and had wanted to study there, but his father insisted that he go to Meiji College. If he had gone to Hiroshima, he very likely would have died in the atom bomb blast. The second atom bomb was also fateful for Fujita. While teaching at Meiji College, he lived near Kokura Terminal, which was the initial target for the second bomb. The weather that day was not suitable for the mission, so the secondary target, Nagasaki, was chosen instead. Fate had other plans for him.

In September 1945, a month after the atomic bombings of Hiroshima and Nagasaki, the Japanese government sent Fujita to both sites to research the number of bombs dropped and their detonation heights. He used his powers of observation of "starburst" patterns in the rubble as well as scorch marks to discover that there was only one bomb for each city. What he observed there became the basis for his extraordinary future insights. By 1946, Fujita, who was always interested in weather, decided to pursue meteorology and applied for a Department of Education grant in Weather Science, hoping to teach.

In 1947, Fujita was conducting research near Seburiyama when a thunderstorm struck. He had been at a nearby weather station observatory, and the recorded pressures, temperatures, and wind speeds/velocities became the data he used to observe, analyze, discover and conclude that thunderstorms produced a "downdraft" of cooler air inside the storm, and that this made the storm spread out from the high pressure dome. He called this a "thundernose." Fujita also mapped another thunderstorm movement using lightning timings, finding that the storm did not move in a smooth path and had three lightning activity subcenters. This observation was contrary to the then current textbook explanations.

On September 26, 1948, Fujita surveyed the damage of a tornado strike on his island of Kyushu. This was his first such encounter. The tornado began as a waterspout on Ariake Bay, moved onshore, flattened crops and blew off roofs, and was named the Enoura tornado. Fujita followed along the entire six mile damage trajectory, observing the whirling damage patterns. In 1949, Fujita surveyed the damage of his first typhoon, called a hurricane in the Western Hemisphere, also in Japan.

During these years between 1947 and 1950, Fujita developed his micro-analytical study of a thunderstorm and worked on research, while lecturing on the thundernose concepts. In 1950, he had decided to translate his micro-analytical study of a thunderstorm into English, so he bought an English typewriter and painstakingly created his paper. Once more, fate stepped into Fujita's life. Fujita's colleagues had found a meteorological journal in the trash from a nearby American radar station and gave it to him. It was a copy of a research paper by a noted meteorologist from America, Dr. Horace Byers of the University of Chicago, regarding nonfrontal thunderstorms. Excited that someone else was doing similar thunderstorm research, Fujita wrote to Byers, sending him the English copy of his micro-analytical thunderstorm study.

Five years earlier, in the United States, Congress had passed a law that the Weather Bureau must study thunderstorms because of commercial aviation accidents that were occurring too often. The Thunderstorm Project was given to Byers to direct. During 1946-47, fifty-five weather stations were installed, balloons gathered data, radar probed airflow in and around thunderstorms and cumulus clouds, and military aircraft penetrated the storms at different altitudes. After all the data taken was analyzed, research reports were released in 1948-49.

It was in this context that Dr. Horace Byers received the correspondence from a young Japanese researcher. Byers was impressed with Fujita, and complimented his work, especially since Fujita, using only ground based instruments and data and his keen observation skills, had proven some of the same findings of the Thunderstorm Project, only without spending millions of dollars.

Byers answered Fujita's letter in January 1951, and included a copy of the final project report, *The Thunderstorm*. In his letter, Byers stated to Fujita, "In particular, you deserve credit for noting the importance of the thunderstorm downdraft and outflowing cold air" (Smith, 2010, p.117). Once again, the patterns of downdrafts and cold air spreading out mirrored the starbursts and whirls of his earlier observations.

Fujita took the next several years to finish his doctoral degree from the University of Tokyo. It was an investigation of three consecutive years of typhoon damage on the coast of his island of Kyushu, titled *Analytical Study of Typhoons*. He was awarded his doctorate in 1953. That year, Byers invited Fujita to come to Chicago for two years on a research appointment. While there, Fujita began his research on tornado outbreaks in Kansas and Oklahoma on June 25, 1953. Applying his microanalysis techniques, he gave birth to a new way to view small meteorological phenomena within thunderstorms and tornadoes. Using barograph tracings of the tornadoes, he discovered highs and lows, which he called "mesocyclones." Plotting these on a graph created a "mesoscale," which could then be used to identify mesolows and mesohighs. He could then name features in the storms' structures which could apply to all tornadoes.

