Tornado Load Design per ASCE 7-22 and the 2024 International Building Code

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Credit: NOAA

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Course Introduction

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Course Overview

- Introduction to engineering design for tornadoes
- Tornado characteristics
- New tornado load requirements in ASCE 7-22 and 2024 IBC – for 'conventional buildings'
- Design requirements for tornado shelters and safe rooms

Credit: FEMA

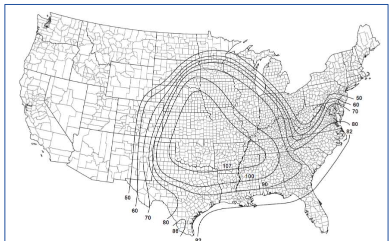
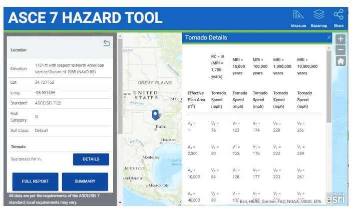
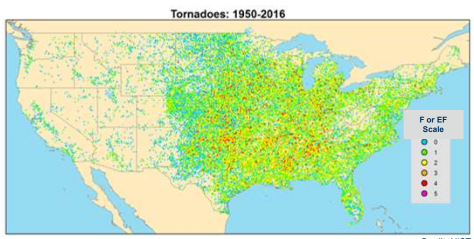


FIGURE 32.5-1E Tornado Speeds for Risk Category IV Buildings and Other Structures, for Effective Plan Area of 100,000 ft² (9,290 m²)





Credit: NIST

Credit: NIST

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Seminar Learning Outcomes

- Upon completion of this course, you will be able to :
  - Identify key properties and defining characteristics of tornadoes
  - Explain the current state of practice with regard to design for tornadoes, including options for higher levels of tornado protection beyond ASCE 7-22 minimums
  - Summarize the scope and limitations of ASCE 7-22 tornado load requirements
  - Determine tornado speed for any geographic location, building/facility size, shape, and Risk Category
  - Evaluate tornado loads for a building
  - Determine controlling loads on a building using Strength and ASD load combinations

This is important on the job because …

- Establishes a basic understanding of tornado hazards and considerations for engineering design
- Provides a foundation for application of the latest tornado design standards for conventional buildings and other structures as well as storm shelters

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Seminar Outline and Schedule

- Unit 1: Introduction and Tornadoes 101
- Unit 2: Tornado Load Procedures and Tornado Hazard Maps
- Unit 3: Tornado Load Coefficients and Equations
- Unit 4: Tornado Load Calculations and Load Combinations
- Unit 5: Tornado Shelters and Safe Rooms

Schedule

Thursday, June 8: 9:00 am – 5:00 pm EDT

Friday, June 9: 9:00 am – 4:00 pm EDT

One hour lunch break and short breaks in morning and afternoon each day

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References

- ASCE 7-22 Minimum Design Loads and Associated Criteria for Buildings and Other Structures
  - Chapter 32 Tornado Loads
  - Chapters 26, 27, 29, 30, 31 Wind Loads
  - Chapter 1 General
  - Chapter 2 Load Combinations
  - Available for purchase from ASCE in online, e-book, or print formats at https://www.asce.org/publications-and-news/asce-7
- ASCE 7 Hazards Tool
  - Free tool - available at https://asce7hazardtool.online/

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Additional Resources

NIST and FEMA Publications

- Economic Analysis of ASCE 7-22 Tornado Load Requirements
  - https://doi.org/10.6028/NIST.TN.2214
- FEMA/NIST Design Guide for New Tornado Load Requirements in ASCE 7-22
  - https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=935883

NCSEA Resources – Worked Example Problems

- Tornado Loads – Schools
- Tornado Loads - Hospital

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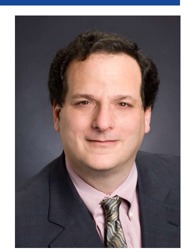
Meet Your Instructor



- National Institute of Standards and Technology (NIST) / US Dept. of Commerce
  - Lead Research Engineer (and former Director), National Windstorm Impact Reduction Program
    - Lead Investigator – National Construction Safety Team, 2011 Joplin MO Tornado
    - Lead Investigator – Research Team, NIST study of the 2013 Moore OK Tornado
    - Co-Investigator - National Construction Safety Team, Hurricane Maria in Puerto Rico
- Louisiana State University
  - Charles P. Siess Jr. Associate Professor of Civil Engineering
  - Director, LSU Hurricane Center
  - Co-Director, LSU Wind Tunnel Laboratory
- Texas Tech University
  - Managing Director, Wind Engineering Research Field Laboratory
  - B. Arch., and BS, MS, & PhD in Civil Engineering
- Consultant
  - Analysis and Design for Extreme Winds
  - Post-Storm Investigations
  - Expert Witness

- Over 100 publications on wind, hurricane, and tornado engineering research/practice
- Committee Chair
  - ASCE 7 Tornado Task Committee
  - ASCE Wind Speed Estimation Standard Cmte
  - ICC 500 Storm Shelter Standard Cmte
  - ASCE Petrochemical Energy Wind-Induced Forces Task Committee
- Past-President, American Association for Wind Engineering (AAWE)

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Around the Room Introductions

- Matthew Roberts
  - Administrator, Technology and Media, ASCE
- Participants
  - Name
  - Affiliation
  - City, State
  - Interest in tornadoes/tornado loads

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Course Introduction

Questions / Discussion

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Unit 1

Tornadoes 101

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Unit 1 Outline

Tornadoes 101

- Tornado Meteorology
- Tornadic Winds and the EF Scale
- Tornado Climatology
- Tornado Hazards
- Tornado Impacts and Rationale for Tornado Design
- History, Development and Recent Practice for Tornado Design
- Summary

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Unit 1: Learning Outcomes

- Upon completion of this unit, you will be able to :
  - **Identify** key properties and defining characteristics of tornadoes
  - **Estimate** tornado speeds required to cause specific levels of damage to typical buildings
  - **Understand** the historical development and current rationale on design for tornadoes
- This is important on the job because …
  - Provides the necessary background on tornadoes and associated hazards needed to understand why design for tornadoes is now required

Source: USACE

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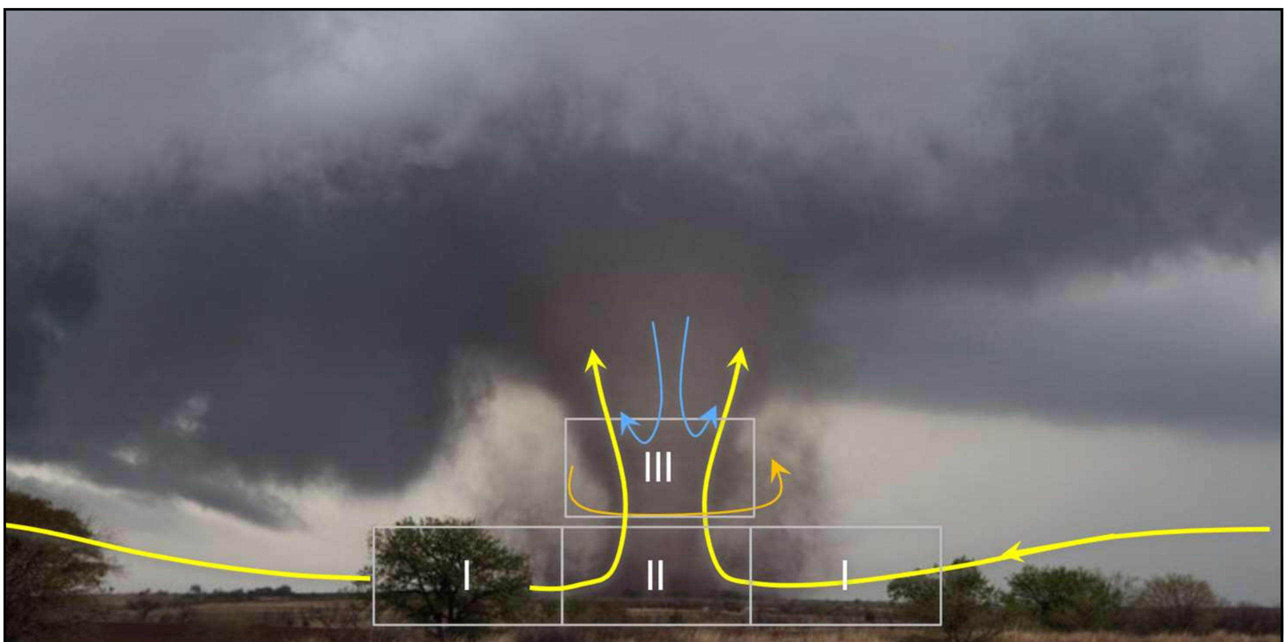

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Tornado Meteorology

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What is a Tornado?

Tornado - A rapidly rotating column of air extending vertically from the surface to the base of a cumuliform cloud, often with near-surface circulating debris/dust when over land or spray when over water.

Source: American Meteorological Society

- Tornadoes are nature's most violent storms
- Spawned from powerful thunderstorms, tornadoes can cause fatalities and devastate a neighborhood in seconds
- Winds of a tornado may reach 300 mph or more
- Damage paths can be in excess of one mile wide and 50 miles long

Source: National Weather Service

Source: OAR/ERL/National Severe Storms Laboratory (NSSL)

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Guest Lecture

- National Weather Service Warning Decision Training Division
  - Team Leader and Master Instructor
- Warning Decision Training Division
  - Lead developer on:
    - Tornado Warning Guidance
    - EF Scale and Damage Surveying
    - Winter Storm Warning Decision-Making
- Education
  - BS Meteorology, SUNY Oswego; MS Meteorology University of Oklahoma
- Other
  - Served on three NWS Service Assessment Teams (Spencer, SD tornado 1998; Enterprise, AL tornado 2007; Super outbreak in the SE US 2011)
  - Served on numerous Quick Response Team to evaluate strong tornadoes

- 70 publications in severe weather and damage surveying
- Committee Chair
  - ASCE/SEI/AMS Standard Committee for Wind Speed Estimation in Tornadoes and Other Windstorms
  - AMS Committee Engineering Resilient Communities

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Tornado Types: Nonmesocyclonic Tornadoes

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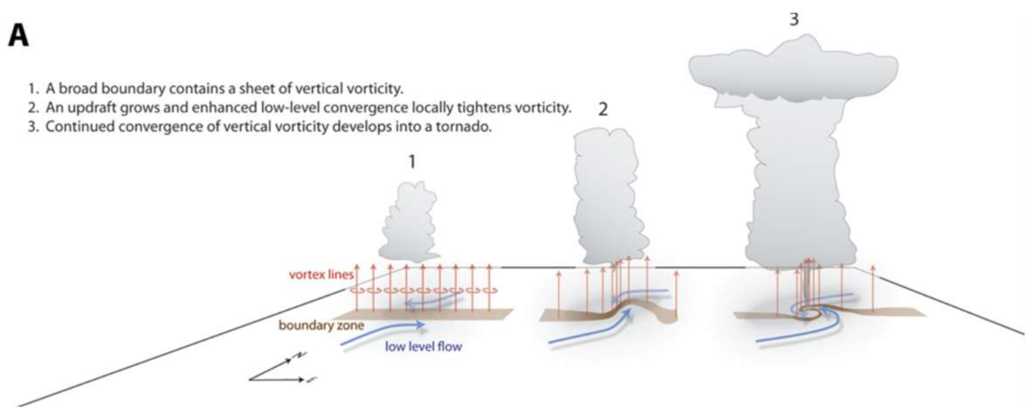
How Nonmesocyclonic Tornadoes Form



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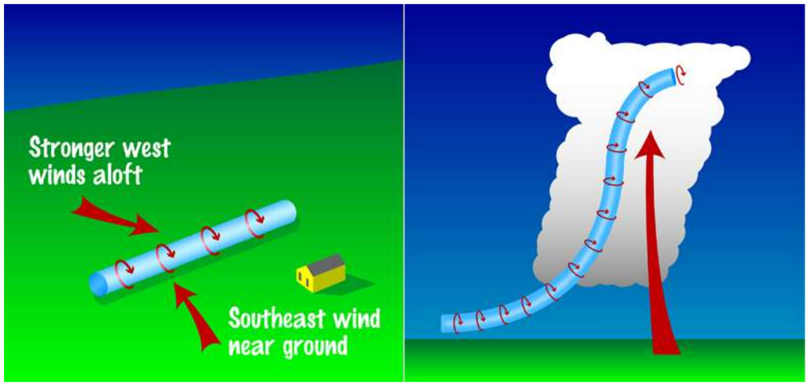
The Supercell, the Producer of the Strongest Tornadoes: Part 1



Source: NOAA

Supercells produce the majority of strong tornadoes. A supercell forms as a cumulonimbus cloud forms in an atmosphere with strong vertical wind shear such as when strong westerly winds aloft ride over a stream of southeasterly winds near the ground. That shear produces horizontal vorticity which can be tilted into the vertical by the updraft of the cumulonimbus cloud.

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The Supercell, the Producer of the Strongest Tornadoes: Part 2

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The Entire Supercell Rotates

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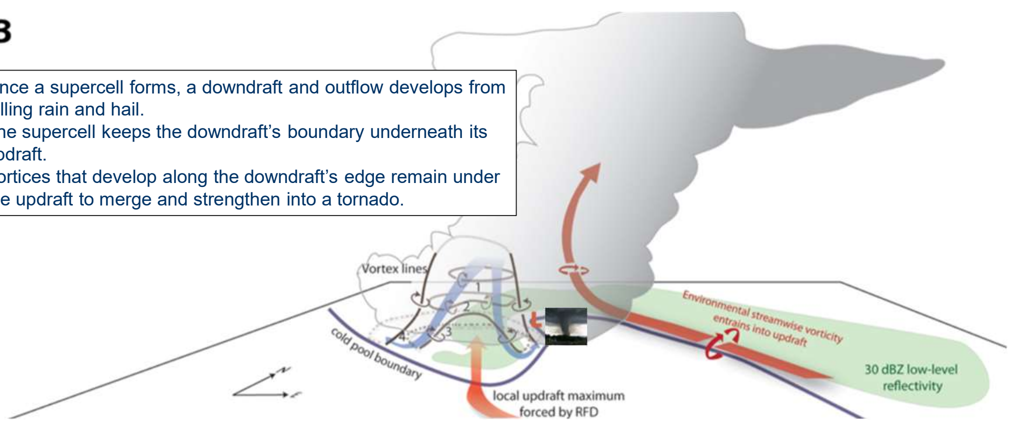
Mesocyclonic Tornado Formation: The Downdraft and Outflow

B

1. Once a supercell forms, a downdraft and outflow develops from falling rain and hail.
2. The supercell keeps the downdraft's boundary underneath its updraft.
3. Vortices that develop along the downdraft's edge remain under the updraft to merge and strengthen into a tornado.



