



Latest Developments in Tornado Hazard Characterization and Tornado Loads on Buildings and Structures

October 21, 2020

DOE/NRC NPH
Meeting

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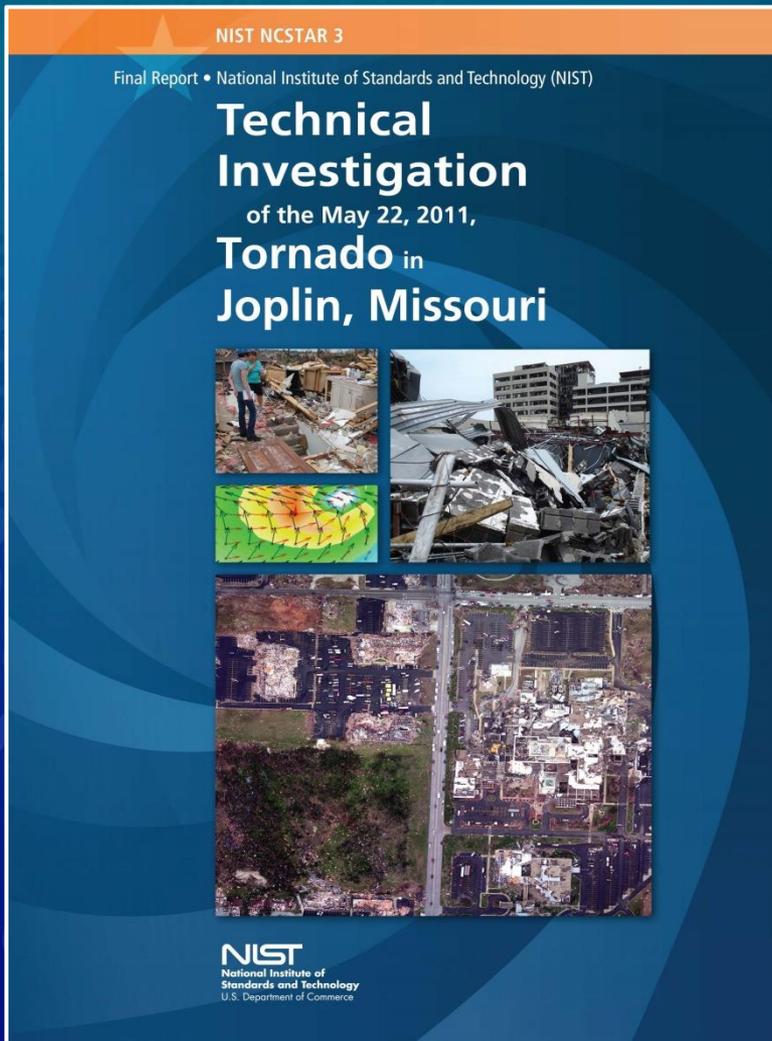
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Presentation Overview

- Background and Introduction
- ASCE/SEI/AMS Standard on Estimation of Wind Speeds in Tornadoes and other Windstorms
- **New Tornado Hazard Maps**
- Tornado Load Provisions of ASCE 7-22



NIST Joplin Tornado Investigation



Joplin was the deadliest (161 fatalities) and costliest (\$2.8B) single tornado since official recordkeeping began in 1950

The NIST investigation was the first study to integrate analysis of tornado characteristics, building performance, emergency communication and human behavior – incl. assessment of the impact of each on fatalities

Final Report provides 16 recommendations for improving:

- Tornado hazard characterization
- How buildings and shelters are designed and constructed in tornado-prone regions
- Emergency communications that warn of threats from tornadoes.

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



List of Joplin Recommendations

Hazard Characteristics

R #	RECOMMENDATION SUMMARY
1	Development and deployment of technology to measure tornado wind fields
2	Archival of tornado event data
3	Development of tornado hazard maps considering spatially based hazard estimates
4	Improvement and standardization of EF Scale; adoption by NWS

Buildings, Shelters, Designated Safe Areas, and Lifelines

5	Development of performance-based standards for tornado-resistant design
6	Development of performance-based tornado design methodologies
7	a) Development of tornado shelter standard for existing buildings; b) Installation of tornado shelters in more buildings in tornado-prone regions
8	Development of guidelines for public tornado sheltering strategies
9	Development of guidelines for selection of best available refuge areas
10	Prohibition of aggregate coverings or ballast in tornado-prone regions
11	Development of requirements for enclosures of egress systems in critical facilities
12	a) Development of tornado vulnerability assessment guidelines for critical facilities; b) Performance of vulnerability assessments by critical facilities in tornado-prone

Emergency Communication

13	Development of codes, standards, and guidance for emergency communications; Development of joint plan by emergency mgrs/media/nws for consistent alerts
14	Deployment of “push” technologies for transmission of emergency information
15	Research to identify factors to enhance public perception of personal risk
16	Develop technology for real-time, spatially-resolved tornado threat information

NOTE –
Summaries are provided here for context. The complete recommendations are available in the final report of the NIST Technical Investigation of the Joplin Tornado, at <https://dx.doi.org/10.6028/NIST.NCSTAR.3>



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EF Scale Recommendation

Recommendation	Interested Parties	Lead Organization
Group 1: Tornado Hazard Characteristics and Associated Wind Field		
<p>Recommendation 4: NIST recommends that new damage indicators (DIs) be developed for the Enhanced Fujita tornado intensity scale to better distinguish between the most intense tornado events. Methodologies used in the development of new DIs and associated degrees of damage (DODs) should be, to the extent possible, scientific in nature and quantifiable. As new information becomes available, a committee comprised of public and private entities should be formed with the ability to propose, accept, and implement changes to the EF Scale. The improved EF Scale should be adopted by NWS.</p>	Academia, ATC, FEMA, NRC , NSF, OSTP	NWS



ASCE/SEI/AMS Standard on Wind Speed Estimation in Tornadoes and Other Windstorms

New standard under development

- NIST and the National Weather Service (NWS) proposed and co-chair the Committee
- Joint American Society of Civil Engineers and American Meteorological Society standard
- Committee approved and began meeting in 2015
- 100+ Committee members with expertise including
 - Meteorology
 - Wind engineering
 - Structural engineering
 - Architecture
 - Construction materials
 - Forest biology
 - Emergency management

Scope

- Measurements-based Methods
 - Radar
 - In situ
- Estimates Inferred from Damage
 - **EF Scale**
 - Forensic Engineering
 - Treefall Patterns
 - Remote Sensing Imagery

Data and Metadata collection and archival



EF-Scale Methodology Improvements

- **Explicit consideration of wind resistance for each Damage Indicator** (replaces EXP, UB, LB)

- Typical resistance
- Stronger than typical resistance
- Weaker than typical resistance

- **Additional EF Scale methodology improvements**

- Explicit consideration of uncertainty
- Update existing DIs
- Add New DIs
 - 1-2 family residences from FEM-based fragilities (NIST)*
 - Concrete (Jersey) barriers (NIST)*
 - Passenger vehicles*
 - Center Pivot Irrigation Systems

* based on validated modeling and/or wind tunnel testing (instead of the expert elicitation used in original EF Scale)

DI # – Center Pivot Irrigation Systems (CPIS)

DoD	Damage description	Estimated Wind Speed (mph) ¹		
		Weaker than Typical Resistance	Typical Resistance	Stronger than Typical Resistance
1	Threshold of visible damage. One span damaged or overturned. Remainder of CPIS intact.	65	75	85
2	Multiple spans overturned or flipped on side - one time.	75	85	95
3	Multiple spans overturned several times, rolled or twisted.	80	95	110
4	1 or more spans separated from system. Pivot point is severely damaged or separated. Entire unit tumbles.	>80	>95	>110

¹Actual wind speeds are estimated to be ±20% of the values of this table.

SOURCE: ASCE/SEI/AMS Committee on Wind Speed Estimation in Tornadoes. Used with Permission.



ASCE/SEI/AMS Standard on Wind Speed Estimation in Tornadoes and Other Windstorms

Standards Development Progress

- Complete drafts of chapters for all methods in the standard
- Chapters in Main Committee (MC) ballot
 - Radar
 - **EF Scale**
 - Forensic Eng.
 - Treefall Pattern
- Chapters in Subcommittee review prior to MC ballot
 - In Situ
 - Remote Sensing Condition Assessment

Opportunities to Stay Informed/Participate

- **All ASCE Standards Committee meetings are public**
- **meeting schedule**
<https://www.asce.org/codes-and-standards/codes-and-standards/>

UPCOMING MEETINGS

ASCE rules require a 30 day advance meeting announcement. Please complete this form to request a meeting date and time.

- Wind Speed Estimation in Tornadoes Standards Committee will hold a Virtual Meeting on Wednesday, October 21, 2020. Contact James LaDue at james.g.ladue@noaa.gov for more information.
- Wind Speed Estimation in Tornadoes Standards Committee will hold a Virtual Meeting on Wednesday, November 18, 2020. Contact James LaDue at james.g.ladue@noaa.gov for more information.



Tornado Map Recommendation

Recommendation	Interested Parties	Lead Organization
Group 1: Tornado Hazard Characteristics and Associated Wind Field		
Recommendation 3: NIST recommends that tornado hazard maps for use in the engineering design of buildings and infrastructure be developed considering spatially based estimates of the tornado hazard instead of point-based estimates	ASCE, DOE, FEMA, ICC, NRC	NIST

Contracted with Applied Research Associates, Inc. (ARA) beginning in September 2014 for a multiyear tornado hazard map research and development program, in support of implementation of R3.