In 1955, Fujita went back to Japan to apply for a permanent visa to the United States. There, he coauthored the research paper on his new field of Mesoanalysis, which came out in 1956. Fujita returned permanently to Chicago in July 1956, and was appointed Research Professor and Senior Meteorologist.

On June 20, 1957, a violent tornado struck Fargo, North Dakota. It killed ten people, injured over 100, and laid down a wide swath of damaged buildings. It was slow moving, about 20mph, and many photos were taken while it crossed through the area. Byers asked Fujita to perform a study of this tornado, which took two years using 150 photos from 53 locations taken by people and news agencies.

You could compare this task to reassembling a huge exploded object back together with no tools. According to Mike Smith, "Consider this: There was no radar. There were no weather satellite images. The only weather station in the area was at the Fargo Airport, miles away, and the second nearest station was tens of miles away. Studying the genesis of a tornado, the size of which was measured in hundreds of yards, seemed an impossible task" (Smith, 2010, p.117). Fujita was meticulous in assembling the photos. He had not lost the talent for seeing the photos as three dimensional representations: side to side, back and forth, up and down. Now he needed another dimension-time. He plotted the path in one minute intervals, as well as the accompanying cloud and thunderstorm evolutions. Fujita was the first to discover the now common storm features such as "wall cloud" and "tail cloud." These identified features help storm spotters today quickly broadcast warnings. Fujita's findings were published in 1960 in his paper, *A Detailed Analysis of the Fargo Tornado of June 20,* *1957*. The Weather Bureau also published his findings in a government pamphlet selling for 45 cents, which sold out.

On Palm Sunday in 1965, a swarm of 36 tornadoes struck the Midwest. Fujita took aerial surveys of the paths of the tornado damage, covering thousands of miles. He then mapped and studied the outbreak, using mesocyclones to discover families of tornadoes from the same supercell. One picks up where another ends, making it seem as though it is one long seamless tornado on the path. Fujita also discovered that by studying the spiral marks left in the plowed fields, certain tornadoes must contain more than one vortex. There is a "suction vortex" (a mini-vortex) that rotates around the primary funnel and causes the most intense destruction. This can explain why two buildings might be destroyed while a similar structure between them stays relatively undamaged.

Fujita worked with the Satellite and Mesometeorology Research Project (SMRP) in the 1960s. He became an Associate Professor of Meteorology in 1962 and full professor in 1965, using satellites to study severe storm development. In 1968, Fujita and his first wife divorced, and he became an American citizen. He added the middle name "Theodore," and his colleagues called him Ted.

Prior to 1970, little was known about tornado wind strength. One could not make any direct measurements because of tornadoes' short life and erratic behavior, and because any sensor would likely be destroyed. In the 1960s and 1970s the Nuclear Regulatory Agency was very interested in tornado wind speeds as they pertained to nuclear power plant design and potential damage. The agency turned to Fujita, and, with the assistance of his second wife, Sumiko, he invented a system called the Fujita scale, or

