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The Impact of Temporal and Spatial Variation in Building Codes on the Hurricane Wind Vulnerability of Residential Single Family Homes

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Abstract

Building codes evolve as engineers and scientists learn more about the destructive capability of natural phenomena and how to design structures to effectively withstand these extreme events. The 2012 building and residential codes published by the International Code Council have recently seen significant updates to the wind hazard and design criteria, and have generally decreased the design wind speeds along much of the hurricane-prone East and Gulf Coasts. Catastrophe models, which integrate a stochastic hazard with views of building vulnerability in order to provide reliable risk estimates, can be used to quantify the impact of spatial and temporal building vulnerability changes. This study quantifies the impact of the building code related changes in a catastrophe modeling framework using a sophisticated hurricane model and an actuarial metric: average annual loss. A resulting discussion is provided detailing the implications of this study.

INTRODUCTION

Natural disasters serve as a litmus test for building code effectiveness and often act as catalysts for significant code overhauls when Mother Nature asserts her dominance. For instance, following the devastating effects of Hurricane Andrew in 1992, significant advances were made in building technology, material, and construction practices (Florida DCA, 2008). Around the same time, organizations such as the International Code Council (ICC) emerged with the sole purpose of developing a single set of comprehensive and coordinated model building codes that are implemented today across nearly all coastal hurricane prone states in the United States. In addition to the evolution of building codes such as the Council of American Building Officials (CABO) One and Two Family Dwelling Code, the Standard Building Code (SBC), and the ICC codes, the load standards referred to in these codes (see, e.g. American Society of Civil Engineers (ASCE) ASCE-7 standard (2010)) also evolve due to new research. Some updates are quite impactful, while other updates are less significant. For example, the 2012 update to the ICC's Building and Residential Codes, along with updates to the referenced ASCE 7-10 standard caused significant changes to the design wind speeds and wind borne debris regions in a number of hurricane states. Furthermore, code adoption and enforcement practices vary by state (see, e.g. IBHS (2015) and ISO (2015)), and it is often the case that individual counties or cities amend building codes to their liking. Without the occurrence of hurricane events, the effectiveness of the most recent building code is difficult to quantify, yet the need to do so remains.

Catastrophe risk assessment models serve as excellent platforms to not only project potential future hurricane losses, but to also help test the impact of regional/local building codes and their effectiveness with respect to the exposed hurricane risk. These models integrate a stochastic hazard coupled with detailed views of building vulnerability in order to estimate reliable loss distributions. The aim of the current study is to investigate the impact of the evolution of building codes and wind load standards along with their enforcement on the wind vulnerability of residential homes in select states along the hurricane prone east coast of the United States. A modeling routine for catastrophic hurricane events (AIR Worldwide, 2016), which has been validated using past hurricane event claims data from insurance companies, will be used to assess the aforementioned impact measured in terms of probabilistic loss metrics. A case study is presented that examines the location-specific difference in vulnerability between two average single family homes, built before and after the 2012 ICC code adoptions in several hurricane states with different levels of code enforcement. In particular, these exposures are modeled in coastal and inland locations in South Carolina and Virginia and their vulnerability, as measured in terms of a commonly used actuarial metric, Average Annual Loss (AAL), is compared. Although many other hurricane states, including Florida, Louisiana, Georgia, and parts of Mississippi, to name a few, did adopt the 2012 ICC codes, an analysis including other states is out of the scope of this study. Discussion will be provided explaining the vulnerability differences among the considered locations and structure years-built.

IMPORTANCE AND EVOLUTION OF BUILDING CODES

Currently engineers in the United States follow two sets of guidelines, i.e., building standards and building codes, to design and construct a building and it is imperative to understand the differences between the two. Building standards are developed by professional organizations, such as ASCE, and offer in-depth provisions based on recent advancements in building, material, and construction research. They also furnish minimum design loads against certain atmospheric and geological natural hazards to protect the well-being of building occupants. Building Codes, on the other hand, are described by the Federal Emergency Management Agency (FEMA) as "… sets of regulations governing the design, construction, alteration and maintenance of structures;" in other words, building codes must be followed by law (FEMA 2016). Building codes are legally adopted by state and/or local jurisdictions through legislative processes and are enforced by local governments. They provide minimum life safety requirements for buildings and their occupants against certain hazards. Building standards are generally adopted by reference into the building codes.

