

HURRICANE RISK AND COASTAL PROPERTY OWNER CHOICES

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Abstract

Purpose - The purpose of this paper is to contrast the behavior of a homeowner exposed to hurricane risk with government policies designed to limit hurricane losses. Owners limit these losses by selecting structural improvements or mitigation and wind and flood insurance.

Design/Methodology/Approach – We use mitigation costs, hurricane probabilities and insurance premiums to frame rational cost-minimizing choices for the homeowner.

Findings - First, even though nationwide hurricane damage costs are large, the cost-minimizing response for an individual property owner may be to buy no mitigation or structural improvements, no flood insurance and minimal wind insurance, as probabilities of strong hurricanes striking particular locations are extremely low. Second, additional insurance is a less costly defense than structural improvement, even under much higher insurance premiums and hurricane strike probabilities. Third, federally subsidized flood insurance may reduce the effectiveness of government programs encouraging structural mitigation.

Originality/value – The last few years were underscored by the catastrophic damages of Hurricanes Katrina, Ike and Wilma. Enormous costs suffered by the public and private sectors could have been avoided with greater mitigation by homeowners. This paper examines the financial incentives for such mitigation. Those incentives are examined in a previously untested framework.

Keywords – Disaster mitigation, hurricane, retrofitting, risk reduction

Paper type – Research paper

Introduction

Hurricanes Frances, Jeanne and Ivan struck Florida in 2004, Katrina made landfall in 2005, and Hurricanes Gustav and Ike made history in 2008. This elevated hurricane activity since 2004 highlights special risks and exposures of the public in general, and coastal property owners in particular, to hurricane damage. To minimize the expected costs of exposure to hurricanes, homeowners choose a combination of insurance, structural defensive measures and deductibles as a function of the cost of the insurance and these measures relative to the probable costs of hurricane damages. Current discussions of damage minimization focus upon this insurance coverage and those defensive structural improvements beyond building code guidelines.

In this paper we construct a model of a risk-neutral coastal property owner who chooses insurance policies and structural improvements to minimize the expected costs of future hurricane damage. This individual cost-minimizing behavior raises issues for the private insurance industry, the construction and real estate industries, and government disaster insurance and mitigation programs.

From a public policy perspective, the government sponsors several hurricane damage mitigation programs. As the private market eliminates wind insurance in high-risk areas, state governments require that insurance companies participate in wind insurance pool programs. Do these wind pool programs distort homeowner behavior? Recent hurricane strikes motivate insurance companies to raise premiums or drop coverage. How does a typical cost-minimizing homeowner respond? Might increases in insurance premiums cause the substitution of structural improvements for insurance purchases? We consider how best a property owner might respond,

given observed hurricane strike probabilities and the costs of various insurance programs or mitigation efforts to “harden” the home.

At the federal level, the U.S. Federal Emergency Management Agency (FEMA) subsidizes flood insurance through the National Flood Insurance Program (NFIP) and promotes structural improvements through such programs as Project Impact. FEMA provides an exhaustive literature on sundry mitigating options, their costs and potential efficacy. The success of these federal programs, and the value of this literature, depends on property owner responses to program incentives. Do these programs significantly affect property owner choices? If so, do these programs promote efficient mitigation activities?

The next section provides a background and review of selected literature relevant to these issues. The third section parameterizes the model for a case study structure in Wilmington, N.C. Wilmington and the surrounding Cape Fear Region are the sites of several successive hurricane landfalls in the late 1990’s, and an additional five category 1 hurricane or tropical storm landfalls between 2003 and 2009. Areas along the Gulf Coast have been the regions with the most damaging hurricane activity since 2005. The Cape Fear Region, however, has historically been among the areas most likely to suffer hurricane landfalls. In the fourth section, cost-effective combinations of structural improvements and insurance are determined for alternative hurricane strike probabilities and insurance schedules. A summary and a brief policy discussion conclude the paper.

Some Background

Potential losses for insurers and property owners at hurricane-risk, and the appropriateness of certain government responses, encourage recent empirical and theoretical examinations; these studies consider the real estate market in an area at elevated exposure to hurricanes, and the impact of hurricanes on homeowners and the business community.

Graham and Hall (2001, 2002) note respectively that in an area subject to recurring damaging hurricane landfalls (not all tropical systems making landfall cause great damage), property values suffer, and real estate market behavior is impacted not only with lower closed home sale prices, but also with larger listing/selling spreads, fewer sales, and longer marketing times required for home sales. More recent work by Morgan (2007), on the impacts of Hurricane Ivan along the Gulf Coast, echoes these findings for housing markets in that region. Graham, Hall and Schuhmann (2007) note in more recent work that the residential market returns to “normal” with the passage of time, but that return is slowed in an area suffering four major hurricane landfalls in less than four years.

Pisani (1993), with remarks related to the devastation of Hurricane Andrew south of Miami in 1992, anticipates much of the recent discussion concerning the importance of the measurement of, and response to, hurricane risks. Risks to life and property from hurricanes are highlighted by the collective power of the storms of 2004, 2005 and 2008. Grace, Klein and Liu (2006) underscore these escalating hurricane losses between 1985 and 2005; their work precedes the egregious losses of Hurricane Ike in 2008. Unsettled arguments may exist concerning the propensity of the Tropical Atlantic to generate hurricanes in the years to come, but no such disagreement exists about the enormous property damages over the past few years.

Homeowners might reduce current hurricane damages, and lessen expected future losses, with a set of home improvements designed to protect the home from hurricanes – storm shutters, hardened garage doors and window frames, along with roof tie-downs, come to mind. Some coastal homes that include this sort of costly mitigation actually command higher market prices.

Simmons, Kruse, and Smith (2002) find that home values on a Gulf Coast barrier island increase as structural integrity increases. They suggest that the purchase of storm blinds is cost-effective as home values are increased by an amount greater than the cost of these installed shutters. Previously, Kleindorfer and Kunreuther (1999) show that roof reinforcements reduce insurer exposure in the event of a hurricane and that homeowners are “slightly better off” with these defenses.

