

# Climate Change Impacts on Extreme Windstorms and Implications for Structural Design in the United States: A Review

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**Abstract:** Climate change impacts various extreme windstorms associated with specific meteorological phenomena in different ways. Since various windstorms contribute to the design wind speeds, this study systematically reviews the state-of-the-art understanding of climate change effects on wind events that collectively contribute to structural wind design in North America, particularly the United States, including extratropical cyclones (as well as nor'easters), tropical cyclones, thunderstorms, and tornadoes. For each windstorm type, the general evidence of climate change impacts on storm activities (e.g., occurrence frequency and intensity) is first summarized, followed by the introduction of existing simulation frameworks for yearly (or sub-

yearly) maximum storm winds under changing climate; and then relevant simulation results demonstrating climate change impacts on design wind speeds are presented. In addition, major challenges associated with climate/weather/wind simulations (e.g., resolution and duration) and data analyses (e.g., sample extrema and nonstationary extreme value analysis) to quantify the climate change effects on design wind speeds are discussed in this review.

**Keywords:** Climate Change, Windstorm, Design Wind Speed, Extreme Wind Speed, Structural Design

## INTRODUCTION

Scientific evidence for warming of the climate system is unequivocal, and nontrivial climate change impacts on windstorms have been observed, although wind speeds cannot yet be projected with a medium-to-high degree of certainty ([PCAST 2023](#)). The uncertainty in the projection of climate (resulting mainly from greenhouse gas emission scenario design, internal climate variability, and uncertainty inherent in climate models themselves) along with downscaling uncertainty poses great challenges for a reliable prediction of future wind conditions ([IPCC 2022](#)). Since different methodological approaches are needed for each type of windstorm (with different spatial/temporal scales as well as occurrence rates), current knowledge levels about future wind conditions from each type of windstorm are very different ([Biondini et al. 2024](#)).

The currently adopted methodology in defining wind climate characteristics for structural design is to use statistical models based on a combination of historical surface data of windstorms with high occurrence and, where appropriate, Monte Carlo simulations of windstorms with relatively low occurrence for a particular site ([ASCE 2023](#)). Specifically, the yearly (or sub-yearly) maximum storm wind speeds are first obtained from historical observations and/or numerical simulations through block maxima or peaks-over-threshold techniques, and then are utilized to determine design wind speed based on either non-parametric or parametric methods ([Pintar et al. 2015](#)). The non-parametric methods typically involve ranking the wind data and then calculating the quantile corresponding to the desired return period, typically referred to as mean recurrence interval (MRI). It is noted that the MRI is a concept that is only applicable under stationary conditions (i.e., when the probability distributions of climatic parameters are or are assumed to be time invariant). In a nonstationary climate, the MRI is an invalid concept and might cause confusion. In the following review, however, the concept of MRI is used in cases when the literature still uses it. Non-parametric methods offer the advantage of not assuming a specific shape for the probability density function (PDF) of extreme winds. Nonetheless, this technique is

constrained by the length of the available wind data, as it lacks the capability to extend extrapolation beyond the timeframe during which the data were collected. On the other hand, the parametric methods assume that the PDF of extreme wind speeds follows a known statistical distribution. The most common approach is to use a specified type of extreme value distribution fitted to wind data for extrapolation beyond observed extreme events within each storm type, and accordingly calculate the quantile corresponding to the desired return period ([Gomes and Vickery 1978](#)). Although several extreme value distributions have been used (e.g., Gumbel, Weibull and Pareto distributions), the combination of the peaks-over-threshold (POT) approach to identify all extremes within a year and fitting the generalized Pareto distribution (GPD) to them has shown superior results ([Pintar et al. 2015](#)). Specifically, the POT technique extracts all excesses above a specified threshold value, then the GPD is applied to the POT of the generated data. Following this approach, the design wind speeds associated with various return periods can be determined. Since separate fits are made to each storm type, their probabilities need to be combined to determine relationships between design wind speed, directionality, and MRI. The obtained design wind speeds associated with a specific MRI are then used in conjunction with appropriate aerodynamic pressure coefficients and other wind load parameters reported in structural design standards such as ASCE 7 ([ASCE 2022](#)) or obtained from project-specific wind tunnel test data to calculate the wind loading to be used for structural design. Wind directionality considerations are typically simplified into the use of a directionality factor in codes and standards ([ASCE 2022](#)). The extreme value analysis approach herein described assumes stationarity for extreme wind speeds, which is inconsistent with observed trends and climate science-based predictions of climate change effects (e.g., [Klink 1999](#); [Pryor et al. 2009, 2012](#)).

Current design practices in wind engineering primarily focus on a single MRI corresponding to the ultimate limit state (ULS) for low-rise buildings, whereas the design of mid- and high-rise buildings typically considers various MRIs for both ULS and serviceability limit state (SLS) design

(ASCE 2022). The consideration of occupant comfort through limiting the peak acceleration at any given floor is also a common practice in the design of mid- to high-rise buildings based on international codes (ISO 2007) or industry best practices guidance (ATC 2019). These practices are an intrinsic component of the performance-based wind design (PBWD) methodology (Scott et al. 2023), and have been included as major performance criteria in a recently-published ASCE PBWD pre-standard (ASCE 2023). The PBWD pre-standard provides guidance on how to design structures subjected to wind hazards while targeting simultaneously various performance objectives, such as occupant comfort, operational structure, continuous occupancy (or limited interruption), life safety, and collapse prevention, corresponding to MRIs varying between one year and several thousand years (ASCE 2023). Figure 1 illustrates wind hazard curves in an assumed stationary climate (i.e., wind speeds corresponding to any given MRI) for the various storm types discussed in this review. It is noted that Fig. 1 is not representative of any given location in the United States and serves only illustrative purposes. Specifically, each individual wind hazard curve reported in Fig. 1 corresponds to a specific windstorm type and is based on observed or modeled data representative of a specific but different location in the United States, which is prone to that specific windstorm type. As a result, each wind hazard curve corresponds to a different geographic location. Depending on the specific location, the intersections and slopes of the curves in Fig. 1 will be different, leading to different windstorms controlling the structural design at different return periods. For example, tropical cyclones (TCs) may not be of any concern for an inland location (e.g., Nebraska), whereas in locations along the East Coast (e.g., Miami) they may overwhelm other storm types even at fairly low MRIs. Thunderstorms tend to dominate the composite hazard curve over extratropical cyclones (ETCs) at MRI > 50 yr in most inland locations of the US East of the Rockies (Lombardo 2014). Tornadoes, even in the most tornado-prone regions, usually do not enter the hazard curve until fairly long MRIs. It is also noted that, although nor'easters have been treated differently than other ETCs in the literature, the extreme winds induced by nor'easters have not been separately considered in the development of design

wind speeds provided in building codes or used in engineering practices. The composite wind hazard curve can be used to design structures for various performance goals and can be determined using a mixed distribution (Gomes and Vickery 1978), which considers the probability distributions of each storm type independently. Since the design wind speed of engineered structures based on the extreme value theory is a function of the MRI, the various windstorms that control each performance goal need to be holistically considered under changing climate conditions, as their characteristics will likely change in different manners as the climate changes. In this study, the climate change effects on these wind events that collectively contribute to structural wind design in North America, including ETCs, nor'easter, TCs, thunderstorms and tornadoes, are systematically reviewed.

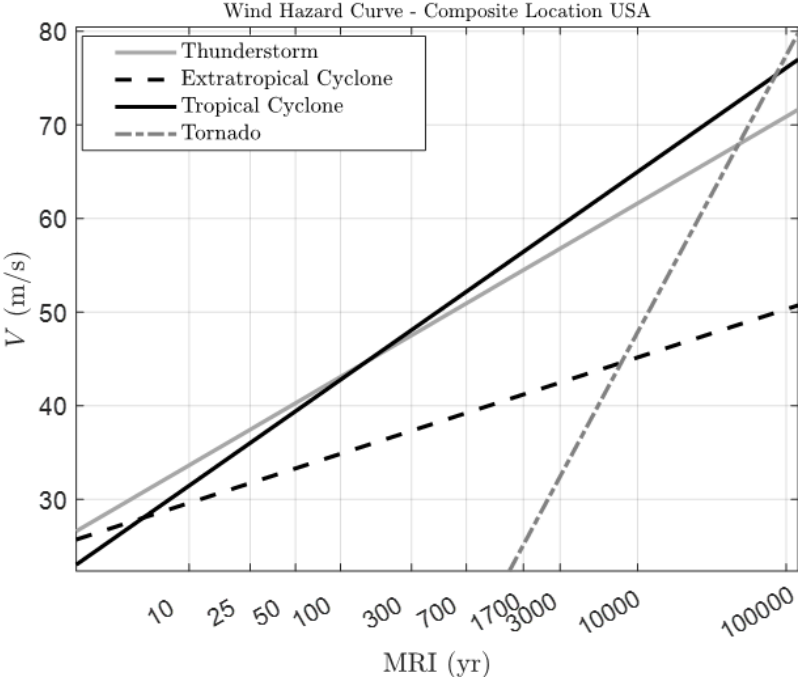


Figure 1: Wind hazard curves for different windstorms at various locations in the United States.

It is critical to acquire enough yearly (or sub-yearly) maximum wind speed data of each storm type from climate/weather/wind simulations under changing climate to quantify the climate change effects on structural wind design. For low-occurrence windstorms (e.g., TCs and tornadoes), the

major simulation challenge is that data needs to be simulated for very long periods, in the order of thousands of years for simulated TCs (Vickery et al. 2000) and millions of years for simulated tornadoes (Twisdale et al. 2023). For small-scale windstorms (e.g., thunderstorms and tornadoes), the major simulation challenge is that data is needed at a very high spatial resolution. For example, the desirable spatial resolution for tornadoes is in the order of 10-m grid (Mashiko and Niino 2017) while that for TCs is in the order of 10-km grid (Murakami and Sugi 2010). It is noted that the current review mainly focuses on the wind speeds averaged at a temporal/spatial scale that is relevant for structural engineering applications, thus excluding literature that focuses on the full resolution of the fine-scale storm structures. To accurately simulate the atmospheric boundary-layer turbulence that might be important to structural aerodynamics, the Kolmogorov dissipation scale on the order of 1 mm might need to be resolved (Schneider et al. 2023). To identify research needs for achieving a proper representation (trade-off between desirable and feasible space and time granularities) of extreme wind events under the projected nonstationary climate conditions, this review compiles the current publicly available research on climate-driven wind speed changes from the point of view of structural engineering applications. Specifically, it reports the current state-of-the-art in modeling the climate change effects on different types of windstorms with a particular focus on extreme wind values that control different design limit states of main wind force resisting and envelope systems for both prescriptive and performance-based structural designs. This study also highlights uncertainties and limitations in the models currently available to climate scientists and engineers to simulate and predict projected changes in weather patterns and extreme wind events.

