THE 1999 OKLAHOMA TORNADO OUTBREAK: 10-YEAR RETROSPECTIVE

RMS Special Report

INTRODUCTION

With atmospheric conditions ideal for producing hail, straight-line winds, lightning, flash floods, and tornadoes, May is the most active month for severe convective storms in the U.S. At this time of year, potent, extra-tropical storms force the warm, moist air from the Gulf of Mexico far enough northward to clash with the cool, continental air mass over the U.S., producing an environment conducive to the most violent weather that can be found anywhere on Earth.

May of 1999 proved to be an exceptionally destructive month in severe convective storm history. Beginning on May 3, a large upper-level trough over the Western U.S. allowed moisture rich air and intense wind shear to advect into Northern Texas, Oklahoma, and Southern Kansas, creating conditions ripe for severe weather. Nearly 70 tornadoes were reported on May 3 alone, including two dangerous, long-lived F4 and F5 tornadoes on the Fujita Scale that passed near Wichita, Kansas and Oklahoma City, Oklahoma, respectively (Figure 1). May 4–6 brought over 60 additional tornadoes to areas of the Southern Plains, the Tennessee Valley, and South Carolina. The events of May 3–6 became known as the 1999 Oklahoma Tornado Outbreak, costing many lives as they wreaked havoc throughout the region.

The strongest of these events, a large and destructive F5 tornado that touched down near Oklahoma City on the evening of May 3, caused $1.3 billion in damage in 2009 dollars (Brooks and Doswell, 2001). Adjusted for inflation, it remains the costliest tornado in U.S. history. The tornado claimed 36 lives, making it the deadliest tornado since the 1979 Wichita Falls Tornado. At its peak, it measured up to one mile wide with winds in excess of 300 mph (480 km/hr), the highest wind velocity ever measured (Center for Severe Weather Research, 2009).

Ten years after the event, Risk Management Solutions (RMS) revisits the 1999 Oklahoma Tornado Outbreak, with a focus on the spectacular May 3 F5 tornado near Oklahoma City, summarizing the meteorological conditions and the damage that the tornado caused. The RMS® U.S. Severe Convective Storm Model is used to assess insured losses if a similar tornado were to recur in 2009, considering its original path as well as trajectories through the urban corridors of Dallas and Chicago. The paper concludes with an assessment of the current risk from tornado hazard in the U.S. and the implications of this risk for insurance risk management.

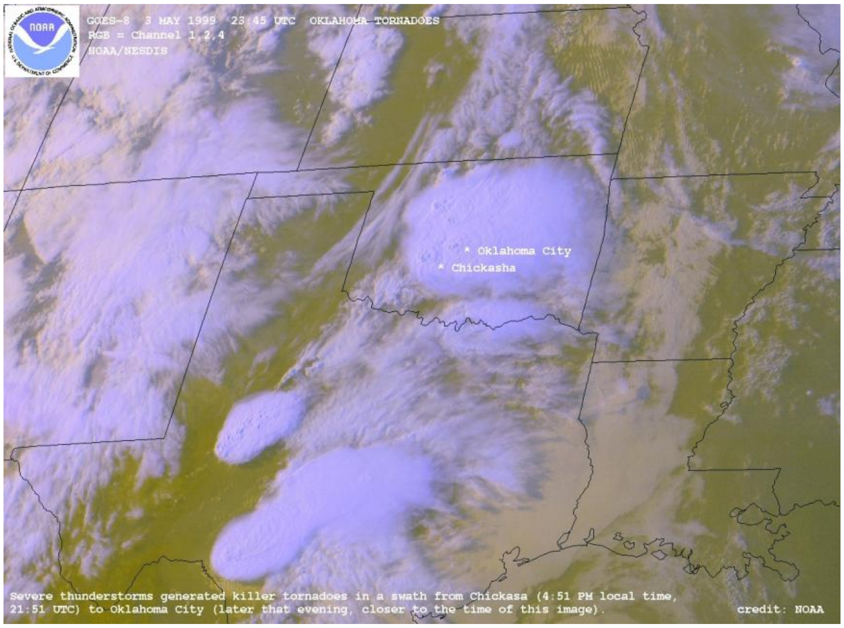

Figure 1: Satellite view of supercells over Oklahoma City hours before the F5 tornado on May 3, 1999 (Source: NOAA)

THE 1999 OKLAHOMA TORNADO OUTBREAK

"Tornado Alley" is a geographical area in the Central U.S. extending from northern Texas to southeastern South Dakota, southern Minnesota, and western Iowa (Figure 2). The area broadly corresponds to the Central Plains region of the U.S., reaching from the Rocky Mountains in the west to the Appalachian Mountains in the east. Climatologically, this central region of the continental U.S. experiences a relatively high frequency of tornadoes in the spring of each year, primarily due to the clashing of air masses. As Figure 2 illustrates, warm moist air from the Gulf of Mexico moves north to collide with cold, dry air from the Northern U.S. and warm dry air from the Southwestern U.S., generating severe weather in the Central Plains.