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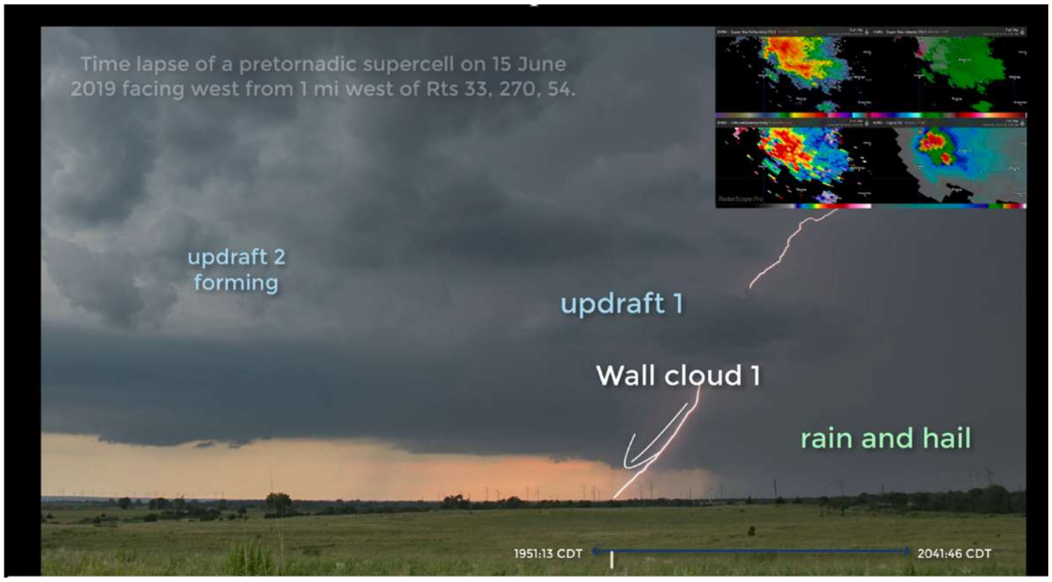
Example of a Supercell as it Becomes Tornadic



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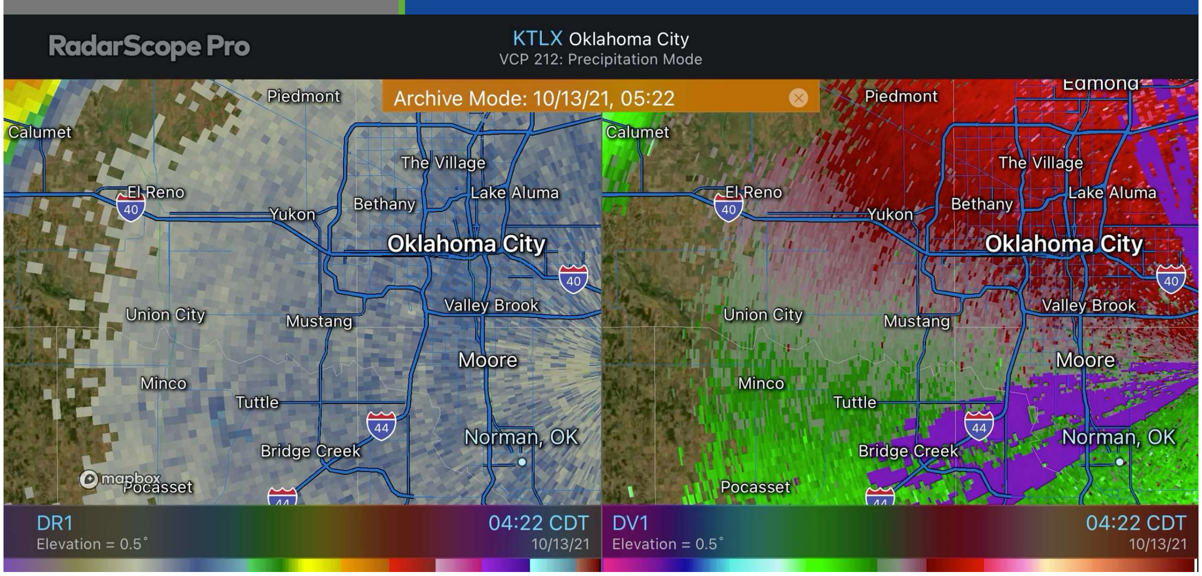
Squall Lines Also Produce Tornadoes



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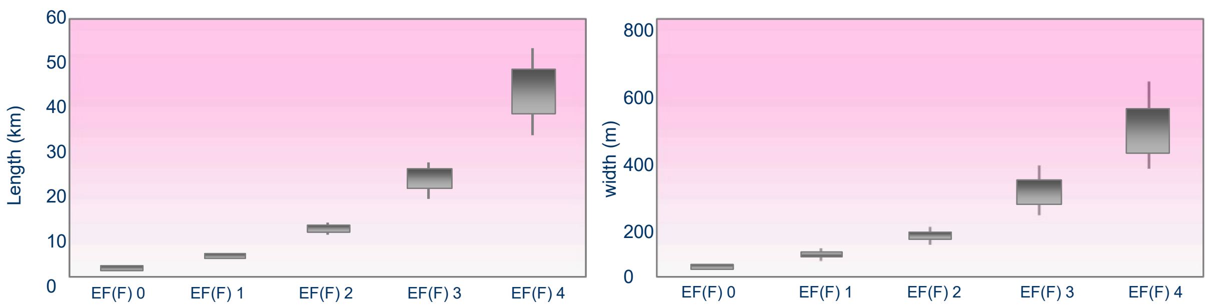
Tornado Paths versus Tornado Strength



After Brooks (2004)
https://doi.org/10.1175/1520-0434(2004)019<0310:OTROTP>2.0.CO;2

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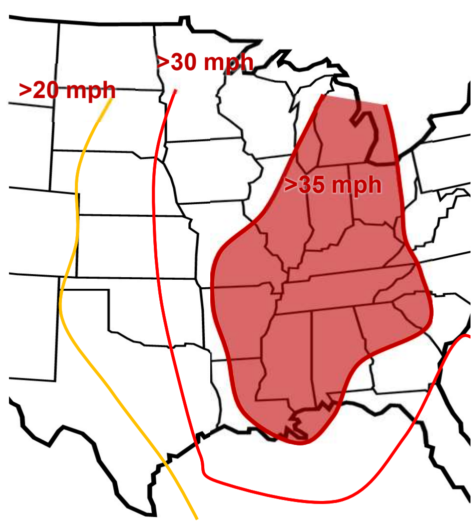
Tornado Translational Speeds

- Typical tornado speeds 20-40 mph
- But the range is from 0 to >70 mph
- Higher speeds from the MS valley east.
- Slowest speeds in the high Plains.



Modified from Strader and co-authors
https://doi.org/10.1175/WCAS-D-20-0107.1

Presentation at
https://youtu.be/_cTC3LXa_I0?t=990

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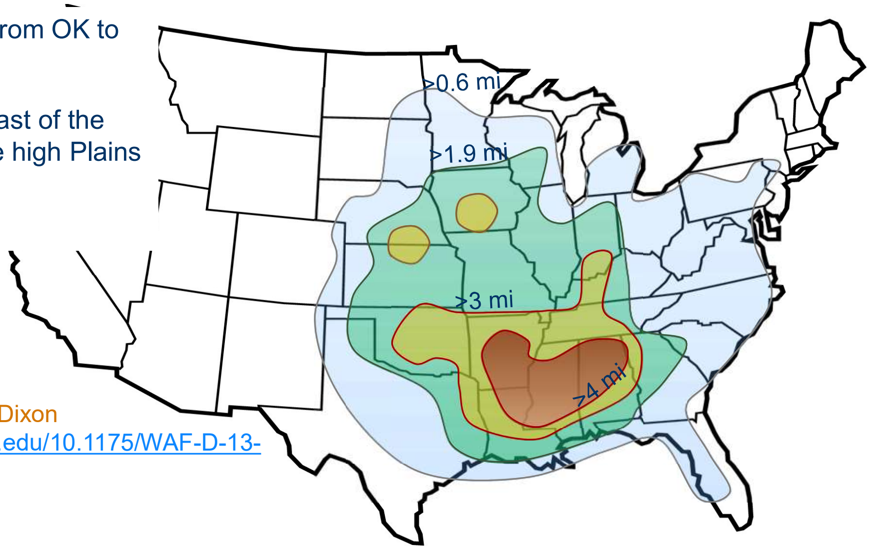
Average Path Length for Strong Tornadoes

- Longer path lengths from OK to AL.
- Lower path lengths east of the Appalachians and the high Plains westward.



Modified from Coleman and Dixon
https://doi-org.ezproxy.lib.ou.edu/10.1175/WAF-D-13-00057.1

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Tornado Structure

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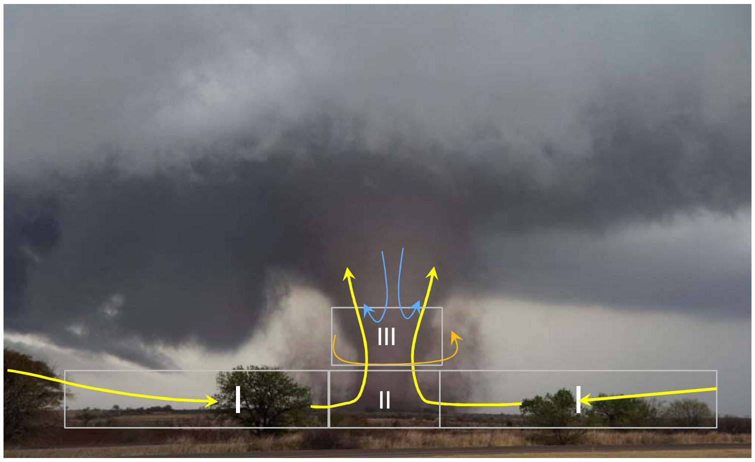
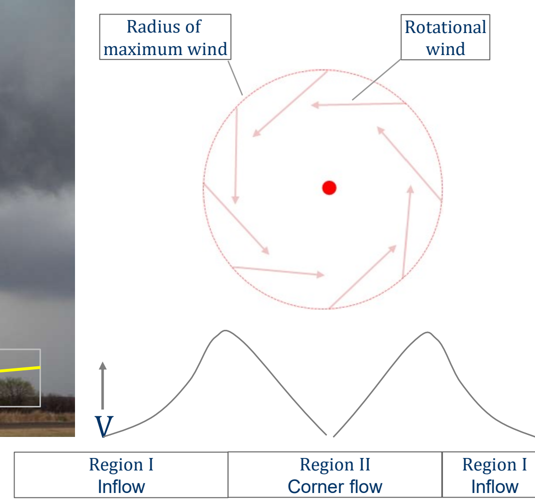
Wind Pattern of a Stationary Tornado





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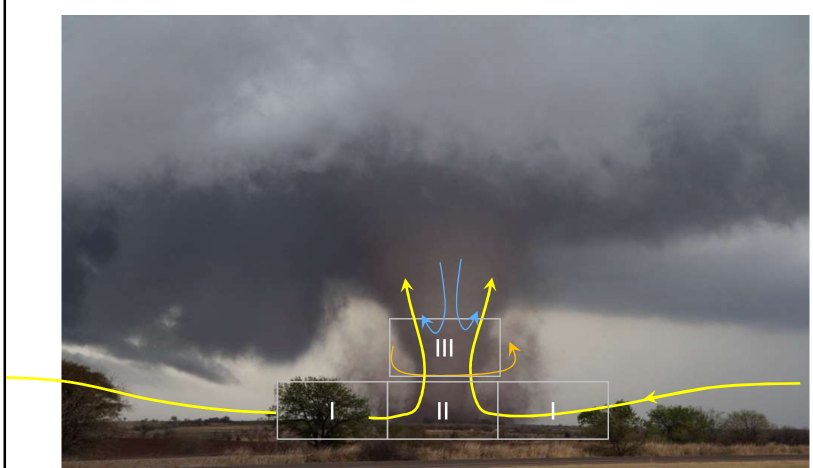
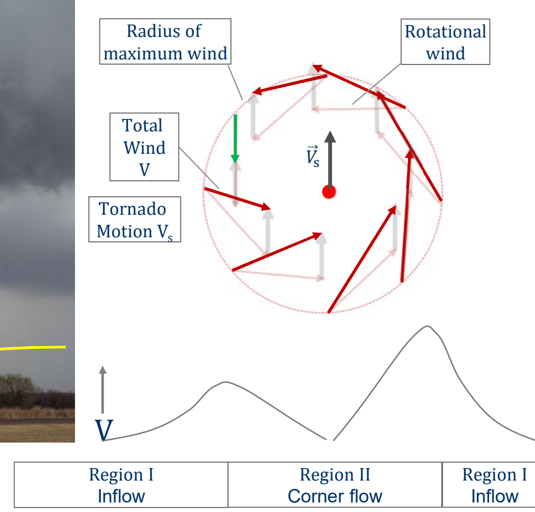
Wind Pattern of a Moving Tornado





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Damage Path Characteristics

A. Rochelle, IL
2015-04-09
EF3

B. Joplin, MO
2011-05-22
EF4

C. Haleyville, AL
2011-04-27
EF1

Aerial imagery from NOAA

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Tornadoes Can Be More Complex

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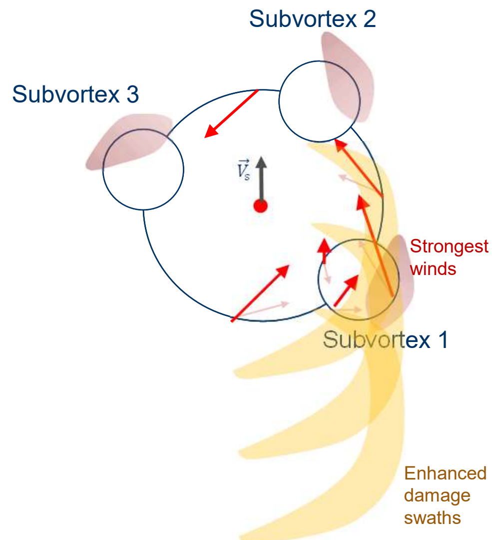
Tornado Structure – Multi Vortex



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Summary: Tornado Characteristics

- Tornado Types
  - Nonmesocyclonic tornadoes
  - Mesocyclonic tornadoes (from supercells)
  - Squall line tornadoes
- Tornado formation
  - Need a parent updraft from a thunderstorm.
  - Nonmesocyclonic tornadoes form as the thunderstorm draws up a pool of pre-existing low-level vorticity.
  - Mesocyclonic and Squall line tornadoes form as the parent thunderstorm generates its own low-level vorticity and then draws from it.
- Tornado track characteristics
  - Strong tornadoes produce longer and wider tracks than weaker tornadoes.
  - Tornado speed tends to be highest in the eastern US and lowest in the high Plains.
  - Strong tornadoes in the southeastern US produce the longest path lengths.
- Tornado structures
  - Region I has accelerating inflow with higher winds closer to the ground than normal.
  - Region II is the corner flow where the inflow abruptly turns upward and damage is at its worst.
  - Region III is where the tornado exhibits more pure rotation
  - Moving tornadoes produce the strongest winds on their right sides.
  - Tornado damage paths are typically long and narrow with converging damage pattern.
  - Multi-vortex tornadoes consist of more than one subvortex rotating around the main tornado and produce complex damage patterns.

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Tornado Meteorology

Questions / Discussion

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Tornadic Winds and the EF Scale

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Measuring Tornadic Winds

- Direct measurements of tornado winds are infrequent
  - Doppler radar
  - Anemometry
- Most tornado speeds are estimated from damage using the Enhanced Fujita (EF) Scale
- Other less common methods include
  - Photogrammetry
  - Forensic engineering
  - Treefall pattern analysis

The strongest measured wind speed in a tornado was 318 mph on May 3, 1999 near Bridge Creek/Moore, Oklahoma, measured by mobile Doppler radar. (source: NSSL)

Source: NWS

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Fujita Scale (F Scale)

- Dr. Ted Fujita
  - Mechanical engineering undergraduate degree, later completed a doctoral degree in meteorology
  - First researcher to conduct extensive scientific study of tornadoes
    - Also credited with discovering downbursts/microbursts

PBS Documentary on his life and work – *Mr. Tornado: One Man's Pursuit to Understand the Deadliest Storms*
https://www.pbs.org/wgbh/americanexperience/films/mr-tornado/

- Developed the eponymous Fujita Scale for rating tornado damage intensity
  - Wind speed ranges are estimated, based on the extent of observed damage
  - Introduced in 1971 and subsequently adopted by the National Weather Service

F Scale	Character	Estimated winds	Description
Zero (F0)	Weak	40-72 mph	**Light Damage.** Some damage to chimneys; branches broken off trees, shallow-rooted trees uprooted, sign boards damaged.
One (F1)	Weak	73-112 mph	**Moderate damage.** Roof surfaces peeled off; mobile homes pushed foundations or overturned; moving autos pushed off road.
Two (F2)	Strong	113-157 mph	**Considerable damage.** Roofs torn from frame houses; mobile homes demolished; boxcars pushed over; large trees snapped or uprooted; light objects become projectiles.
Three (F3)	Strong	158-206 mph	**Severe damage.** Roofs and some walls torn from well- constructed houses; trains overturned; most trees in forested area uprooted; heavy cars lifted and thrown.
Four (F4)	Violent	207-260 mph	**Devastating damage.** Well- constructed houses leveled; structures with weak foundation blown some distance; cars thrown; large missiles generated.
Five (F5)	Violent	260-318 mph	**Incredible damage.** Strong frame houses lifted off foundations, carried considerable distances, and disintegrated; auto-sized missiles airborne for several hundred feet or more; trees debarked.

