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# Measuring the Climate Risk Exposure of Insurers

Hyeyoon Jung | Robert Engle | Shan Ge | Xuran Zeng

## **Measuring the Climate Risk Exposure of Insurers**

Hyeyoon Jung, Robert Engle, Shan Ge, and Xuran Zeng

*Federal Reserve Bank of New York Staff Reports*, no. 1066

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### **Abstract**

Insurance companies can be exposed to climate-related physical risk through their operations and to transition risk through their \$12 trillion of financial asset holdings. We assess the climate risk exposure of property and casualty (P&C) and life insurance companies in the U.S. We construct a novel physical risk factor by forming a portfolio of P&C insurers' stocks, with each insurer's weight reflecting their operational exposure to states associated with high physical climate risk. We then estimate the dynamic physical climate beta, representing the stock return sensitivity of each insurer to the physical risk factor. In addition, using the climate beta estimates introduced by Jung et al. (2021), we calculate the expected capital shortfall of insurers under various climate stress scenarios. We validate our approach by utilizing granular data on insurers' asset holdings and state-level operational exposure. Our findings indicate a positive association between larger exposures to risky states and higher holdings of brown assets with higher sensitivity to physical and transition risk, respectively.

Key words: insurance, climate change, physical risk, transition risk

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# 1 Introduction

As climate change worsens, many natural disasters are becoming more frequent and severe. Households and businesses hedge natural disaster risk with insurance companies. To shed light on the ability of the insurance sector to withstand climate change, it is crucial to understand insurers' exposure to climate risk. Moreover, how climate change affects financial stability is an important topic for financial institutions, regulators, and academics. As important financial institutions, insurers' exposure to climate risk is a key channel through which climate change risk can threaten broader financial stability.

Climate change risks, commonly categorized into physical risk and transition risk, can significantly impact insurance companies. Physical risk relates to the potential damage caused by extreme events and climate pattern shifts, while transition risk arises from policy, technology, and preference changes towards less carbon-intensive economies. On the physical risk side, insurance companies may face unexpected claim payouts exceeding projections due to the increasing frequency and intensity of natural disasters.<sup>1</sup> Moreover, insurers' asset side can also be affected as physical climate events could cause losses to the value of financial assets. For example, sea level rise or hurricanes can cause damage to coastal properties, thereby decreasing the value of mortgage bonds. On the transition risk side, insurers can also be exposed through their \$12 trillion of asset holdings. Those that invest heavily in fossil fuel companies may suffer adverse effects as these assets become "stranded" amid the shift away from fossil fuels. These outcomes can magnify the impact on insurers' current and future profits, ultimately leading to systemic undercapitalization of the insurance sector. The global financial crisis has demonstrated the negative externalities that arise from undercapitalized financial institutions including insurance companies, emphasizing the importance of addressing potential climate change risks.

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<sup>1</sup>[Holzheu et al. \(2021\)](#) forecasts that global property insurance premiums will rise by 5.3% annually to 2040, with climate change as the main driver. If natural hazard events increase in frequency, scope, and severity, the existing catastrophe models and rate-setting practices used by insurers may become less effective ([International Association of Insurance Supervisors, 2018](#)).

Despite its significance, our understanding of climate change risk, including both physical and transition risks, in the insurance sector remains limited. The omission of the insurance sector in many regulatory climate stress tests is a notable concern, as highlighted by [Financial Stability Board and Network of Central Banks and Supervisors for Greening the Financial System \(2022\)](#). Out of the 35 stress testing exercises conducted by 23 jurisdictions at both country and EU levels, only one-third of the exercises incorporated the insurance sector (e.g., [Bank of England, 2021](#); [Autorité de Contrôle Prudentiel et de Résolution, 2020](#)). A recent review conducted by [Acharya et al. \(2023\)](#) calls for research on the effects of climate change on insurance companies.

One major challenge comes from the measurement of risk and insurers' exposure to such risk, especially physical climate risks. First, adequate and reliable data on climate risks is crucial for assessing insurers' exposure. Data on future climate scenarios and projections are inherently uncertain and subject to various modeling assumptions, further complicating risk measurement. One solution is to use historical data to proxy for such future risks. However, historical data on climate-related disasters may be limited, especially for long-tail events with low frequency but high severity. Second, climate risks are dynamic and can evolve over time. Insurers' exposure to climate risks may change as new hazards emerge or existing risks intensify. This time-varying nature of climate risks and insurers' exposure adds complexity to their measurement.

