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Insuring future climate catastrophes

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Abstract The combined influences of a change in climate patterns and the increased concentration of property and economic activity in hazard-prone areas has the potential of restricting the availability and affordability of insurance. This paper evaluates the premiums that private insurers are likely to charge and their ability to cover residential losses against hurricane risk in Florida as a function of (a) recent projections on future hurricane activity in 2020 and 2040; (b) insurance market conditions (i.e., soft or hard market); (c) the availability of reinsurance; and (d) the adoption of adaptation measures (i.e., implementation of physical risk reduction measures to reduce wind damage to the structure and buildings). We find that uncertainties in climate projections translate into a divergent picture for insurance in Florida. Under dynamic climate models, the total price of insurance for Florida (assuming constant exposure) could increase significantly by 2040, from $12.9 billion (in 1990) to $14.2 billion, under hard market conditions. Under lower bound projections, premiums could decline to $9.4 billion by 2040. Taking a broader range of climate change scenarios, including several statistical ones, prices could be between $4.7 and $32.1 billion by 2040. The upper end of this range suggests that insurance could be unaffordable for many people in Florida. The adoption of most recent building codes for all residences in the state could reduce by nearly half the expected price of insurance so that even under high climate change scenarios, insurance premiums would be lower than under the 1990 baseline climate scenario. Under a

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full adaptation scenario, if insurers can obtain reinsurance, they will be able to cover 100 % of the loss if they allocated 10 % of their surplus to cover a 100-year return hurricane, and 63 % and 55 % of losses from a 250-year hurricane in 2020 and 2040. Property-level adaptation and the maintenance of strong and competitive reinsurance markets will thus be essential to maintain the affordability and availability of insurance in the new era of catastrophe risk.

1 Introduction

Insurance is an important risk management tool; today the insurance industry absorbs around 40 % of catastrophe economic losses in the industrialized countries (Hoeppe and Gurenko 2006). This paper explores the potential implications of climate change for the availability and affordability of insurance in the United States focusing on wind-related property insurance in Florida. Specifically, the paper evaluates the implications of current and projected hurricane activity in the future on the price of insurance and the ability of the private insurance sector to provide coverage. We also evaluate the benefits of adaptation and competitive reinsurance markets in reducing premiums and increasing insurance coverage.

Recent experience suggests that the world has entered a new era of catastrophe risk. Of the 25 most costly insured catastrophes worldwide between 1970 and 2010, 15 have occurred since 2001. With the exception of the terrorist attacks on September 11, 2001, all 25 of these catastrophes were natural disasters. More than 80 % of these were weather-related events with nearly three-quarters of the claims in the United States (Kunreuther and Michel-Kerjan 2011). The observed increase in the costs of disasters results from several parallel influences. These comprise rapid population growth, an increase in the value at risk (e.g., more assets at risk in hurricane-prone areas), density of insurance coverage and the possible impact of global warming on the frequency and severity of hurricanes and flooding.

The state of Florida, the focus of this study, provides an example of why losses from natural disasters have increased so rapidly. Until recently, the economic impact of hurricanes there was limited due to Florida's low population; in 1950, the state ranked 20th in population in the U.S. with 2.8 million inhabitants. With the large influx of new residents, Florida was the fourth most populous state in the U.S. in 2010 with 18.8 million people, nearly a 570 % increase since 1950. It is estimated that, after correcting for inflation, the damage from Hurricane Andrew, which hit Miami in 1992, would have been more than twice as great if it had occurred in 2005 (Pielke et al. 2008).

This increased exposure to hurricanes is not unique to Florida. As of December 2007, Florida and the state of New York each had nearly $2.5 trillion[1] in insured property value located on the coast. The coastal insured value in the United States for the top 10 states combined accounts for more than $8.3 trillion (Kunreuther and Michel-Kerjan 2011). If one adds flood-related damage coverage by the federally-run National Flood Insurance Program, the insured property value at risk would be augmented by $1 trillion (Michel-Kerjan 2010). These figures reflect only the insured portion of the total exposure. Such huge concentrations of value in highly exposed areas indicates that any very strong hurricane that hits these regions is likely to inflict hundreds of billions of dollars of economic losses.

Cost-effective adaptation measures can play an important role in constraining losses from hurricanes. A recent analysis of four states, Florida, New York, South Carolina and

[1] All dollar figures used in this paper are in U.S. dollars.

Texas, reveals that if the latest building codes were enforced on all residential homes, damage from hurricanes would be reduced significantly. For example, losses from a hurricane with a 500-year return period hitting Florida would be reduced by more than 50 % compared to the status quo if all residential structures met the requirements defined by the Institute for Business and Home Safety (Kunreuther and Michel-Kerjan 2011). However, despite extensive experience with natural catastrophes and adequate resources to prepare for them, the United States still has inadequate loss-reduction measures in place to deal with large-scale natural disasters. Recent catastrophe losses and the failure of residents in hazard-prone areas to invest in adaptation measures highlight the challenges of reducing the impact of natural disasters (Bouwer et al. 2007; Cummins and Mahul 2009; Kunreuther and Michel-Kerjan 2011; Michel-Kerjan and Kunreuther 2012).