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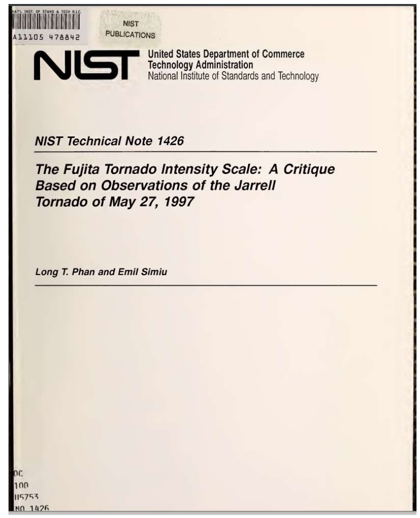
Challenges with the F Scale

- NIST study of the 1997 tornado in Jarrell, Texas showed the buildings could be destroyed by much less intense winds than those estimated by the F scale
  - No consideration of variations in construction and design speeds for buildings
  - Tornado was rated as F5
  - Engineering assessment indicated that wind speeds of F3 intensity could have caused the observed destruction to the houses in Jarrell


NIST PUBLICATIONS

NIST United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

NIST Technical Note 1426

The Fujita Tornado Intensity Scale: A Critique Based on Observations of the Jarrell Tornado of May 27, 1997

Long T. Phan and Emil Simiu

https://nvlpubs.nist.gov/nistpubs/Legacy/TN/nbstechnicalnote1426.pdf

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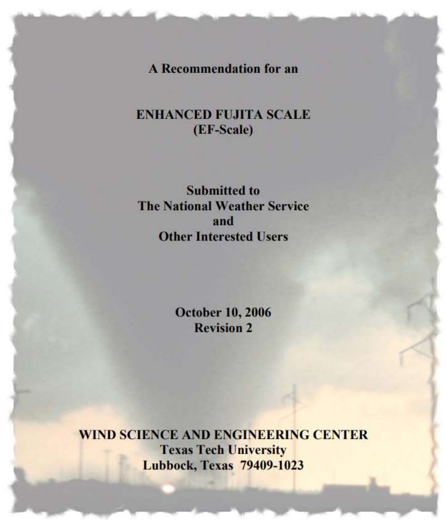
Enhanced Fujita (EF) Scale: Part 1

- Development led by Texas Tech University
  - Funded by NIST
  - In collaboration with the National Weather Service (NWS)
- Formalization and recalibration of the F scale
- Explicit Damage Indicators (DIs)
  - Common building and structure types
  - Trees
- Each DI has unique Degrees of Damage (DODs) and associated wind speed estimates
- Wind speed estimates developed through Expert Elicitation



https://www.spc.noaa.gov/efscale/ef-ttu.pdf

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Enhanced Fujita (EF) Scale: Part 2

- Tornado wind speeds are estimated from observed damage using the Enhanced Fujita (EF) Scale
- 28 Damage Indicators
  - 23 building types
  - 3 tower/pole types
  - 2 tree types
- Adopted by NWS in February 2007

EF Rating	Wind Speeds	Expected Damage
EF-0	65-85 mph	'Minor' damage: shingles blown off or parts of a roof peeled off, damage to gutters/siding, branches broken off trees, shallow rooted trees toppled.
EF-1	86-110 mph	'Moderate' damage: more significant roof damage, windows broken, exterior doors damaged or lost, mobile homes overturned or badly damaged.
EF-2	111-135 mph	'Considerable' damage: roofs torn off well constructed homes, homes shifted off their foundation, mobile homes completely destroyed, large trees snapped or uprooted, cars can be tossed.
EF-3	136-165 mph	'Severe' damage: entire stories of well constructed homes destroyed, significant damage done to large buildings, homes with weak foundations can be blown away, trees begin to lose their bark.
EF-4	166-200 mph	'Extreme' damage: Well constructed homes are leveled, cars are thrown significant distances, top story exterior walls of masonry buildings would likely collapse.
EF-5	> 200 mph	'Massive/incredible' damage: Well constructed homes are swept away, steel-reinforced concrete structures are critically damaged, high-rise buildings sustain severe structural damage, trees are usually completely debarked, stripped of branches and snapped.

Source: NWS

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Enhanced Fujita Scale Damage Indicators

NUMBER (Details Linked)	DAMAGE INDICATOR	ABBREVIATION
1	Small barns, farm outbuildings	SBO
2	One- or two-family residences	FR12
3	Single-wide mobile home (MHSW)	MHSW
4	Double-wide mobile home	MHDW
5	Apt, condo, townhouse (3 stories or less)	ACT
6	Motel	M
7	Masonry apt. or motel	MAM
8	Small retail bldg. (fast food)	SRB
9	Small professional (doctor office, branch bank)	SPB
10	Strip mall	SM
11	Large shopping mall	LSM
12	Large, isolated ("big box") retail bldg.	LIRB
13	Automobile showroom	ASR
14	Automotive service building	ASB
15	School - 1-story elementary (interior or exterior halls)	ES
16	School - jr. or sr. high school	JHSH
17	Low-rise (1-4 story) bldg.	LRB
18	Mid-rise (5-20 story) bldg.	MRB
19	High-rise (over 20 stories)	HRB
20	Institutional bldg. (hospital, govt. or university)	IB
21	Metal building system	MBS
22	Service station canopy	SSC
23	Warehouse (tilt-up walls or heavy timber)	WHB
24	Transmission line tower	TLT
25	Free-standing tower	FST
26	Free standing pole (light, flag, luminary)	FSP
27	Tree - hardwood	TH
28	Tree - softwood	TS

https://www.spc.noaa.gov/efscale/ef-scale.html

Note – DI descriptions and graphics on following slides are from links on this NOAA EF Scale web page

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DI 2: One- or two-family residences (FR12)

- One and Two Family Residence
  - Most commonly used *building* DI
  - Most commonly used of all DIs for rating intense tornadoes
- EXP: Expected – traditional construction
- LB: Lower Bound – accounts for weak construction
- UB: Upper Bound – accounts for strong construction
- Wind speeds in mph

2. ONE-AND TWO-FAMILY RESIDENCES (FR12)
(1000 – 5000 sq. ft.)

Typical Construction

- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard or mono-sloped roof or combinations thereof
- Plywood/OSB or wood plank roof deck
- Prefabricated wood trusses or wood joist and rafter construction
- Brick veneer, wood panels, stucco, EIFS, vinyl or metal siding
- Wood or metal stud walls, concrete blocks or insulating-concrete panels
- Attached single or double garage

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

* DOD is degree of damage

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Degrees of Damage

- DODs rank ordered
  - DOD 1 is lowest wind speed
  - DOD 10 is greatest wind speed
- DIs can and do have different numbers of DODs

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FR12 DOD Guidance

FR12: DOD 2: Loss of roof covering (<20%)

FR12: DOD 6: Large sections of roof removed; most walls remain standing

FR12: DOD 10: Total destruction of entire building

FR12: DOD 4: Uplift of roof deck and loss of roof covering (>20%); garage door collapses outward

FR12: DOD 7: Top floor (First floor in this case) exterior walls collapsed

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Assigning a Tornado Rating Using the EF Scale

- The NWS is the only federal agency with authority to provide 'official' tornado EF Scale ratings.
- The goal is to assign an EF Scale category based on the highest wind speed that occurred within the damage path.
- First, trained NWS personnel will identify the appropriate damage indicator (DI) from more than one of the 28 used in rating the damage.
- The construction or description of a building should match the DI being considered, and the observed damage should match one of the degrees of damage (DOD) used by the scale.
- The tornado evaluator will then make a judgment within the range of upper and lower bound wind speeds, as to whether the wind speed to cause the damage is higher or lower than the expected value for the particular DOD.
- This is done for several structures not just one, before a final EF rating is determined

Source: National Weather Service

https://www.weather.gov/oun/efscale#:~:text=The%20Enhanced%20Fujita%20Scale%20or,wind%20speeds%20and%20related%20damage.&text=From%20that%2C%20a%20rating%20(from,EF0%20to%20EF5)%20is%20assigned.

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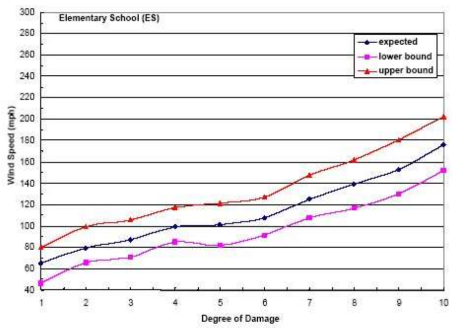
DI 15: Elementary School (ES)

- Elementary School DI
  - Common institutional building DI
  - Can also use for non-elementary school buildings with similar construction

General Description
- These buildings are typically single story with flat roofs
- Building may contain a small gym or cafeteria with moderately long spans between supports
- Buildings have long interior hallways with bearing or non-bearing walls
- BUR, single-ply membrane, or metal standing seam roof panels
- Metal or plywood roof decking supporting a light-weight poured gypsum deck
- Roof structure consists of open web steel joists bearing on exterior walls and steel interior girders
- Exterior non-bearing walls constructed with CMUs, glass curtain walls or metal studs with brick veneer, stucco, or EIFS cladding
- CMU bearing walls with brick veneer, stucco, or EIFS cladding
- Walls can have a large percentage of window glass



DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	47	80
2	Loss of roof covering (<20%)	79	66	99
3	Broken windows	87	71	106
4	Exterior door failures	99	85	118
5	Uplift of some roof decking; significant loss of roofing material (>20%); loss of rooftop HVAC	101	82	121
6	Damage to or loss of wall cladding	108	92	127
7	Uplift or collapse of roof structure	125	108	148
8	Collapse of non-bearing walls	139	117	162
9	Collapse of load-bearing walls	153	130	180
10	Total destruction of a large section of building or entire building	176	152	203

* Degree of Damage

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ES DOD Guidance

ES: Single story with flat roof; built-up roofing with gravel; brick veneer; large percentage of window glass; long interior hallways; load-bearing walls

ES: DOD 5: Significant loss of roofing material (>20%); uplift of roof decking

ES: DOD 9: Collapse of load-bearing walls

ES: DOD 5: Significant loss of roofing material (>20%); uplift of roof decking

ES: DOD 8: Uplift of entire roof structure and collapse of non-bearing walls

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EF Scale Wind Speed Estimation - Example

- The elementary school shown was struck by a tornado
- Description: The building was constructed in 2005 using with reinforced concrete masonry unit perimeter walls laterally braced by a metal roof system that consisted of wide-rib metal roof decks covered with rigid thermal insulation and supported by open-web steel roof joists

1. Determine the appropriate DI
2. Determine the DOD which best describes the damage
3. Determine the associated estimated wind speed

Source: NIST

Source: NIST

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EF Scale Wind Speed Estimation - Example

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10	Total destruction of a large section of building or entire building	176	152	203

* Degree of Damage

Source: NIST

- DI: Elementary School (ES)
- DOD: 10 – total destruction of a large section of the building or entire building
- Estimated wind speed: 176 mph

50

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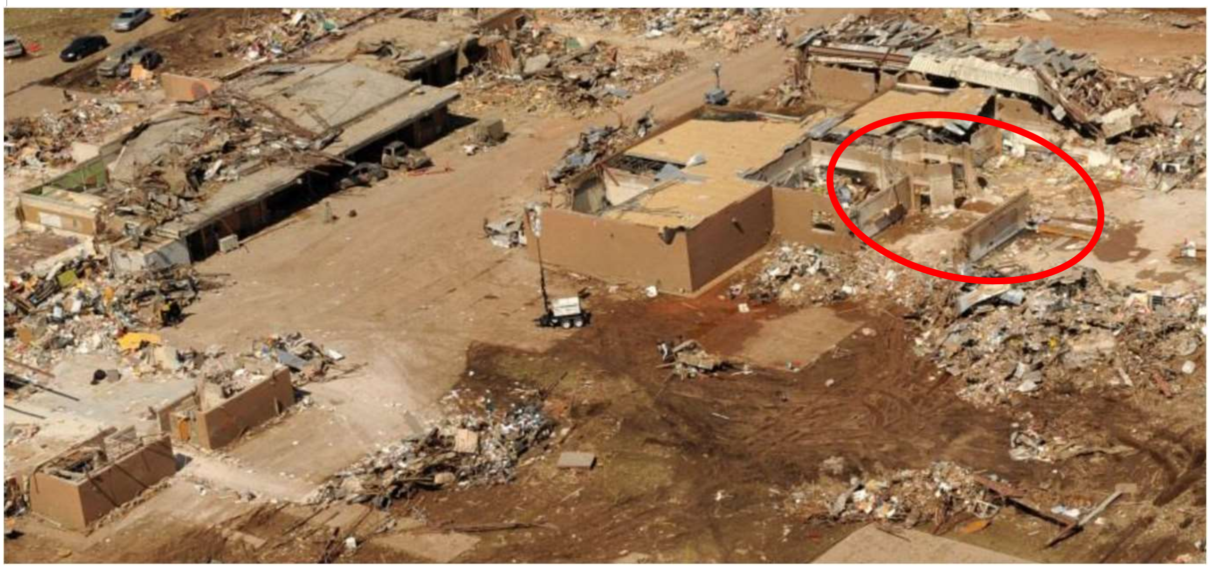
Plaza Towers Elementary School

Newcastle-Moore, Tornado, May 20, 2013



Source: NOAA

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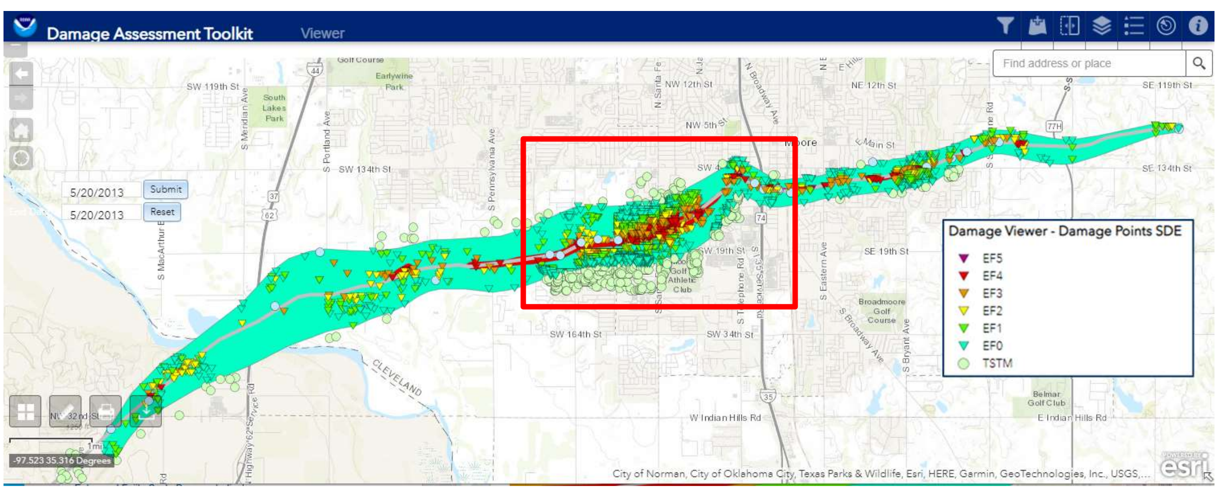
Newcastle-Moore, OK Tornado



https://apps.dat.noaa.gov/stormdamage/damageviewer/

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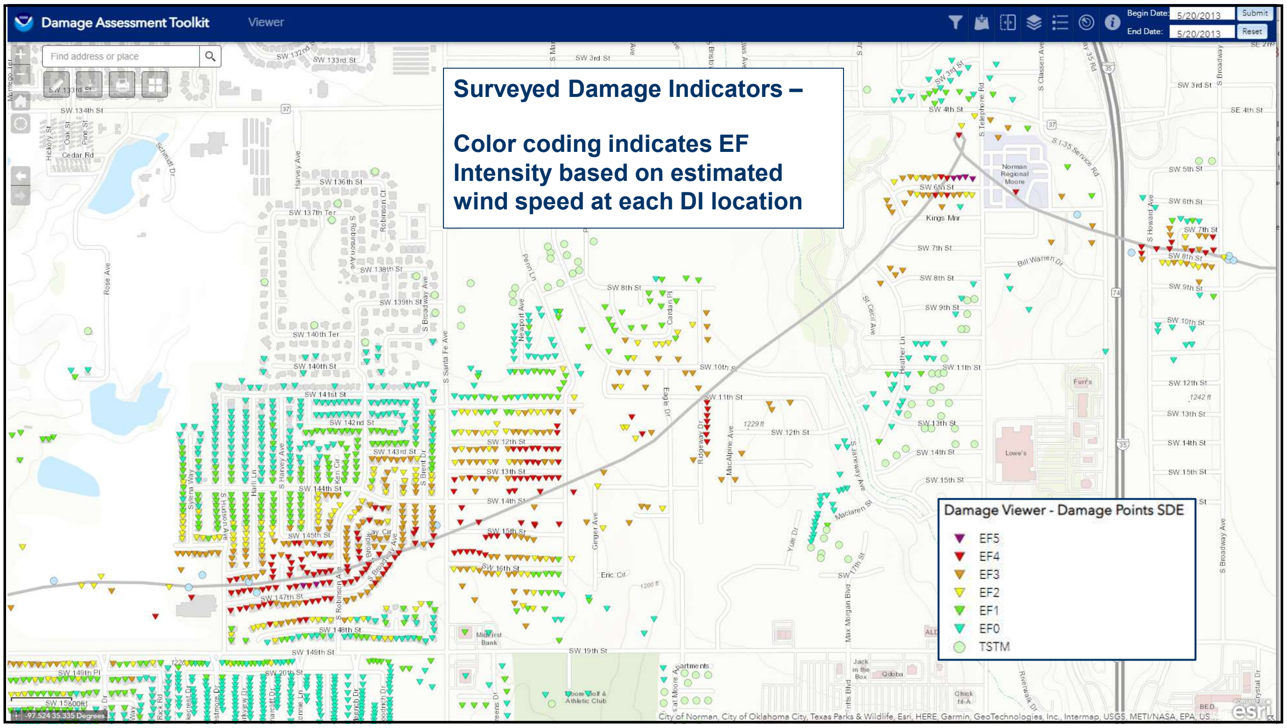
Damage Assessment Toolkit
Viewer
Surveyed Damage Indicators –
Color coding indicates EF Intensity based on estimated wind speed at each DI location
Damage Viewer - Damage Points SDE
EF5
EF4
EF3
EF2
EF1
EF0
TSTM