Many at-risk homeowners do not retrofit their homes against hurricane damage. An evolving literature suggests two main reasons why homeowners don’t respond to the risk of these low-probability, high-consequence events with the purchase of defensive measures. Burrus, Dumas, and Graham (2002, 2005) suggest first that the availability of insurance undermines the incentive to protect against hurricane damages using structural mitigation. Most mortgages require insurance against storm damage – some homeowners and lenders overlook flood insurance – and take the insurance-purchase decision out of the homeowner’s hands.

Second, and perhaps the most popular explanation for the lack of mitigation devices, homeowners underestimate hurricane strike probabilities. Kruse and Simmons, (2005) believe these homeowners have a “can’t happen to me” attitude about catastrophic risk; similarly, Kunreuther and Pauly (2004) suggest that homeowners underestimate probabilities due to the search costs of obtaining good probability information. Further, and even if strike probabilities are not underestimated, Burrus, Dumas, and Graham (2005) show that homeowners may underestimate damage resulting from a strike.

Insurer responses vary, and a related literature has developed from the perspective of the insurance company. Quinn (1998) considers the risk models used by insurers to illustrate their exposure to hurricanes. He highlights the importance of the accuracy of these models in allowing insurers to anticipate losses from hurricanes. Davidson (1998) echoes Quinn’s concerns with his support for a “comprehensive national strategy” to brace insurers for the funding requirements of catastrophic losses. With amounts normalized to account for changes in purchasing power, population and wealth, Pielke and Landsea (1998) find that the average annual US hurricane damage for the 73 years ended in 1997 was \$5.2 billion. Losses between 2004 and 2008 averaged over \$20 billion per year. Half or more of these losses were covered by insurance.

Additional research considers actions by lenders, property owners and the government in reducing individual and insurance company exposure to hurricanes. Smith (1998) considers the impact of natural disasters on real estate lending. Meyer and Meyer (1999) propose a set of comparative statics for use by the insured in selecting hurricane insurance and insurable assets as a function of the insured’s wealth, the availability of insurance, the insurable asset’s price and the cost of insurance. Kozlowski and Mathewson (1997) highlight the importance of “good exposure data” in modeling the impact of hurricanes – for regulatory agencies and insurance companies - and in reducing the expense to insurers of these hurricane losses. The value to the insurers of motivating homeowner mitigation activity is clear. Pisani (1993) reports \$16 billion in insurance claims for Hurricane Andrew; the Library of Congress suggests that Katrina’s total insured and uninsured losses were conservatively ten times that amount.

Adams (1995 and 1997) reviews regulatory responses in the insurance sector after Andrew, and before the historic landfalls of the early 21st century. He finds that policymaker concerns focused both upon assuring the continuing availability of insurance in hurricane-prone areas and upon assuring capital markets that insurers would survive the substantial claims of that hurricane. Markets survived Andrew, and the far more costly Katrina, thirteen years later.

Thus, research is broadly conducted first, towards better understanding responses by the varied parties to the continuing risk of hurricane landfalls – and, second, to the greater damages that result with the more recent storms and increasing population concentrations along the Atlantic coast. The research is generally encouraged by the impacts suffered by various stakeholders (insurers, property owners, state and local governments, etc.) in the hurricane paradigm. Extending this literature, we construct a model to frame coastal property owner behavior in the context of hurricane risk.

The Model

We construct a model towards revealing optimal property owner behavior, after making a few simplifying assumptions. Tropical weather severity is indexed by discrete random variable, $i = 0 \dots 5$ (see Table 1). Tropical storms are denoted $i = 0$. Intensities $i = 1 \dots 5$ denote hurricane categories 1 through 5 on the Saffir-Simpson scale. The Saffir-Simpson index is the standard used to describe hurricane intensity (Simpson 1974, Saffir 1977). Each category is associated with a combination of high winds and storm surge flooding. Time is measured in yearly increments denoted t . The probability of experiencing tropical weather of severity i in year t is denoted P_{it} . Tropical weather of severity i is distributed identically and independently across the owner's time horizon. We rule out the possibility of multiple tropical weather strikes per year, though we admit they infrequently occur – Fran and Bertha struck within 50 miles of one-another in 1996, Jeanne and Francis in 2004. Consequently, $P_{it} = P_{it+1} = P_i < 1$.

Consider a property owner with home s square feet in size. The building has initial dollar value h_0 ; internal contents are valued at c_0 dollars. In the event of tropical weather, the structure is subject to wind damages and flood damages. Wind damages are caused by the failure of property features including roofs, windows, doors, and garage doors, and the subsequent destruction of internal contents. Building code guidelines require that structural features withstand specified wind speeds with no damage. The ability of stricter building requirements to reduce hurricane damage is well documented (Rogers, 1994 and Fronstin and Holtmann, 1994). Flood damages include the destruction of foundations, walls and internal contents.

The owner's time horizon is $t = 0 \dots T$. At the beginning of the time horizon, the owner has the option to purchase structural defensive measures beyond building code guidelines. Defensive measures are purchased individually or in combination. Expenditures on wind defenses per square foot of structure are denoted c^w ; expenditures on flood defenses per square foot of structure are denoted c^f . Defensive measures are installed correctly and do not depreciate over the owner's time horizon.

Annual wind-related and flood-related property damages depend on wind and flood-related defensive expenditures. Wind damages to structure and contents in any year are denoted $D_i^w(c^w)$; similarly, flood damages are denoted $D_i^f(c^f)$. Both wind and flood damages are non-

increasing in expenditures on defensive measures, $\frac{\partial D_i^w(c^w)}{\partial c^w} \leq 0$ and $\frac{\partial D_i^f(c^f)}{\partial c^f} \leq 0$.