The impact of climate change on current and future risk is somewhat uncertain. The debate is still ongoing as to whether the series of major hurricanes that affected the USA in 2004, 2005 and 2008 might be partially attributable to anthropogenic climate change. It is clear that 2005 was one of the warmest years on record in the Atlantic basin region (e.g., Knutson et al. 2010; Hegerl et al. 2007) and that higher ocean temperatures lead to an exponentially higher evaporation rate in the atmosphere, which increases the intensity of hurricanes and the amount of precipitation. In the North Atlantic (Atlantic, Caribbean, Gulf of Mexico), the total number of Category 4 and 5 hurricanes rose from 16 in the period 1975–1989 to 25 in the period 1990–2004; however, the limited history of high quality data records means that it is currently not possible to discern whether this apparent trend is due to manmade climate change or part of a natural cycle.

Looking forward, Knutson et al. (2010) indicate that future projections based on theory and high-resolution dynamical models consistently reveal that globally, climate change will cause a shift in tropical storm intensities towards stronger storms. But the study is also cautious, stressing that, for all cyclone parameters, projected changes for individual basins show large variations between different studies. For the Atlantic Basin, the majority of the studies reviewed by Knutson et al. project, on average, an increase in storm intensity (i.e., maximum wind speeds), although a minority of individual models do project reductions. Given that damages from such storms are related to (at least) the cube of the wind speed (Emanuel 2005), all else being equal, an increase in the number of major hurricanes will translate into a greater number hitting the coasts and more severe damage to residences and commercial buildings in the coming years. These future projections raise issues with respect to the insurability of hurricane risk in hazard-prone areas.

To better understand the implications of future climate variability on the affordability and availability of insurance in hazard-prone areas, this paper address the following questions:

- What prices will insurers/reinsurers charge to cover wind damage from hurricanes in Florida in future years based on different climate scenarios under soft and hard market assumptions?
- How much insurance protection (i.e., capacity) will the private sector provide in Florida against losses from severe hurricanes with different return periods using different climate scenarios if they limit their capacity to a certain portion of their surplus?[2]
- What will be the impact on insurance/reinsurance prices and availability of coverage if all homeowners in Florida adopted recommended adaptation measures (i.e., those incorporated in the current statewide building code)?

[2] By surplus we mean the difference between an insurer's assets and liabilities, i.e., its net worth.

2 The price of insurance under different climate scenarios

2.1 Scenarios for hurricane risk in Florida and insured portfolio

Scenarios of future hurricane risk in Florida are taken from Ranger and Niehörster (2012) (hereafter, RN2012). RN2012 uses a climate-catastrophe modeling approach to generate a set of 24 scenarios based on the most recent hazard projections from the scientific literature. Six representative scenarios are selected from their set and are depicted in Table S1 of Online Resource A (*Scenarios of Future Hurricane Risk*). Our analyses focus specifically on two of these scenarios (from Bender et al. 2010) that reflect the upper- and lower-bound hazard projections from recent *dynamical* model simulations. Bender et al. use a technique known as dynamical-downscaling, which couples projections from a global circulation model (GCM) to a high resolution regional model able to simulate the characteristics of localized tropical storms. The two scenarios presented here are based on the GFDL-CM2.1 and UKMO-HadCM3 GCMs.[3]

The UKMO scenario predicts an average of 8.1 named storms in the Atlantic basin per year at horizon 2020 and 6.9 in 2040. This compares to 9.9 for the 1990 baseline. This model also predicts an average of 0.96 major storms (hurricanes of category 4 or 5) per year at horizon 2020 and 0.8 in 2040. This compares to 1.2 for the 1990 baseline. We refer to this as the low climate change scenario (see Figure S1 in Online Resource A).

The GDFL-CM2.1 scenario predicts an average of 9.8 named storms in the Atlantic basin per year at horizon 2020 and 9.7 in 2040. This model also predicts an average of 1.7 major storms (hurricanes of category 4 or 5) per year at horizon 2020 and 2.0 in 2040 (see Figure S1). We refer to it as a high climate change scenario. Further details on the hazard scenarios are given in Online Resource A and RN2012.

Some scientists have suggested that the range of outcomes predicted by current dynamically-based models (e.g., Bender et al. 2010) may be too narrow. For this reason, we also provide projections in Online Resource A for the *upper-bound* and *lower-bound* scenarios from RN2012 based on a statistical-downscaling approach as discussed in Vecchi et al. (2008). For purposes of this study, all scenarios should be treated with equal confidence.