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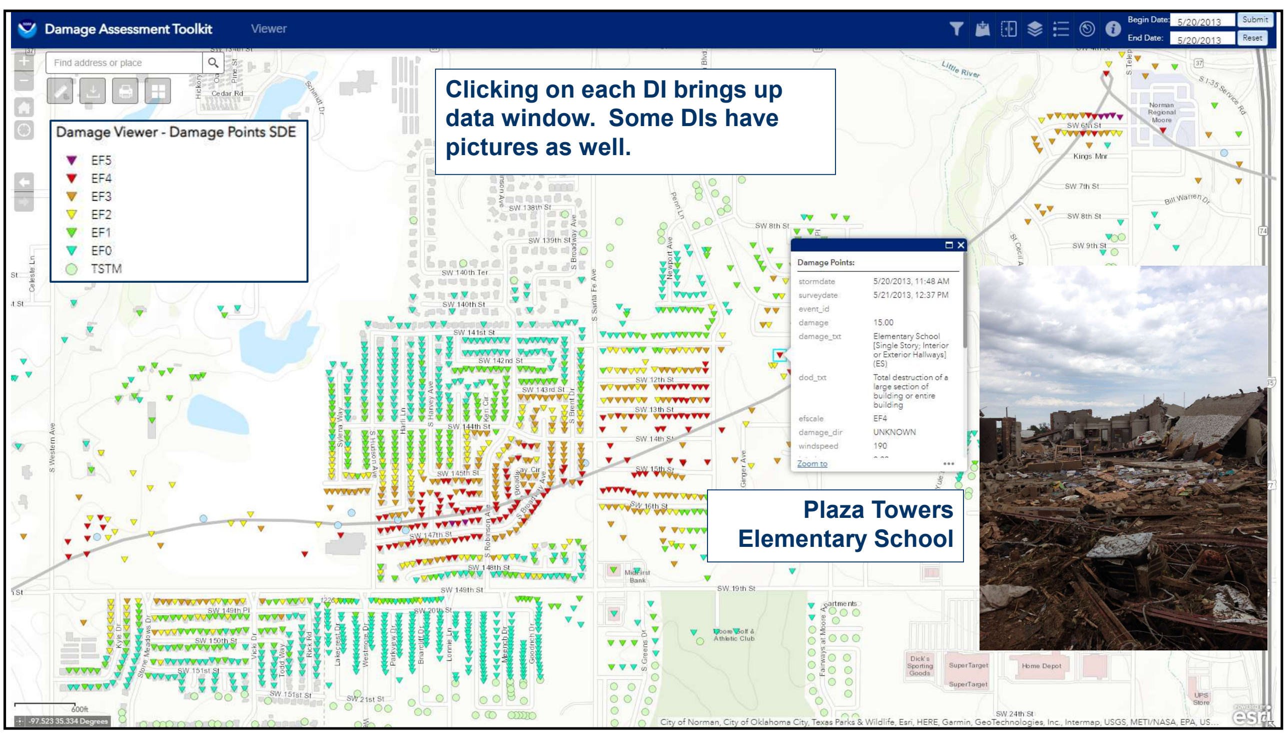
Damage Assessment Toolkit
Viewer
Clicking on each DI brings up data window. Some DIs have pictures as well.
Damage Viewer - Damage Points SDE
EF5
EF4
EF3
EF2
EF1
EF0
TSTM
Plaza Towers Elementary School

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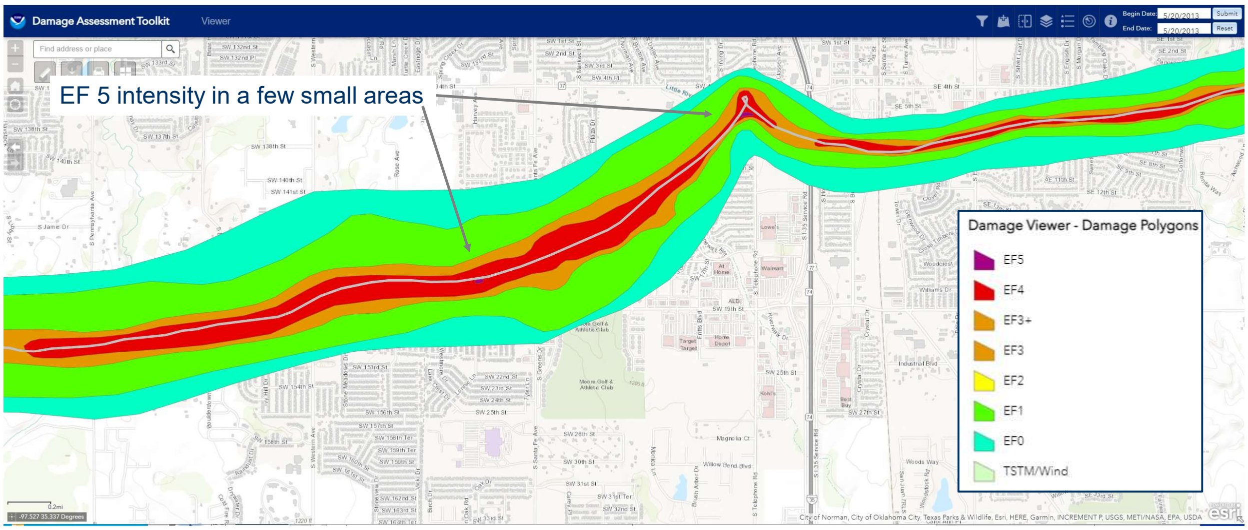
Path Length & Width Intensity Variation



May 20, 2013 Moore, OK Tornado

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Moore, OK Tornadoes: Part 1

Four Violent tornadoes in the span of 15 years

Moore, Oklahoma Tornadoes (1890-Present)

Weather.gov > Norman, OK > Moore, Oklahoma Tornadoes (1890-Present)

Norman, OK
Weather Forecast Office

Current Hazards | Current Conditions | Radar | Forecasts | Rivers and Lakes | Climate and Past Weather | Local Programs

SPC ID #	Date	Time (CST)	Path Length (miles)	Path Width (yards)	F-Scale	Killed	Injured	County	Path
	04/25/1893	1645				0	0	Cleveland	3.5 E "Case" (~15 E Moore)
	04/25/1893	1830	45			31	many	Cleveland/ Pottawatomie	SW of Moore - near "Case" (12 E Moore)
37-1	06/09/1937	1630	35	320		4	7	Canadian/ Cleveland	W of Union City - SE of Mustang - near Moore (possibly series)
51-3	04/05/1951	1320	6	127	F2	0	0	Cleveland	NW of Norman (near Newcastle) - NW of Moore
60-24	04/28/1960	2058	8	500	F2	0	0	Cleveland	W and N of Moore
60-25	04/28/1960	2105	4	400	F2	0	6	Cleveland	Moore
60-70	05/19/1960	1625	n/a	n/a	F2	0	0	Cleveland	Moore
61-43	05/06/1961	2350	n/a	n/a	F?	0	0	Cleveland	Between Moore and Norman
61-44	05/07/1961	0045	n/a	n/a	F?	0	0	Cleveland	Near Moore
65-68	08/31/1965	1415	12	50	F0	0	0	Oklahoma/ Cleveland	Near SW 80th/May - NW Corner of Moore - SE Oklahoma City
73-69	11/19/1973	1930	24	500	F3	5	46	McClain/ Cleveland/ Oklahoma	Blanchard - Moore - Del City - SE Oklahoma City
74-40	08/01/1974	1540	1.0	50	F1	0	0	Cleveland	Moore (near NW 2nd/Santa Fe)
75-12	05/13/1975	1515	2	50	F2	0	0	Cleveland	OKC (southeast of SW 89th/ Western) - N Moore
91-43	05/02/1991	1920	0.5	30	F1	0	0	Cleveland	Moore
	10/04/1998	1934	3	580	F2	0	0	Cleveland	Moore
	05/03/1999	1726	38	1760	F5	36	583	Grady/ McClain/ Cleveland/ Oklahoma	2 SSW Amber - far N Newcastle - SW Oklahoma City - N Moore - S Del City - W Midwest City
	05/08/2003	1610	17	700	F4	0	134	Cleveland/ Oklahoma	Moore - OKC (SE) - Midwest City (SE) - Choctaw (~1/2 mile N of SW 134th and Santa Fe to 1/2 mile ESE of Reno and Choctaw)
	06/09/2004	1635	0.3	20	F0	0	0	Cleveland	8 E Moore (SE edge of Lake Draper. near SE 140th between Westminster and E Stanley Draper Drive)
	05/10/2010	1620	24	2000	EF4	2	49	Cleveland/ Oklahoma	Far north Norman (near Santa Fe/ Indian Hill Road) - south Moore - Lake Draper - I-40/Choctaw - 1.5 SSE Harrah
	05/10/2010	1622	4	250	EF1	0	0	Cleveland	South and east Moore (near Broadway/Eastern - NE of SE 119th/Sunnylane)
	05/10/2010	1627	0.5	50	EF1	0	0	Cleveland	Far southeast Moore (near SE 34th St./Sooner Road)
	05/20/2013	1356-1435	14	1900	EF5	24	212	McClain/ Cleveland	Newcastle (3 NW US-277/SH-130) - 4.8 E Moore
	03/25/2015	1734-1750	11	50	EF2	0	7	Cleveland	4.5 WNW - 7 SE Moore

Records taken from the Storm Prediction Center archive data, "Storm Data", and data from the National Weather Service office in Norman. Data modified as described in NOAA Tech Memo NWS SR-209 (Speheger, D., 2001: "Corrections to the Historic Tornado Database").

Historic data, especially before 1950, are likely incomplete.

Source: NOAA/NWS

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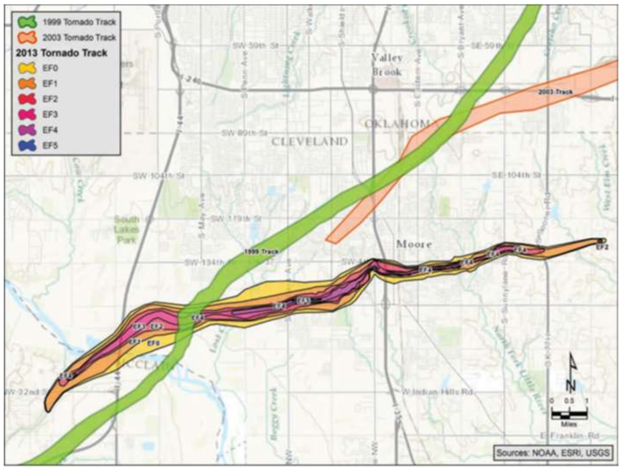
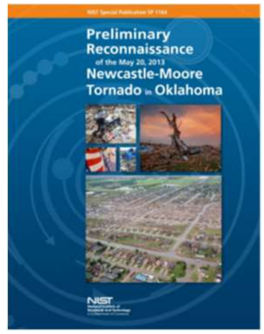
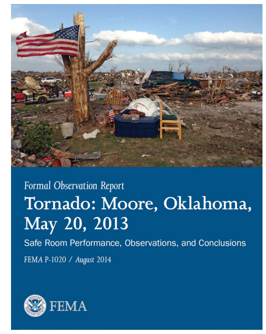
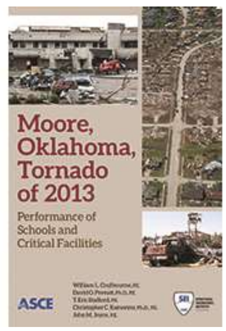
Moore, OK Tornadoes: Part 2

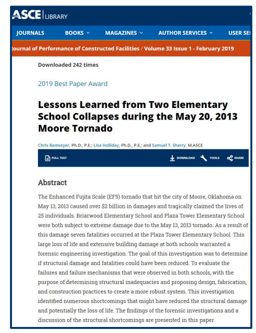


Source: FEMA









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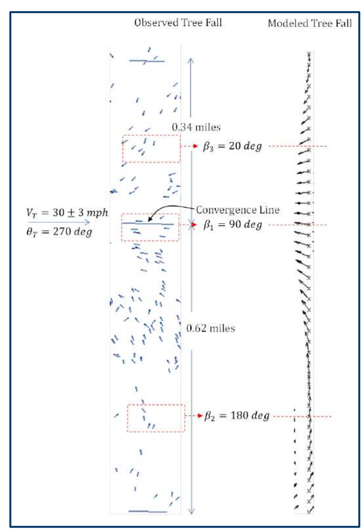
Potential Changes to the EF Scale: Part 1

New standard under development:
Wind Speed Estimation in Tornadoes and Other Windstorms

- Joint ASCE/SEI/AMS standard (AMS=American Meteorological Society)
- Scope includes several methods
  - Radar
  - In-situ
  - **EF Scale**
  - Forensic Engineering
  - Treefall Pattern and Forest Damage
- Development began in 2015, public comment draft anticipated by 2024-2025

Source: NSSL

Source: NCEI



Source: NIST

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Potential Changes to the EF Scale: Part 2

Anticipated EF Scale Updates

- More explicit guidance on construction type/quality/condition
  - EXP, UB and LB replaced with
    Typical, Stronger than Typical, Weaker than Typical
- Significantly revised DIs
  - FR12 split into wood frame and masonry
  - Trees combined into a single DI
- Potential new DIs such as
  - Heritage churches
  - Center-pivot irrigation systems
  - Grain bins and silos
  - Multi-tree
  - Alternate for Residential - Smart DI

Source: NCEI

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Tornado Wind Speed Estimate Problem

Practice Your Knowledge

Estimate the tornado speed required to cause the damage shown

1. Use the EF Scale Manufactured Homes-Single Wide (MHSW) Damage Indicator and determine the Degree of Damage (DOD) that best fits the observed conditions. DOD = ____
2. Select best estimate for the wind speed ____ mph

Source: NOAA/NWS/SPC

3. MANUFACTURED HOMES – SINGLE WIDE (MHSW)

Typical Construction

- Steel undercarriage supported on concrete block piers
- Metal straps and ground anchors (Frame and/or over-the-top strap anchors
- Asphalt shingles or one-piece metal roof covering
- Wood roof joists
- Metal, vinyl, or wood siding
- Wood roof joists
- Wood stud walls and partitions
- Better construction in post 1974 models in coastal areas

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	61	51	76
2	Loss of shingles or partial uplift of one-piece metal roof covering	74	61	92
3	Unit slides off block piers but remains upright	87	72	103
4	Complete uplift of roof; most walls remain standing	89	73	112
5	Unit rolls on its side or upside down; remains essentially intact	98	84	114
6	Destruction of roof and walls leaving floor and undercarriage in place	105	87	123
7	Unit rolls or vaults; roof and walls separate from floor and undercarriage	109	96	128
8	Undercarriage separates from unit; rolls, tumbles and is badly bent	118	101	136
9	Complete destruction of unit; debris blown away	127	110	148

* Degree of Damage

https://www.spc.noaa.gov/efscale/ef-scale.html

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Tornadic Winds and the EF Scale