This state-of-the-art review represents a necessary addition to the literature because most of the existing review papers on climate-driven wind changes address issues from the point of view of climate science, which is more focused on the trends of general environmental factors instead of extreme events (e.g., Moemken et al. 2018), or for different types of engineering applications,

e.g., prediction of wind energy production (e.g., [Tobin et al. 2015](#); [Johnson and Erhardt 2016](#); [Chen 2020](#)). This work is extremely significant, as it is expected to inform continuous efforts for updating structural design standards of the United States (e.g., ASCE 7) and provide a knowledge basis for PBWD efforts that will influence structural design in the decades to come.

## **CLIMATE CHANGE IMPACTS ON EXTREME WINDSTORMS**

This review focuses on the following windstorm types: (1) ETCs, (2) nor'easters, (3) TCs, (4) thunderstorms, and (5) tornadoes. To highlight the implications of climate change impacts on extreme windstorms and on design wind speeds used in structural design, this state-of-the-art review is organized as follows for each windstorm type: (1) the windstorm type is briefly presented; (2) the general evidence of climate change impacts on storm activities (e.g., occurrence, frequency, and intensity) is summarized; (3) the state-of-the-art simulation framework(s) for generating yearly (or sub-yearly) maximum storm wind speeds under changing climate is(are) described; and (4) the relevant simulation results demonstrating climate change impacts on design wind speeds are presented.

### **Extratropical Cyclones (ETCs)**

An ETC is a storm system with a length scale of ~1000 km that primarily obtains its energy from the horizontal temperature contrasts that exist in the atmosphere ([Wood et al. 2023](#)). ETCs can be dominant wind hazards in many regions across North America, and the corresponding design wind speeds in codes and standards are typically derived from historical surface observations ([Pintar et al. 2015](#); [Sinclair et al. 2020](#)). Given that historical wind data cannot confidently extrapolate the nonstationarity of wind speed exhibited in the historical period to future climates ([Li et al. 2017](#); [Li and Irwin 2018](#); [Li 2023a](#)), projections of future climates need to be employed in determining the design wind speeds for structures and infrastructure expected to experience future ETCs.

### ***Climate change impact on ETC activities***

Early studies generally suggested that a warming climate may result in an overall reduction in the number of ETCs above certain threshold wind speeds in the Northern hemisphere (Chang 2013; Priestley and Catto 2021; Basu and Sauchyn 2024). Chang (2013) employed 23 models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) to project the storm-track changes over the Continental United States and southern Canada, and he reported a significant reduction in ETC activity over North America under representative concentration pathway (RCP) 8.5 forcing by the late twenty-first century (2081–2100) relative to a 1980–1999 historical baseline. Colle et al. (2015) focused their simulations from CMIP models on the Eastern North American and Western Atlantic regions during the cool season, and they found a 10%–30% decrease in ETC track density and weakening of ETC over the Western Atlantic storm track. By contrast, they found a 10%–20% increase in ETC track density over the Eastern United States, including 10%–40% more intense (< 980 hPa) ETCs and 20%–40% more rapid deepening rates just inland of the US East Coast. Marciano et al. (2015) found, using a pseudo–global warming approach forced by thermodynamic changes from CMIP3 models under the IPCC AR4 A2 emissions scenario, that increased latent heat release in future climates results in stronger ETC intensity along the U.S. East Coast. However, more recent studies suggested the potential for an increase in storm intensity is due mainly to a decrease in future mean sea level pressure (MSLP) and the associated changes in MSLP gradient (Jeong and Sushama 2018; Priestley and Catto 2021; Krieger and Weisse 2025). Based on CRCM5 simulations for 2071–2100 under RCP4.5 and RCP8.5, Jeong and Sushama (2019) suggested that typical wind-generating systems may weaken, but the most extreme ETC-related wind speeds (50-year return levels) could increase in some regions. It is noted that the various windstorms considered to assess wind speed changes due to climate change were not explicitly identified and separated in Jeong and Sushama (2019), although the spatial resolution of the Global Environmental Multiscale regional climate model used in that study suggests that the wind data considered may be essentially from large-scale ETCs. To summarize

the 6th Assessment Report (AR6) of the IPCC (IPCC 2022), the confidence on projected changes in the frequency and intensity of ETCs, and accordingly in the frequency and intensity of extreme ETC-related winds, is *medium* (Priestley and Catto 2021; Crawford et al. 2023).

### ***Simulation framework for ETC extreme winds***

Since a particular site may experience dozens of ETCs each year, extreme wind speed data under historical or present climate can be identified from the wind speeds recorded by surface weather observation stations. On the other hand, the continuous wind speeds at various resolutions (e.g., 20-minute or 1-hour average wind speeds) under changing climate need to be simulated using global climate models (GCMs) or coupled GCMs and regional climate models (RCMs). Under these conditions, each numerical grid point for future wind data serves as an analogy to the surface weather observation station for historical wind data. It is noted that the existing GCMs/RCMs do not provide projections of the ETC 3-s gust wind speed that are used for structural design applications in ASCE 7 (ASCE 2022). Whereas the projections of direct climate variables (e.g., temperature and precipitation) are characterized by high confidence levels, most derived climate variables, including wind speeds, have lower confidence levels due to the complexity of the physical process and the limited number of studies available in the literature (Cannon et al. 2020; Gaur and Lacasse 2022). Since the kilometer-scale models that could provide the desired granularity of data for structural engineering applications also require an excessively high computational cost, a possible alternative modeling approach is to use a coarser model resolution (e.g., with a 10- to 50-km grid) and perform more advanced bias corrections, e.g., using artificial intelligence (AI) tools (Schneider et al. 2023). However, the performance of these AI models for generating sufficiently granular data for structural engineering applications is still unknown. The available state-of-the-art results obtained from GCMs, RCMs, and various downscaling approaches (generally at 10-m height with spatial resolution in the order of 10 km and temporal resolution in the order of 1 hour) indicate that a decreasing yearly mean wind speed

can be expected in this century in many regions, including North America (Jeong and Sushama 2019; Martinez and Iglesias 2024), as indicated in the latest Intergovernmental Panel on Climate Change (IPCC) report (IPCC 2022). However, parts of Central North America (e.g., the Great Plains) may experience higher wind speeds in this century (IPCC 2022). The predicted yearly mean wind speeds from ensemble GCMs or RCMs show nonstationary trends across the near-, medium-, and long-term periods of the 21st century. However, structural wind design applications need information on the yearly (or sub-yearly) maximum winds under changing climate, instead of average trends (Lai et al. 2022). Both block maxima and peaks-over-threshold techniques can be leveraged to obtain these extreme winds. Cheng et al. (2012, 2014) were among the earliest studies that used downscaled climate modelling to investigate the impact of climate change on extreme wind speeds in North America. Their study focused on South Ontario, Canada. Eight GCM simulations under the A2 scenario were statistically downscaled. Their study found that the frequency of extreme wind speeds above a certain threshold can increase by about 10% to 40% in future climates. Pryor et al. (2012) compared 13 regional climate modelling outputs from the North American Regional Climate Change Assessment Program (NARCCAP) with various climate forcings. The results indicated that the Western United States showed some evidence for lower values of the central tendency in the future period, and more than half of the model showed higher extreme wind speeds at some grid points.

### ***Implication on design wind speeds***

Parametric and non-parametric methods can both be utilized to obtain the design wind speeds corresponding to different limit states and for buildings of various risk categories when simulated yearly (or sub-yearly) maximum wind speeds under changing climate are available for a particular location. However, the impacts of climate change on ETC winds are complex and require further investigation in order to provide sufficiently detailed and reliable information for structural design applications. Some studies suggest that ETC winds may increase in the United States (Colle et

al. 2015; Lin et al. 2019); however, significant uncertainty remains, due largely to the challenges associated with relying on non-TC wind speed data from weather station records, which may not be always ideally suited for investigating climate change effects on ETCs. In coastal regions where TC winds often prevail, some researchers have assumed a stationary distribution for non-TC winds (e.g., Hintermaier and Lin 2024); however, this assumption may not apply to inland regions where extreme winds are frequently driven by thunderstorm activity (Twisdale and Vickery 1992) and ETCs (Colle et al. 2015). Pryor et al. (2012) estimated the 20- and 50-year return period wind speed by fitting annual maxima from each simulated time series to a double exponential cumulative probability distribution, highlighting the increased design wind speeds with higher RCM resolution. Other percentile values of the wind speed distribution for any given RCM grid were also derived from rank ordering of model output. Michaelis et al. (2017) indicated that while the frequency of strong ETC events in the North Atlantic might decrease, there could be slight increases in maximum and average 10-m wind speeds off the Northeastern United States. Jeong and Sushama (2018) estimated the 50-year return period wind speed by fitting annual maximum time series of 3-hourly wind speed to the Gumbel distribution, suggesting general increases in the 50-year return levels for central and eastern Canada by the end of the 21st century. A recent study by Li et al. (2022) utilized 15 ensembles of simulations under the RCP 8.5 scenario to investigate design-level wind speeds in future climates across Canada. The study found that non-stationarity was exhibited in most regions across Canada with different magnitudes of severity. Similarly, Li (2023a) demonstrated that the design wind speeds for annual exceedance probabilities of 1/20 and 1/50, commonly used in wind turbine design, exhibit different nonstationary trends across North America under RCP8.5 scenarios. The West Coast, from California and further north, and the East Coast, from Florida and further north, can exhibit increased design wind speeds. Central America and Canada exhibit smaller increased design wind speeds. West to the central part of Mexico exhibits decreased design wind speeds. Li and Kopp (2023) found that climate change can also impact the duration of extreme wind speeds,

which may influence certain design criteria and practices. Future research should also aim to more accurately assess climate change influences on hybrid events (e.g., extratropical transitions), which are currently not well captured by existing models but potentially could lead to significantly increased wind speeds in the interior United States as well as along the mid-Atlantic and Northeastern coasts ([Hintermaier and Lin 2024](#)).

### **Nor'easters**

Nor'easters are a special class of ETCs affecting the East Coast of North America, with winds over the coastal area that typically come from the northeast. They are most commonly observed between October and April, and can produce a diverse array of impacts, including storm surges, powerful waves, coastal flooding, high winds, and intense precipitation ([Dolan and Davis 1992](#); [Von Ahn et al. 2004](#); [Shimkus et al. 2017](#); [Chen et al. 2025](#)). Nor'easters typically form in the mid-Atlantic region and then travel in a northeastward direction. As ETCs, their typical diameter is three to four times larger than that of a TC. This large size and associated slow movement enable them to batter vast shorelines and cause structural damage ([Butman et al. 2008](#); [Zhang et al. 2001](#)).