Prior to 2000, three model building codes were enforced across the United States. The Building Officials and Code Administrators (BOCA) codes and enforcement personnel operated primarily in the Northeast and Midwest, the International Conference of Building Officials (ICBO) and its associated Uniform Building Code (UBC) were dominant in the West, and the Southern Building Code Congress International, Inc.'s (SBCCI) Standard Building Code (SBC) was used primarily in the South. These three groups combined in 1994 and formed the International Code Council (ICC) in an effort to create code uniformity across the country (Listokin and Hattis, 2005). The first edition of the ICC codes (e.g., International Building

Codes (IBC) and International Residential Codes (IRC)) was published in 2000, and new editions of the ICC codes are published regularly; generally, this occurs every three years. Currently, the majority of the country, and nearly all of the East Coast and Gulf hurricane states, use the ICC codes as the basis for state and local codes.

In addition to the evolution of building codes the load standards referred to in these codes (e.g. ASCE 7) also evolve due to new research. Thus most of the changes to the building standards will eventually find their way to the building codes. For instance, the wind provisions of ASCE 7 are adopted by referenced in the ICC's Building and Residential Codes and therefore changes to this standard also affect structures' vulnerability. As the majority of the significant changes in the wind section of IBC and IRC codes are due to the changes to the wind provisions of ASCE 7, this study examines the changes introduced in the latest version of ASCE 7 in order to evaluate the wind vulnerability changes over time.

In 2010, the ASCE 7 "Wind Loads" section went through its most comprehensive change since 1998, mostly due to the introduction of the new design wind speed maps. The ASCE 7 basic wind speed maps defining the wind hazard had not changed from the ASCE 7-98 version to the ASCE 7-05 version of the standard. ASCE 7-10 introduced a number of major changes to the wind speed maps, some of which are listed below:

- Firstly, the maps involve a baseline design methodology shift from Allowable Strength Design (ASD) to Load and Resistance Factor Design (LRFD), which was implemented in order to make the wind and earthquake methodologies consistent
- Secondly, risk category factors were introduced into the design wind speed maps, resulting in three unique maps: a map each for Risk Category I and II structures, respectively, and a separate map for Risk Category III and IV structures combined
- The last change mentioned in this paper, and also the most significant change regarding structural vulnerability, has to do with the representation of the hazard itself. This change is comprehensively described below, and was largely made due to new research indicating that the wind speed maps in ASCE 7-98 and ASCE 7-05 gave a conservative view of the wind hazard along the hurricane-prone East and Gulf Coasts

ASCE design wind speed map hazard re-evaluation, changes, and impact. The design wind speed map significantly changed between the 2005 and 2010 versions of the ASCE 7 standard due to the incorporation of the most recent hurricane data. This recent hurricane data was used in determining wind speeds with given Mean Recurrence Intervals (MRIs). It was generally found that the previous estimates for the hurricane wind speeds were higher, especially along the hurricane-prone coastline. Additionally, the design wind speed was given a consistent MRI in each risk category map (ASCE, 2010). As stated in the Commentary of the previous versions of the standard, the previous basic wind speed maps yielded predictions of 50-100 year return period peak gust wind speeds along the coast (see, e.g. ASCE (2000)). As such, when translating the new maps to an ASD equivalent 50-year MRI design wind speed map, it is apparent that the changes generally result in lower design wind speeds (and therefore lower design wind pressures) along the hurricane prone region, while further inland the design wind pressures were mostly unchanged.