These scenarios represent plausible long-term trends due to manmade climate change. They do not account for annual variability in hurricanes due to natural phenomena, such as the El Nino Southern Oscillation and the chaotic nature of weather. Such natural variations would occur in addition to the trend due to manmade climate change, meaning that losses in any particular year could be above or below the trend in average annual loss. Bender et al. 2010 and RN2012 suggest that changes in storm activity driven by manmade climate change are unlikely to exceed the range of this natural variability for at least a decade and potentially several decades. This means that estimates of annual losses (and the total insurance price) given in this study represent an average value over time (here, a 5-year average). Accordingly, actual values in a single year may be significantly above or below this value.

2.2 Pricing of hurricane insurance for the studied residential portfolio

The outputs of RN2012 are exceedance probability (EP) curves for each hazard scenario. Projections are given for 5-year time slices centered on 2020 and 2040. These EP curves use

[3] The climate model names are typically the names of the institutions that built them. GFDL-CM2.1 was built by the U.S. National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory. The UKMO model HadCM3 was built by the United Kingdom Met Office.

proprietary loss information provided by the modeling company Risk Management Solutions, Inc. (RMS) for a synthetic portfolio representing residential property in Florida. The portfolio (named the "Hybrid Exposure Set") is defined in Risk Management Solutions (RMS) (2010) and includes almost 5 million residential buildings across Florida, with a total insured value of $2 trillion. The portfolio represents residential exposure in Florida in 2009 and will be held constant over time across all our simulations.

For simplicity we treat this as a single insurance portfolio.[4] We investigate the price of different layers of risk for the entire residential property portfolio in Florida, where each layer represents a possible tranche of insurance or reinsurance coverage. We generated estimates of the Average Annual Loss (AAL) and standard deviations (σ) of the AAL for wind-related hurricane risk[5] for each layer of coverage under the set of climate scenarios and two vulnerability conditions: *Current Adaptation* and *Full Adaptation. Current Adaptation* characterizes the existing construction status of homes in Florida (as of 2009). The *Full Adaptation* condition upgrades all homes in Florida so they are in compliance with the Florida Building Code 2004. Given that most buildings in Florida were constructed prior to 2004 (85 % of the portfolio), this represents a significant upgrade in building standards in their resistance to wind and would require a significant capital investment to retrofit the existing residential building stock.

We assume that the representative insurer sets prices for different layers of coverage. More specifically, consider a layer of coverage (Δ) for wind damage from hurricanes in Florida (e.g., Δ=$5 billion to $10 billion). The price of insurance (P_Δ) for this layer of coverage is determined by calculating the average annual losses (AAL) in this layer and applying a given loading factor to it. The loading represents the additional premiums the insurer needs to charge to compensate for costs other than the expected loss (i.e., the marketing, brokerage, claims processing expenses, taxes, and cost of capital) while at the same time ensuring that the coverage earns a high enough expected return on equity so it is attractive so investors want to allocate some of their capital to this insurance company.

The price also reflects the variance of the AAL since this determines the amount of surplus (i.e., net worth) that should be kept liquid to protect the insurer against the possibility of insolvency or a significant catastrophe loss. As the variance of AAL increases, the insurer will charge a higher price for a given portfolio or layer of that portfolio to reflect the lower return that this portion of surplus can earn, so it is easily convertible to cash should a catastrophic loss occur.

As discussed in Kunreuther and Michel-Kerjan (2011), reinsurers often determine the premium (P_Δ) for a specific layer of coverage (Δ) that captures these concerns by using the following formula:

$$\mathrm{P}_\Delta = \mathrm{E}(\mathrm{L}_\Delta)(1+\lambda) + \mathrm{c}\cdot\sigma_\Delta \tag{1}$$

where $E(L_\Delta)$ is the expected loss or AAL for the given layer Δ, λ *is* the loading factor, σ_Δ is the standard deviation of a pre-specified portfolio of layer Δ and c can be viewed as the

[4] One could think of the portfolio of the Florida Hurricane Catastrophe Fund (FHCF) that has been providing subsidized reinsurance to *all* insurers in Florida since the aftermath of Hurricane Andrew in 1992. Note also that it would be a complex exercise to model the dynamics of any insurance market involving hundreds of companies of different sizes, natures (e.g., public, private, publicly traded, mutual), operations (e.g., Florida only, national, international), risk concentrations (e.g., homeowner coverage only or multi-risk lines). It would also require access to proprietary data that is beyond the scope of this paper. We thus assume that a representative insurer covering the whole state can reflect the market equilibrium in Florida.

[5] Storm surge losses are not included here.

degree of risk aversion of the (re)insurer. More specifically, a lower value of c translates into the insurer providing more capacity for a given price, all things being equal.

L_Δ reflects the loss distribution for layer Δ. The higher the value of σ_Δ, the more the insurer will want to charge for covering losses from layer Δ. An insurer who is highly risk averse (or whose shareholders are) will specify a higher value of c reflecting its concern with taking on any new book of business.