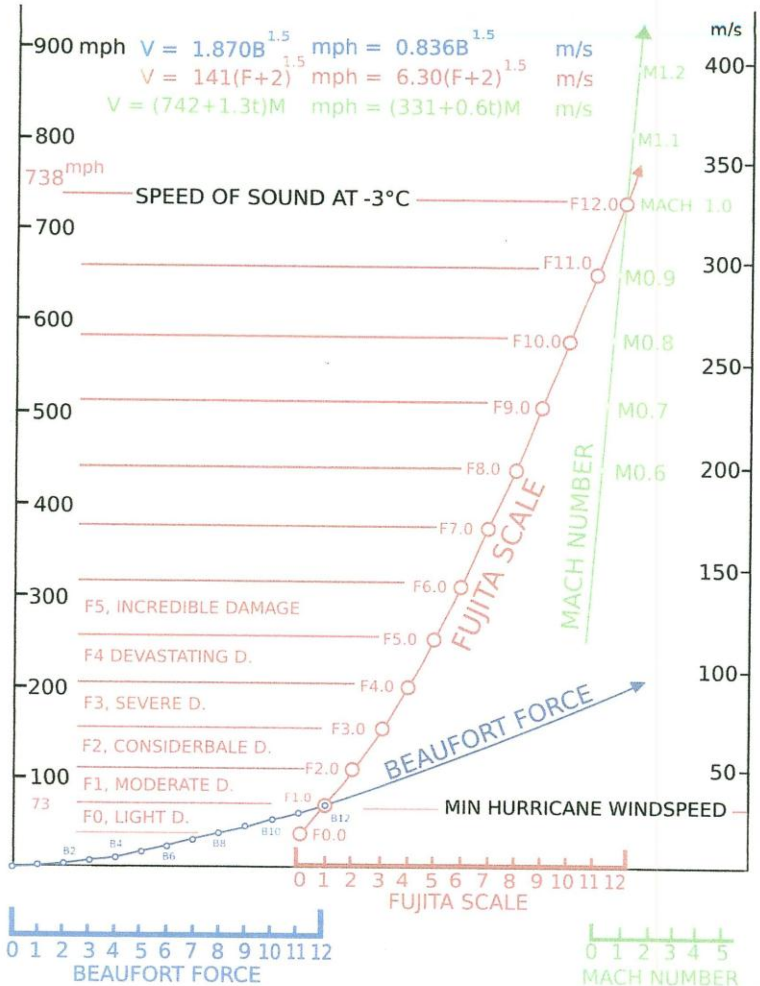
F-Scale, that could numerically correlate tornado wind speed to man-made structure damage observations.

In February 1971, Fujita published his plan entitled *Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity*. This became the standard for over 35 years worldwide. Fujita's brilliance in constructing his scale led to national fame. He became known as "Mr. Tornado."

A brief summary of the F-Scale is warranted. Fujita wanted to join his scale to existing scales, the Beaufort Wind Scale, which measures winds ending at 73mph and the Mach 1 number starting at 738mph, which is the speed of sound. He divided his scale into six increasing steps, F0-Gale, F1-Weak, F2-Strong, F3-Severe, F4-Devastating, and F5-Incredible. His F1 would correspond to the highest Beaufort 12, and there were theoretical steps F6 through F12, which would correspond to Mach 1, but are thought to be impossible in reality (See Figure 1).

Each of the F-Scale numbers corresponds to an estimated wind speed range, and the corresponding structural damage descriptions are assigned to each number. Because the wind speeds cannot be verified, the assessment of the post-event damage is the critical part that categorizes the F-Scale number of any tornado. Eventually, the F-Scale was modified to make the damage estimate indicators more precise. The new Enhanced Fujita Scale was adopted in 2007, but kept the original concept intact (See Figure 2).

In 1972, Fujita verified data sent by new weather satellites by using aerial photos to conduct experiments on tops of thunderstorms. These projects were underwritten by NASA and NOAA, and they led to the development of new instruments that were used



900 mph
800
738 mph
700
600
500
400
300
200
100
73
V = 1.870B^1.5 mph = 0.836B^1.5 m/s
V = 141(F+2)^1.5 mph = 6.30(F+2)^1.5 m/s
V = (742+1.3t)M mph = (331+0.6t)M m/s
m/s
400
350
300
250
200
150
100
50
SPEED OF SOUND AT -3°C
F12.0
MACH 1.0
M1.2
M1.1
F11.0
M0.9
F10.0
M0.8
F9.0
M0.7
F8.0
M0.6
F7.0
F6.0
F5.0
F4.0
F3.0
F2.0
F1.0
F0.0
FUJITA SCALE
MACH NUMBER
BEAUFORT FORCE
F5, INCREDIBLE DAMAGE
F4 DEVASTATING D.
F3, SEVERE D.
F2, CONSIDERBALE D.
F1, MODERATE D.
F0, LIGHT D.
MIN HURRICANE WINDSPEED
0 1 2 3 4 5 6 7 8 9 10 11 12
FUJITA SCALE
0 1 2 3 4 5 6 7 8 9 10 11 12
BEAUFORT FORCE
0 1 2 3 4 5
MACH NUMBER

Figure 1

Fujita Tornado Damage Scale

Developed in 1971 by T. Theodore Fujita of the University of Chicago

SCALE	WIND ESTIMATE (MPH)	TYPICAL DAMAGE
F0	<73	**Light Damage**. Some damage to chimneys; branches broken off trees, shallow-rooted trees pushed over: sign boards damaged.
F1	73-112	**Moderate Damage**. Peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads.
F2	113-157	**Considerable Damage**. Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
F3	158-206	**Severe Damage**. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.
F4	207-260	**Devastating Damage**. Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.
F5	261-318	**Incredible Damage**. Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 meters (109yds); trees debarked; incredible phenomena will occur.