Engagement with NRC

- Began in 2014 while planning implementation of Joplin recommendations
- NRC-NIST Interagency Agreement in August 2017
 - Evaluate epistemic uncertainties and incorporate in the ongoing NIST tornado map development process
 - Propagate uncertainties to produce derived mean tornadic wind speeds
 - Produce maps that reflect aleatory and epistemic uncertainties for strike probabilities across multiple spatial scales

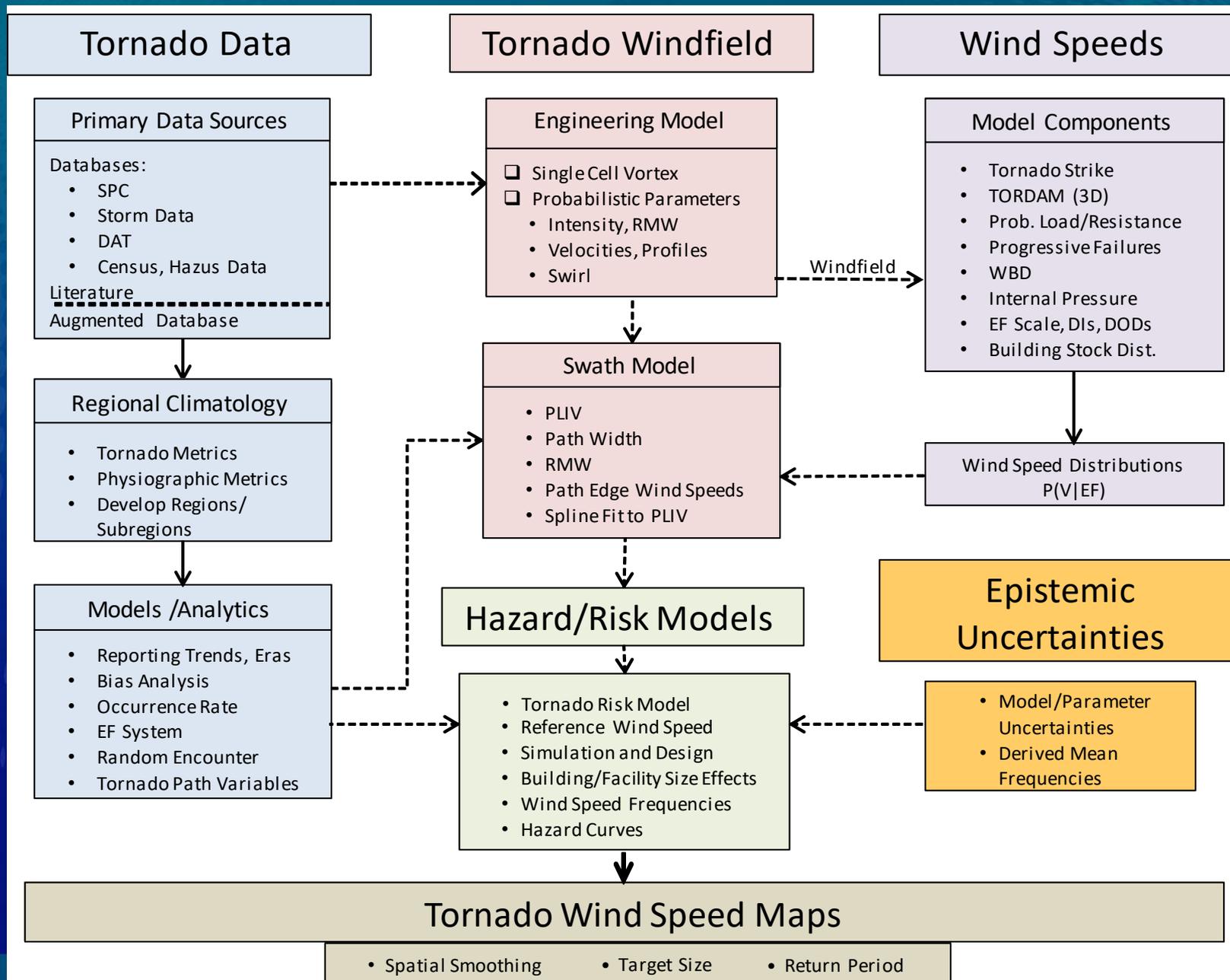
Tornado Map Stakeholder Workshops

Included participation from NRC staff and others in the nuclear power industry

- **1st Workshop, Sept. 2015**
 - Presented planned methodology
 - Obtained input on methodology and user needs
- **2nd Workshop, May 2019**
 - Presented methodology and draft maps
 - Obtained valuable feedback on the methodology, draft maps and planned implementation in the ASCE 7 standard



Overview of Mapping Project Components



Uncertainties

- Epistemic Uncertainties are often called “modeling uncertainties”
- Aleatory Uncertainties are often referred to as “randomness”
- Many epistemics in modeling tornado wind speeds
- Approach:
 - Modeled numerous random variables, many regionally, to capture randomness.
 - Modeled epistemic uncertainties in 5 key areas characterized by:
 - Significant uncertainties in mean values
 - Uncertainties in models/parameters
 - Expert judgment
- 12 Implementations:
 - 5 implemented explicitly (4 sampling + 1 grid smoothing)
 - 6 derived mean input distributions (1 EF Scale + 5 separate epistemic input elements for EF Wind speeds)
 - 1 computed derived mean (occurrence rate)
- The modeling philosophy for the uncertainty modeling was “best-estimate.”

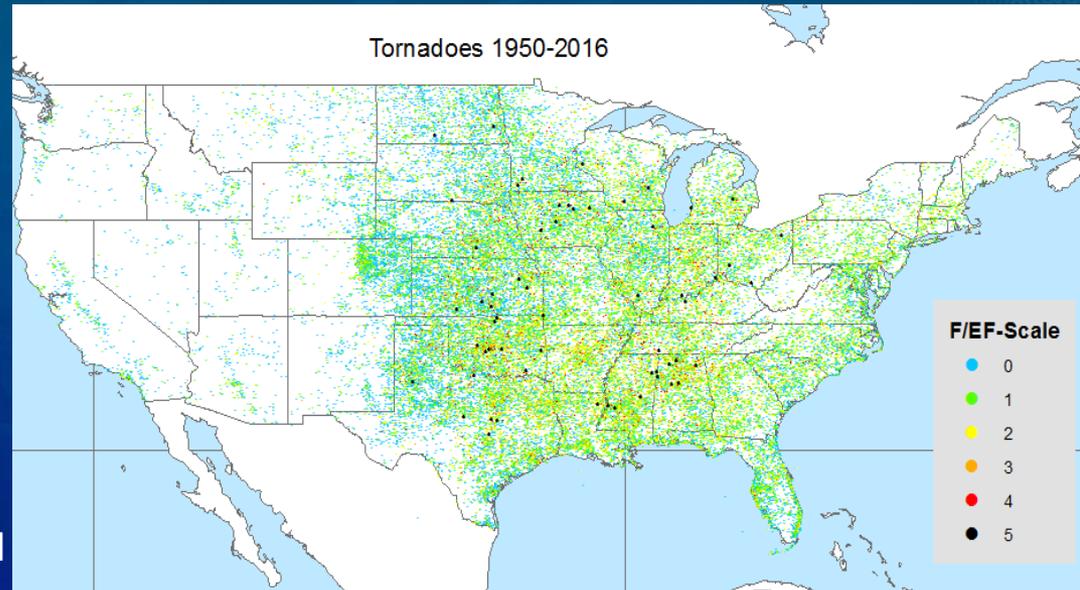
Group	Epistemic Topic	Model/Parameter Uncertainty
1	Tornado Regionalization	Region-Subregion Boundaries
2	Tornado Occurrence Rates	Region/Subregion Occurrence Rates
3	Tornado Intensity and Path Variables	a. EF-Scale
		b. Path Length
		c. Path Width
4	Tornado Windfield and Swath Model	a. Windfield
		b. Swath
5	Damage Modeling/EF Wind Speed Analysis	a. Engineering Interpretation in EF DODs Descriptions
		b. Structural Quality Factor
		c. DOD to EF Distribution
		d. House DOD 9-10 Model
		e. Bayesian Prior Wind Speed Distribuion



Regionalization of Tornado Risk

Overview

1. Broad Regions of Similar Tornado Climatology
2. Ten climatology metrics evaluated
3. Multivariate statistical analysis method used to discern areas of similar “climatology”
4. Uniform climatology assumed within regions
5. Grid based approach
6. Uncertainties in region boundaries estimated and used in wind speed grid smoothing



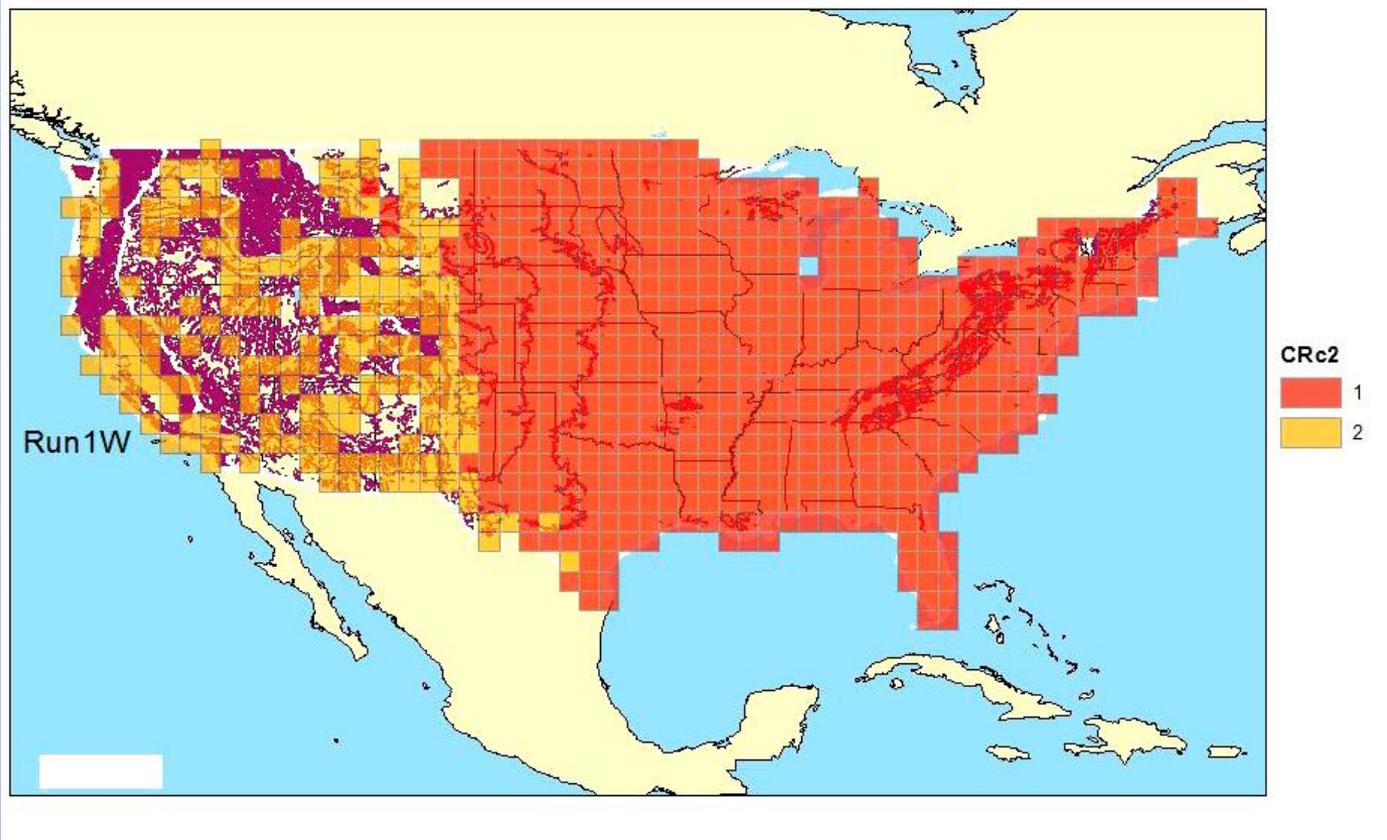
End Product

1. Regions reflect the raw, empirical data without bias corrections
2. Regions are broad and contiguous
3. Regions have different degrees and types of climatological separations
4. Sub-regions later developed within several regions based on significant “within-region” differences in occurrence rate and EF scale distribution
5. Reasonable smoothing across regional boundaries



