# *Reducing Expected Hurricane Damages: A Microeconomic Perspective*

Robert T. Burrus, Jr., Assistant Professor of Economics, Burrusr@uncwil.edu

Christopher F. Dumas, Assistant Professor of Economics, Dumasc@uncwil.edu

J. Edward Graham, Jr., Assistant Professor of Finance, Edgraham@uncwil.edu

Department of Economics and Finance
University of North Carolina at Wilmington
601 South College Rd.
Wilmington, NC 28403
Phone: (910) 962-3510
FAX: (910) 962-7464

June 14, 2002

**Acknowledgements:** All authors contributed equally to this study. This research was funded in part by grants from the Center for Applied Real Estate Education and Research, University of South Carolina, and the Charles L. Cahill Faculty Research and Development Award program, University of North Carolina at Wilmington. The authors thank builder David Clark for construction cost estimates for the Wilmington, N.C., region. We also thank Anneke Archer, Spence Temple and Catherine Wosczyna for outstanding student research assistance.

# *Reducing Expected Hurricane Damages: A Microeconomic Perspective*


**Abstract**

Homeowners mitigate potential hurricane losses by purchasing insurance and structural improvements. We construct and parameterize a model of optimal homeowner choice for a representative property in Wilmington, N.C., a hurricane prone region. Given existing insurance policies, National Weather Service location-specific hurricane strike probabilities, structural improvement costs, and an existing building code, our model simulations show that insurance is a substitute for structural mitigation. These simulation results hold under higher storm strike probabilities, higher insurance premiums, risk-neutrality, and risk-aversion. The findings are consistent with recent hedonic pricing model results for coastal island properties that find a substitute relationship between insurance and mitigation. Our results contrast with those based on proprietary insurance industry models that find insurance and mitigation to be complements.


## Introduction

Although advances in hurricane surveillance and early warning technology have reduced the threat of hurricanes to human life (NRC 1989), tropical weather systems continue to cause billions of dollars in property damage in the United States.[1] For example, although no hurricane in the last 30 years has caused more than 30 deaths in the U.S. (Hebert, Jarrell and Mayfield 1997, Pielke and Pielke 1997), it is estimated that recent Hurricanes Hugo, Andrew, and Floyd caused approximately \$7.91 billion, \$28.62 billion, and \$5.45 billion in property damage, respectively, to South Carolina, South Florida, and North Carolina (Hebert, Jarrell and Mayfield 1997, N.C. Office of the Governor 1999). Pielke and Landsea (1999) find that average annual

US hurricane damage for the 73 years ending in 1997 is $5.2 billion. From 1960-1990, hurricane damages increased even though hurricane strike frequencies decreased (Hebert, Jarrell and Mayfield 1997, Landsea et al. 1996). Peilke and Landsea (1998) conclude that increasing coastal development will likely exacerbate such damage in the future. Thus, hurricanes continue to pose a tremendous threat to property along the east and gulf coasts of the United States.

The economics of natural disasters and appropriate government policy responses have been topics of investigation for over thirty years (Dacy and Kunreuther 1969). However, recent, large hurricane losses have accelerated interest in determining cost-effective means of mitigating hurricane damage and spreading hurricane damage risk through insurance, reinsurance and other financial instruments (Kleindorfer and Kunreuther 1999a).

Determining the best mix of coastal development location, structural mitigation (through retrofit and building code modifications), and wind and flood insurance purchases to achieve hurricane risk management goals is an important issue. The issue is complicated by the fact that hurricane strikes are low-probability, high-consequence events (Kunreuther 1978). Kunreuther (1976, 1996) and Camerer and Kunreuther (1989) argue that individuals at risk for such events may underestimate the probability of occurrences (the "it will not happen to me" response) and may exhibit myopia (inappropriately high discount rates) when evaluating the benefits and costs of damage mitigating activities, and may assign zero probability to events that occur with probability below some threshold. These behaviors may explain the observed tendency of many individuals in disaster-prone areas to forego disaster insurance and protective mitigation activities (Kunreuther et al. 1978, Kusler and Larson, 1993, Palm et al. 1995).

Insurance companies, as well as state insurance boards, to explore incentives to property owners to install better protection for their property and demand construction techniques that minimize damage from storms. FEMA has recently initiated programs to encourage voluntary mitigation by individuals as well as communities. Home builders are concerned about buyer response to the increased cost of fortified homes. Many mitigation features are not visible once construction is complete. Within the insurance industry, there has been interest in creating premium incentives for homes that meet certain engineering requirements. For homes that meet these requirements, a "seal of approval" could be issued by the insurance industry (IIPLR 1995).

Economists have investigated the economic

A fourth and recent research track considers the economic implications of structural damage mitigation. Based on results from proprietary catastrophe models, Kleindorfer and Kunreuther (KK) (1999b) find for two case study regions (Oakland, CA, and Miami/Dade County, FL) that an increase in the percentage of property owners required to adopt a well-defined structural mitigation measure decreases expected insurance company exposure in the event of a natural disaster. As a result, homeowner mitigation requirements encourage insurers to offer coverage to a larger percentage of the homeowners in each region.[2] This apparent complementarity between mitigation and insurance coverage results in the average homeowner being “slightly better off with mitigation.” Despite the apparent gains to homeowners suggested by KK’s model results, KK acknowledge that many homeowners do not engage in structural mitigation. KK attribute homeowners’ lack of interest in mitigation to homeowner myopia and the failure of insurance companies to offer lower premiums or deductibles in response to homeowner adoption of mitigation measures.[3] Based on their findings, KK recommend: (1)

encouraging mitigation through insurance premium reductions and lower deductibles tied to mitigation activities, and/or (2) forcing homeowner mitigation through the adoption of more stringent building codes.