Questions / Discussion

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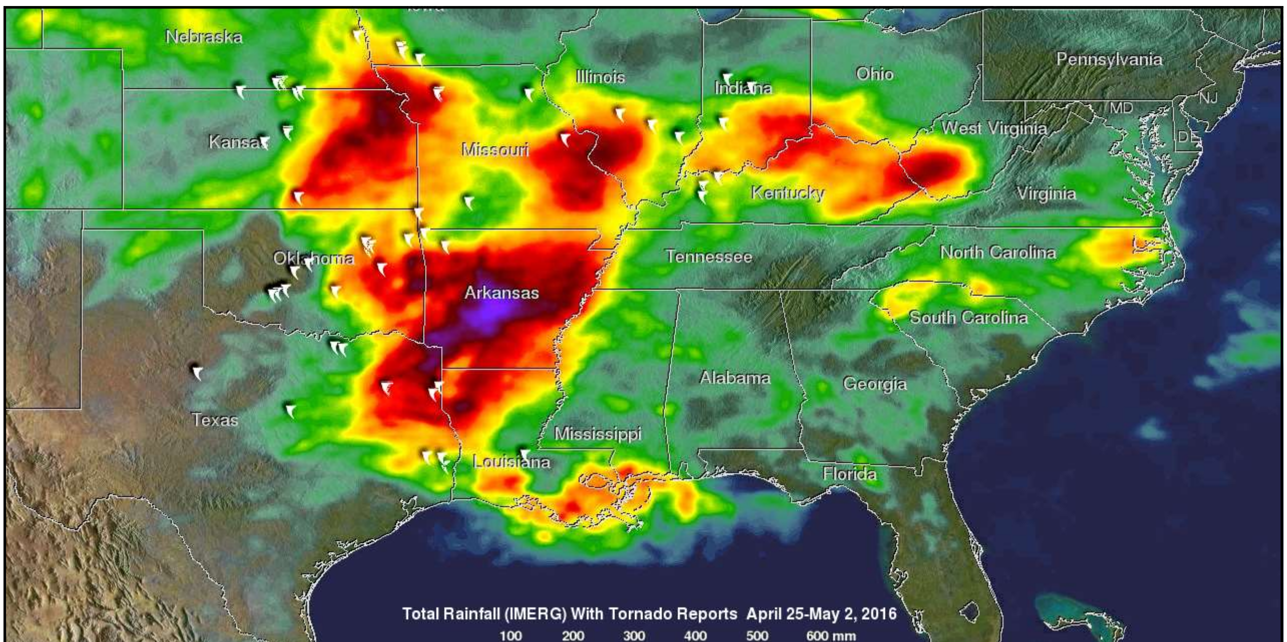

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Tornado Climatology

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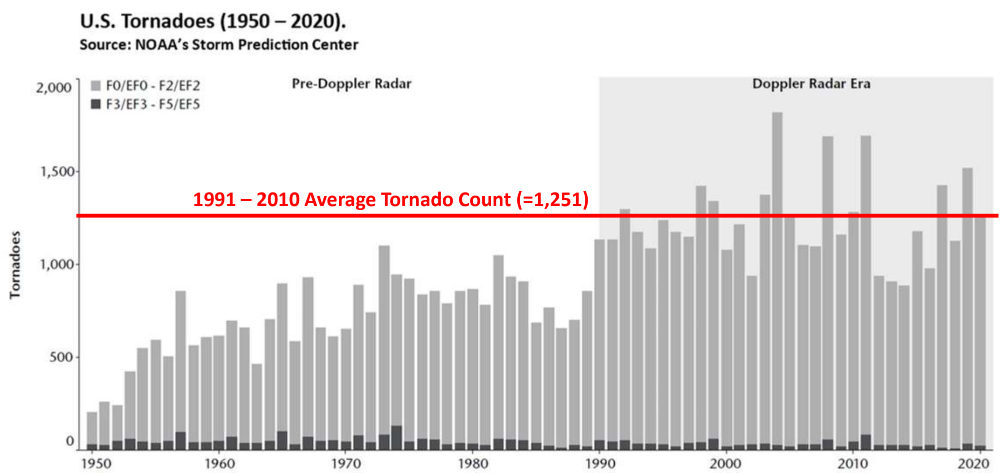
How Frequently do Tornadoes Occur?



This plot shows the number of *reported* tornadoes per year. Many more tornadoes go unreported.

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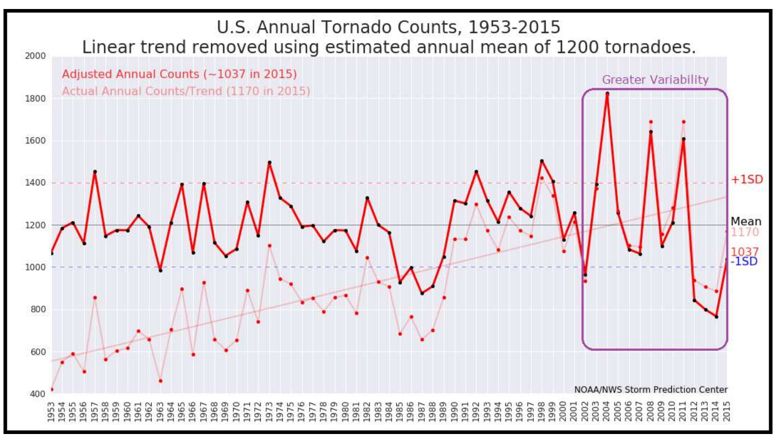
Are Tornadoes Becoming More Frequent?

- Tornado *reports* have increased
  - Mainly more weak (EF0-EF1) tornadoes
- Causes for increase
  - better detection, esp. after installation of NEXRAD Doppler radar system in the mid 1990s
  - greater media coverage
  - aggressive warning verification efforts
  - storm spotting
  - storm chasing
  - developmental sprawl (damage targets)
  - more people
  - better documentation incl. cell phones



Source: NOAA/NWS/SPC

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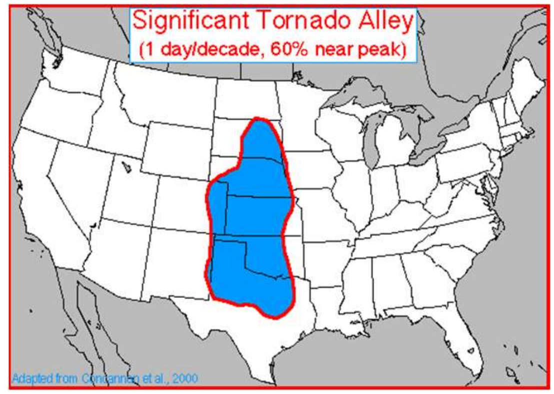
Where do Tornadoes Occur? Part 1

- Tornadoes occur on all continents except Antarctica
  - Most frequent and strongest are in North America, and US in particular
- Tornadoes occur in all 50 states
- Tornado Alley is a nickname in the popular media for a broad swath of relatively high tornado occurrence in the central U. S.
  - Outdated concept
  - No standardized definition
  - One of many maps of tornado alley shown at right



Source: NOAA/NWS/SPC

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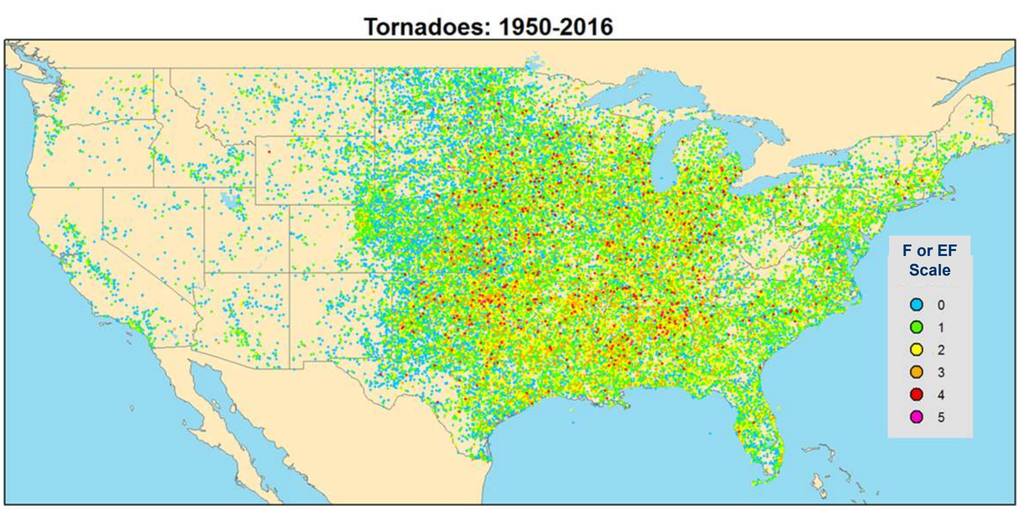
Where do Tornadoes Occur? Part 2



Source: NIST, from NOAA data

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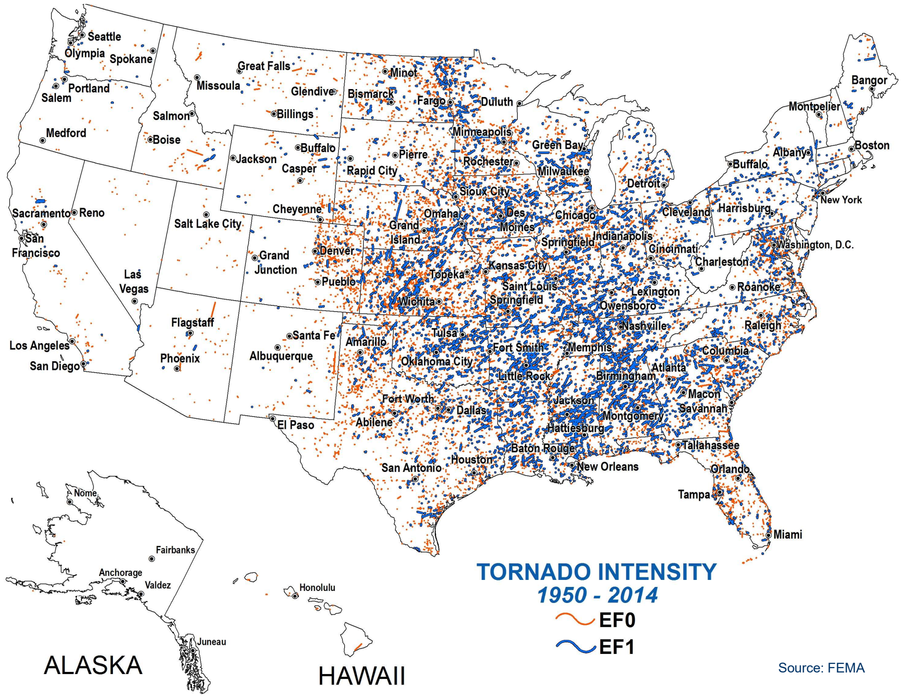
Weak Tornadoes (EF0 – EF1)



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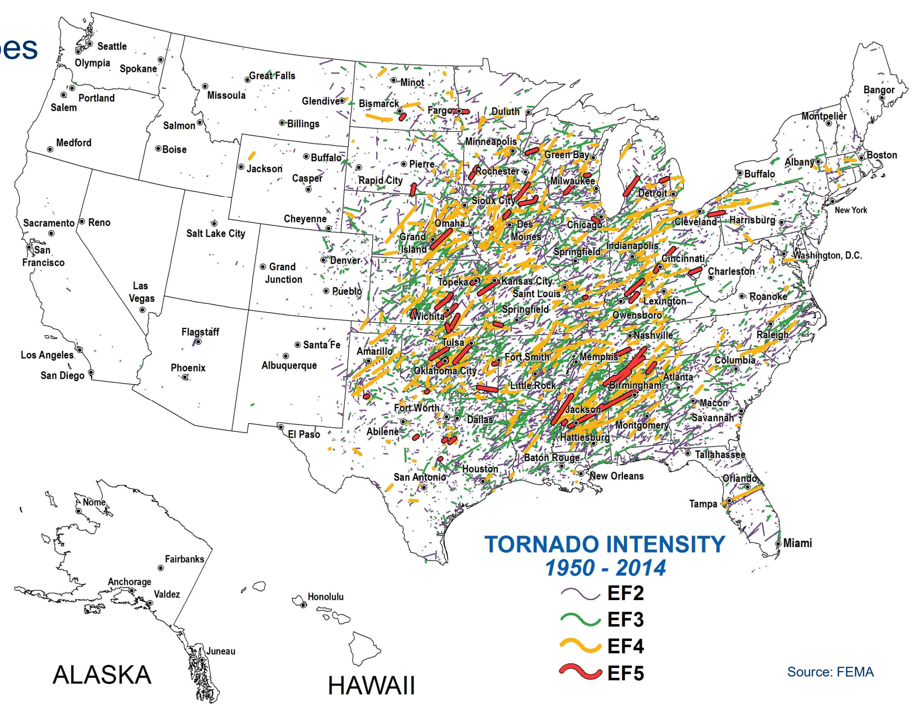
Significant Tornadoes

Includes:

- Strong (EF2-EF3) &
- Violent (EF4-EF5)

tornadoes



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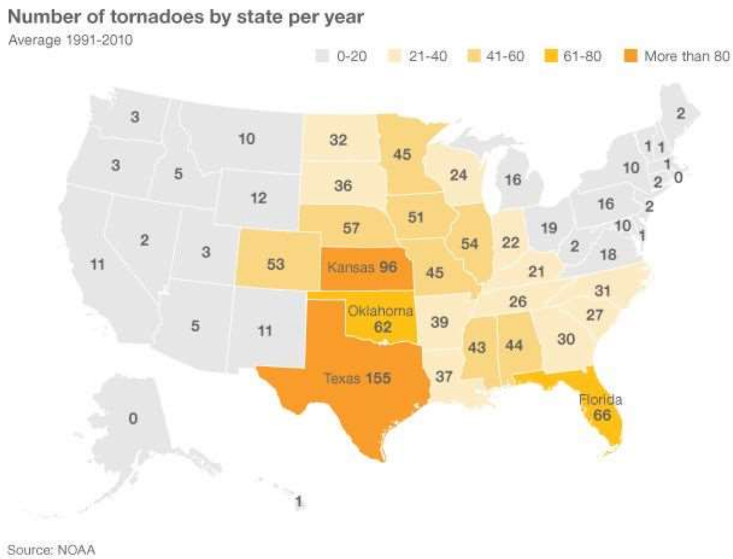
ASCE | KNOWLEDGE & LEARNING — Tornado Counts by State



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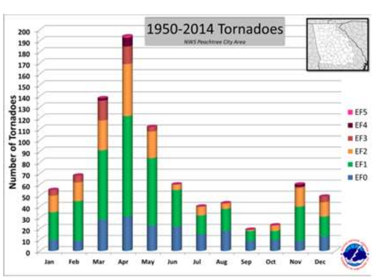
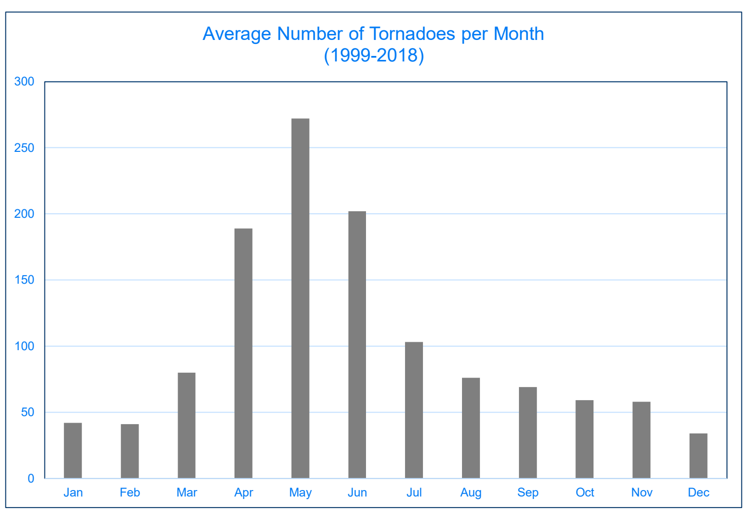
ASCE | KNOWLEDGE & LEARNING — Tornado Frequency by Month

- Tornadoes occur year-round
- Peak in spring/early summer
- The shape of the distribution varies somewhat in different parts of the country