Total wind and flood damages cannot exceed the total value of the structure and contents, $h_0 + c_0$. Damages are first attributed to flood, with any remaining damages attributed to wind. This is consistent with insurance adjusters who typically distinguish between damages covered under flood insurance and damages covered under wind insurance by the high water mark on the structure's walls. Flood insurance covers damages below the high water mark and wind insurance covers the balance; a one-story home flooded halfway from floor to ceiling would have half the damages to the home covered by the flood insurance. This ignores contents.

Consequently, residual wind damages in any year are expressed as $\min\left[D_i^w(c^w), \frac{h_0 + c_0}{s} - D_i^f(c^f)\right]$. Recent hurricanes, though, have been marked by insurers attempting to attribute all damages to flooded homes to the floodwaters, excusing themselves from liability. Continuing litigation should one day clarify this issue.

Wind and flood insurance are available to the homeowner and protect against hurricane losses. If the owner insures, he insures for the full value of the structure and contents. A wind insurance combination is a set $\{\pi^w, \delta^w\}$, where π^w is the annual insurance premium and δ^w is the deductible. A flood insurance combination is a set $\{\pi^f, \delta^f\}$, where π^f is the annual insurance premium and δ^f is the deductible. The owner is responsible only for wind and flood damages up to δ^w and δ^f , respectively. Thus, the maximum amount of uncovered wind damages in any year is $\min\left[\delta^w, s \min\left[D_i^w(c^w), \frac{h_0 + c_0}{s} - D_i^f(c^f)\right]\right]$. The maximum amount of uncovered flood damages is $\min\left[\delta^f, s D_i^f(c^f)\right]$. If no insurance is purchased, the deductible is the total value of the structure and contents.

Allowing for a government wind insurance subsidy, σ^w , the annual wind premium is defined by $\pi^w(\delta^w, \sigma^w, h_0 + c_0)$. The annual wind insurance premium is decreasing in the wind deductible, $\frac{\partial \pi^w}{\partial \delta^w} < 0$, decreasing in wind insurance subsidies, $\frac{\partial \pi^w}{\partial \sigma^w} < 0$, and increasing in the value of structure and contents, $\frac{\partial \pi^w}{\partial (h_0 + c_0)} > 0$. Allowing also for a flood insurance subsidy, σ^f , the annual flood insurance premium is defined by $\pi^f(\delta^f, \sigma^f, h_0 + c_0)$. The annual flood insurance premium is decreasing in the flood deductible, $\frac{\partial \pi^f}{\partial \delta^f} < 0$, decreasing in flood insurance subsidies, $\frac{\partial \pi^f}{\partial \sigma^f} < 0$, and increasing in the value of structure and contents, $\frac{\partial \pi^f}{\partial (h_0 + c_0)} > 0$.

The owner chooses insurance deductibles and structural defensive measures beyond building code guidelines to minimize the discounted expected costs, C, associated with tropical weather over time horizon, T. (Fronstin and Holtmann [1994] comment on the impact of coastal building code requirements in Dade County, Florida, following Hurricane Andrew.)

The owner's cost-minimization problem becomes:

$$\min_{c^w, c^f, \delta^w, \delta^f} C = s \cdot c^w + s \cdot c^f + \underbrace{\sum_{t=1}^T \frac{\pi^w(\delta^w, \sigma^w, h_0 + c_0) + \pi^f(\delta^f, \sigma^f, h_0 + c_0)}{1 + r^t}}_{(+r^T)} + \underbrace{\sum_{t=1}^T \frac{\sum_{i=0}^5 P_i \left\{ \min\left[\delta^w, s \cdot \min\left[D_i^w(c^w), \frac{h_0 + c_0}{s} - D_i^f(c^f)\right]\right] + \min\left[\delta^f, s \cdot D_i^f(c^f)\right] \right\}}{1 + r^t}}_{(+r^T)}$$

given $s, h_0, c_0, \sigma^w, \sigma^f, T, P_i$, for all i , and r , where r denotes an annual, real rate of interest.

Parameterization of the Model

We define a representative structure in Wilmington, N.C., as a new, 2,150 square foot, one-story, wood frame residential structure with vinyl siding valued at \$140,000. The structure conforms to the 1999 North Carolina 110-mph coastal building code. Most residential structures in the region meet the wind and flood requirements of applicable building codes. Following the insurance and regulatory standard, the structure's contents are valued at 70% of structure value, or \$98,000. The structure includes three bedrooms, two bathrooms, a living room, a dining room, a kitchen, and a two-car garage. The structure rests on a crawl space. It is located within five miles of the ocean, landward of the intracoastal waterway.

We choose a coastal mainland location for two reasons. First, available wind speed data are measured at mainland stations and underestimate wind speed experienced on barrier islands. Second, a mainland location is not subject to wave action and scour erosion. Even small breaking waves generate extremely powerful forces on structure and structural defenses (Rogers 1994). Consideration of these hydrodynamic forces requires substantial, additional engineering analysis beyond the scope of the study.

In addition, the structure has eleven 3'x5' windows, three 3'x7' exterior doors and one 9'x16' garage door. The annual real rate of interest is seven percent. Below, we parameterize P_i , $D_i^w(c^w)$ and $D_i^f(c^f)$, for all i , $\pi^w(\delta^w, \sigma^w)$ and $\pi^f(\delta^f, \sigma^f)$ for the representative structure.

Hurricane Wind Speed Probability Distribution

We consider all tropical storms and hurricanes passing within 100 nautical miles of Wilmington during the last century, regardless of landfall. Because wind speeds decrease rapidly with distance outward from the hurricane eyewall, we assume that storms with centers passing farther away than 100 nautical miles from Wilmington cause negligible wind and storm surge damage. This assumption was cast in doubt by Katrina's 10-foot or more surges 80 miles from the eyewall, but Katrina's surge was captured by the northern Gulf Coast (not a factor in the mid-Atlantic where surges have more room to dissipate), and Katrina was nearly unique in her size and coverage. As well, we do not consider flood damage due to upstream rainfall, but rather focus on wind and storm surge damages only.