In this paper, we use a novel approach to quantify the climate risk exposure of insurance companies. We use a market-based approach, relying solely on publicly available data including those from the stock market, which effectively tackles the first challenge stemming from the lack of adequate and reliable data. Specifically, we construct several portfolios that are designed to fall in value as physical risk rises. For instance, we exploit data on US property and casualty (P&C) insurers' premiums across states, combined with data on state-level natural disaster events. We form a portfolio of the P&C insurers in the U.S. where the weight is each insurer's premium exposure to the states with high past damages

due to natural disasters, and we refer to the return on this portfolio as an *insurer premium physical risk factor*.<sup>2</sup>

To test the validity of the constructed physical risk factors, we conduct event study analyses and show that the factors decline after natural disaster events with large economic damages. This empirically validates the factors, as it indicates that insurers with significant exposure to states associated with high physical risk on average experience a decline in stock returns following severe natural disasters.

Using the constructed physical risk factors, we estimate insurers' stock return sensitivity, *physical climate risk beta*. To capture the *time-varying* nature of this beta, we employ the dynamic conditional beta model proposed by Engle (2002, 2016), addressing the challenge of the inherent uncertainties and modeling assumptions associated with future climate scenarios and projections. Then, we compute insurers' expected capital shortfall in a climate stress scenario, which we call *CRISK*, using the climate beta estimates within the framework proposed by Jung et al. (2021). By incorporating transition risk factors, developed by Jung et al. (2021), in addition to our physical risk factors, we quantitatively analyze insurance companies' exposure to climate risk in both dimensions.

We apply the methodology to large life insurers and P&C insurers in the U.S. to understand their climate change risk exposure. We focus on life insurers' transition risk exposure and P&C insurers' physical risk, since life insurers have a much larger portfolio of financial assets (\$9.4 trillion) than P&C insurers (\$3 trillion) and P&C insurers are more naturally exposed to physical risk than life insurers.

On the life insurer's transition risk side, we observe a notable increase in their transition climate beta during the 2019-2020 collapse of fossil fuel prices. Furthermore, our findings reveal a significant increase in the aggregate transition *CRISK*, which represents the expected capital shortfall in a severe transition risk scenario. Specifically, from 2019 to 2020, the ag-

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<sup>2</sup>We additionally propose a few portfolios capturing various types of risk. For example, we proxy insurers' physical risk exposure based on their premiums and losses. We assign portfolio weights to each insurer based on losses relative to its market capitalization.

gregate CRISK of all life insurers in the U.S. increased by more than \$150 billion, equivalent to approximately 28% of their market cap. Our analysis reveals that the expected capital shortfall solely attributed to climate stress, known as *marginal CRISK* (mCRISK), experienced an increase of more than \$85 billion during the same period. Compared to banks which experienced an increase of more than \$500 billion in CRISK and around \$100 billion in mCRISK over the same time period, the magnitude of transition climate beta is similar, while the CRISK and mCRISK in dollars are smaller, partly because banks' balance sheets are larger than insurers'.

On the P&C insurers' physical risk side, we find that their climate beta went up sharply during 2008-2010; however, we do not find any secular trend in the climate beta. The top ten P&C insurers' CRISKS have mostly been negative, suggesting no sign of potential systemic undercapitalization. As of the end of 2020, their aggregate mCRISK stood at \$20 billion, representing 8% of their market capitalization.

We next assess the validity of our methodology. On the liability side, we investigate the relationship between the estimated physical climate beta of P&C insurers and their exposure to physical risk through operations. We utilize P&C insurers' premium data based on their annual regulatory filings, which provide information on the premiums collected by insurers in each state. We use the occurrence of weather disasters at the state level to proxy for each state's climate risk. We characterize insurers' level of physical risk exposure by measuring their exposure to each state using the premium data and our measure of state-level climate risk.

We observe a significant positive correlation between insurers' market-based physical climate beta and the proportion of their premiums in high-risk states, indicating that insurers who have a larger share of their policies in states that face greater natural disaster risks have higher exposure to physical climate risk based on our measure. This evidence corroborates the economic validity of our physical climate risk measure.

On the asset side, we undertake an empirical comparison by investigating the relationship

between the estimated transition climate beta of life insurers and their corresponding asset holdings. We obtain insurers’ asset holdings from insurers’ statutory reports, which provide detailed information on insurers’ investments in equities, corporate bonds, municipal bonds, and other assets annually. We focus on life insurers’ corporate bond holdings, which make up on average 34% of their invested assets, their largest category of investment (Ge and Weisbach 2021). By linking corporate bonds to their respective industries using CUSIP and NAICS, we characterize insurers’ assets by industry.<sup>3</sup>

We document that insurers’ market-based transition climate beta aligns with their holdings of corporate bonds that are exposed to transition risk. In other words, insurers who have a larger share of their corporate bond investments in industries that face greater risks related to climate transition, have higher exposure to transition climate risk based on our measure. This correlation is significantly positive after controlling insurers’ characteristics and after adding the insurer fixed effects.