### ***Climate change impacts on nor'easter activities***

The intensification of Nor'easters derives from the temperature difference between the cold air above land and the relatively warmer air over the ocean, as indicated in Fig. 2 ([Davis and Dolan 1993](#); [Jones and Davis 1995](#)). These temperature differentials might be significantly influenced by the effects of climate change ([Sinclair et al. 2020](#)). As warmer air has an increased capacity to hold moisture, northeasterly winds channel this moisture-laden warm air into the northeastern region ([Catto et al. 2019](#)). In addition, under high-emission scenarios, warmer winter temperatures are expected to reduce the occurrence of extreme cold conditions and bring temperatures closer to the freezing point ([Colle et al. 2015](#)). This phenomenon has the potential to generate powerful winds along with other extreme hazards ([Colle et al. 2015](#); [Lopez-Marti et al. 2025](#)).

Although climate change is expected to influence most of the known wind systems, the bulk of research for nor'easters has been essentially centered on the shifts in their frequency and intensity, with less focus on extreme variations owing to their sporadic nature (Vose et al. 2014). While several climate projections, based on medium- to high-emission scenarios, suggest a slight poleward shift in storm tracks, there is no consensus on the frequency and intensity changes (Bengtsson et al. 2009; Catto et al. 2011). The investigation of the historical data of storm activity during the Northern hemisphere's cold season since 1950 has provided evidence of an increase in the frequency of nor'easters, as reported by Wang et al. (2013). Climate change is expected to affect various parameters that can directly influence nor'easter activity. For instance, a reduction in the surface meridional temperature gradient would reduce the potential energy accessible for nor'easters (Bengtsson et al. 2009). A reduction of ozone in the stratosphere in polar latitudes and rising concentrations of tropospheric greenhouse gases can amplify the meridional temperature gradient, leading to more intense storms (Bengtsson et al. 2009). Major circulation patterns, like the El Niño–Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), which affect the nor'easter activity, are anticipated to shift as a result of climate change (Hirsch et al. 2001; Pryor and Ledolter 2010; Vose et al. 2014). This alteration is likely to impact the frequency, intensity, and geographical occurrence of nor'easters. Yet, the intricate interplay among these factors remains poorly comprehended, presenting challenges in deriving definitive conclusions about the anticipated behavior of nor'easters in a warming climate (Bengtsson et al. 2009; Neu 2009; Catto et al. 2011; Vose et al. 2014).

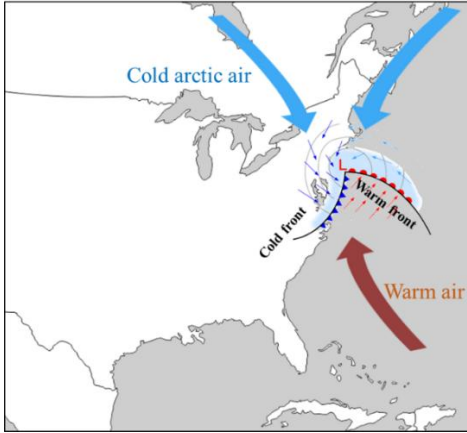


Figure 2: Conceptual model of a Nor'easter.

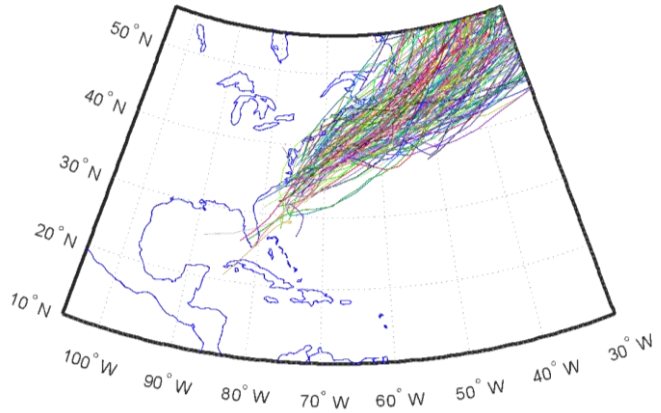


Figure 3: Sample of synthetic nor'easters.

### ***Simulation frameworks for nor'easter extreme winds***

Numerous approaches can be utilized to evaluate the hazard probabilities and, by extension, the risk associated with nor'easter winds. Like the simulation frameworks used for ETC extreme winds, an effective way involves leveraging historical wind data from nor'easters and fitting probability distributions to this dataset. However, this methodology is confined to the specific site under investigation and cannot be extrapolated to encompass broader geographical areas. Furthermore, the limited data available can compromise the accuracy of the fitted probability distributions, particularly in the tail regions. Alternatively, the single-site probability approach proposed by Russel (1971) can be used to calculate site-specific statistics for critical storm parameters, such as central pressure. The process involves a Monte Carlo simulation step, where samples are drawn from the statistical distribution of each storm parameter. Subsequently, a nor'easters wind model, driven by these sampled storm parameters, is employed to effectively generate the corresponding hazard probabilities. The US Federal Emergency Management Agency (FEMA) employs a different methodology that involves the initial selection and perturbation of a limited set of intense historical nor'easters to generate multiple samples from which extreme wind speeds can be described (FEMA 2014). However, this approach cannot

capitalize on valuable data related to nor'easters that closely approach a specific region without making landfall.

The conceptual model by Shapiro and Keyser (1990), founded based on remote sensing techniques and space-based observations, can be leveraged to portray a detailed life cycle of nor'easters and their intricate structure; however, this model has not been used to assess the effects of climate change. Recently, an advanced method known as the 'track approach', primarily employed for TC events, has been adopted also for nor'easters (Hall and Booth 2017). One of the standout features of this approach is its ability to extrapolate information from a broader geographical area onto the specific target region. The development of synthetic nor'easter tracks comprises four primary elements: (1) genesis, (2) tracking, (3) intensity, and (4) dissipation (Hall and Booth 2017). These track components rely on two distinct climate factors: ENSO as the Nino3.4 index, and the monthly NAO index. The genesis, tracking, and dissipation modules are derived based on local regression techniques, while intensity is predicted through a weighted sampling approach (Hall and Booth 2017). The necessary nor'easters dataset for the generation of the new synthetic tracks is retrieved from the European Centre for Medium-Range Weather Forecasts re-analysis (ERA-Interim) meteorological dataset. The resulting synthetic tracks, as shown in Fig. 3, encompass the 6-hourly coordinates of the nor'easter center (latitude and longitude), time, and central pressure deficit.

An efficient wind model is then needed to generate the wind probabilities. However, wind simulation for nor'easters is typically derived by combining high-fidelity wind models and observational data (e.g., Adamson et al. 2006; Beare 2007), primarily due to the complex nature of these storms. While these detailed methods hold promise for accurately representing the wind hazards associated with nor'easters, they are less suitable for conducting probability and risk assessments under changing climate. Recently, a knowledge-enhanced deep learning (KEDL) model has been developed for the simulation of nor'easter boundary layer winds (Snaiki and Wu

2022). The system loss function incorporates both physics-based equations and semi-empirical formulas to provide regularization for the neural network. This newly developed KEDL, which utilizes standard storm parameters (such as spatial coordinates, central pressure deficit, translational speed, approach angle, latitude of the storm center, and surface roughness) as its input, has the capability to efficiently and accurately generate the three-dimensional boundary-layer wind field for nor'easters. By coupling the synthetic nor'easters and the KEDL-based wind model, Snaiki and Wu (2022) generated the hazard probabilities along the US Northeast Coast in terms of annual exceedance probability. Figure 4 illustrates the return periods of wind speeds at the height of 10 m for two coordinates [i.e., (31.23°; 81.28°) and (43.00°; 70.74°)], located in the US Southeast and Northeast, respectively. As depicted in Fig. 4, the wind speed at coordinate of (43.00°; 70.74°) is always higher for any MRI value than that at coordinate of (31.23°; 81.28°). This difference aligns with expectations, given that the northeast location is more regularly affected by nor'easters in comparison to the southeast location.

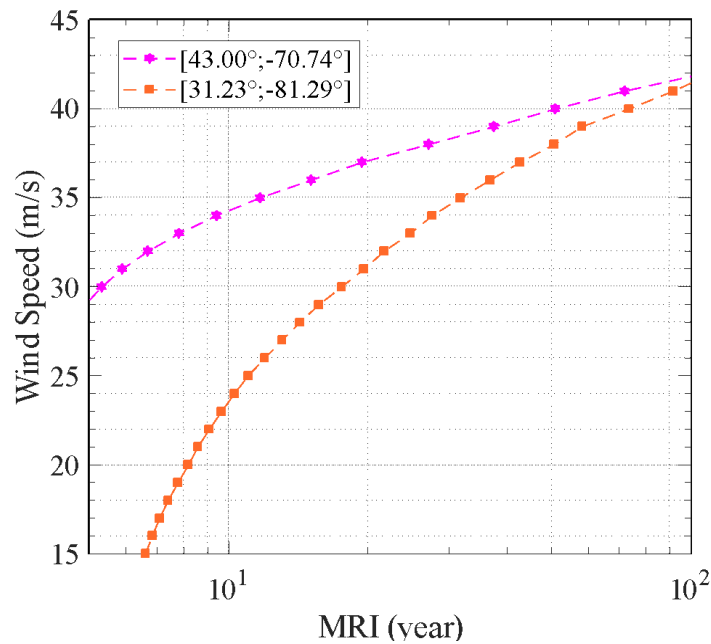


Figure 4: MRI distribution of wind speeds at two locations with coordinates (31.23°; 81.28°) and (43.00°; 70.74°).

### ***Implication on design wind speeds***

Nor'easters tend to persist for longer durations than typical TCs, and they occur more frequently, with an annual average of approximately up to 30 per year (Zhang et al. 2001; Birchler et al. 2015). In certain coastal regions, particularly along the mid-Atlantic and Northeast United States, this frequency means Nor'easters may govern design wind speeds associated with lower return periods compared to less frequent but potentially more intense TCs (Barthelmie et al. 2021). This relationship varies geographically, however, with the relative impact of Nor'easters versus TCs potentially differing substantially for higher-return-period winds, especially in inland and northern areas. Crucially, the design wind speeds in ASCE 7 do not consider the nor'easters explicitly (ASCE 2022). Future research is required to investigate the effects of separating the effects on wind speeds of nor'easters from other windstorms and incorporating their induced extreme winds into design wind speeds. The synthetic approach for nor'easter tracks has the potential to be extended to encompass the effects of climate change by incorporating environmental factors that are directly impacted by changing climatic conditions, such as the ENSO and NAO indices. These environmental factors under a changing climate affect the trajectories of the synthetic storms and impact the storm frequencies and intensities. Additionally, using advanced wind models that incorporate key environmental factors [e.g., sea surface temperature (SST)] offers a valuable opportunity to investigate how environmental conditions impact both the wind profile and the wind speed probabilities associated with nor'easters.