All tropical storms and hurricanes are identified using U.S. Department of Commerce annual North Atlantic Hurricane Tracking Charts (Cry 1965, *National Hurricane Center Atlantic Hurricane Season Annual Summaries*, various years). The use of other screening criteria excludes some of these storms (Jarrell, et al. 1992). We identify the date on which the storm passed closest to the study location and obtain local sustained wind speed data from the US Weather Bureau from 1900 to 1946, the local print media from 1947 to 1975, the Monthly Weather Review (published by the American Meteorological Society from 1976 to 1994, and the Local Climatological Data (published by the National Climate Center) from 1995 to 1999. The frequency of nearby landfalls, and the lack of any significantly damaging intensities among the storms between 2000 and 2009, obviates the need for their inclusion.

Official tropical wind speed data are typically "1-minute maximum sustained surface winds," defined as the maximum wind speed sustained for 1 minute at an elevation of 10 meters (considered "surface," or "ground level" elevation) within the hurricane eyewall at landfall. The Saffir-Simpson scale of hurricane intensity is based on these sustained winds. Many of the wind speeds recorded are significantly lower than the wind speeds reported by the media and used in prior studies. Media often report eyewall wind speeds for locations not hit directly by the eyewall. For example, Jarrell, et al. (1992) find that only eight hurricanes affected the study

location during the last century. Of these storms, six were assigned hurricane category numbers that imply wind speeds significantly above the actual wind speeds measured in Wilmington. Our wind speed probability distributions are constructed with surface wind speeds measured by National Weather Service stations at the case study location.

The annual hurricane strike probabilities, equal to the observed strike frequencies, are reported in Table 2. Only two (three, including Andrew) category 5 hurricanes and 14 cat' 4's (13, excluding Andrew) impacted the entire US coastline during the 20th century. Early in the 21st century, Katrina was a category 3, Ike a 2 and Charlie a 4. The media often report higher probabilities based on strikes occurring *anywhere* along the coast. However, the probability of a particular location experiencing tropical weather of given intensity is lower (Jarrell, et al 1992, and Rogers, 1994). In simulations to follow, we proxy the property owner's annual expected tropical weather probabilities, P_i , with the probabilities reported in Table 2.

The implications of alternative assumptions regarding wind speed measurement methodology and expected wind speed probabilities in Table 2 are explored in several model simulations. For comparison, probabilities provided by the National Weather Service's HURISK hurricane simulation model, discussed in Neumann and McAdie (1991) are also reported in Table 2. The HURISK model predicts lower strike probabilities for category 0-3 storms and non-zero strike probabilities for category 4 and 5 storms.

Wind Damages and Structural Defenses

The representative structure meets a 110-mph building code. We interpret this to mean that, where no additional structural defensive measures are undertaken, each structural feature suffers zero damage from sustained winds below 110-mph but fails completely if exposed to sustained winds above 110-mph. Thus, our unprotected structure suffers zero wind damages for tropical weather below hurricane category 3 and \$238,000 in damages for tropical weather equal to or exceeding hurricane category 3.

We recognize that actual damage is not likely to exhibit such discontinuity. However, engineering data needed to refine these relationships and to specify probabilistic failure rates are scarce. Hence, we assume that the current building codes reflect "best practice" engineering knowledge and that a structure built to a 110-mph code will withstand 110-mph winds. In addition, the structure also suffers potential damage from falling objects (trees, signs, etc.) dislodged by extreme winds or from wind-blown objects (roof tiles, tree limbs, lumber, pine cones, etc.). We assume these hazards are negligible for the example property.

We assume that wind defenses mitigate expected damages depending on the structural features protected. Protecting a roof prevents damages equal to the value of the entire structure and contents, or \$238,000. Protecting windows prevents damages equal to the cost of replacing the windows, or \$3,729 (\$139 for materials and \$200 for labor, per eleven windows), plus the cost of replacing the contents of eight rooms, or \$93,100 (95 per cent of total content value, with 5 percent of the value residing in the windowless garage). Protecting exterior doors prevents damages equal to the cost of replacing the doors, or \$1,143 (\$131 for materials and \$250 for labor per 3 doors), plus the cost of replacing the contents of three rooms (out of eight rooms in the example structure), or \$34,913 – losses equaling three-eighths of the 95 per cent of total contents value, a typical value for a residential structure in the study region.

Finally, protecting the garage door prevents damages equal to the cost of replacing the garage door, or \$680 (\$480 for materials and \$200 for labor), plus the cost of replacing garage contents, or \$4,900 (.05 x \$98,000).

For each structural feature considered, we identify a range of damage-reducing activities from FEMA reports on hurricane damage reduction. For each activity, we gather wind speed ratings and installation costs. We assume that damage-reducing activities perform as rated. To our knowledge, measures of the likelihood of failure for the various structural defenses are not available.

The property owner chooses the least-cost defensive activities to achieve a given wind speed rating. For example, three alternative damage-reduction activities provide a wind speed rating of 140-mph for windows: storm panels, accordion shutters and hurricane-paned glass. The property owner chooses the least expensive option (storm panels). (Panels of data describing the costs of varying defensive measures are available from the authors on request.) For each hurricane category with midpoint wind speed (see Table 1) above 110-mph, Table 3 presents the minimum costs of fully protecting each structural feature or combination of structural features against wind damage. Table 3 also illustrates hurricane damages for each combination of protected structural features using the wind damage schedule above.

Hurricane category 3 has a midpoint wind speed of 120-mph (Table 1). If the property owner protects only his windows against a wind speed of 120-mph, there are 10 possible damage-reducing activities, varying from costly windows and storm shutters to less costly plywood shutters. The least-cost damage-reducing activity that protects windows against a wind speed of 120-mph includes plywood window covers and wood screws, at a cost of \$0.1520 per sq. ft. This value is reported in row “W” for hurricane category 3 (Table 3). For Table 3 rows indicating protection of multiple structural features, we sum across the least-cost damage-reducing activities for each structural feature. We assume that the roof defensive measure sufficient to defend against a minimum Category 4 wind speed is also sufficient to defend against the midpoint Category 4 wind speed. We assume roof defenses are unavailable for midpoint category 5 hurricanes; no such hurricane has made landfall in the study region in recorded history, though non-zero strike probabilities for such a landfall exist.