**Contribution to Literature** This paper contributes to the growing body of literature studying the effect of physical climate risk in various asset markets, including equities (Acharya et al., 2022; Alekseev et al., 2022), fixed-income (Acharya et al., 2022; Goldsmith-Pinkham et al., 2022; Painter, 2020; Auh et al., 2022; Liu et al., 2021), and real estate (Giglio et al., 2021b; Bernstein et al., 2019; Ge et al., 2022).<sup>4</sup> We propose a novel approach to measure forward-looking physical climate risk, which is new to the literature. Specifically, we develop a novel approach to construct a physical risk factor that is designed to decrease in value as physical risk escalates. Additionally, through event study analyses, we empirically demonstrate the decline of the proposed physical risk factor subsequent to natural disaster events with significant damages. Our factor can potentially be used to measure physical

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<sup>3</sup>To ensure robustness, we use multiple approaches to identify brown corporate bonds. We classify corporate bonds as brown if they are issued by coal mining, gas mining, gas utilities, and electric utilities. Additionally, we characterize corporate bonds based on the issuer industry’s stock return sensitivity to transition climate risk, measured by transition climate beta.

<sup>4</sup>Acharya et al. (2023); Giglio et al. (2021a); Hong et al. (2020); Krueger et al. (2020) provide comprehensive reviews of the literature on climate risk and financial system.



risks of firms beyond the insurance sector.

This paper is closely related to [Jung et al. \(2021\)](#), who propose a market-based approach called CRISK to measure climate transition risk exposure of financial institutions. We contribute beyond the existing CRISK framework in two important ways. First, we construct a physical risk factor and propose a way of measuring physical risk exposure, which can be generalized to other firms beyond the insurance section. Second, we focus on insurers, recognizing the critical importance of analyzing their liability side to comprehensively assess their climate risk exposure. Unlike banks, P&C insurers' liabilities predominantly stem from policyholder claims and obligations which can be directly exposed to physical climate risk. This distinction underscores the unique nature of insurers' risk profiles and necessitates a distinct approach to evaluating their climate risk.

Additionally, this paper contributes to the literature studying the impact of climate change on the insurance sector. We are the first paper, to our knowledge, to come up with measures of forward-looking physical risks faced by insurers. Previous studies ([Hagendorff et al., 2015](#); [Howerton and Bacon, 2017](#); [Schuh and Jaeckle, 2023](#)) have examined the relationship between disasters and insurers' stock prices. Some studies suggest that increased physical climate risk leads to an increase in demand for insurance. If insurers are able to adjust premia appropriately, physical climate risk might not impact expected profits ([Holzheu et al., 2021](#); [Alekseev et al., 2022](#); [Grimaldi et al., 2020](#)). However, other studies suggest that the above mechanism is limited due to financial and regulatory frictions. [Ge \(2022\)](#) document that following P&C divisions' losses due to unusual weather damages, life divisions change prices in order to generate more immediate financial resources. [Ge and Weisbach \(2021\)](#) suggest that when P&C insurers become more constrained due to operating losses (damage caused by weather shocks), they shift towards safer bonds on the asset side. [Oh et al. \(2022\)](#) find that insurers may be less prepared to deal with large losses and may respond by exiting markets or dropping important product features, though this kind of action is limited due to the rate-setting frictions. [Massa and Zhang \(2021\)](#) document that prop-

erty and reinsurance companies react to Hurricane Katrina by shifting from bond financing to bank-based borrowing. While these papers suggest that insurers are implementing risk management strategies, it is not clear to what extent insurers could manage their risk of undercapitalization in the face of abrupt physical or transition risk realizations.

**Outline of the Paper** The remainder of the paper proceeds as follows: Section 2 describes the data. Section 3 develops various climate stress scenarios by constructing physical climate risk factors. Section 4 analyzes P&C insurers’ exposure to physical climate risk, and section 5 studies life insurers’ exposure to transition climate risk. Section 6 examines the systemic climate risk exposure of insurers. Section 7 validates the measures. Section 8 concludes.

## 2 Data

Drawing from the insurance literature and recognizing that different types of insurers may face distinct climate risks, we classify insurers into two categories: P&C insurers and life insurers.<sup>5</sup> Our sample period covers 2000 to 2023.

Our analysis relies on three primary sources of data: (i) natural disaster event data to capture climate-related physical risk; (ii) stock and corporate bond data to construct market-based climate risk factors; and (iii) insurers’ asset holdings and operational exposure data to investigate the relationship between climate risk and insurers’ assets and liabilities.