In a classic paper, Ehrlich and Becker (1972) investigate the interaction of market insurance, self-insurance and self-protection (i.e., mitigation) activities from a theoretical perspective. In contrast to KK, Ehrlich and Becker find that insurance and mitigation can be either complements or substitutes, depending on the existence and strength of a feedback relationship between market insurance premiums and self-protection activities.

More recently, Simmons, Kruse and Smith (2002) construct a hedonic pricing model to estimate the impact of mitigation on the resale prices of residential property on a Gulf Coast barrier island. Two measures of mitigation activity are considered, storm blinds and a structural integrity index based on wind engineering analysis. Each measure of mitigation has a statistically influence on home resale prices. The authors conclude that individuals place positive value on mitigation.

We construct a microeconomic model of a rational coastal property owner who protects his home against hurricane losses associated with high winds and storm surge waters by choosing a combination of insurance and mitigation activities. We focus on developing an understanding of the factors influencing individual homeowner choices rather than aggregate results at the regional level. The owner's decision regarding how best to prevent losses is complicated by the availability of multiple combinations of insurance deductibles and premiums and multiple mitigation measures.[4] Furthermore, the owner makes these decisions under the assumption that his home is built to *existing building code guidelines*.[5] While the models used by KK are proprietary, our assumptions and model development are transparent; we gather data on actual structural improvement costs, insurance costs, and location-specific hurricane strike probabilities based on the historical record. We consider a typical homeowner in Wilmington, N.C., the site of several recent hurricane landfalls (Bertha and Fran in 1996, Bonnie in 1998, and Dennis and Floyd in 1999). Our model results indicate that mitigation efforts beyond the current building code are not cost-effective for the typical homeowner in Wilmington, N.C.

The next section of the paper develops a model of homeowner behavior under the threat of hurricane damage. The third section parameterizes the model for a case study structure in Wilmington, N.C. In the fourth section, optimal combinations of structural improvements and insurance are determined over alternative hurricane strike probabilities and insurance schedules for a risk-neutral and then a risk-averse property owner. A summary and a brief policy discussion conclude the paper.

## Model

Tropical weather severity is indexed by discrete random variable, $i = 0 \ldots 5$ (see Table 1). Tropical storms are denoted $i = 0$. Intensities $i = 1 \ldots 5$ denote hurricane categories 1 through 5 on the Saffir-Simpson scale.[6] 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.[7] We rule out the possibility of multiple tropical weather strikes per year.[8] Consequently, $P_{it} = P_{it+1} = P_i < 1$.

Consider a residential structure 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.[9] Flood damages are caused by the destruction of foundations, walls and internal contents. Building code guidelines require that structural features withstand specified wind speeds with no damage.[10] In addition, the structure is elevated to a height above sea level sufficient to withstand certain flood stages with no damage.

The owner's time horizon is t = 0 . . . 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 (per square foot of structure) to structure and contents in any year are denoted $D_i^w(c^w)$; similarly, flood damages per square foot of structure are denoted $D_i^f(c^f)$. Both wind and flood damages are non-increasing in expenditures on defensive measures, $\frac{?D_i^w(c^w)}{?c^w} ? 0$ and $\frac{?D_i^f(c^f)}{?c^f} ? 0$.

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.[11] Consequently, residual wind damages per square foot of structure in any year are expressed as

$$\min ? D_i^w(c^w), \frac{h_0 ? c_0}{s} ? D_i^f(c^f) ?.$$

Wind and flood insurance policies 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 {$?^w$, $?^w$}, where $?^w$ is the annual insurance premium and

$?^{w}$ is the deductible. A flood insurance combination is a set {$?^{f}$, $?^{f}$}, where $?^{f}$ is the annual insurance premium and $?^{f}$ is the deductible. The owner is responsible only for wind and flood damages up to $?^{w}$ and $?^{f}$, respectively. Thus, the maximum amount of uncovered wind damage for a category i storm in any year is $L_i^w \; ? \; \min ? ?^{w}, s \; ?\min ? D_i^w(c^w), \frac{h_0 \; ? \; c_0}{s} \; ? \; D_i^f(c^f) ?? .$ The maximum amount of uncovered flood damages for a category i storm in any year is $L_i^f \; ? \; \min ? ?^{f}, s \; ? D_i^f(c^f) ? .$ If no insurance is purchased, the deductible is the total value of the structure and contents.

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

We consider the optimal choices of both risk-neutral and risk-averse homeowners regarding insurance and mitigation. A risk neutral owner chooses insurance deductibles and structural defensive measures beyond building code guidelines[12] to minimize the discounted expected costs associated with tropical weather over time horizon, T. Expressing mitigation expenditures in annuitized form, the owner's cost-minimization problem is the same in every year and is expressed as:

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

where C is annual, hurricane-associated cost, and r denotes the annual, real rate of interest.

A risk-averse owner chooses insurance deductibles and structural defensive measures beyond building code guidelines[13] to maximize expected utility. Assuming that preferences and hurricane strike probabilities are stable over time, expressing mitigation expenditures in annuitized form, denoting other household wealth by $w_0$, and noticing that none of the arguments of the utility function depend on time, the owner's expected utility maximization problem is the same in every year and can be expressed as:

$$(2) \qquad \max_{c^w, c^f, ?^w, ?^f} EU = \sum_{i=0}^{5} P_i \cdot U(w_0 + h_0 + c_0 - C),$$

where U is the owner's von Neumann-Morgenstern utility function.

## Parameterization

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.[14] 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. The structure is located within five miles of the ocean, landward of the intracoastal waterway.[15] 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, ? $^w$?? $^w$, ? $^w$? and ? $^f$(? $^f$, ? $^f$) for the representative structure.