In addition, ASCE 7-10 re-introduced Exposure D as an applicable exposure category for hurricane-prone regions along the East Coast and Gulf of Mexico. In ASCE 7-10 Exposure D applies to at least the first 600 feet from the coastline, as long as the water surface prevails 5000 feet in the upwind direction. This partly compensates for the reduction of the design wind velocity pressure in the coastal areas, where the Exposure D definition is applicable. Table 1 below shows the ratio between the design wind velocity pressure in ASCE 7-10 and ASCE 7-05 for select cities in three U.S. coastal states, two of which are discussed later in the paper. The table indicates the ratio of the velocity pressures between ASCE 7-10 and ASCE 7-05 in two cases: the first is for a structure classified using the same exposure category in both versions of the code, and the second is for a structure located within the first 600 feet of the coast, which would be classified as Exposure C in ASCE 7-05 and Exposure D in ASCE 7-10. The comparison is done for a one-story (15-foot height) house (Category II). It is important to note that the changes to the design wind speed maps also propagate to other specifications. For example, the wind-borne debris region, which is defined based on the design wind speed, has been significantly reduced in some hurricane states (ASCE, 2010).

Table 1. The ratio between the design wind velocity pressure in ASCE7-10 and ASCE7-05 for 15 ft. tall Category II buildings.

State	City	Design Wind Speed* (mph) – 3 sec gust		Velocity Pressure Ratio (ASCE 7-10 to ASCE 7-05)	
		ASCE 7-05	ASCE 7-10	Same Exposure Category	Exp.D (ASCE 7-10) to Exp.C (ASCE 7-05)&
Virginia	Richmond	90	115	0.98	N/A
	Virginia Beach	114	122	0.69	0.83
	Arlington	90	115	0.98	N/A
South Carolina	Myrtle Beach	131	148	0.77	0.93
	Columbia	95	115	0.88	N/A
	Charleston	131	147	0.76	0.92
Mississippi	Biloxi	139	160	0.79	0.96
	Jackson	91	115	0.96	N/A

*Design wind speeds are taken from http://windspeed.atcouncil.org/
&N/A indicates that these cities are inland and exposure category D is not applicable

BUILDING CODE ADOPTION AND ENFORCEMENT PRACTICES AT THE REGIONAL SCALE

The vulnerability of structures is highly location dependent not only due to differences in hazard maps, but also due to differences in state adoption and enforcement practices (see Figure 1 for coastal state building code adoptions). Although it is obviously advantageous for state and local building code departments to adopt the latest building codes and begin enforcing these as soon as possible, there is generally a non-uniform lag in adoption due to many factors. These include the financial, training, and personnel resources available to the departments in addition to the length and stringency of the procedures required by the legislature for official code adoption. Adoption may occur within a year of code publication in states which mandate an adoption deadline through the state building code agency. However, in hurricane prone states that do not require adoption by a state-mandated date, adoption in local jurisdictions (i.e. counties, cities, towns, or other incorporated or unincorporated areas with local ordinances) may occur several years after code publication. In extreme cases, building codes may not be required to be adopted at all, and indeed several jurisdictions in Mississippi currently do not require buildings to be designed under any building code, as shown in Figure 2.