While hundreds of tornadoes occur in Tornado Alley each year, with the month of May historically showing the greatest frequency of events, most are weak in intensity and tend to impact rural, sparsely populated areas. Only 1% of these tornadoes become violent, measuring EF5 on the Enhanced Fujita (EF) Scale[1]. However, if these storms track through populated urban areas, they can cause severe damage and fatalities. The strongest event of the 1999 Oklahoma Tornado Outbreak, the F5 tornado that ripped through Oklahoma City, Oklahoma on May 3, met these unfortunate odds.

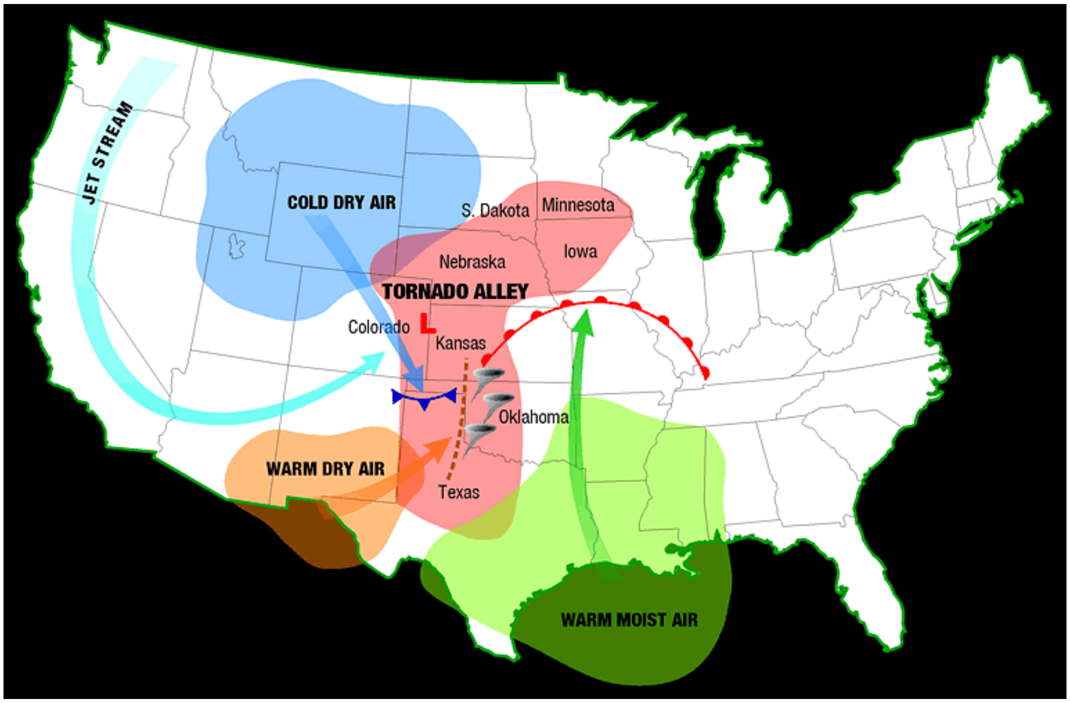

Figure 2: Tornado Alley (Source: NOAA)

Meteorological Conditions on May 3, 1999

The meteorological conditions allowing the formation of large supercells or supercell thunderstorms in Tornado Alley on May 3, 1999, were very similar to the conditions depicted in Figure 2. Supercell thunderstorms are a type of thunderstorm with a stable rotating updraft, capable of producing large hail, high winds, and violent tornadoes. A large trough (low pressure system) located over the Western U.S. progressed from Arizona to western Oklahoma and Kansas throughout the day. As this trough deepened, a surface low pressure moved

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[1] The Enhanced Fujita (EF) Scale was developed by the National Weather Service of the U.S. National Oceanic and Atmospheric Administration (NOAA) and has been operational since February 1, 2007. The EF Scale is a revision to the historical Fujita Scale or Fujita-Pearson Scale, first developed by Ted Fujita and Allen Pearson in the early 1970s, which measures the strength of a tornado based on the damage it causes. For more information, see http://www.crh.noaa.gov/arx/efscale.php.

