Catastrophic Risk, Homeowner Response and Wealth Maximizing Wind Damage Mitigation

Published in 2002 in *The Financial Services Review*

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Abstract

Many experts encourage homeowners to improve their houses to better survive natural catastrophes and reduce overall societal costs. However, we find these encouragements are not necessarily financially sound for the homeowner at risk of hurricane wind damage. We find that subsidized insurance reduces the incentive for a risk-neutral homeowner to purchase structural mitigation, as mitigation does not generally reduce damages to below subsidized deductibles. If insurance premiums increase or if hurricane strike probabilities or market returns decrease, the wealth maximizing homeowner drops insurance and purchases mitigation. For homeowners to purchase both mitigation and insurance, high deductible/low premium insurance must be offered.

JEL classification: D1; H2

Keywords: Hurricane; Catastrophic Risk; Wind Pool; Mitigation; Insurance

1. Introduction

Published remarks on the human and material costs of catastrophic events such as floods, earthquakes, and hurricanes range from an inventory of the personal and financial impacts of

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these events to calls for greater government involvement in catastrophic event prediction and mitigation. Potential losses for insurers and property owners and the appropriateness of certain government responses to hurricane risk encourage recent empirical and theoretical research. Extant studies consider the costs and predictability of hurricanes (Pielke and Landsea, 1999; Herbert, Jarrell and Mayfield, 1997), examine the exposure of the insured, the insurer and the lender (Chichilnisky and Heal, 1998; Angbazo and Narayanan, 1996; Kozlowski and Mathewson, 1997; Brostoff, 1995; Dezube, 1994), and measure the impact of hurricanes on property values (Graham and Hall, 2001). Camerer and Kunreuther (1989) and Kunreuther (1996) note that many homes are vulnerable to extreme weather risks, yet many homeowners do not purchase additional structural defenses.

A few papers suggest that it is cost-effective for homeowners to purchase structural mitigation. Kleindorfer and Kunreuther (1999) show that structural mitigation activity by property owners reduces insurance company exposure in the event of an earthquake or a hurricane strike. Though regional mitigation efforts reduce insurer exposure, homeowners often do not engage in these activities. Kleindorfer and Kunreuther attribute the known lack of mitigation to "myopia" on the part of homeowners and the failure of insurance companies to offer lower premiums in response to mitigation measures. Though they consider only one mitigation activity (roof protection) and one insurance pricing scenario (premiums equal to two times the annual expected loss for the homeowner), the authors suggest that owners are "slightly better off" with this mitigation activity.

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-

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effective as home values are increased by an amount greater than the cost of installed storm shutters "under very modest assumptions on discounting and depreciation."

Our study extends the work of Kleindorfer and Kunreuther (1999) and Simmons, Kruse, and Smith (2002). In practice, homeowners choose from an *array* of mitigation activities. In this paper, we determine which combinations of mitigation activities are wealth-enhancing for a homeowner at hurricane risk. This decision is complicated by the existance of state wind pools that offer insurance at rates below market; even homeowners at high risk can purchase insurance. These low rates may cause homeowners to forgo structural defense purchases.

A typical coastal homeowner at hurricane wind risk may undertake several actions to maximize wealth. (We consider a home that is not at flood risk.) The owner can buy insurance, structural defensive measures beyond building codes (such as storm shutters and roof tie-downs), or combinations of both insurance and defensive measures. As well, the homeowner can simply build the home to existing building codes, placing funds not spent on insurance or home improvements in alternative investments; most mortgages, though, require insurance to protect the value of the mortgage's collateral, and "not insuring" is often not a practical option.

In the next section, we portray hurricane damages for a typical homeowner and compare losses over various combinations of structural defenses. In section 3, we develop a wealth maximization model for a risk-neutral homeowner. We employ the model in section 4 to calculate expected wealth over various insurance and/or structural defense combinations. The section also illustrates expected wealth-maximizing levels of insurance and defensive measures over a thirty-year ownership horizon. We consider, in section 5, wealth-maximizing levels of insurance and structural defenses with changing insurance premiums and deductibles, changing hurricane strike probabilities, and changing rates of return. We review the public policy implications of our findings and summarize our results in the conclusion.