In order to reflect the cyclical nature of insurance markets due to competitive pressure, loss history, interest rates, etc., we also distinguish between two different market conditions.[6] We first look at what is often referred to as a “soft” market in the insurance industry. Soft markets typically are characterized by new entrants into the business, generous underwriting provisions, and aggressive discounting of premiums to gain volume. Hard markets occur when insurers and reinsurers want to charge a much higher price because they have suffered large losses from recent catastrophes and face a higher cost of capital to protect themselves against catastrophic losses.

To reflect these two market conditions in our Eq. (1), we assume based on our experience and discussions with insurers and reinsurers, that c=0.4 in a soft market and c=0.7 in a hard market. Six loss layers were specified, using attachment and exhaustion points so that losses double from one layer to the next (Fig. 1); that is, \$0 to \$5 billion for *Layer 0*, \$5 billion to \$10 billion for *Layer 1*, \$10 billion to \$20 billion for *Layer 2*, \$20 billion to \$40 billion for *Layer 3*, \$40 billion to \$80 billion for *Layer 4*, and greater than \$80 billion for *Layer 5,* the residual layer. With these defined layers, a loss model was run to determine $E(L_\Delta)$ and σ_Δ for each layer Δ.

Figure 1 depicts the return periods associated with the attachment and exhaustion points for the Florida portfolio under the baseline climate conditions (i.e., 1990), as well as the average annual loss and standard deviation for each layer. For example, Layer 4 which covers insured losses from \$40 billion to \$80 billion (i.e., \$40 billion in excess of \$40 billion in reinsurance terminology) has an attachment point with an annual probability of 1 in 40 and an exhaustion point with annual probability of 1 in 145.

In this paper, we assume that there is no loading factor on top of the pure premium (i.e., λ=0 in Eq. (1)) so $P_\Delta=E(L_\Delta)+c\cdot\sigma_\Delta$.[7] Tables 1 and 2 summarize the price of insurance for (a) different layers under the two market conditions (soft/hard market), (b) different years (1990, 2020, and 2040), and (c) the low and high climate change projections (i.e., the U.S. NOAA’s GFDL-CM2.1 model and the UKMO GMC model, respectively), assuming current adaptation levels for residences in Florida.[8]

Tables 1 and 2 show that there are important differences in the prices depending on the condition of the insurance markets and the climate change scenario used to generate losses in 2020 and 2040. For the baseline climate case of 1990, the premium for all layers of coverage ranges from \$9.3 billion (soft market) to \$12.9 billion (hard market). When projecting future losses, the insurance price to cover the portfolio falls by over 21 % in 2020 and 29 % in 2040 relative to the 1990 base case for the low climate change scenario (Table 1), and are projected to rise by around 5 % in 2020 and 10 % in 2040 for the high climate change scenario (Table 2).

[6] See Gron (1994) and Doherty and Garven (1995) for detailed discussion of the origins and implications of soft/hard market conditions on insurance underwriting cycles.

[7] It is also possible to compute the ratio $c\cdot\sigma_\Delta/(E(L_\Delta)$ to measure the effect of volatility on reinsurance prices but this is outside the scope of this paper.

[8] We assume that only one insurer provides coverage for the more than 5 million residences in the portfolio. Hence we cannot compare these results with what each insurer doing business in Florida in 1990 was actually charging for its individual portfolio.

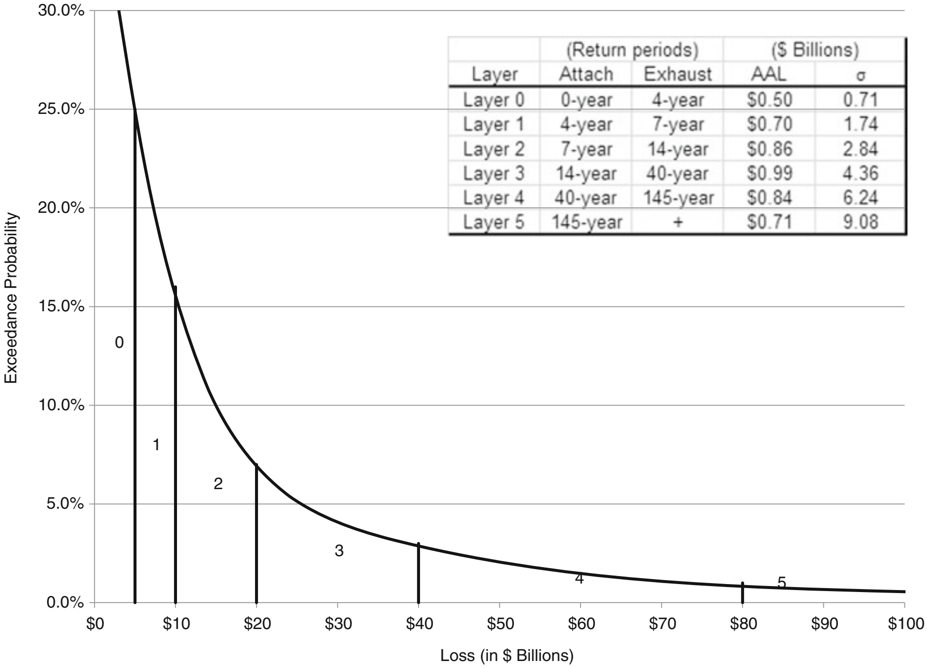

Fig. 1 Loss layers of the Florida residential portfolio for different return periods (baseline 1990 climate conditions and current adaptation)

The worst-case and best-case risk scenarios from RN2012 provide an even broader range of possible future prices (see Online Resource B for full data); from a baseline of $12.9 billion in 1990, to $4.7 billion (best case) to $24.2 billion (worst case) in 2020 and $4.7 billion (best case) to $32.1 billion (worst case) in 2040 under hard market conditions (Figures S2 and S3 in Online Resource B).