Source: NOAA/NWS



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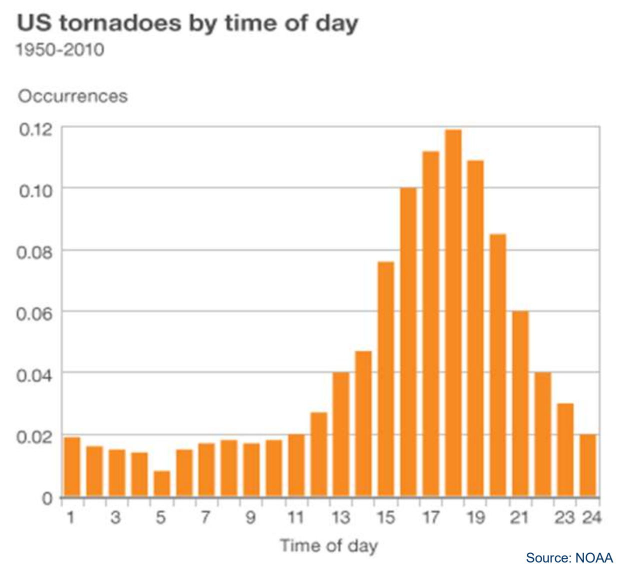
Tornado Frequency by Time of Day

- Tornadoes occur any time of day
- Peak times in later afternoon/early evening
- The shape of the distribution varies somewhat in different parts of the country and at different times of the year



Source: NOAA

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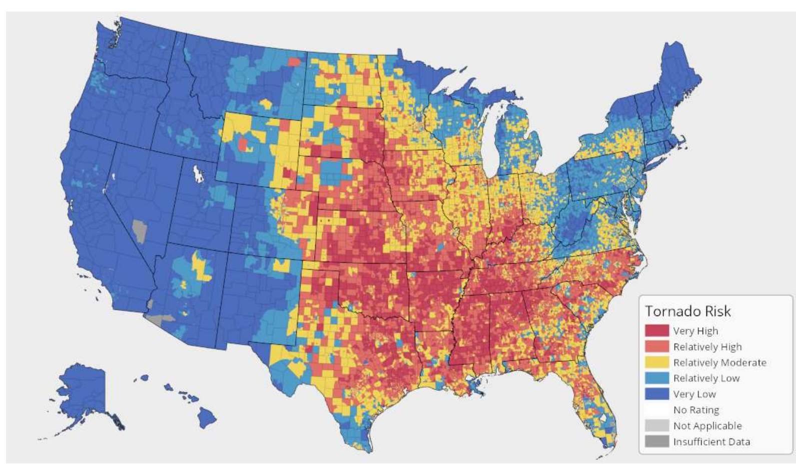
Tornado Risk

- FEMA Tornado Risk Index
  - represents a community's *relative* risk for Tornadoes when compared to the rest of the US
- Risk Index incorporates
  - Tornado hazard
    - annualized frequency
  - Exposure
    - a community's building value ($) and population
  - Historic loss ratio
    - representative percentage of the exposed consequence type value (building or population) expected to be lost due to a Tornado hazard occurrence



https://hazards.fema.gov/nri/tornado

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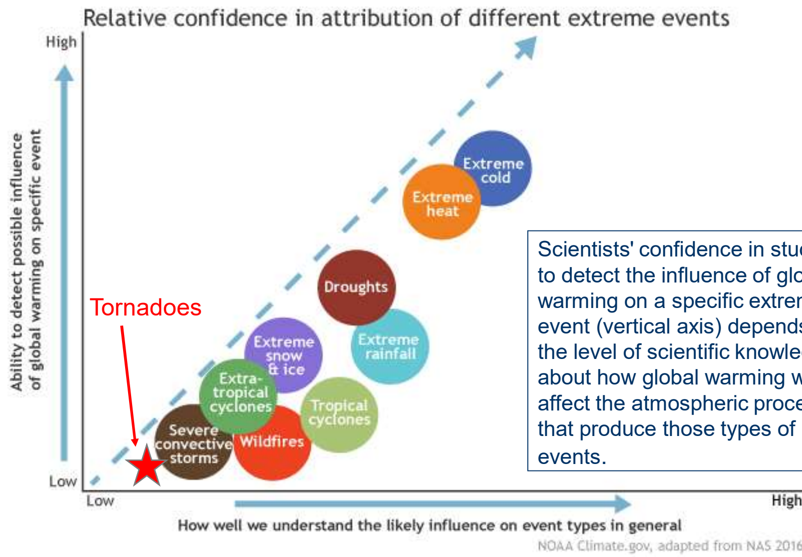
Climate Change and Tornadoes: Part 1

- Attribution analysis depends on 'three pillars' of scientific knowledge:
  - The quality of the observational record,
  - The ability of models to simulate a given type of extreme event, and
  - How well we understand the physical processes that create an event and how global warming may influence those processes.



Scientists' confidence in studies to detect the influence of global warming on a specific extreme event (vertical axis) depends on the level of scientific knowledge about how global warming will affect the atmospheric processes that produce those types of events.

https://www.climate.gov/news-features/understanding-climate/extreme-event-attribution-climate-versus-weather-blame-game

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Tornadoes Shifting Eastward?

- National annual frequencies of tornado reports have remained relatively constant, but significant spatially-varying temporal trends in tornado frequency have occurred since 1979.
- Negative tendencies of tornado occurrence have been noted in portions of the central and southern Great Plains
- Robust positive trends have been documented in portions of the Midwest and Southeast United States

Gensini, V.A., Brooks, H.E.
Spatial trends in United States tornado frequency.
npj Clim Atmos Sci **1,** 38 (2018).
https://doi.org/10.1038/s41612-018-0048-2

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Climate Change and Tornadoes: Part 2

"How will climate change influence tornado occurrence?"

The best answer is: *We don't know.*

Roger Edwards, NOAA/NWS/Storm Prediction Center

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Tornado Climatology

Questions / Discussion

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Break

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Tornado Hazards

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Tornado Hazards

- **Extreme Winds**
- **Atmospheric Pressure Change**
- **Windborne Missiles**
- **Other Windborne Debris**
- **Laydown Hazards**
- **Falling Debris Hazards**
- **Collapse Hazards**
- Lightning
- Hail
- Rain and Wind-driven Rain
- Flash Flooding

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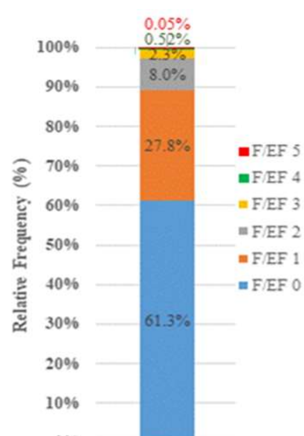
Extreme Winds

- Strong and violent tornadoes are relatively infrequent
- From 1995-2016, of the over 1,200 tornadoes/year
  - 89% were EF0-EF1
  - 97% were EF0-EF2
- Most of the area impacted by a tornado does not experience the greatest winds, e.g., in the 2011 EF-5 Joplin Tornado (NIST, 2014)
  - 72% of area swept by tornado experienced EF0-EF2 winds
  - 28% experienced EF3+ winds

EF SCALE

	EF #	3-s Gust (mph)
Violent	5	Over 200
	4	166-200
Strong	3	136-165
	2	111-135
Weak	1	86-110
	0	65-85

Tornado Intensity Distribution



Source: NIST, from NOAA data

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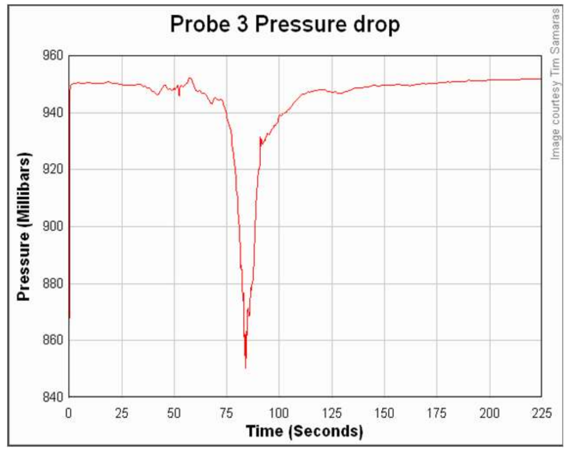
Atmospheric Pressure Change (APC)

- Tornadoes, like hurricanes, have low atmospheric pressure at their center
- As a tornado passes over an enclosed building having low permeability, the atmospheric pressure outside the building can drop in relation to the pressure inside the building
- This pressure difference effectively behaves as a positive internal pressure - pushing up on the roof and outward on the walls



Source: NOAA/NWS/Storm Prediction Center

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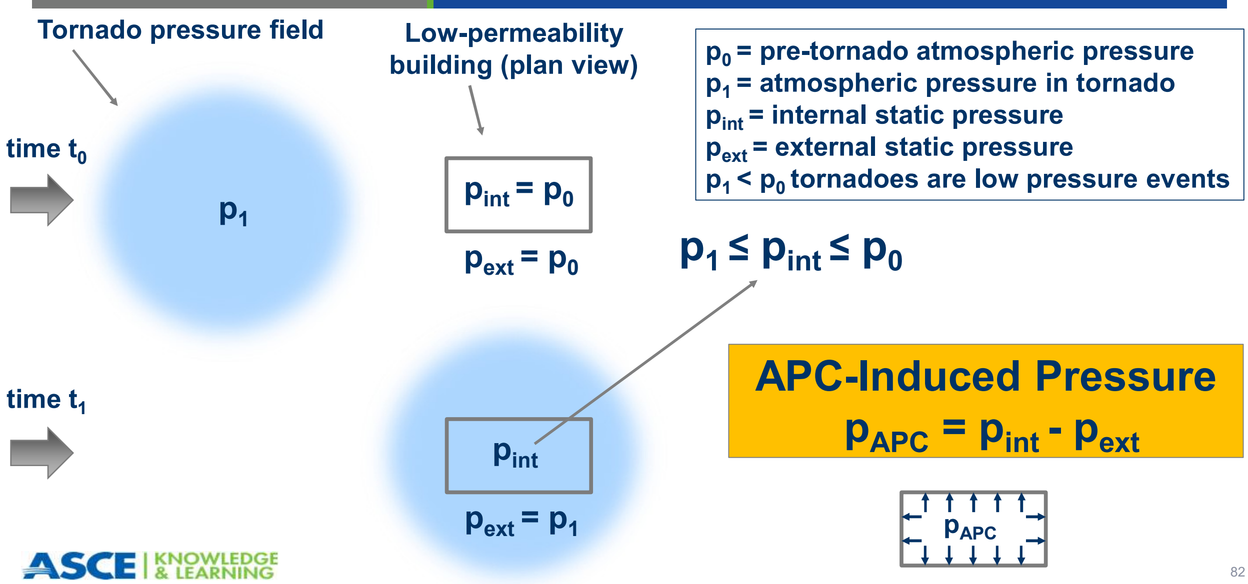
Atmospheric Pressure Change (APC) Part 1



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Atmospheric Pressure Change (APC) Part 2

- The net contribution of APC to the building internal pressure depends on many factors
  - Maximum pressure drop in the tornado
  - Shape/size of pressure deficit field
  - Translational speed of tornado
  - Plan size of the building relative to the size of the tornado pressure field
  - Location of the building relative to the translating pressure field
  - Internal volume of the building
  - Permeability of the building
    - Permeability may change over the duration of the tornado as damage occurs to the building, creating larger openings that allow for more rapid pressure equalization

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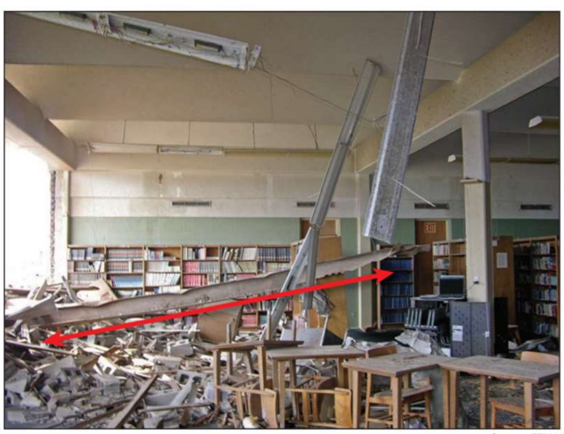
Windborne Missiles



Source: FEMA

Figure B8-3. Large debris: Steel beam that blew into a school (Greensburg, KS, 2007 tornado)

Source: FEMA

Source: FEMA

Figure B8-9. Refrigerator pierced by a 2x6. The portion of the 2x6 that is visible was 4 feet 8 inches long. It went several inches into the freezer compartment. (Oklahoma City, OK, 1999 tornado)

SOURCE: FEMA 342

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Other Windborne Debris (Lofted)

Source: NIST

Source: FEMA

Laydown Hazards

Source: NIST

Source: Marc Levitan / LSU Hurricane Center

Source: NOAA/NWS

Source: FEMA

Falling Debris Hazards

Source: FEMA

Source: FEMA

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Collapse Hazards

Figure 1: An EOC in Tuscaloosa, AL, that saw a loss of operations but remained intact even though the story above it collapsed (Tornado 2011)
PHOTO COURTESY OF THE TUSCALOOSA COUNTY SHERIFF'S OFFICE.

Source: FEMA

Source: FEMA

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Tornado Hazards

Questions / Discussion

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Tornado Impacts and Rationale for Tornado Design

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Why Haven't We Considered Tornadoes in Conventional Engineering Design?

Common Misperceptions

- Too rare
- Losses from tornadoes are small compared to other hazards
- Nothing we can do about them
- Inadequate knowledge
- Buildings would all have to be concrete bunkers
- Too expensive

Credit: NOAA/ITAE

Perceptions may be shaped by the few violent tornadoes per year that make the headlines

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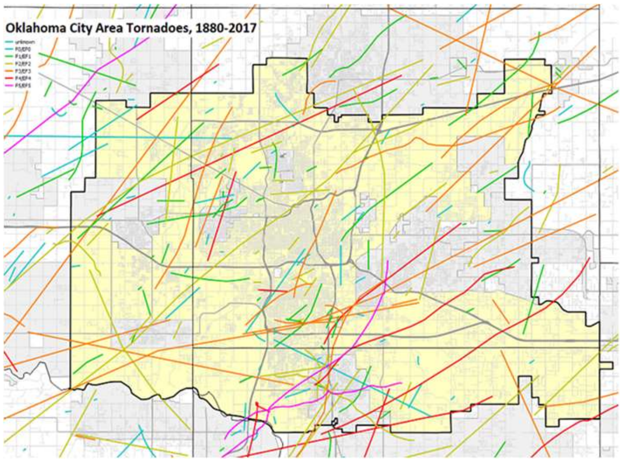
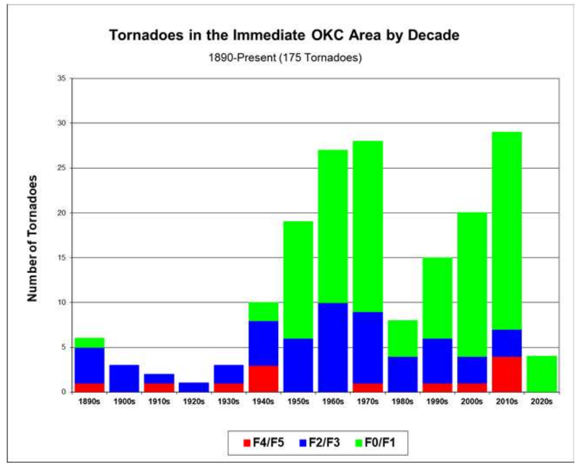
How Rare are Tornadoes?