2. Hurricane Damages

Our "typical" homeowner lives in a 2,150 square foot, one-story, wood frame residential structure valued at $140,000; it is located in Wilmington, NC and just conforms to 1999 North Carolina coastal building codes. The home has eight rooms with three exterior doors, one garage door, and eleven windows – typical for a home this size. The homeowner resides in North Carolina's New Hanover County, a coastal area where four hurricanes have recently made landfall; Bertha and Fran struck the area late in the summer of 1996, Bonnie made landfall in August of 1998, and Floyd hit in September of 1999.

The homeowner purchases homeowner's insurance from a private insurer. However, private insurers often do not offer wind and hail coverage for homes near the beach. Wind and hail insurance, covering the full value of the home and contents up to 70% of the dwelling limit ($98,000), is purchased from the North Carolina Insurance Underwriting Association (NCIUA) at subsidized rates. These rates represent the maximum rates that a coastal homeowner in the area pays for wind and hail coverage.

We assume the homeowner is risk-neutral. He or she faces the risk of hurricane strikes of different intensities and attempts to maximize expected wealth over a thirty-year ownership horizon, while repairing any hurricane damage to the home. We measure hurricane intensity using the Saffir-Simpson hurricane scale. According to this scale, Table 1 reports the annual probabilities of experiencing a Tropical Storm and Category 1 through 5 storms for Wilmington, NC. These probabilities, computed by the National Weather Service, are assumed constant over the thirty-year period. The probability of no tropical storm or hurricane strikes is 80% (1 – sum of the probabilities of tropical storm and hurricane strikes).

Table 1
Saffir-Simpson tropical weather wind speed categories

Hurricane Category	Wind Speed Range	Strike Probability
Tropical Storm	39-73	0.15336
Cat 1	74-95	0.02826
Cat 2	96-110	0.00817
Cat 3	111-130	0.00520
Cat 4	131-155	0.00254
Cat 5	156+	0.00010

Coastal building codes in the study area call for homes to withstand winds up to 110 mph. Since Tropical Storms and Category 1 and 2 hurricanes do not generate these winds, we assume no wind damage from these storms. Recent anecdotal experiences by the authors in the study region support a premise of only limited hurricane wind-damage for a code-compliant home in a Tropical Storm (Dennis) or "Cat 1" or "Cat 2" hurricanes such as Bonnie or Floyd. However, Category 3-5 storms are assumed to completely destroy the home since the lowest wind speeds of these storms exceed the building code requirements. This destructive allowance provides the greatest possible encouragement for defensive measures, though market insurance rates may be set according to a *different* set of hurricane damage expectations.

The homeowner can reduce expected wind damages with structural defenses purchased at the beginning of the thirty-year ownership period. The purchase reduces the owner's initial wealth. Further, we assume that structural defenses perform as rated. For example, if a structural defense is rated to withstand 130 mph wind speeds, we assume that the defense holds for *any* Category 3 hurricane, but fails in a Category 4 or 5 storm.

In addition to gathering insurance price data, we survey defensive measures and their costs in the study area. We find window defenses rated from 120 to 300 mph, roof defenses rated from 110 to 130 mph, door defenses rated from 120 to 280 mph, and garage door defenses rated from 120 to 135 mph. In only two circumstances do we find defenses rated to defend a home against Category 5 winds. However, since the home likely loses its roof in such winds, intact windows or doors are of little consequence. Thus, we assume the home is destroyed in a "Cat 5" storm regardless of defensive purchases.

The owner chooses the least-cost structural improvements to defend against structural failure in a Category 3 or 4 hurricane. Least-cost roof, window, door, and garage door defenses are listed in Table 2.

Table 2
Least-cost defensive activities to protect against a Category 3 or 4 hurricane.

Structural Feature Defended	Category 3	$/sq. ft. of structure	Category 4	$/sq. ft. of structure
Roof (R)	Reinforcing Eves and Gables	1.5349	Reinforcing Eves and Gables *plus* Apply Structural Foam Adhesive *plus* Install Rafter Bracing	2.7628
Window (W)	Plywood Window Covers and Wood Screws	.1520	Storm Panels	.6523
Door (D)	Plywood Door Covers and Wood Screws	.0580	Storm Panels	.2491
Garage Door (G)	Reinforced Steel Garage Door	.5636	Reinforced Steel Garage Door	.6032

Notes: Category 3 least-cost roof defenses include anchoring rafters to wall top plates, reinforcing wall sheeting attachment to bottom plate/mud sill, and installing angle brace anchors between bottom plate/mud sill and footings. Category 4 roof defenses include those used to defend against a Category 3 storm plus application of structural foam adhesive to all sub-facia/rafter and sheeting/rafter joints to 2 feet up the rafters, installation of rafter bracing, and application of structural foam adhesive to all sheeting/rafter and sheeting/sheeting joints.