Suppose the property owner purchases least-cost roof and window protection. If the owner spends \$2.1473 per sq. ft. of structure, the structure’s roof and windows suffer no damage in a category 3 hurricane. Total roof and window mitigation expenses of 2,150 square feet times \$2.1473, or \$4,617, are incurred. Damage to structure and contents arising from unprotected doors (including garage) is \$41,636, *if a hurricane strikes*. In the event of a category 4 or 5 storm, this level of expenditures does not protect the structure's roof and windows. Thus, damage to the structure and its contents is complete (\$238,000). If the property owner spends \$3.4151 per sq. ft. of structure, roof and window damage is reduced to \$41,636 in the event of a category 4 storm but complete in the event of a category 5 storm. The consensus is that no level of conventional structural defenses prevents the loss of the structure's roof in category 5 winds; we assume no available protection against category 5 winds. For each storm category, we plot residual wind damage per sq. ft. of structure against least-cost structural feature expenditures. Least-cost sequences of structural wind defenses are the lower boundaries, or "lower envelopes," of these plots. These sequences are *wind damage-reduction functions*, parameterized as:

$$\begin{aligned}
 D_i^w &= 0, & i &= 0 \dots 2, \\
 D_3^w &= \text{MIN}[110.69, 2.8289\text{E}+10 * c^w \wedge (-29.229)], \\
 D_4^w &= \text{MIN}[110.69, 1.7589\text{E}+6 * c^w \wedge (-10.338)], \text{ and} \\
 D_5^w &= 110.69,
 \end{aligned}$$

where D_i^w is wind damage in dollars per sq. ft. of structure under weather intensity i , c^w is expenditures on wind defensive measures in dollars per sq. ft. of structure, and 110.69 is maximum wind damage in dollars per sq. ft. of structure. Wind damage from weather intensities $i = 3$ and 4 is decreasing and convex in wind defense expenditures beyond some lower threshold. Category 5 hurricane winds completely destroy the structure, regardless of the level of expenditures on structural defenses.

Storm Surge, Flood Damages and Structural Defenses

Storm surge is the increase in mean water level above mean sea level (MSL) due to tropical weather. Although the extreme rainfall associated with tropical weather causes flood damage, as with Hurricane Mitch and 20,000 or more flood-related deaths in Central America in 1998, the primary flood threat in coastal areas is storm surge. The National Weather Service's Sea, Lake and Overland Surges from Hurricanes (SLOSH) model, calibrated for Wilmington, N.C., estimates the relationship between tropical weather wind speed and storm surge as,

$$SS = -0.47246 + 0.000764*(WS)^2,$$

where SS is storm surge measured in feet above MSL, and WS is maximum sustained wind speed measured in miles per hour (Jarvinen and Lawrence 1985). Using the SLOSH model, predicted storm surges per hurricane category are presented in Table 1.

Flood damages depend on flood depth. Flood depth is storm surge above the zero damage elevation (ZDE), where ZDE is defined as the elevation above MSL at which flooding first damages the structure or its contents; ZDE is equal to the ground floor elevation. The representative structure rests on a 3-foot crawl space at a ground elevation of 9 feet above MSL. As the unprotected structure is on a 3-foot crawl space, ZDE is 12 feet (9-foot ground elevation above MSL plus the 3-foot crawl space). Flood depths per tropical weather category are listed in Table 1. There, a 15.2 foot storm surge produces a 6.2 foot water level above the ground (15.2 foot storm surge - 9 foot ground elevation) but only 3.2 feet of flood depth above ZDE (15.2 foot storm surge - 12 foot ZDE).

Flooding typically causes a greater percentage loss to a structure's contents than to the structure. Based on FEMA claims data (USCE 1993, 1997, 1998), we parameterize the following:

$$PDS = e^{(-1.88+0.75*\ln(FD))}/(1+e^{(-1.88+0.75*\ln(FD))}) \text{ and}$$

$$PDC = e^{(-1.62+0.86*\ln(FD))}/(1+e^{(-1.62+0.86*\ln(FD))}),$$

where PDS is percentage damage to the structure, PDC is percentage damage to contents, and FD is flood depth.

Flood defenses mitigate these damages. Unlike the case of wind damage-reduction, where the owner chooses whether to defend each structural feature, one flood damage-reduction activity protects all features and obviates the need for multiple flood defenses. Flood defenses include elevation on closed foundation or open foundation (pilings), levee construction, floodwall construction, elevation-on-fill, and off-site relocation. We estimate activity implementation costs sufficient to achieve various degrees of flood protection. Our mitigation purchase and installation data show that flood damage for a water level six feet above ground level is prevented by additional fill (\$11.87 per sq. ft.), elevating the house on pilings (\$20 per

sq. ft.), relocating to higher ground (\$27 per sq. ft.), or building a 6-foot high levee (\$40.16 per sq. ft.). The most cost-effective activity varies by flood depth.

For each storm category, we plot residual flood damage per sq. ft. of structure against least-cost flood defense expenditures. *Flood damage-reduction functions* are the lower boundaries, or "lower envelopes," of these plots, parameterized as:

$$\begin{aligned} D_i^f &= 0, & i &= 0 \dots 3, \\ D_4^f &= \text{MAX}[0, 33.10939 + 0.002572 * (1 - \exp(0.5115*c^f))], \text{ and} \\ D_5^f &= \text{MAX}[0, 59.0546 + 0.15183 * (1 - \exp(0.235*c^f))], \end{aligned}$$

where D_i^f is flood damage in dollars per sq. ft. of structure for weather intensity i , and c^f is expenditures on flood defensive measures in dollars per sq. ft. of structure.