- Oklahoma City – averages about 20 *reported* tornadoes per decade





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https://www.weather.gov/oun/tornadodata-okc

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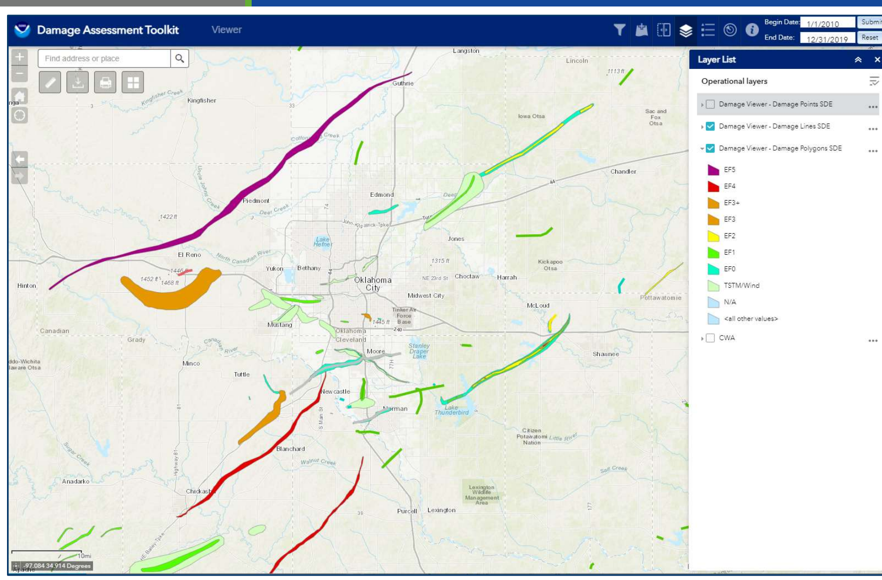
OKC –Area Tornadoes from 2010-2019



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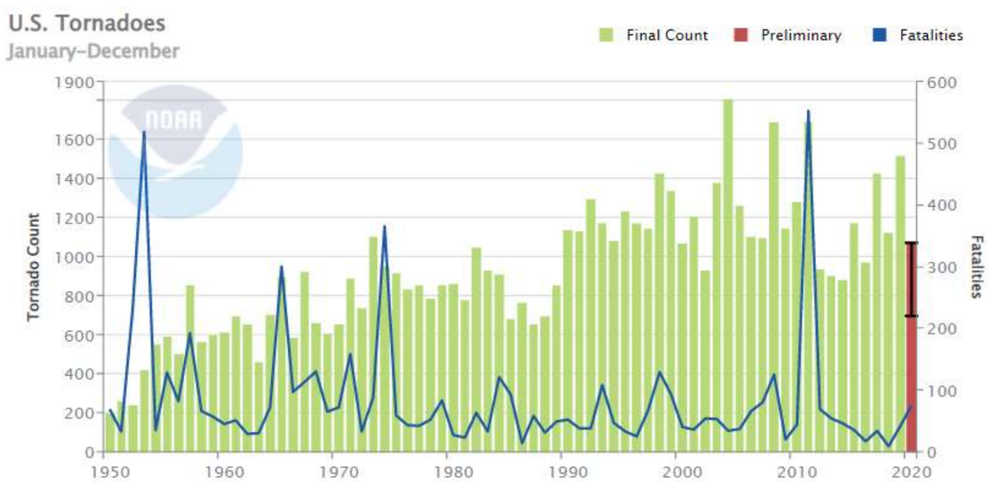
How Deadly are Tornadoes?



During the period from 1950-2011, tornadoes caused more than 5,600 fatalities in the US, which is more than hurricanes and earthquakes combined (NIST, 2014).

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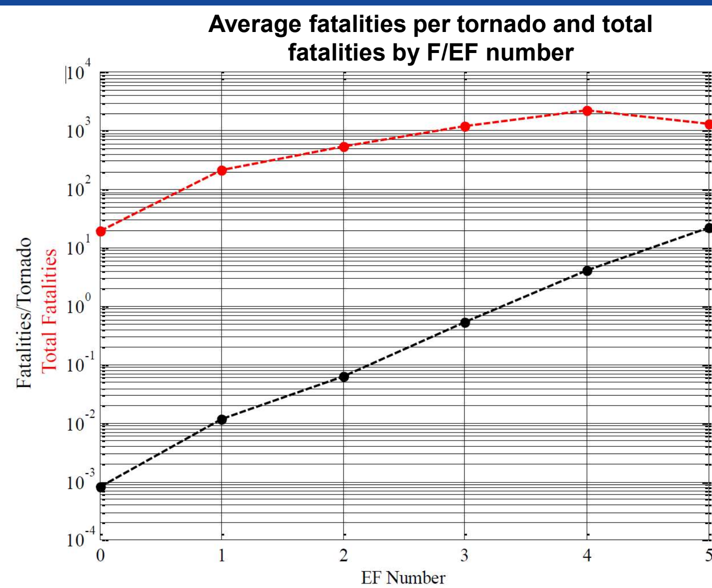
U.S. Tornado Fatalities by Intensity

- Most fatalities occur in strong and violent tornadoes (EF2-EF5)
- **Most fatalities occur inside buildings**
- Source: NIST (2014)
  - Using NOAA data for 1950-2011
  - https://doi.org/10.6028/NIST.NCSTAR.3



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How Much Damage is Caused by Tornadoes?

Insurance Information Institute

Over the 20-year period, 1997 to 2016, events involving tornadoes, including other wind, hail and flood losses associated with tornadoes made up **39.9%** of total catastrophe insured losses, adjusted for inflation.

Hurricanes and tropical storms were a close second largest cause of catastrophe losses, accounting for **38.2%** of losses

Source: https://www.iii.org/article/spotlight-on-catastrophes-insurance-issues#:~:text=Hurricanes%20and%20tropical%20storms%20were,winter%20storms%20(6.7%20percent)

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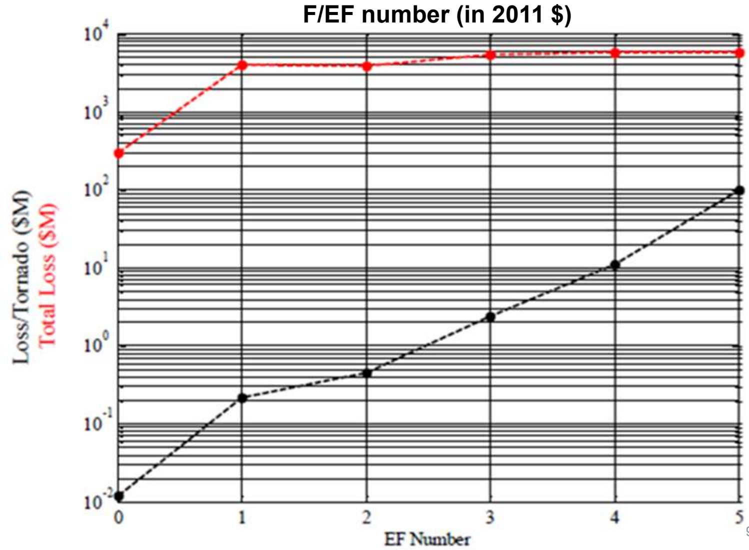
U.S. Tornado Losses by F/EF Number

- Property damage and resulting losses per individual tornado (black curve) increase dramatically with F/EF rating
- Aggregate losses for all tornadoes per F/EF number (red curve) are of the same magnitude (except EF0)
  - because there are so many more tornadoes with lower intensities
- Source: NIST (2014)
  - Using NOAA data for 1950-2011
  - https://doi.org/10.6028/NIST.NCSTAR.3

Average loss per tornado and total loss by F/EF number (in 2011 $)



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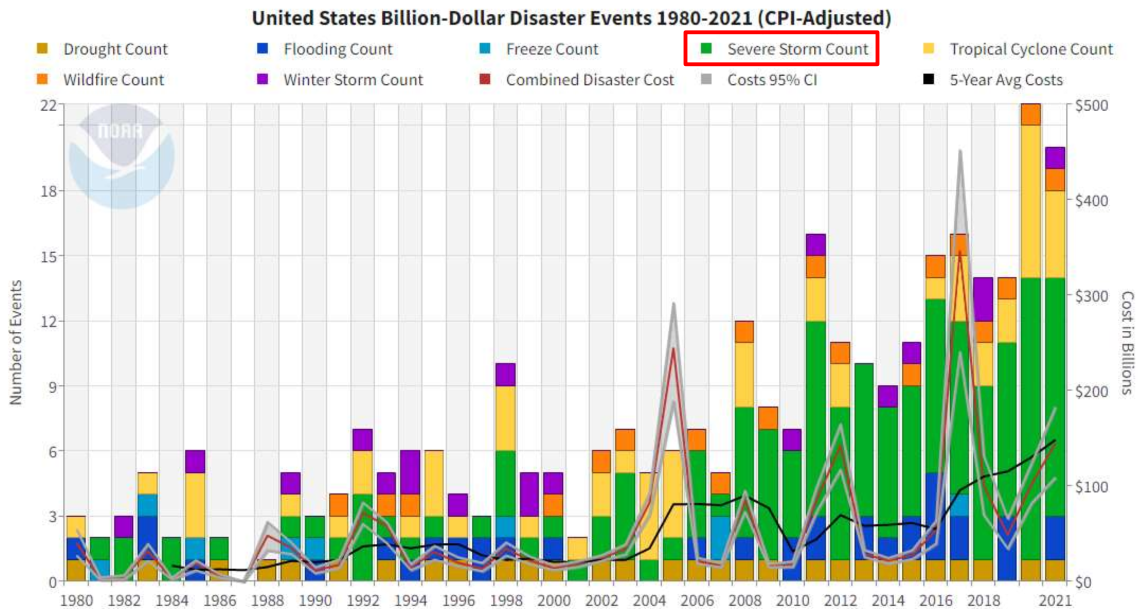

https://www.ncdc.noaa.gov/billions/time-series/US

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Example Tornado Impacts on Critical Facilities

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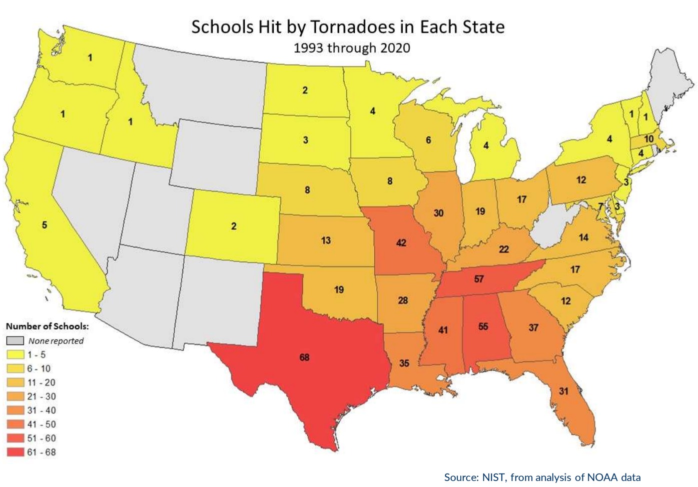

- Over the past 28 years, NOAA records include documentation of at least **648** tornado strikes on schools
  - over 23 schools/year on average
  - preK-12 schools
  - damage ranged from slight/none to complete destruction
  - This is a lower bound estimate; many school hits not included in the Storm Events Database, which was not specifically designed for that purpose
- Recent notable events
  - Enterprise High School, AL, 2007
    8 fatalities
  - Plaza Towers Elementary, OK, 2013
    7 fatalities

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Tornado Strikes on Schools

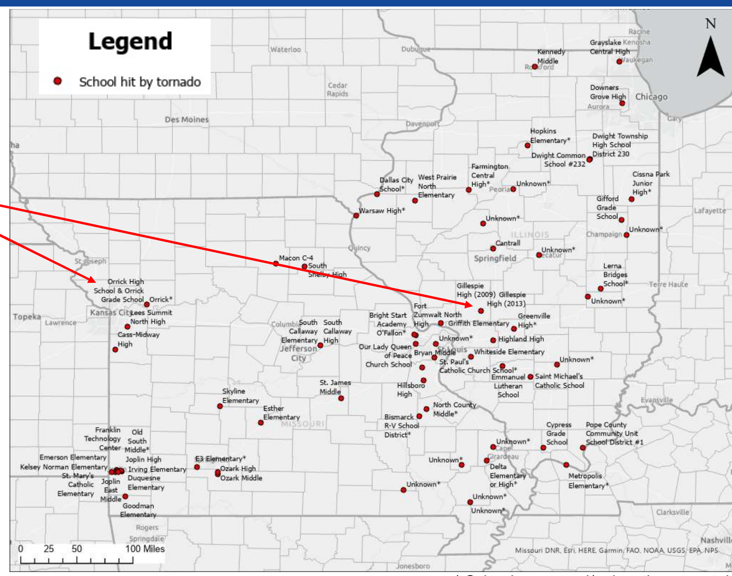
Source: NIST, from NOAA data

Tornado Strikes on Schools in Missouri and Illinois

1993 – 2020

These schools appear to have been struck by tornadoes on two separate occasions

- Actual number of strikes during this time period is likely about double what is shown here



Note: 1 mi = 1.609 km.

* School name and/or location uncertain

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Paradigm Shift Needed

Source: NOAA

Ignoring tornado hazards in the design of our built environment is not an appropriate response

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Tornado Impacts and Rationale for Tornado Design

Questions / Discussion

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History, Development and Recent Practice for Tornado Design

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Recent Practice in Design for Tornadoes

- With a few notable exceptions, design for tornado hazards has been very rare
- Exceptions
  - Nuclear Power Plants
  - Specialty Applications
  - Moore, OK and Joplin, MO building codes
  - Tornado Shelters and Safe Rooms
- ASCE 7-22 is the first national standard for tornado load design of *conventional* buildings and structures

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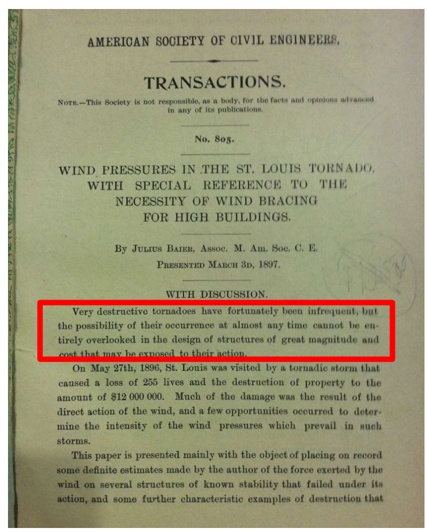
Early Engineering Analysis and Design Guidance

St. Louis Tornado

- May 27, 1896
- 255 fatalities
- 12,000 buildings damaged or destroyed
- $12M losses

"It is scarcely possible that buildings would yield to any of the pressures found by Mr. Baier, and that degree of provision (structural capacity) would be neither difficult nor extravagant."

Source: NOAA



AMERICAN SOCIETY OF CIVIL ENGINEERS.

TRANSACTIONS.

NOTE.—This Society is not responsible, as a body, for the facts and opinions advanced in any of its publications.

No. 805.

WIND PRESSURES IN THE ST. LOUIS TORNADO, WITH SPECIAL REFERENCE TO THE NECESSITY OF WIND BRACING FOR HIGH BUILDINGS.

By JULIUS BAIER, Assoc. M. Am. Soc. C. E.
PRESENTED MARCH 3D, 1897.

WITH DISCUSSION.

Very destructive tornadoes have fortunately been infrequent, but the possibility of their occurrence at almost any time cannot be entirely overlooked in the design of structures of great magnitude and cost that may be exposed to their action.

On May 27th, 1896, St. Louis was visited by a tornadic storm that caused a loss of 255 lives and the destruction of property to the amount of $12 000 000. Much of the damage was the result of the direct action of the wind, and a few opportunities occurred to determine the intensity of the wind pressures which prevail in such storms.

This paper is presented mainly with the object of placing on record some definite estimates made by the author of the force exerted by the wind on several structures of known stability that failed under its action, and some further characteristic examples of destruction that

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1957 Dallas Tornado

- April 2 tornado (F3) carves 17-mile path through west Dallas over 45 minute period
  - 10 fatalities, 200+ injuries
  - Nearly 600 buildings damaged or destroyed

Source: NOAA

- Well documented through photographs and film
- Important advances in tornado research

"The Tornados at Dallas, Texas, April 2, 1957," Research Paper No. 41, US Weather Bureau, Washington, D.C., 1960

"The most comprehensive observation of a tornado made to that date was that of the Dallas, Texas, tornado of 2 April 1957."

"Wind Speed and Air Flow in the Dallas Tornado of April 2, 1957," Monthly Weather Review, 88, 5, 167, 1960 W. H. Hoecker, Jr.

"Hoecker employed photogrammetric analysis of a large number of motion pictures of that storm to deduce the related low-level wind field."

(Antaki, 2016)

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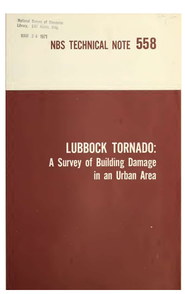
1970 Lubbock Tornado

- May 11 tornado (F5) cuts 8.5-mile path of destruction through downtown Lubbock and the airport
  - 26 fatalities, 500+ injuries
  - Nearly 9,000 buildings damaged or destroyed
  - Damage swath of 15 sq. miles covered ¼ of Lubbock

Photograph 20—Center of City with 20-story Great Plains Life Building in foreground. View looking northeast. (Location 13)



https://doi.org/10.6028/NBS.TN.558

SOCIETAL IMPACTS AND LESSONS LEARNED:

Although devastating to Lubbock, a number of positive outcomes resulted from the Lubbock tornado of 1970:

1. The tornado was used as inspiration and justification for the establishment of the Wind Science and Engineering (WISE) Research Center at Texas Tech University.