In other words, taking a hard market as an example, the price of insurance in 2020 could either drop 63 % or increase 88 % depending on which climate scenario one considers. In 2040, under the best-case climate scenario, prices will remain stable compared to 2020 but will increase by another 33 % under the worst-case scenario (which would be a nearly 150 % increase from the 1990 baseline).

These results present a real challenge for an insurer. If one focuses only on dynamic models, the range of possible climate scenarios is relatively manageable ([−29 %; +11 %] as shown in Tables 1 and 2). But if the insurer also integrates estimates from the statistical models (best- and worst-case scenarios we just discussed) the range become significant: ([−63 %; +150 %]) in 2040 relative to the 1990 baseline as depicted in Figures S2 and S3 in online Resource B.

3 Impact of adaptation on insurance price

Hurricane activity in the United States since the 1990s highlights the importance of investing in cost-effective loss reduction measures to property from future storms. Indeed, hundreds of billions of dollars of damages have resulted from severe winds and poorly designed structures in the affected areas.

Table 1 Price of insurance under UKMO low climate change scenario (in US$ billions)

Low estimate		All layers	Layer 0 0–4 years	Layer 1 4–7 years	Layer 2 7–14 years	Layer 3 14–40 years	Layer 4 40–145 years	Layer 5 145 years +
1990	PRICE (SOFT)	$9.3	$0.8	$1.4	$2.0	$2.7	$3.3	$4.3
	PRICE (HARD)	$12.9	$1.0	$1.9	$2.9	$4.0	$5.2	$7.1
2020	PRICE (SOFT)	$7.3 *(−21.5 %)*	$0.3	$0.9	$1.5	$2.2	$2.6	$3.9
	PRICE (HARD)	$10.3 *(−20.1 %)*	$0.4	$1.2	$2.1	$3.2	$4.1	$6.4
2040	PRICE (SOFT)	$6.6 *(−29.0 %)*	$0.2	$0.7	$1.3	$1.9	$2.4	$3.7
	PRICE (HARD)	$9.3 *(−27.9 %)*	$0.3	$0.9	$1.8	$2.9	$3.7	$6.0

Table 2 Price of insurance under NOAA high climate change scenario (in US$ billion)

High estimate		All layers	Layer 0 0–4 years	Layer 1 4–7 years	Layer 2 7–14 years	Layer 3 14–40 years	Layer 4 40–145 years	Layer 5 145 years +
1990	PRICE (SOFT)	$9.3	$0.8	$1.4	$2.0	$2.7	$3.3	$4.3
	PRICE (HARD)	$12.9	$1.0	$1.9	$2.9	$4.0	$5.2	$7.1
2020	PRICE (SOFT)	$9.8 *(+5.4 %)*	$0.8	$1.5	$2.1	$2.9	$3.5	$4.5
	PRICE (HARD)	$13.5 *(+4.7 %)*	$1.1	$2.1	$3.1	$4.3	$5.5	$7.3
2040	PRICE (SOFT)	$10.3 *(+10.7 %)*	$0.9	$1.7	$2.3	$3.1	$3.7	$4.6
	PRICE (HARD)	$14.2 *(+10.0 %)*	$1.2	$2.3	$3.3	$4.6	$5.8	$7.5

Values in brackets indicate changes from 1990

Table 3 Change in price of insurance over time under full adaptation for hard market

Year	High climate change scenario		Low climate change scenario	
	Current adaptation	Full adaptation	Current adaptation	Full adaptation
1990	$12.9 billion	$5.8 billion	$12.9 billion	$5.8 billion
2020	$13.5 billion	$6.3 billion	$10.3 billion	$5.0 billion
2040	$14.2 billion	$7.2 billion	$9.3 billion	$4.4 billion

This section examines the role that adaptation (i.e., implementation of physical risk reduction measures to make buildings more resilient to wind) can play in reducing expected losses and variance, thus the price of insurance.[9] The adaptation measure we consider is the adoption of a package of physical property-level resistance and resilience measures consistent with the Florida Building Code 2004.

We evaluated the impact of *Full Adaptation* on wind-related losses from hurricanes by calculating new EP curves based on proprietary information provided by Risk Management Solutions. For this analysis, we utilize only the high and low climate change dynamical scenarios.