Tornado Climatology – Region Identification

Animation of Sequential Cluster Formation - 1° Grid



Variables Include

Latitude, Longitude

Elevation

Std Dev Elevation

Land Fraction

Tornado Days/Year

Path Length

Occurrence Rates

- All Intensities
- Moderate
- Strong

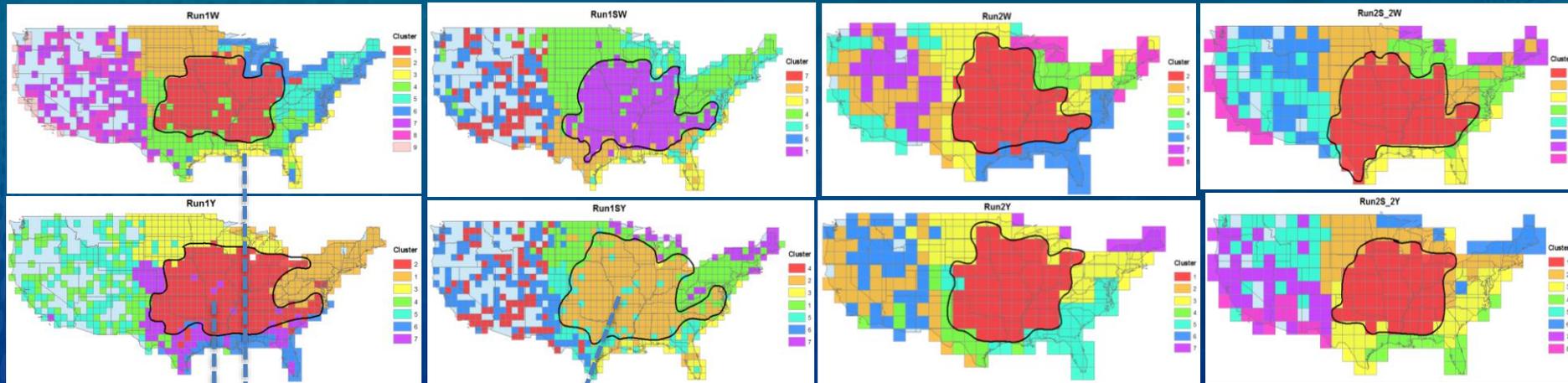
Point Strike
Probability

Also ran 2° grid and repeated 1° and 2° cluster analyses with grids shifted over and down half a grid cell

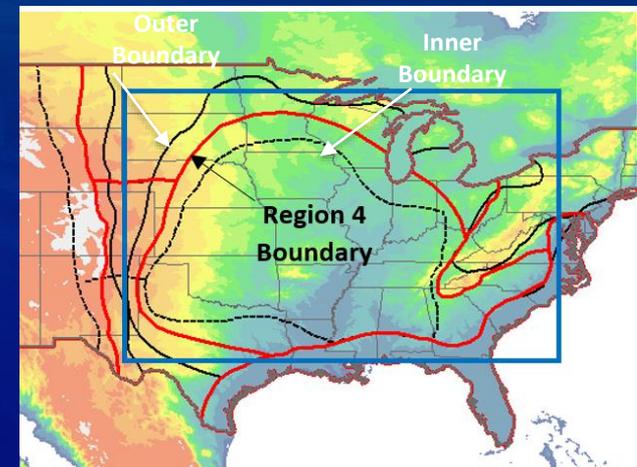
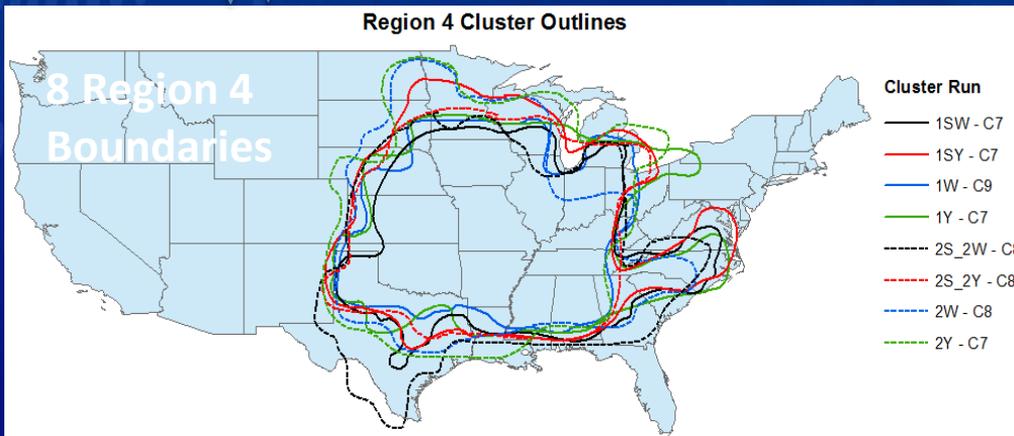


Region Boundaries and Uncertainties

8 Model Cluster Runs



Region 4 Cluster Outlines

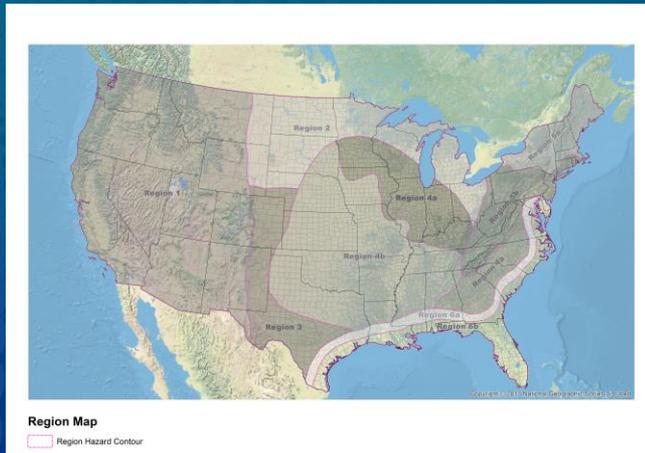


The boundary contours are also used to quantify region boundary uncertainties through spatial smoothing, described on the Map Development Process slide.

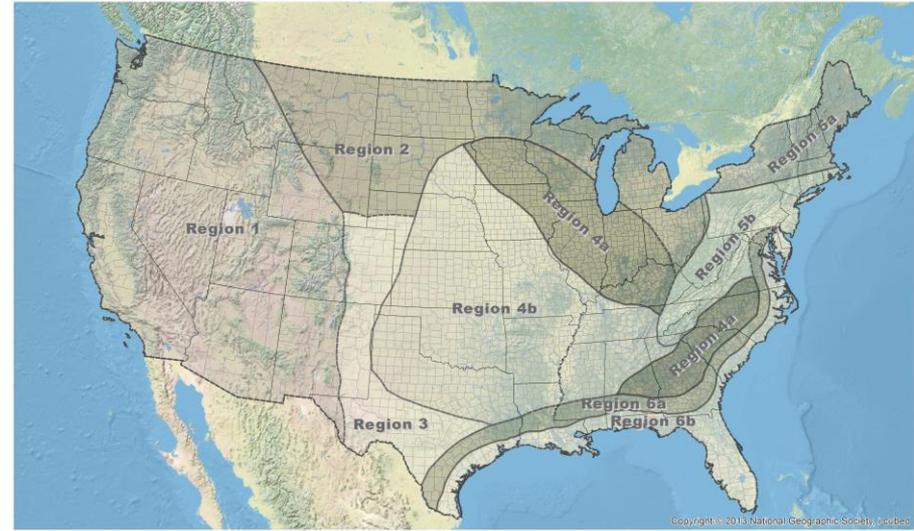


Final Region/Subregion Boundaries

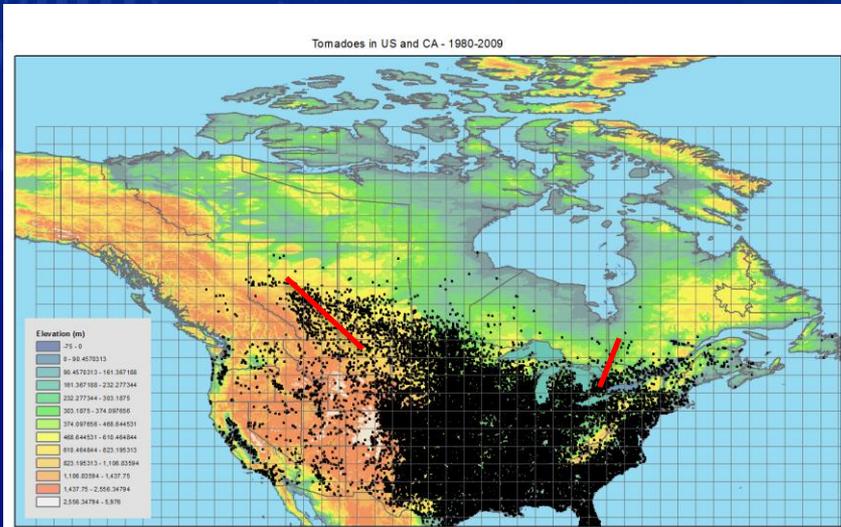
Hazard Regions from Cluster Analysis and Sub-region analysis



Final Climatology Regions for Tornado Maps



Additional Data on Tornadoes in Canada



Final regional boundaries determined using regions from cluster analysis with modifications, including