*Hurricane Wind Speed Probability Distribution*

We consider all tropical storms and hurricanes passing within 100 nautical miles of Wilmington from 1900 to 1999, regardless of landfall.[16] 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 (see Appendix Table A1).[17] Many of the wind speeds recorded are significantly lower than the wind speeds reported by the media and used in prior studies.[18]

The annual hurricane strike probabilities, equal to the observed strike frequencies, are reported in Table 2.[19] 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, 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.[20] For comparison, probabilities provided by the National Weather Service's HURISK hurricane simulation model are reported also in Table 2 (Neumann and McAdie 1991, Neumann 2000). Compared to observed strike probabilities, the HURISK model predicts lower strike probabilities for category 0-3 storms but non-zero strike probabilities for category 4 and 5 storms.

*Wind Damages and Structural Defenses*

The representative structure meets a 110-mph building code.[21] 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.[22] 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.

Wind defenses mitigate these expected damages depending on the structural features protected.[23] If the roof is not protected from category 3 or stronger winds, the roof is lost, and damages are equal to the value of the entire structure and contents, or $238,000 (Rogers 1985, Rogers and Sparks 1990, Rogers 1994). Given roof protection, 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).[24] 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.[25] 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. All combinations of window, door and garage door protection are considered.

For each structural feature considered, we identify a range of damage-mitigation activities from Federal Emergency Management Agency (FEMA) reports on hurricane damage reduction.[26] For each activity, we gather wind speed ratings and implementation costs (see Appendix Tables A3a-A3d). We assume that damage-reducing activities perform as rated.[27]

The property owner chooses the least-cost defensive activities to achieve the desired level of protection (wind speed rating) for each structural feature.[28] 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.[29] Table 3 gives also hurricane damages for each combination of protected structural features using the wind damage schedule above.[30]

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

$D_i^w = 0, \qquad i = 0 \ldots 2,$

$D_3^w = \text{MIN}[110.69, 2.8289\text{E}+10 * c^w \wedge (-29.229)],$

$D_4^w = \text{MIN}[110.69, 1.7589\text{E}+6 * c^w \wedge (-10.338)]$, and

$D_5^w = 110.69$ ,

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, because no conventional roof defense can withstand category 5 winds.

*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.[31] 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,

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

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 (USCE 1993).[32] The representative structure rests on a 3-foot crawl space at a ground elevation of 9 feet above MSL.[33] 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.[34]

Flooding typically causes a greater percentage loss to a structure's contents than to the structure. Based on FEMA claims data (USCE 1993), 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.[35] Flood defenses include elevation on closed foundation or open foundation (pilings), levee construction, floodwall construction, elevation-on-fill, and off-site relocation (USCE 1993, 1997, 1998; FEMA 1998e).[36] We estimate activity implementation costs sufficient to achieve various degrees of flood protection.[37] The 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

$$D_i^f = 0, \qquad i = 0 \ldots 3,$$

$$D_4^f = \mathrm{MAX}[0, 33.10939 + 0.002572 * (1 - \exp(0.5115 * c^f))], \text{ and}$$

$$D_5^f = \mathrm{MAX}[0, 59.0546 + 0.15183 * (1 - \exp(0.235 * c^f))],$$

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.[38] For weather intensities i = 0 to 3, our property experiences no flood damage. For each weather intensity i = 4 to 5, flood damage is decreasing and concave in flood defense expenditures beyond a critical threshold. For a given storm surge level, flood damage is concave in flood damage expenditures, because a small elevation protects only the *upper* portion of a house, whereas elevating further protects the *lower* portion, where most contents value (i.e., most appliances, furniture, clothes, etc.) is located.

*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, many policies no longer provide wind damage coverage. Property owners 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 decrease in wind deductibles but not with mitigation activities. Assuming a continuous relationship between wind premiums and wind deductibles, we parameterize the following "baseline" insurance relationship with NCJUA data:

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

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 activity.

Homeowner's insurance does *not* cover flood damage. The federal government offers flood insurance to communities participating in the National Flood Insurance Program (NFIP) (FEMA 1997a). The property 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). The structure is located in FIRM flood zone designation A10, with a BFE of 10 feet above mean sea level.[39] The structure is elevated two feet above BFE; hence, NFIP flood insurance is available.[40]

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:

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

where $?^{f}_{s}$ is the structure-only deductible, $?^{f}_{c}$ is the contents-only deductible, and $?^{f} = ?^{f}_{s} + ?^{f}_{c}$. This relationship is constant in real terms over the property owner's time horizon.

## Simulation and Results

We first consider the case of a risk-neutral (RN) property owner where the RN owner's problem is given in (1). We then compare these results with those of a risk-averse (RA) property owner where the RA owner's problem is given in (2).

We investigate RN homeowner choices under two alternative wind speed measurement methodologies: sustained wind speed and "maximum gust" wind speed (Table 2). Exploring the implications of higher storm frequencies due to El Nino--La Nina cycles or global climatic change, Table 2 provides dramatically higher strike probabilities for a hypothetical "Hurricane Alley" scenario. As the optimization problems are 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 97 to identify global model solutions.

*RN Simulation 1: Observed Maximum Sustained Wind Speeds - 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 and the fact that no mitigation activity prevents roof destruction in the event of a category 5 hurricane—insurance is the only defense against a category 5 storm. 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.

*RN Simulation 2: HURISK Sustained Probabilities - Baseline Insurance*

Simulation 2 results (Table 4, top panel, column three) are based upon NWS HURISK simulation model probabilities rather than observed strike frequencies. Under HURISK probabilities, the expected cost-minimizing allocation includes again no structural defenses. The owner chooses a higher wind insurance deductible ($19,196) with a lower premium ($90). However, with non-zero strike probabilities for category 4 and 5 storms, the owner is exposed now to a slight risk of storm surge flooding. As a result, the owner purchases high deductible ($49,166), low premium ($92) flood insurance. On balance, under HURISK probabilities the present value of expected property costs (i.e., insurance premiums and uninsured damages) increases to $5,737.

*RN Simulation 3: Observed Maximum Gust Probabilities - Baseline Insurance*

Building code officials debate whether sustained winds or wind gusts are the best determinants of wind damages (Avery 1999). In this third simulation, maximum wind gusts from Table A2 determine wind speed categories. Results are presented in Table 4, top panel, column four. 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.

