ASCE 7-22 Tornado Loads

ICC 500 Briefing

Marc L. Levitan

With recognition of a <u>large</u> number of collaborators who have made this possible!

National Institute of Standards and Technology
U.S. Department of Commerce

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

NIST

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

Photo Credit: NOAA/ITAE

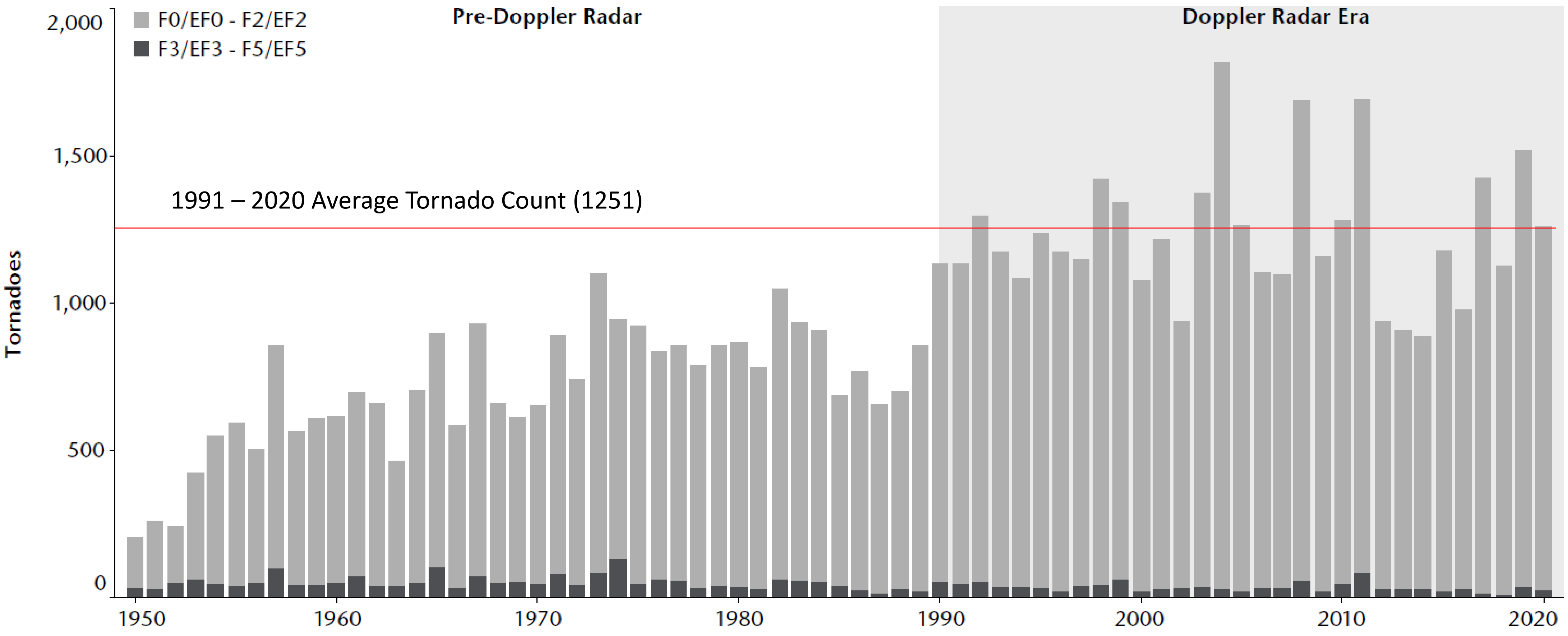
Perceptions may be shaped by the few violent tornadoes per year that make the headlines

How Rare are Tornadoes?

Source: NIST, from NOAA data

NIST

U.S. Tornadoes (1950 – 2020).
Source: NOAA's Storm Prediction Center

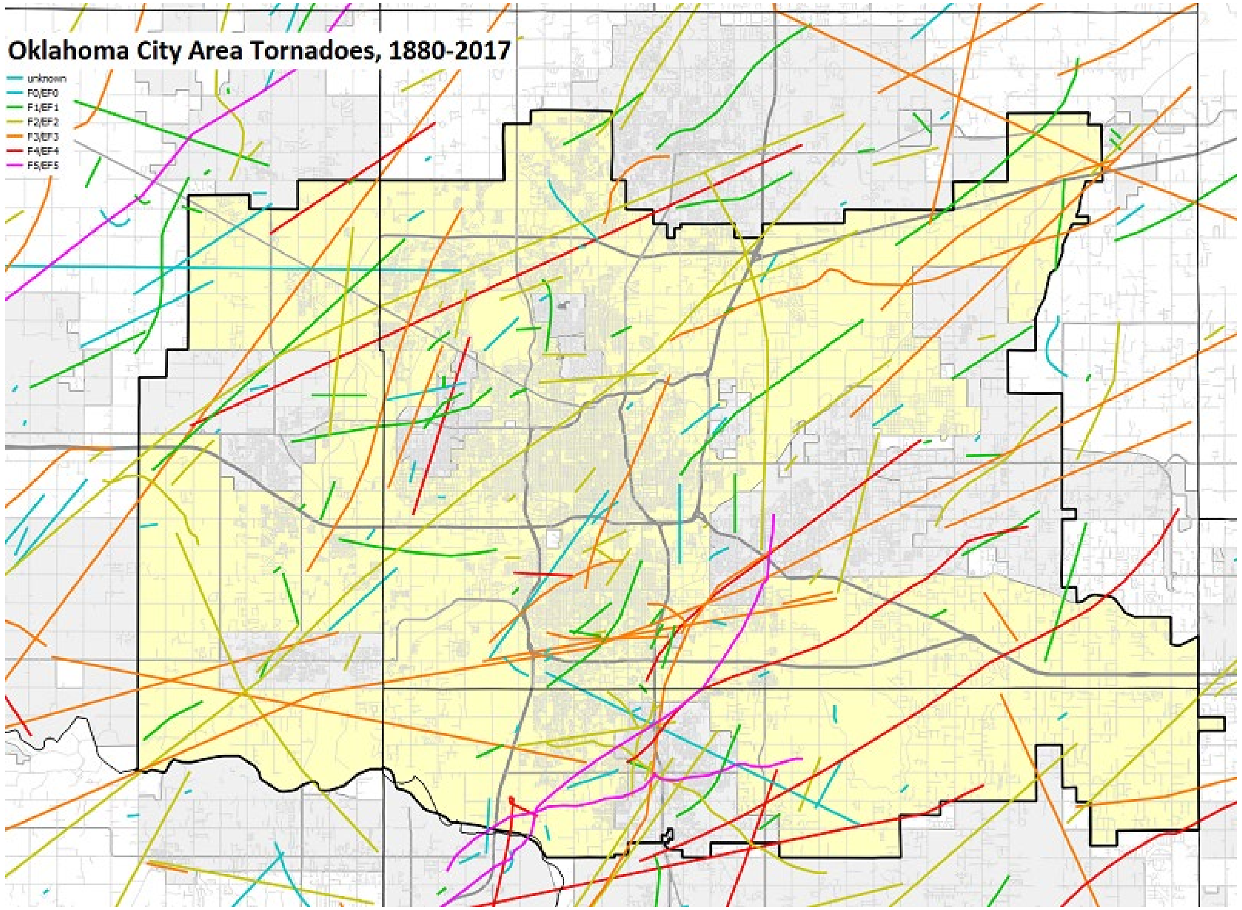


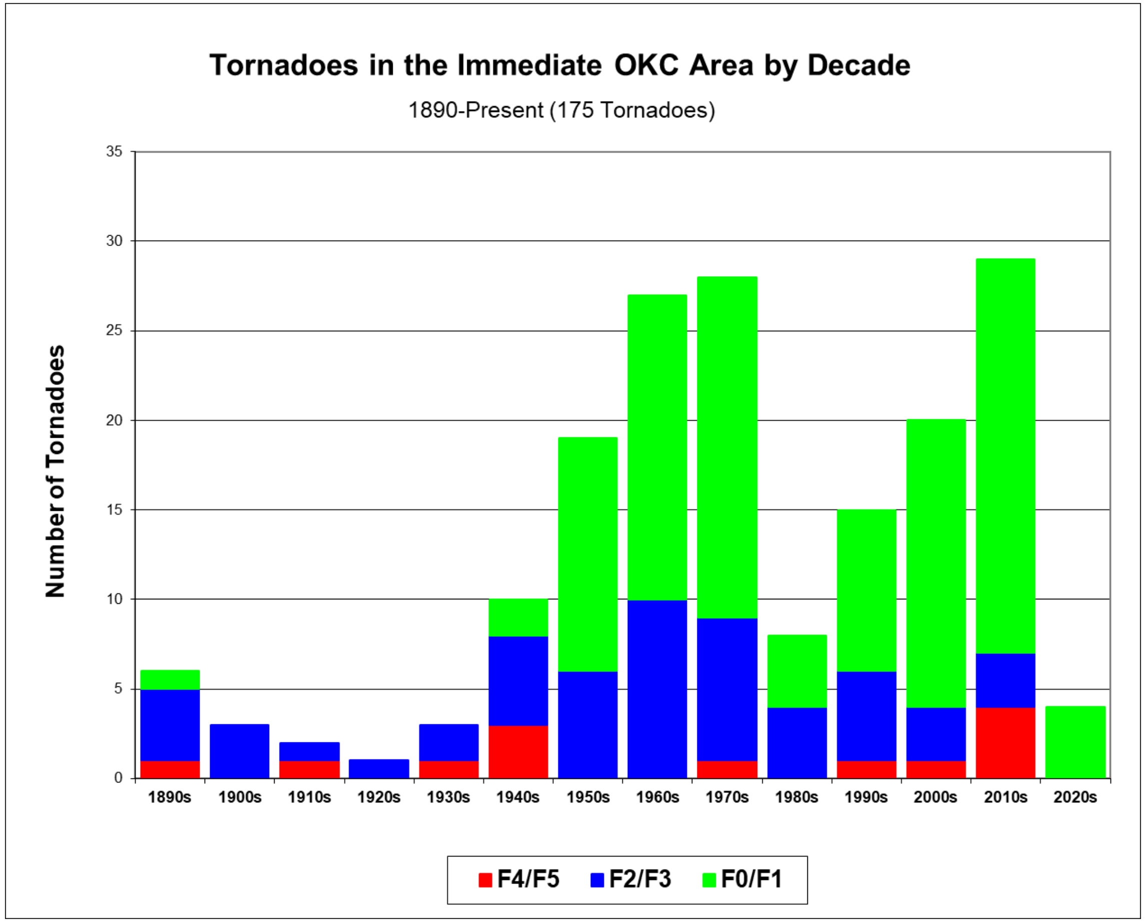
This plot shows the number of *reported* tornadoes per year.
Many tornadoes go unreported.

How Rare are Tornadoes?

Source: NIST, from NOAA data

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





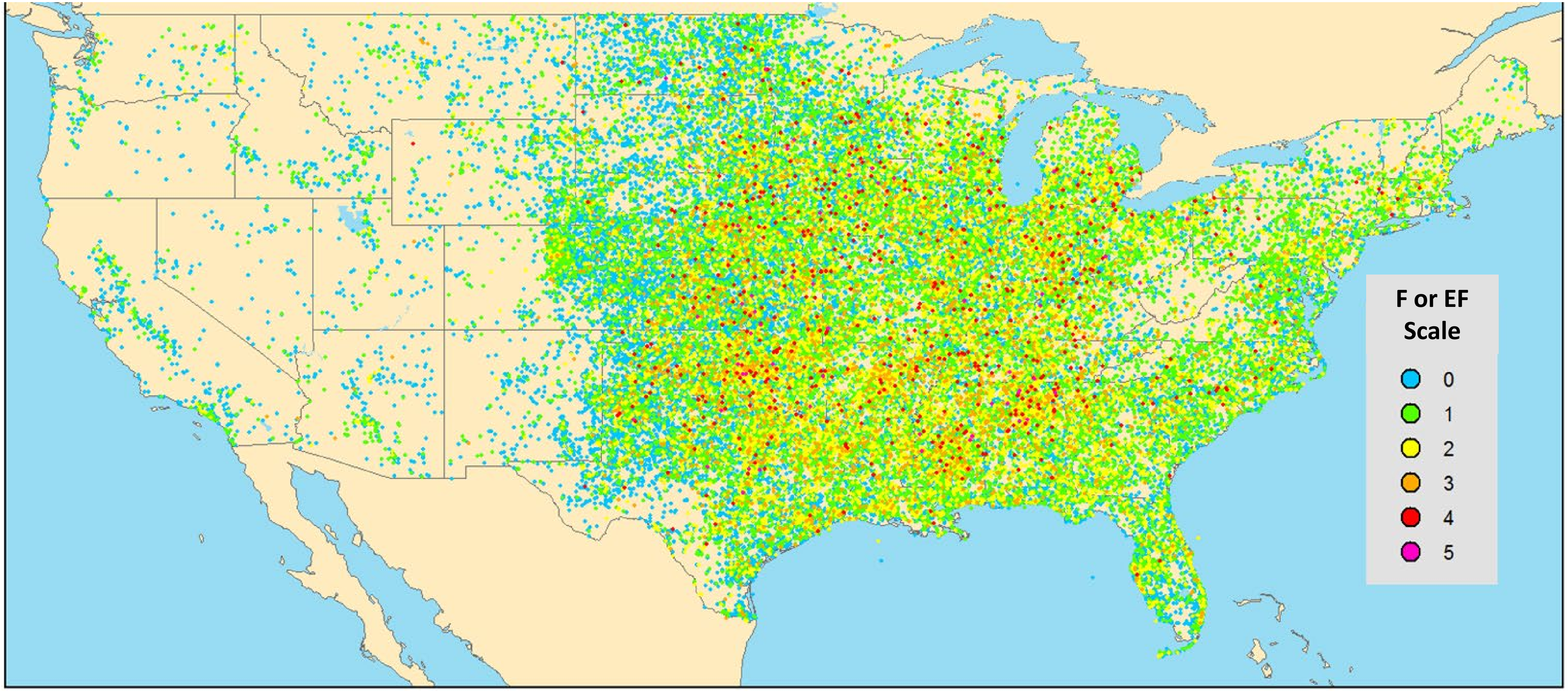
https://www.weather.gov/oun/tornadodata-okc

Where do Tornadoes Occur?

Source: NIST, from NOAA data

Tornadoes occur in all 50 States, but primarily east of the Continental Divide

U.S Tornadoes: 1995-2016



How Many Lives are Lost in Tornadoes?

NIST

Tornadoes kill more people per year in the U.S. than hurricanes and earthquakes combined

Tornado fatalities overwhelmingly occur inside buildings.

Tornado Fatalities are a *Buildings* Problem

High Tornado Death Toll

≈5,600 killed (1950 – 2011)

Average deaths/year:

Tornadoes:	91.6
Hurricanes:	50.8
Earthquakes:	7.5

Moore OK Tornado – 2013. Damage to the hallway and classrooms of the new main classroom building (complete loss of roof and many walls) where the 7 fatalities occurred (most of the debris has already been removed). This hallway area was a "designated area of safety." NIST SP 1164 (2013)

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Storm Shelters for Life Safety Protection

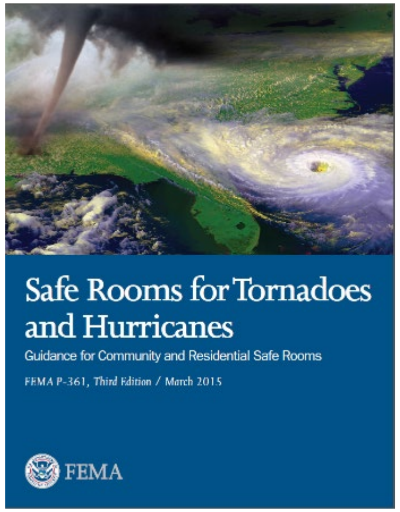
<u>We *can* design for mother nature's worst</u>

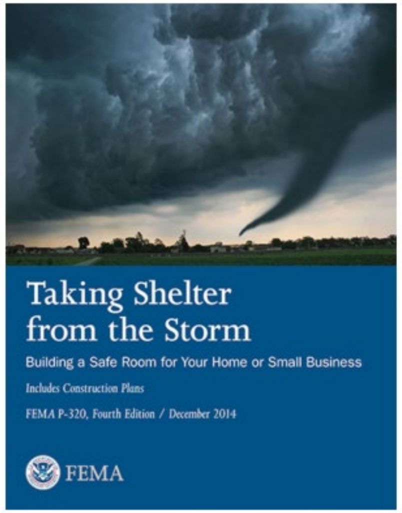
FEMA Safe Rooms are designed for 'near-absolute' life safety protection, ICC 500 Storm Shelters have almost identical requirements

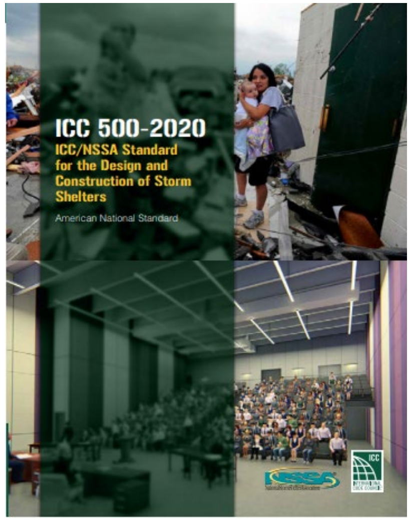
- **250 mph tornado winds**
- **Impact of 15-pound 2x4 traveling at 100 mph**
- **No reported failures of safe rooms or shelters constructed to FEMA or ICC 500 requirements**

In-Residence Safe Room
Joplin, MO, May 22, 2011

Source: FEMA







Winston County Commission
Community Safe Room
Arley, AL, November 30, 2016

How Much Damage do Tornadoes Cause?

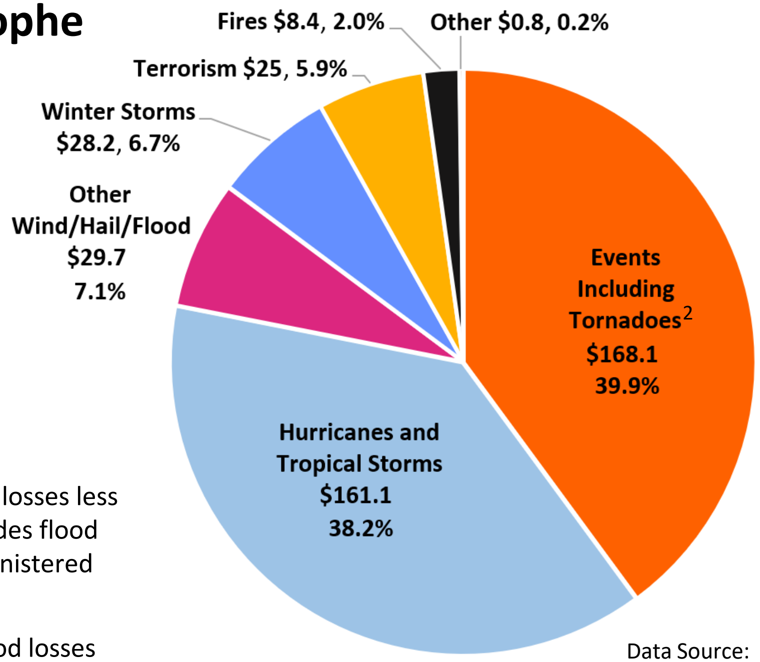
NIST

"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."

U.S. Insured Catastrophe Losses By Cause,[1] 1997-2016

(in 2016 $ billions)



[1] Excludes catastrophes causing direct losses less than $25 million in 1997 dollars. Excludes flood damage covered by the federally administered National Flood Insurance Program.