**Natural Disaster Event Data** We utilize monthly data from National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Information to construct physical risk factors. This data is sourced from the Spatial Hazard Events and Losses Database for the United States ([SHELDUS](#)) database, which provides information on

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<sup>5</sup>We identify P&C insurers using the NAICS (North American Industry Classification System) code 524126. Then we manually look up each firm’s main focus and delete insurers who are not property (and casualty) insurance, multi-line insurance, specialty insurance, or reinsurance firms. We identify life insurers using SIC (Standard Industrial Classification) code 6311. Then we combine our data with [Koijen and Yogo \(2022\)](#) life insurer list to create our final list of life insurers.

natural hazard events and their economic losses across the country from 1980 to 2019. SHEL-DUS includes data on hurricanes, tornadoes, floods, wildfires, earthquakes, and more. Our focus is on assessing property damage resulting from coastal, drought, flooding, heatwaves, hurricanes, wind, wildfire, and winter weather disasters. In [Figure 1](#), the map displays the average county-level property damage caused by all hazards from 2000 to 2019, with California, Texas, and Florida being particularly affected. Panel A of [Figure 1](#) presents summary statistics of property damage for different hazard types, highlighting hurricanes and floods as the most destructive disasters.

To validate our physical risk factors, we employ the [Billion-Dollar Weather and Climate Disasters Database](#) maintained by NOAA, which tracks *daily* weather and climate events causing at least one billion dollars in damage from 1980 to 2023. This database provides additional details, including start and end dates, event summaries, CPI-adjusted estimated costs, and fatalities. It covers a range of disasters, such as droughts, floods, winter events, hurricanes, and wildfires. Panel B of [Figure 1](#) presents the summary statistics of Billion Dollar disaster events, highlighting hurricanes, droughts, and wildfires as the most destructive shocks. While hurricanes, winter disasters, and winds typically last less than a week, flooding, wildfires, and droughts can persist for months.

**Stock and Corporate Bond Data** In the construction of physical risk factors, we use the U.S. P&C insurance companies' stock returns from CRSP-Compustat merged data set. We use a risk-free rate from [Kenneth R. French Data Library](#). Additionally, we gather corporate bond information from Mergent Fixed Income Securities Database (FISD), municipal bond characteristics from Mergent Municipal Bond Database, and municipal bond transaction data from MSRB's Municipal Securities Transaction Data.<sup>6</sup>

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<sup>6</sup>We utilize the crosswalk developed by [Acharya et al. \(2022\)](#) to link municipal bond issuers with their corresponding county locations. We thank Viral Acharya, Tuomas Tomunen, and their coauthors for sharing the data.

**Insurers’ Asset Holdings and Operational Exposure Data** In order to measure insurers’ liability-side exposures to physical risk, we utilize individual insurers’ direct premiums earned (DPE) at the state-year level in homeowners’ multiple peril line and commercial multiple peril line from the National Association of Insurance Commissioners (NAIC) and SNL Financial.<sup>7</sup> To study the relationship between insurers’ climate risk and their asset holding, we obtain insurers’ holding data from Schedule D Part 1 of the Annual statement.

## Sample Characterization

We first focus on large insurance companies to understand their climate risk exposure, and then analyze the systemic risk of all insurers in the U.S. in section 6. Table 1 presents the summary statistics of the top ten P&C insurers and life insurers based on their average market capitalization from 2000 to 2021.<sup>8</sup>

**P&C Insurers** To understand P&C insurers’ operational exposure to risky states, we construct *risky state exposure*, defined as the share of premium earned from risky states:

$$\text{Risky State Exposure}_{it} = \frac{\text{Premium Earned from Risky States}_{it}}{\text{Total Premium Earned}_{it}}$$

We identify risky states as Texas, Florida, and California, the top three states in terms of the average annual property damage caused by all hazards based on historical data from SHELDUS. These states have recorded average annual property damage caused by all hazards of \$ 4.07 billion, \$ 2.94 billion, and \$ 2.36 billion, respectively, from 1980 to 2019 (all in adjusted U.S. dollars with the base year of 2019).

If an insurer’s operation is well diversified across a number of states, even if it collects a large amount of premiums in a risky state, its diversification will dampen the effect of

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<sup>7</sup>The NAIC also offers insurers’ direct losses incurred at the state-year level. Both DPE and LSS reflect insurers’ liability exposure to each state and are strongly correlated. In this paper, we utilize DPE as a measure of insurers’ exposure.

<sup>8</sup>Note that we analyze American International Group separately given its speciality.

its total exposure to the risky states. To measure the degree of each insurer’s operational portfolio diversification, we compute *Concentration* of each insurer’s portfolio similar to the Herfindahl-Hirschman Index (HHI):

$$Concentration_{i,t} = \sum_{j \in J} (\text{DPE Exposure}_{i,j,t})^2 \quad (1)$$

where  $\text{DPE Exposure}_{i,j,t}$  is insurer  $i$ ’s share of premium earned in state  $j$  in year  $t$ . A higher *Concentration* value indicates a lower level of diversification, implying that the insurer predominantly sells policies in a small number of states. *Concentration* equals 1 indicates that the insurer sold 100% of its policies in a single state.