eastward from the Rocky Mountains, bringing southwesterly warm, dry air from Arizona and New Mexico. In addition, a large mass of warm, moist air moved northward from Texas into Oklahoma and Kansas. A dry line formed at the meeting place of these moist and dry air masses. Dry lines, also called dew point lines, are often associated with severe weather and convective activity, as, by definition, they denote an unstable boundary between moist and dry air masses[2]. Unstable boundaries between air masses create sustained convection, which in turn can lead to severe weather formation. Very moist air (blue-green shaded area in Figure 3) present at the boundary provides energy for developing strong convection. Figure 3 also shows the dry line (brown, open scalloped line) that formed on May 3, extending south-to-north from eastern Texas through Oklahoma, Kansas and Nebraska.

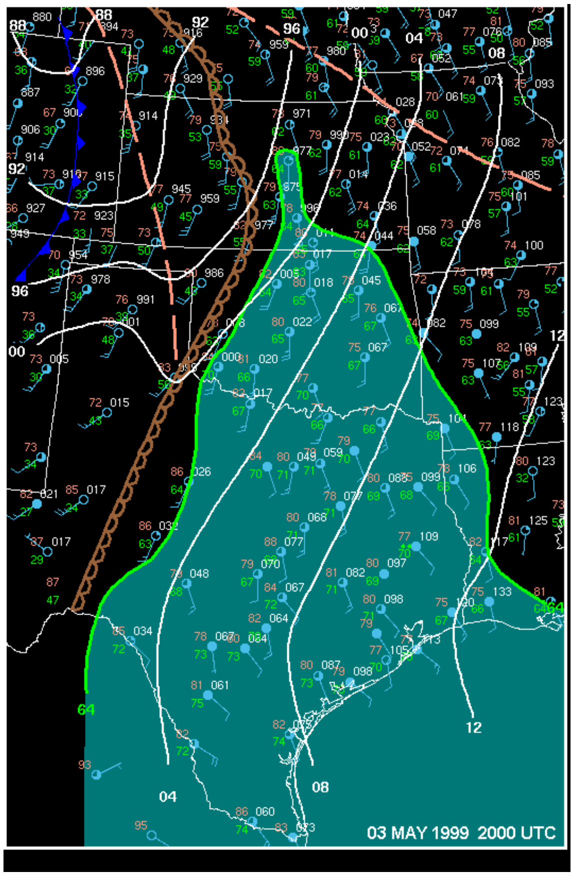

Figure 3: Meteorological conditions during May 3, 1999 at 20:00 UTC over the Plains, highlighting the north-south dry line (scalloped brown line) located near the boundary of moist air (blue-green) and dry air (black) and denoting surface dew points above the mid-50°s F (Source: Thompson and Edwards, 2000)

Beginning in the late afternoon on May 3, 1999, a jet streak—high velocity winds in the jet, relative to the surrounding stream—located in the mid-troposphere and upper troposphere moved in an east-northeast direction into the Plains, generating increased mid-level and upper level winds. This jet streak produced an environment containing strong vertical shear, an important parameter for convective storm formation. Two initial clusters of thunderstorms formed in southwestern Oklahoma during the afternoon, one near Lawton and another near the town of Altus. The first cluster near Lawton spawned Storm A, the supercell that was responsible for the F5 tornado (Thompson and Edwards, 2000). The second cluster near Altus was responsible for forming Storm B, the F4 tornado that impacted the western neighborhoods of Oklahoma City (Figure 4).

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[2] For more information on dry lines, see http://forecast.weather.gov/glossary.php?word=dry%20line.

Convective Available Potential Energy (CAPE) is a measure of energy available for deep convection and is commonly measured using weather balloon soundings. It represents the energy released if a parcel of air was to be lifted and cooled to the point of condensation. High values of CAPE enable strong updrafts to form and are correlated with damaging hail, increased lightning activity, and in some cases, violent tornadoes. Generally, CAPE values above 2500 J/kg indicate a highly unstable atmosphere. Soundings during the formation of supercell A were in excess of 5000 J/kg (Thompson and Edwards, 2000).