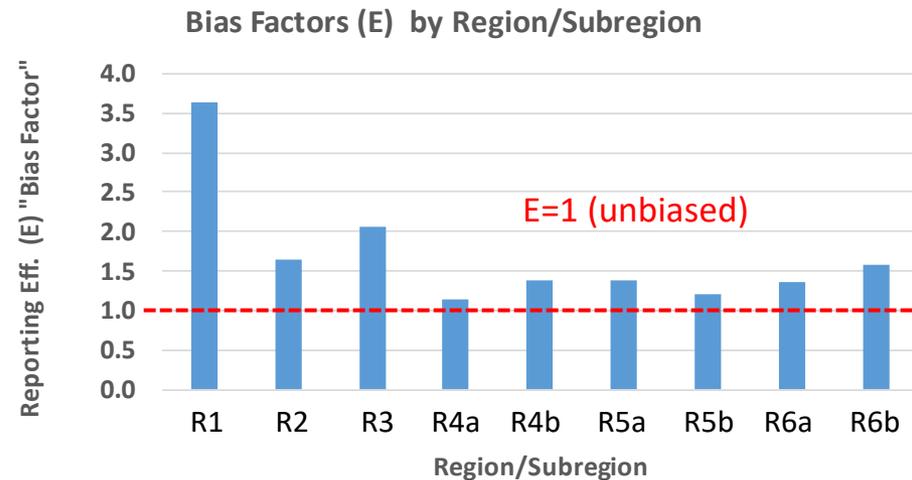
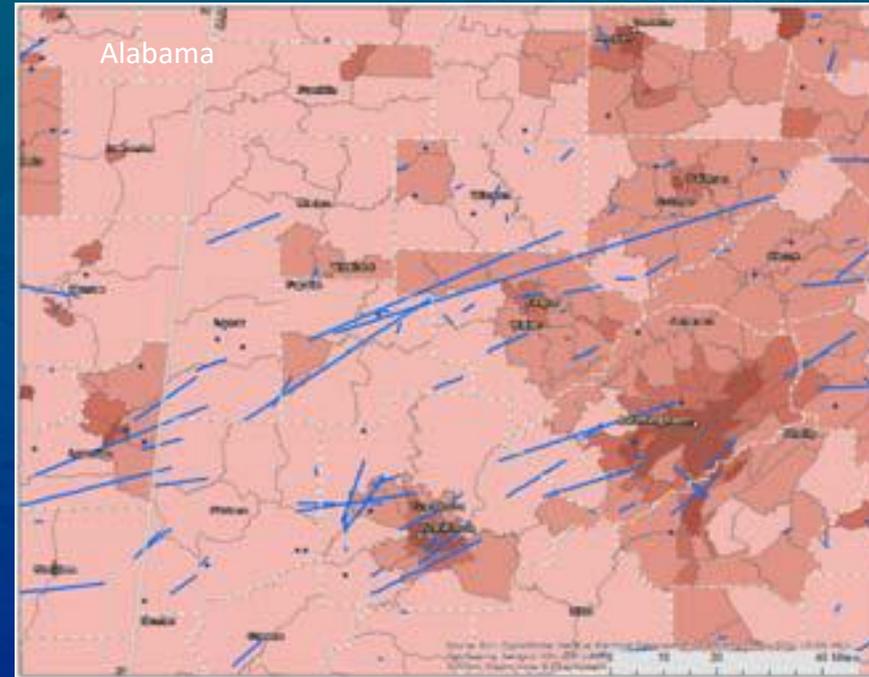
- Smoothing of certain boundaries to improve map contouring near multi-region intersections
- Adjusted Region 1-2 boundary in Montana-Wyoming to follow tornado trends in combined US-Canadian tornado maps and land elevation



Tornado Occurrence Rate Analysis

- Researchers have long studied tornado reporting efficiency (“population bias”) in order to estimate the under-reporting of tornadoes in rural areas.
- We use Census Tract (CT) data, coupled with Building Density (BD) data to estimate “unbiased” values of tornado occurrences.
- We evaluated several tornado counting methods and develop tornado density data, conditional on BD, to estimate reporting bias in rural areas.
- We find that high building density census tracts can have notably higher tornado densities.
- Occurrence rates are based on tornado densities computed over a weighted range of BD thresholds to treat epistemic uncertainties.

Reported tornado tracks overlaid on Census Tracts with darker reds indicating higher Building Densities



Wind Speed Distributions

Develop engineering-based approach to determine wind speeds from damage using damage to houses, since the EF Scale Damage Indicator for 1 & 2 family residences (FR12) was found to dominate the rating of strong (EF 2-3) and violent (EF 4-5) tornadoes

1. Simulate tornado loads and resistances (w/validated finite element models) for 44 house configurations to estimate probability of damage as a function of wind speed, $P(d_i|v_j)$
2. Correlate modeled damage with Degree of Damage (DOD) from Enhanced Fujita (EF) Scale, $P(DOD_i|v_j)$

3. Use Bayesian approach to estimate probability of wind speed given a DOD, $P(v_j|DOD_i)$
4. Estimate probability of tornado wind speed given an F Scale or EF Scale rating, $P(V|EF)$

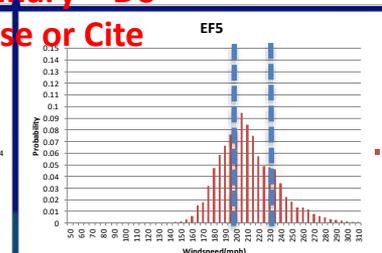
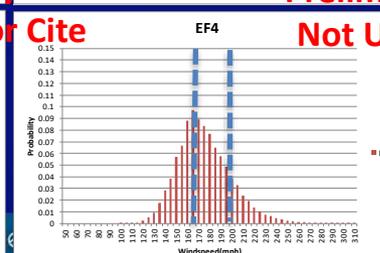
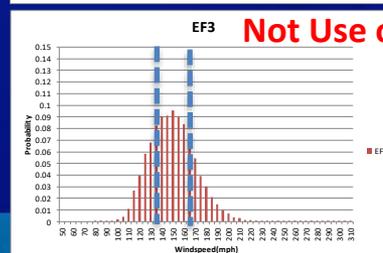
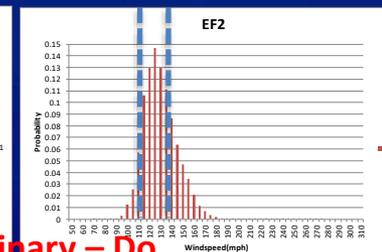
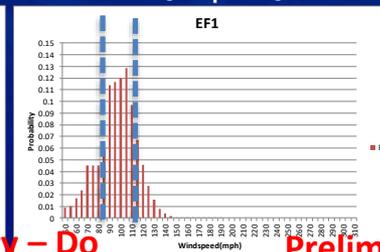
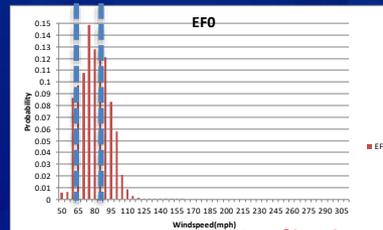
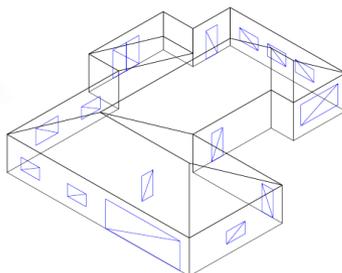
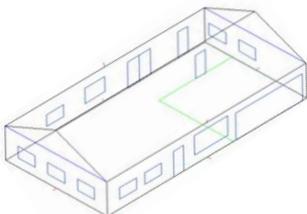
EF SCALE	
EF #	3 Sec Gust (mph)
0	65-85
1	86-110
2	111-135
3	136-165
4	166-200
5	Over 200

$P(V|EF)$

Example House Models

Simple Gable

Complex Hip

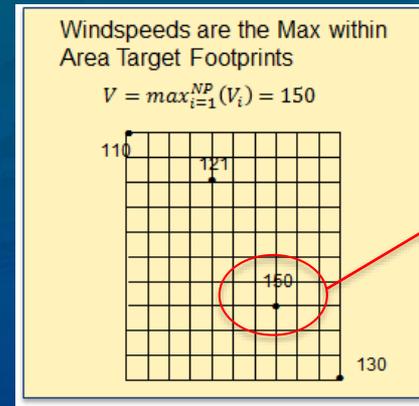


Preliminary – Do Not Use or Cite

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Reference Wind Speed

- Reference wind speed (RWS) is the maximum horizontal wind speed (assumed nominal gust) experienced (within target area) at 10 m height.
- As for non-tornadic winds, the RWS is the free-field wind speed ignoring presence of the target.
- Once the target is positioned (randomly) within the tornado path, the RWS is quantified in each simulation by advancing the tornado past the target.
- With random target positioning, the RWS therefore includes contributions from multiple EF intensity tornadoes and sampled target position, such as in inside or outside RMW.
- For area targets, the RWS in any simulation may occur over a small or large part of the target.
- Using maximum horizontal winds as the RWS assumes appropriately developed load parameters for:
 - MWFRS and C&C size factors
 - Vertical winds
 - APC
 - Wind borne-debris
- In summary, the RWS is NOT based on worst case assumptions of tornado track *vis a vis* target position.

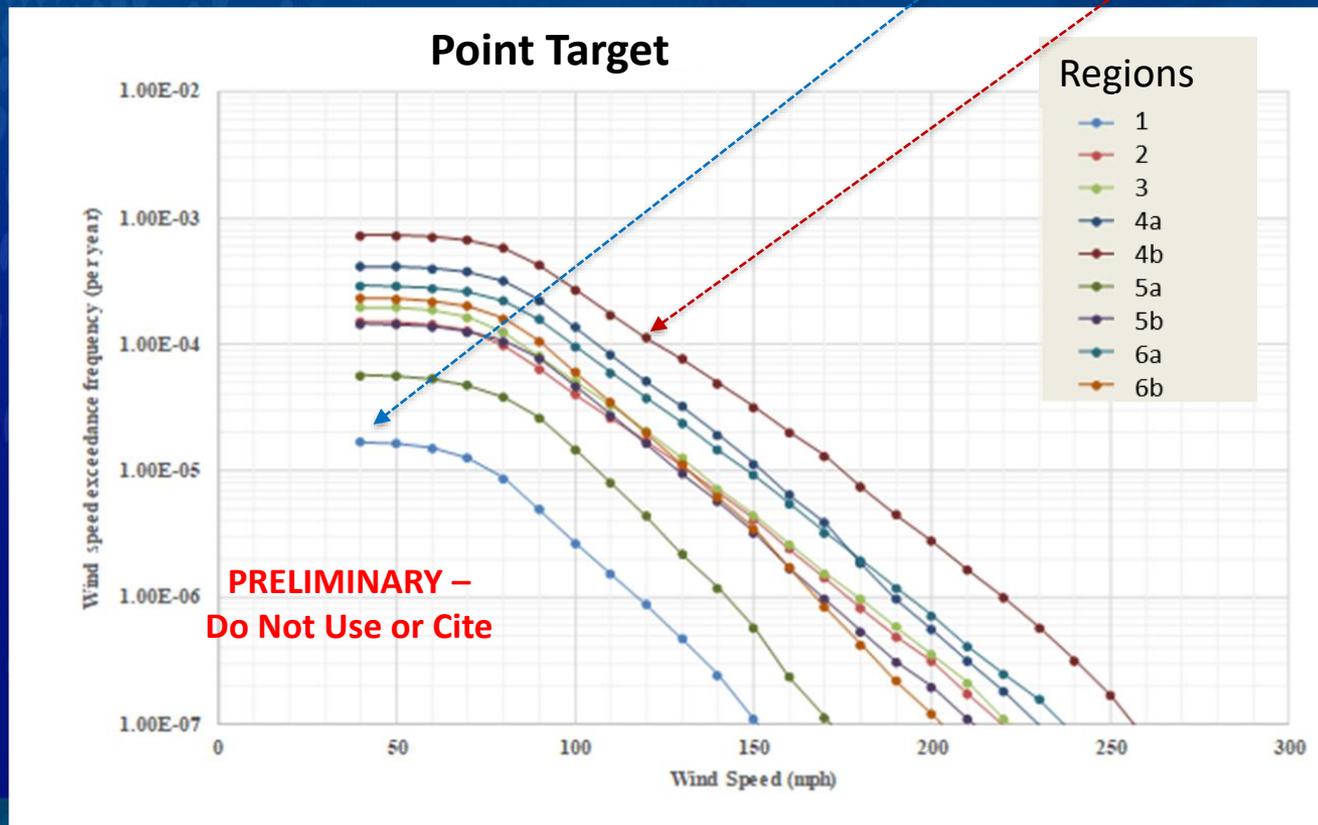


The RWS for this structure is close to the center of building



Hazard Curves: Point Target

Windspeed Exceedance Frequencies (WEFs) are developed for each region and subregion, for a range of target sizes