### **Tropical Cyclones (TCs)**

TCs are rapidly rotating, warm-core, low-pressure systems with diameters of a few-hundred kilometers and are usually characterized by destructive high winds, torrential rain, and storm surges. In the United States, they are commonly referred to as tropical depressions, tropical storms, or hurricanes, depending on their maximum sustained wind speeds (NOAA 2025a). Among the multiple hazards associated with TCs, wind hazard is of great significance since a

substantial part of economic and life losses resulting from TC events are directly or indirectly related to winds (e.g., wind-induced aerodynamic load, wind-driven rain, and wind-driven storm surge and waves) ([NOAA 2025b](#)).

### ***Climate change impacts on TC activities***

In the past few years, a succession of TC seasons characterized by above-average intensity and significant economic impacts has sparked inquiries into the potential role of climate change in driving the increasing TC activity observed in the North Atlantic Ocean Basin. Between 2011 and 2019, there has been an annual average of approximately 15 named storms in the Atlantic basin, marking a 25% increase compared to the preceding three decades ([Grenier et al. 2020](#)). There is significant evidence that the substantial rise in TC-related damage can be partially attributed to the expanding population and communities along the coastline of the United States. Nevertheless, climate change is also a contributing factor to the exacerbated damage caused by TCs ([Mendelsohn et al. 2012](#); [Dinan 2017](#); [Balaguru et al. 2023](#); [Carstens et al. 2025](#)).

Climate change can impact TCs primarily via increasing SST, which supplies more energy for TC formation and intensification. Additionally, a warmer atmosphere has the capacity to retain more water vapor, which may result in increased rainfall that interacts with TC winds ([Snaiki and Wu 2019a, 2020a](#); [Wu et al. 2022](#)). Climate change could also affect several other critical parameters, including vertical wind shear, mid-level moisture, and environmental stability, consequently impacting TC frequency, intensity, trajectory, and size. Increasing evidence shows that TC intensity will increase under changing climate, while there is a debate on the changes in overall TC frequency due to the trade-off between intensity and frequency ([Kang and Elsner 2015](#); [Pérez-Alarcón et al. 2023](#)). For example, statistically significant trends (i.e., variability with respect to time) in TC numbers and intensities have been observed in the Atlantic over the past few decades, and trends in other basins are increasingly being identified (e.g., [Walsh et al. 2016](#); [Camargo et al. 2023](#)). However, trend detection is impeded by substantial limitations in the

availability and quality of global historical records of TCs (Knutson et al. 2010, 2019, 2020). The spatial distribution of TCs may also change in the future climate, with decreased TC counts over the southern Gulf of Mexico and Caribbean and increased counts over the central Atlantic, as projected under the SRES A1B emissions scenario (Colbert et al. 2013). More recent assessment studies indicate that, under medium- to high-emission scenarios, the proportion of TCs that reach very intense (Category 4–5) levels is expected to increase with global warming (Knutson et al. 2019, 2020; Vecchi et al. 2025). In addition, there is evidence suggesting a poleward expansion of the position of maximum TC intensity in the western North Pacific and that TC translation speeds will slow down (Kossin 2018). Many researchers have investigated the difference in TC wind speeds (representing TC intensity) between the current and future climate scenarios (e.g., RCP 2.6, RCP 4.5, and RCP 8.5) (e.g., Mudd et al. 2014a, 2014b; Ellingwood and Lee 2016; Cui and Caracoglia 2016; Rosowsky 2018; Esmaeili and Barbato 2021; Hintermaier and Lin 2024; Michalek et al. 2024). At the same time, fewer studies have focused on the climate change impact on TC wind directions (e.g., Cui and Caracoglia 2019; Wang et al. 2022). In addition to wind speed and direction, Snaiki and Wu (2020a) recently noted that climate change may significantly modify TC wind pattern (in terms of gradient wind profile). To summarize the IPCC AR6 (IPCC 2022), the confidence on projected changes in the frequency and intensity of TCs, and accordingly in the frequency and intensity of extreme TC-related winds, is *medium*.

### ***Simulation framework for TC extreme winds***

Several approaches are available to simulate TC wind distributions. The simplest approach to calculate the annual maximum TC wind speeds consists in using extreme value analysis in conjunction with historical data (Simpson and Lawrence 1971). However, due to the relatively low frequency of TC occurrence in any specified site, the available historical wind data may be insufficient to predict scenarios corresponding to rare events (Bloemendaal et al. 2020). One way to address this issue is to leverage the paleotempestology technique that utilizes coastal sediment

records to uncover historical instances of coastal floods caused by TCs, offering insights spanning thousands of years in the past for specific regions (Nott and Hayne 2001; Lin et al. 2014). However, this method is constrained to small coastal areas and not practical for global applications. Alternatively, statistical techniques have been developed to create a large synthetic TC wind database. For example, the single-site probabilistic simulation, initially pioneered by Russell (1971) and refined by other researchers (e.g., Batts et al. 1980; Georgiou et al. 1983; Neumann 1991), has gained widespread use (e.g., Li and Hong 2015; Hong et al. 2016). In this approach, the extreme TC wind speed at a specific location is determined using Monte Carlo simulation based on site-specific statistical distributions of storm parameters, including central pressure deficit, radius of maximum winds, heading angle, forward speed, and coast-crossing position. These simulations are then used in conjunction with a storm dissipation model. The adequacy and accuracy of the distributions of these storm parameters rely on the availability of historical storm information. Limitations can exist when only limited historical storm information is available. Most importantly, it is challenging for both paleotempestology and single-site probabilistic techniques to integrate climate change effects at a basin level. This technique is also incapable of quantifying the spatial correlation among different locations.

Another method to simulate TC extreme wind distributions involves creating synthetic TC tracks, where the tracks and intensities of TCs are statistically resampled and simulated (e.g., Vickery et al. 2000; Emanuel et al. 2006; Lin et al. 2012; Haigh et al. 2014; Li and Hong 2014; Odériz et al. 2025). This approach generates a large database of synthetic storms from the TC genesis to dissipation stage. The historical best track datasets and reanalysis/reconnaissance data can be used to develop the storm track model. By projecting data from a broader geographic range onto the target region, this approach can provide sufficient information for TC-prone areas, enabling the determination of the annual probability of rare, high-impact wind events. The synthetic track technique can be broadly categorized into two primary approaches: (1) a

regression model that uses Markov Chains for both track generation and intensity simulation dynamically interacting with environmental fields (e.g., [Vickery et al. 2000, 2009](#); [Li and Hong 2014, 2015](#)), and (2) a combined statistical-dynamical model that utilizes autoregressive functions for TC track generation and dynamic models for intensity simulation (e.g., [Emanuel et al. 2006](#); [Lee et al., 2018](#); [Snaiki and Wu 2020b](#)).

Regarding climate change, there have been efforts in the engineering community to account for the influence of a warming climate on TC activities by integrating the projected environmental conditions from GCMs (often medium- to high-emission scenarios) into a TC risk assessment frameworks (e.g., [Rosowsky et al. 2016](#); [Rosowsky 2018](#); [Esmaeili and Barbato 2022](#)), generally using TC track models that generate a large synthetic storm catalogues as previously discussed. The assessment of TC surface wind hazard under changing climate can be achieved by coupling a genesis model, a track model, an intensity model, and a dissipation model with a wind field model (e.g., [Mudd et al. 2014a, 2014b](#); [Ellingwood and Lee 2016](#); [Cui and Caracoglia 2016](#); [Rosowsky 2018](#); [Pant and Cha 2019](#); [Hintermaier and Lin 2024](#)). Figure 5 illustrates a recently-developed climate-dependent stochastic simulation framework of TC wind hazard ([Orcesi et al. 2022](#)). This framework essentially consists of three components: (1) an enhanced TC track model to generate the synthetic storms (including a physics-based intensity model integrating SST, wind shear, and convective instability contributions) ([Snaiki and Wu 2020b](#)), (2) a thermal wind balance-based model to simulate the gradient wind profiles (explicitly considering environmental conditions of SST, temperature at the top of atmospheric boundary layer, and outflow temperature) ([Snaiki and Wu 2020a](#)), and (3) an efficient hazard model for wind simulations ([Snaiki and Wu 2018, 2020c](#)). Similar efforts have been made for climate-dependent stochastic simulations of TC hazards (e.g., [Lee et al. 2018](#); [Jing and Lin 2020](#)).

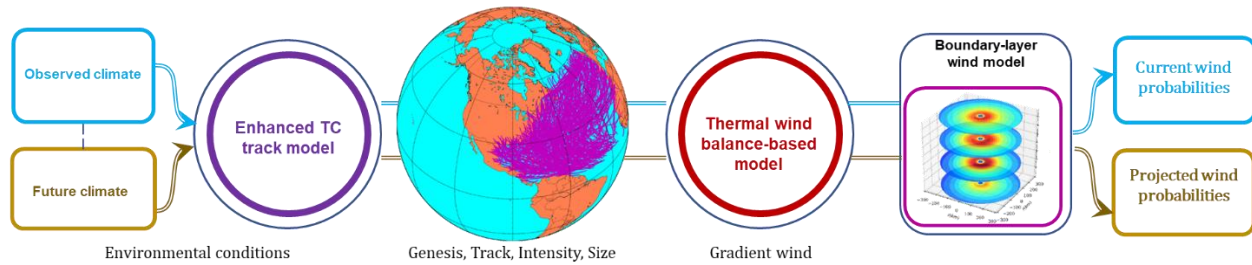


Figure 5: A climate-dependent stochastic simulation framework for TC wind hazard.