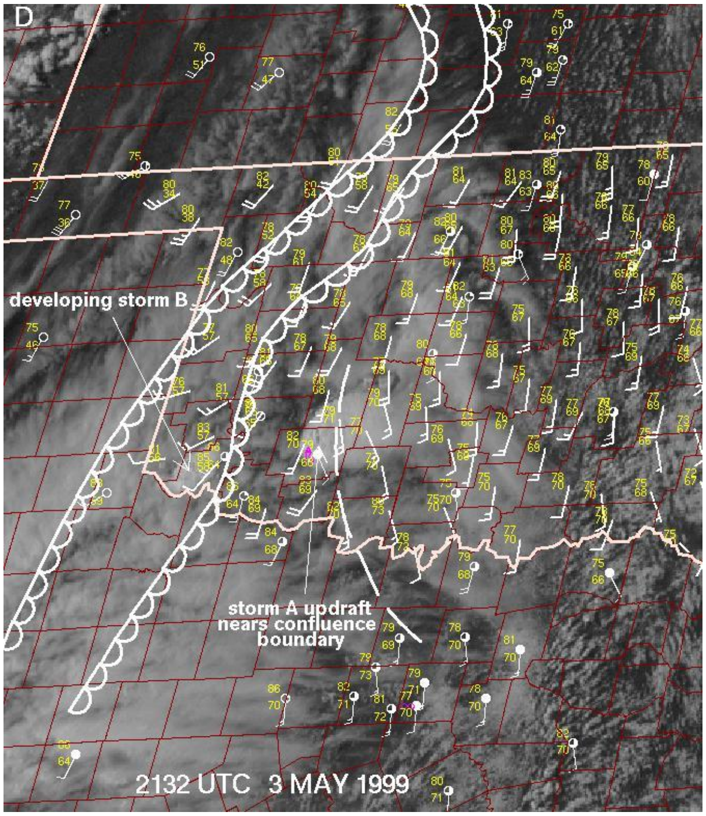

Figure 4: Satellite image and associated surface station data plot at 21:32 UTC on May 3, 1999, highlighting position of Storm A, near Lawton, and developing Storm B near Altus (Source: Thompson and Edwards, 2000)

Issuing Warnings to the Public

The Severe Prediction Center (SPC) and National Weather Service (NWS) continually monitored the situation and conditions, and without their operational forecasting and warning systems, in conjunction with local emergency services, fatalities would certainly have been more severe. The SPC began with a 1-day convective outlook, indicating a slight risk of severe weather. By midday on May 3, warm moist advection, an intensifying dry line, and soundings indicating high values of CAPE led forecasters at the SPC to raise the outlook to moderate. As conditions continued to develop favorable convective parameters, the SPC raised their outlook to a high chance of severe weather in the early afternoon of May 3.

The swift updates to the tornado outlooks throughout the day were tied to the difficulty of properly resolving the correct tropospheric flow and associated deep vertical sheer by operational models. With the convective outlook remaining uncertain as it rapidly changed, the prudent course was to issue frequent updates. By 4 p.m. on the afternoon of May 3, 1999, the NWS put 44 counties in Oklahoma under a tornado watch. Shortly thereafter tornado warnings were issued. At 6:57 p.m. the Norman, Oklahoma NWS put out its first ever

“Tornado Emergency” for Oklahoma City and its metropolitan area due to an approaching large and damaging tornado, which would later become the Oklahoma City F5 tornado.

THE MAY 3 F5 TORNADO

Path of the F5 Tornado

Just before 7 p.m. local time on May 3, 1999, the strongest tornado of the outbreak touched down southwest of Oklahoma City in the city of Amber, Oklahoma. After touching down in Amber, the tornado moved northeast through the communities of Bridge Creek and Newcastle and into suburban Oklahoma City, devastating the town of Moore before turning north and moving through Del City and Midwest City (Figure 5). It also passed over the western edge of Tinker Air Force Base as it moved through the region.

Figure 5: The F5 tornado path of May 3, 1999: a view in Newcastle two days following the event, showing the dark mud trail of the tornado's path as it moved through the region. The town of Moore and south Oklahoma City can be seen in the distance (in the upper portion of photo) (Source: National Severe Storms Laboratory)

As Figure 6 illustrates, storms A and B were the primary storms of the outbreak, spawning a total of 34 tornadoes between them. Storm A spawned the longest track and the most intense tornadoes of the day. Specifically, the F5 tornado spawned by Storm A had a full track length of 38 miles, and at its widest, it measured one mile wide (Speheger et al., 2002). It reached F5 strength twice: once as it passed through Bridge Creek, and again as it passed through the town of Moore. However, for almost its entire lifetime, it consistently remained at F3 strength or above.