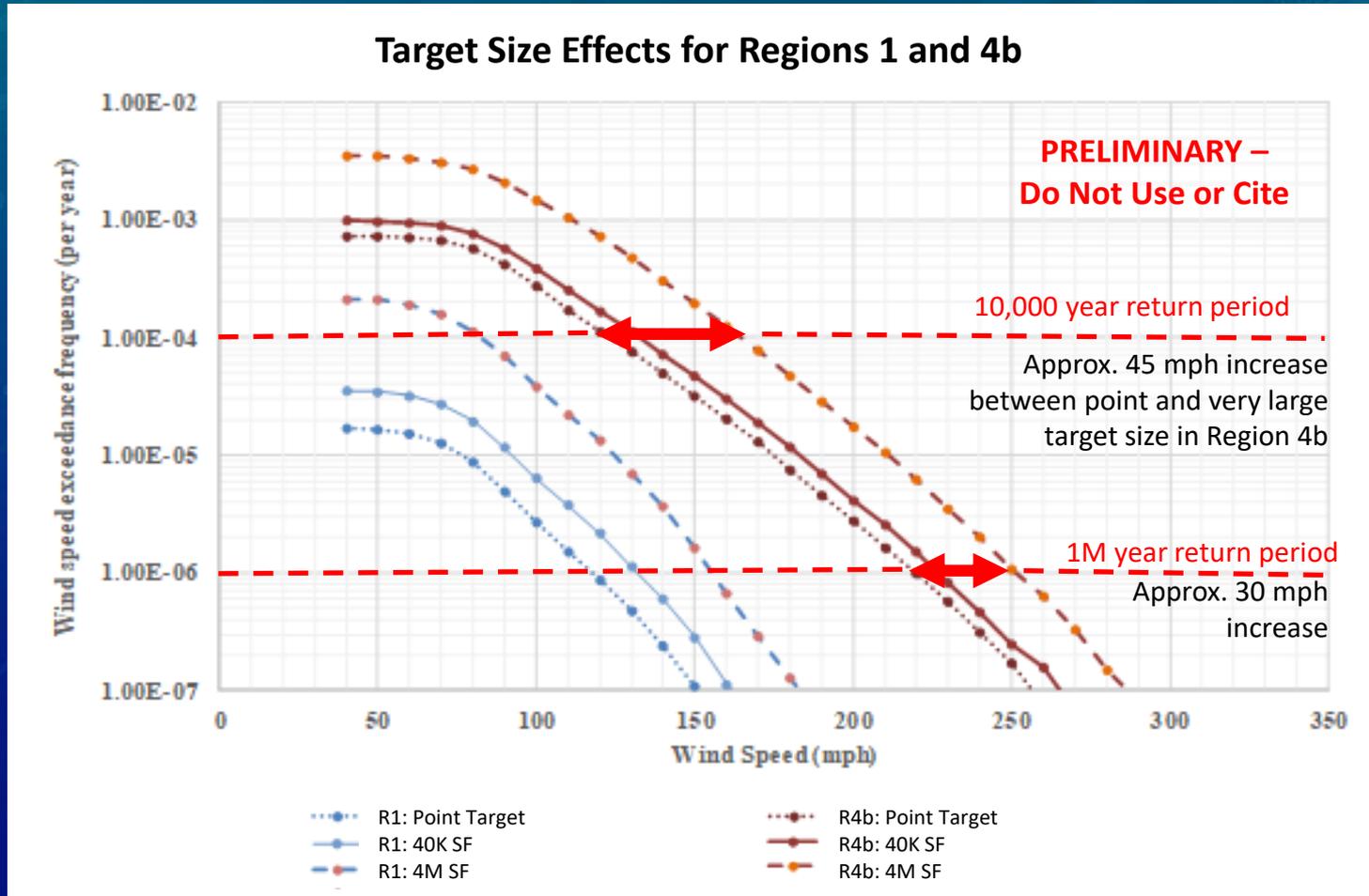
Point Target
Examples:

Freestanding tower
and pole structures



Target Size Sensitivity

- Sensitivity varies with region. Region 1 shows more sensitivity than 4b due to smaller tornadoes
- Sensitivity decreases with increasing return period
- Orientation Sensitivity
- Virtually no sensitivity for square targets
- Modest sensitivity for oblong targets
- Results are not provided for line targets



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.

1. Hazard Curve WEFs
(Given Target Size)

2. Interpolate
Windspeeds to
Return Periods

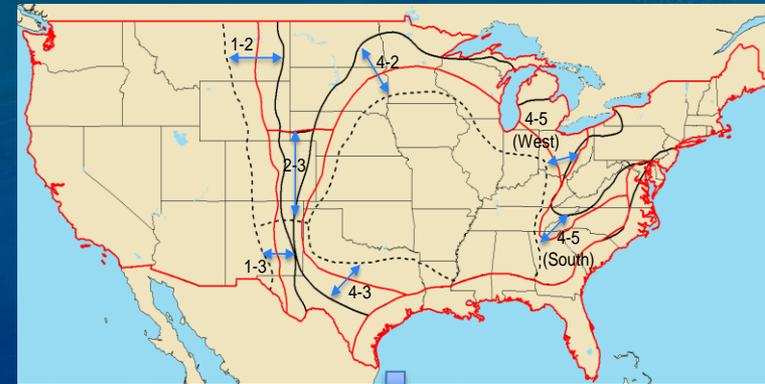
3. Input Windspeeds
to Region/Subregion
Grid Cells

4. Gaussian
Smoothing

5. ArcGIS Kriging

6. PAEK Smoothing and
Hand Adjustments for
Final Maps

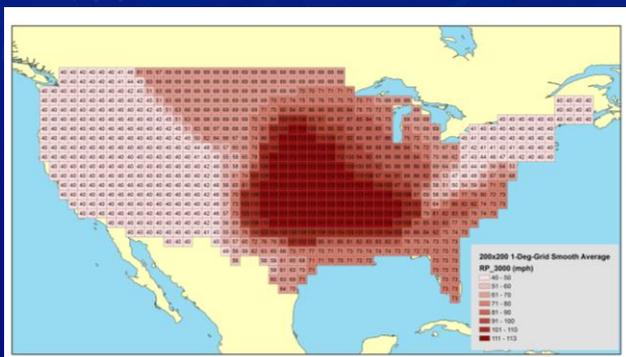
Regional Boundary Uncertainties



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.



Example Grid After Smoothing



Maps Produced

Return Periods (years)

1. 300
2. 700
3. 1,700
4. 3,000
5. 10,000
6. 100,000
7. 1,000,000
8. 10,000,000

Target Sizes, ft² (target dimensions)

1. Geometrical Point (no area)
2. 2,000 (45' x 45')
3. 10,000 (100' x 100')
4. 40,000 (200' x 200')
5. 100,000 (316' x 316')
6. 250,000 (500' x 500')
7. 1,000,000 (1,000' x 1,000')
8. 4,000,000 (2,000' x 2,000')

The return periods of 300, 700, 1700, and 3000 years were chosen to match return periods used for ASCE 7-16 Risk Category I, II III & IV buildings/structures, respectively