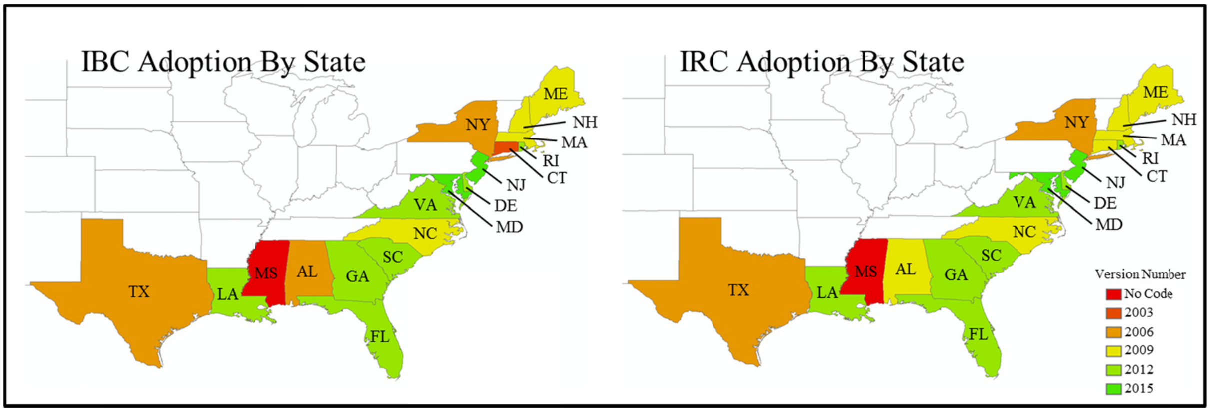

Figure 1. ICC Code adoption by state for coastal states, as of January 2016.

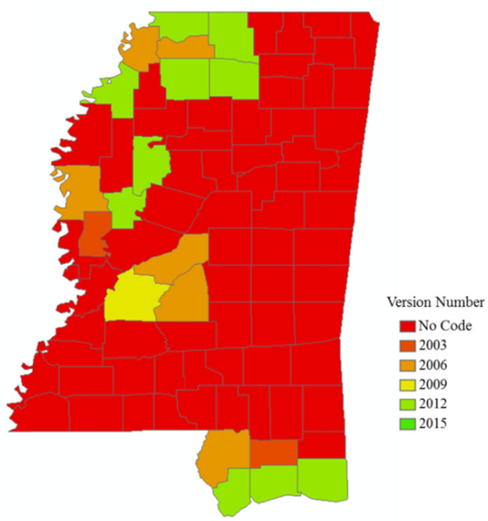

Figure 2. Mississippi ICC Code adoption in unincorporated areas by county, as of January 2016.

In addition to differences in adoption practices, code enforcement practices may vary considerably across and within states. Generally, code enforcement is more stringent in the coastal counties as these have a higher risk, though a department's financial resources, which are used for code official/inspector salaries and training, also come into play. An overview of the adoption and enforcement practices in the states later discussed in the "Case Studies and Discussion" section is presented below. The majority of this information was obtained through phone calls to state or local building code departments unless otherwise cited, although some indication of the adoption and enforcement practices was also collected from the IBHS *Rating the States Report* (IBHS, 2015) and the ISO *National Building Code Assessment Report* (ISO, 2015). Figure 3 hereafter shows the qualitative results of these two independent building code effectiveness investigations.