If the structure is not yet built, the least cost flood damage-reducing activity for low flood depths is building the structure upon additional fill dirt. For higher flood depths, raising the house on pilings and, for even higher flood depths, total relocation of the house are the least-cost flood damage-reducing activities, respectively. The cost of raising an existing structure on fill dirt is much higher. As we assume that the example structure already exists, levees and floodwalls are the least-cost activities for the lowest flood depths. If we rule out total relocation of the structure, raising the structure on pilings is the least cost flood damage-reducing activity for higher flood depths.

For weather intensities $i = 0$ to 3 , our property experiences no flood damage. For weather intensities $i = 4$ to 5 , flood damage is decreasing and concave in flood defense expenditures beyond a critical threshold. Flood damage is decreasing and concave in flood defense expenditures, as house elevation provides increasing marginal benefits. For a given storm surge level, a small elevation protects only the upper portion of a house. Elevating further protects the lower portion, where contents of the greatest value - most appliances, costlier furniture, - are located.

Choices relative to flood mitigation are particularly meaningful given the experiences of Hurricane Katrina, in New Orleans and along the Gulf Coast as much as 120 miles east of that city. Within New Orleans, damage to low-income housing highlighted the need for retrofitting homes to much higher ZDE's. In Biloxi and Gulfport, well east of New Orleans, the need for mitigation in anticipation of the powerful surge of the gulf (not suffered inside of New Orleans) was highlighted. Lower cost elevation of the homes might have been adequate in the Ninth Ward; far more expensive elevation and retrofitting would likely be required along Casino Row in Biloxi. Many of the few homes rebuilt in the Ninth Ward were elevated. Biloxi responded with far more generous building codes, allowing casinos to locate inland, and not requiring them to be floating on barges in the Gulf of Mexico or on the bays just inside the area's barrier islands.

Insurance

Wind insurance is generally included in a homeowner's insurance policy. Because insured hazards include also fire, theft and liability, the contribution of each part of the homeowner's policy to the overall premium is unclear. In Wilmington, however, standard homeowner's policies no longer provide wind damage coverage. Property owners typically separately purchase stand-alone wind insurance from the North Carolina Joint Underwriters Association (NCJUA). NCJUA wind policies are available with deductible levels of \$250, \$500, \$1,000, and \$2,500. Premiums are decreasing in wind deductibles. Assuming a continuous relationship

between wind premiums and wind deductibles, we parameterize the following baseline insurance relationship with NCJUA data:

$$\pi^w = e^{[6.17109 - .00869(\delta^w/100)]}$$

This relationship is constant in real terms over the property owner's time horizon. We assume that claims filed by the property owner do not lead to higher future premiums and that owners derive no insurance premium reduction from retrofit or mitigation activity.

Homeowner's insurance does not cover flood damage. Though a few judicial outcomes in areas impacted by Katrina suggested homeowners could claim flood damages against their homeowner's policies, those outcomes were the exception: homeowners at flood risk must buy flood insurance to protect against flood losses.

The federal government offers flood insurance to communities participating in the National Flood Insurance Program (NFIP). The property in this study is located in a participating NFIP community. Private insurance agents market NFIP policies featuring separate deductibles for structure and contents, each ranging from \$500 to \$5,000. Premiums are decreasing in both deductibles. Premiums depend also on the elevation of the structure relative to the NFIP base flood elevation (BFE). The structure is located within a Special Flood Hazard Area as identified by an NFIP Flood Insurance Rate Map (FIRM). It is located in the FIRM flood zone designation A10, with a BFE of 10 feet above mean sea level.

The NFIP identifies several flood hazard zones. Zones A or V are subject to a 100-year flood, a flood event with a 1-percent chance of being equaled or exceeded in any given year. V zones are subject to wave action. Because the structure is located in flood zone A, direct wave action is no threat; properties directly along the Gulf Coast during Katrina – as with the casinos in Biloxi – were in flood zone V. The structure we consider is elevated two feet above BFE; hence, NFIP flood insurance is available.

A new structure in either zone A or V must be elevated to the BFE to qualify for NFIP insurance. Although an owner gains access to NFIP insurance by elevating a structure to the BFE, new construction is typically elevated two feet above BFE. NFIP premiums decrease rapidly with the first two feet of elevation above BFE, but only negligibly thereafter.

Homeowners purchase flood insurance policies with equal structure and contents deductibles. Assuming a continuous relationship between flood premiums and flood structure and contents deductibles, we parameterize the following “baseline” flood insurance relationship with NFIP data:

$$\pi^f = e^{[5.93185 - .00287(\delta^f/100)],}$$

where δ_s^f is the structure-only deductible, δ_c^f is the contents-only deductible, and $\delta^f = \delta_s^f + \delta_c^f$. This relationship is constant in real terms over the property owner's time horizon.

Simulation and Results

We conduct simulations of the property owner's cost-effective insurance and defensive measure choices under sustained and “gust” wind speed probability scenarios (Table 2). Exploring also implications of El Nino--La Nina cycles or global climatic change, Table 2 provides dramatically higher probabilities for a hypothetical “Hurricane Alley” scenario. As the cost-minimization problem is not globally differentiable and convex, numerical solution

techniques are necessary. We employ grid search techniques and iterated use of the numerical optimization feature of Microsoft Excel to identify global model solutions.

Simulation 1: Observed Maximum Sustained Wind Speed Simulation - Baseline Insurance

Simulation 1 results are reported in Table 4, top panel, column two. Given hurricane probabilities based on observed strike frequencies, the expected cost-minimizing allocation includes no structural improvements beyond existing building code. The owner chooses a wind policy with an extremely high deductible (\$16,403) and low premium (\$115), opting to forego flood insurance. These results are driven by the very low strike probabilities of hurricane categories 3-5. The present value of (zero) structural expenditures, premiums, and expected uncovered losses over the 30-year horizon is \$3,469. Assuming an efficient real estate market and awareness by potential home-buyers of these expected hurricane costs, the current value of the home (\$140,000) reflects devaluation by this amount. In other words, absent expected hurricanes, the value of the home is \$143,469.