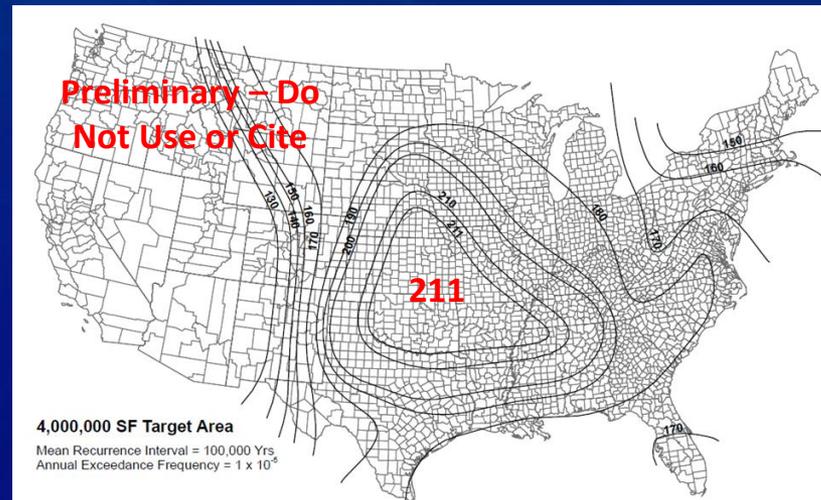
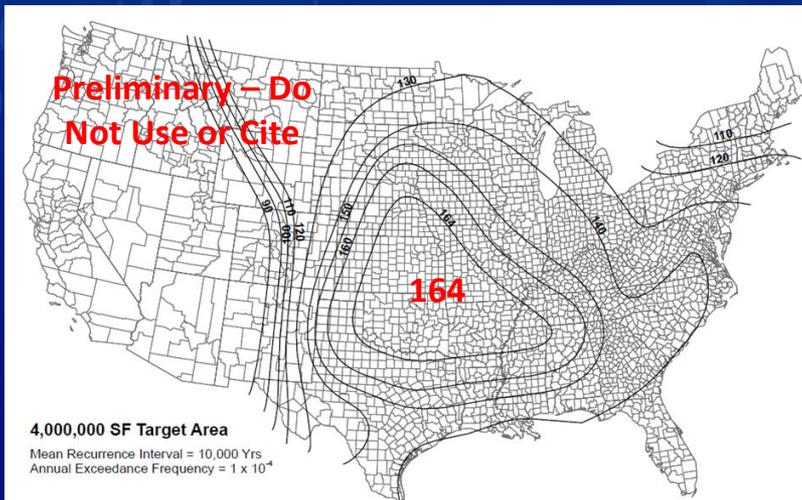
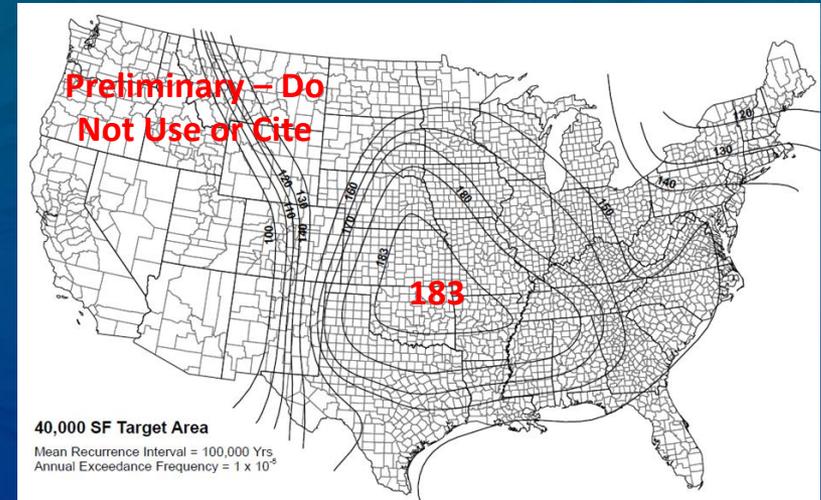
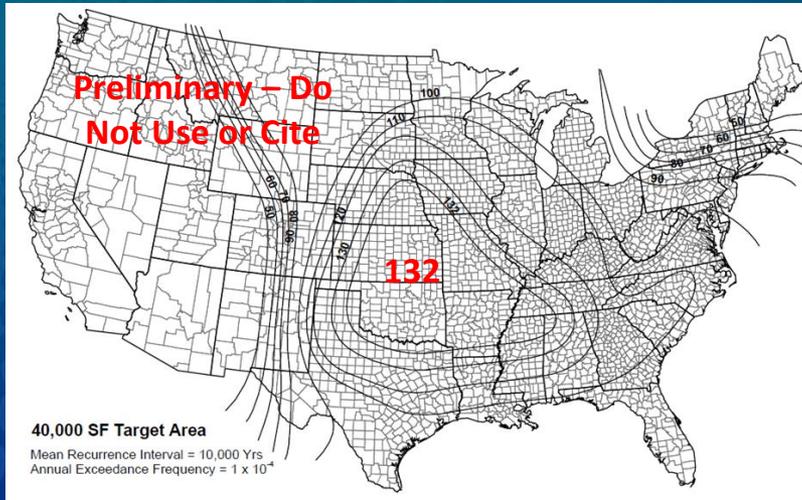
For each RP, maps were produced for each target size.* The target sizes were developed in coordination with the NRC



Example Maps (1/2)

10,000 Year

100,000 Year



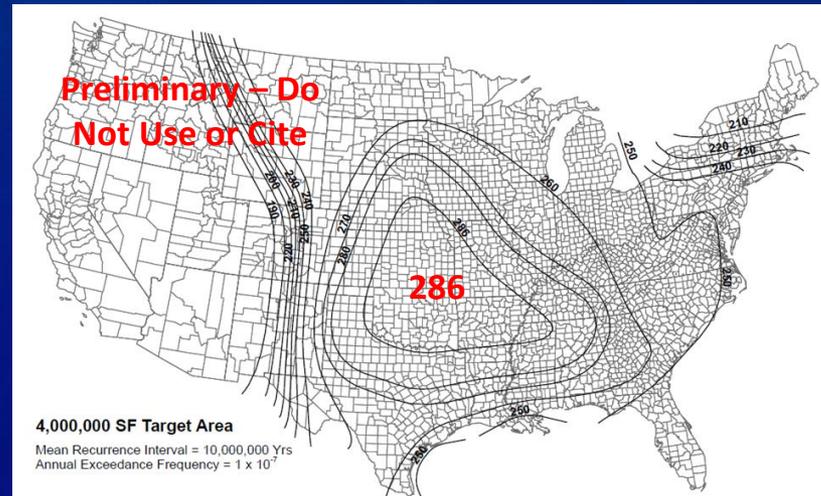
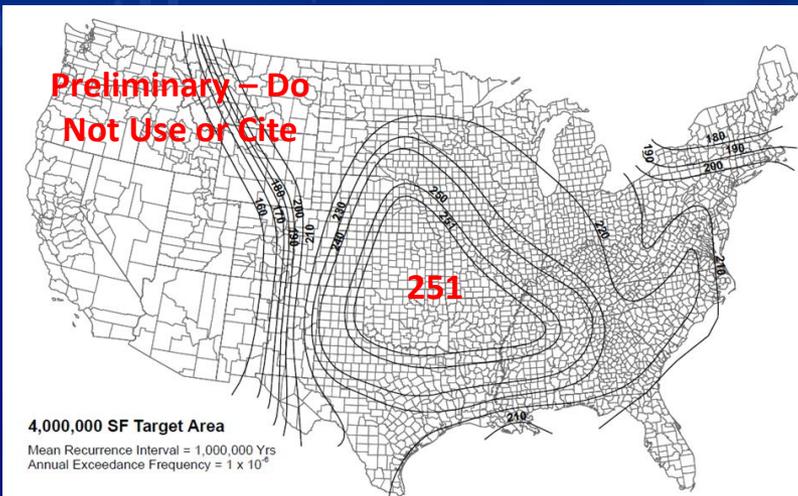
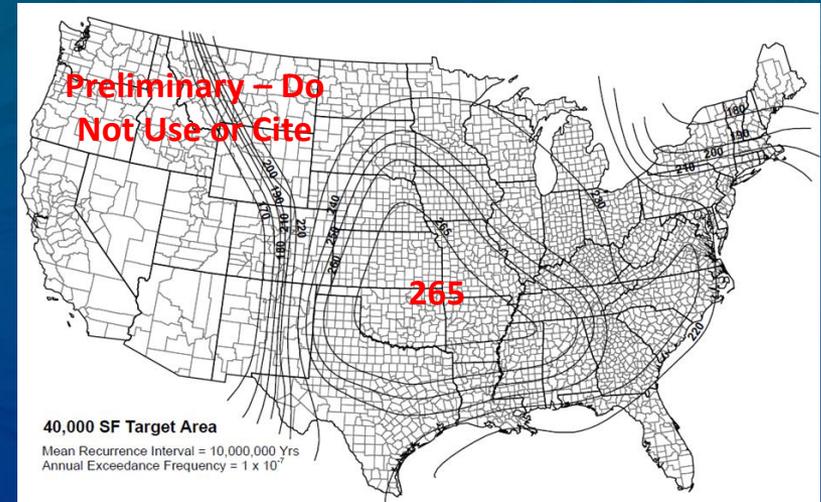
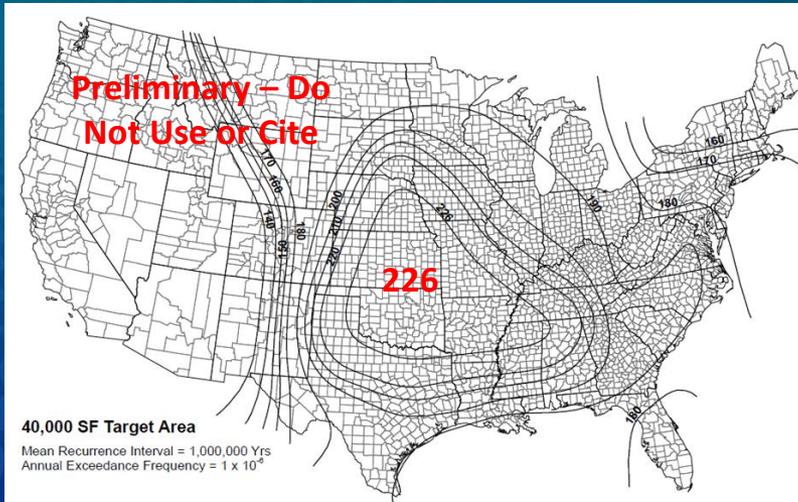
Tornado speeds are 3-s peak gusts at 10 m height, in mi/h



Example Maps (2/2)

1,000,000 Year

10,000,000 Year



Tornado speeds are 3-s peak gusts at 10 m height, in mi/h



Comparison with NUREG

NUREG/CR-4461, Rev. 2, "Tornado Climatology of the Contiguous US" WEF results for 1E-05, 1E-06, and 1E-07. Used tornado data from 1950-2003.



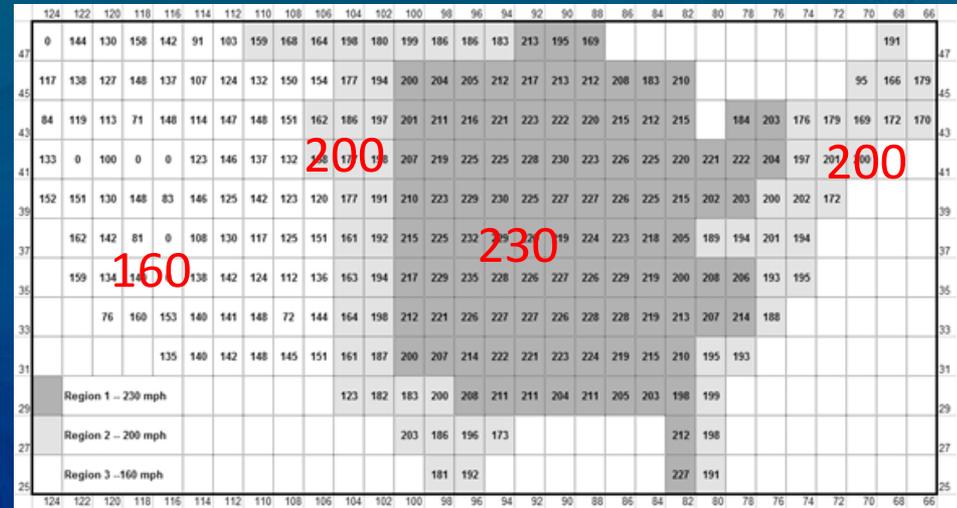
10 Million Year (1E-07) RP NUREG Map

Comparisons of several cities are illustrated in the table for a 200x200 target.