The benefit of defending the various structural features equals the damage avoided if those features had failed. If the roof blows off, the entire value of the house and contents is lost, even if other features are rated to withstand the wind speed at which the roof fails. Other structural features can fail without the full loss of the house and contents. If the windows fail, window damages are 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). If the doors fail, door damages are 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 (three eights of $93,100). Insurance industry standard holds that five per cent of the total content value is in the garage. Thus, if the garage door fails, damages are 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, 5% of $98,000 or $4,900. If both the windows and doors fail, damages are equal to the cost of replacing the windows and doors plus the cost of replacing the contents of eight rooms, or $103,552.

Damages experienced in either a Category 3 or 4 hurricane are given in Table 3 assuming spending on various combinations of least-cost defensive measures. Note that spending on Category 3 defenses does not help in a Category 4 storm, while Category 4 defenses do protect the home in a Category 3 storm.

Table 3 portrays also reductions in hurricane wind-damages for differing levels of spending on defensive measures. To protect against either a Category 3 or 4 hurricane, the first measure purchased is always roof protection (R), as other defensive measures are worthless to protect the home if the roof blows off. The next feature purchased, in addition to roof defense, is window defense (for a combination of RW), as each dollar spent on window defense (given roof protection) reduces total damage to the home by $189 (($103,552 - $41,636)/(2,150 x $.152)) for a Cat 3 hurricane and $44 for a Cat 4 hurricane. Next, door defense is purchased in combination with roof and window defense (for a combination of RWD) as each dollar spent reduces damage by $289 for a Cat 3 hurricane and $67 for a Cat 4 hurricane. Garage protection is extremely costly and gives the least return per dollar. We conclude that, in general, the owner will choose the defense combinations: roof (R), roof and window (RW), roof, window, and door (RWD), and roof, window, door and garage (RWDG), in that order.

Table 3
Structural defense combinations, least-cost (LC) expenditures, and resulting wind damages for category 3 and 4 hurricanes.

Defense Combinations	LC Spending $ per sq. ft. of structure (Category 3 Defenses)	Wind Damages (Cat. 3)	Wind Damages (Cat. 4)	LC Spending $ per sq. ft. of structure (Category 4 Defenses)	Wind Damages (Cat. 3)	Wind Damages (Cat. 4)
None	0	$238,000	$238,000	0	$238,000	$238,000
Roof (R)	1.5349	$103,552	$238,000	2.7628	$103,552	$103,552
Window (W)	0.152	$238,000	$238,000	0.6523	$238,000	$238,000
Door (D)	0.058	$238,000	$238,000	0.2491	$238,000	$238,000
Garage (G)	0.5636	$238,000	$238,000	0.6032	$238,000	$238,000
RW	1.6869	$41,636	$238,000	3.4151	$41,636	$41,636
RD	1.5929	$102,409	$238,000	3.0119	$102,409	$102,409
RG	2.0985	$97,972	$238,000	3.366	$97,972	$97,972
WD	0.21	$238,000	$238,000	0.9014	$238,000	$238,000
WG	0.7156	$238,000	$238,000	1.2555	$238,000	$238,000
DG	0.6216	$38,000	$238,000	0.8523	$38,000	$38,000
RWD	1.7449	$5,580	$238,000	3.6642	$5,580	$5,580
RWG	2.2505	$36,056	$238,000	4.0183	$36,056	$36,056
RDG	2.1565	$96,829	$238,000	3.6151	$96,829	$96,829
WDG	0.7736	$238,000	$238,000	1.5046	$238,000	$238,000
RWDG	2.3085	$0	$238,000	4.2674	$0	$0

Notes: Acronyms for defense combinations are given in the table. For example, RW denotes the defense combination which protects the roof and windows while RWDG denotes the defense combination that protects the roof, window, doors, and the garage.