Simulation 2: Observed Maximum Gust Wind Speed Probabilities - Baseline Insurance

There is a continuing debate among building code officials about whether sustained winds or wind gusts are the best determinants of wind damages. Given that, with this second simulation, maximum wind gusts from the history of tropical storms passing within 100 miles of the study location – Wilmington and the Cape Fear Region – are employed. Results are presented in Table 4, top panel, column three. The owner now purchases much more flood insurance, reducing his flood deductible to \$2,709 and increasing his annual premium to \$349. Again, the cost-minimizing owner purchases no structural defenses. Although his flood insurance deductible is now lower, the owner's expected property costs increase to \$8,126, reflecting increased insurance premiums and more frequent hurricane damage.

Simulation 3: "Hurricane Alley" Wind Speed Probabilities - Baseline Insurance

Simulation 3 examines much higher, hypothetical, "Hurricane Alley" strike probabilities, presented in Table 2, column five. Results are presented in Table 4, top panel, column four. Structural defenses are still not cost-effective. However, the owner now chooses the lowest available deductibles (here, \$0 deductibles). Given the dramatic increase in strike probabilities, the present value of expected costs increases to \$10,616. Though insurance premium payments are high, hurricane damage costs are now very low, as the owner has purchased minimum-deductible insurance.

Simulations 4-6: Doubled Insurance Premiums

Wind insurance premiums offered by private insurance companies are higher, and rising in hurricane-prone areas. Although the NFIP currently offers low-premium (i.e., subsidized) flood insurance, flood insurance premiums could increase from two to five-fold, according to insurance industry sources, if large future claims force the agency to adjust rates. Given that, in simulations 4-6 (Table 4, middle panel), we consider doubled wind and flood insurance premiums (or equivalent reductions in insurance subsidies). The owner accepts higher deductibles under the observed sustained winds, and observed gust probabilities. However, he is willing to pay enormous premiums for zero wind and flood deductibles under "Hurricane Alley." Even under doubled insurance premiums, structural defenses are not cost-effective relative to insurance.

Simulations 7-9: No Insurance Availability

In contrast to the results of simulations 1-6, situations exist where the purchase of additional structural improvements is cost-effective. In simulations 7-9, neither wind nor flood insurance is available, due perhaps to policy cancellation. Without the option of NCJUA insurance, results presented in Table 4, bottom panel, indicate that the owner purchases *wind* structural defenses under *all* wind speed probability scenarios. However, as flood defenses provide increasing marginal benefits, flood defense purchases exhibit "all-or-nothing behavior." No flood defenses are purchased unless the owner faces extreme Hurricane Alley strike probabilities, under which he makes extremely large flood defense expenditures. With no insurance available under Hurricane Alley strike probabilities, the expected present value of hurricane damages and structural improvement costs (\$345,923) exceeds the initial value of the structure and contents (\$238,000). Even with purchased structural defenses, the owner expects to rebuild the structure and replace the contents several times over the 30-year time horizon. To retain this coastal property, the owner must derive consumer surplus from the structure and contents beyond expected rebuilding costs (\$345,923).

Summary and Conclusion

Hurricane strikes cause tremendous property damage along the Atlantic and Gulf coasts of the United States. Increasing coastal development amplifies potential damage. In this paper, we model the hurricane damage mitigation decisions of risk-neutral property owners. These decisions influence the magnitude of aggregate hurricane damages, insurance industry liability and profitability, demand for defensive structural improvements, and the effectiveness of government disaster mitigation programs.

Hurricane damage mitigation is location-specific. We determine location-specific hurricane strike probabilities for a representative property and find that they are quite low relative to coast-wide strike probabilities reported by the media. If the homeowner overlooks the location-specific nature of strike probabilities and relies on higher, coast-wide strike probabilities, higher insurance premiums and lower deductibles are chosen, resulting in higher expected costs.

We develop methodologies to identify hurricane wind damage-reduction and flood damage-reduction functions. Marginal wind damage-reduction diminishes with additional wind defense expenditures, while marginal flood damage-reduction increases with additional expenditures. The implication of increasing returns in flood damage reduction is "all-or-nothing" behavior in flood defense expenditures.

Under location-specific hurricane strike probabilities and baseline insurance schedules, simulation results indicate that the cost-minimizing owner purchases high deductible wind insurance. For the representative property, no structural improvements (beyond 110-mph building code requirements) are cost effective. As the probabilities of stronger hurricanes increase, the owner chooses lower wind deductibles and begins to purchase flood insurance. The sum of discounted insurance premiums and uncovered hurricane losses indicates the impact of the hurricane threat on the capitalized value of the representative property given cost-effective mitigation by the homeowner.

State wind insurance pools provide coverage in high-risk areas where the market does not voluntarily provide coverage. Results for the representative property indicate that the existence of wind pool insurance, even at double current premium levels, reduces purchases of structural

wind defenses under all strike probability scenarios. Hence, these pool programs distort homeowner behavior away from structural improvements.

At the federal government level, FEMA's National Flood Insurance Program (NFIP) subsidizes flood insurance in coastal areas. Absent the subsidy, private sector remarks suggest that flood insurance premiums might be two to five times higher. Under current strike probabilities, the existence of the subsidy induces the owner to purchase more flood insurance, increasing NFIP exposure. Furthermore, the subsidy may distort owner incentives to fortify homes and avoid flood-prone areas. It is little wonder that the NFIP has suffered enormous claims following recent hurricane strikes.

Under current subsidized flood insurance rates, insurance expenditures provide higher expected returns to the homeowner, even under much higher hurricane strike probabilities. Under current probabilities, a *fifteen-fold* increase in insurance rates is necessary to make structural flood defenses cost-effective. Only if insurance were *unavailable*, and then only under severe strike probabilities, does the cost-minimizing property owner purchase flood defenses beyond building code guidelines.

The results presented here are representative for a hurricane prone area; they are not representative for all property types and locations. Regional differences in strike probabilities, topography, structural design, and building codes imply differences in cost-effective combinations of insurance and structural defenses across regions. Nonetheless, our findings provide rich fodder for the recently amplified discussions concerning the mitigation of catastrophic losses.