*RN Simulation 4: "Hurricane Alley" Probabilities - Baseline Insurance*

Simulation 4 examines much higher, hypothetical, "Hurricane Alley" strike probabilities, presented in Table 2, column six. Results are presented in Table 4, top panel, column five. 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.

*RN Simulations 5-8: Doubled Insurance Premiums*

Wind insurance premiums offered by private insurance companies are rising in hurricane-prone areas (Wilmington Morning Star 1999). Although the NFIP currently offers low-premium (i.e., subsidized) flood insurance, flood insurance premiums could increase from two to five-fold, if large future claims force the agency to adjust rates (Letsinger 2000). In simulations 5-8 (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, HURISK 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.

*RN Simulations 9-12: No Insurance Availability*

In contrast to the results of simulations 1-8, situations exist where the purchase of additional structural improvements is cost-effective. In simulations 9-12, 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. These purchases are roughly equivalent to least cost RWD defenses up to a category 3 hurricane for observed sustained winds, RWD defenses up to a category 4 hurricane for observed gusts, somewhere between these expenditure combinations for the HURISK scenario, and RWDG defenses up to a category 4 hurricane for the hurricane alley scenario. With no insurance available, the homeowner is definitely better off mitigating. If the homeowner chooses not to mitigate when no insurance available, the present value of all costs to the homeowner is $24,775, significantly higher than the $10,143 with mitigation.

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, hypothetical "Hurricane Alley" strike probabilities, under which he makes extremely large flood defense expenditures, roughly equivalent to raising the home on pilings. With no insurance available and 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, expected repair costs over the 30-year time horizon exceed initial home value. To purchase/retain a coastal property having such a large repair cost liability, the owner must derive at least $345,923 in consumer surplus from the structure and contents.

*RN Simulations*

Policymakers point out that asymmetric information, externalities, and other market failures may make mitigation socially desirable even if it is not in a particular homeowner's economics interest to mitigate [cite Paying the Price and The Hidden Cost of Coastal Hazards]. If policymakers decide to require additional mitigation, through either enforcing more stringent building codes or retrofit ordinances, the model can be used to calculate the cost to the homeowner. If homeowners are required to increase their roof protection to withstand a category 3 hurricane (e.g., as considered by Kunreuther _______) under HURISK strike probabilities, at a minimum cost of $2.05 per square foot of structure, the present value of homeowner costs increases to $10,303. In this case, homeowners by wind insurance with a $25,000 deductible and no flood insurance. It is interesting that increasing roof protection to withstand a category 4 hurricane under the same strike probabilities results in the same insurance purchases and a present value of homeowner costs of $10,298. That is, the marginal cost of increasing roof protection from category 3 to category 4 is almost exactly offset by a decline in expected damage costs. Furthermore, the present value of homeowner costs in these last two scenarios is approximately the same as that under the no insurance available scenario. An implication of this observation is that homeowners would be indifferent between (A) a situation in which they do not mitigate and insurance companies stop writing insurance policies and (B) a situation in which homeowners are forced to mitigate in one of the ways described in this section and baseline insurance is made available. In other words, if homeowners are threatened with the loss of insurance coverage, they would be willing to mitigate to retain access to coverage.

*RA Simulations*

For the RA owner, we assume a negative exponential utility function consistent with constant absolute risk aversion (CARA). Alternative degrees of risk aversion are characterized by the *risk premium*, defined as the amount of money the homeowner would pay to ensure the average (mean) level of hurricane damage with certainty, rather than face the risk of more (or less) severe damage. Table 5 provides results under baseline conditions and HURISK hurricane probabilities for seven alternative levels of risk aversion consistent with *annual* risk premiums of \$10, \$100, \$500, \$1000, \$2,500, \$5,000 and \$10,000. A low risk premium indicates little aversion to risk, while a high-risk premium indicates substantial risk aversion. At low levels of risk aversion, the owner spends nothing on structural mitigation and purchases both wind and flood insurance with high deductibles. At higher levels of risk aversion, indicated by higher risk premiums, the owner chooses lower insurance deductibles but continues to forego structural defenses.

## 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 decision of a representative property owner. This decision-making process influences the magnitude of aggregate hurricane damages, insurance industry liability and profitability, demand for defensive structural improvements, and the effectiveness of government disaster mitigation programs.

Under location-specific hurricane strike probabilities and baseline insurance schedules, simulation results indicate that the representative cost-minimizing owner purchases high deductible wind insurance and no flood insurance. For the representative property, no structural improvements (beyond building code requirements) are cost-effective unless insurance is completely unavailable. 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. Results for the risk-averse owner are similar.

Based on our model, the known lack of mitigation purchases is entirely consistent with the assumption of rationality. Three aspects of the owner's situation drive model results concerning low mitigation expenditures. First, the owner lives in a specific location, and location-specific tropical weather strike probabilities are very low based on the historical record. Second, the 110mph building code present in the study region protects the representative structure from damage in a tropical storm, category 1 or category 2 hurricanes. As a result, mitigation provides no benefit for these storm categories. Third, no conventional mitigation measures prevent roof loss (and complete house destruction) in a category 5 hurricane. In sum, mitigation provides benefits against category 3 and category 4 storms only. These storms arrive much less frequently than lower category storms and cause less damage than a catastrophic category 5 storm. Against this limited range of storm categories, mitigation is simply not cost effective relative to insurance except in the trivial case where insurance is completely unavailable.