3. Wealth Maximization Model

Our risk-neutral homeowner has an initial, liquid wealth endowment of W in addition to the value of the house and contents. To protect the value of the home and sheltered personal property, the homeowner purchases structural defenses at the beginning of a time horizon, t. If wind insurance is purchased, the owner maintains the same policy by paying an annual premium throughout the assumed thirty-year ownership period. The premium is paid at the beginning of each year. The portion of the wealth endowment not invested in structural defenses or insurance is invested in a stock market index fund, providing an average, inflation adjusted, after-tax return of r.

Since the value of the home is maintained, damages to the house and contents are repaired. Further, we assume that inflation-adjusted home value and insurance costs are constant. Thus, the homeowner maximizes the expected wealth endowment over the ownership time horizon, while using the endowment's accumulation to pay for expected losses and insurance premiums. We ignore the homeowner's mortgage financing.

The owner's annual expected hurricane wind losses, E(HL), are equal to the minimum of the owner's wind insurance deductible and annual expected hurricane damage as a function of defensive measure expenditures:

$$E(HL) = P_{none}(0) + P_{ts}(0) + P_1(0) + P_2(0) + P_3\min[d,\ D_3(s)] + P_4\min[d,\ D_4(s)] + P_5\min[d,\ 238{,}000], \qquad (1)$$

where P_{none} and P_{ts} represent the probabilities of no storm or a tropical storm, respectively, P_j is the probability of a Category j hurricane strike, j = 1…5 (see Table 1), d is the insurance deductible, s is structural defense expense, and $D_3(s)$ and $D_4(s)$ represent the damages experienced in a Category 3 or 4 storm as a function of defensive expenditures (see Table 3). Expected losses are realized at the end of each year. Damages in no storms, Tropical Storms, or

Category 1 or 2 hurricanes are 0 while damages in a Category 5 storm are $238,000 , regardless of mitigation spending. If the homeowner purchases no defensive measures and no insurance , damages are equal to $238,000 in Category 3 - 5 storms. Absent mitigation beyond code, annual expected damages are equal to $1,866 or the sum of the probabilities of each Category 3-5 storm in Table 1 times the total loss of $238,000.

The owner's expected wealth accumulation at the end of one year becomes:

$$(W - s)(1 + r) - p(1 + r) - E(HL), \tag{2}$$

or the one-period future value of the wealth endowment reduced by defensive expenditures, s, less the annual insurance premium, p, and expected hurricane losses, E(HL).

Using recursive substitution and noting that structural defens es are purchased only at the beginning of the time horizon, we find that at time t the owner's expected wealth is:

$$(W - s)(1+ r)^t - p(1 + r)(FVIFA_{i,t}) + E(HL)(FVIFA_{i,t}), \tag{3}$$

where $FVIFA_{i,t}$ is the future value interest factor for an ordinary annuity.

4. Expected Wealth-Maximizing Wind Mitigation

We consider alternative plans to maximize expected wealth over a thirty -year ownership horizon while maintaining the value of the home. The owner's initial wealth endowment is $20,000, and the inflation-adjusted, after-tax real return is 4.9%. This equates with the pre-tax long-run average annual return for NYSE stocks (between 1925 and 2001) of 7.42%, after inflation (Rose, 2003). We assume federal and state tax rates of 27 percent and 7 percent, respectively, and a real after-tax return of approximately 4.9 percent. We assume that the owner does not mix Category 3 defenses with Category 4 defenses.

We first consider the expected wealth-maximizing decision for an owner when insurance is unavailable.

Table 4
Expected wealth values at the end of 30 years over different levels of defensive expenditures – no insurance purchased

	Defense Combinations	LC Expenditures	Annual Expected Hurricane Losses	Expected Wealth after 30 Years
	None	0	$1,865.92	-$37,858.68
Category 3 Defenses	*R*	$1.5349/sq. ft. (Total: $3,300.04)	$1,166.79	-$6,059.78
	RW	$1.6869/sq. ft. (Total: $3,626.84)	$844.82	$13,594.92
	RWD	$1.7449/sq. ft. (Total: $3,751.54)	$657.34	$25,315.89
	RWDG	$2.3085/sq. ft. (Total: $4,963.28)	$628.32	$22,121.41
Category 4 Defenses	*R*	$2.7628/sq. ft. (Total: $5,940.02)	$825.29	$5,154.85
	RW	$3.4151/sq. ft. (Total: $7,342.47)	$346.06	$30,562.70
	RWD	$3.6642/sq. ft. (Total: $7,878.03)	$66.99	$46,539.07
	RWDG	$4.2674/sq. ft. (Total: $9,174.91)	$23.80	$43,912.63

Notes: Assumes an inflation adjusted, after-tax real interest rate of 4.9 percent and an initial wealth endowment of $20,000. In the table, roof defenses only are denoted R; roof and window defenses are denoted RW; roof, window, and door defenses are denoted RWD; and roof, window, door, and garage defenses are denoted RWDG.