2. The tornado also helped in the selection of Lubbock as one of the very first NWS offices to receive a WSR-74C radar.

3. The study of the meteorological data from May 11, 1970, in combination with an extensive damage survey completed in Lubbock of the aftermath, helped, in part, in the development of the Fujita Tornado Damage Scale (F-scale) by Tetsuya Theodore (Ted) Fujita. The F-scale is the de facto standard used to rank tornadoes by the amount of damage that they inflict.

4. The study of the damage patterns, especially from overhead with aerial photos, allowed Dr. Fujita to further develop his theory that some tornadoes contained more than one vortex (i.e., there were multiple vortex tornadoes).

Source: National Weather Service/Lubbock TX WFO
https://www.weather.gov/lub/events-1970-19700511#societal_impacts

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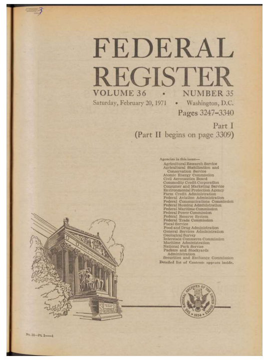
Nuclear Facilities: Part 1

- Brief history - design for tornadoes at Nuclear Power Plants (NPP)
  - https://becht.com/becht-blog/entry/tornado-design-for-nuclear-power-plants-a-brief-history/



CRITERIA

I. Overall Requirements

Criterion 1—Quality standards and records. Structures, systems, and components important to safety shall be designed, fabricated, erected, and tested to quality standards commensurate with the importance of the safety functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency and shall be supplemented or modified as necessary to assure a quality product in keeping with the required safety function. A quality assurance program shall be established and implemented in order to provide adequate assurance that these structures, systems, and components will satisfactorily perform their safety functions. Appropriate records of the design, fabrication, erection, and testing of structures, systems, and components important to safety shall be maintained by or under the control of the nuclear power unit licensee throughout the life of the unit.

Criterion 2—Design bases for protection against natural phenomena. Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the safety functions to be performed.

Criterion 2—Design bases for protection against natural phenomena. Structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as earthquakes, **tornadoes**, hurricanes, floods, tsunami, and seiches without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect: (1) Appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena and (3) the importance of the safety functions to be performed

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ANSI A58.1-1982

- Precursor to ASCE 7
- Secretariat: National Bureau of Standards (now NIST)
- 1982 edition included a paragraph and references on design for tornadoes in the Commentary
- Tornado Commentary expanded in ASCE 7-95, then unchanged through ASCE 7-10

ANSI A58.1-1982 Commentary

In recent years great strides have been made in understanding the effects of tornadoes on buildings. This understanding has been gained through extensive documentation of building damage caused by tornadic storms and through analyses of the collected data. Currently, buildings and structures related to the nuclear power industry are designed to resist tornadic forces. Sufficient information is available to implement tornado-resistant design for aboveground shelters and for buildings that house essential facilities for post-disaster recovery. This information is in the form of tornado risk probabilities, tornadic windspeeds, and associated forces. References [4] through [10] provide guidance in developing wind load criteria for tornado-resistant design.

[4] Abbey, R.F. Jr. Risk probabilities associated with tornado windspeeds. In: R.E. Peterson, Ed., 1976 proceedings of the symposium on tornadoes: Assessment of knowledge and implications for man. Lubbock, Texas: Institute for Disaster Research, Texas Tech University.

[5] Interim guidelines for building occupants protection from tornadoes and extreme winds. Washington, D.C.: Defense Civil Preparedness Agency; 1975; TR-83A. 24 p. Available from Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

[6] McDonald, J.R.; Mehta, K.C.; Minor, J.E. Tornado-resistant design of nuclear power-plant structures. Nuclear Safety. 15(4): 432-439; July-August 1974.

[7] Mehta, K.C.; Minor, J.E.; McDonald, J.R.; Manning, B.R.; Abernathy, J.J.; Koehler, U.W. 1975 engineering aspects of tornadoes of April 3-4, 1974. Washington, D.C.: National Academy of Sciences; 1975.

[8] Mehta, K.C.; McDonald, J.R.; Minor, J.E. Tornadic loads on structures. In: Ishizaki and Chiu, Eds., Wind effects on structures, Proceedings of the second USA-Japan research seminar. Tokyo, Japan: University of Tokyo Press; 1976: 15-26.

[9] Minor, J.E.; McDonald, J.R.; Mehta, K.C. The tornado: An engineering-oriented perspective. Norman, OK: National Severe Storms Laboratory; 1977; NOAA Tech. Memo. ERL NSSL-82. 196 p.

[10] Wen, Y.K.; Chu, S.L. Tornado risk and design windspeed. J. Structural Div., ASCE. 99(ST 12): 2409-2421; December 1973.

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Nuclear Facilities: Part 2

- Multiple Regulations, Standards and Guides for Tornado Design

NUREG-0800

U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

3.3.2 TORNADO LOADS

REVIEW RESPONSIBILITIES

Primary - Organization responsible for structural analysis reviews

Secondary - None

I. AREAS OF REVIEW

The following areas are related to the design of structures that must withstand the effects of the specified design-basis tornado for the plant. These areas are reviewed to ensure conformance with 10 CFR 50, Appendix A, General Design Criterion (GDC) 2.

The specific areas of review are as follows:

1. The design parameters applicable to the tornado, including the tornado wind translational and rotational speeds; the tornado-generated atmospheric pressure change; and the spectrum of tornado-generated missiles, including their characteristics, from the standpoint of use in defining the input parameters for the structural design criteria appropriate to account for tornado loads.
2. The procedures that are used to transform tornado parameters into effective loads on structures, including the following:
   A. The transformation of tornado wind into equivalent loads applied to structures, taking into consideration the geometrical configuration and physical

Revision 3 - March 2007

U.S. NUCLEAR REGULATORY COMMISSION

March 2007
Revision 1

REGULATORY GUIDE

OFFICE OF NUCLEAR REGULATORY RESEARCH

REGULATORY GUIDE 1.76

(Draft was issued as DG-1143, dated January 2006)

DESIGN-BASIS TORNADO AND TORNADO MISSILES FOR NUCLEAR POWER PLANTS

A. INTRODUCTION

This regulatory guide provides licensees and applicants with new guidance that the staff of the U.S. Nuclear Regulatory Commission (NRC) considers acceptable for use in selecting the design-basis tornado and design-basis tornado-generated missiles that a nuclear power plant should be designed to withstand to prevent undue risk to the health and safety of the public. This guidance applies to the contiguous United States, which is divided into three regions; this document provides separate guidance for each region.

NUREG/CR-4461, Rev. 2
PNNL-15112, Rev. 1

Tornado Climatology of the Contiguous United States

Pacific Northwest National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

American Nuclear Society

estimating tornado, hurricane, and extreme straight line wind characteristics at nuclear facility sites

an American National Standard

REAFFIRMED
June 29, 2016
ANSI/ANS-2.3-2011; R2016

published by the
American Nuclear Society
555 North Kensington Avenue
La Grange Park, Illinois 60526 USA

U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

July 2016
Revision 2
Technical Lead
Gordon Curran

REGULATORY GUIDE

REGULATORY GUIDE 1.117

(Draft was issued as DG-1313, dated August 2015)

PROTECTION AGAINST EXTREME WIND EVENTS AND MISSILES FOR NUCLEAR POWER PLANTS

(Previously titled, "TORNADO DESIGN CLASSIFICATION")

A. INTRODUCTION

Purpose

This regulatory guide (RG) describes an approach that the staff of the U.S. Nuclear Regulatory Commission (NRC) considers acceptable for identifying those structures, systems, and components of light-water-cooled reactors that should be protected from the effects of the worst case extreme winds (tornados and hurricanes) and wind-generated missiles, so that they remain functional.

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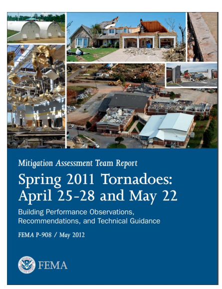
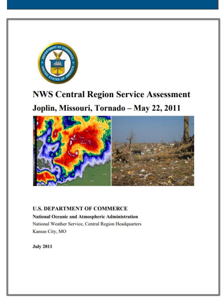
2011-2013 Tornado Seasons

- 2011
  - 3rd most tornadoes since 1950
  - 553 fatalities - deadliest year since 1950
  - Deadliest single tornado since 1950 (Joplin, 161 fatalities)
  - Single costliest tornado ever (Joplin, approx. $3B)
- 2013
  - EF5 Moore tornado killed 7 children at an elementary school
    - 4th violent tornado in Moore in past 15 years
  - Widest tornado ever (El Reno, OK, 2.6 miles)
    - Initially rated EF5 due to radar-measured speeds, changed to EF3 based on maximum observed damage





Responses

- Significant expansion of tornado R&D
- Joplin, MO and Moore, OK amend local building codes to require more wind resistant residential construction
- St. John's Regional Medical Center in Joplin demolished & rebuilt as a tornado-resistant facility using lessons learned
- NOAA expands social science R&D to craft warning messages that will be more likely to elicit protective actions
- 2015 International Building Code begins requiring tornado shelters in schools and emergency response facilities
- ASCE 7-16 adds extensive tornado commentary, including tornado load design method and examples

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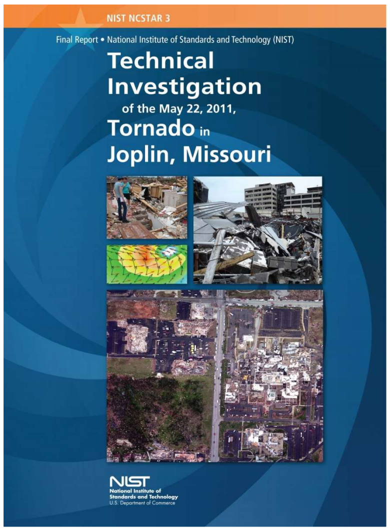
Genesis of Tornado Loads in ASCE 7-22



http://dx.doi.org/10.6028/NIST.NCSTAR.3

The first tornado study to include storm characteristics, building performance, emergency communication and human behavior together - with assessment of the impact of each on fatalities

16 recommendations for improving:

- Tornado hazard characterization
  - **R3 - develop new tornado hazard maps considering spatial estimates of tornado hazard**
- Design and construction of buildings and shelters in tornado–prone regions
  - **R5 - develop performance-based tornado-resistant design standards**
  - **R6 - develop tornado design methodologies**
- Emergency communications that warn of threats from tornadoes

NOTE: Summaries of the recommendations are provided in this presentation for context. The complete recommendations are available in the final report, available through the link shown at left.

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History, Development, and Recent Practice for Tornado Design

Questions / Discussion

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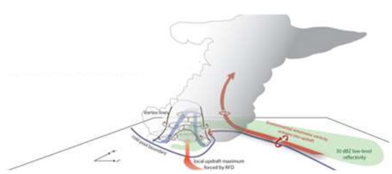
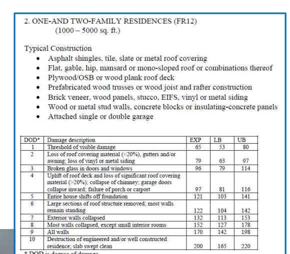
Unit 1 Summary

Unit 1: Summary Part 1

- Tornado Description
  - Formation and life cycle
  - Types
  - Wind patterns
- Tornadic Wind Measurements
  - Mainly estimated from observed damage
    - Fujita (F) Scale prior to 2007
    - Enhanced Fujita (EF) Scale from Feb. 2007
- EF Scale
  - 28 Damage indicators (DIs) – buildings, poles, towers, trees
  - Each DI has several Degrees of Damage (DoDs)
    - EXPected, Lower Bound, and Upper Bound wind speed estimates based on estimated strength of construction

Tornado - A violently rotating column of air touching the ground, usually attached to the base of a thunderstorm



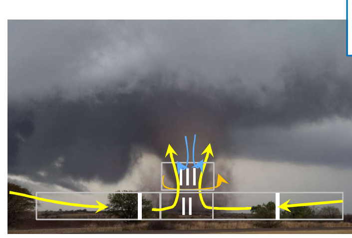


2. ONE-AND TWO-FAMILY RESIDENCES (FR12)
(1000 – 5000 sq. ft.)

Typical Construction
- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard or mono-sloped roof or combinations thereof
- Plywood/OSB or wood plank roof deck
- Prefabricated wood trusses or wood joist and rafter construction
- Brick veneer, wood panels, stucco, EIFS, vinyl or metal siding
- Wood or metal stud walls, concrete blocks or insulating-concrete panels
- Attached single or double garage

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

* DOD is degree of damage



FR12: DOD 10: Total destruction of entire building

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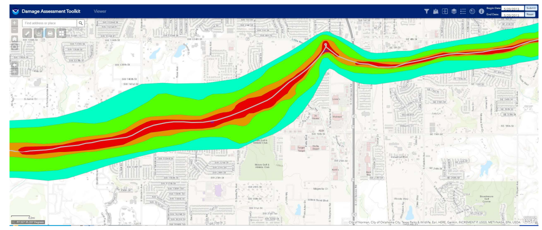
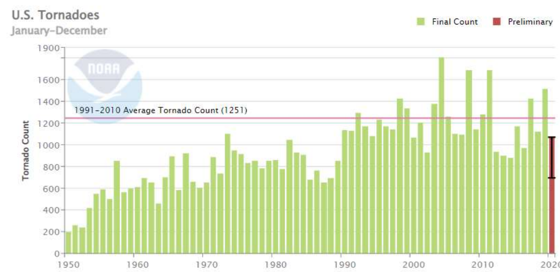
Unit 1: Summary Part 2

- Official Tornado Rating (F or EF)
  - Assigned by the National Weather Service
  - Based on analysis of wind speeds from all DIs surveyed
- NWS Damage Assessment Toolkit
  - Allows exploration of recent (last decade or so) tornadoes, inc. individual DIs
- Tornado Frequency
  - Over 1,250 reported tornadoes/year in the U.S.
- How is Climate Change Impacting Tornado Climatology?
  - Not known at this time





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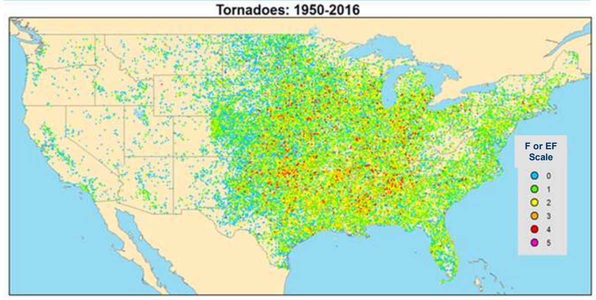
Unit 1: Summary Part 3

- Where do Tornadoes Occur?
  - On every continent except Antarctica
  - All 50 states, but primarily east of the Continental Divide
- When do Tornadoes Occur?
  - Year-round, w/ peak in spring and early summer
  - Any time of day or night, w/ peak in late afternoon/ early evening
- Primary Tornado Hazards
  - Extreme winds
  - Atmospheric Pressure Change
  - Windborne missiles
  - Other debris hazards

Tornadoes: 1950-2016



FEMA

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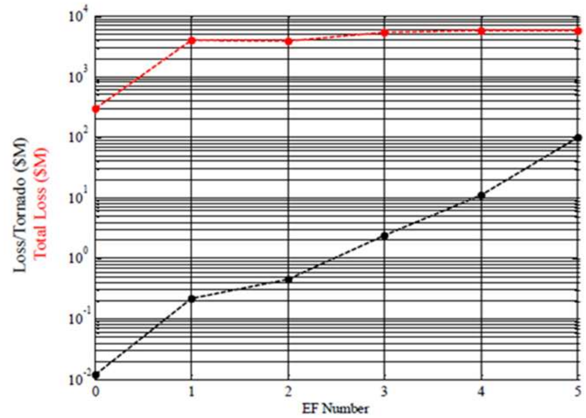
Unit 1: Summary Part 4

- Tornado Fatalities
  - Tornadoes kill more people in the U.S. than earthquakes and hurricanes combined
  - Most tornado fatalities occur in buildings
- Tornado Damage
  - Much of the total tornado damage is caused by lower intensity (EF0-EF2) tornadoes
  - Most tornadoes (97%) are EF2 and below
- Design for Tornadoes
  - Buildings have not previously been designed to resist tornado loads, with primary exceptions of
    - Tornado shelters
    - Nuclear facilities

Average loss per tornado and total loss by F/EF number (in 2011 $)



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Break

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