[2] Includes other wind, hail, and/or flood losses associated with catastrophes involving tornadoes.

Data Source: Insurance Information Institute

INSURANCE INFORMATION INSTITUTE

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

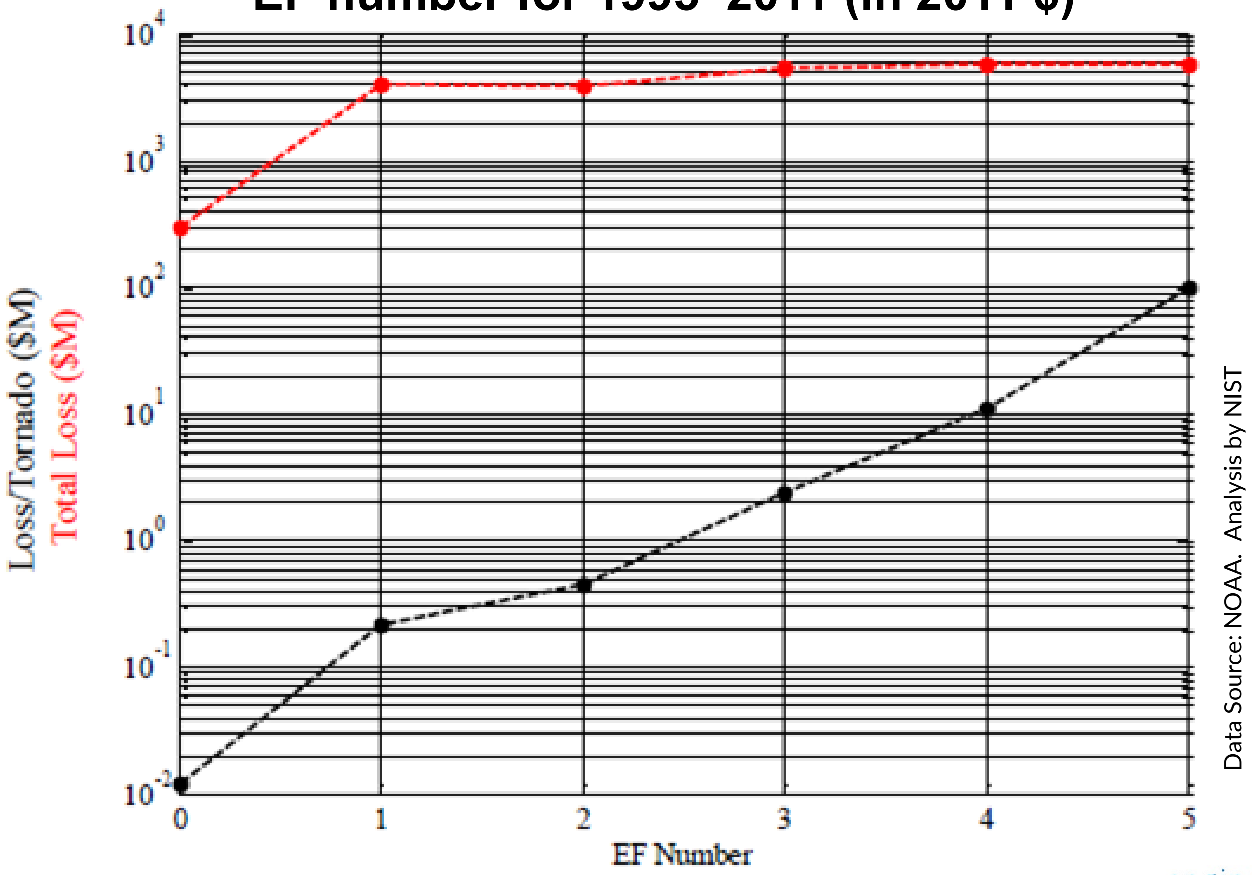
Isn't Most Damage Caused by the Big Tornadoes?

Property damage and resulting losses per *individual* tornado (black curve) increase dramatically with EF rating

However, *aggregate* losses for all tornadoes per EF number (red curve) are of the same magnitude (except EF0)

- because there are so many more tornadoes with lower intensities

Average loss per tornado and total loss by EF number for 1995–2011 (in 2011 $)



Source: NIST (2014)

https://doi.org/10.6028/NIST.NCSTAR.3

Opportunity for Tornado Loss Reduction

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

We don't *have* to design everything to withstand the most violent tornadoes in order to significantly reduce tornado damage

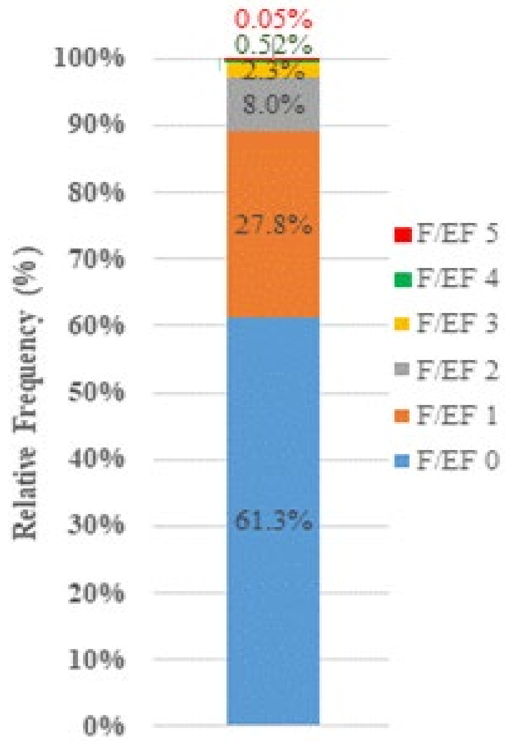
From 1995-2016, of the over 1,200 tornadoes/year

*** 89.1% were EF0-EF1, 97.1% 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**

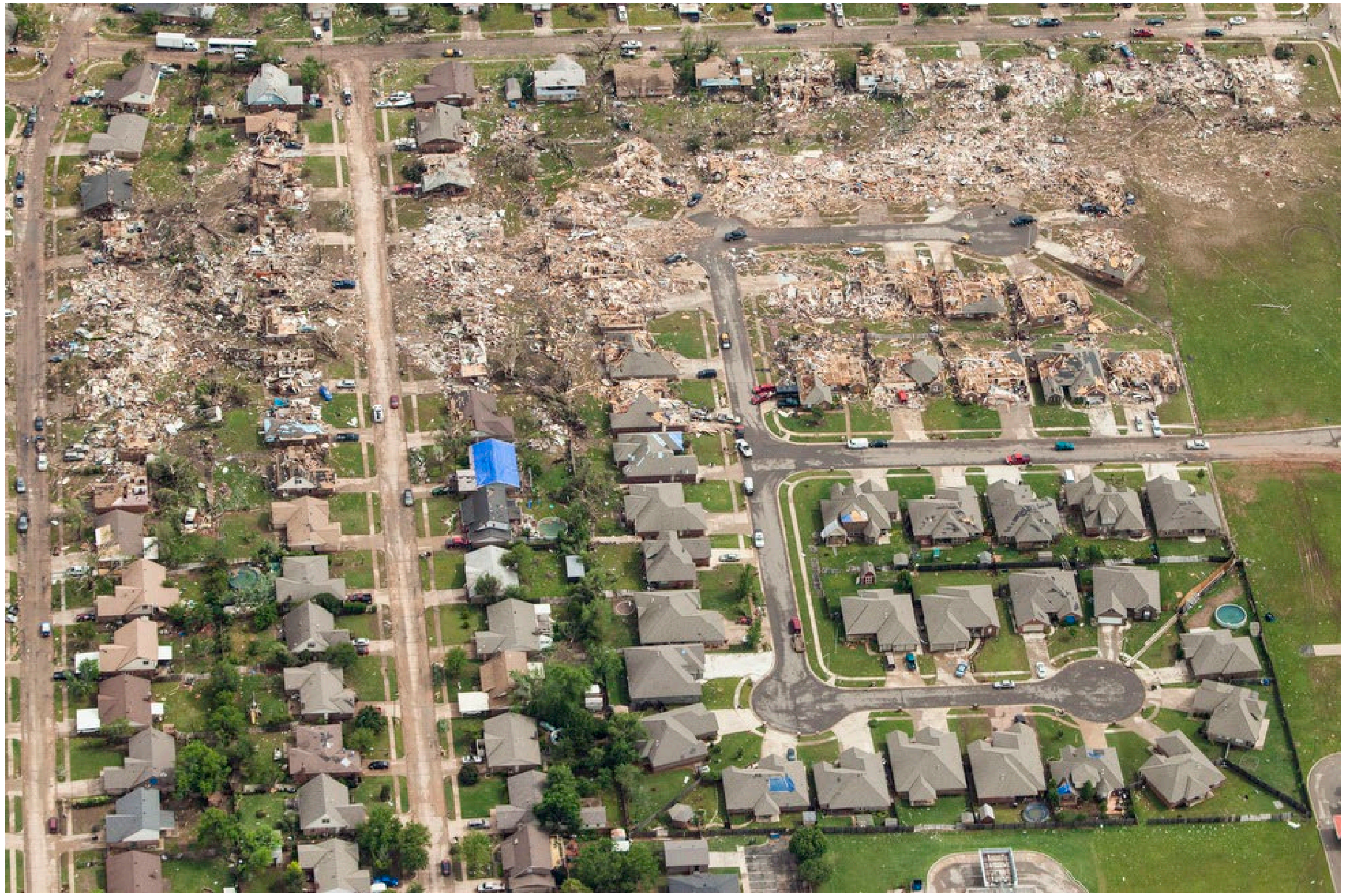
*** 28% experienced EF3-EF5 winds**



Data Source: NOAA. Analysis by NIST

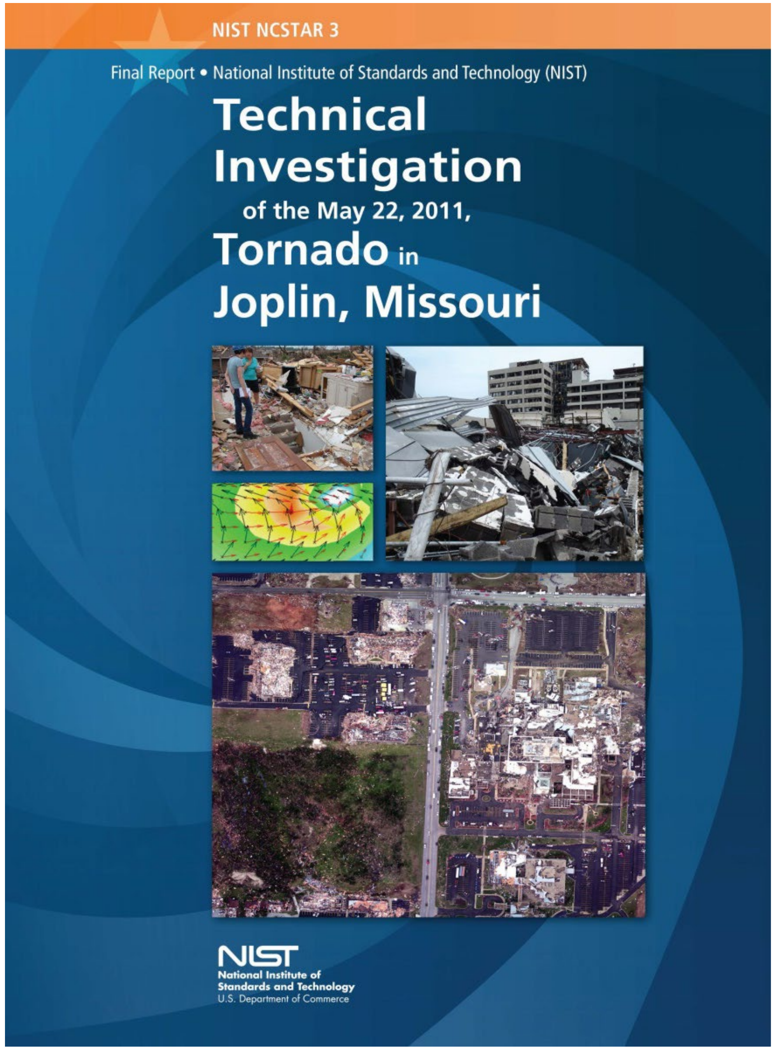
Paradigm Shift Needed

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



Genesis of Tornado Loads in ASCE 7-22

NIST



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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Context – Building Codes and Standards

NIST

National model building codes, standards, and practices seek to achieve life safety for the hazards considered in design.

Until ASCE 7-22, tornado hazards were not considered in the design of buildings, except for safety–related structures in nuclear power plants, storm shelters, and safe rooms.

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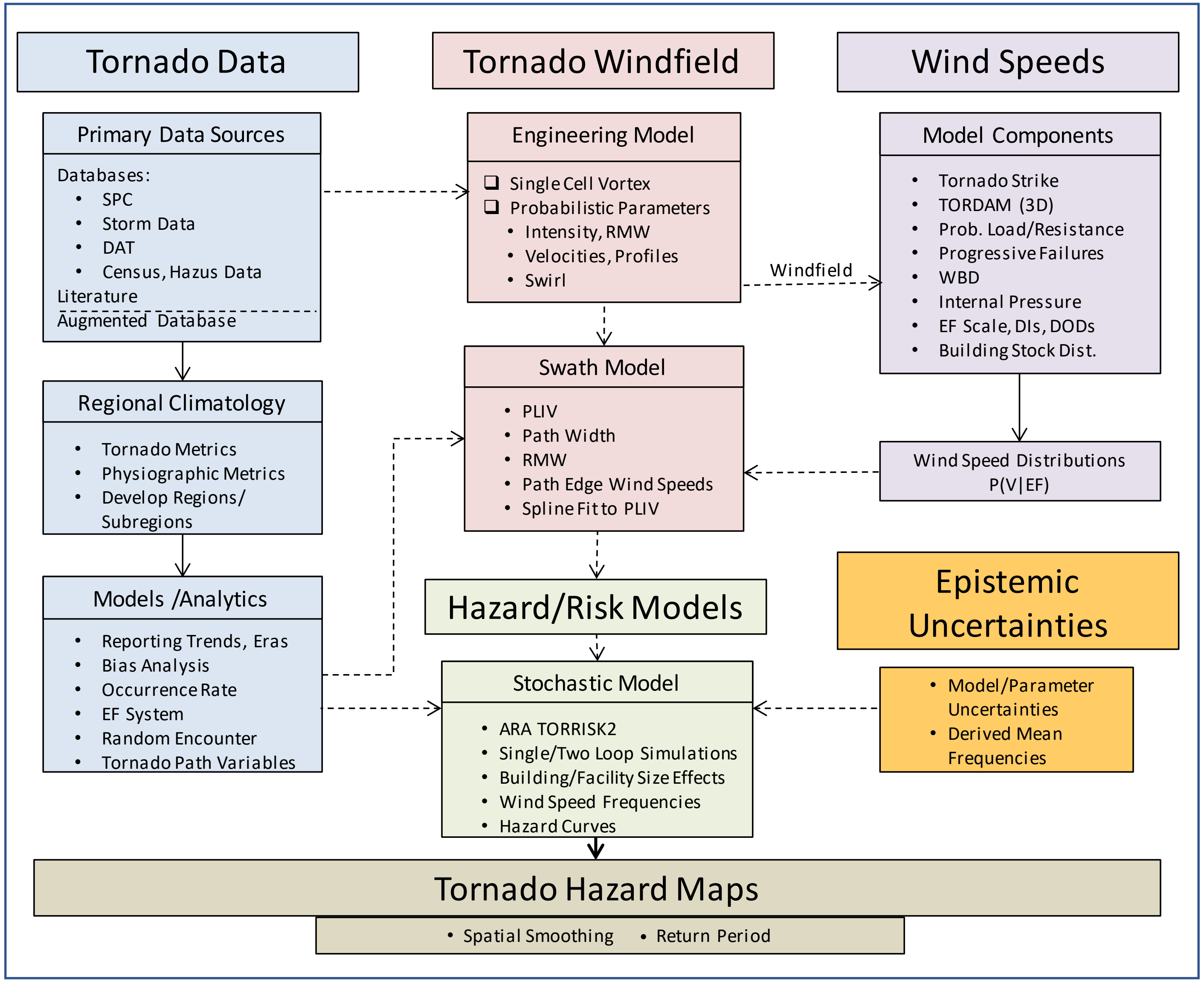
Development of the Tornado Load Methodology

Tornado Hazard Maps

Map Development Overview

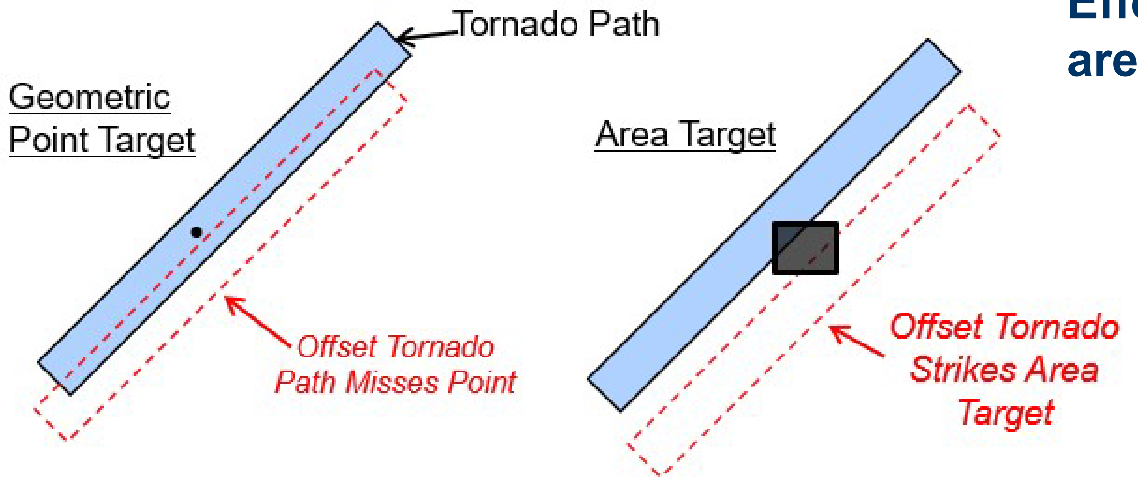
- Tornado Risk Mapping Project Components
- Six year effort, working with Applied Research Associates, Inc. (ARA) under contract to NIST, led by Dr. Larry Twisdale
- The US Nuclear Regulatory Commission supplemented NIST funding to include the analysis of epistemic uncertainties



Target Size Effects

Tornado risk and tornado speeds are a function of building or facility size and shape (effective plan area)

- Tornado strike probabilities increase with increasing plan area of the target building or structure (target size)
- For a given return period (i.e., mean recurrence interval), tornado speeds increase with increasing target size