Table 4 shows that, with no insurance, the defensive measure combination that maximizes expected wealth and maintains the value of the home over the thirty-year period is roof, window, and door defenses that protect up to a Category 4 hurricane. Purchasing no defensive measures yields negative expected wealth at the end of thirty years. In other words, returns on the $20,000 initial wealth are smaller than expected annual hurricane losses ($1,865.92), where expected hurricane losses equal expected hurricane damages in the absence of insurance. Without insurance, the owner purchases defensive measures adequate to lower annual expected losses to only $67. Though the amount of front-end wealth foregone is second highest (implying many years of lost returns), the future value of the stream of expected annual savings (lower expected losses) is large. Spending to the highest possible level is not the desired choice; although it reduces expected annual losses to $23.80, front-end costs increase by almost $1,300.

For the homeowner able to insure, two wind-insurance options are available. In the study region, homeowner's insurance does not necessarily cover wind damages; however, wind insurance is available through a wind insurance pool, and the cost of wind insurance can be separated from overall costs of homeowner's insurance. Two baseline wind insurance policies offered by the NCIUA during 1999 and 2000 are considered. The first policy has a deductible of $500 with an annual premium of $ 493; the second has a deductible of $2,500 with an annual premium of $420 (Insurance Services Office, 2000).

Table 5
Expected wealth values at the end of 30 years over different levels of defensive expenditures - $500 deductible/$493 premium wind insurance policy purchased

	Defense Combinations	LC Expenditures	Annual Expected Hurricane Losses *plus* Insurance Premium	Expected Wealth after 30 Years (Home Value Maintained)
	None	0	$521.08	$49,971.87
Category 3 Defenses	*R*	$1.5349/sq. ft. (Total: $3,300.04)	$521.08	$36,111.21
	RW	$1.6869/sq. ft. (Total: $3,626.84)	$521.08	$34,738.61
	RWD	$1.7449/sq. ft. (Total: $3,751.54)	$521.08	$34,214.85
	RWDG	$2.3085/sq. ft. (Total: $4,963.28)	$518.48	$29,295.16
Category 4 Defenses	*R*	$2.7628/sq. ft. (Total: $5,940.02)	$521.08	$25,022.91
	RW	$3.4151/sq. ft. (Total: $7,342.47)	$521.08	$19,132.41
	RWD	$3.6642/sq. ft. (Total: $7,878.03)	$521.08	$16,882.98
	RWDG	$4.2674/sq. ft. (Total: $9,174.91)	$517.21	$11,688.63

Notes: Assumes an inflation adjusted, after-tax real interest rate of 4.9 percent and an initial wealth endowment of $20,000. In the table, roof defenses only are denoted R; roof and window defenses are denoted RW; roof, window, and door defenses are denoted RWD; and roof, window, door, and garage defenses are denoted RWDG.

Table 5 shows that, with the low deductible insurance policy, the owner maximizes expected wealth by purchasing *no* defensive measures; maximum damages from a hurricane strike are reduced to the level of the deductible ($500). For the structurally unmitigated home built to code, a deductible of $500 renders expected hurricane damages equal to the sum of the probabilities of the three storm categories times $500, or $3.92. Since the owner pays the insurance premium of $493 at the beginning of each year, the owner suffers expected end-of-year costs of $517.16 ($493 times 1.049) plus $3.92, or $521.08, annually. Since defensive measures do not lower damages below $500 for either a Category 3 or 4 storm (save in the case of RWDG defenses – see Table 3), defensive measures are not purchased with this insurance policy. In the case of Category 3 or 4 RWDG defenses, a wealth-maximizing owner does not pay $4,963 or $9,175 to reduce expected annual expenses by $2.60 ($521.08 minus $518.48) or $3.87 ($521.08 minus $517.21), respectively.