For 1000x1000 NPP power block area, the differences are larger, particularly at the lower RPs.

Comparing to NUREG EF and F: roughly mid way

NUREG EF Tornado Climatology (2007)



Location	NUREG EF (mph)			Wind Speed Maps (200x200) (mph)			(Maps - NUREG) (mph)		
	1.0E-05	1.0E-06	1.0E-07	1.0E-05	1.0E-06	1.0E-07	1.0E-05	1.0E-06	1.0E-07
St Louis	143	180	213	178	220	260	35	40	47
Dallas	141	178	211	181	224	262	40	46	51
Boston	126	165	200	130	164	197	4	-1	-3
Miami	116	157	191	150	180	220	34	23	29
WDC	128	167	202	150	185	224	22	18	22
Denver	106	149	187	140	183	223	34	34	36
Los Angeles	0	118	160	100	130	170	100	12	10
Columbus, OH	150	186	219	147	187	228	-3	1	9
Jackson, MS	158	193	225	174	216	257	16	23	32
New York	86	135	172	140	175	213	54	40	41
Minneapolis	156	192	224	160	197	237	4	5	13

Avg ≈ 20-25 mph increase



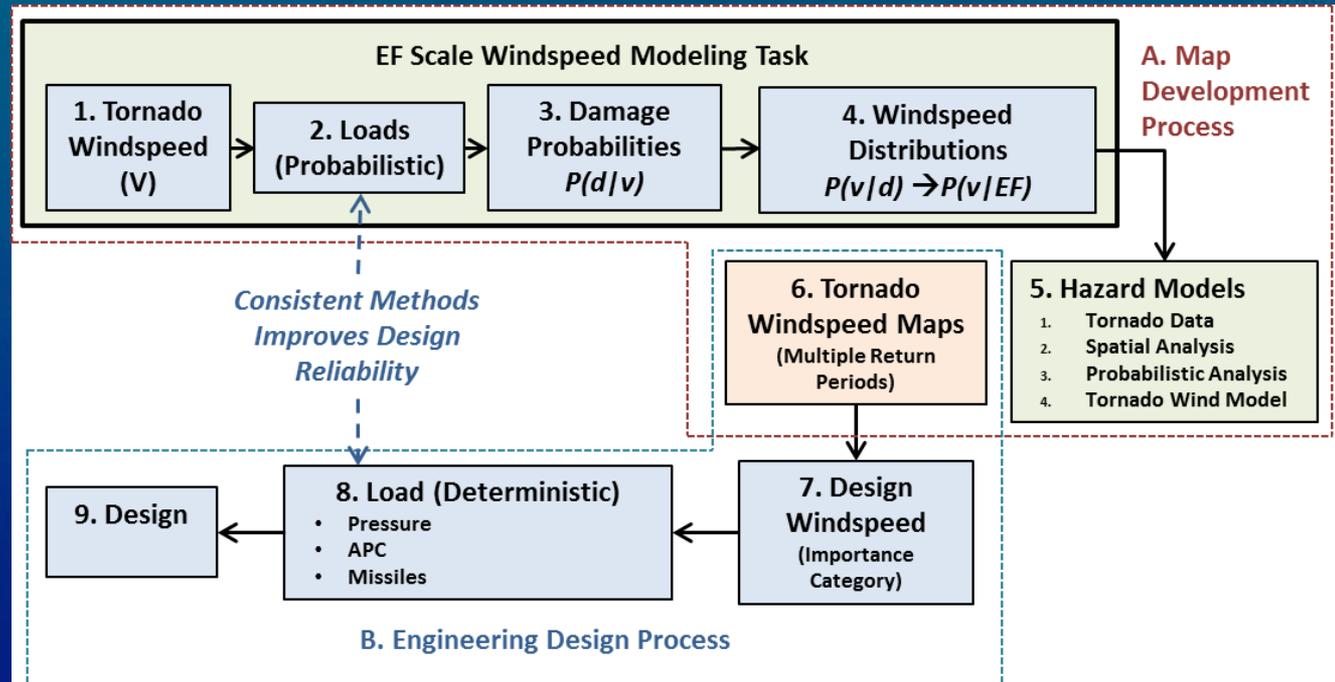
Tornado Map Summary

1. We have used an “engineering” modeling process to develop tornado wind speed maps in order to systematically produce wind speeds for a wide range of return periods.

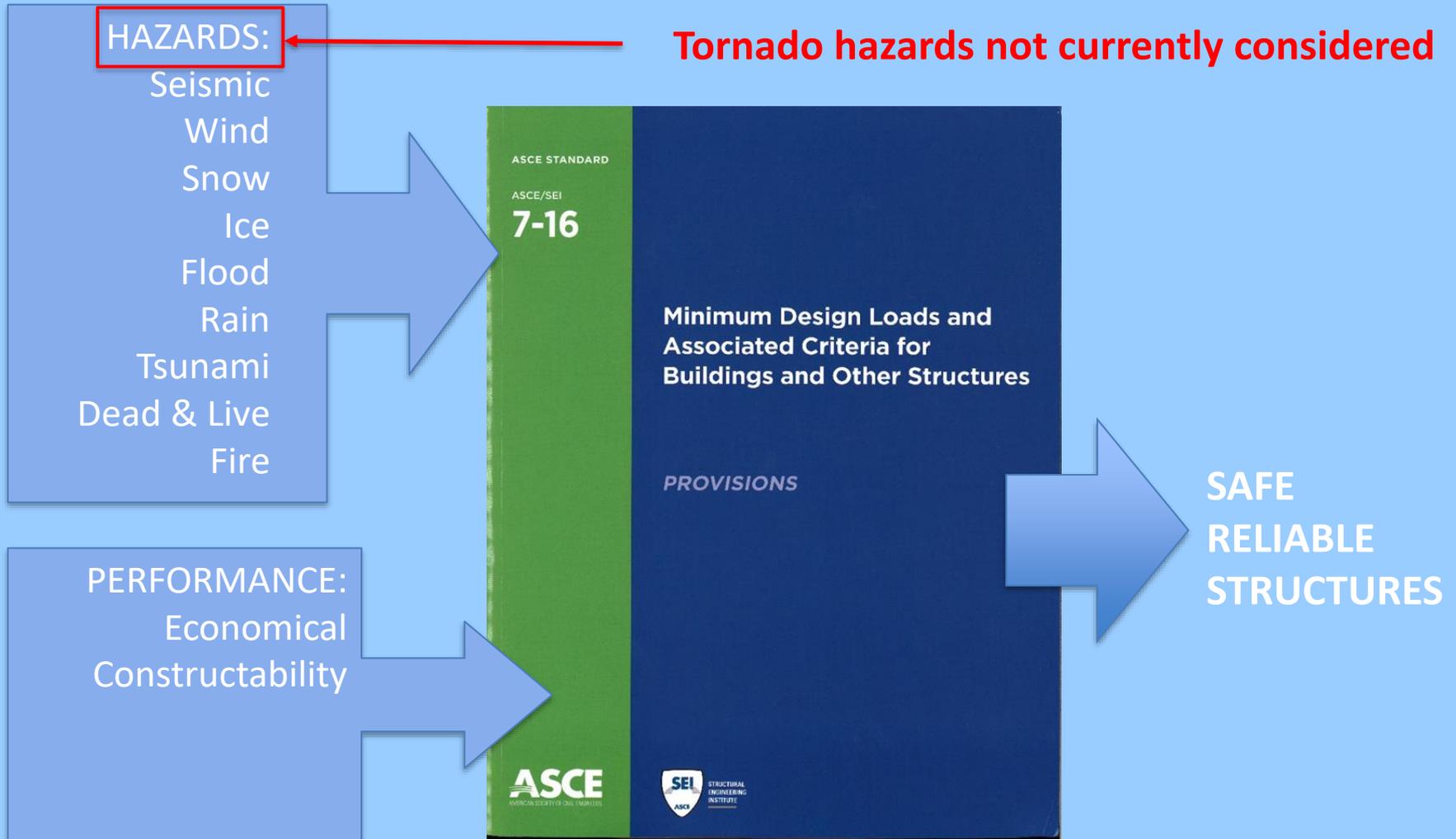
2. Our goal was “best-estimate” modeling, consistent with ASCE wind hazard maps and NPP HW PRA Standards

3. By using an engineering process for wind speed estimation, we believe that the modeled tornado wind speed hazard can be reasonably associated with the return periods and usable for engineering design.

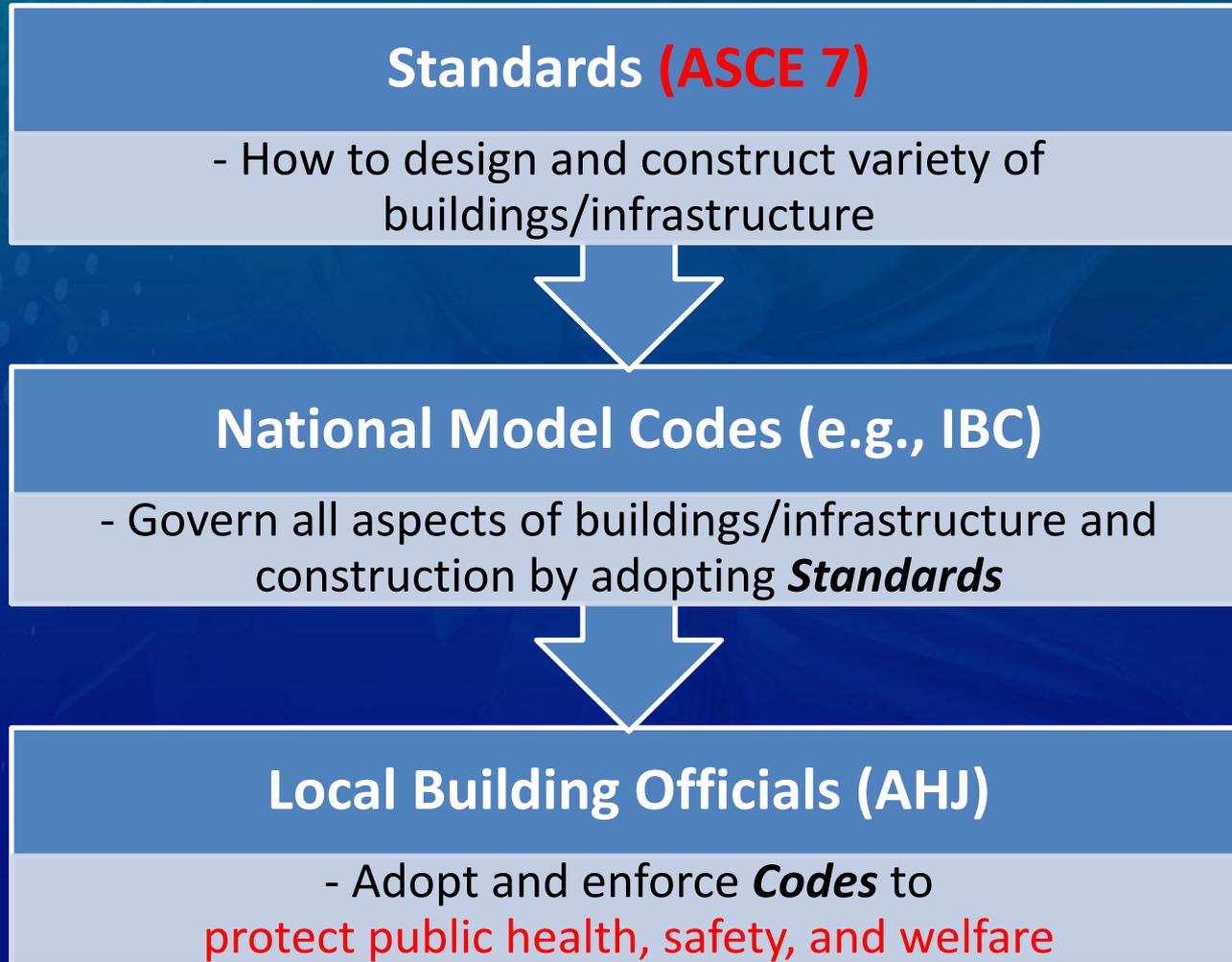
4. We attempted to quantify epistemic uncertainties for key variables. Nevertheless, the resulting hazard curves and associated maps have large residual epistemic uncertainties.