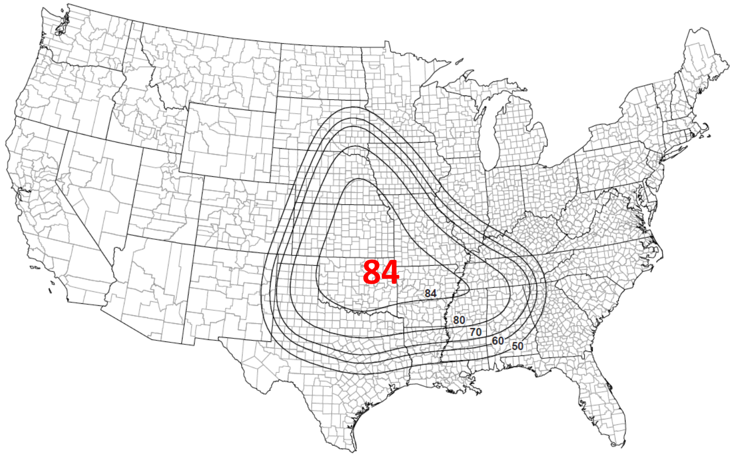
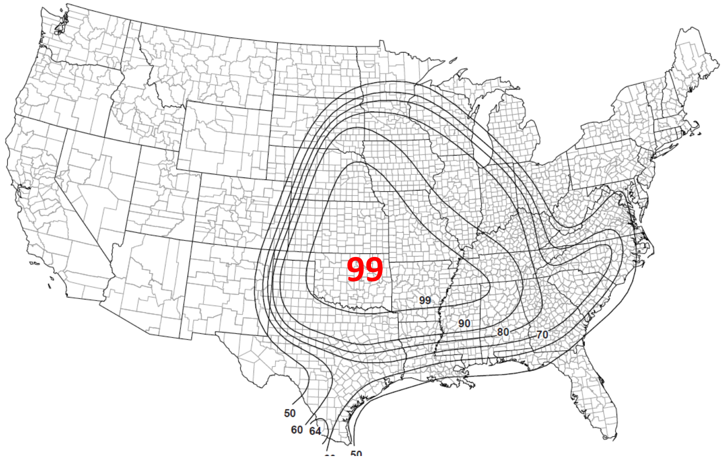
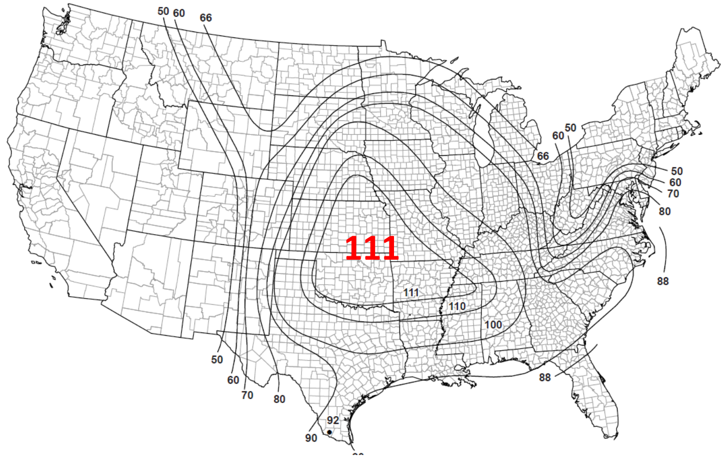
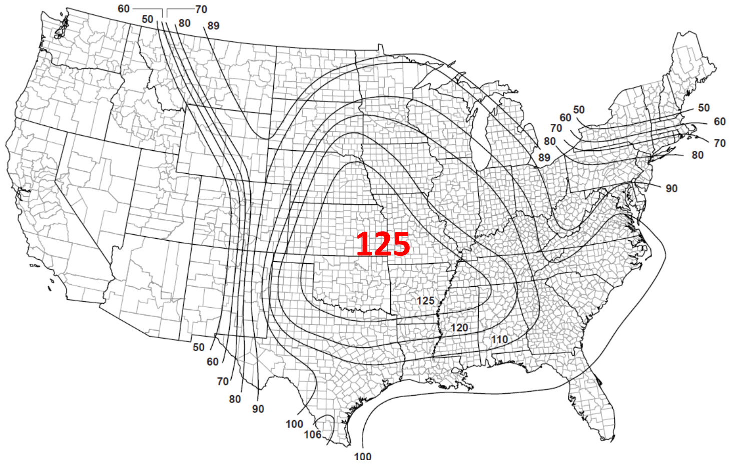
Effects of building or facility plan area on tornado strike probability

"Does the Flap of a Butterfly's Wings in Brazil Set off a Tornado in Texas?"
Edward U. Lorenz, Sc.D.
Professor of Meteorology
Massachusetts Institute of Technology, Cambridge

https://www.ias.ac.in/article/fulltext/reso/020/03/0260-0263

Tornado Hazard Maps - Examples

NIST

Effective Plan Area, A_e (ft^2)	Risk Category III (1,700 Year)	Risk Category IV (3,000 Year)
10K		
1M		

Map labels (10K, Risk Category III): 84, 84, 80, 70, 60, 50

Map labels (10K, Risk Category IV): 99, 99, 90, 80, 70, 50, 60, 64, 50

Map labels (1M, Risk Category III): 111, 50, 60, 66, 60, 50, 66, 50, 60, 70, 80, 88, 111, 110, 100, 88, 50, 60, 70, 80, 92, 90

Map labels (1M, Risk Category IV): 125, 60, 70, 50, 80, 89, 60, 50, 70, 80, 89, 50, 60, 70, 80, 90, 125, 120, 110, 50, 60, 70, 80, 90, 100, 106, 100

8 mapped effective plan area sizes, A_e (target sizes), from 1 to 4M sq ft

Mapped tornado speeds also developed for longer return periods

- 10,000 years
- 100,000 years
- 1,000,000 years
- 10,000,000 years

Tornado speeds are 3-s peak gusts in mph at 33 ft (10 m) height

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Tornadic Wind Characteristics

NIST

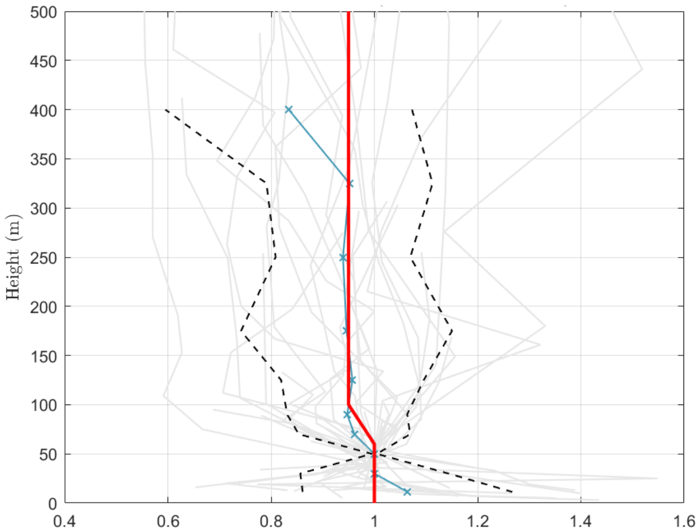
Very different from straight-line winds

- Climatology
- Short duration
- Rapidly changing speeds and directions
- Strong updrafts
- Decreasing speed with height above ground
- Atmospheric Pressure Change
- More intense windborne debris

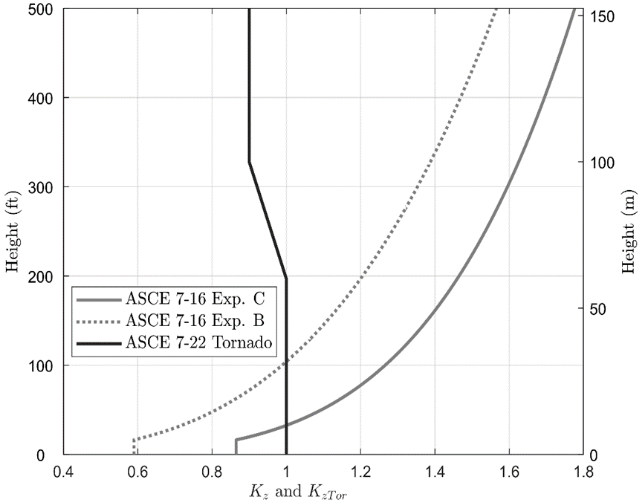
Worked closely with mobile radar community

- Analyzed radar-measured tornado wind speeds
- Developed tornado velocity profiles, very different from boundary layer profiles
- Developed idealized velocity pressure profile for design

Source: NSF



Normalized Tornado Velocity Profiles



ASCE 7-22 Velocity Pressure Profiles for Tornadic and Straight-Line Winds

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Tornadic Wind-Structure Interaction

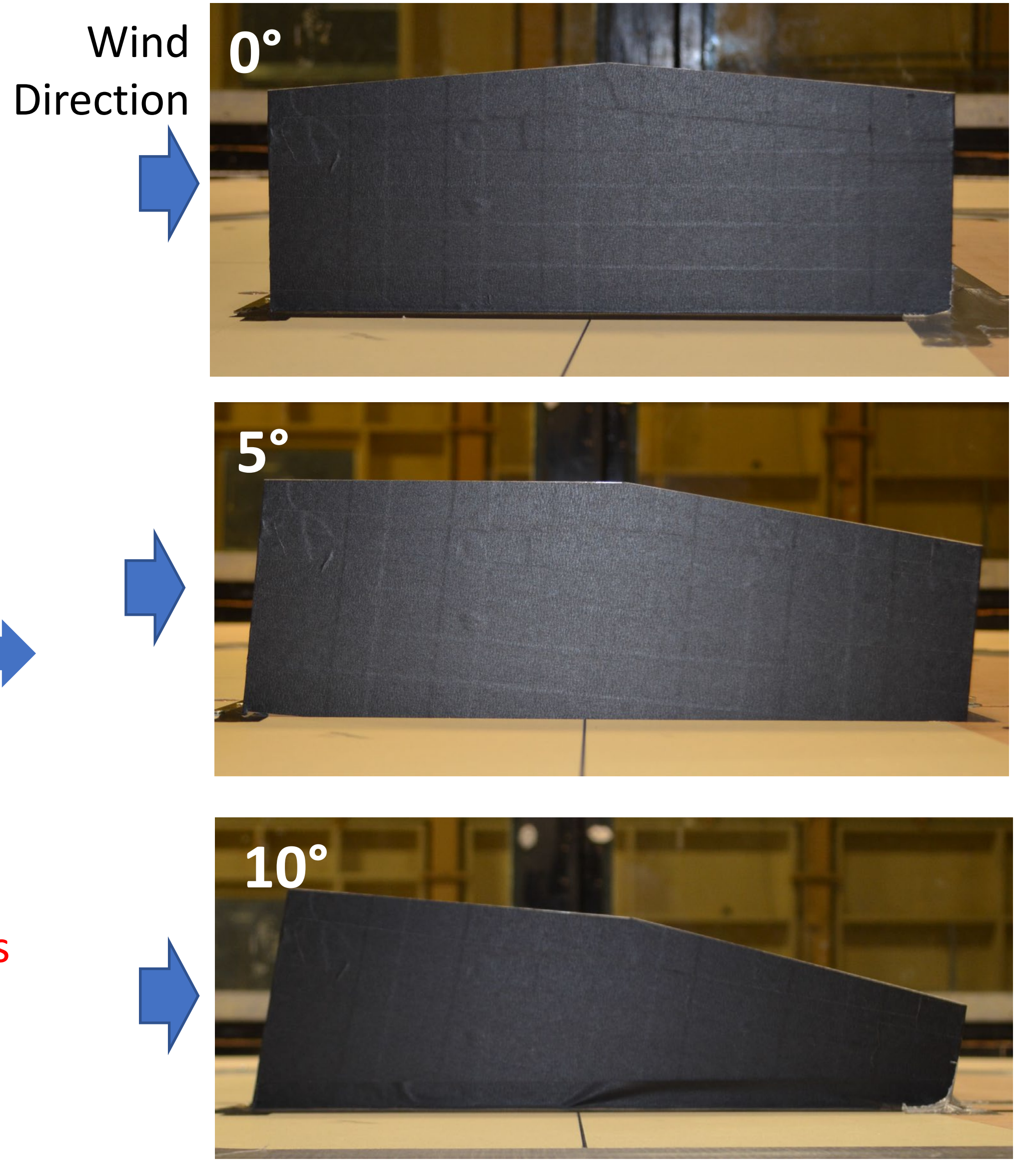
NIST

Very different from straight-line winds

- Climatology
  - New probabilistic hazard maps, including target size effects
- Short duration
  - Changes to gust effect factor
- Rapidly changing speeds and directions
  - Changes to directionality factor
- Strong updrafts
  - Added factor to account for increase in roof uplift pressures

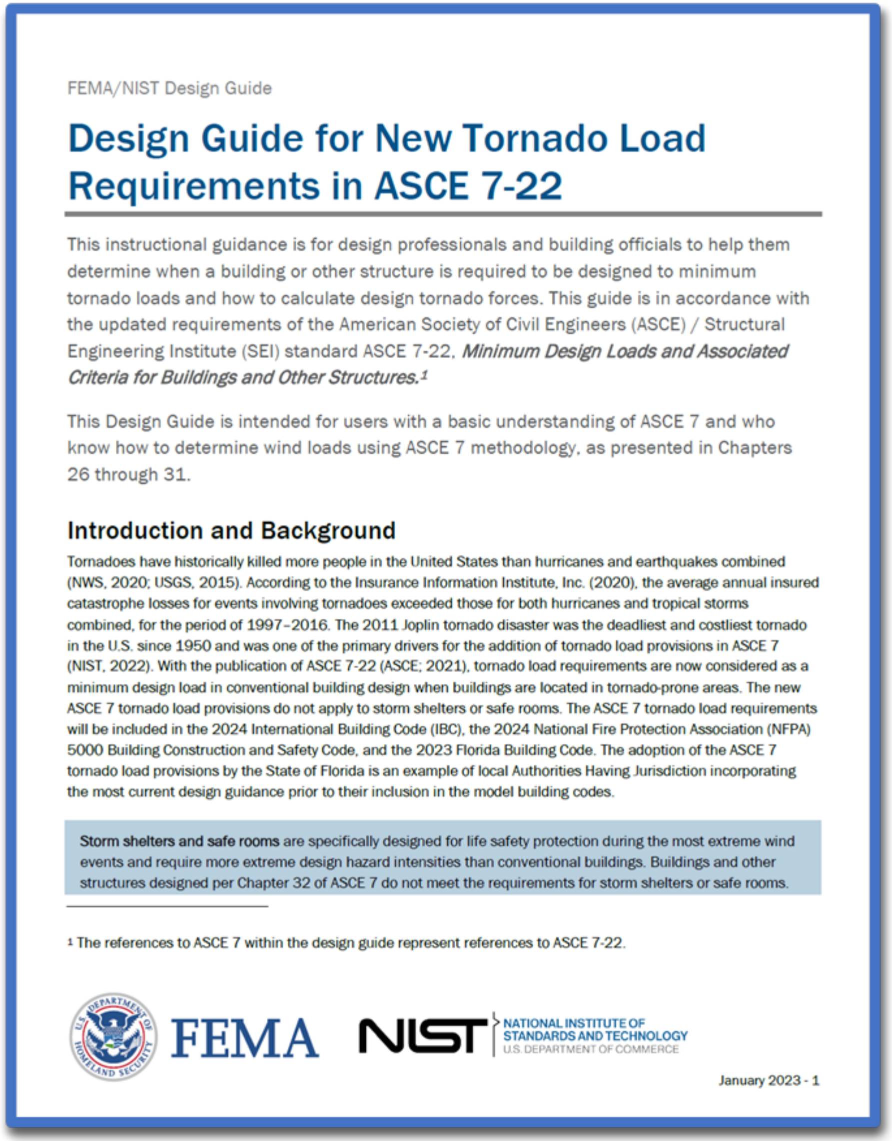
Conducted wind tunnel tests to simulate the effective change in wind angle at the leading edge of the roof

- Decreasing speed with height above ground
  - Changes to velocity pressure exposure coefficient
- Atmospheric Pressure Change
  - Changes to internal pressure coefficient to account for contributions of APC
- More Intense Windborne Debris
  - Requirements for protection of glazed openings



FEMA/NIST Tornado Design Guidance

NIST



FEMA/NIST Design Guide

Design Guide for New Tornado Load Requirements in ASCE 7-22

This instructional guidance is for design professionals and building officials to help them determine when a building or other structure is required to be designed to minimum tornado loads and how to calculate design tornado forces. This guide is in accordance with the updated requirements of the American Society of Civil Engineers (ASCE) / Structural Engineering Institute (SEI) standard ASCE 7-22, ***Minimum Design Loads and Associated Criteria for Buildings and Other Structures.***[1]

This Design Guide is intended for users with a basic understanding of ASCE 7 and who know how to determine wind loads using ASCE 7 methodology, as presented in Chapters 26 through 31.

Introduction and Background

Tornadoes have historically killed more people in the United States than hurricanes and earthquakes combined (NWS, 2020; USGS, 2015). According to the Insurance Information Institute, Inc. (2020), the average annual insured catastrophe losses for events involving tornadoes exceeded those for both hurricanes and tropical storms combined, for the period of 1997–2016. The 2011 Joplin tornado disaster was the deadliest and costliest tornado in the U.S. since 1950 and was one of the primary drivers for the addition of tornado load provisions in ASCE 7 (NIST, 2022). With the publication of ASCE 7-22 (ASCE; 2021), tornado load requirements are now considered as a minimum design load in conventional building design when buildings are located in tornado-prone areas. The new ASCE 7 tornado load provisions do not apply to storm shelters or safe rooms. The ASCE 7 tornado load requirements will be included in the 2024 International Building Code (IBC), the 2024 National Fire Protection Association (NFPA) 5000 Building Construction and Safety Code, and the 2023 Florida Building Code. The adoption of the ASCE 7 tornado load provisions by the State of Florida is an example of local Authorities Having Jurisdiction incorporating the most current design guidance prior to their inclusion in the model building codes.

Storm shelters and safe rooms are specifically designed for life safety protection during the most extreme wind events and require more extreme design hazard intensities than conventional buildings. Buildings and other structures designed per Chapter 32 of ASCE 7 do not meet the requirements for storm shelters or safe rooms.

[1] The references to ASCE 7 within the design guide represent references to ASCE 7-22.

FEMA NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY U.S. DEPARTMENT OF COMMERCE

January 2023 - 1

Available online from FEMA and NIST

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ASCE/SEI 7-22
Tornado Provision Highlights

Marc Levitan

Chair
ASCE 7-22 Tornado Task Committee

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Tornado Loads: Placement in 7-22

Red indicates differences from ASCE 7-16

- **Chapter 1: General**
  - Add Tornadoes to Risk Categorization Table 1.5-1
- **Chapter 2: Load Combinations**
  - Add Tornado Loads to load combinations
- **Chapter 26: Wind Loads**
  - Add requirement to check Tornado Loads per Ch. 32
- **New Chapter 32: Tornado Loads**
  - Complete provisions to determine Tornado Loads
- **New Appendix G: Tornado Hazard Maps for Long Return Periods**
  - Tornado speed maps for longer return periods, in support of tornado PBD and other applications

Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Tornado, Snow, Earthquake, and Ice Loads

	Risk Category
Buildings and other structures that represent low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life	III
Buildings and other structures designated as essential facilities Buildings and other structures, the failure of which could pose a substantial hazard to the community Buildings and other structures required to maintain the functionality of other Risk Category IV structures	IV

WIND LOADS: GENERAL REQUIREMENTS

26.1 PROCEDURES

26.1.1 Scope. Buildings and other structures, including the main wind force resisting system (MWFRS) and all components and cladding (C&C) thereof, shall be designed and constructed to resist the wind loads determined in accordance with Chapters 26 through 31.

Risk Category III and IV buildings and other structures, including the MWFRS and all C&C thereof, shall also be designed and constructed to resist tornado loads determined in accordance with Chapter 32, as applicable.

The provisions of this chapter define basic wind parameters for use with other provisions contained in this standard.

….

~~**26.14 TORNADO LIMITATION**~~

~~Tornadoes have not been considered in the wind load provisions.~~

COMMENTARY

C26.1 PROCEDURES

C26.1.1 Scope.