The $500 deductible insurance option in Table 5, with no defensive measures, is superior to having no policy with the wealth-maximizing defensive measure purchases in Table 4. Wealth lost with an initial purchase of defensive measures plus $66.99 in annual expected hurricane losses exceeds the wealth lost with annual premium payments. An owner who purchases wealth-maximizing structural defenses and no insurance forgoes over $3,400 ($49,972 - $46,539) in wealth accumulation over the 30-year period. The rational risk-neutral homeowner purchases the $500 deductible policy and buys no "extra" defensive measures.

Data in Table 6 underscore the results portrayed in Table 5. A $2500 deductible policy with a lower premium of $420 is contrasted with the suitability of defensive purchases. Again, home "refits" beyond code are discouraged. In addition, this less expensive policy is preferred, given the greater wealth accumulation ($53,949.00) in Table 6 versus the ending wealth ($49,971.87) in Table 5. While the deductible for this policy is higher, the owner does not expect high damages with the observed strike probabilities, even in an area at perceived elevated hurricane risk. We conclude that, with low strike probabilities, the low price of high deductible wind insurance coverage, and a home built to withstand 110 mph winds, the owner maximizes wealth with this less expensive low premium/high deductible policy and no defensive measures.

Table 6
Expected wealth values at the end of 30 years over different levels of defensive expenditures - $2500 deductible/$420 premium wind insurance policy purchased

	Defense Combinations	LC Expenditures	Annual Expected Hurricane Losses *plus* Insurance Premium	Expected Wealth after 30 Years (Home Value Maintained)
	None	0	$460.18	$53,949.00
Category 3 Defenses	*R*	$1.5349/sq. ft. (Total: $3,300.04)	$460.18	$40,088.35
	RW	$1.6869/sq. ft. (Total: $3,626.84)	$460.18	$38,715.74
	RWD	$1.7449/sq. ft. (Total: $3,751.54)	$460.18	$38,191.98
	RWDG	$2.3085/sq. ft. (Total: $4,963.28)	$447.18	$33,951.51
Category 4 Defenses	*R*	$2.7628/sq. ft. (Total: $5,940.02)	$460.18	$29,000.04
	RW	$3.4151/sq. ft. (Total: $7,342.47)	$460.18	$23,109.54
	RWD	$3.6642/sq. ft. (Total: $7,878.03)	$460.18	$20,860.11
	RWDG	$4.2674/sq. ft. (Total: $9,174.91)	$440.83	$16,676.75

Notes: Assumes an inflation adjusted, after -tax real interest rate of 4.9 percent and an initial wealth endowment of $20,000. In the table, roof defenses only are denoted R; roof and window defenses are denoted RW; roof, window, and door defenses are denoted RWD; and roof, window, door, and garage defenses are denoted RWDG.

These findings provide a counter-example to the results of other studies suggesting that the purchase of structural mitigation is beneficial to homeowners. The difference in our study is the existence of a state-mandated wind insurance pool, with resulting regulated and lowered rates. In more competitive and less regulated insurance markets with more complete information, the higher premium equals the buyer's expected claim plus administrative costs and "normal" profits for the insurer.

In the absence of full information, insurers attempt to classify risks by employing descriptive variables that reveal high and low risks, though some states limit the use of certain variables by insurers (Harrington and Doerpinghaus, 1993). The same is true of wind insurance providers. As these insurers resolve information asymmetries about the hurricane risks confronting individual homeowners, they have an incentive to reduce their exposure; they accomplish this by increasing insurance premiums, canceling existing policies, and avoiding new policies for homes at higher risk of hurricane damage. Higher premiums, though, often lead the homeowner to forgo insurance, even in high risk areas (Roth, 1998). State legislatures are sensitive to these insurer actions and, in North Carolina as in many other states, legislators require that private insurers pool together to provide insurance to high risk homeowners – notably those who live close to the beach. The rates charged by these pools are regulated by the state Department of Insurance. An adverse selection problem develops as these policies attract homeowners at higher risk; a subsidization of high risk homeowner premiums is provided by the premiums of lower risk homeowners. Browne (1992) and Browne and Doerpinghaus (1993) suggest similar phenomena in individual health insurance markets.