Model results suggest that insurance premium subsidies reduce expenditures on structural defenses. State wind insurance pools provide subsidized coverage in high-risk areas where the private market does not voluntarily provide coverage. Results for the representative property indicate that wind pool insurance crowds out wind mitigation expenditures under all strike probability scenarios. This result holds even when the subsidy is reduced sufficiency to double current premium levels. Hence, these pool programs may 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. If this subsidy were not available, private flood insurance premiums would be approximately two to five times higher (Letsinger 2000). Under current strike probabilities, the existence of the subsidy induces the owner to purchase more flood insurance, increasing NFIP exposure. Furthermore, the subsidy may reduce owner incentives to fortify homes and avoid flood-prone areas. It is no wonder that NFIP has suffered enormous claims following recent hurricane strikes (for example, FEMA expects that the total claims for one storm, hurricane Floyd, will reach $460 million). In summary, for an area with relatively strict building codes, cheap insurance may crowd out mitigation purchases.

Instead of reducing the insurance subsidy, FEMA has attempted to create an additional, countervailing government program, Project Impact, to decrease the magnitude of hurricane-related flood claims through the promotion of expenditures on structural improvements beyond building code. Under current, subsidized flood insurance rates, we would not expect the typical homeowner in our study region to be receptive to Project Impact promotions because insurance expenditures provide higher expected returns, even under much higher hurricane strike probabilities. Under current strike probabilities, flood insurance premiums would need to rise *fifteen-fold* to make structural flood defenses cost-effective.

Although 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. Further, we assume that insurance rates are independent of recent weather history and defensive measure purchases. [cite Kunreuther on mitigation contingent premiums] Future work should consider insurance schedules contingent on both recent tropical weather strikes and mitigation activities.

Two final caveats are in order. First, if a property owner suffers intangible (Simmons and Kruse 2000), psychic, or evacuation (Whitehead *et al*. 2001) costs not covered by insurance, then a combination of both mitigation and insurance may be cost effective. However, these uncovered costs would need to be on the order of $______ to make mitigation worthwhile. Second, if mitigation reduces externalities in the form of economic dislocations and other social costs in addition to the costs suffered by the owner (Cohen and Noll 1981, Kunreuther 1998), then mitigation may be cost-effective from *society's* point of view, if not the owner's.

## References


Adams, M. H., 1995. Florida Debates Solutions to Storm Crisis, *National Underwriter*, Chicago. Oct. 16.

Angbazo, L. A. and R. Narayanan ,1996. Catastrophic Shocks in the Property-liability Insurance Industry: Evidence on Regulatory and Contagion Effects, *Journal of Risk and Insurance,* Mt. Vernon, December.

Avery, Thomas. 1999. Structural Engineer, North Carolina Building Code Council. Wilmington, N.C. Personal communication. November 30, 1999.

Calhoun, Charles R., and Laszlo G. Fulop. 1996. *The Hurricanes Are Coming: How to Retrofit and Build Coastal Homes to Better Withstand Hurricane Winds*. Callez Research Alliance. Minneapolis, M.N.

Camerer, Colin, and Howard Kunreuther. 1989. Decision Processes for Low-Probability Events: Policy Implications. *Journal of Policy Analysis and Management*. 8:565-592.

Chichilnisky, G. and G. Heal, 1998. Managing Unknown Risks. *Journal of Portfolio Management*, New York. Summer.

Clark, David. 1999. "Hurricane Damage Research--Construction Cost Estimates." Report by David Clark, North Carolina licensed general contractor and home inspector. Wilmington, N.C.

Cohen, Linda, and Roger Noll. 1981. The economics of building codes to resist seismic structures. *Public Policy* (Winter):1-29.

Cry, G.W. 1965. Tropical Cyclones of the North Atlantic Ocean: Tracks and Frequencies of Hurricanes and Tropical Storms, 1871-1963. U.S. Department of Commerce, U.S. Weather Bureau Technical Paper No. 55. Washington, DC.

Dacy, Douglas, and Howard Kunreuther. *The Economics of Natural Disasters: Implications for Federal Policy*. Free Press. New York. 1969.

FEMA. 1986. Coastal Construction Manual. Federal Emergency Management Agency. FEMA-55. Washington, D.C.

FEMA. 1992. Building Performance: Hurricane Andrew in Florida. Federal Emergency Management Agency - Federal Insurance Administration. FIA-22. Washington, D.C.

FEMA. 1993a. Building Performance: Hurricane Iniki in Hawaii. Federal Emergency Management Agency - Federal Insurance Administration. FIA-23. Washington, D.C.

FEMA. 1993b. Against the Wind--Protecting Your Home From Hurricane Damage. Federal Emergency Management Agency. FEMA-247. Washington, D.C.

FEMA. 1996a. Building to Resist Hurricanes Fact Sheet #5: Connecting the Roof to a Wood Wall. Federal Emergency Management Agency. Washington, D.C.

FEMA. 1996b. Building to Resist Hurricanes Fact Sheet #6: Connecting the Roof to a Masonry Wall. Federal Emergency Management Agency. Washington, D.C.

FEMA. 1996c. Building to Resist Hurricanes Fact Sheet #10: Shutters and Hurricane Panels. Federal Emergency Management Agency. Washington, D.C.

FEMA. 1997a. Answers to Questions About the National Flood Insurance Program. Federal Emergency Management Agency. FEMA-FIA-2. Washington, D.C.

FEMA. 1997b. Building Performance: Hurricane Fran in North Carolina. Federal Emergency Management Agency--Mitigation Directorate. FEMA-290. Washington, D.C.

FEMA. 1998a. Mitigation: Reducing Risk Through Mitigation. Protecting Your Property From Wind--Reinforce or Replace Garage Doors. Federal Emergency Management Agency web site address: http://www.fema.gov/MIT/how2016.htm. August 4, 1998.

FEMA. 1998b. Mitigation: Reducing Risk Through Mitigation. Protecting Your Property From Wind--Install Shutters or Plywood Window Covers. Federal Emergency Management Agency web site address: http://www.fema.gov/MIT/how2017.htm. August 4, 1998.

FEMA. 1998c. Mitigation: Reducing Risk Through Mitigation. Protecting Your Property From Wind--Gable End Roof Framing. Federal Emergency Management Agency web site address: http://www.fema.gov/MIT/how2018.htm. August 4, 1998.