The goal of this framework is to derive the distribution of the annual maximum wind speed for the selected locations under both present and future climate scenarios. The initial step involves defining circular zones centered around the areas of interest. Within these designated zones, all synthetic storms that traverse with an intensity surpassing a predefined threshold are identified. For each synthetic storm trajectory, a wind field model is applied to calculate the wind speed. This process was developed in early studies (e.g., [Georgiou 1985](#); [Vickery et al. 2000](#)) and has been widely applied in later studies (e.g., [Vickery et al. 2010](#); [Li and Hong 2015, 2016](#); [Cui and Caracoglia 2019](#); [Snaiki and Wu 2020c](#); [Sheng and Bocchini 2025](#)). Given the substantial number of synthetic tracks, the use of an efficient wind field model capable of rapidly simulating the boundary-layer wind field is essential. Several analytical height-resolving wind models have been developed to address this need, assuming that wind speed can be decomposed into a gradient wind and a friction wind component (e.g., [Meng et al. 1995](#); [Kepert 2001](#); [Snaiki and Wu 2017a, 2017b](#); [Fang et al. 2018](#); [He et al. 2019](#); [Yang et al. 2021](#)). Machine learning techniques have also been proposed for TC wind simulation (e.g., [Wei 2015, 2019](#); [Snaiki and Wu 2019b](#)). Alternatively, simplified approaches such as the gradient wind model by [Holland \(1980\)](#), adjusted to surface level with reduction factors and an empirical inflow angle expression, have been employed. It is important to note that a bias correction is necessary for the synthetic TC wind speed data generated from climate models in order to mitigate GCM inherent biases, such as the underestimation of peak wind intensities due to limited spatial resolution, systematic errors in the frequency and spatial distribution of storm tracks, and related uncertainties in mean and extreme

near-surface wind speeds arising from imperfect physical parameterizations. The resulting bias-corrected wind speed data are then adjusted to align with code specifications regarding averaging time and terrain type. These adjusted values are subsequently used to determine the annual maximum wind speed distribution.

Another recently-developed methodology introduced a statistical approach to develop maximum annual wind speed distributions at given sites along the US Gulf Coast and Atlantic Coast as a function of the average SST increase under various RCPs (e.g., RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) (Esmaeili and Barbato 2021). The advantage of this methodology is the low computational cost, which allows the quick exploration of multiple scenarios and has been shown to provide similar results (in terms of maximum annual wind speed distributions) to those of more advanced and computationally expensive simulation approaches. However, this methodology is based on an assumed linear relationship between TC parameters (i.e., peak hurricane wind speed, radius to maximum wind speed, and translational wind speed) and local SST; thus, for design wind speed determination under climate change, it is recommended that a model explicitly accounting for the physics of TCs should be employed.

### ***Implication on design wind speeds***

Figure 6 presents the MRI curves of 10-m, 3-s gust wind speeds induced by TCs for Atlantic City, New Jersey. The results are derived from three 10,000-year stochastic simulations documented in Snaiki and Parida (2023): a 'Simulated Current Climate' (1990–2020) based on IBTrACS, and two future scenarios (2020–2050) driven by large-scale environmental fields from the CMIP6 HighResMIP simulations with CMCC-CM2-VHR4 ('Future Climate 1') (Scoccimarro et al. 2022) and EC-Earth3P-HR ('Future Climate 2') (Haarsma et al. 2020), respectively, under the SSP5-8.5 high-emission scenario. In the present review, these previously published synthetic wind datasets are post-processed by converting the simulated TC winds to site-specific 10-m, 3-s gusts at Atlantic City and extracting annual maxima to derive the MRI curves shown in Fig. 6. In addition,

ASCE 7-22 MRI results are provided for comparison; however, it is noted that only the high MRI values are included in the ASCE 7-22 dataset, as the lowest return periods are generally governed by non-TC winds and are not captured by the simulation framework. In general, the simulation framework (Fig. 5) produces results that are in good agreement with the ASCE 7-22 outcomes. Furthermore, a significant rise in the design wind speed is anticipated in Atlantic City, particularly with 'Future Climate 1'. For instance, the simulations suggest that the wind speed intensity for the 100-year MRI will increase by 10.9% with 'Future Climate 1', compared to a 3.1% increase based on 'Future Climate 2'. Likewise, for the 300-year MRI, the wind speed is projected to increase by 17.7% with 'Future Climate 1', in contrast to a 2.6% increase from 'Future Climate 2'. It is important to note that the substantial variability between the results from GCMs, despite identical radiative forcing, primarily arises from differences in their governing equations (with inherent assumptions) and resolutions.

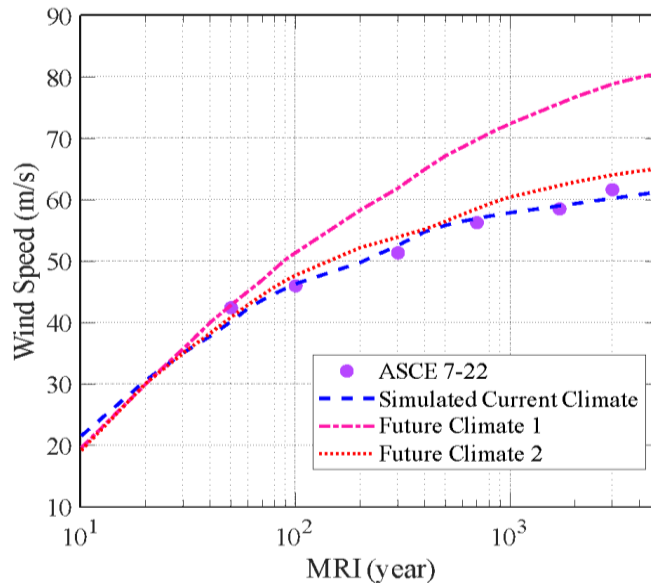


Figure 6: MRIs for the 10-meter, 3-s gust winds under current and future climate scenarios at Atlantic City.

## **Thunderstorms**

Non-tornadic winds generated from thunderstorms are generally accelerated downward toward the surface, and are characterized by different spatio-temporal scales (i.e., length scale of ~1 km to ~10 km and time scale of ~1 min to ~1 hour) and production mechanisms. These mechanisms are linked to the thunderstorm morphology and cannot all be grouped into ‘downbursts’ (Fujita 1981), which has been the assumption in civil engineering application (Prein 2023; Roegner et al. 2024). Losses from thunderstorm winds are significant, totaling \$331M in 2022, with over \$1B in losses considering all thunderstorm-related hazards (e.g., tornadoes and hail) (NOAA 2022). As an example, the August 2020 derecho (a particular type of widespread and severe thunderstorm event), which affected Iowa and other midwestern states, caused \$11B in damage and was the costliest thunderstorm-related disaster in the history of the United States (NPR 2020).

### ***Climate change impacts on thunderstorm activities***

The context of climate change impacts on thunderstorm winds has been primarily focused on changes in their frequency, intensity, and location (FIL). Although thunderstorm-generated wind speeds have relatively small spatial and temporal scales, the knowledge of potential climate change impacts on thunderstorm FIL has been significantly improved by the use of dynamical downscaling (e.g., Prein 2023). Nevertheless, there is still substantial room for improvement (e.g., Vose et al. 2014; Lombardo and Ayyub 2015). The discussions herein necessarily focus on FIL changes in thunderstorms (and not the winds generated by them), but the end objective is to assess potential changes in FIL to thunderstorm winds using a simulation framework.

In early studies of climate change effects on the FIL of thunderstorms, the emphasis was on “environmental” parameters such as Convective Available Potential Energy (CAPE) and vertical shear of the horizontal winds (hereinafter, wind shear). These parameters were derived from GCMs and are known to be partly responsible for thunderstorm frequency and intensity. The CAPE and wind shear were found to increase and decrease, respectively, in the future climate

(Trapp et al. 2007). However, the joint probability of CAPE and wind shear combinations that are favorable for severe thunderstorm occurrence are expected to increase for a large portion of the United States, leading to an increase in the yearly number of days that are favorable for thunderstorms (Trapp et al. 2007; Trapp et al. 2009; Diffenbaugh et al. 2013). Several other studies have also found increases in frequency and intensity of thunderstorms using GCMs across the globe (e.g., Del Genio et al. 2007; Allen et al. 2014; Seeley and Romps 2015).

Work on the topic has progressed recently from GCMs to high-resolution regional models. Some of these models, including the Weather Research and Forecasting (WRF) model, can simulate convection (thunderstorms), thus representing a significant improvement in simulating thunderstorms, as the mere presence of large-scale parameters favorable for thunderstorms does not necessarily imply that thunderstorms will occur (e.g., Trapp et al. 2007). Although much higher spatial and temporal resolution than GCMs was used to assess potential changes (e.g., horizontal grid spacings of 4km), the work still required the use of grid-scale proxies to objectively identify severe thunderstorm events (e.g., Trapp et al. 2011). Using WRF modeling to separate convective wind events has been implemented in wind engineering applications in past studies (e.g., Li et al. 2021). Gensini and Mote (2015), using a proxy based on updraft helicity and simulated radar reflectivity, found a frequency increase of up to 27% in the spring months in the Mississippi and Ohio River valleys 100 years in the future. Using a slightly different proxy, Hoogewind et al. (2017) found that the frequency and intensity of severe thunderstorms are expected to increase for most locations in a warming climate. Using simulated radar reflectivity as a proxy, Haberlie et al. (2022) found significant increases in the most intense thunderstorms in most of the country and an overall increase in annual activity, although they also identified some specific regional and seasonal decreases. Using a combination of observations, RCMs, and theoretical considerations, Prein (2023) found that climate change is expected to increase the frequency of high thunderstorm winds. In particular, the extreme wind speeds and the spatial footprint affected by thunderstorm

winds were found to have expanded rapidly over the period of historical observations. Li (2024) used CAPE and Lifted Index threshold values determined by comparing the simulated historical convective events to historical thunderstorm observations to detect future thunderstorm activities and associated extreme wind speeds for selected cities in Ontario, Canada. Their study found that the climate change impact on thunderstorm winds is not geographically uniform. The occurrence of future thunderstorm activities could increase by an order of 10%. The contribution to the design wind speeds by counting the thunderstorm winds impact from climate change is less or about 5% for the selected cities, which is comparable to previous studies that did not specifically separate the thunderstorm winds from mixed wind climates, indicating that the climate impact to thunderstorms could be comparable to non-thunderstorm winds. To summarize the IPCC AR6 (IPCC 2022), the confidence on projected changes in the thunderstorm frequency and intensity is *high*, but the confidence on the details of these projections, which would include the details of extreme winds, is *low*.