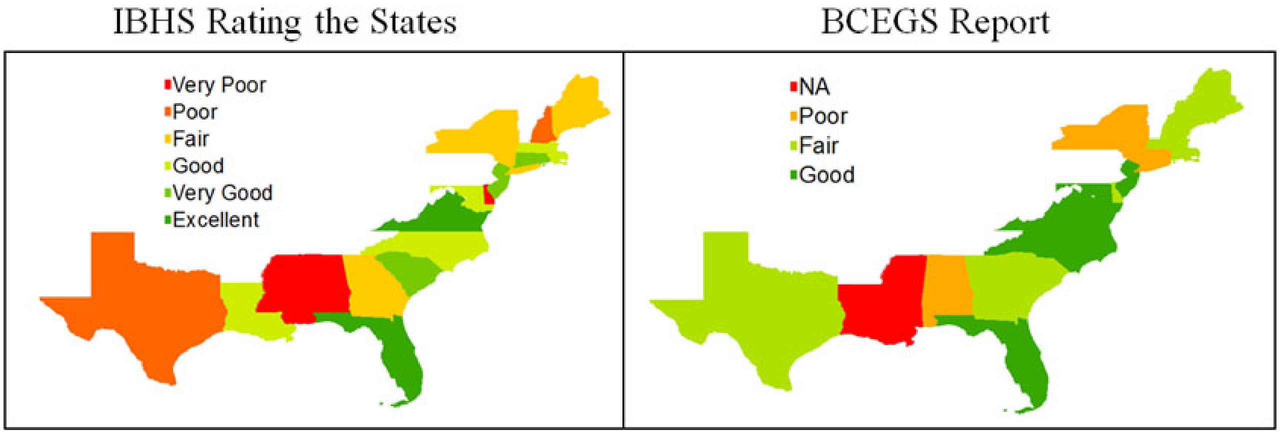

Figure 3. IBHS State 2015 Rating (left) and ISO Building Code Effectiveness Grading Schedule State Adoption Report (right).

South Carolina. South Carolina's state legislature first adopted a formal policy giving local jurisdictions the power to adopt the Standard Building Code in 1972. Prior to this few jurisdictions within the state passed building code ordinances (Mittler, 1991). Between 1972 and June of 1997, local jurisdictions that chose to adopt building codes were legally permitted to do so; however, once a jurisdiction began adopting codes it became mandatory for that jurisdiction to continue adopting the codes authorized by the Building Codes Act within one year of publication. Beginning in July of 1997 it was required that jurisdictions either adopt the building codes approved by the state building code council or legally "opt out" of adopting codes, and at the time of writing this paper no jurisdictions have opted out of code adoption (SCBCC, 2016).

The ICC codes were first enforced in South Carolina in 2001, and the latest versions have been regularly adopted and implemented within 2-3 years of publication, with the exception of the 2009 series of the codes, which was adopted but not implemented. The 2012 IBC and IRC were implemented beginning in July of 2013 and the 2015 versions of the codes were implemented beginning in July 2016. Therefore, the entire state of South Carolina currently enforces the most recent version of the ICC codes. South Carolina does allow state and local modifications to the adopted base ICC codes, but these must be approved by the South Carolina Building Codes Council (SCBCC, 2016). With respect to current enforcement practices, South Carolina requires certification, licensing, and continuing education requirements for building code officials and requires licensing of contractors (IBHS, 2015). Therefore, in general, the code enforcement may be assumed to be good for this state as a whole.

Virginia. The 1996 Virginia Uniform Statewide Building Code (USBC) came into effect in 2000 and was based on the 1996 version of the BOCA National Building Code and the 1995 CABO Code for One and Two Story Single Family Homes. The 2003 USBC came into effect on Oct 1st 2003 and was based on the 2000 International Building Code (Virginia DHCD, 2015). Each subsequent edition of the IBC has been adopted on a 3-year cycle. Virginia has set the standard in terms of adoption, enforcement and continued training for state officials and inspectors which has earned them the highest rating by both IBHS and ISO. As of July 2014, Virginia adopted the 2012 edition of both the IBC and the IRC. The most significant change in Virginia in terms of wind design under the 2012 International Building Code is the lower design wind speeds (for Risk Category II buildings) as well as the complete removal of all areas in the state from the wind-borne debris region. In other words, coastal regions which used to mandate opening protection no longer require opening protection as they now fall outside the wind-borne debris region. Additionally, ASD design wind speeds have been reduced by as much as 20 mph under the 2012 Building Codes.

Implications in other states. As states start adopting the 2012 IBC and subsequent versions, the general consensus is that the wind provisions may be less stringent than earlier versions of the code, particularly along the northeast coastline. For instance, states like Georgia, Maryland, and Delaware have seen large reductions in design pressures and almost complete removal from the code defined “wind-borne debris region.” Other states, such as Florida and Louisiana, have also seen reductions in design pressures which ultimately affect the building strength. However, the design wind speed in the most vulnerable areas of states such as Florida and Louisiana near the coast is sufficiently high that although the wind-borne debris region has reduced, window protection is still required along the coastline and further inland in some counties.