Our results indicate that, for the high-risk coastal homeowner, the availability of insurance at below market prices stifles mitigation purchases. Mitigation might be encouraged, however, were the NCIUA to adopt a pricing scenario similar to its counterpart in the state of Florida, the Florida Wind Underwriters Association (FWUA). The FWUA writes policies giving reduced premiums for mitigation purchases, a pricing strategy proposed by Kunreuther and Kleffner

(1996) and Kenreuther (1998). Currently, however, the NCIUA does not have a mechanism to encourage the adoption of mitigation measures.

Given this regulated market for wind insurance compromised by adverse selection (similar to the findings of Browne and Doerpinghaus, 1993, and Harrington and Doerpinghaus, 1996), we speculate that insurance premiums for the homeowner at lower risk of wind damages are higher than the rates a competitive market would charge. We further speculate that low-risk homeowners, subject to higher than competitive market premiums, may choose mitigation instead of insurance (an issue that we briefly address in the next section). In other words, low-risk homeowners may, at the margin, choose mitigation while high-risk homeowners choose insurance.

5. Sensitivity Analysis

Changes in insurance premiums, deductibles, strike probabilities and interest rates impact optimal homeowner responses. We employ equation (3) to determine the sensitivity of wealth-maximizing decisions to these changes.

First, we consider a change in insurance premiums, both for the high deductible ($2,500) and the low deductible ($500) wind insurance policies. For the high deductible policy, the insurance premium must be increased to around $528 before the homeowner purchases any defensive measures. If this higher premium is observed, the homeowner purchases Category 4 RWD defensive measures but drops any wind insurance. Likewise, for the low deductible policy, the insurance premium must be increased to just over $543 before the homeowner purchases any defensive measures (and drops insurance). As the premium for the high-deductible policy increases, the low-deductible policy becomes preferred. The high deductible policy is preferred until its premium reaches $ 478; above $478, the low-deductible policy, *ceteris paribus*, becomes a better buy.

Increasing the deductible also influences homeowner response. For example, increasing the deductible for the low premium policy decreases expected wealth but does not alter the "insurance only" mitigation decision unless the deductible is increased to over $ 16,970. Similarly, the deductible for the high premium policy must increase to almost $7,205 to alter the insurance only mitigation decision. At these deductible levels, the homeowner opts for Category 4 RWD defensive measures and drops all wind insurance.

Note that in the preceding considerations, the wealth-maximizing owner purchases *either* insurance *or* structural defenses. Why doesn't the owner purchase a combination of *both* insurance *and* defenses?

An asset is purchased if the price is less than the discounted expected future benefits of the asset, where expected future benefits are normally a straight-forward calculation. In the case of structural defenses, the expected future benefits of mitigation depend on the level of the deductible; *structural defenses may increase expected wealth if they reduce damages below deductible levels*. Although reducing damages below deductible levels is necessary for an increase in expected wealth, it is not sufficient. Damage reduction below the deductible must exceed the cost of the defenses.

Consider the baseline deductible level of $2,500. Table 3 shows that only Category 3 RWDG defenses and Category 4 RWDG defenses decrease damages below this deductible. In Table 6, we find that Category 3 RWDG defenses reduce the sum of annual expected hurricane losses and insurance premiums from $460.18 to $447.18, a decrease of $13 per year, equivalent to a future value benefit of $849.02. Similarly, Category 4 RWDG defenses lower the sum of losses and premiums from $460.18 to $440.83, a reduction of $19.35 per year, equivalent to a future value benefit of $1,263.73. However, Category 3 RWDG defenses cost $4,963.28 (equivalent to a future value cost of $20,847), and Category 4 RWDG defenses cost $9,174.91 (equivalent to a future value cost of $38,535). With a deductible level of $2,500, damage reduction below the deductible does not exceed the cost of the defenses. Even at much higher hurricane strike probabilities (e.g., a fifty-fold increase in strike probabilities), damage reduction below the deductible does not exceed the cost of the defenses.

Lower hurricane strike probabilities encourage the owner to purchase mitigation exclusively as a substitute for insurance. Assuming the original high deductible insurance policy, hurricane strike probabilities must decrease by 70% for the owner to purchase defense expenditures (RWD, Category 3) and drop insurance. For the low deductible policy, strike probabilities must decrease by 60% for the owner to justify the substitution of defensive measures (RWD, Category 3) for insurance. It follows that, perhaps counter-intuitively, higher hurricane strike probabilities may motivate homeowners to purchase less mitigation.