…

Tornado loads are treated separately from wind loads, as described in Section C32.1.

…

~~**C26.14 TORNADO LIMITATION**~~

~~Tornadoes have not been considered in the wind load provisions because of their very low probability of occurrence~~….

<delete the entirety of the C26.14 tornado limitation commentary and associated references>

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Ch. 32: Tornado Loads

- Built on ASCE 7 wind load procedures framework
  - Designed to provide similar look and feel with the wind provisions for improved ease of use
- Most wind load coefficients and equations are modified to account for differences in tornadic wind and wind-structure interaction
- Despite similarities in procedures, tornado loads are treated separately from wind loads

CHAPTER 32
TORNADO LOADS

32.1 PROCEDURES

32.1.1 Scope Buildings and other structures classified as Risk Category III or IV and located in the tornado-prone region as shown in Figure 32.1-1, including the main wind force resisting system (MWFRS) and all components and cladding (C&C) thereof, shall be designed and constructed to resist the greater of the tornado loads determined in accordance with the provisions of this chapter or the wind loads determined in accordance with Chapters 26 through 31, using the load combinations provided in Chapter 2.

> **User Note:** The tornado loads specified in this chapter provide reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for MWFRS, and therefore are only required for Risk Category III and IV buildings and other structures (see Return Period discussion in Section C32.5.1 for more information). The tornado loads are based on tornado speeds using 1,700- and 3,000-year return periods for Risk Category III and IV, respectively (which are the same return periods used for basic wind speeds in Chapter 26). The tornado speed at any given geographic location will range from approximately Enhanced Fujita Scale EF0 – EF2 intensity, depending on the risk category and effective plan area of the building or other structure (see Section C32.5.1). Options for protection of life and property from more intense tornadoes include construction of a storm shelter and/or design for longer-return-period tornado speeds as provided in Appendix G, including performance-based design. A building or other structure designed for tornado loads determined exclusively in accordance with Chapter 32 cannot be designated as a storm shelter without meeting additional critical requirements provided in the applicable building code and ICC 500, the ICC/NSSA *Standard for the Design and Construction of Storm Shelters*. See Commentary Section C32.1.1 for an in-depth discussion on storm shelters.

32.1.2 Permitted Procedures The design tornado loads for buildings and other structures, including the MWFRS and C&C elements thereof, shall be determined using one of the procedures as specified in this section and subject to the applicable limitations of Chapters 26 through 32, excluding Chapter 28.

An outline of the overall process for the determination of the tornado loads, including section references, is provided in Figure 32.1-3.

32.1.2.1 Tornado Loads on the Main Wind Force Resisting System Tornado loads for the MWFRS shall be determined using one or more of the following procedures, as modified by Chapter 32:

1. Directional Procedure for buildings of all heights as specified in Chapter 27 for buildings meeting the requirements specified therein;
2. Directional Procedure for Building Appurtenances (such as rooftop structures and rooftop equipment) and Other Structures (such as solid freestanding walls and solid freestanding signs, chimneys, tanks, open signs, single-plane open frames, and trussed towers) as specified in Chapter 29 for buildings meeting the requirements specified therein; or
3. Wind Tunnel Procedure for all buildings and all other structures as specified in Chapter 31 for buildings meeting the requirements specified therein.

32.1.2.2 Tornado Loads on Components and Cladding Tornado loads on the C&C of all buildings and other structures shall be determined using one or more of the following procedures, as modified by Chapter 32:

1. Analytical Procedures as specified in Parts 1 through 5, as appropriate, of Chapter 30, for buildings meeting the requirements specified therein; or
2. Wind Tunnel Procedure for all buildings and all other structures as specified in Chapter 31, for buildings meeting the requirements specified therein.

32.1.3 Performance-Based Procedures Tornado design of buildings and other structures using performance-based procedures shall be permitted subject to the approval of the Authority Having Jurisdiction. The performance-based tornado design procedures used shall, at a minimum, conform to Section 1.3.1.3 and be documented and submitted to the Authority Having Jurisdiction in accordance with Section 1.3.1.3.

32.2 DEFINITIONS

The following definitions apply to the provisions of Chapter 32. Terms not defined in this chapter shall be defined in accordance with Chapters 26 through 31, as appropriate, excluding Chapter 28.

ASCE TORNADO DESIGN GEODATABASE: The ASCE database (version 2020-1.0) of geocoded tornado speed design data.

OTHER STRUCTURES, SEALED: A structure that is completely sealed or has controlled ventilation such that tornado-induced atmospheric pressure changes will not be transmitted to the inside of the structure, including but not limited to certain tanks and vessels.

TORNADO-PRONE REGION: The area of the contiguous United States most vulnerable to tornadoes, as shown in Figure 32.1-1.

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Scope

- Risk Category III and IV buildings and other structures
- Located in the tornado-prone region
- Design of MWFRS and C&C
- Must resist the greater of tornado loads or wind loads, using load combinations in Chapter 2

32.1 PROCEDURES

32.1.1 Scope Buildings and other structures classified as Risk Category III or IV and located in the tornado-prone region as shown in Figure 32.1-1, including the main wind force resisting system (MWFRS) and all components and cladding (C&C) thereof, shall be designed and constructed to resist the greater of the tornado loads determined in accordance with the provisions of this chapter or the wind loads determined in accordance with Chapters 26 through 31, using the load combinations provided in Chapter 2.

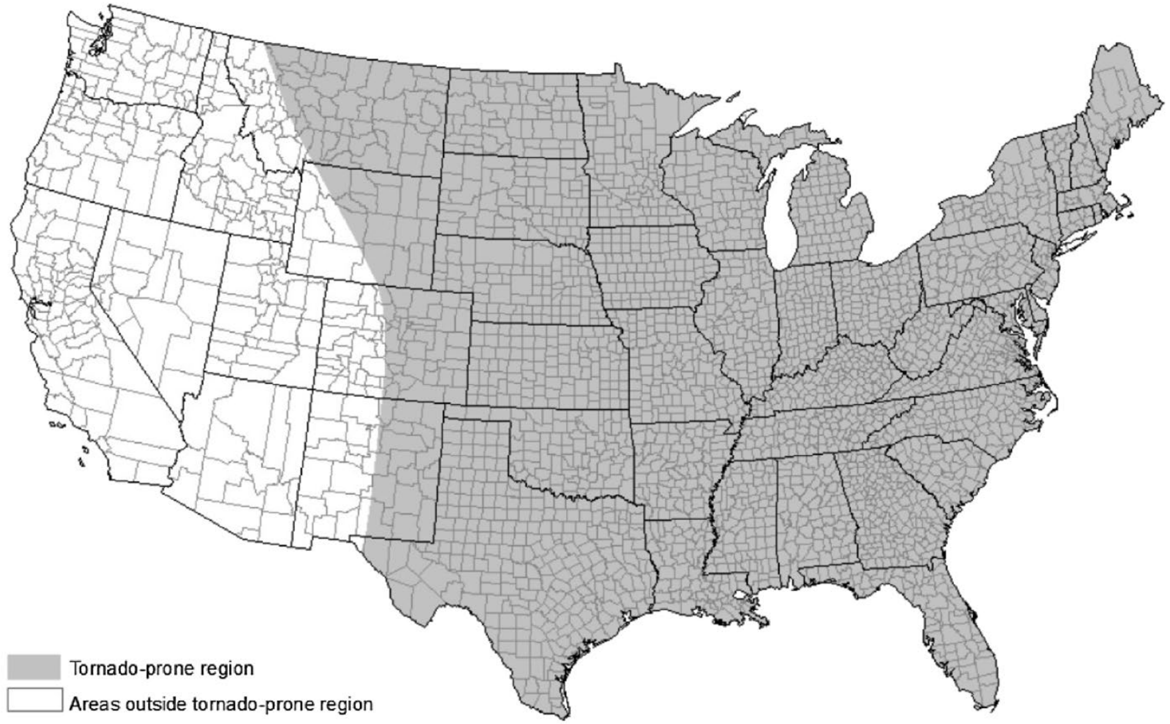

Figure 32.1-1. Tornado-prone region.

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User Note

- Highlights key features/ explanations of tornado load provisions
- Design tornado speeds range from 60-138 mph, approximately EF0-EF2 intensity,
  - Dependent on Risk Category, geographic location, and effective plan area (target size)
- Return periods for Risk Category III and IV are 1,700 and 3,000 years, respectively (the same as used for wind loads)
- Options for protection from more intense tornadoes include storm shelters and PBD
- Tornado shelters cannot be designed solely using Chapter 32 – pointers to commentary

User Note: The tornado loads specified in this chapter provide reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for MWFRS, and therefore are only required for Risk Category III and IV buildings and other structures (see Return Period discussion in Section C32.5.1 for more information). The tornado loads are based on tornado speeds using 1,700- and 3,000-year return periods for Risk Category III and IV, respectively (which are the same return periods used for basic wind speeds in Chapter 26). The tornado speed at any given geographic location will range from approximately Enhanced Fujita Scale EF0 – EF2 intensity, depending on the risk category and effective plan area of the building or other structure (see Section C32.5.1). Options for protection of life and property from more intense tornadoes include construction of a storm shelter and/or design for longer-return-period tornado speeds as provided in Appendix G, including performance-based design. A building or other structure designed for tornado loads determined exclusively in accordance with Chapter 32 cannot be designated as a storm shelter without meeting additional critical requirements provided in the applicable building code and ICC 500, the ICC/NSSA *Standard for the Design and Construction of Storm Shelters*. See Commentary Section C32.1.1 for an in-depth discussion on storm shelters.

Risk Category IV vs Tornado Shelter Requirements

Ch. 32 RC IV Tornado Speed

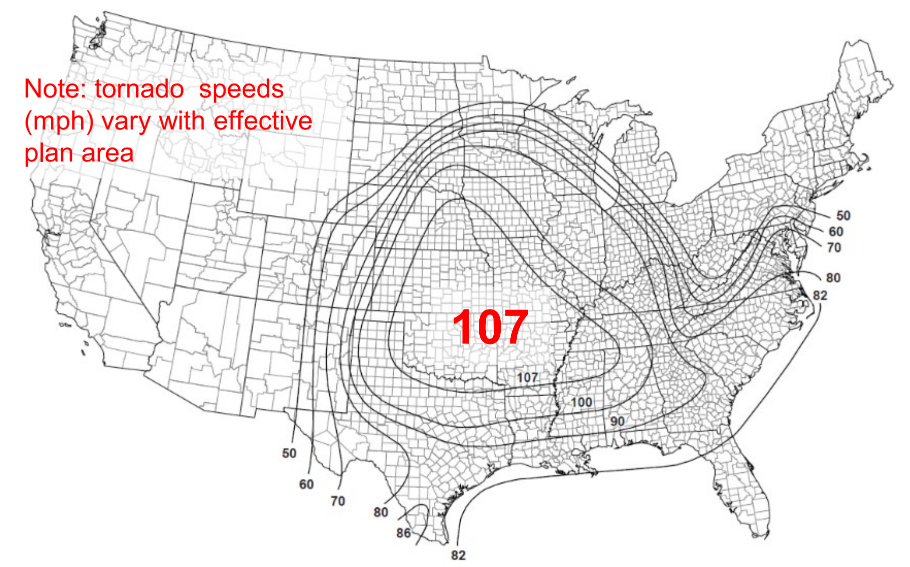

FIGURE 32.5-1E Tornado Speeds for Risk Category IV Buildings and Other Structures, for Effective Plan Area of 100,000 ft² (9,290 m²)

Source: ASCE 7-22

Enhanced Fujita (EF) Scale	
RATING	3-s GUST (mph)
0	65-85
1	86-110
2	111-135
3	136-165
4	166-200
5	200+

ICC 500 Tornado Shelter Speed

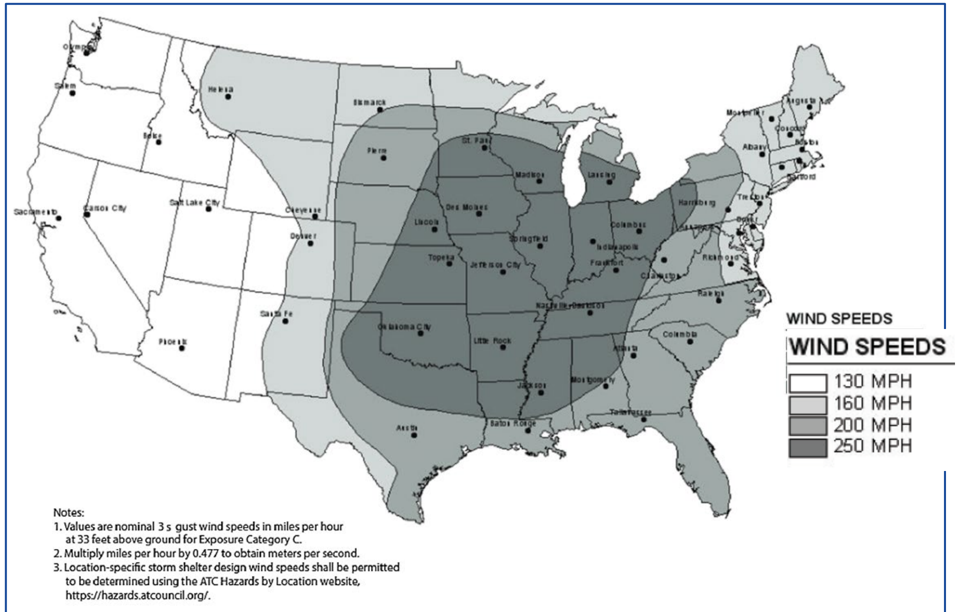

Figure C32.1-1. Tornado wind speeds for design of tornado shelters and tornado safe rooms (ICC 2020).

Source: ASCE 7-22 - Chapter 32 Commentary

ASCE 7-22 Chapter 32

- Tornado Intensity: generally in EF0 – EF2 range
  - Probabilistic – same return periods used for basic wind speed
  - Tornado speeds increase with effective plan area
- Wind-borne debris: 9-lb sawn lumber 2x4 at 34 mph
  - Requirements for glazed openings in *essential facilities*

ICC 500 has additional, more stringent requirements for shelters compared to ASCE 7 RC IV

ICC 500-2020 Tornado Shelters

- Tornado Intensity: EF2 – EF 5 range
  - Deterministic - near-worst case scenario/most intense tornadoes
- Wind-borne debris: 15-lb sawn lumber 2x4 at 80-100 mph
  - All shelter exterior walls must resist missile impacts

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Reliability/Return Periods

- Conducted a series of risk informed analyses to compare the proposed tornadic wind load criteria with the reliability delivered by the existing (ASCE 7-16) wind load provisions
  - Collaboration between ASCE 7 Load Combinations Subcommittee and Wind Load Subcommittee
  - Adaptation of the reliability analysis used for ASCE 7-16 wind maps

Key Finding
Using 1,700- and 3,000-year maps for Risk Category III and IV, respectively, the tornadic wind load criteria provide reasonable consistency with the reliability delivered by the existing criteria in Chapters 26 and 27 for main wind force-resisting systems.

ASCE 7-22 Wind and Tornado Map Return Periods

Risk Category	Ch. 26 Wind Return Period (years)	Ch. 32 Tornado Return Period (years)
I	300	n/a
II	700	n/a
III	1,700	1,700
IV	3,000	3,000

No significant tornado risk at 300 and 700 year return periods

Wind vs Tornado Load Procedures

Ch. 26 Wind Load Procedures

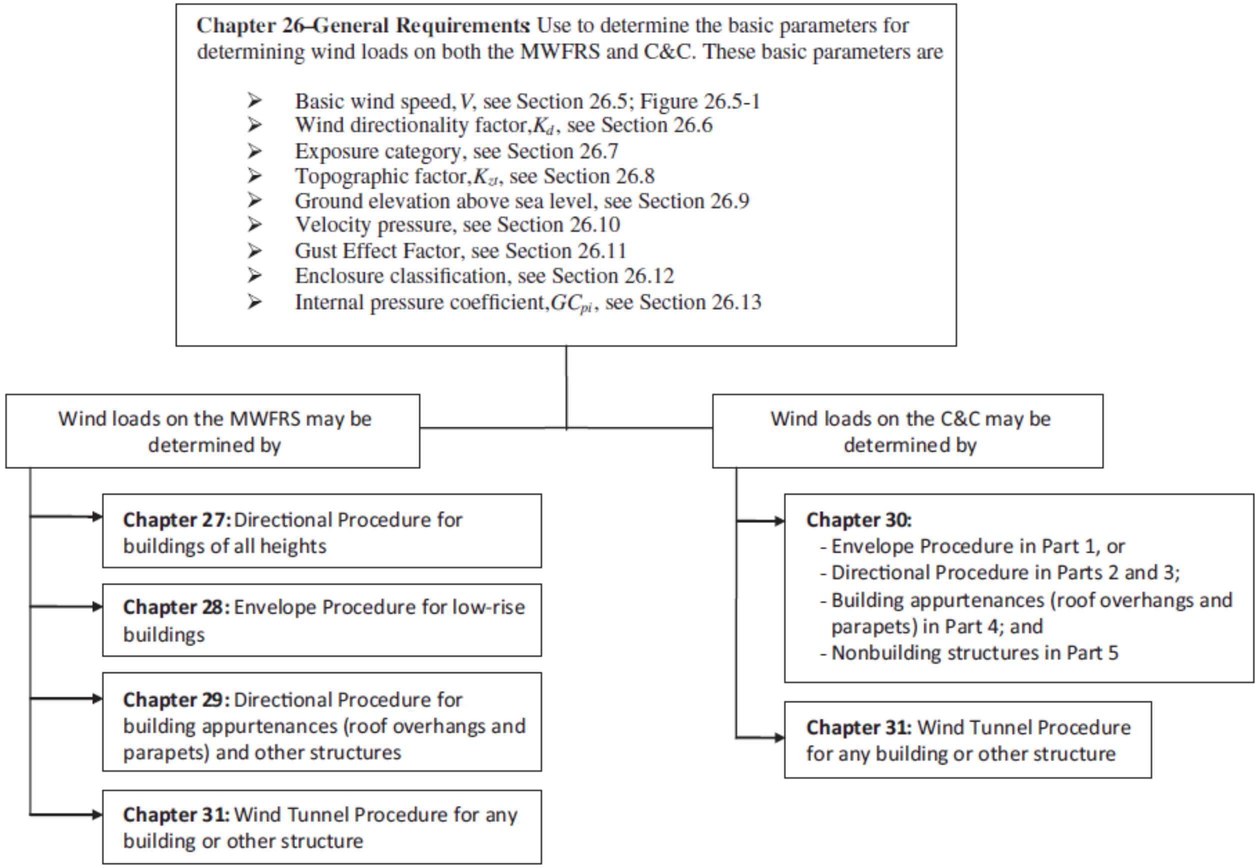


Figure 26.1-1. Outline of process for determining wind loads.