Figure 2

on the ground by tornado chasers. He continued to work on the scientific characteristics of thunderstorms and tornadoes.

On April 3-4, 1974, a super outbreak of 148 tornadoes swept through 11 southern and midwest states and killed 319 people. Fujita led a team of meteorologists to survey the path and damage of every single tornado, and rate each with an F-Scale number. The map they constructed of the entire event spanned over 2200 miles. After this report came out, all tornadoes since 1971 have been given an F-Scale value, and even significant historical tornadoes going back as far as 1680 have all been retroactively categorized.

In the analysis of the 1974 storm path, Fujita once again recognized a familiar pattern of damage. According to John D. Cox: "In some instances, uprooted trees had been felled in a small but distinct starburst pattern, not a twisted whirl but splayed out by a wind that must have shot straight down out of the clouds and burst across the ground" (Cox, 2002, p.228). He had seen these same patterns at Hiroshima and Nagasaki, and reasoned that downdrafts that have enough strength to reach the ground will spread out, producing something he called an outburst effect. Little did he know that soon he would be in a position to change aviation forever, and save lives.

On June 24, 1975, Eastern Airlines Flight 66, from New Orleans to JFK International in New York, crashed on landing approach after running into a wall of heavy rain and a blast of wind, killing 112 people. The National Transportation Safety Board (NTSB) announced the cause to be "adverse winds." Fujita thought this cause was not exactly right because eleven other airplanes had landed safely ahead of Flight 66. What made the difference? He analyzed all the conditions in his meticulous way, and conceived a theory that incorporated all his lifetime of observations of downdrafts, outflows, starbursts, and outburst effects. He called what happened to Flight 66 a "downburst"-a rapidly falling column of air that accelerates and spreads out when it reaches the ground. It could reach speeds of 70mph or more, and a plane may not be able to navigate the quickly changing wind speeds and directions (See Figure 3).

When Fujita published his results, it opened up a firestorm of controversy because Fujita had no hard evidence that downbursts really existed. As Cox states:

> Fujita's unorthodox approach left him open to attack. He was working at the edge of scientific convention, rushing hypotheses into print without peer review or the volume of data that others would require…Fujita's oft–stated dictum must have sounded cavalier to some: it was his job to get his ideas out, and it was up to others to prove him wrong. If he was right half the time, meteorology would be well served. For all the swagger, however, he was not an easy mixer in the give-and-take of Western science. The world was divided into bursters and anti-bursters. Perhaps because of his early training in the oriental formalisms of prewar Japan, public criticism was a personal matter. The scientist would recall that the controversy surrounding his downburst concept "led to several sleepless nights" (Cox, 2002, p.230).

Meanwhile, every 18 months, on average, from 1964 through 1985, there was an airline crash caused by what officials called wind shear. Over 500 people were killed.

In May 1978, the National Center for Atmospheric Research (NCAR) and Fujita observed their first downbursts on Doppler radar. During that summer, they detected 50 more. Fujita finally not only had proof that downbursts existed, but they were more common than supposed. Fujita published a book, called *The Downburst*. He had continued his research in the summer of 1982, and identified an even smaller, more intense downburst, which he named a "microburst." 186 microbursts were detected that summer at Denver's Stapleton International Airport. These were even more deadly because the wind gusts they could generate could be as strong as 150mph. Pilots would not be able to take off or land safely in such a sudden emergency situation.