Based on Eq. (1), Table 3 compares the price of insurance for the *Current Adaptation* and *Full Adaptation* scenarios for a hard market where $c=0.7$ for the two climate change scenarios. When all structures utilize adaptation measures as specified in Florida's building code for hurricane-prone areas (*Full Adaptation*), the price of insurance falls significantly. For example, under baseline 1990 climate conditions (Table 3; first row), the total price to cover all structures in Florida decreases from $12.9 billion in the *Current Adaptation* scenario to $5.8 billion in the *Full Adaptation* scenario. The change in price in 2020 and 2040 with climate change, with and without adaptation, is depicted graphically in Fig. 2, where the arrows represent the price difference with adaptation.

Consider the estimates for 2040 (Table 3; third row). Under a high climate change scenario, adoption of the building codes for all residences in Florida will decrease the price of insurance by nearly half every year, from $14.2 billion to $7.2 billion. This shows that even in the case of a high climate change scenario, full adaptation leads to insurance prices much lower than under the 1990 climate based on current adaptation.

We also look at events with specific return-periods. Table 4 compares the gross wind losses in Florida from hurricanes with return periods of 100, 250 and 500 years with current and full adaptation measures in place. The impact of *Full Adaptation* is highly significant, cutting the loss by more than 50 % for the 100-year return period, and by approximately 45 % and 40 % for the 250- and 500-year return period hurricanes, respectively.

4 Ability of insurers to cover losses with and without adaptation

This section examines the ability of the insurance industry to cover losses from hurricanes. Specifically, we determine what fraction of losses from a 100-year, 250-year and 500-year

[9] For instance, homes can be retrofitted by reinforcing gabled roofs, applying additional adhesives to roof shingles, installing hurricane straps and clips to ensure the roof stays in place despite high winds. Hurricane resistant shutters, as well as impact resistant glass, may help keep windows closed from driving rain, despite flying debris. One can also reinforce garage doors and entry doors.

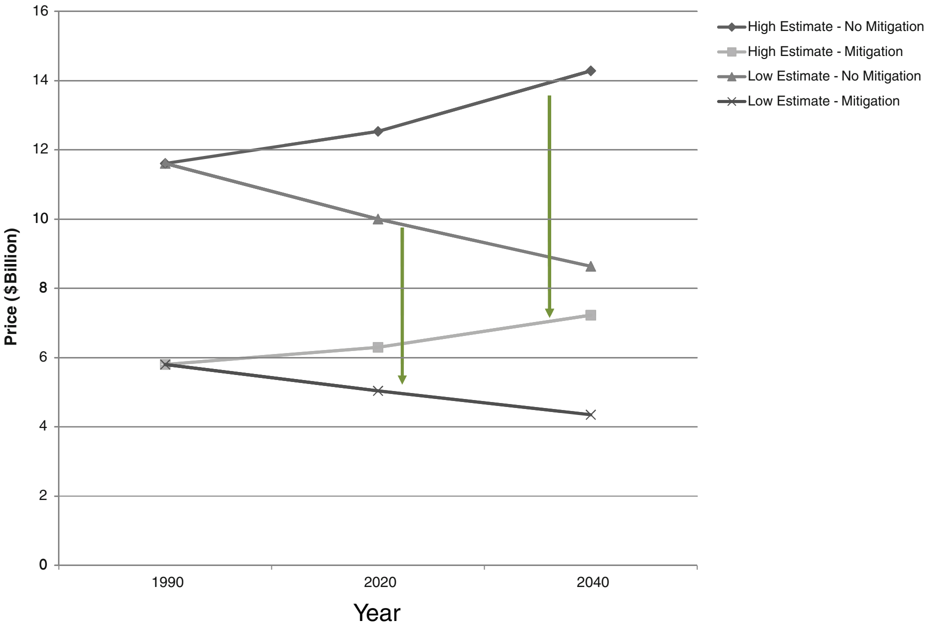

Fig. 2 Change in price of insurance with full adaptation for the high and low climate change scenarios

hurricane the private insurance market could cover in scenarios with and without climate change and adaptation measures in place if reinsurance were available. To determine how much capacity insurers are willing to provide to cover losses from such hurricanes in a competitive market, we follow the methodology developed in Kunreuther and Michel-Kerjan (2011) and outlined in Online Resources C (*Calculations of the Percentage of Loss Covered by the Private Market*). We assume that each insurance group operating in Florida is willing to risk 10 % of its surplus to provide coverage for wind losses from hurricanes that have a 100-year, 250-year or 500-year return period. This 10 % figure was confirmed as a reasonable assumption for these analyses by insurers and rating agencies. Insurers limit the portion of their surplus covering a specific risk in a given region as a central part of their geographical diversification strategy. By diversifying their portfolio, say between floods in Europe, earthquakes in China and hurricane risks in Florida, they avoid putting all their eggs in the same basket. The logic is that with 40 % or 50 % exposure in Florida (often considered the world peak zone for hurricanes), an insurer would inevitably face a very serious liquidity issue, if not insolvency, should a cat 3 or cat 4 hurricane hit Florida. A rating agency will consider this insurer too exposed and give it a lower rating, which in turn means that the insurer will have to purchase capital (from banks or reinsurers) at a higher cost.