Ch. 32 Tornado Load Procedures

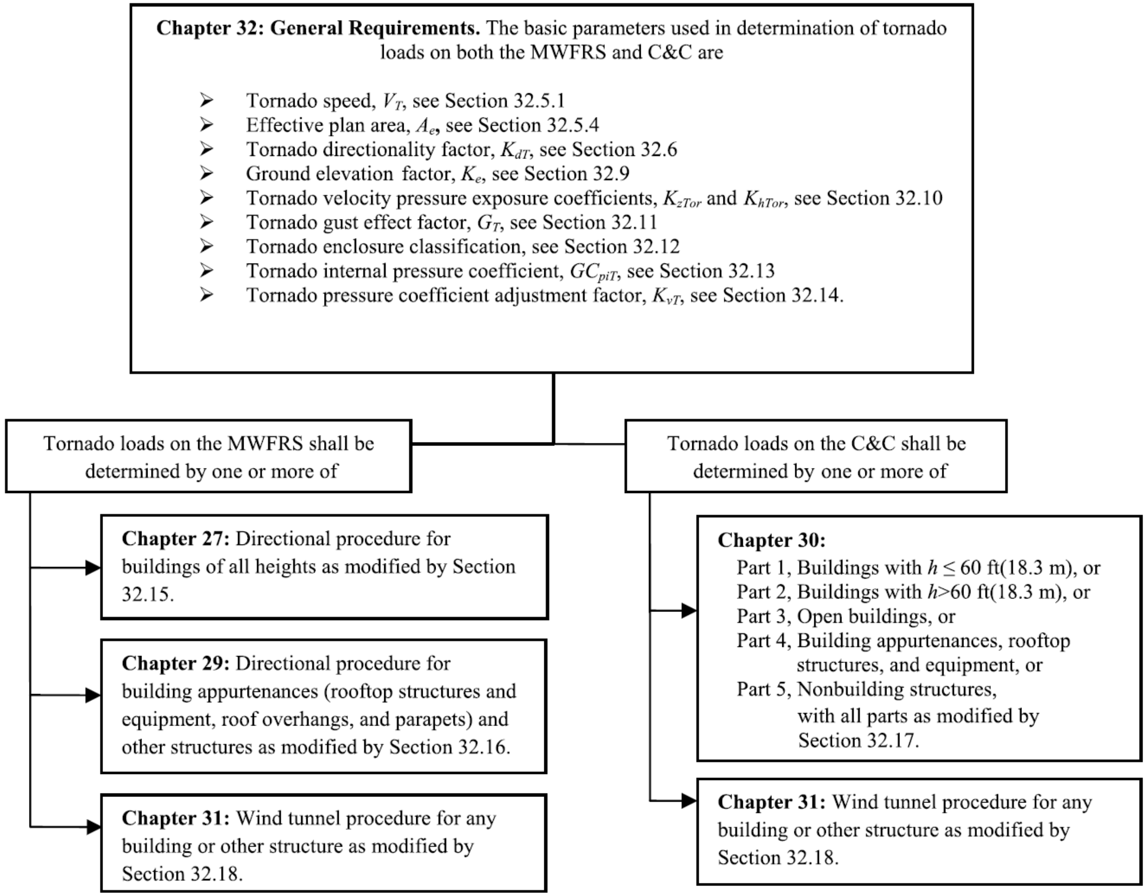


Figure 32.1-3. Outline of process for determining tornado loads.

Tornado Load Procedures

- Based on wind load procedures framework
- Most wind load parameters and equations have been modified to reflect differences between tornadic and non-tornadic wind and wind-structure interaction characteristics
- A few wind parameters eliminated and new tornado parameters added
- Tornado chapter heavily references wind chapters 26-31, except 28
- Chapter 28 (Envelope Procedure for MWFRS Loads) not applicable to tornadoes
- Limited applicability for Wind Tunnel Method
- Explicit permission to use performance-based tornado design

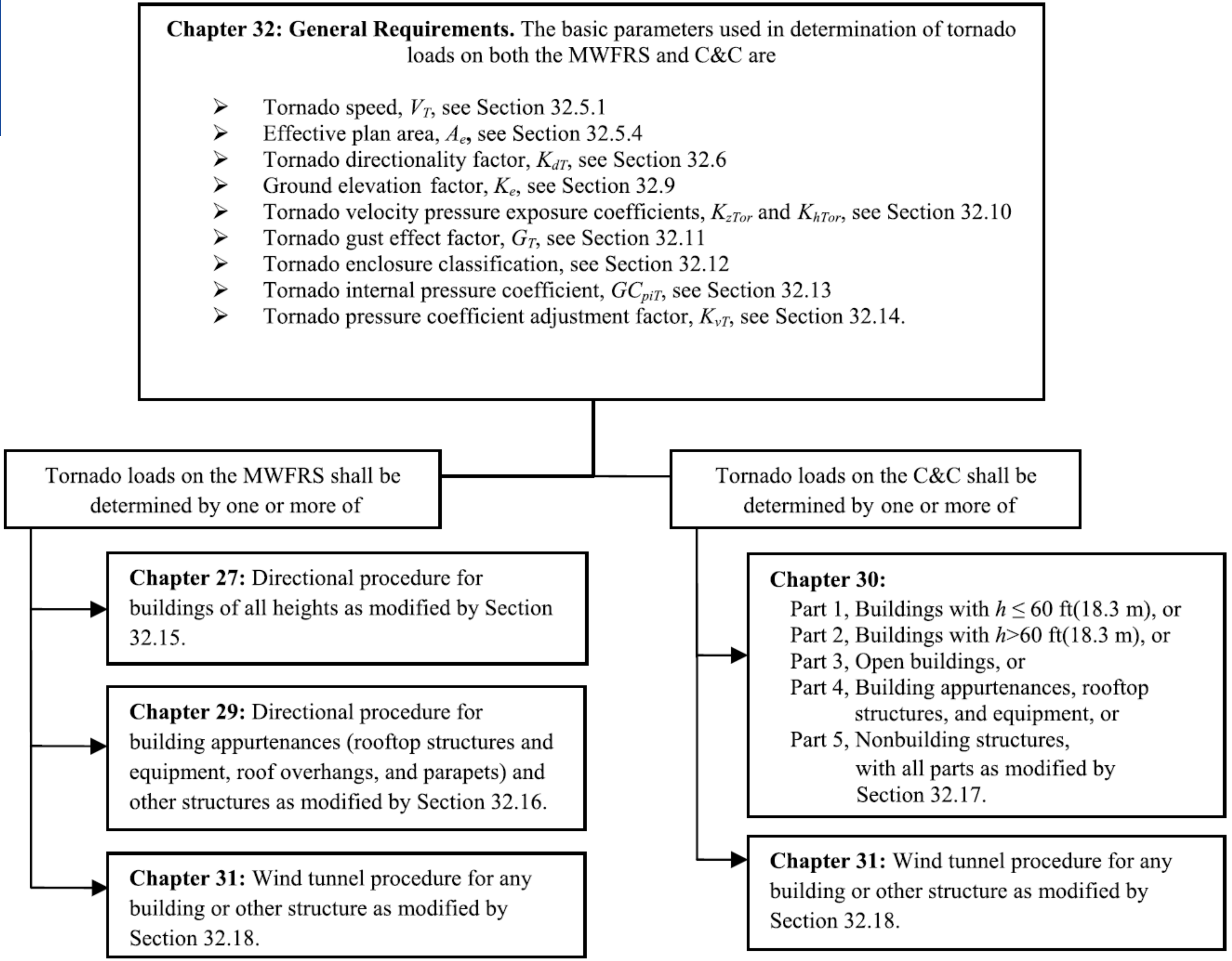


Figure 32.1-3. Outline of process for determining tornado loads.

Ch. 32 Organization Part 1

Parallel organization for Chapters 26 and 32

Same provisions for wind and tornado

No parallel provisions between wind and tornado

- 32.7 and 32.8 are placeholders for potential future tornado provisions
- Include brief commentary on state-of-knowledge

Chapter 26 Wind Loads Section numbers and titles	**Chapter 32 Tornado Loads** Section numbers and titles
26.1 Procedures	32.1 Procedures
26.2 Definitions	32.2 Definitions
26.3 Symbols	32.3 Symbols and Notation
26.4 General	32.4 General
26.5 Wind Hazard Map	32.5 Tornado Hazard Maps
26.6 Wind Directionality Factor	32.6 Tornado Directionality Factor
26.7 Exposure	32.7 Tornado Exposure
26.8 Topographic Effects	32.8 Tornado Topographic Factor
26.9 Ground Elevation Factor	32.9 Ground Elevation Factor
26.10 Velocity Pressure	32.10 Tornado Velocity Pressure
26.11 Gust Effects	32.11 Tornado Gust Effects
26.12 Enclosure Classification	32.12 Tornado Enclosure Classification
26.13 Internal Pressure Coefficients	32.13 Tornado Internal Pressure Coefficients
N/A	32.14 Tornado External Pressure Coefficients

Ch. 32 Symbols

- **Notes on Terms and Symbols**
  - Use wind load chapter (26) for symbols not defined in Ch. 32
  - Tornado-specific versions of wind load parameters are identified through addition of “Tornado” to parameter name and addition of subscript capital *“T”*, to the symbol, e.g.,
    - Gust Effect Factor becomes Tornado Gust Effect Factor
    - *G* becomes G_T
  - Exception: Velocity Pressure Exposure Coefficient
    - K_z becomes K_{zTor} instead of K_{zT}, to avoid confusion with K_{zt}, the topographic factor for wind loads

32.3 SYMBOLS AND NOTATION

The following symbols apply only to the provisions of Chapter 32. Symbols and notations not defined in this chapter shall be defined in accordance with Chapters 26 through 31, as appropriate, excluding Chapter 28.

A_e = Effective plan area of the building, other structure, or facility, ft^2 (m^2), as defined in Section 32.5.4

F_{hT} = Lateral design tornado force for rooftop structures and equipment from Equation (32.16-3), lb (N)

F_T = Design tornado force for certain other structures from Equation (32.16-2), lb (N)

F_{vT} = Vertical design tornado force for rooftop structures and equipment from Equation (32.16-4), lb (N)

G_T = Tornado gust-effect factor as defined in Section 32.11

GC_{piT} = Product of internal pressure coefficient that includes the effects of atmospheric pressure change and gust-effect factor, to be used in determination of tornado loads for buildings and some other structures, as determined in Section 32.13

K_{dT} = Tornado directionality factor as defined in Section 32.6

K_{hTor} = Tornado velocity pressure exposure coefficient evaluated at height $z = h$, as determined in Section 32.10

K_{vT} = Tornado pressure coefficient adjustment factor for vertical winds as defined in Section 32.14 . . .

Tornado Velocity Pressure (Ch 32)

Red indicates differences from ASCE 7-16 wind load parameters

$q = ½\,\rho\,V^2$ (section C26.10.2)

$q_T = 0.00256 * K_{zTor} K_e V_T^2$ (equation 32.10-1)

q_T Tornado velocity pressure (psf)

ρ Air density

- 0.00256 = ½ ρ (incl. unit conversions)

K_{zTor} Tornado velocity pressure exposure coeff

~~K_{zt} Topographic factor~~

K_e Ground elevation factor

V_T Tornado speed (mph)

Notes:

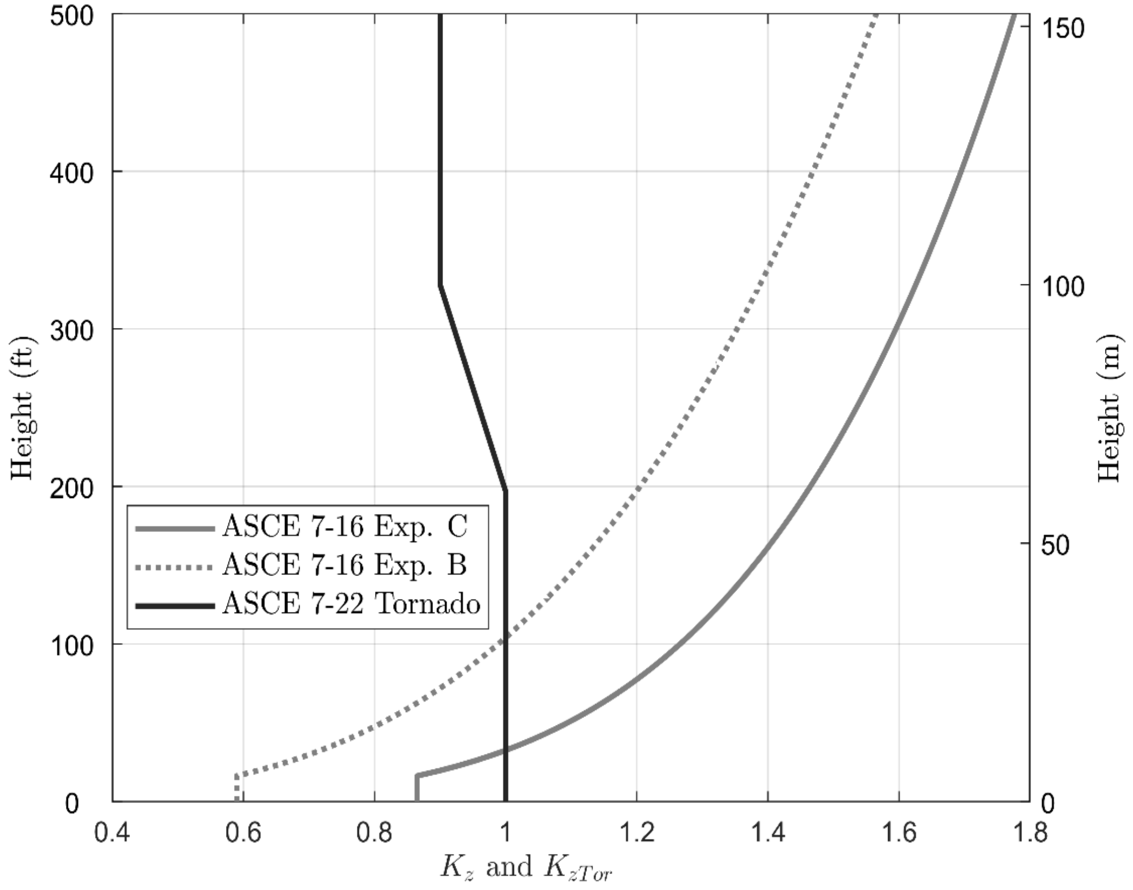
- Different exposure coefficients
- No topographic factor for tornadoes
- Tornado directionality factor moved to pressure and force equations
- Tornado speed uses different maps than wind speed

Tornado Velocity Pressure Exposure Coefficient

- Tornado velocity pressure variation with exposure is not yet understood
- Therefore, K_{zTor} as currently defined is independent of exposure

Table 32.10-1 Tornado Velocity Pressure Exposure Coefficients, K_{zTor} and K_{hTor}

Height above Ground Level, z		K_{zTor} and K_{hTor}
ft	m	
0-200	0-61.0	1.0
250	76.2	0.96
300	91.4	0.92
>328	>100	0.90



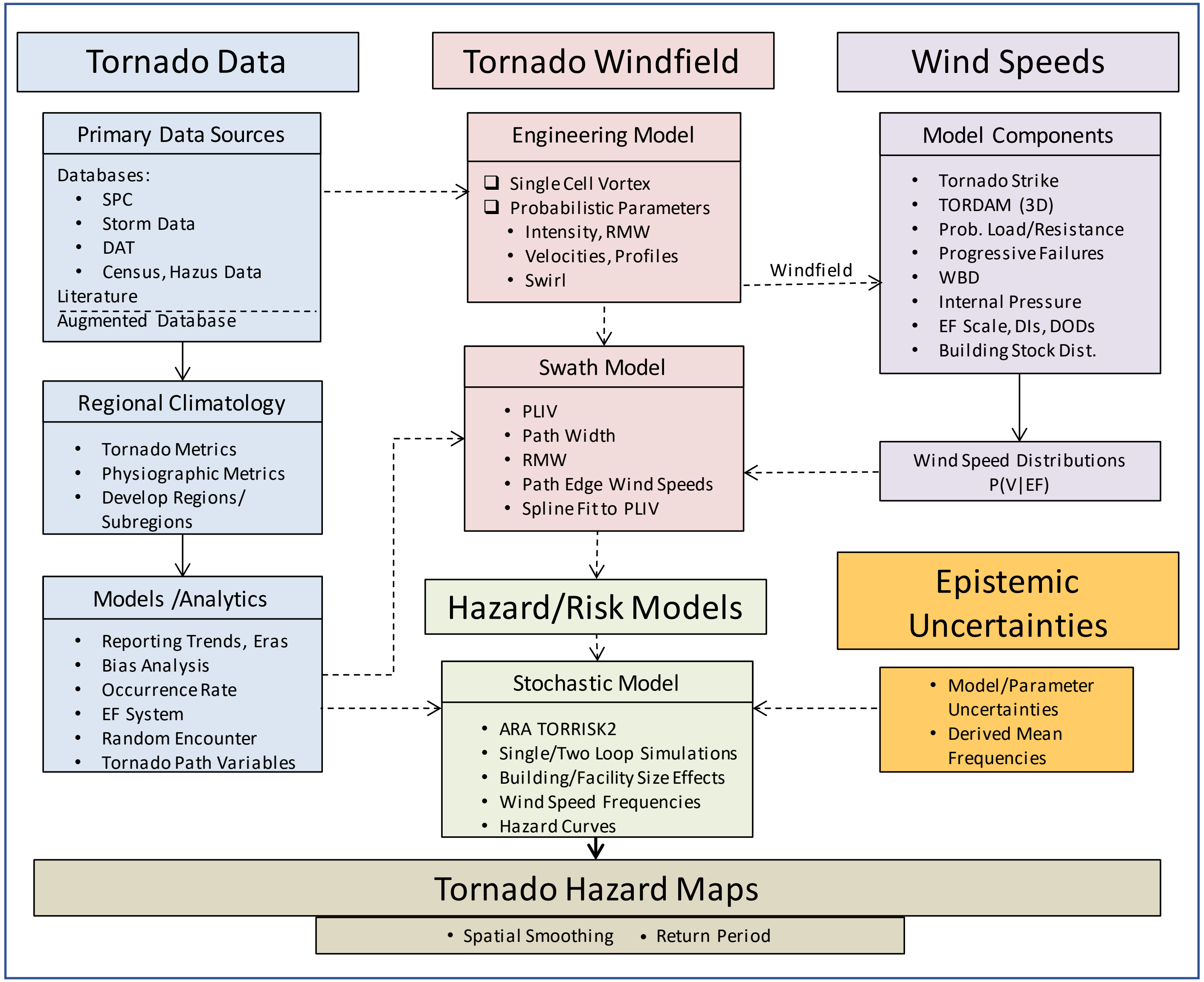
ICC 500 – use new K_{zTor} instead of Kz Exp C

- increases loads for h<33 ft
- decreases loads for h>33 ft

Tornado Hazard Maps

Map Development Overview

- Tornado Risk Mapping Project Components
- Six year effort, working with Applied Research Associates, Inc. (ARA) under contract to NIST, led by Dr. Larry Twisdale
- The US Nuclear Regulatory Commission supplemented NIST funding to include the analysis of epistemic uncertainties