FEMA. 1998d. Mitigation: Reducing Risk Through Mitigation. Protecting Your Property From Wind--Reinforce Double Entry Doors. Federal Emergency Management Agency web site address: http://www.fema.gov/MIT/how2019.htm. August 4, 1998.

FEMA. 1998e. Homeowner's Guide to Retrofitting: Six Ways to Protect Your House From Flooding. Federal Emergency Management Agency. FEMA 312. Washington, D.C.

FEMA. 1998f. Project Impact: Building a Disaster Resistant Community. Program description brochure. Federal Emergency Management Agency. Washington, D.C.

Fronstin, Paul, and Alphonse G. Holtmann. 1994. The Determinants of Residential Property Damage Caused by Hurricane Andrew. *Southern Economic Journal*. 61(2):387-397.

Grace, Martin, Robert Klein, and Paul R. Kleindorfer. 2000. “Supply of Catastrophic Insurance Under Regulatory Constraints.” NBER Working Paper.

Hebert, Paul J., Jerry D. Jarrell and Max Mayfield. 1997. The Deadliest, Costliest and Most Intense United States Hurricanes of this Century (and other frequently requested hurricane facts). NOAA Tech. Memo. NWS TPC-1. National Hurricane Center, Miami, FL.

Hoyt, R. E. and R. D. Williams, 1995. The Effectiveness of Catastrophic Futures as a Hedging Mechanism for Insurers: An Empirical and Regulatory Analysis, *Journal of Insurance*

*Regulation*, Kansas City. Fall.

IBHS. 1998. Is Your Home Protected From Hurricane Disaster--A Homeowner's Guide to Hurricane Retrofit. Institute for Business & Home Safety. Boston, M.A.

Jarvinen, B.R., and M.B. Lawrence. 1985. An evaluation of the SLOSH storm-surge model. *Bulletin of the American Meteorological Society*. 66:1408-1411.

Jarrell, Jerry D., Paul J. Hebert and Max Mayfield. 1992. Hurricane Experience Levels of Coastal County Populations From Texas to Maine. U.S. Department of Commerce. NOAA Technical Memorandum NWS NHC-46.

Kleindorfer, Paul R. and Howard C. Kunreuther, "Challenges Facing the Insurance Industry in Managing Catastrophic Risks." In *The Finanancing of Catastrophe Risk*. Kenneth A. Froot, editor. National Bureau of Economic Research. University of Chicago Press. Chicago. 1999a.

Kleindorfer, Paul R. and Howard C. Kunreuther, 1999b. "The Complementary Roles of Mitigation and Insurance in Managing Catastrophic Risks." *Risk Analysis* 19:727-738.

Kunreuther, Howard, et al. *Disaster Insurance Protection: Public Policy Lessons*. John Wiley and Sons. New York. 1978.

Kunreuther, Howard. 1996. Mitigating disaster losses through insurance. *Journal of Risk and Uncertainty*. 12:171-187.

Kunreuther, Howard. "A Program for Reducing Disaster Losses Through Insurance." In *Paying the Price-The Status and Role of Insurance Against Natural Disasters in the United States*. Joseph Henry Press. Washington, D.C. 1998.

Kusler, J., and L. Larson. 1993. Beyond the Ark: A new approach to United States floodplain management. *Environment*. 35(5):7.

Landsea, C.W., N. Nicholls, W.M. Grey and L.A. Avila. 1996. Quiet early 1990s continues trend of fewer intense Atlantic hurricanes. Geophys. Res. Lett. 23:1697-1700.

Letsinger, Philip S. 2000. North Carolina State Coordinator, National Flood Insurance Program. Raleigh, N.C. Personal communication. February 7, 2000.

National Climatic Data Center. Various years. *Local Climatological Data* -- *Wilmington, NC.* National Climatic Data Center. Asheville, NC.

National Hurricane Center. 1999. National Weather Service, Tropical Prediction Center, Internet web site: http://www.nhc.noaa.gov/pastall.html. Miami, F.L. October 28, 1999.

National Hurricane Center Atlantic Hurricane Season Annual Summaries. Various years. *Monthly Weather Review.* American Meteorological Society. Boston, MA.

N.C. Building Code. 1999. North Carolina State Building Code, Volume VII -- Residential. 1997 Edition with 1998 and 1999 Revisions. North Carolina Building Code Council, North Carolina Department of Insurance. Raleigh, N.C.

N.C. Office of the Governor. 1999. "Governor Hunt Calls Special Session for Flood Relief." Press release, North Carolina Office of the Governor, Raleigh, N.C. December 8, 1999.

Neumann, Charles J. 1975. A Statistical Study of Tropical Cyclone Positioning Errors with Economic Applications. NOAA Technical Memorandum NWS-SR-82. National Hurricane Center. Miami, FL.

Neumann, Charles J. Personal communication. Science Applications International Corporation, Monterey, C.A. March 6, 2000.

Neumann, Charles J., and Colin J. McAdie. 1991. A Revised National Hurricane Center NHC83 Model (NHC90). NOAA Technical Memorandum NWS NHC-44. National Hurricane Center. Coral Gables, F.L.

Palm, Risa. *Earthquake Insurance: A longitudinal study of California homeowners*. Westview Press. Boulder, CO. 1995.

Pielke, Jr. R. A., and C. W. Landsea, 1998: Normalized Atlantic hurricane damage, 1925-1995. *Weather Forecasting*. 13: 621-631.

________ and _________, 1999. La Nina, El Nino and Atlantic Hurricane Damages in the United States, *Bulletin of the American Meterological Society*, Boston. October.

Rogers, Spencer M., Jr. 1985. Hurricane Diana: Impact on Coastal Development. Coastal Zone 1985, vol. 2. pp. 2468-2486.