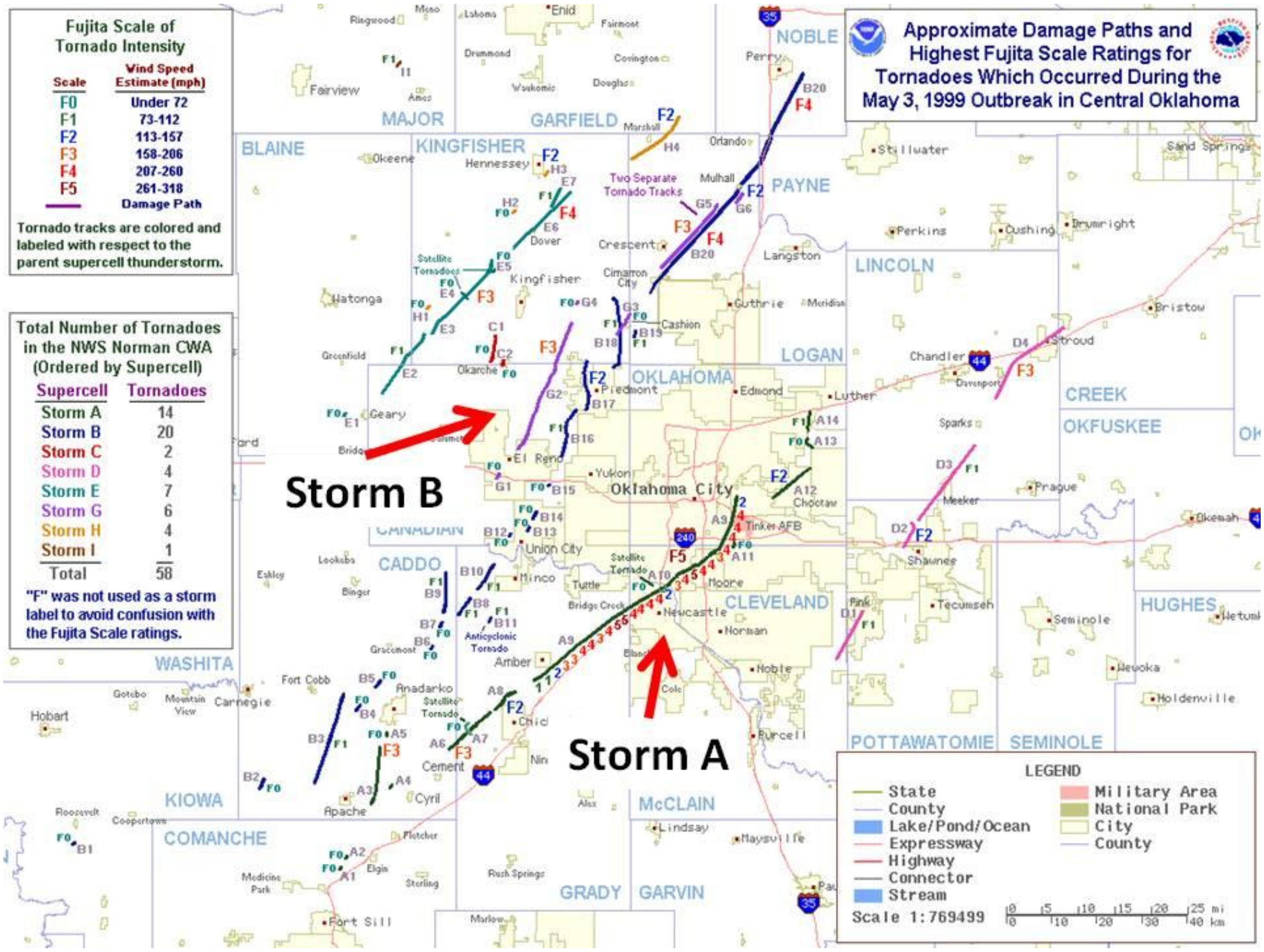

Figure 6: Map of tornadoes and their intensity spawned by all storms during the May 3, 1999 Outbreak. Storm A (dark green) produced the long-lived F5 tornado through southern Oklahoma City (Source: NOAA)

Tornado Damage in the Oklahoma City Area

After the dust, debris, and devastation had settled, survey teams were deployed to the area from around the country. Various methods were used to assess the damage, including ground reconnaissance surveys and aerial observations. Thousands of homes and business were destroyed in the Greater Oklahoma City area, including Kelly Elementary School, the Emerald Springs Apartments, and numerous other residential and commercial structures. As shown in Table 1, the majority of damaged or destroyed structures were within Oklahoma and Cleveland counties.