The last two columns in Panel A of [Table 1](#) display P&C insurer operational exposure to states in the U.S. On average, the top ten P&C insurers collect approximately 18.6% of their premiums in risky states. However, there is significant variation among insurers, with percentages ranging from 3.6% to 29.2%. For example, Allstate earns approximately 16% of its premiums in California, and 7% each in Texas and Florida. The average *Concentration* of the top ten P&C insurers is 0.07, indicating that, an average insurer’s operational exposure is well diversified across states.

**Life Insurers** To understand life insurers’ corporate bond portfolio exposure to brown industries, we construct two measures. We define *brown share* as the fair value of brown corporate bonds divided by the fair value of all corporate bonds held by the insurer. To identify brown industries, we build on the general equilibrium model estimates of [Jorgenson et al. \(2018\)](#). We define brown industries as the top four industries: coal mining, gas mining, gas utilities, and electric utilities. We merge CUSIP-year-level holding data with Mergent and Compustat databases using 6-digit CUSIP to get the NAICS industry for each corporate bond.

*Brown exposure* is estimated based on a more general approach of [Jung et al. \(2023\)](#). Specifically, we compute the proportion of insurer  $i$ ’s corporate bond portfolio value that

would be lost if policy  $P$  gets implemented.

$$\text{Brown Exposure}_{i,t}^P = \sum_{j \in J} w_{i,j,t} \text{Markdown}_j^P \quad (2)$$

where  $w_{ijt}$  is proportion of insurer  $i$ 's corporate bond invested in industry  $j$  at time  $t$ ,  $\text{Markdown}_j^P$  is the drop in the output of industry  $j$  under policy  $P$ . We consider a policy with a carbon tax of \$50 with a growth rate of 5%.<sup>9</sup> The key assumptions behind this approach are that (1) insurers lose the value of bonds proportionally to the drop in the output of the borrower's industry and (2) each insurer maintains its allocation of corporate bonds across industries as of time  $t$ .

The final two columns in Panel B of [Table 1](#) present the two measures, brown share and brown exposure of the top ten P&C insurers. Based on the brown share measure, we find that 14.7% of their corporate bond portfolio is exposed to industries that are expected to be most adversely affected by carbon taxes. Based on the brown exposure measure, we find that, on average, they are expected to lose 4.6% of their corporate bond portfolio under a severe carbon tax scenario.<sup>10</sup> The brown exposure estimates are similar to that of large US banks, 3–4%, when computed in the same manner as in [Jung et al. \(2023\)](#).

### 3 Design of Climate Stress Scenarios

We start with designing climate risk scenarios using a market-based approach to estimate the potential undercapitalization of insurance companies. Specifically, we construct portfolios that are designed to decrease in value as climate risk heightens, which we use as our construct physical climate factors. In this section, we describe how we construct these factors, discuss their advantages over potential alternative methods, and then empirically test their validity.

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<sup>9</sup>Appendix [Table A.4](#) reports the drop in industry output and we use the worst scenario (the last column) for the calculation of brown share and brown exposure.

<sup>10</sup>While not directly comparable, a study by [New York Department of Financial Services \(2021\)](#) reveals that in New York State, 11% of insurers' investments in equities and fixed income are allocated to carbon-intensive sectors.

We also briefly describe transition climate factors by [Jung et al. \(2021\)](#).

**Physical Climate Factors** We consider several physical risk factors, constructed based on P&C insurers’ stock returns. The first physical climate factor, *insurer premium factor*, uses information on P&C insurers’ operational exposure across states. We focus on P&C insurers’ operations because it is natural to hypothesize that P&C insurers are particularly affected by natural disasters due to their role in providing coverage for properties against natural disasters. The projected escalation of physical risk, including the increased occurrence of floods and wildfires, has the potential to create underinsurance or even a lack of insurance coverage. Consequently, significant market disruptions may occur, such as premium losses, higher rates of self-insurance, or increased demand for public sector disaster relief. This can lead to significant financial losses for insurers and contribute to a decline in P&C insurers’ stock prices.

We construct the insurer premium factor in the following steps. We first merge P&C insurers’ DPE with property damage from SHELDUS at the state-year level. Then, for each year, we compute each insurer  $i$ ’s physical risk exposure, denoted  $RISK$ , as:

$$RISK_{t,i} = \sum_j^N \left[ \left( \frac{DPE_{i,j,t-1}}{\sum_j^N DPE_{i,j,t-1}} \right) \times \text{Property Damage}_{j,t-1} \right] \times \frac{1}{ME_{i,t-1}} \quad (3)$$

where  $DPE_{i,j}$  denotes the direct premium earned by insurer  $i$  in state  $j$ ,  $\text{Property Damage}_{j,t-1}$  denotes the total property damage in state  $j$  in the previous year, and  $ME_{i,t-1}$  denotes the market cap of insurer  $i$  in the previous year. We form a portfolio of all U.S. P&C insurers where the weight is  $RISK$ . Finally, we subtract the risk-free rate from the portfolio return to obtain the insurer premium factor. Intuitively, insurance companies with a substantial premium (policy) exposure to states characterized by high physical risk would be associated with elevated  $RISK$ . Consequently, the insurer premium factor gives greater weight to insurers with high  $RISK$ , while assigning lower weights to those with low  $RISK$ . In light of this, we anticipate a decline in this factor subsequent to an unanticipated escalation in

physical risks, such as a sharp increase in the frequency or severity of natural disasters.