### ***Simulation framework for thunderstorm extreme winds***

To the best of the authors' knowledge, no simulation framework is available in the United States that can relate the large-scale parameters or the downscaled model results to wind speeds at 10-m height, 3-s gust, which are the standard parameters for design or 'basic' wind speed published in ASCE 7. The major barrier for such a framework is the different spatio-temporal scales between downscaled regional models and WRF-based simulations (which typically are performed with a horizontal resolution in the order of 1 to 4 km), and the scales needed to fully resolve thunderstorm wind gusts (which are of the order of 100-150 m). Individual downdrafts are the basis for wind engineering modeling of thunderstorm winds, which includes parameters such as 'track', 'footprint', and the associated wind field model, similar to the approach used for TCs. However, in addition to downdrafts and, in particular, downbursts (Fujita 1981), atmospheric processes in association with rear-inflow jets and "mesovortices" also contribute to extreme winds, and are

likely responsible for the highest observed thunderstorm wind speeds at the ground level (Weisman and Trapp 2003). The spatial and temporal scales of such thunderstorm winds generated from different thunderstorm types [e.g., supercell and mesoscale convective system (MCS)] have gained some recent interest in the engineering community since the 2020 Iowa derecho (an MCS) (Roegner et al. 2024).

Simulations and/or simulation frameworks from an engineering perspective similar to those of TCs are scarce since nearly all analyses of thunderstorm winds have been based on observations. Aboshosha et al. (2020) developed a numerical model for thunderstorm winds using large-eddy simulation, compared that model to wind speed data from actual events for validation, and then simulated thunderstorm samples over long time periods using Monte Carlo simulation. The numerical model used in that study contains both a 'track' and a wind field model. Work from Lombardo and Zickar (2020) found that, when the single or joint parameter space (e.g., CAPE and wind shear) was favorable for thunderstorms based on large-scale re-analysis data, the probability of extreme winds near the ground ( $> 30$  mph or  $13.4$  m/s) was relatively small, usually less than 20%. In addition, observed extreme winds were scattered throughout all CAPE values, suggesting no obvious relationship between large-scale parameters and gust magnitude. Spassiani et al. (2023) used a Bayesian hierarchical modeling approach to account for observational artifacts, and then used observations in conjunction with global reanalysis data to estimate annual occurrence of thunderstorm winds gusts in Australia. A possible simulation framework could include the use of Monte Carlo simulations in a conditional probability framework similar to Lombardo and Zickar (2020) and Spassiani et al. (2023) to generate a thunderstorm wind occurrence, and then use extreme value probability distributions to arrive at the simulated magnitude. Other works have proposed a PGW approach where historical storms were simulated in their original environment and a perturbed environment that represents projected modifications of the atmosphere due to climate change (Trapp 2020).

### ***Implication on design wind speeds***

Observed thunderstorm winds have generally been fit to extreme value models to predict extremes at specified annual probabilities of occurrence with a known (or unknown) assumption of stationarity. Given its historical usage, and the general climate change framework considering FIL, using extreme value modeling seems an acceptable approach to assess climate change impacts on design wind speeds for thunderstorms. In fact, FIL changes and/or uncertainty can be directly or indirectly incorporated into the extreme value modeling. Herein, the data analysis procedure is illustrated using the generalized extreme value distribution (GEVD) with cumulative distribution function given by  $F(V) = \exp \left\{ - \left[ 1 + c \left( \frac{V-u}{a} \right) \right]^{-1/c} \right\}$  in which  $V$  = wind speed,  $u$  = location parameters,  $a$  = scale parameter, and  $c$  = shape parameter. It is noted that  $u$  and  $c$  are real numbers and  $a > 0$ . Typically, the use of this distribution is associated 'block maxima' with the length of the block being one year. The corresponding distribution is associated with an annual probability of exceedance when discussing extremes for engineering applications. However, the use of only annual maximum wind speeds necessarily means that the annual rate ( $\lambda$ ) is simply equal to 1. To accommodate potential climate change impacts, it is prudent to assess the GEVD (or any other distribution) using sub-annual maxima. To assess annual probability for sub-annual maxima, the cumulative density function is taken to the  $\lambda$  power (e.g., Cook 2014). Therefore, the distribution has four parameters to potentially modify in the face of climate impacts:  $u$ ,  $a$ ,  $c$  and  $\lambda$ . Any combination of these four parameters could be modified to bring about potential changes in FIL. The parameter that likely has the most justifiable modification is the annual rate of thunderstorm wind speeds ( $\lambda$ ) associated with the sub-annual block maxima. Based on NASEM (2016), predictions of climate change effects on severe convective storms, including thunderstorm winds, have the lowest confidence given the limited ability to detect possible influence of global warming on the events and the level of scientific understanding. Among all related factors, confidence in the change of annual rate of thunderstorms has been relatively high based on the

studies assessed here. To link the rate of thunderstorms to the rate of thunderstorm wind speeds, a quantitative relationship between them is needed.

An example of this process is illustrated through a Monte Carlo simulation. In this case, the annual rate of thunderstorms is increased by 25% ( $\lambda = 20$  to  $\lambda = 25$ ), similar to the 27% increase in thunderstorms as discussed in Gensini and Mote (2015). It is noted that these results are simply based on a single downscaling experiment. Other parameters used for the GEVD are  $u = 36$  mph (16 m/s),  $a = 6$  mph (2.6m/s) and  $c = 0$ . These parameters, including  $\lambda$ , are well within the range of sub-annual maximum GEVD thunderstorm parameters for the Eastern United States (Lombardo and Zickar 2019). Figure 7 shows the annual maximum values from 20,000 years of simulation sorted and plotted on Gumbel paper. As expected, the overall extremes are larger for the higher rate, which was simulated using a Poisson process. When sorting the data and fitting them to a GEVD (with  $c = 0$ ), there is an approximately 2.5% increase in the  $u$  parameter, as it is observed from the plot in Fig. 7. These sorts of changes (e.g., a 25% increase in frequency  $\approx$  2.5% increase in  $u$ ) could be implemented to the fitted probability distributions based on the observed data to account for climate change impacts (i.e., frequency changes).

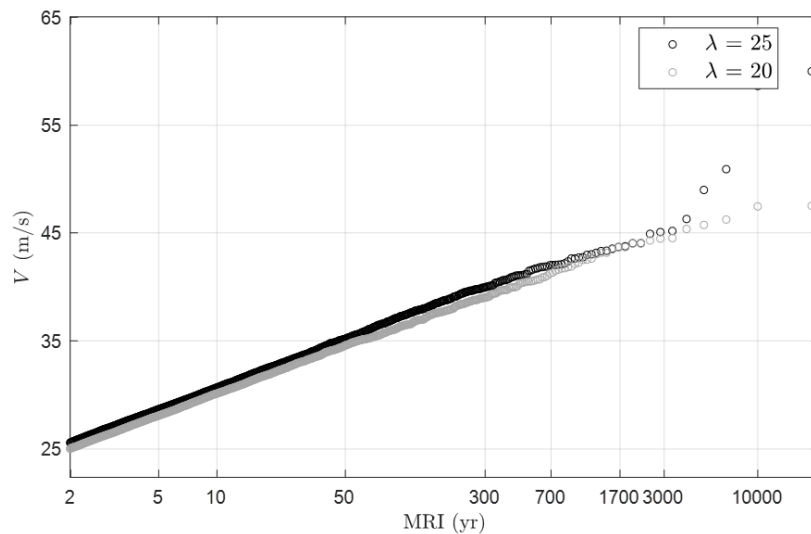


Figure 7: Sorted annual maxima from the 20,000 years of simulation plotted on ‘Gumbel paper’.

There is significant uncertainty in the estimation of design wind speed without considering climate impacts given the significant number of non-climate factors that affect the magnitude of extremes, such as the small scales, significant influences of underlying terrain, data length, data quality control, micrometeorological effects (e.g., averaging time), choice of probability distribution, and many others. It should also be noted that the method(s) described above do not address the physical mechanisms responsible for thunderstorm winds at the surface. More rigorous simulations similar to those used for TCs in the form of parametric (e.g., [Vickery et al. 2000](#)) or more physically-based models (e.g., [Lin et al. 2010](#)) should be explored. These simulations should, on some level, consider climate change impacts (e.g., [Mudd et al. 2014a](#); [Snaiki and Wu 2020b](#)). Some progress along those lines could be made for thunderstorm winds that have relatively large scales, such as rear-inflow jets from MCSs that are projected to increase in frequency and intensity in a warmer climate ([Schumacher and Rasmussen 2020](#)).

## **Tornadoes**

Tornadoes are violently rotating columns of air in contact with the ground and are usually attached to the base of a thunderstorm. Tornadoes have typical length and time scales at the orders of ~100 m and ~1 min, respectively, and are generated from a complicated sequence of processes involving the wind shear, downdrafts, and updrafts ([Trapp 2013](#)). They are considered as one of the most violent natural hazards in the world ([Zhao et al. 2024](#)). Numerous tornadoes, accompanied by significant structural damage and heavy casualties, are reported annually across North America ([Honerkamp et al. 2022a](#); [Graber et al. 2024](#)).

### ***Climate change impacts on tornado activities***

There is little consensus on how climate change affects tornadoes because the spatial and temporal resolutions of typical dynamical models that simulate future climate change are too low to represent a tornado vortex ([Chen et al. 2020](#); [Woods et al. 2023](#)), including the widest one ever recorded (2.6 miles or 4.2 kilometers) ([Bluestein et al. 2015](#)). To be specific, even GCMs/RCMs

with grid spacings of ~1 km are still too coarse: tornadoes cannot be explicitly simulated unless a grid spacing of ~50 meters or less is used. Also, the temporal frequency of typical GCM/RCM output is too low (monthly averaged, 6-hour averaged, or 3-hr averaged, with the best as 30-min averaged) to resolve a typical tornado duration at the order of ~1 min. Therefore, the recent research focus has either been on the use of storm proxies within downscaled simulations with ~4 km grid spacings (e.g., [Lee 2012](#); [Moore et al. 2022](#); [Ashley et al. 2023](#)) or on GCM-represented environmental ingredients known to support the formation of tornado-bearing thunderstorms, e.g., CAPE and wind shear. GCMs (as well as theory) clearly indicate that the unequal temperature increases across the globe due to late-21st Century climate change under high-emission scenarios lead to a decrease in vertical wind shear, as assessed over long-term seasonal means ([Trapp et al. 2007](#); [Diffenbaugh et al. 2013](#); [Hoogewind et al. 2017](#)). However, when wind shear is evaluated only on days when the air is more unstable, wind shear increases are instead indicated, especially for shear that is distributed over vertical depths extending only over the lowest 1 km above the ground ([Diffenbaugh et al. 2013](#)). Thus, ingredients necessary for potentially tornado-generating thunderstorms are projected to become more abundant in the future. Other environmental ingredients that are specifically related to tornado formation must also be considered, however. These include the lifted condensation level, convective inhibition, and storm-relative helicity, which are combined through the significant tornado parameter (STP; [Thompson 2012](#)). Recently, [Woods et al. \(2023\)](#) showed that the STPs of two tornado cases with and without the inclusion of future climate change had magnitudes consistent with the tornado intensities simulated with a high-resolution model in the corresponding environments, which assumed late 21st Century climate change under high-emission scenarios. These results provide evidence in support of the use of this particular environmental parameter to assess future tornado intensity, as do the observations-based study of [Sessa and Trapp \(2023\)](#) and the GCM-based study for Canada from 1980 and 2020 ([Hanesiak et al. 2024](#)). By downscaling the ERA5 reanalysis using WRF, [Pilguy et al. \(2022\)](#) reconstructed the tornado environments for 12 cases

between 1957 and 2021 and demonstrated the importance of performing high-resolution simulations in reconstructing tornado events. Kawazoe et al. (2023) projected the change in tornado environments in Japan using pseudo-soundings from the high-resolution fifth-generation ECMWF reanalysis, and employed thermodynamic, kinematic, and multivariate tornado parameters to identify F2 tornadoes. They found more days with F2+ tornado potential in the future. Forbis et al. (2024) studied how mid-century climate change will impact tornado activity from landfalling tropical cyclones by conducting four-member ensembles of convective-allowing (4-km resolution) regional climate model simulations. They found that TC-tornadoes may become more frequent and severe in the future. Nevertheless, the current understanding of how global warming and climate change will influence the different atmospheric processes that produce tornadoes and modulate their intensity is still limited. Indeed, as inferred from the IPCC AR6 (IPCC 2022), the confidence on projected changes in tornadoes is *low*, especially any details of tornado-driven extreme winds.