Table 1. Impacts of the May 3, 1999 tornado in Oklahoma, Cleveland, and surrounding counties (Source: http://www.srh.noaa.gov/oun/storms/19990503/tornadofacts.php)

	Oklahoma and Cleveland Counties	**Other Counties**
Homes damaged/destroyed	6,720	1,412
Apartments damaged/destroyed	1,041	—
Businesses damaged/destroyed	127	133
Churches/schools destroyed	5	2
Public buildings damaged/destroyed	—	11

The large size and long track length of the tornado through the densely populated areas allowed reconnaissance teams to collect extensive information on the structural integrity of the properties in its path, and the damage patterns caused by this violent and destructive tornado. In general, property damage from tornadoes comes from three major sources: the direct impact of winds on a structure, the impact of windborne debris on a structure, and the impact of internal pressurization on a structure. A survey performed by the Building Assessment Performance Team (BAPT) revealed that internal pressurization of structures was a predominant mode of building failure (BAPT, 1999). Internal pressurization occurs when the building envelope is breached during intense winds, causing positive pressure to build up and eventually lead to roof failure. In the F5 tornado, garage doors were found to be the primary failure points of the building envelope, allowing pressure to build up internally and lead to roof damage. Other openings, such as windows and doors, were also shown to contribute to structural failure from internal pressurization.

The majority of structures that were surveyed for damage consisted of one-story, single-family residential structures, constructed of wood framing with brick veneer (Pan et al., 2002). While most of the homes in the damage path had similar construction and year built characteristics, the resulting damage had a wide range of variability. This variability was the result of both the highly complex nature of the tornado wind field over a short distance, as well as the amount of debris picked up by the tornado and projected toward a damaged structure.

Often during violent tornadoes, the direct damage to a structure is dictated as much by the stability of surrounding structures as it is by the characteristics of the particular structure itself. During this tornado outbreak, airborne debris from destroyed homes was launched into neighboring structures, pelting them with "broken pieces of wood from houses, furniture, and trees" (Marshall, 2002). Reports of vehicles being tossed nearly 3,300 ft (1,000 meters) by the destructive funnel were recorded. Moreover, damage often manifested itself in what was referred to as "cones of damage" (Doswell and Brooks, 2002), beginning with a poorly built structure failing, generating debris and projectiles that compromise the integrity of neighboring structures. This pattern continues, causing damage to radiate outward in a cone-like pattern along the path of the storm (Figure 7).

Figure 7: F5 tornado damage in Moore, Oklahoma as a result of the May 3, 1999 tornado (Source: National Severe Storms Laboratory)

AN F5 TORNADO IN 2009

Using the RMS® U.S. Severe Convective Storm Model, the effects of a tornado with the same footprint size and intensity as the 1999 Oklahoma City Outbreak's May 3 F5 tornado were simulated and analyzed against present-day exposure in several at-risk metropolitan areas: Oklahoma City, Oklahoma; Dallas, Texas; and Chicago, Illinois. Although Dallas and Chicago have not been hit by a strong tornado to date, they are located in tornado-prone areas of the U.S., putting the high values of exposure in these cities at potential risk.

Catastrophic damage on the scale of the 1999 Oklahoma City tornado is representative of the most destructive and violent storms. Most structures, aside from some steel frame and concrete construction, will be completely obliterated by tornadoes of this magnitude, which represent a measurement of F5 on the Fujita scale or EF5 on the Enhanced Fujita scale[3].

Modeling the Oklahoma City Tornado

The footprint of damage from the F5 tornado that passed through Oklahoma City on May 3, 1999, was reconstructed from reconnaissance reports and aerial surveys (e.g., BAPT, 1999). This damage footprint was then overlaid on the variable resolution grid (VRG), a geographic indexing system developed by RMS to optimize risk assessment. The U.S. Severe Convective Storm Model includes VRG cells ranging in size from 0.05 degree (5 km/3 mi) to 0.50 degree (50 km/31 mi). The granularity of the grid is governed by the local hazard and exposure concentration, and the grid supports modeling areas at 10 mi^2 (25 km^2). Because of the relatively high tornado hazard and very high exposures, all three modeled metropolitan areas of Oklahoma City, Dallas, and Chicago fall into the highest resolution VRG cells.

Damage in each VRG cell was translated using damage patterns from the actual 1999 tornado. The U.S. Severe Convective Storm Model allows for the partitioning of each VRG cell by tornado intensity, so that accurate calculations can be conducted, associating the correct proportionate intensity to damage ratio within each cell. Though the model is capable of modeling perils other than tornado, such as lightning, hail, and straight-line winds, only tornado damage was included in this simulation.