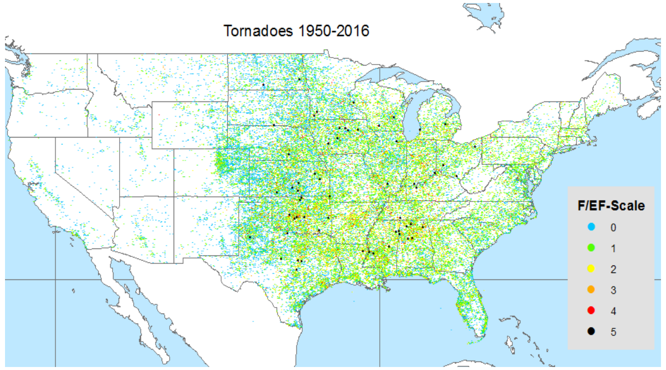
Tornado Climatology

Tornado Risk Regionalization

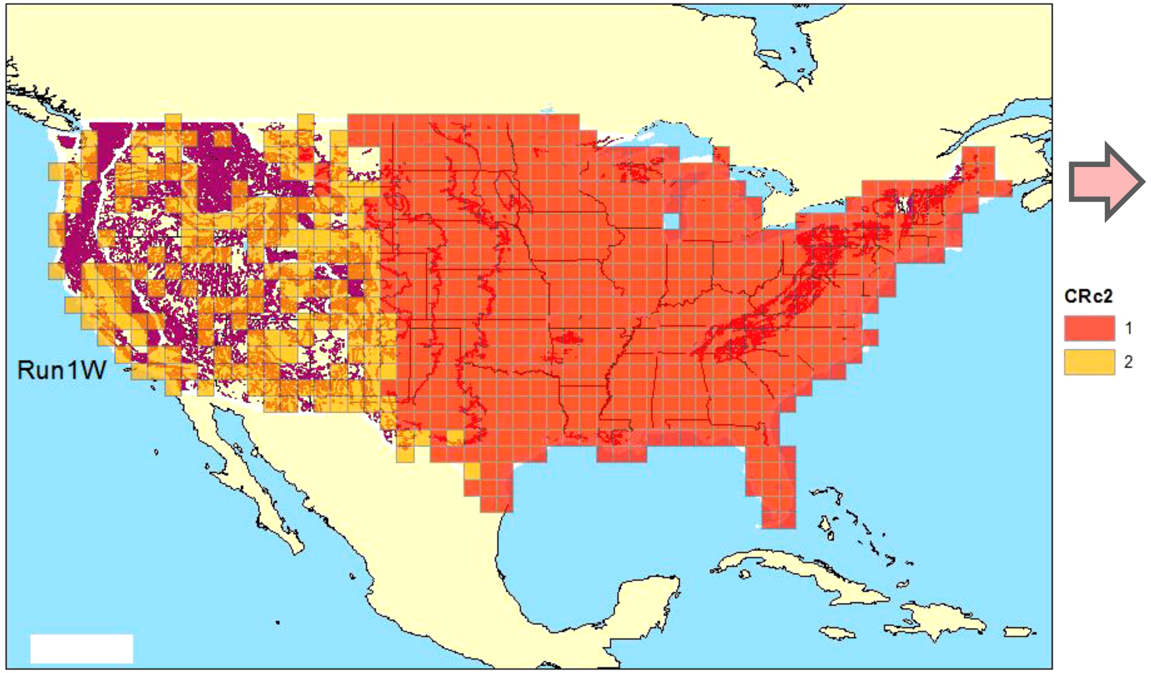
- Broad regions of similar tornado climatology
- Ten climatology metrics evaluated
- Multivariate statistical analysis method used to discern areas of similar "climatology"
- Uniform climatology assumed within regions
- Grid based approach
- Uncertainties in region boundaries estimated and used in wind speed grid smoothing

Variables

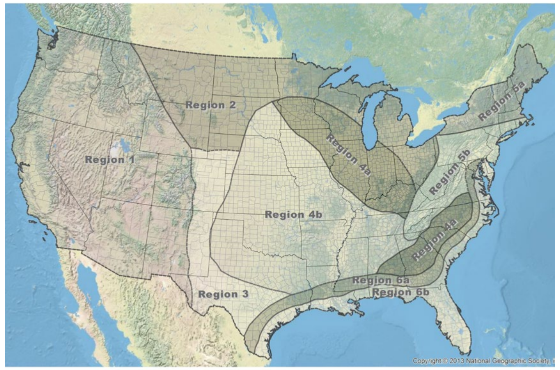
Latitude, Longitude	Tornado Days/Yr
Elevation	Path Length
Std Dev Elevation	Occurrence Rates
Land Fraction	Point Strike Probability



Animation of Sequential Cluster Formation - 1° Grid

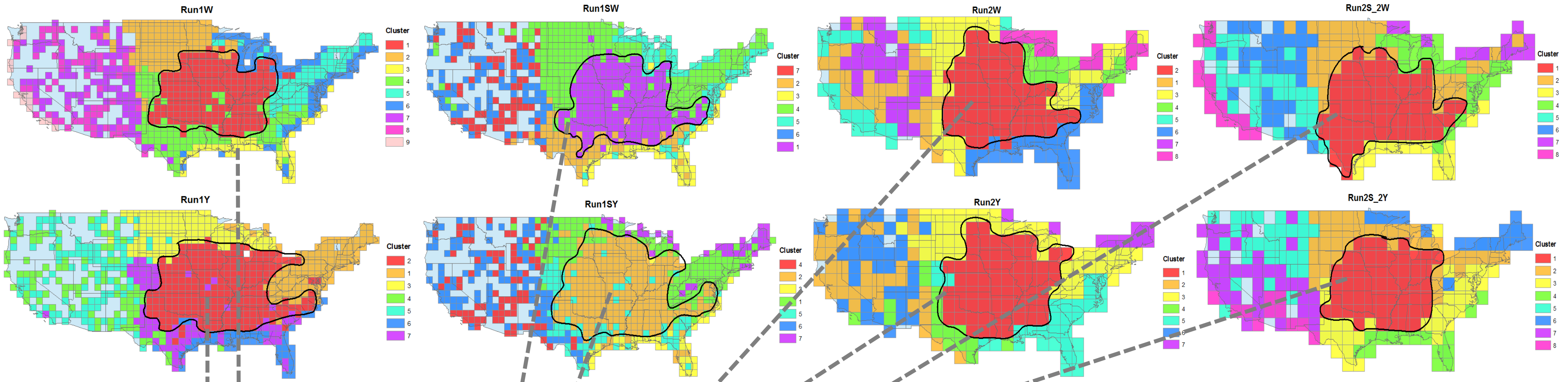


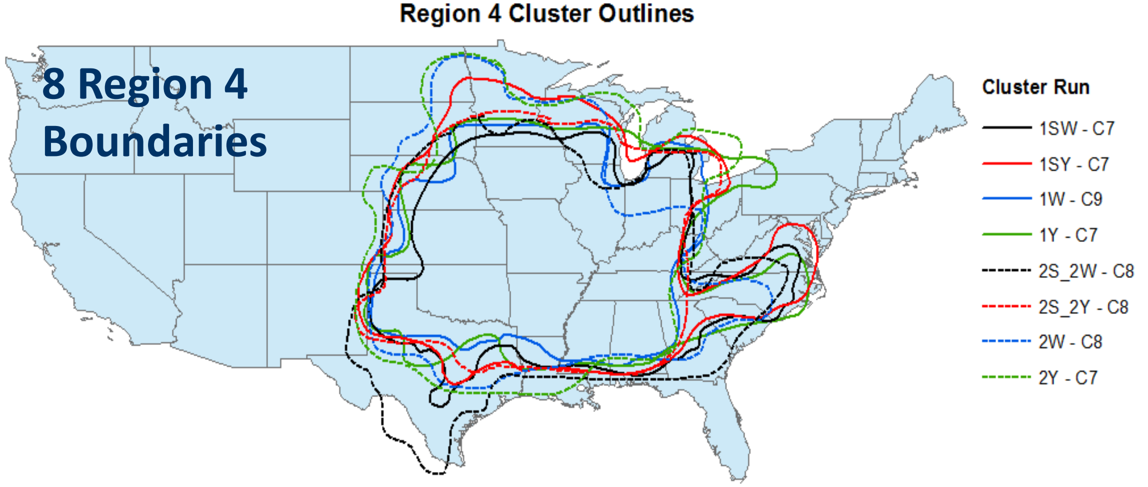
Final Regions

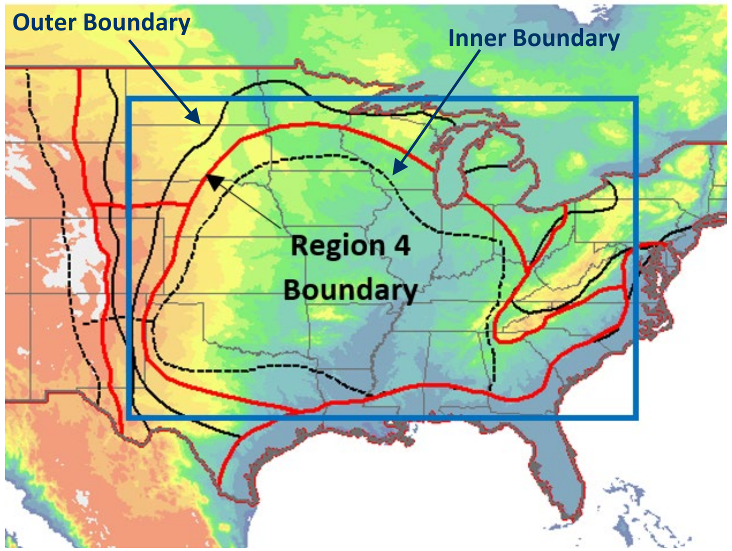


Region Boundaries and Uncertainties

8 Model Cluster Runs





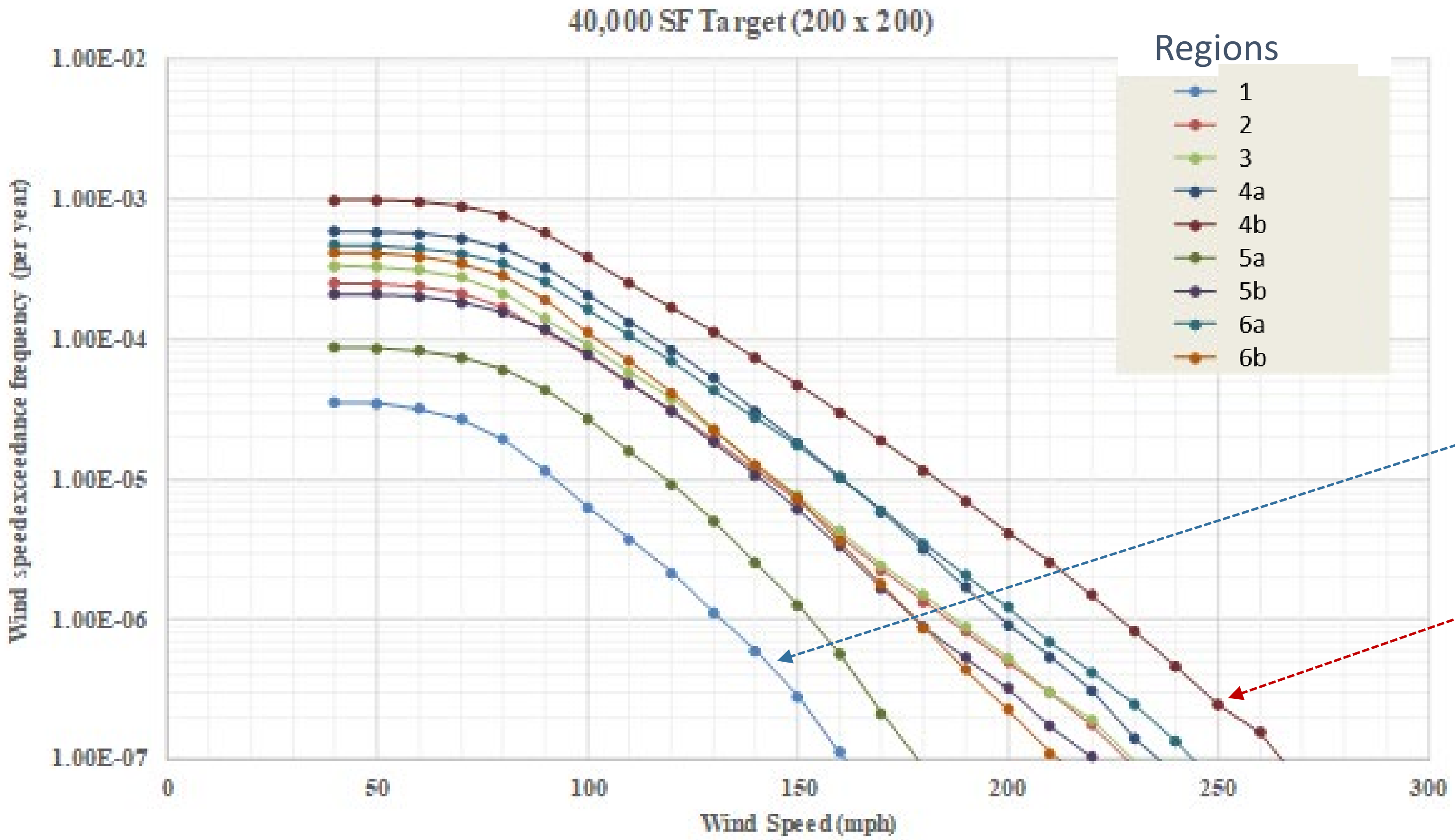


Credit: NIST

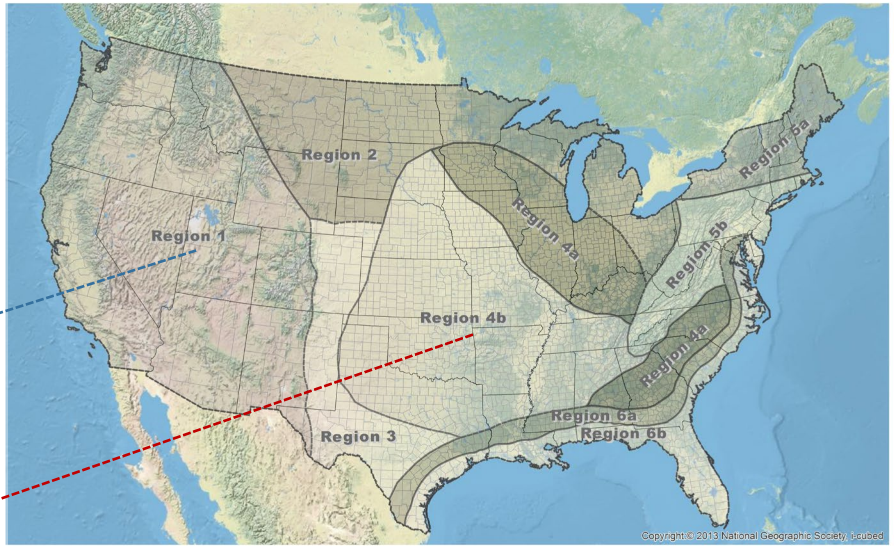
Windspeed Exceedance Frequencies

WEFs developed for each region and subregion, for a range of target sizes

Windspeed Exceedance Frequencies (WEFs)



Final Tornado Regions/Subregions

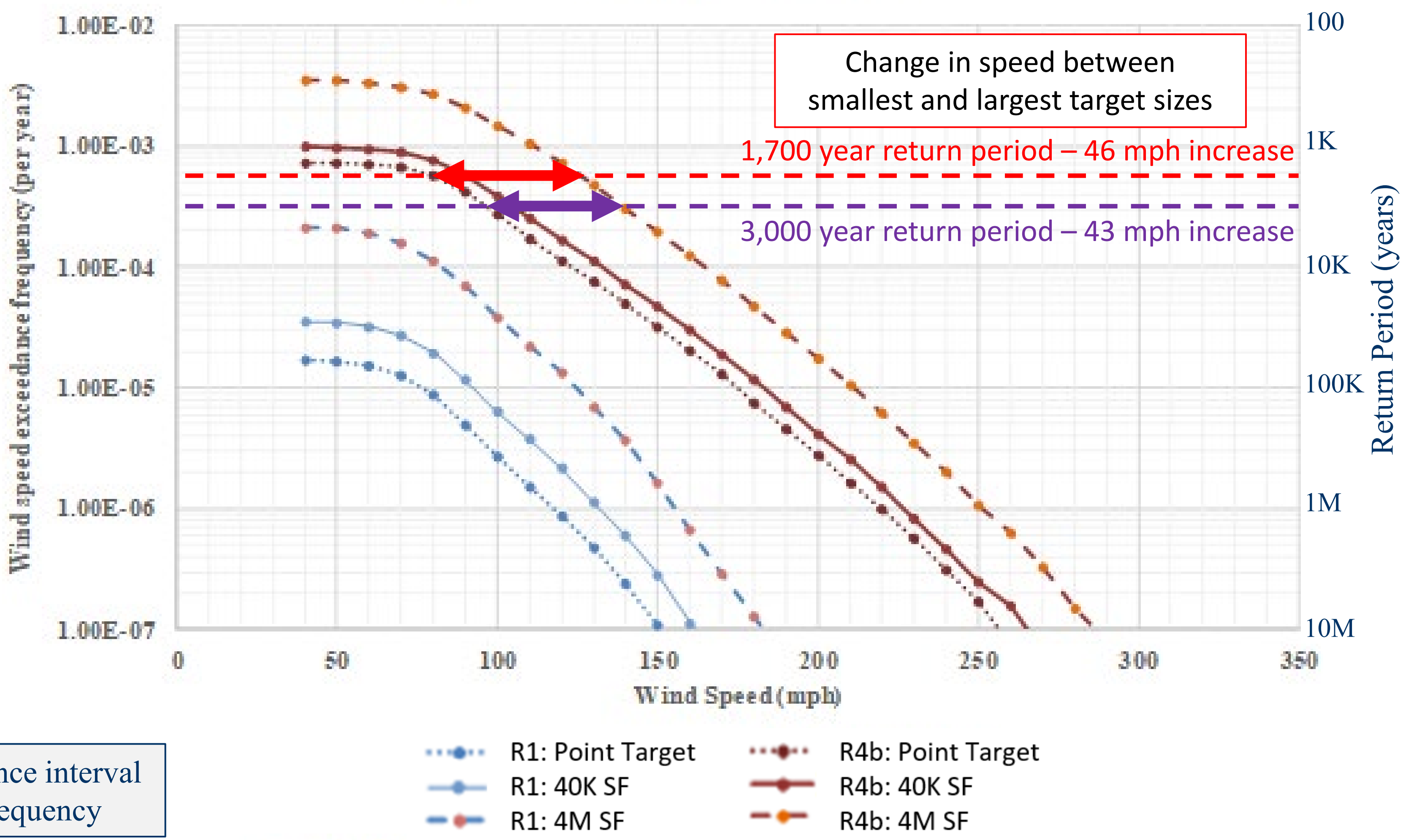


Target Size Effects

- The effects of target size depend on the Region and the tornado wind speed
- The effect of target size is reduced for high return periods
- The effects of target size are greater in regions with lower wind hazard, such as Region 1, since the tornadoes are smaller and the impact of increasing target size has a more dominant effect on the resulting risk.