Besides the research based on data produced from GCMs/RCMs, the research based on historical tornado records provided the trend of tornado activities. Based on the tornado records since the 1950s, which include over 60,000 known historical tornado events in the Storm Prediction Center (SPC) database, the frequency of outbreaks with many tornadoes—including the most damaging tornadoes—is increasing (Brooks et al. 2014; Tippett et al. 2016; Graber et al. 2024). Allen (2021) explored the relationship between climate change and tornadoes; he concluded that the impact of climate change on severe storms and tornadoes varies by region and favorable conditions to generate tornadoes in the Northern Hemisphere and higher latitudes will increase. In contrast, the frequency of days per year with at least one tornado rated EF1 or greater is decreasing (Brooks et al. 2014; Graber et al. 2024). Such a negative trend is revealed most noticeably during the late spring and summer months, and within the Plains States (Graber et al. 2024); tornado days during early spring and within the Southeast U.S. exhibit a positive

trend, however. This suggests a change in the seasonality and regionality of U.S. tornado activity, characterized by an increasing tendency for activity northward and eastward from the Plains States (Tippett et al. 2016; Gensini and Brooks 2018; Corey et al. 2023; Graber et al. 2024; Coleman et al. 2024). Although it is not yet clear if these changes have been caused by climate change, they do affect tornado risk assessment.

### ***Simulation framework for tornado extreme winds***

The spatial and temporal variation in spawn days of historical tornadoes over a specified period has been used in the literature to quantify tornado risk (Brooks et al. 2003; Farney and Dixon 2015). The minimum assumption method (Schaefer et al. 1986; Standohar-Alfano and van de Lindt 2015) was applied to estimate the tornado occurrence probability, which equals the sum of the tornado areas divided by the total observation years and the area of the grid of interest. Compared to TCs, the impacted area of a tornado is very small and the probability of occurrence at a given location is extremely low. Therefore, it is not feasible to use solely observed data or tracks to quantify the tornado risk for a given structure or a city that has not been affected by historical tornadoes. Fan and Pang (2019) developed a Monte Carlo simulation-based framework to generate synthetic tornado tracks for an extremely long period, using the statistics of historical tornado records. This stochastic simulation framework uses the following three sub-models: (1) a genesis model to determine the spawn frequency and location, where the occurrence of tornado can be reasonably modeled using a Poisson process, (2) a tracking model to simulate track parameters (e.g., path width, length, heading direction and intensity), where the tornado parameters are geographic dependent and sampled from the probability distribution of the related parameters of historical tornadoes, and (3) a wind field model to compute the wind speeds within the tornado footprint.

### ***Implication on design wind speeds***

For the present climate, Fan and Pang (2019) determined the design tornadic wind speeds (hazard maps) by taking the following four steps: (1) pre-process the historical tornado records to remove incomplete tornado records and reconcile inconsistent records; (2) apply the developed stochastic tornado simulation framework to produce the simulated (synthetic) tornado tracks for 1 million years; (3) validate the simulation framework by comparing the statistics of the simulated tornado tracks with historical observations in the SPC database, in terms of track length, path width and intensity, to verify that the simulated tornado hazard matches the observed trend; and (4) compute the maximum wind speeds occurred inside the domain, develop tornado hazard curves, and develop tornado hazard maps. A similar approach was used to generate tornado maps (design wind speeds) in the current ASCE 7 standard (Twisdale et al. 2023). The stochastic tornado simulation framework can be improved by including the tornadic wind field data based on large-eddy simulations (Yuan et al. 2019; Li et al. 2020; Zhao et al. 2021; Zhao et al. 2022). Considering that ASCE7-22 does not provide the specifications on determining tornado-induced wind loads for Risk-Category I and II buildings, CFD simulations or laboratory tornado simulator testing can be used to model tornado-structure interaction, which can provide tornadic wind loading (Zhao et al. 2024; Li et al. 2023; Honerkamp et al. 2022b; Honerkamp et al. 2022c).

This method can be expanded to project future design tornadic wind speed, if the formation and intensity of future tornadoes can be projected from GCM data, as illustrated in Fig. 8. To achieve this goal, an AI-based system can be first developed to establish the relationship between environmental factors (e.g., temperature, humidity, CAPE, wind shear, and precipitation) and the tornado formation and intensity using historical data (Maas et al. 2024). Then, the GCM data need to be dynamically downscaled by running WRF, and the downscaled data can be input into the trained AI system to project the tornado formation and tornado intensity, leading to a large number of synthetic tornado events associated with various climate change scenarios. Based on the new

addition of future tornadoes into the existing tornado records, the NIST-adopted Monte Carlo simulation method can also be applied to determine the tornadic wind speed for a certain risk category of buildings at a specific location (Twisdale et al. 2023).

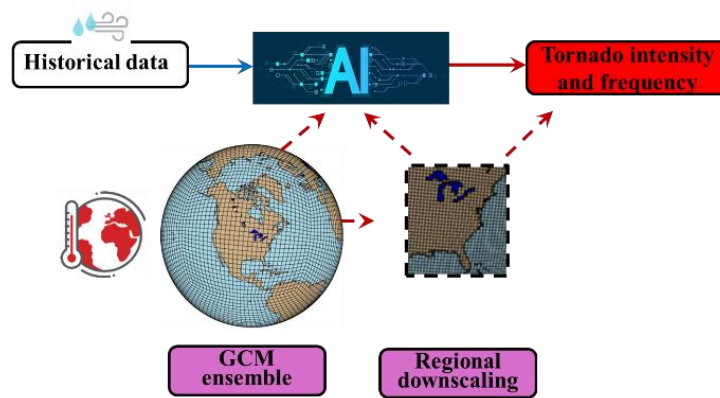


Figure 8: Enriching tornado climatology data by projecting the formation and intensity of future tornadoes.

## DISCUSSION

Predicting the changes in extreme winds from future windstorms in the context of climate change remains a complex and challenging task. Table 1 presents a summary of climate change impacts on extreme windstorms separated by storm type based on the results of the review. Implications on design wind speeds are given simply by an arrow indicating the trend based on the literature with a prescribed confidence level. The confidence listed in Table 1 is different than that often referred to in global climate change assessment report, e.g., IPCC, where the scientific confidence is established based on the understanding of the mechanisms that are able to confidently modeled and explained in the climate modeling, and affluent evidences in various global or regional studies on the comparable phenomena. The confidence defined below is the level of uncertainties and accuracy in comparison with that exhibited in historical observations that have been dealt with and accepted in engineering decision-making. To gain further confidence in design wind speed implications, multiple and significant sources of uncertainty need to be quantified and accounted for in order to derive design wind speeds that are rigorously

consistent with the probabilistic framework used for structural design. Among the many sources of uncertainty, the following discussion highlights the prediction uncertainty and nonstationary extreme value analysis, which are the most relevant for the quantification of design wind speeds and structural reliabilities.

Table 1: Summary of implications on design wind speeds.

Storm Type	Design Wind Speed	Confidence	Notes
Extratropical Cyclone	↑ or →	Medium	Regional dependence
Nor'easter	↑ or →	Low–Medium	Regional dependence
Tropical Cyclone	↑	Medium	Higher design winds mainly driven by increases in the most intense storms (Cat 4–5) and high return periods; regional and scenario dependence
Thunderstorm	↑	Low	Regional dependence
Tornado	↑	Low	Regional dependence

### Prediction Uncertainty

A significant challenge in predicting future changes in extreme winds is the scarcity of reliable historical data, particularly for specific regions and timeframes (IPCC 2021). This lack of data is especially problematic for rare and intense events, as it limits the ability to establish robust statistical relationships between climate variables and extreme winds (Katz and Brown 1992). For instance, the limited availability of long-term, high-quality data on thunderstorm wind speeds makes it challenging to assess historical trends and understand how these trends might likely evolve. Another primary source of uncertainty in wind projections stems from uncertain emission pathways. The degree of future climate change is heavily dependent on greenhouse gas emissions, which are impacted by human activities and policy decisions. Different emission scenarios can lead to varied climate outcomes, influencing predicted wind patterns. For example,

a high-emission scenario, such as RCP 8.5, could result in more drastic changes in wind patterns than a low-emission scenario, such as RCP 2.6 ([IPCC 2023](#)).

The complexity of climate models themselves introduces additional uncertainty. Climate models are powerful tools that offer valuable insights into potential changes in atmospheric circulation, temperature gradients, and other factors influencing wind patterns. However, they depend on many variables and assumptions, and uncertainties related to model forcings, model structure, and input data can impact projection accuracy ([DelSole and Tippett 2018](#); [Seneviratne et al. 2021](#)). For example, uncertainties in simulating SSTs, a crucial factor for TC development, can lead to variations in projected TC intensity and frequency ([Knutson et al. 2010](#)). Furthermore, accurately simulating extreme wind events, particularly those with small spatial and temporal scales like thunderstorms and tornadoes, necessitates high-resolution models and extended simulation periods. Current GCMs often do not provide the necessary granularity for these events, primarily due to the immense computational demands of running kilometer-scale models for extended periods. The resolution of small-scale processes necessitates the use of additional statistical or dynamical downscaling approaches. These approaches, while improving local predictions, carry their own sources of uncertainty, including the choice of downscaling technique, biases in driving data, the lack of ensembles, and assumptions in regional modeling frameworks.