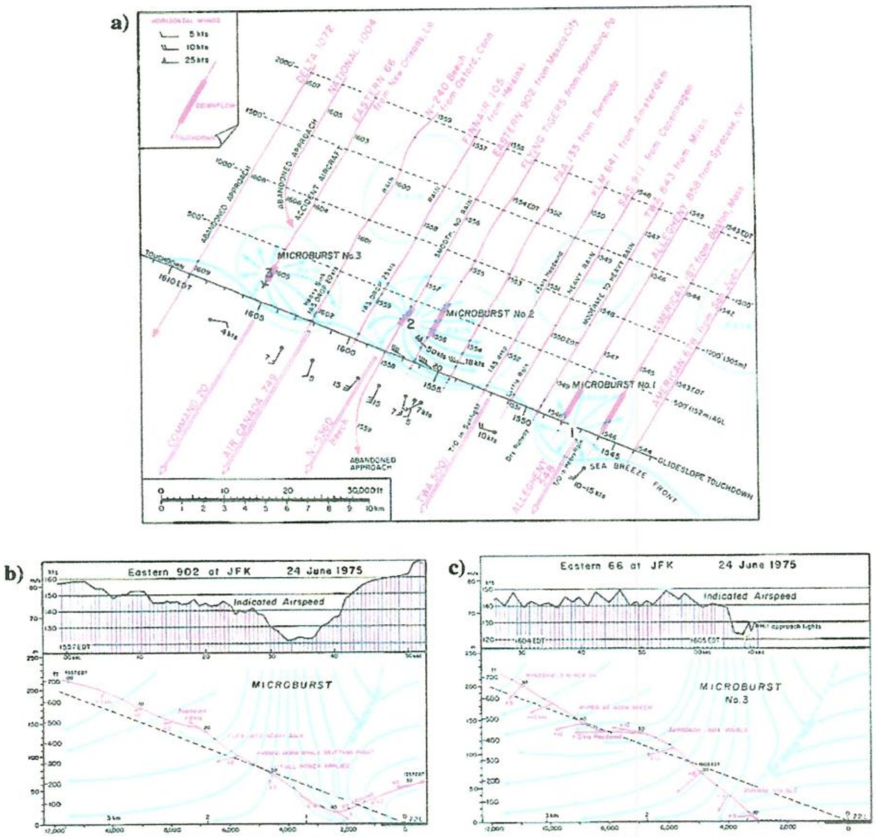

a)
b)
Eastern 902 at JFK 24 June 1975
Indicated Airspeed
MICROBURST
c)
Eastern 66 at JFK 24 June 1975
Indicated Airspeed
MICROBURST No.3

Figure 3

It was there at Denver that Fujita finally did witness his one and only "live" tornado. On June 12, 1982, he was monitoring a Doppler radar station at Stapleton . He related, "when I noticed a tornado maybe was coming down. I told all the radars to scan that area. My first sighting of a tornado was one with the best tornado data ever collected" (Encylopedia.com, 2007, p.4).

By the middle of the 1980s, other researchers finally began to find the causes and structures of microbursts. They were discovered to be small currents of dry air, quickly cooling within the thunderstorms, becoming denser, and gaining momentum as they fell. It was similar, as Cox notes, "to what is observed when a water hose is pointed at a hard surface…Wind hits the ground like a shock wave, bursting outward in all directions from its center" (Cox, 2002, p.231). Microbursts were hard to find, and were not previously identified because they were such transient events, too small and brief for conventional monitoring. Fujita was starting to change the minds of the meteorology and aviation community, but, unfortunately, not soon enough.

On August 2, 1985, Delta Airlines Flight 191 from Ft. Lauderdale to Dallas/Fort Worth International crashed on landing approach in a microburst, killing 137 of 167 people. Once again, Fujita had been called in to analyze the crash, and, once again, in his unique way, he wrote an entire book, *DFW Microburst on August 2, 1985,* producing a detailed explanation of how and why the crash happened.

Fujita's book and research were used in the famous trial of Delta Airlines, et al, vs. the United States agencies, the National Weather Service (NWS) and the Federal Aviation Administration (FAA). The publicity of the science behind the catastrophic crash convinced the FAA to quickly change its regulations. The NWS changed its data and warning responsibility structure. Even though the NWS and the FAA won the court case, they and rank-and-file meteorologists were microburst doubters no more.

Pilots are now given special “Wind-Shear Training Aid” on how to handle microbursts. Airports now are equipped with Terminal Doppler Radar Systems that can give some degree of warning for a pilot to take evasive action. Since the Delta 191 crash in 1985, there has only been one microburst crash, in 1994. According to Smith, “Given the ever-increasing number of people and planes in the air, the number of lives saved due to Fujita’s pioneering research that eventually led to implementation of microburst avoidance procedures in the United States is well over two thousand, not to mention the hundreds of millions of dollars of aircraft losses prevented” (Smith, 2010, p.173).