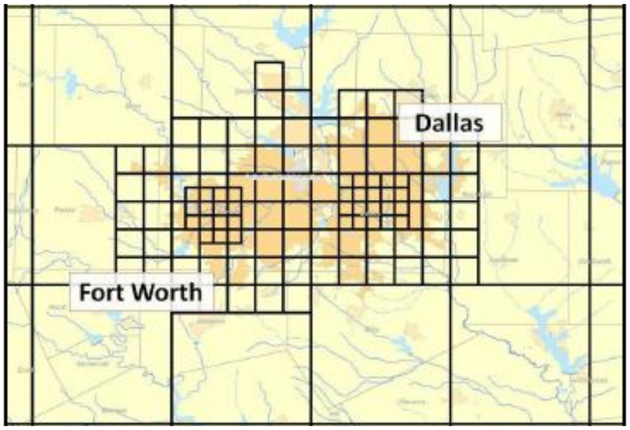

Figure 8: Map showing the variable resolution grid (VRG) size and distribution in the Dallas area, with the smallest cells at 0.05 degrees (5km/3mi) to capture central business district exposure

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[3] For a comparison between wind speeds for a F5 tornado and an EF5 tornado, see the RMS Special Report on the 2008 U.S. Severe Convective Storm Season (http://www.rms.com/publications).

Exposure at Risk

The tornado's damage footprint was analyzed against the 2009 RMS® U.S. Industry Exposure Database (IED), which captures exposure values at the ZIP Code resolution for three primary insurance coverages: building/structure, contents, and time element (commonly known as business interruption or additional living expenses).

The U.S. IED also captures the appropriate structural characteristics for each line of business affected in the central business district (CBD) and surrounding suburbs in Oklahoma City, Dallas, and Chicago. Structural characteristics accurately reflect the local, city, and state building codes, as well as building information including average building height, year built, and other characteristics unique to each metropolitan area important for damage and loss modeling. For example, within the tornado footprint, Chicago's financial district contains the highest concentration of high-value commercial towers, whereas Dallas' high-value exposure is more spread out. Overall values of insured property at risk in the Oklahoma City, Dallas, and Chicago metropolitan regions are shown in Table 2. It should be noted that in this study, only the exposure within the tornado footprint is considered; exposure values are not inclusive.

Table 2. Value of insured residential and commercial property at risk from an EF5 tornado in 2009, based on the 2009 RMS® U.S. Industry Exposure Database

Metropolitan Region	Residential Exposure ($ billions)	Commercial Exposure ($ billions)	Total Exposure ($ billions)
Oklahoma City	$13.4	$12.8	$26.2
Dallas	$71.9	$110.7	$182.6
Chicago	$146.6	$187.9	$334.5

Unlike earthquakes and hurricanes, where building codes and methods of construction can significantly mitigate damage in some cases, tornadoes with the highest intensities, like the tornado analyzed here, cause virtually total destruction when structures are exposed to the highest winds (Wurman et al., 1996; Wurman and Gill, 2000; Wurman, 2002; Wurman and Alexander, 2005). Thus, all F5/EF5 tornadoes generate high damage ratios in their paths, regardless of the size of the town or mix of building attributes.

Analysis Results

Table 3 shows the insured loss that would result from the reconstructed May 3, 1999 F5 tornado damage footprint in Oklahoma City, Dallas, and Chicago in 2009. In Oklahoma City, losses would be $1 billion greater than in 1999, translating into an increase of more than 75% in insured loss. The large jump in loss is due to increasing exposure value from new construction and inflation. However, the insured loss in Oklahoma City is a fraction of the loss expected in Dallas and Chicago. Losses in these metropolitan areas from a violent EF5 tornado in 2009 are on the same scale of the 1994 Northridge Earthquake (at $18.2 billion in 2008 dollars) and 1992's Hurricane Andrew (at $23.8 billion in 2008 dollars).[4] Moreover, damage ratios, measuring the ratio of insured loss to property at risk across the impacted regions range between approximately 7% and 10%.

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[4] Insured losses in 2008 dollars are estimated by the Insurance Information Institute (See http://www.iii.org/media/facts/statsbyissue/catastrophes/).

Table 3. Insured losses to the residential and commercial lines of business from an EF5 tornado impacting the metropolitan regions of Oklahoma City, Dallas, and Chicago in 2009

Metropolitan Region	Insured Loss ($ billions)	Damage Ratio
Oklahoma City	$2.3	8.8%
Dallas	$17.5	9.6%
Chicago	$25.2	7.5%

Figures 9(a) through 9(c) illustrate the damage footprint overlaid on the exposure at risk in each metropolitan region. The major insured loss in Dallas and Chicago is caused by the destruction of the structures in the tornado's damage footprint corresponding to the most intense winds. Because tornado winds increase with height, the middle and upper parts of skyscrapers in Chicago and Dallas would be buffeted by increasingly higher wind velocities, causing greater damage.