Map Implementation in ASCE 7



Role of ASCE 7



NIST, ARA, & the ASCE 7 Tornado Task Committee Working Together:

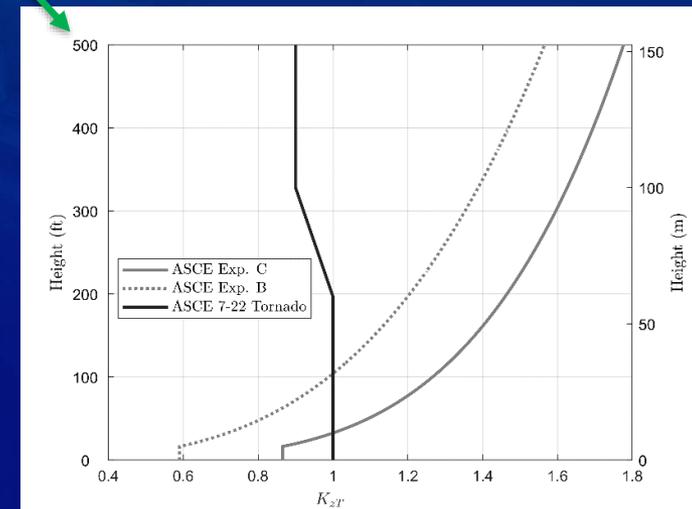
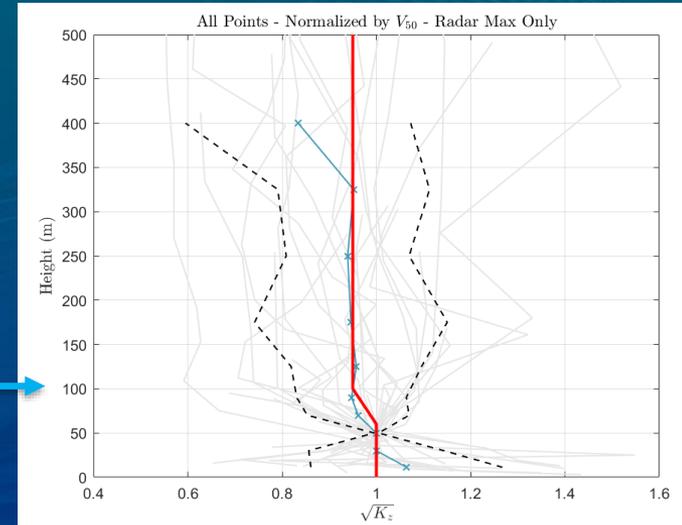
Developed tornado load provisions for the 2022 edition of ASCE 7

- Tornado hazard maps, at return periods consistent with ASCE 7 reliability targets
- Vertical profile of horizontal component of tornado winds
- Tornado pressure and load coefficients
 - Effects of vertical component of wind handed through a modification factor on roof pressure coefficients
- Procedures to determine tornado loads on
 - Main Wind Force Resisting System (MWFRS)
 - Components and Cladding (C&C)



Tornado Design Methods and Standards

- Built on ASCE 7-16 Wind Load Framework
- Worked closely with mobile radar community to analyze radar-measured tornado wind speeds and develop tornado velocity pressure profile, consistent with assumptions used in development of tornado hazard maps
- Developed New and Modified Wind Load Factors for Tornadoes
 - Tornado Directionality Factor K_{dT} , for MWFRS and C&C
 - Internal Pressure Coefficient GC_{piT} , including effects of Atmospheric Pressure Change
 - Tornado Pressure Coefficient Adjustment Factor for Vertical Winds K_{vT} , for MWFRS and C&C

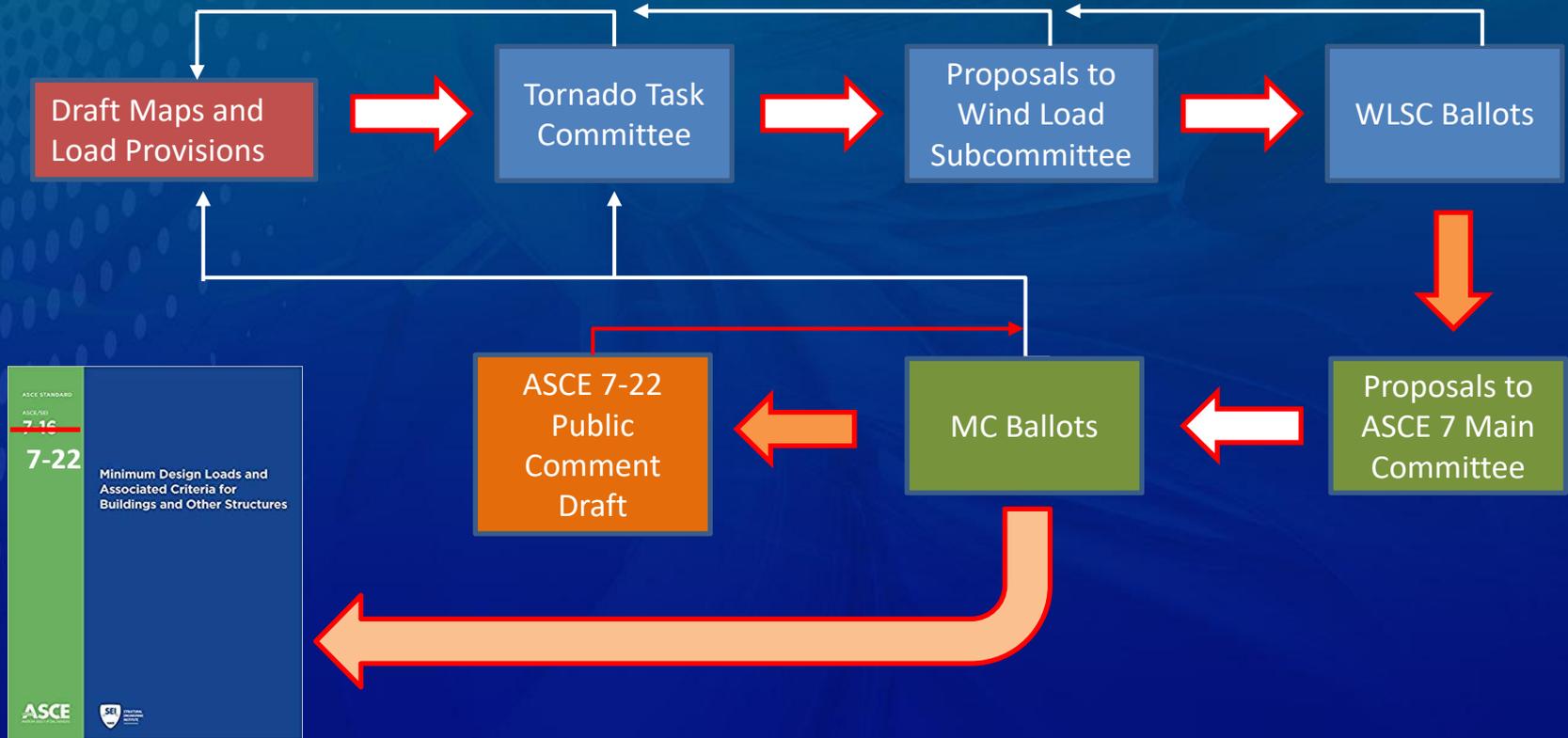


Tornado Provisions

- Chapter 32
 - Proposed new chapter on Tornado Loads
 - Includes tornado maps at return periods consistent with reliability requirements for Risk Category III and IV buildings and structures (including places of public assembly, and critical and essential facilities)
- Chapter 32 Appendix
 - Proposed new Appendix with long return period Tornado Maps to support the nuclear industry and performance-based design
 - 10,000 to 10,000,000 year Mean Recurrence Intervals, for point target through 4M sq ft target size



ASCE 7 Consensus Process



WLSC: ASCE 7 Wind Load Subcommittee

MC: ASCE 7 Main Committee



Opportunities to Stay Informed/Participate

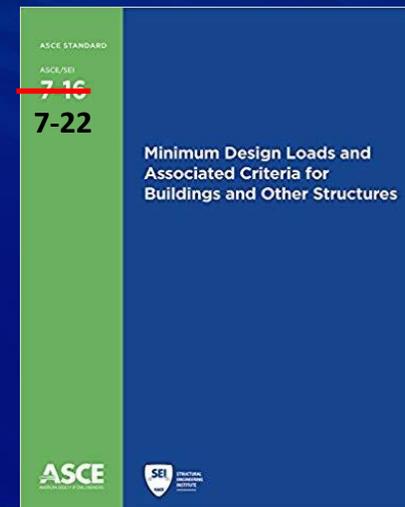
All ASCE 7 Committee meetings are public

- meeting schedule:
<https://www.asce.org/structural-engineering/asce-7-and-sei-standards/>



Public Comment Draft of ASCE 7-22

- June-July of 2021
- 45-day comment period
- All comments must be considered and responded to by the Main Committee





October 21, 2020

DOE/NRC NPH
Meeting

Latest Developments in Tornado Hazard characterization and Tornado Loads on Buildings/Structures

Questions?

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