Note: Return Period (also referred to as mean recurrence interval or MRI) is the inverse of the annual exceedance frequency

Target Size Effects for Regions 1 (West) and 4b (Center)



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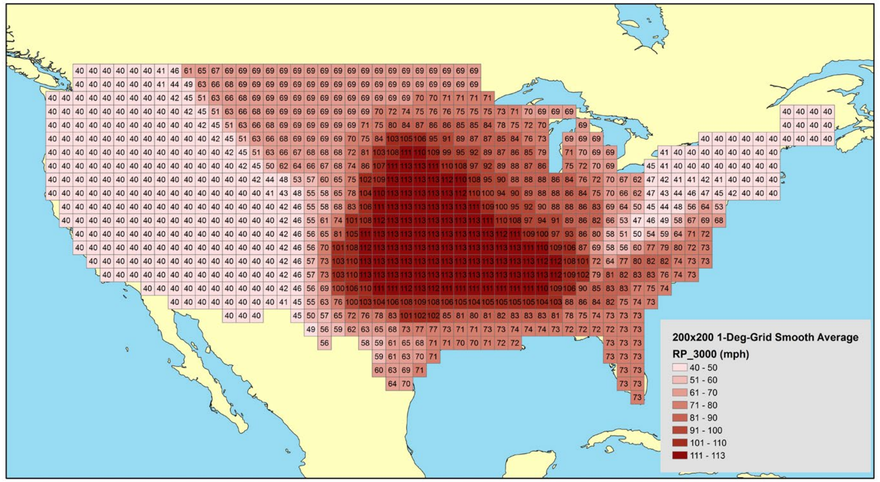
Tornado Hazard Map Development

Map Development Process

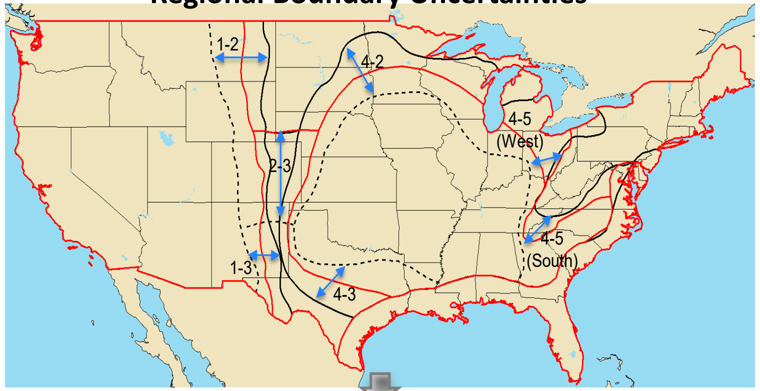
1. A six step process is used to develop maps.
2. The grid wind speeds for a given Return Period and Target Size were smoothed using Gaussian smoothing.
3. The Kriging was performed in ArcGIS with default parameters, similar to the current ASCE 7 non-tornadic maps.

Example Grid After Smoothing



1. Hazard Curve WEFs (Given Target Size)
2. Interpolate Windspeeds to Return Periods
3. Input Windspeeds to Region/Subregion Grid Cells
4. Gaussian Smoothing
5. ArcGIS Kriging
6. PAEK Smoothing & Hand Adjustments for Final Maps

Regional Boundary Uncertainties



Region Boundary	Mean Distance (mi)	Approx. Number of 1 Deg. Cell Widths
Region 1- Region 2	166	2.8
Region 1 – Region 3	125	2.1
Region 2 - Region 3	416	6.9
Region 4 – Region 2	217	3.6
Region 4 – Region 3	130	2.2
Region 4 – Region 5 (West of Appalachians)	85	1.4
Region 4 – Region 5 (South and East of Appalachians)	177	3.0
Overall Mean	**188**	**3.1**

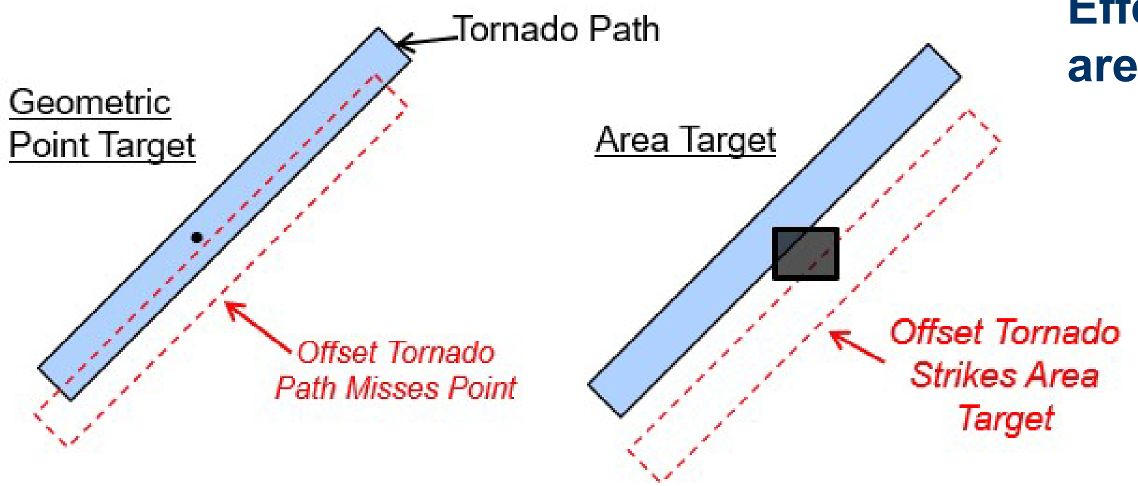
0.0099	0.0239	0.0320	0.0239	0.0099
0.0239	0.0575	0.0770	0.0575	0.0239
0.0320	0.0770	0.1031	0.0770	0.0320
0.0239	0.0575	0.0770	0.0575	0.0239
0.0099	0.0239	0.0320	0.0239	0.0099

Gaussian Smoothing Weights

Tornado Speed Variation with Plan Size

Tornado risk and tornado speeds are a function of building or facility size and shape (effective plan area)

- Tornado strike probabilities increase with increasing plan area of the target building or structure (target size)
- For a given return period (i.e., mean recurrence interval), tornado speeds increase with increasing target size



Effects of building or facility plan area on tornado strike probability

"Does the Flap of a Butterfly's Wings in Brazil Set off a Tornado in Texas?"
Edward U. Lorenz, Sc.D.
Professor of Meteorology
Massachusetts Institute of Technology, Cambridge

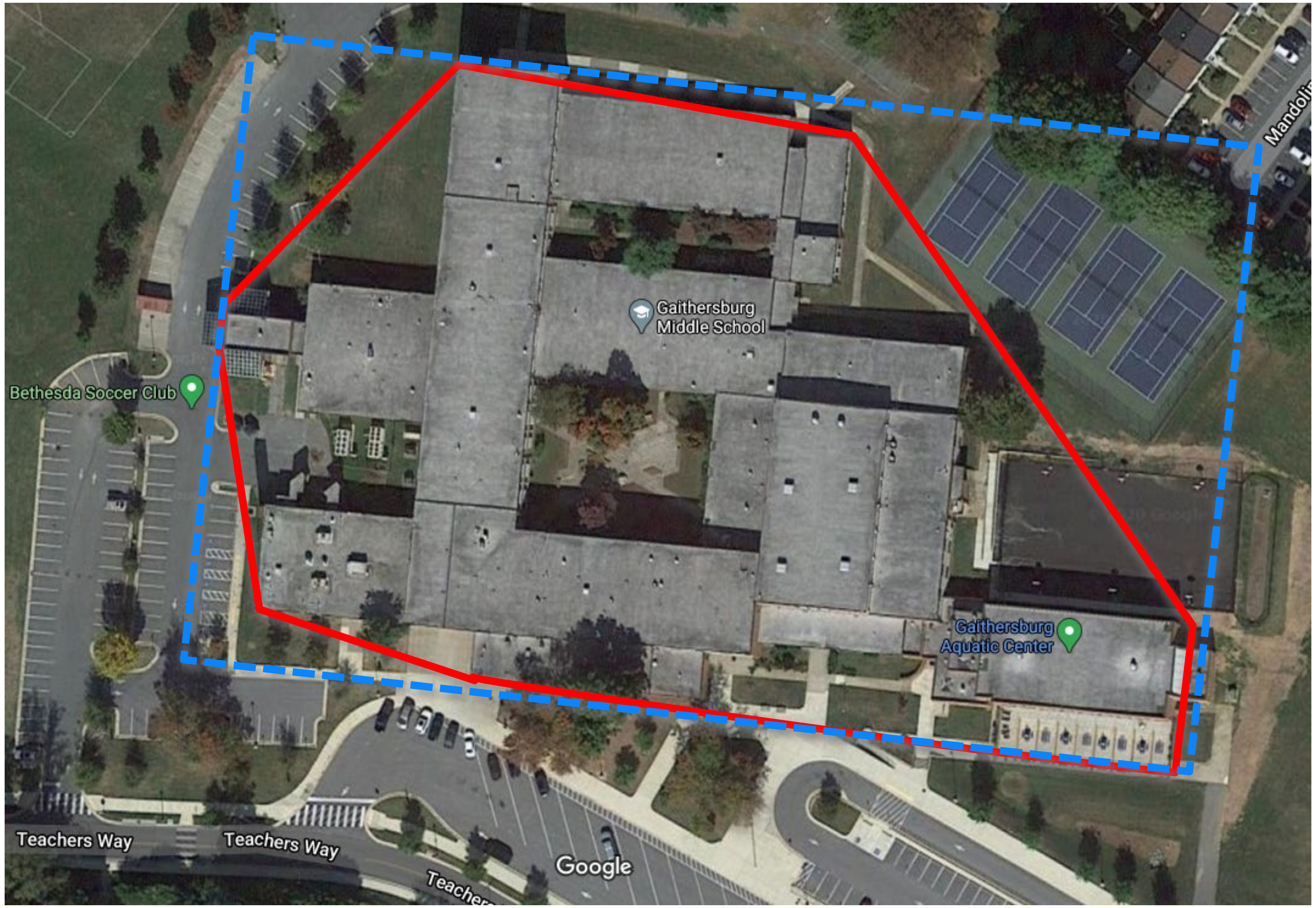
https://www.ias.ac.in/article/fulltext/reso/020/03/0260-0263

Effective Plan Area, A_e

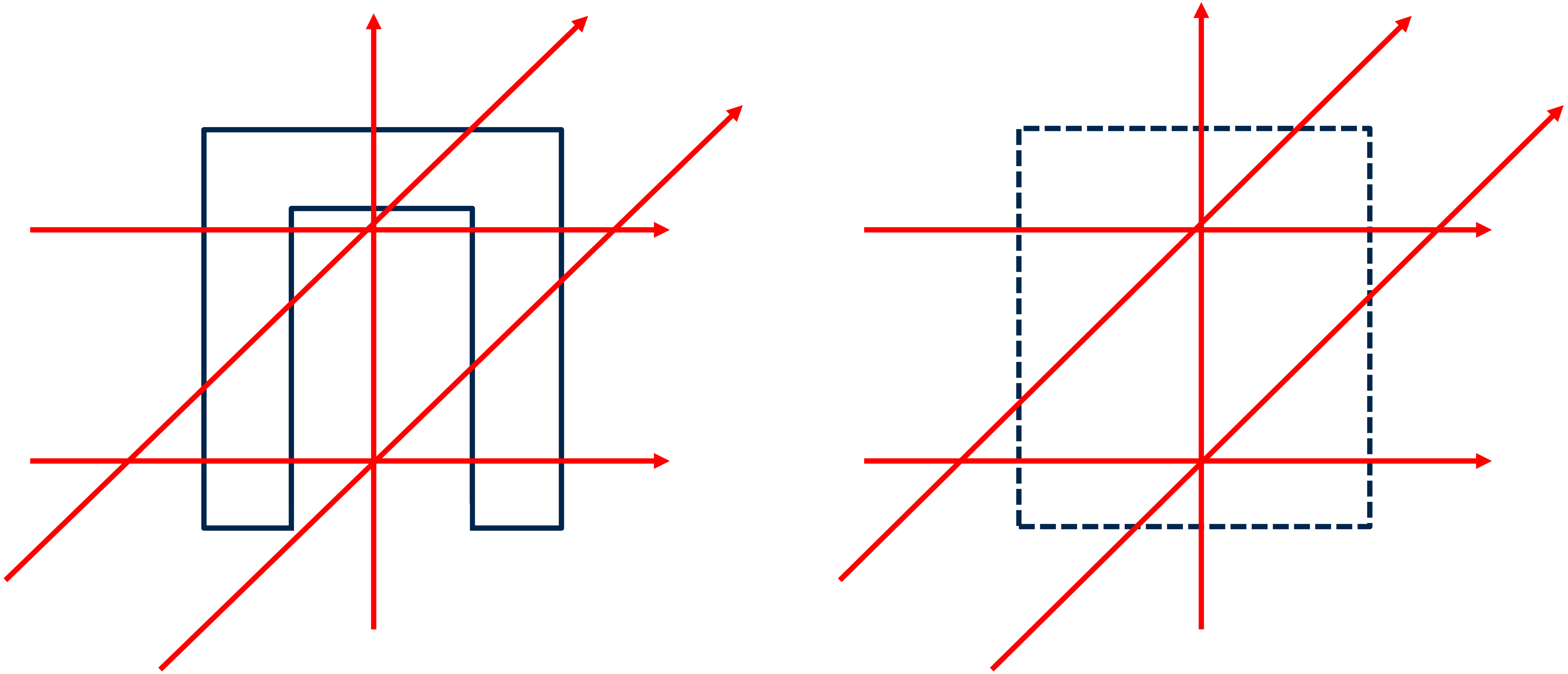
The effective plan area A_e shall be equal to the area of the smallest convex polygon enclosing the plan of the building, other structure, or facility.

Commentary:

Alternatively, A_e can simply and conservatively be calculated as the area of the smallest rectangle that encloses the maximum plan area



A_e - Smallest Convex Polygon



A_e for Essential Facilities

32.5.4.1 Essential Facilities. For Essential Facilities and buildings and other structures required to maintain the functionality of Essential Facilities, the effective plan area shall be equal to the area of the smallest convex polygon enclosing both the Essential Facility and all of the buildings and other structures that maintain the functionality of the Essential Facility.

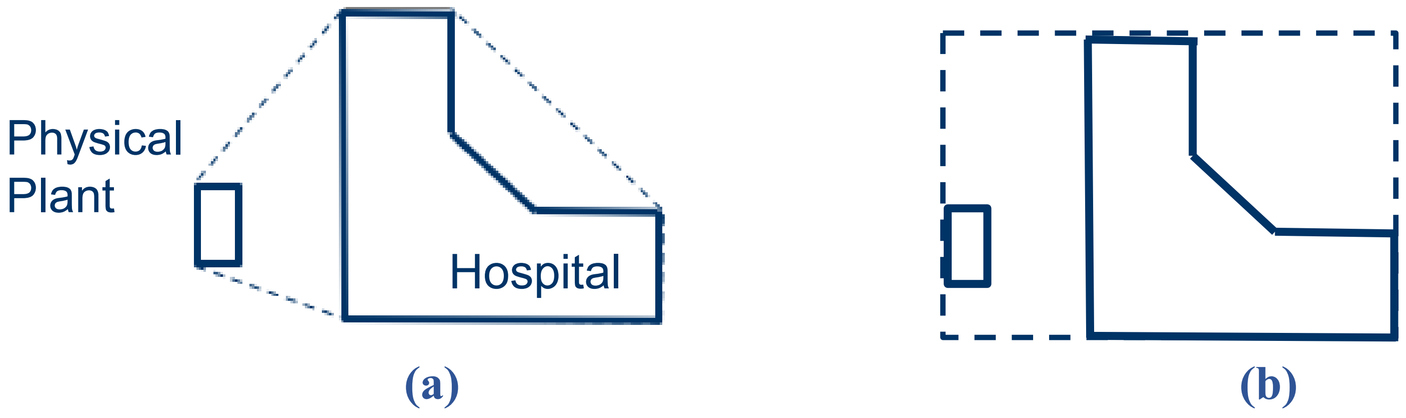
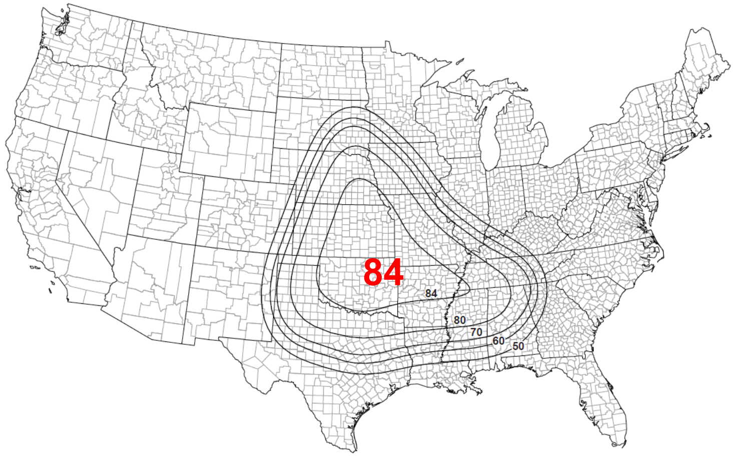
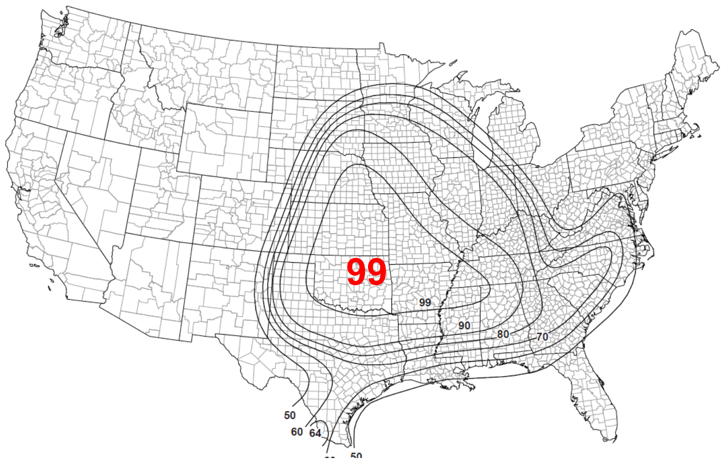
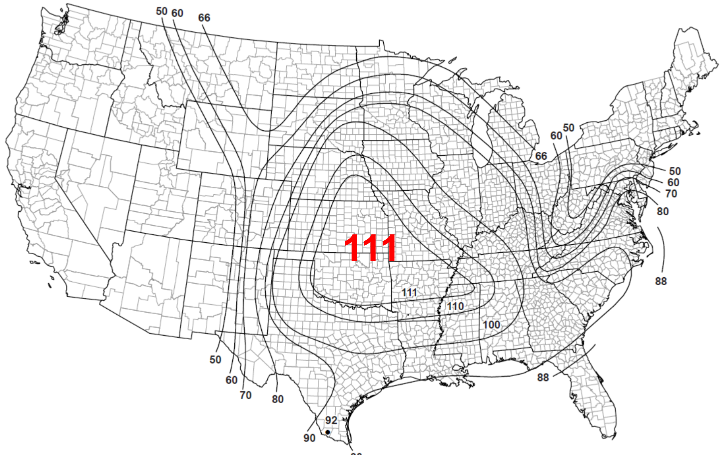
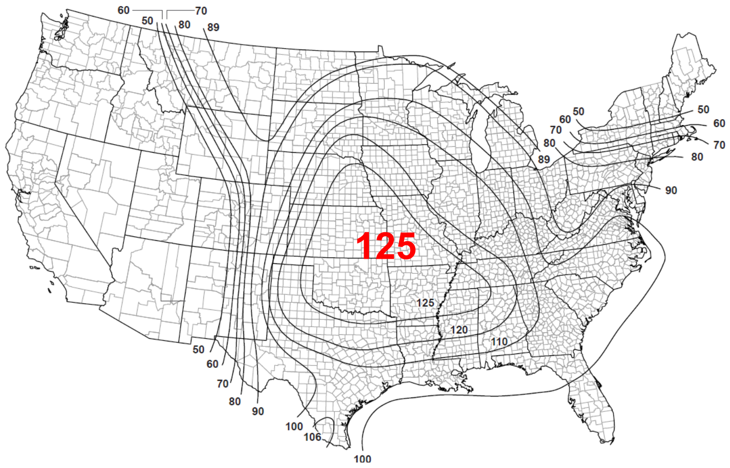


FIGURE C32.5-2. Effective plan area for a hospital and its central utility plant determined using (a) the smallest convex polygon enclosing the facility, and (b) rectangle enclosing the facility.