Ted Fujita was a tireless scientist. Under his direction, the Satellite and Mesometeorology Research Project (SMRP) team at the University of Chicago continued analyzing the atmosphere throughout the decades of the 60s through the 80s. He pioneered cloud motion and tracking analysis, both in the lab and using remote sensing. Using satellite imagery, aircraft and ground observations, he had important cloud investigations of height, growth and decay that relate to cloud-drift winds. He used geostationary satellites to provide insights into atmospheric circulation over many parts of the world, including the tropics and the equator. Fujita even tracked a Saharan dust cloud! Later applications derived from the cloud/wind relationship would be the possibility of forecasting hurricane trajectories and the feasibility of predicting El Niños from intertropical breeze belt shifts.

In 1988, the SMRP was renamed the Wind Research Laboratory (WRL) to reflect the broader scope of Fujita’s lifetime work, and he was named Director. In that same year, he was presented with the American Meteorological Society's (AMS) Award of Outstanding Contribution to Applied Meteorology, a high honor. This award was not his first. In 1967, he received the AMS Meisinger Award for contributions to meteorological satellite use and mesometeorological analysis. In 1985, he received a special award from the National Space Club at the Smithsonian's National Air and Space Museum for pioneering satellite imagery in mesoscale weather and severe thunderstorms, tornadoes and hurricanes. In 1989, he was named the Charles Merriam Distinguished Professor, from the University of Chicago.

As his later career was coming to an end, he still maintained an interest in wind research. Building on his doctoral work long ago in Japan, his aerial survey of the powerful Hurricane Camille in 1969, investigations of Hurricanes Alicia in 1983, Hugo in 1989, and especially Iniki and Andrew in 1992, Fujita identified another first, the mini-swirl. These are tiny vortices of high wind pulled upward into the eyewall edge. As they contract, they spin ever faster, reaching up to 80mph. Added to the already existing hurricane winds, total speeds of these extremely short-lived bursts (.2-.3 second) can exceed 240mph in a category 5 hurricane. This explained why some homes in Andrew were leveled while neighboring homes withstood the storm. Fujita, once again, had used his detective skills to confirm at least 20 mini-swirls, and estimated about 100 were created inside Andrew.

In 1990, Fujita formally retired from teaching, but, as the hurricane research will attest, he did not stop working on research. In 1992, Fujita published his memoirs, titled *The Mystery of Severe Storms*. In his final years, he suffered declining health from the chronic condition of diabetes, but used his grad students and research assistants to aid his research, even as his illness confined him to bed. As his former grad student and colleague, Roger Wakimoto noted regarding the proposal for an AMS event honoring Fujita:

> The event was unprecedented since all of the previous named symposia approved by the Society were held posthumously. The case for an exception to this rule, owing to Ted's lifelong achievements, was presented to the AMS Council and they quickly approved of the Fujita Symposium at their October 1998 meeting. I was thrilled to call Ted and inform him of the good news. He was deeply touched and humbled by the honor but also told me that he would not be able to attend. I understood the implicit meaning behind his reply, but, nevertheless, was deeply shocked and saddened when he passed away the following month. (Wakimoto, 2001, p.9).

Ted Fujita died on November 19, 1998, aged 78. He was survived by his second wife, Sumiko (Susie), and son, Kazuya Fujita, who is a Professor of Geology at Michigan State University. He left behind an incredible body of work that expanded the frontiers of meteorological knowledge and completely changed aviation worldwide. Fujita was himself joyful that his discoveries had led to saving lives. He noted, "When people ask me what my hobby is, I tell them it's my research. I want to spend the rest of my life in air safety and public safety, protecting people against the wind" (Encyclopedia.com, 2007, p.4).

The AMS did hold a two-day symposium honoring Fujita on January 10-11, 2000, with dozens of events and hundreds of participants. A banquet was held, and plaques were presented to Fujita's wife and son which said, in part:

> In honor of the greatest meteorological detective of our times. A person who defined the field of mesometeorology and showed our discipline, by his tireless work habits, that much could be learned by analyzing sparse and disparate data. His most satisfying accomplishment was in the knowledge that his pioneering research made the world a safer place from the havoc resulting from severe local storms. The atmospheric sciences community will always reserve the name "Mr. Tornado" in his memory. (Wakimoto, 2001, p.11).

The AMS further dedicated the entire issue of the January 2001 monthly Bulletin of the American Meteorological Society to Fujita. All articles were authored by colleagues and were devoted to descriptions of his work. Ted Fujita’s brilliance had finally and fully been recognized by his peers.

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