The second physical climate factor, *insurer loss-to-equity factor*, is constructed based on P&C insurers’ ratios of losses incurred relative to its market capitalization. Specifically, we compute the ratio by:

$$\text{Loss-to-Equity}_{i,t} = \frac{\sum_j \bar{\rho}_{i,j,t-1} DPE_{i,j,t-1}}{ME_{i,t-1}} \quad (4)$$

where  $\rho_{i,j,t}$  can be considered “risk weights” of insurer  $i$  in state  $j$  and year  $t$ :

$$\rho_{i,j,t} = \frac{\text{Loss}_{i,j,t}}{DPE_{i,j,t}}$$

and  $\bar{\rho}$  is exponentially smoothed risk weights.<sup>11</sup>

The form of loss-to-equity measure resembles the inverse of the risk-based capital (RBC) ratio. The RBC ratio is a measure of an insurer’s capital adequacy by dividing its total adjusted capital by its required capital:

$$RBC_{i,t} = \frac{\text{Equity}_{i,t}}{\text{Required Equity}_{i,t}} \quad (5)$$

A higher RBC ratio indicates that the insurer has a larger buffer of capital to absorb potential losses and meet its obligations to policyholders. Our proxy measure loss-to-equity resembles the inverse of RBC ratio, and therefore a higher value indicates a higher risk.

Similar to the first physical factor, we form a portfolio of all P&C insurers in the U.S. where the weight is Loss-to-Equity. The loss-to-equity factor is computed as the portfolio return minus the risk-free rate. Naturally, insurance companies that experience substantial losses are often associated with high risk. Therefore, the loss-to-equity factor assigns greater weight to insurers with a higher Loss-to-Equity ratio, and we anticipate a decline in this factor following an unanticipated escalation in physical risks.

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<sup>11</sup>We use the optimal bandwidth.



Figure 2 shows the 6-month cumulative returns of the market portfolio (SPY), transition risk factor (stranded asset factor), and physical risk factor (insurer premium factor and insurer loss-to-equity factor). There is a strong temporal correlation (0.90) between the two physical climate factors. Hence, we primarily utilize the insurer premium factor as the physical climate factor in the following sections.

Unlike conventional climate shocks measured by temperatures or certain specific types of natural disasters, our approach offers distinct advantages. First, they are market-based, allowing us to incorporate the expectations of investors and reduce the reliance on uncertain geophysical climate models. Second, they assess the impact of physical climate risks on national financial markets as a whole, rather than being limited to specific regions. Focusing on specific disasters or geographical areas may not fully capture the systemic implications of climate risk. Finally, our market-based approach provides higher-frequency data compared to traditional approaches that rely on sparse event series. Climate events such as extreme temperatures or natural disasters occur relatively infrequently, making it challenging to capture their effects accurately using event-based data alone.

**Physical Climate Factor Responses around Natural Disasters** To test whether the insurer premium factor captures physical climate risk, we conduct event study analyses using natural disaster events that caused more than \$1 Billion of damages. We use the following specification to test the physical risk factor’s responses to the disaster events:

$$PCF_t = \alpha + \sum_{n=0}^{20} \gamma_n shock_{t-n} + MKT_t + \varepsilon_t \quad (6)$$

where PCF denotes the insurer premium factor,  $shock_t$  takes the value of 1 if it was the start date of a natural disaster event, and a value of 0 if there was no disaster on day  $t$ . To control for overall market movements, we utilize the SPDR S&P 500 ETF as the market return, denoted as  $MKT$ . The coefficient  $\gamma$  is expected to be negative since the occurrence of a natural disaster is associated with a positive shock and a decrease in the value of PCF. The

standard errors are adjusted using the Newey-West method to account for serial correlation.