The total amount of funds that insurers have available to cover losses from hurricanes in Florida that reflects 10 % of their surplus is $15.4 billion.[10] We analyze the percentage of loss covered and the required surplus for full coverage of the risk by the private insurance industry, under two assumptions: (1) insurers cannot purchase reinsurance and (2) they can purchase

[10] In reality, of course, the determination by each insurer as to how much surplus it is willing to assign to a specific risk (e.g., wind damage) in Florida depends on its financial characteristics (assets, credit rating), the distribution of its portfolio for that risk and other risks in Florida as well as other states and other countries, its risk appetite, and how much state insurance regulators allow it to charge to cover the risk.

Table 4 Effect of full adaptation on hurricane wind losses ($ billions)

Adaptation case	Return period (years)	1990	2020		2040	
		All	Low climate change scenario	High climate change scenario	Low climate change scenario	High climate change scenario
Current Adaptation	100	$51	$44	$55	$36	$63
	250	$80	$73	$88	$64	$100
	500	$113	$107	$116	$92	$126
Full Adaptation	100	$24	$20	$27	$15	$34
	250	$46	$39	$51	$35	$57
	500	$68	$60	$72	$51	$78

reinsurance to provide more hurricane risk coverage. The methodology is described in the supplemental online material along with a graphical representation of our findings *with* and *without* access to reinsurance (see results in Online Resource D, Figures S4 and S5).

Table 5 focuses on the second assumption where insurers can purchase reinsurance. The findings in Table 5 indicate that with the current status of buildings in Florida (*Current Adaptation*) the insurance industry is not able to provide protection against a significant portion of the losses even for hurricanes with 100-year return periods. Table 5 also indicates the significant impact that enforcement of building codes and retrofitting of existing properties would have on the ability of insurers to cover losses from these hurricanes (*Full Adaptation*).[11] To see this, one only has to look at the percentage of losses covered by insurers in the *Current Adaptation* case. With the high climate change scenario and *Full Adaptation*, all structures will be insured for the 100-year hurricane in the year 2040 compared to only 62 % in the *Current Adaptation* scenario.

When reinsurance is available and all homes meet current building codes, insurers are able to cover all losses from hurricanes with a 100-year return period, and between 55 % and 91 % of losses for hurricanes with a 250-year return period, as shown in Table 5. This percentage of coverage is much larger than for the *Current Adaptation* scenarios with reinsurance in place where insurers can cover between 32 % and 50 % of the losses from a hurricane with a 250-year return period.

5 Discussion

This paper constitutes a first attempt to systematically measure the implications of future climate scenarios for the pricing of catastrophe risk insurance and providing capacity under various insurance market conditions, adoption of cost-effective loss reduction measures and the availability of reinsurance. Based on current building designs and using a high climate change scenario, the price of insurance could increase increase significantly, possibly to the point where it becomes unaffordable for many people in Florida. Furthermore, there would be limited capacity by insurers to cover the losses from a severe hurricane. Reinsurance and

[11] The current analysis reflects only the benefits of adaptation measures. Some of these measures may not be cost-effective on existing structures but worthwhile undertaking when they are integrated into the design of new construction as shown by Aerts and Botzen (2011a) and Jones et al. (2006) for the design of buildings with respect to the flood risk.

Table 5 Percentage of loss covered and required surplus for full coverage by insurers *with reinsurance*. Comparison of *Current and Full Adaptation* ($ billions)

Year	Scenario	Return period (years)	Full adaptation				Current adaptation			
			Gross losses	Reinsurance coverage	Unreinsured losses	Percent of market covered	Gross losses	Reinsurance coverage	Unreinsured losses	Percent of market covered
1990		100	$24	$14.3	$9.4	100 %	$51	$30.6	$20.1	76 %
		250	$46	$23.6	$22.1	70 %	$80	$41.5	$38.8	40 %
		500	$68	$29.2	$38.6	40 %	$113	$48.5	$64.0	24 %
2020	High Climate Change Scenario	100	$26.9	$16.2	$10.7	100 %	$54.8	$33.1	$21.8	71 %
		250	$50.8	$26.2	$24.5	63 %	$87.8	$45.4	$42.4	36 %
		500	$72.4	$31.2	$41.2	37 %	$116.4	$50.2	$66.2	23 %
	Low Climate Change Scenario	100	$19.9	$12.0	$7.9	100 %	$43.5	$26.3	$17.3	89 %
		250	$38.5	$19.9	$18.6	83 %	$72.5	$37.5	$35.0	44 %
		500	$59.8	$25.8	$34.0	45 %	$106.9	$46.1	$60.9	25 %
2040	High Climate Change Scenario	100	$34.1	$20.6	$13.5	100 %	$62.9	$37.9	$25.0	62 %
		250	$57.4	$29.7	$27.7	55 %	$100.0	$51.7	$48.3	32 %
		500	$77.9	$33.6	$44.3	35 %	$125.7	$54.2	$71.5	21 %
	Low Climate Change Scenario	100	$15.0	$9.1	$6.0	100 %	$35.9	$21.7	$14.3	100 %
		250	$34.9	$18.0	$16.8	91 %	$64.2	$33.2	$31.0	50 %
		500	$51.4	$22.2	$29.2	53 %	$91.6	$39.5	$52.1	29 %