Example Tornado Hazard Maps

Effective Plan Area A_e (ft^2)

	Risk Category III (1,700 Year)	**Risk Category IV (3,000 Year)**
10K		
1M		

Tornado speeds are 3-s peak gusts in mph at 33 ft (10 m) height

Mapped values are available through the ASCE 7 Hazards Tool, free of charge

8 mapped effective plan area sizes (target sizes), from 1 to 4M sq ft

Mapped tornado speeds for longer return periods at each of the 8 sizes are provided in Appendix G

- 10,000 years
- 100,000 years
- 1,000,000 years
- 10,000,000 years

ASCE 7-22 also includes a new Appendix F with longer return period *wind speed* maps

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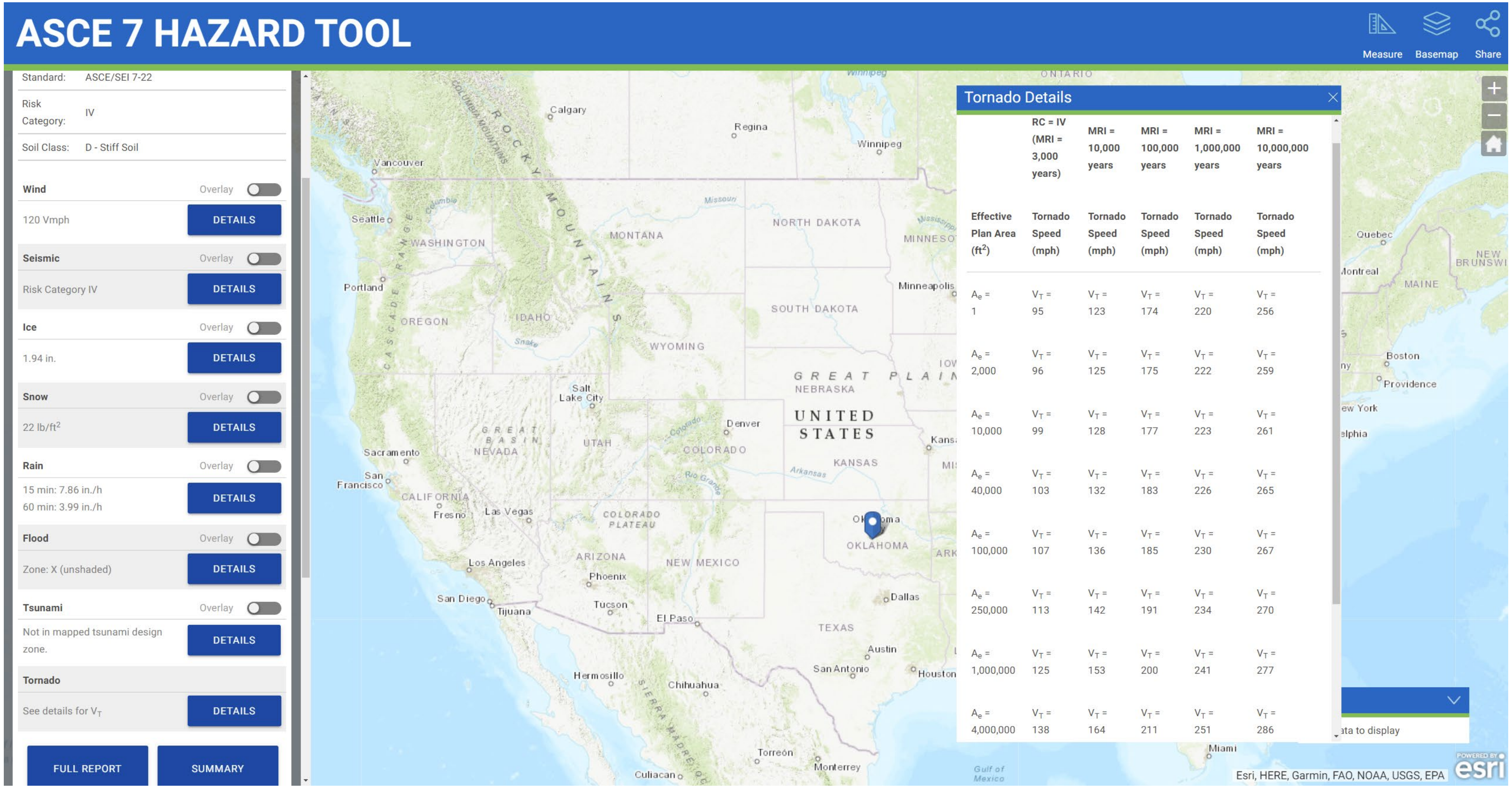
Wind & Tornado Speed Maps-Hazards Tool

https://asce7hazardtool.online *FREE!*



Tornado Design Pressures (Ch 32)

Red indicates differences from ASCE 7-22 wind load equations

MWFRS $p_T = q_T G_T K_{dT} K_{vT} C_p - q_{iT}(GC_{piT})$ (eqn 32.15-1)

C&C (h<60') $p_T = q_{hT}[K_{dT} K_{vT}(GC_p) - (GC_{piT})]$ (eqn 32.17-1)

C&C (h>60') $p_T = q_T K_{dT} K_{vT} (GC_p) - q_{iT}(GC_{piT})$ (eqn 32.17-2)

p_T	Tornado design pressure (psf)
q_T	Tornado velocity pressure (psf)
K_{dT}	Tornado directionality factor
K_{vT}	Tornado pressure coefficient adjustment factor
G_T	Tornado gust effect factor
C_p	External pressure coefficient
(GC_p)	External C&C pressure coefficient
(GC_{piT})	Tornado internal pressure coefficient

Note – K_{dT} is not applied to tornado internal pressure coefficient (GC_{piT}), since atmospheric pressure change (APC) contributes to internal pressures and APC is not dependent on direction.

Tornado Directionality Factor

- Probabilistic method of accounting for reduced probability of peak wind speed coming from a direction where pressure coefficients are at their peaks
- Methodology to determine K_{dT} adapted from K_d analysis for Chapter 26, incorporating the tornado model used to develop the hazard maps

Table 32.6-1 Tornado Directionality Factor, K_{dT}

Structure Type	Tornado Directionality Factor K_{dT}	Wind Directionality Factor (Ch. 26) K_d
Buildings		
Main Wind Force Resisting System	0.80	0.85
Components and Cladding		0.85
For Essential Facilities and for buildings and other structures required to maintain the functionality of Essential Facilities	1.0	
Roof Zone 1′ as shown on Figure 30.3-2A	0.90	
All other cases	0.75	
Arched Roofs, Circular Domes, and All Other Structures	Use value from Table 26.6-1	Table 26.6-1

No change for ICC 500 – stay with K_d = 1.0

Tornado Gust Effect Factor

- G_T Uses the rigid structure gust effects provisions from Chapter 26
  - 0.85, or
  - Full rigid structure analysis
    - with exposure C terrain constants
- The duration of a tornado is sufficiently short such that the gust factor provisions for flexible or dynamically sensitive buildings and other structures (G_f) do not apply.

Tornadic winds may vary in both direction and speed over the building or structure, resulting in lower peak load effects compared to atmospheric boundary layer winds, whose mean wind speed and direction are comparatively more constant over the building or structure

No effect on shelter design – Exposure C was already mandated for tornado if using full rigid structure analysis

Tornado Internal Pressure Coefficient

- GC_{piT}, Tornado internal pressure coefficient, accounts for combined effects of internal pressure and atmospheric pressure change (APC)
  - based on tornado load simulations

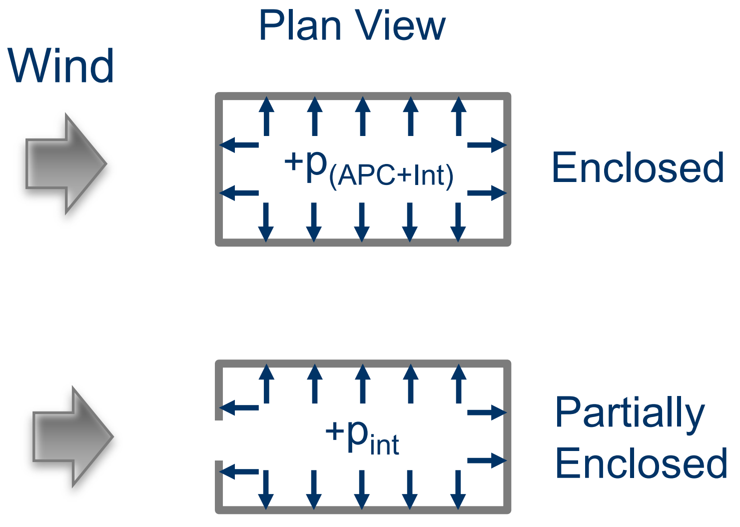


Table 32.13-1 MWFRS and C&C Tornado Internal Pressure Coefficient, (GC_{piT})

Enclosure Classification	Internal Pressure combined with APC	Tornado Internal Pressure Coefficient, (GC_{piT})
Sealed Other Structures	Extreme	+1.0
Enclosed buildings	High	+0.55
		- 0.18
Partially enclosed buildings	High	+0.55
		- 0.55
Partially open buildings	Moderate	+0.18
		- 0.18
Open buildings	Negligible	0.00

Note the high positive internal pressures for both enclosed and partially enclosed buildings

No changes for ICC 500 -keep the vented method for Enclosed Buildings

Tornado Pressure Coefficient Adjustment Factor for Vertical Winds

- New modifier on external pressure coefficients to account for effects of updrafts in the core of the tornado (vertical component of tornadic wind)

- K_{vT} used to modify roof uplift pressure coefficients that were previously developed for boundary layer winds to account for these effects

$$C_p \text{ and } (GC_p) \rightarrow K_{vT}C_p \text{ and } K_{vT}(GC_p)$$

  - $K_{vT} > 1.0$ for roof uplift coefficients (from 1.05 to 1.3)
  - $K_{vT} = 1.0$ for downward acting roof pressure coefficients and wall coefficients

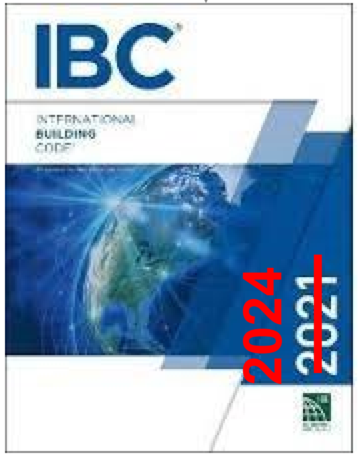
ICC 500 – increase roof uplift pressures 5 to 30%

STRUCTURE TYPE	K_{vT}
Buildings	
Negative (Uplift) Pressures on Roofs	
Main Wind Force Resisting System	1.1
Components and Cladding	
Roof Slope <=7 degrees	
Zone 1	1.2
Zone 2	1.05
Zone 3	1.05
Roof Slope > 7 degrees	
Zone 1	1.2
Zone 2	1.2
Zone 3	1.3
Positive Pressures (Downward acting) on Roofs	1.0
Wall Pressures	1.0
All Other Cases	1.0

Tornado Loads - New in ASCE 7-22

NOAA Photo Library, NOAA Central Library; OAR/ERL/National Severe Storms Laboratory (NSSL).

Approved for 2023 Florida Building Code



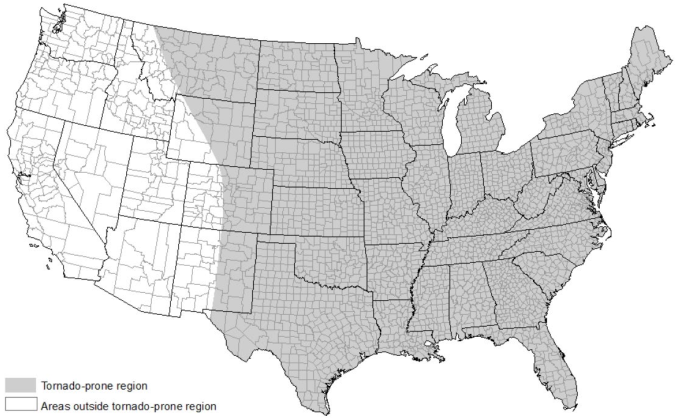
Approved for 2024 IBC

ASCE 7-22 Tornado Load Requirements Summary

NIST

- Tornado load methodology adapted from wind load Ch 26-31 (excl. 28)
  - Most parameters and equations have been modified
- Risk Category III/IV buildings in TPR
  - Assembly occupancies, schools, nursing homes, hospitals, fire, police, etc.
- Design Tornado speeds ≈ EF0-EF2
  - Depends on Risk Category, location, and plan size and shape
- **Designing for most common tornadoes, not most intense**
  - Same reliability targets as wind loads
- Loads can increase significantly, sometimes >100%

Tornado-Prone Region (TPR)



Enhanced Fujita (EF) Tornado Intensity Scale

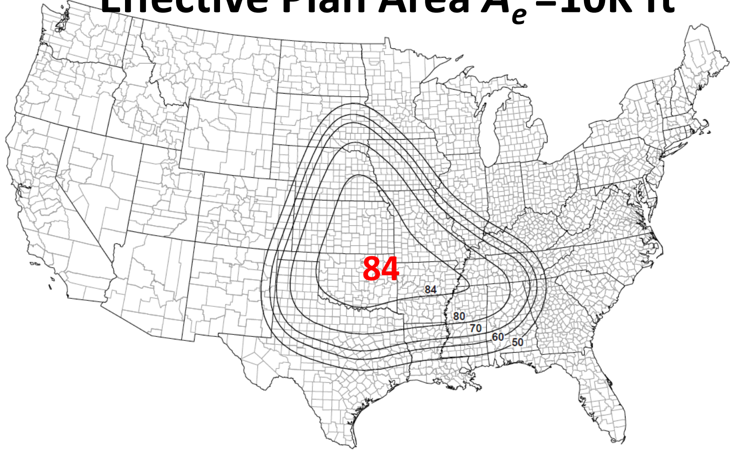
EF #	Gust Speed (mph)	% U.S. Tornadoes[1]
0	65-85	61.3
1	86-110	27.8
2	111-135	8.0
3	136-165	2.3
4	166-200	0.52
5	Over 200	0.05

97.1% (EF 0–2)

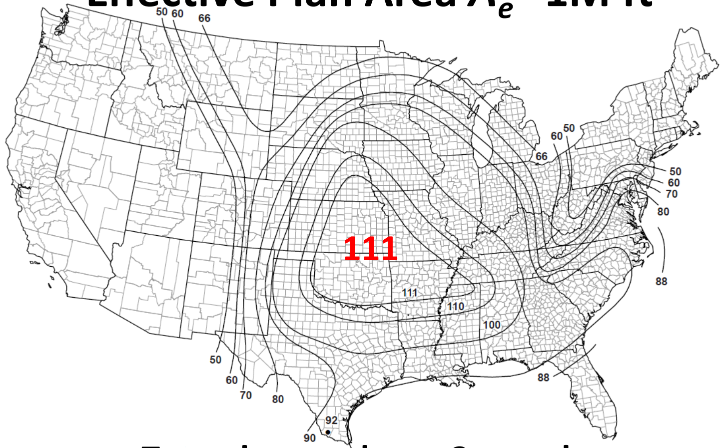
[1] 1995-2016. Source: NIST, using NOAA data.

Risk Category III (1,700 Year)

Effective Plan Area A_e =10K ft^2



Effective Plan Area A_e =1M ft^2



Tornado speeds are 3-s peak gusts in mph at 33 ft height

Where Tornado Loads are Likely to Control

NIST

- Tornado loads are more likely to control at least some element(s) of the wind load design for structures that
  - are located in the central and southeast US (except near the coast where dominated by hurricanes)
  - are Risk Category IV
  - are designated as Essential Facilities
  - have large effective plan areas
  - are located in Exposure B
  - have low mean roof heights
  - are classified as enclosed buildings for wind loads

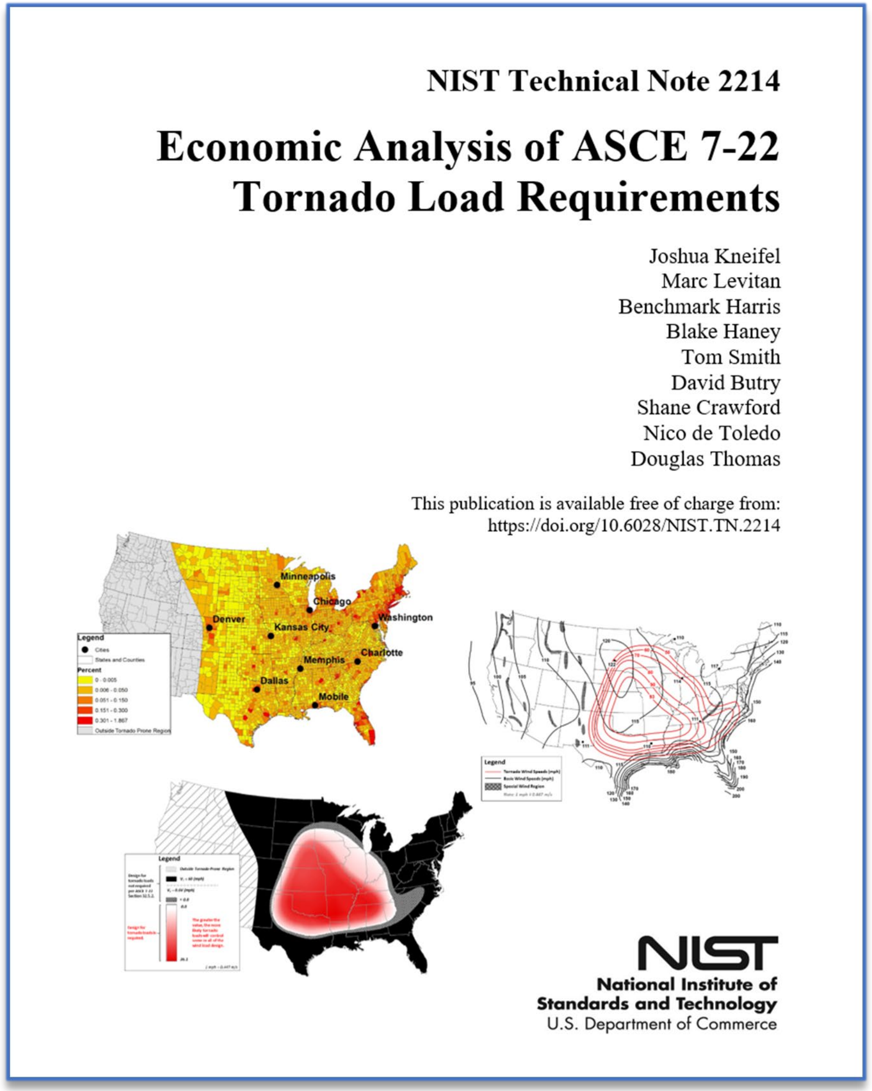
Nursing Home
Caddo County, Oklahoma
August 19, 2007

Credit: FEMA

Where tornado loads control, design uplift pressures on roofs will typically increase. This will help reduce the most common failures in tornadoes and other windstorms

Economic Analysis of ASCE 7-22 Tornado Loads

- Study analyzes the changes in design loads and potential costs from implementing load requirements in the ASCE 7-22
- Including ASCE 7-22 tornado loads significantly impacts design loads in the central and southeast U.S. for Risk Category III and IV buildings
- Meeting ASCE 7-22 tornado loads requires minimal changes to construction designs (e.g., additional fasteners, anchors, slightly larger member sizes)
- Required construction design changes can be met with minimal additional construction costs
  - Typically less than 0.15 % of construction budget for the elementary and high school case studies in this report



NIST Technical Note 2214

Economic Analysis of ASCE 7-22 Tornado Load Requirements

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This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.2214

National Institute of Standards and Technology
U.S. Department of Commerce

https://doi.org/10.6028/NIST.TN.2214