Rogers, Spencer M., Jr., Peter R. Sparks and Katharine M. Sparks. 1985. A Study of the Effectiveness of Building Legislation In Improving the Wind Resistance of Residential Structures. Proceedings of the Fifth U.S. National Conference on Wind Engineering. Texas Tech University, Lubbock, TX. November 6-8, 1985.

Rogers, Spencer M., Jr. 1986. Coastal Erosion Issues in Flood Hazard Mapping. Report to Association of State Floodplain Managers Coastal Committee. Department of Civil Engineering, North Carolina State University and UNC Sea Grant, Marine Advisory Service, Kure Beach, N.C.

Rogers, Spencer M., Jr. 1990. Designing for Storm and Wave Damage in Coastal Buildings. ASCE Coastal Engineering Conference. Delft, Netherlands. pp. 2908-2921.

Rogers, Spencer M., Jr. 1993. Relocating Erosion-Threatened Buildings: A Study of North Carolina Housemoving. Coastal Zone. 1993.

Rogers, Spencer M., Jr. 1994. Hurricane Andrew & the South Florida Building Code: Relevance to the North Carolina Building Code. University of North Carolina Sea Grant. Raleigh, N.C.

Rogers, Spencer M., Jr., and Peter R. Sparks. 1990. Damage to Buildings: Hurricane Hugo. *Shore and Beach*. Journal of the American Shore and Beach Preservation Association. October 1990. pp. 48-52.

Saffir, H.S. 1977. Design and Construction Requirements for Hurricane Resistant Construction. American Society of Civil Engineers. New York. Preprint Number 2830. 20 pp.

Schwerdt, R.W., F. P. Ho and R. R. Watkins. 1979. Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Gulf and East Coasts of the United States. NOAA Technical Report NWS 23. Washington, D.C. 317 pp.

Simpson, R.H. 1974. The hurricane disaster potential scale. *Weatherwise*. 27:169,186.

Simmons, Kevin M., and Jamie Brown Kruse. 2000. Market value and perceived risk: Empirical results. *Journal of Economics*. 26:41-51.

Sizemore, Brad. Insurance agent, Nationwide Insurance. Wilmington, N.C. Personal communication. November 30, 1999.

Smith, Alex. 1999. Insurance agent, James E. Moore Insurance Agency. Wilmington, N.C. Personal communication. December 20, 1999.

Smith, Stanley K., and Christopher McCarty. 1996. Demographic Effects of Natural Disasters: A Case Study of Hurricane Andrew. *Demography*. 33(2):265-275.

Sparks, P.R. 1989. The Risk of Hurricane Wind Damage to Buildings in South Carolina: A White Paper. Coastal Hazards Advisory and Mitigation Project, Department of Civil Engineering, Clemson University. Clemson, S.C.

Sugg, Arnold L. 1967. Economic Aspects of Hurricanes. *Monthly Weather Review*. 95:143-146.

USCE. 1993. Flood Proofing: How to Evaluate Your Options. U.S. Army Corps of Engineers, National Flood Proofing Committee. Washington, D.C.

USCE. 1997. Flood Proofing: Techniques, Programs and References. U.S. Army Corps of Engineers, National Flood Proofing Committee. Washington, D.C.

USCE. 1998. Flood Proofing Performance: Successes and Failures. U.S. Army Corps of Engineers, National Flood Proofing Committee. Washington, D.C.

U.S. Weather Bureau. Various years. *U.S. Weather Bureau Original Monthly Record of Observations for Wilmington, NC.* National Climatic Data Center. Asheville, NC.

West, Carol T., and David G. Lenze. 1994. Modeling the Regional Impact of Natural Disaster and Recovery: A General Framework and an Application to Hurricane Andrew. *International Regional Science Review.* 17(2):121-150.

Whitehead, John C. 1999. "Using Revealed and Stated Preference Data to Estimate the Costs of Hurricane Evacuation." Working paper, Department of Economics, East Carolina University. Greenville, N.C.

Whitehead, John C., Bob Edwards, Marieke Van Willigen, John R. Maiolo and Kenneth Wilson. "Hurricane Evacuation Behavior of Coastal North Carolina Residents During Bonnie, Dennis and Floyd." In *Facing Our Future--Hurricane Floyd and Recovery in the Coastal Plain*. Coastal Carolina Press. Wilmington, NC. 2001.

Wilmington Morning Star. 1998. Professor Doubts Speeds: Hurricane Winds May Be Overblown. October 2, 1998. Wilmington, N.C.

Wilmington Morning Star. 1999. "Homeowners Likely to See Increase On Insurance Bill." February 18, 1999. Wilmington, N.C.

Work, Paul A., Spencer M. Rogers, Jr., and Robert Osborne. 1999. Flood Retrofit of Coastal Residential Structures: Outer Banks, North Carolina. *Journal of Water Resources Planning and Management*. 125(2):88-93.

## Endnotes

1

2 These risk modeling companies include Applied Insurance Research, EQECAT, and Risk Management Solutions. The mitigation activity to protect against hurricanes included "bracing roof trusses and gable end walls, applying wood adhesive where the roof decking and roof supports meet, and installing hurricane straps or clips where the roof framing meets the top o f the studs, and anchoring the walls to the foundation."

3 Grace, Klein, and Kleindorfer (2000) show that, at least in Florida, insurers do recognize mitigation in their premium. This finding does not hold in general as insurance purchased via the North Carolina Joint Underwriters Association, which will be used later in this paper, does not change with mitigation.

4 KK assume only one mitigation activity and one insurance premium/deductible combination in their modeling.

5 Fronstin and Holtmann (1994) show that relaxed coastal building code requirements in Dade County, Florida, did not fully protect newer residential structures from extensive damage during Hurricane Andrew. A variety of entrepreneurial products and services that reduce hurricane damage are currently marketed in coastal areas.

6 The Saffir-Simpson index is the standard used to describe hurricane intensity (Simpson 1974, Saffir 1977).

7 Meteorological research suggests that the occurrence of tropical weather and associated damages are autocorrelated (Hebert, Jarrrell and Mayfield 1997, Pielke and Landsea 1999). For simplicity, we abstract from this issue in the present study.