In contrast, in the state of Mississippi the adoption of the 2012 ICC codes has generally decreased the vulnerability of structures in some areas. However, this is primarily due to the traditional lack of building code adoption in this state and the recent push to encourage jurisdictions to adopt building codes. In fact, building codes were not required in the state until after Hurricane Katrina. In response to the devastation Katrina brought five coastal counties, Jackson, Harrison, Hancock, Stone, and Pearl River, and their inclusive municipalities, these began to enforce the wind and flood mitigation requirements of the 2003 ICC Building and Residential Codes beginning in 2006 (Mississippi Legislature, 2006). The remainder of the state was not required to adopt codes until Senate Bill 2378 was passed in 2014 mandating that county boards of supervisors or municipal governing authorities must adopt one of the last three versions of the International Building Code and International Residential Code, or must opt out of adopting codes by November of that year (Mississippi Legislature, 2014). Although a significant number of municipalities did opt out of adopting codes (see Figure 2 for county adoption), this was a significant step for the state in ensuring that new structures are less vulnerable to natural hazards. The jurisdictions that began adopting codes in 2014 would be expected to see an increase in building performance for new structures, assuming that the codes are well-enforced, regardless of the code adopted, due to the previous lack of code adoption.

CATASTROPHE MODELING FRAMEWORK

Figure 4 shows the framework for the subject hurricane model. The *event generation* and *local intensity calculation* modules together comprise the *hazard module* within the framework. The *event generation* module deals with so-called source parameters and answers questions about where events are likely to occur, how large or severe they are likely to be, and how frequently they are likely to occur. The task of this module is to simulate all types of possible, yet realistic, future scenarios. Upon generation of a potential future event probabilistically, the *local intensity* module propagates the event across the affected area by estimating the local intensity (such as location specific surface wind speed or storm surge depth). In this component as well as in the *event generation* component, detailed scientific and meteorological data and algorithms are employed to model the local effects of each simulated event. Windstorm models, for example, use high-resolution digital land use/land cover data to calculate surface frictional effects. Estimates of surface roughness dictate, in part, the behavior of ground level wind speeds.

Figure 4. Components of a hurricane model for the United States (AIR Worldwide, 2016).

The local intensities of each simulated event are superimposed onto a database of exposed properties. The *engineering* or *damage estimation* component then calculates the resulting monetary damage by applying mathematical functions that relate the hazard intensity to a loss metric. These functions go by different names in different fields. Among structural engineers, they are known as vulnerability functions (which are not to be confused with fragility curves), while actuaries refer to them as loss functions. Catastrophe modelers refer to them as vulnerability relationships, vulnerability functions or damage functions. Different nomenclature may or may not reflect material differences in what these functions represent. While fragility curves indicate the probability of exceeding a certain physical damage level of a structure or its components, actuarial loss functions report insurance losses. In the context of a catastrophe modeling framework, as in the present case, damage functions capture the relationship between the intensity of the event (measured in terms of wind speed or storm surge depth) and the damage ratio, which is the ratio of the repair cost of the building to its total replacement value.

While engineering is at the core of a catastrophe model's damage function development framework, the ultimate objective of a catastrophe model is not the estimation of physical damage states or idealized cost estimates; rather, it is the estimation of future monetary losses that an insurer will actually pay out in the aftermath of a catastrophe. To achieve this, factors other than a structure's engineering response must be accounted for, such as building codes and their enforcement, claims adjustment and insurance practices, socio-economic effects, and societal preparedness and response, to mention a few. As it is most likely evident from the preceding discussion in this paper, damage functions are region and time-specific and reflect a thorough understanding of local building codes and construction practices. They provide not only estimates of the mean, or expected, damage ratio corresponding to each level of intensity but, in addition, provide a complete probability distribution around the mean. Because different structures experience different degrees of damage for a given level of intensity, the damage functions need to capture this variability, or so-called secondary uncertainty.