A graphical representation of these results along with those without reinsurance is provided in Online Resource D loss reduction measures can thus increase the availability of insurance in Florida and make it more affordable even under the worst-case climate change scenario we studied.

Adaptation significantly reduces the estimated price of insurance and its uncertainty for any given climate scenario, For example, for a hard market in 2020 the range for the high and low climate change scenarios under the *Full Adaptation* scenario (i.e., with all buildings retrofitted to meet the Florida Building Code 2004) is $5–6 billion compared to a premium range of $10–14 billion with the existing status of buildings (*Current Adaptation*).

Future research could expand the scope of the analysis undertaken in this paper by integrating other climate projections and incorporating the cost of adaptation measures into the analysis. One could then undertake a meaningful benefit-cost analysis under different annual discount rates and time horizons. The resulting premium reductions provided by insurers to property owners could then be compared with the costs of a multi-year loan designed to encourage investment in these risk reduction measures. The *Full Adaptation* scenario, which represents retrofitting 85 % of properties so that they meet the Florida Building Code 2004, is an extreme measure that will be costly to implement. Further research should explore other options, such as retrofitting the highest risk homes and strengthening codes in areas with the highest hurricane risk.

This study has explored only the impacts of climate change on losses. An important (and much less uncertain) driver of losses in Florida is population growth and the accumulation of assets in hurricane-prone areas. Projections of the U.S. Census Bureau suggest that by 2020, the population of Florida could be more than 20 % higher than in 2010. If we assume that the spatial distribution of exposure remains constant, this suggests that aggregate losses could increase by an additional 20 % in 2020 (and much more in some counties of the state). Exposure is growing fastest in hurricane- and flood-prone locations in urban areas on the coast. The effect of this trend on the availability and price of insurance is an open question for further study.

Research is also required to explore approaches to enhance the uptake of risk reduction measures. Our study demonstrates the considerable financial benefits of adaptation, but empirical evidence reveals that many people do not invest voluntarily in such measures even when they are cost effective. It is thus important to appreciate the challenges in incentivizing individuals and enterprises located in disaster-prone areas to invest in those measures and purchase adequate levels of insurance coverage so as to reduce the need for government disaster relief (Kunreuther et al. 2012).

Jaffee et al. (2010) and Michel-Kerjan and Kunreuther (2011) propose encouraging homeowners to invest in cost-effective adaptation measures through multi-year insurance contracts. These multi-year contracts would make the probability of a disaster occurring during the length of the contract more salient and the benefits of adaptation clearer.[12]

6 Conclusions

Recent state-of-the-art climate projections indicate the potential for an increase in hurricane risk in Florida. This paper has attempted to systematically measure the implications of such scenarios for the affordability and availability of private insurance for homeowners. We focus our analyses on two scenarios that represent an upper and lower bound based on current dynamically-based model projections.

[12] See Aerts and Botzen (2011b) for an application of this concept to flood in the Netherlands.

We find that the total price of insurance for Florida (assuming constant exposure) could increase significantly by 2040, from $12.9 billion (in 1990) to $14.2 billion, under hard market conditions. Under the lower-bound projection, premiums could decline to $9.4 billion by 2040. Taking a broader range of climate change scenarios, prices could be between $4.7 and $32.1 billion by 2040. At the upper end of this range, private insurance may become unaffordable for many people in Florida. Adaptation significantly reduces losses and premiums under all scenarios and extends the amount of coverage that could be provided by the private insurance market. The implementation of loss reduction measures and provision of reinsurance against catastrophic losses can increase the availability of insurance in Florida and make it more affordable to residents of the state even under a high climate change scenario.

One of the key messages of this paper is the importance of undertaking scientific assessments of the likelihood and consequences of future hurricanes and permitting insurers to set premiums. This has not been the case in Florida as illustrated by what occurred in the state after the 2004/2005 hurricane seasons. Insurers were not allowed to charge premiums that they felt reflected their risk so many discontinued coverage in the state. As a result, many homeowners could not obtain insurance against wind damage from hurricanes. The state-run company, Citizens Property Insurance Corporation, came into the breach by offering coverage at highly subsidized rates but would have been insolvent had there been a severe hurricane in Florida. Fortunately for Citizens and the residents of Florida, there have been no severe hurricanes between 2006 and 2012. A major hurricane in the coming years might prove that this subsidized premium strategy is not sustainable in the long-run.

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