Table 1 – The Saffir- Simpson Scale of Category 1 – 5 Hurricanes

Storm Intensity	Saffir-Simpson Category	Sustained Wind Speed Range (mph)	Midpoint of Wind Speed Range (mph)	SLOSH Storm Surge (ft above MSL)	Flood Depth* (ft above GE)
i = 0	Trop. Storm	39-73	56.0	1.9	0.0
i = 1	Cat 1	74-95	84.5	5.0	0.0
i = 2	Cat 2	96-110	103.0	7.6	0.0
i = 3	Cat 3	111-130	120.5	10.6	1.6
i = 4	Cat 4	131-155	143.0	15.2	6.2
i = 5	Cat 5	156+	175.0	22.9	13.9

*Assumes Ground Elevation (GE) is 9 ft above Mean Sea Level (MSL)

Table 2 -- Alternative Wind Speed Probabilities for Case Study Location (Wilmington, N.C.)

Storm Intensity	Wind Speed Ranges	Historical Annual Probabilities of Max. Sustained Winds*	Historical Annual Probabilities of Max. Gust Winds	Hypothetical Annual Probabilities ("Hurricane Alley" Scenario)
i = 0	39-73mph	0.17	0.30	0.60
i = 1	74-95mph	0.04	0.03	0.30
i = 2	96-110mph	0.00	0.03	0.30
i = 3	111-130mph	0.01	0.02	0.20
i = 4	131-154mph	0.00	0.01	0.10
i = 5	155+mph	0.00	0.00	0.10

*When winds are measured as maximum sustained winds, Wind Speed Categories 0-5 correspond to Saffir-Simpson categories "Tropical Storm, Hurricane Category 1, Hurricane Category 2, etc.," respectively.

Table 3 -- Least-Cost Wind Defensive Measure Combinations and Conditional Wind Damage For Case Study Property

Structural Feature(s) Protected*	Cost (\$'s per ft ² of Structure) of Least-Cost Activities Necessary to Protect Structural Feature Combinations Against Hurricane Category Midpoint Windspeeds (Table 1)			Conditional Wind Damage to Unprotected Structural Features, Structure, and Contents	
	Hurricane Cat. 3	Hurricane Cat. 4	Hurricane Cat. 5	(\$'s)	(\$'s per ft ²)
None	0.0000	0.0000	NA	238000	110.6977
R	1.9953	2.7628	NA	103552	48.1637
W	0.1520	0.6523	NA	238000	110.6977
D	0.0580	0.2491	NA	238000	110.6977
G	0.5636	0.6032	NA	238000	110.6977
RW	2.1473	3.4151	NA	41636	19.3653
RD	2.0533	3.0119	NA	102409	47.6321
RG	2.5589	3.3660	NA	97972	45.5684
WD	0.2100	0.9014	NA	238000	110.6977
WG	0.7156	1.2556	NA	238000	110.6977
DG	0.6217	0.8523	NA	238000	110.6977
RWD	2.2053	3.6642	NA	5580	2.5953
RWG	2.7109	4.0184	NA	36056	16.7700
RDG	2.6170	3.6151	NA	96829	45.0367
GDW	0.7736	1.5046	NA	238000	110.6977
RWDG	2.7689	4.2674	NA	0	0.0000

* R indicates roof, W indicates all windows, D indicates all doors, G indicates garage door.
 NA indicates that no conventional wind defensive measures could prevent structural collapse at given windspeed.

Table 4 – Simulation Results

Simulations 1-3: Cost-Minimizing Variable Values Under Baseline Conditions			
Hurricane Strike Probability Scenario			
Variable	"Sustained Winds"	"Max. Gusts"	"Hurricane Alley"
Wind Defense Expenditures (\$/ft ²), c^w	0	0	0
Flood Defense Expenditures (\$/ft ²), c^f	0	0	0
Wind Insurance Deductible (\$/yr.), δw	16403	3761	0
Flood Insurance Deductible (\$/yr.), δf	238000	2709	0
Wind Insurance Premium (\$/yr.), πw	115	345	478
Flood Insurance Premium (\$/yr.), πf	0	349	376
Present Value of Defense Expenditures, Premiums and Uncovered Damages (\$), C	3469	10348	10616

Simulations 4-6: Cost-Minimizing Variable Values Under Doubled Insurance Premiums			
Hurricane Strike Probability Scenario			
Variable	"Sustained Winds"	"Max. Gusts"	"Hurricane Alley"
Wind Defense Expenditures (\$/ft ²), c^w	0	0	0
Flood Defense Expenditures (\$/ft ²), c^f	0	0	0
Wind Insurance Deductible (\$/yr.), δw	24379	11737	0
Flood Insurance Deductible (\$/yr.), δf	238000	26878	0
Wind Insurance Premium (\$/yr.), πw	115	345	957
Flood Insurance Premium (\$/yr.), πf	0	349	754
Present Value of Defense Expenditures, Premiums and Uncovered Damages (\$), C	4464	16316	21232

Simulations 7-9: Cost-Minimizing Variable Values With No Insurance Available			
Hurricane Strike Probability Scenario			
Variable	"Sustained Winds"	"Max. Gusts"	"Hurricane Alley"
Wind Defense Expenditures (\$/ft ²), c^w	2.31	3.63	5.02
Flood Defense Expenditures (\$/ft ²), c^f	0	0	18.51
Wind Insurance Deductible (\$/yr.), δw	238000	238000	238000
Flood Insurance Deductible (\$/yr.), δf	238000	238000	238000
Wind Insurance Premium (\$/yr.), πw	0	0	0
Flood Insurance Premium (\$/yr.), πf	0	0	0
Present Value of Defense Expenditures, Premiums and Uncovered Damages (\$), C	5155	17413	345923

Note: A deductible level of \$238,000 is equivalent to the full value of the structure and contents; choosing this deductible level is equivalent to choosing zero insurance.

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