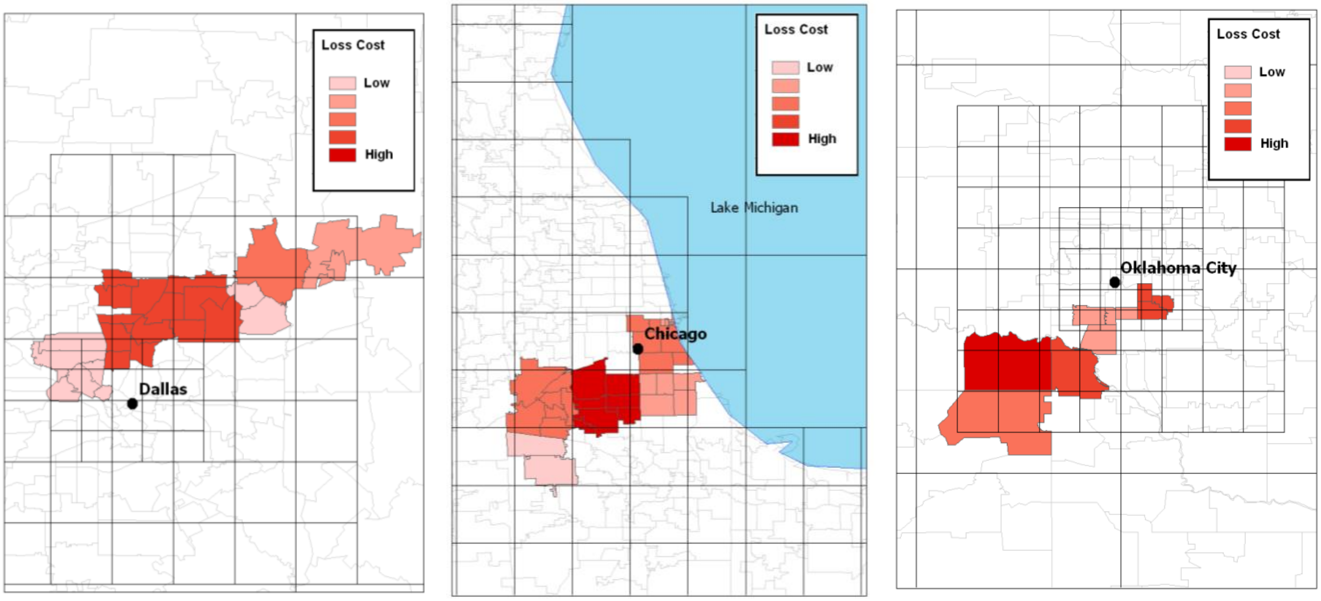

Figure 9: Insured loss cost by ZIP Code for (a) Oklahoma City; (b) Dallas; and (c) Chicago, overlaid on the RMS variable resolution grid (VRG) with city centroid shown. Loss cost is the ratio of loss to the exposure value, normalized by $1000.

Chicago in particular has a number of large commercial towers over 1,000 feet tall, including the Willis Tower (formerly Sears Tower), the Aon Center, the John Hancock Center, and the AT&T Corporate Center. Several large towers are also in the construction or planning phases, such as the Trump International Hotel and Tower and Blue Cross-Blue Shield Expansion Tower, and would also be impacted. It would be expected that these very high-valued buildings would sustain significant damage, and possibly be a total loss.

Implications for Risk Management

While severe convective storms may cause in excess of $10 billion in insured losses during a given year, as seen in 2008, losses are usually accrued throughout the season's many events—which may span multiple days and impact different regions (see RMS, 2009). These severe connective storm events are often small return-period events on an exceedance probability (EP) curve, representing less severe events that are expected to recur more often. In contrast, events that comprise the tail of the EP curve are made up of highly severe, less frequent events, such as large derechos, widespread hailstorms, or severe urban tornadoes like the event analyzed in this study. Urban tornadoes have smaller footprints and are less frequent in comparison to hail and straight-line wind events, as there is a comparatively smaller probability of one striking an area with major exposure.

In order to properly simulate the true frequency and severity of tornado outbreaks to insured property, thousands of years of simulation are needed, as historical insurance claims often do not capture these events due to their infrequency and increases in modern exposure. Probabilistic models, such as the RMS® U.S. Severe Convective Storm Model, are able to run thousands of years of stochastic events, allowing insight and quantification of rare tail events, like urban tornadoes.

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