Natural climate variability further complicates wind pattern and storm characteristic predictions. Events like El Niño and La Niña contribute to this inherent variability, making it difficult to distinguish between the effects of climate change and natural variability. For instance, an El Niño event can enhance hurricane activity in the central Pacific while suppressing it in the Atlantic ([Bell et al. 2014](#)), making it difficult to isolate the long-term impact of climate change on hurricane activity in these regions. Regional variability in climate change impacts also contributes to prediction uncertainty. Since climate change does not affect the globe uniformly, different regions may experience varying degrees of change in wind patterns and storm behavior. Some regions

may experience more frequent and intense storms, while others may experience minimal changes. This regional variability poses difficulties in accurately predicting specific local impacts.

To address these challenges, several promising approaches have emerged in recent years. For instance, high-resolution dynamical downscaling techniques and machine learning-based statistical downscaling approaches have shown significant potential in reducing downscaling uncertainty (Cannon 2018). These approaches, often incorporating fine-scale topographical and meteorological data, aim to better resolve localized phenomena like thunderstorms and tornadoes (Daust and Monahan 2024; Sundar et al. 2024). Additionally, the development of kilometer-scale climate models, while computationally demanding, offers the potential to directly simulate small-scale wind events, improving predictions of extreme winds at the local level (Prein et al. 2015). Concurrent efforts to assimilate improved observational datasets, such as those derived from remote sensing technologies and reanalysis products, are crucial. These enhanced datasets improve model initialization and validation, leading to more accurate simulations and reduced uncertainty. Finally, ensemble-based approaches, which consider multiple climate models and downscaling methods, have become a standard practice to address uncertainty stemming from model biases and structural differences (Tebaldi and Knutti 2007). These ensembles provide a probabilistic framework for quantifying uncertainties, making projections more robust and reliable for decision-making in the face of uncertainty (Kossin et al. 2020). Continued research and development in these areas are essential for improving the accuracy and reliability of future wind projections, particularly at the local scale.

### **Nonstationary Extreme Value Analysis**

The past and current determination of the design level wind speeds has been based on two main practices: (1) the exclusive use of historical surface observations at various meteorological stations or the reanalysis of historical environmental datasets, and (2) the assumption of stationary climate and wind speed distributions. Regarding the use of historical data, the

characteristics of the measurements, such as gust duration (i.e., averaging time), type of anemometer, and sampling duration (measurement duration), affect the quality of the wind speed predictions and the type of engineering applications for which these measurements can be used. These characteristics and their limitations have been discussed in many studies and in the Commentary of ASCE 7 ([ASCE 2022](#)). These meteorological data require comprehensive data screening, quality control, and standardization before being used for any engineering application. As the records are based on real measurements, the confidence in their reliability is high when the appropriate post-processing has been carried out. Regarding the stationarity assumption, it implies that the statistical characteristics of the climate extremes that are derived from past observations can also be extrapolated into future periods. This assumption has been widely adopted in various wind engineering applications, including determining the design wind speeds. In light of climate change, the nonstationary trend has been detected in some regions across North America, even using historical records ([Li et al. 2017](#); [Li and Irwin 2018](#)). More comprehensive works have been conducted using climate modelling considering various greenhouse gas emission scenarios in many studies ([Cheng et al. 2014](#); [Jeong and Sushama 2019](#); [Li et al. 2022](#); [Li 2023a, 2023b](#); [Li and Kopp 2023](#)), which all observed nonstationary trends in different regions across North America; however, the magnitude of the nonstationarity exhibited significant uncertainties in future projections. The nonstationary features of the extreme wind speeds question the conventional approach used to estimate and project the design wind speeds and the continuous use of the MRI concept.

Few of these earlier studies used both full nonstationary extreme value distribution and climate modelling outputs to investigate the impact of climate change on extreme wind speeds at the strength design level over North America. A series of recent studies have been conducted using high-resolution RCM outputs for North America under the emission scenario RCP 8.5. The results were reported in several independent works by Jeong and Sushama ([2018, 2019](#)), Li et al. ([2022](#)),

and Li (2023a, 2023b). An approximated stationarity assumption was adopted by Jeong and Sushama (2018, 2019), assuming the projected data within a period, e.g., 30 years, can still be treated as stationary and used conventional extreme value analysis. The MRI concept was continuously used in their studies. The latter studies by Li et al. (2022) and Li (2023a) considered a full nonstationary wind climate and investigated different nonstationary approaches for a given target annual exceedance probability (AEP). Their results show that the selection of the period in which stationarity is assumed can be uncertain and location-dependent. Large variability was observed when small ensembles of data were employed and if the data exhibited strong nonstationarity. Li et al. (2022) proposed a procedure to analyze the nonstationary wind climates, including trend detection, statistical significance test, data standardization, climate modeling output validation, and nonstationary extreme value analysis. Statistics of the nonstationary probability models derived from Li et al. (2022) were employed in a study by Li (2023a) for structural reliability analysis to examine the adequacy of the proposed nonstationary extreme value analysis and design level values from a structural reliability perspective. Examples of trend detection and estimated nonstationary Gumbel distribution are presented in Fig. 9.

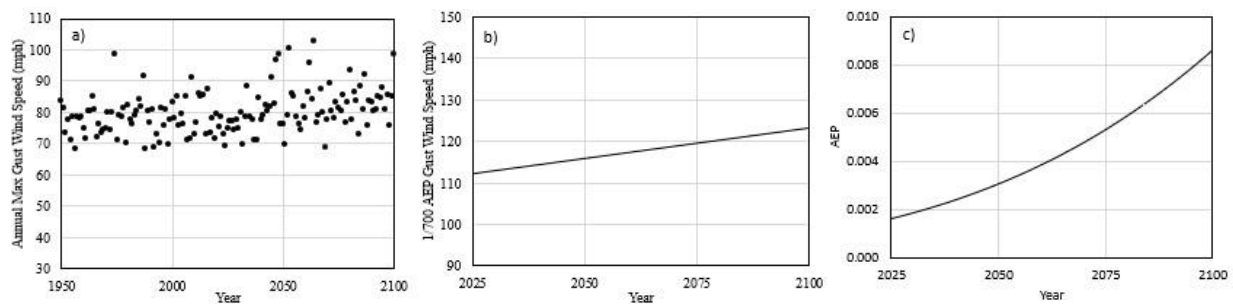


Figure 9: Results from nonstationary extreme value analysis: (a) annual maximum gust wind speeds from climate modeling; (b) time-varying 1/700 AEP value; (c) time-varying AEP for a constant design level wind speed set to be 1/700 AEP value in 2025.

Two main methods were identified by Li et al. (2022): the Minimax approach and the design life level (DLL) approach. The Minimax approach can be directly associated with the AEP,

whereas the DLL employs the total probability of exceedance during the design/service life, or in short, the lifetime exceedance probability. The application of the DLL approach can be performed in two ways: by using a fixed period, and by moving the analysis period with the actual service life. The former results in a design value less than the Minimax and the latter can result in slightly conservative design value. The Minimax was assessed to be easier for adoption by practitioners and the design community (Hong et al., 2021; Li et al., 2022; Li, 2023a). Note that the actual service life can greatly deviate from the assumed design life, as shown by many recent studies that survey the longevity of the infrastructures (Ianchenko et al. 2020). However, even without climate change impact, the effect of a longer service life (e.g., 100 years) than the nominal design life of 50 years can result in a non-negligible, and sometimes even substantial, increase in design loads (Li 2022). As the longer the future period is, the larger the uncertainties would be for different emission scenarios and less availability of projections, which could further complicate the selection of emission scenarios and assessment of the climate change impact. The Minimax approach has been adopted for updating the National Building Code of Canada 2025 edition for climate change impact on design wind speeds and ground snow loads (Li et al. 2022; Li 2023a; Li et al. 2025). Based on the Minimax approach, Li (2023b) extended the study area from Canada to the entire North America and provided climate change impact factors to non-tornadic-non-hurricane extreme wind speeds for two selected AEPs. The design level wind speed in the future period for 2070 and 2100 for many regions across North America shows an increasing trend in the order of 5% to 15% in some western and eastern coastal regions, while the central regions of North America generally show little changes due to climate change.

## **CONCLUDING REMARKS**

This work systematically reviewed climate change impacts on various extreme windstorms and discussed their relevant implications on structural wind design. While there is reasonable confidence about the influence of climate change on extra-tropical cyclones (ETCs) and tropical

cyclones (TCs), there is much less confidence in its impact on nor'easters, thunderstorms and tornadoes.

For ETC winds, there has been a reasonable amount of past work using direct climate projections with data validation, considering emission scenarios, applying different temporal and spatial resolutions. The observed magnitude of changes due to climate change in different studies can vary given different conditions, but general trends are similar. This observation makes the confidence in modeling extra-tropical winds higher than other wind types. However, the attribution of these changes to specific physical mechanisms still requires further studies with better spatial and temporal resolutions considering various emission scenarios. While engineering modelling TC wind hazards under climate change are relatively advanced compared to some other windstorms, there are still limitations and areas for improvement. For instance, despite the availability of more data and sophisticated engineering models for TCs, research on projected changes in TC frequency and intensity under climate change often yields divergent results, highlighting the complexities and uncertainties involved. In contrast, assessing nor'easter and tornado wind risk is still in its early stages, even in the present climate, and its engineering applications require further investigation, including the development of a reliable and efficient wind field model suitable for track methodology. Studies on thunderstorm and tornado winds impose higher demands on climate modeling, including much higher spatial resolution (< 1 km or smaller), shorter temporal resolution (in minutes or seconds), and long-term projections (hundreds to thousands of years, given these winds might govern very low annual exceedance probability). Interim solutions for engineering applications might involve examining the changes in environmental parameters, such as Convective Available Potential Energy (CAPE) and vertical wind shear, to indirectly measure the possible changes in extreme wind speeds induced by thunderstorm and tornado winds. Some studies indicated that the impact of climate change to thunderstorm winds is comparable to ETC winds, which might provide an engineering solution when no sufficient climate projections are available for a better solution.

Despite these advancements, the complexities of atmospheric systems, data limitations, and uncertainties in model projections underscore the need for continued research. Further development of high-resolution climate models, enhanced data collection efforts, and exploration of nonstationary extreme value analysis methods are essential for improving the accuracy and reliability of future wind projections. This ongoing research will ultimately lead to a deeper understanding of how climate change affects extreme wind events, enabling engineers to design structures that can withstand the changing wind loads.

#### **DATA AVAILABILITY STATEMENT**

Some data, models, or code generated or used during the study are available from the corresponding author by request.

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