Panel A of [Figure 3](#) shows the cumulative  $\gamma$  coefficient along with a 95% confidence interval and suggests a negative response to the occurrence of natural disasters, consistent with the hypothesis.<sup>12</sup> Interestingly, the insurer premium factor takes more than 5 days to respond. We find supporting evidence that the slow response is associated with the fact that the impact (e.g., severity and duration) of the event is not obvious within the first few days of the event. In the case of one of the most damaging disasters, hurricane Katrina, on the first day of the event, August 26, 2005, an NYT article says “A Blast of Rain but *Little Damage* as Hurricane Hits South Florida.”<sup>13</sup> On the fifth day, an article suggested the size of the damage.<sup>14</sup> Only after six days, on August 31, an article mentioned its impact on the financial market: “Markets Assess Hurricane Damage, and Shares Fall.”<sup>15</sup> In [Appendix Table A.3](#), we document the series of New York Times articles related to Hurricane Katrina.

In addition, we find that attention to natural disaster events typically peaks between 10 and 15 days after the first date of the disaster. To measure the attention to natural disaster events, we analyze the frequency of event mentions in New York Times (NYT) articles. We focus on the most significant hurricanes (in the 95th percentile of total losses) to capture their greater market impact and heightened public attention. Panel B of [Figure 3](#) illustrates the pattern of these mentions following a hurricane event, with  $t = 0$  indicating the event’s start date. The figure reveals a consistent and relatively low number of mentions in the first five days, gradually increasing thereafter. The peak is observed on the 14th day, followed by a gradual decline in the number of mentions.

**Transition Climate Factor** Following [Jung et al. \(2021\)](#), we use the stranded asset factor as a proxy of transition risk. This factor is derived from the stranded asset portfolio

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<sup>12</sup>Appendix [Figure A.1](#) shows event study findings using the Insurer Loss-to-Equity Factor. Both physical climate factors exhibit similar responses.

<sup>13</sup>New York Times article, “[A Blast of Rain but Little Damage as Hurricane Hits South Florida](#)” mentions that “but there were *no reports of heavy damage* as the hurricane made landfall between North Miami Beach and Hallandale Beach shortly before 7 p.m.”

<sup>14</sup>New York Times article, “[Insurers Estimate Damage at \\$9 Billion](#)”

<sup>15</sup>New York Times article, “[Markets Assess Hurricane Damage, and Shares Fall](#)”

developed by [Litterman et al. \(2021\)](#) and the World Wildlife Fund. The composition of the factor includes a 70% long position in VanEck Vectors Coal ETF (KOL), a 30% long position in Energy Select Sector SPDR ETF (XLE), and a short position in SPDR S&P 500 ETF Trust (SPY). The rationale behind this factor is that, during the transition towards a low-carbon economy, assets in the fossil fuel industries face the risk of devaluation and stranding. Consequently, the return on a stranded asset portfolio serves as a proxy measure that reflects market expectations regarding future transition climate risk. [Jung et al. \(2021\)](#) document that this factor tends to fall following climate policy-related events.

The physical and transition climate factor summary statistics (Appendix [Table A.1](#)), and correlation table (Appendix [Table A.2](#)) are included in the appendix.

## 4 Insurers’ Physical Risk Exposure

### 4.1 Physical Climate Beta

Following the standard factor model approach, we specify the model for insurer  $i$ ’s stock return as follows:

$$r_{i,t} = \beta_{i,t}^{Mkt} MKT_t + \beta_{i,t}^{Physical} PCF_t + \varepsilon_{i,t} \quad (7)$$

where  $r_{i,t}$  is the stock return on insurer  $i$ ,  $MKT_t$  is the market return measured as the return of S&P 500 ETF, and  $PCF_t$  denotes the insurer premium factor. Including the market factor in the model helps to control for confounding factors, such as the COVID shock and aggregate demand shock, that may influence both insurer stock returns and the physical risk factor.  $\beta_{i,t}^{Mkt}$  and  $\beta_{i,t}^{Physical}$  measure the sensitivity of insuree  $i$  to overall market risk and physical risk. We call  $\beta_{i,t}^{Physical}$  physical climate beta.

Panel A of [Figure 4](#) presents the climate beta of the top ten largest insurers in the U.S.. As anticipated, P&C insurers’ climate betas are all positive, ranging between 0 and 1.2.

At the financial institutions level, we observe that all insurers exhibit similar movements in response to climate risk. Regarding the impact of natural disasters, we find that the physical climate betas for insurers increase when they are affected by such events. Notable examples include Hurricane Katrina in 2005 and Hurricane Ike in 2008. These disasters likely intensified insurers’ exposure to physical climate risk, leading to higher sensitivity during those periods. Among the top ten insurers, Hartford Financial Services (Ticker: HIG) stands out with the highest climate beta. This could be attributed to its significant exposure to risky states and a relatively lower market capitalization compared to other insurers. On the other hand, Progressive Corporation (Ticker: PGR), with a low DPE exposure, exhibits a relatively lower climate beta. In the upcoming section, we formally test this relationship between physical climate beta and the insurers’ premium (policy) exposure across states.