Only at much higher deductible levels do structural defenses become attractive *in combination* with insurance. In fact, deductibles must increase to nearly $52,000 if the owner is to experience expected out-of-pocket losses below the future value equivalent of defensive measure costs. If deductibles increase to $52,000, Category 3 RWD defensive measures reduce out-of-pocket losses to $15,765 but cost a future value equivalent of only $15,757. Increasing the deductible to around $52,000 is not, however, sufficient to cause the owner to purchase both defensive measures and insurance. The insurance premium must also be decreased below the baseline levels to just over $158. With the $52,000 deductible/$158 premium wind insurance policy, the owner maximizes expected wealth by purchasing both this wind insurance policy and

Category 3 RWD defenses; the owner's expected wealth at the end of 30 years equals $46,546.63.

In a final analysis, employing the original National Weather Service hurricane probabilities, we find that real after-tax returns must drop from 4.9% to almost 2.6% before owners prefer defensive measures (RWD, Category 4) to the initial high deductible policy. These rates must fall to almost 3.9% for the owner to prefer defensive measures to the initial low deductible policy. In other words, the opportunity cost of purchasing defensive measures at the front end of the 30-year period, in terms of forgone returns, must drop for these purchases to maximize expected wealth. Returns must drop lower for the high deductible policy, as returns lost per year are smaller with the lower premium. This result shows that the choice of real after-tax rates of return matters. For example, if the opportunity cost of defensive measures equals 1.22%, the inflation adjusted, after-tax interest rate on U.S. government notes and bonds from 1925-2001, the owner purchases mitigation over insurance..

We draw several conclusions from our analyses. First, subsidized wind pool insurance premiums precipitate the purchase of insurance in lieu of mitigation by high risk homeowners. As a consequence, low risk owners pay higher insurance premiums and may substitute mitigation for insurance. Second, in the absence of premium discounts for mitigation, wind insurance pools can encourage mitigation and the purchase of insurance only by offering high deductible, low premium policies. Third, perhaps counter-intuitively, higher hurricane strike probabilities may motivate homeowners to purchase less mitigation. Finally, the availability of high return opportunities decreases the wealth maximizing benefits of mitigation.

6. Conclusion

This paper considers the coastal property owner at catastrophic risk who wishes to maximize expected wealth while protecting the value of the home from hurricane wind damage. The owner seeks to mitigate expected damages by purchasing defensive measures, wind pool subsidized insurance, or combinations of both. Purchasing defenses or insurance, however, reduces the accumulation in a liquid wealth endowment.

Given current subsidized insurance prices, building codes, hurricane strike probabilities in an area at elevated hurricane risk, and a real after-tax rate of return of 4.9%, insurance is preferred to defensive measures. If insurance premiums increase or if hurricane strike probabilities or interest rates decrease, mitigation is preferred. Insurance and mitigation are substitutes when the deductible is low, as defensive measures that reduce damages below the deductible are extremely costly. If deductibles are greatly increased while premiums are decreased, insurance and mitigation can be complements.

We conclude that individuals in regions with strong building codes and subsidized wind insurance premiums are not necessarily myopic when they forego structural defenses. Under several alternative assumptions, expected wealth is maximized by refraining from structural mitigation activity. Though some insurance company rhetoric encourages homeowners to purchase structural defenses, current deductible levels (in the absence of mitigation-contingent premium reductions) are often too low to justify such purchases. An adverse selection dilemma evolves for the insurers and low-risk homeowners, as the higher risk owners opt out of costly mitigation and choose artificially low-priced (subsidized) insurance.

Allowing insurance companies to offer higher deductibles, or premium discounts for mitigation as in the state of Florida, might motivate structural defense purchases. Without the ability to provide incentives for homeowners to mitigate, however, insurers are oftentimes reduced to lobbying state legislatures for more strident building standards, as in the coastal areas of North Carolina following the series o f unprecedented hurricane strikes in the 1990's.

Acknowledgment

This research was funded by grants from the Center for Applied Real Estate Education and Research at the University of South Carolina and from the Cameron School of Business at the University of North Carolina at Wilmington. The authors thank three anonymous referees and session attendees at the 2001 AFS annual meetings in Toronto for their helpful comments .

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