[8] Multiple strikes per year do occur on occasion for a given locality (e.g., Wilmington, N.C., 1999). However, the probabilities of multiple strikes are very low relative to the probabilities of single strikes.

[9] Roofs, windows, doors, and garage doors are the four most common external features destroyed by hurricane force winds (FEMA 1993b, IBHS 1998, Rogers 1994).

[10] The ability of stricter building requirements to reduce hurricane damage is well documented (Rogers et al. 1985, Fronstin and Holtmann 1994).

[11] Insurance adjusters 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 all damages below the high water mark; wind insurance covers the balance (Smith 1999).

[12] Fronstin and Holtmann (1994) show that relaxed coastal building code requirements in Dade County, Florida, did not fully protect newer residential structures from extensive damage during Hurricane Andrew.

[13] Fronstin and Holtmann (1994) show that relaxed coastal building code requirements in Dade County, Florida, did not fully protect newer residential structures from extensive damage during Hurricane Andrew.

[14] The structure conforms to the 1999 North Carolina coastal building code. Most residential structures in the region meet the wind and flood requirements of applicable building codes. This may not be the case for all coastal regions (Rogers 1994, Rogers and Sparks 1990, Sparks 1989, Rogers 1985). Mitigation choices involving sub-code property are not pursued.

[15] 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 1990). Consideration of these hydrodynamic forces requires substantial, additional engineering analysis beyond the scope of the study (Rogers 1986).

[16] Because wind speeds decrease rapidly with distance outward from the hurricane eyewall (Schwerdt et al. 1979), we assume that storms with centers passing farther away than 100 nautical miles from Wilmington cause negligible wind and storm surge damage. 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 1999, National Hurricane Center Atlantic Hurricane Season Annual Summaries, various years).

[17] 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.

[18] Media often report eyewall wind speeds for locations not hit directly by the eyewall. Our wind speed probability distributions are constructed with surface wind speeds measured by National Weather Service stations *at the case study location* (U. S. Weather Bureau, various years; National Hurricane Center Atlantic Hurricane Season Annual Summaries, various years; National Climatic Data Center, various years). Jarrell, et al. (1992) find that only eight hurricanes affect the study location from 1900 to 1990 (denoted in Table A1 by an asterisk "*"

following the storm name). Of these storms, six were assigned hurricane category numbers that imply wind speeds significantly above the actual wind speeds measured in Wilmington.

[19] Note the low probabilities for hurricanes above category 3. Only two category 5 hurricanes and 14 category 4 hurricanes (two north of Florida) have impacted the *entire* U.S. coastline this century (Jarrell, et al. 1992).

[20] Both appropriate wind speed measurement methodology (sustained winds or wind gusts) and appropriate expected wind speed probabilities for a particular location are matters of considerable debate in the wind engineering and meteorological communities (Wilmington Morning Star 1998, Sparks 1989). The implications of alternative assumptions regarding wind speed measurement methodology and expected wind speed probabilities (Table 2) are explored in several model simulations.

[21] The barrier islands of North Carolina have 110-mph wind speed building code requirements, with 100-mph wind speed requirements in non-island portions of coastal counties (N.C. Building Code 1999). However, there is discussion of extending the 110-mph requirements inland to the coastal (non-island) counties.

[22] 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.) (Rogers 1994). We assume these hazards are negligible for the example property.

[23] It is possible for extreme winds to cause damage to any or all of several structural features. We assume that all structural features of a given type suffer the same level of wind damage. In addition, failures of various structural feature types are independent events (e.g., window failure does not make roof failure more likely), though some evidence exists that structural failures are interrelated (FEMA 1986, 1992, 1993a; Rogers 1994). Consideration of conditional failure relationships among structural features requires additional, extensive engineering analysis beyond the scope of this study.

[24] Five per cent of total contents resides in the windowless garage (Sizemore 1999).

[25] Losses equal three-eighths of 95 per cent of total contents value, a typical value for a residential structure in the study region (Sizemore 1999).

[26] See FEMA (1992), FEMA (1993a-b), FEMA (1996a-c), FEMA (1997b), FEMA (1998a-d). See also IBHS (1998) and Calhoun and Fulop (1996).

[27] To our knowledge, probabilistic failure rates for the various structural defenses are not available.

[28] 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 (see Appendix Table A3a). The property owner chooses the least expensive option (storm panels).

[29] 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 (all activities in Table A3a with wind speed ratings above 120-mph). 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. (see Appendix Table A3a). 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. Roof defenses are unavailable for midpoint category 5 hurricanes.

[30] 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. However, damage to structure and contents arising from unprotected doors (including garage) is $41,636. 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. As builders estimate that no level of conventional structural defenses prevents the loss of the structure's roof in category 5 winds (Clark 1999), we assume no available protection against category 5 winds.

[31] Although the extreme rainfall associated with tropical weather causes flood damage (as evidenced by the recent flooding in North Carolina due to Hurricane Floyd), the primary flood threat in coastal areas is storm surge.

[32] For the purposes of this study, ZDE is equal to ground floor elevation. We assume that outdoor utilities (e.g., heat pump) are also elevated to ZDE.

[33] This elevation is representative of several important locations in the region, including the downtown Wilmington waterfront, sections of Carolina Beach and Wrightsville Beach.

[34] Thus, 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).

[35] If defensive activities are subject to uncertain mechanical failure, redundant defensive activities provide additional expected damage-reduction. We assume defect-free defensive measures.

[36] The size of many structures relative to utility line height and roadway width restricts off-site relocation (Rogers 1993). We assume that off-site house relocation is not feasible.

[37] Appendix Table A4 indicates 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.).

[38] 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. (Work, Rogers, and Osborne (1999) find that 77% of survey respondents from eastern North Carolina retrofit using pilings.)

[39] 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.

[40] 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.