Finally, insured losses are calculated by applying the specific policy conditions of the cedant (an insurance company purchasing reinsurance) to the total damage estimates in the *financial* module of the catastrophe modeling framework. The model output is usually in the form of probability distribution of losses and their complement, the exceedance probability curves, along with metrics such as average annual loss (AAL) which are used heavily in the insurance space.

CASE STUDY AND DISCUSSION

In order to quantify the impact of the 2012 IRC on the vulnerability of wood frame single family homes, South Carolina and Virginia are chosen as candidate states. Both states have some of the best scores in terms of building code adoption and enforcement practices. However, the relative change in design wind speed zones across the state as captured by the wind speed maps in ASCE 7-10 and their 2005 counterparts is higher in Virginia than in South Carolina. The ASCE 7-05 and 7-10 design wind speed maps were studied for these states and distinct locations were identified at the crossroads of design wind speed zone changes. One story, wood frame, single family homes built in 2008 and 2015 were then modeled at each of these locations in the hurricane model used in this study and estimates of AAL were obtained by running the model through stochastic simulations that generate 50,000 realizations of the next hurricane season. The house built in 2008 will conform to the 2003 version of the IRC as adopted by South Carolina whereas the 2006 IRC was in effect for Virginia in 2008. The home built in 2015 will be in accordance with 2012 versions of the IRC in these states.

While catastrophe models are excellent tools to understand the risk (in the current context, hurricane risk in regional scale), the current research is utilizing the same to quantify the impact of vulnerability related changes mainly dictated by the evolution of building codes and enforcement practices in terms of AAL. Since the hazard is the same for a given location, changes in AAL across different years is a direct reflection of the change in vulnerability of buildings due to different building codes and the corresponding wind load standards.

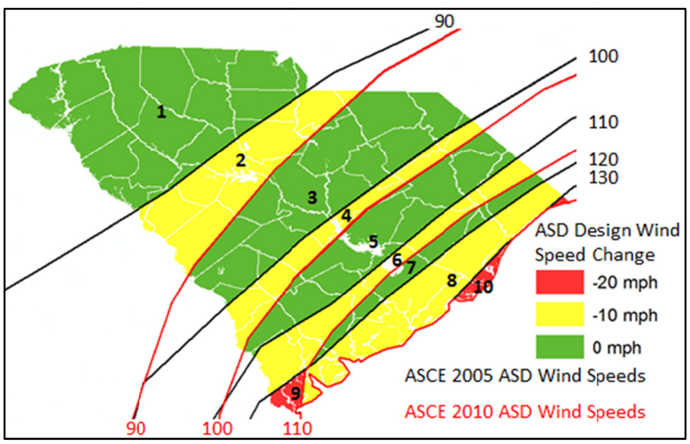

Figure 5. South Carolina Design Wind Speed Map (ASCE 7-05 vs ASCE 7-10).

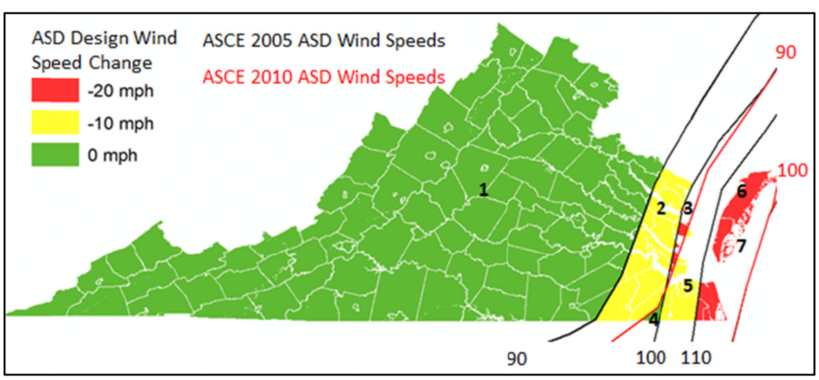

Figure 6. Virginia Design Wind Speed Map (ASCE 7-05 vs ASCE 7-10).