## 4.2 Physical CRISK and marginal CRISK

Following the CRISK methodology in [Jung et al. \(2021\)](#), we compute the expected capital shortfall conditional on physical climate stress. We consider a scenario in which the physical climate factor falls substantially, corresponding to a 1% quantile of the return distribution, over six months. The CRISK is defined as below:

$$CRISK_{it} = kD_{it} - (1 - k)W_{it} \exp(\beta_{it}^{Climate} \log(1 - \theta^{Climate})) \quad (8)$$

where  $W_{it}$  is the market value of equity,  $D_{it}$  is the book value of debt,  $k$  is the prudential ratio of equity to assets, and  $\theta$  is the climate stress level. We set the prudential capital fraction  $k$  to 8% and the climate stress level  $\theta$  to 20% for physical risk, as 20% decline corresponds to the 1% quantile of the six-month return distribution. CRISK is higher for insurers that are larger, more leveraged, and with higher climate beta.

Panel A of [Figure 5](#) shows the estimated physical CRISK of the top ten largest U.S. P&C insurers. Notably, the magnitude of insurer physical CRISK (-50 to 20) is much lower

than bank transition CRISK in [Jung et al. \(2021\)](#) ranging up to \$ 100 billion. This is partly coming from the fact that these insurers are much smaller than large banks. As we compare them in terms of their market cap, the magnitude of P&C insurers' physical CRISK (-100% to 104% of their market cap) is somewhat lower than banks' transition CRISK (-81% to 187% of their market cap).<sup>16</sup>

Marginal CRISK (mCRISK) captures the effect of climate stress in isolation from the realized undercapitalization as well as the effect of market stress. It is defined as the difference between CRISK and non-stressed CRISK:

$$mCRISK_{it} = (1 - k)W_{it}LRMES_{it} \quad (9)$$

where  $LRMES$  is the long-run marginal expected shortfall, defined as the expected firm equity multi-period arithmetic return conditional on a systemic climate change event:

$$LRMES_{it} = -E_t \left[ R_{t,t+h}^i | R_{t+1,t+h}^{ClimateFactor} < C' \right] \quad (10)$$

Panel A of [Figure 6](#) plots the marginal CRISKS of the top ten large U.S. P&C insurers. Marginal CRISK isolates the effect of climate stress from the concurrent undercapitalization coming from the leverage effect. They range between \$ 0 and \$ 4 billion, suggesting no sign of substantial undercapitalization conditional on severe physical climate stress.

### 4.3 Physical CRISK Decomposition

To better understand what drives the decrease in physical CRISK in 2020, we decompose CRISK into three components based on [Equation 11](#):

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<sup>16</sup>We compute the share of CRISK or mCRISK in terms of market cap by calculating the CRISK/market cap for each individual financial institution first, and then take the average across the top 10 institutions.

$$dCRISK = \underbrace{k \cdot \Delta DEBT}_{dDEBT} - \underbrace{(1-k)(1-LRMES) \cdot \Delta EQUITY}_{dEQUITY} + \underbrace{(1-k) \cdot EQUITY \cdot \Delta LRMES}_{dRISK} \quad (11)$$

The first component,  $dDEBT = k \cdot \Delta DEBT$ , is the contribution of the firm's debt to CRISK. CRISK increases as the firm takes on more debt. The second component,  $dEQUITY = -(1-k)(1-LRMES) \cdot \Delta EQUITY$ , is the effect of the firm's equity on CRISK. Here,  $LRMES$  represents the average value of  $LRMES_t$  and  $LRMES_{t+1}$ . CRISK increases as the firm's market capitalization deteriorates. The third component,  $dRISK = (1-k) \cdot EQUITY \cdot \Delta LRMES$ , is the contribution of an increase in climate beta to CRISK. Here,  $EQUITY$  represents the average value of  $EQUITY_t$  and  $EQUITY_{t+1}$ .

Panel A of [Table 2](#) decomposes the change in CRISK of the top 10 P&C insurers in the U.S. during the year 2020 into three components. On average across the P&C insurers, the risk component (due to the rise in climate beta) contributed most, 97%, of the rise in CRISK during 2020.

## 5 Insurers' Transition Risk Exposure

### 5.1 Transition Climate Beta

Similarly, we estimate the transition climate beta for life insurers using the following model:

$$r_{i,t} = \beta_{i,t}^{Mkt} MKT_t + \beta_{i,t}^{Transition} TCF_t + \varepsilon_{i,t} \quad (12)$$

where  $r_{i,t}$  is the stock return on life insurer  $i$  and  $TCF_t$  is the stranded asset factor. Panel B of [Figure 4](#) exhibits the transition climate beta of large U.S. life insurers. At the financial institutions level, all insurers move similarly. Climate betas for insurers, like banks, slightly decreased during the global financial crisis (GFC) and dramatically increased during 2019-

2020 when fossil fuel prices collapsed. The magnitude of the increase in insurers' climate beta during 2019-2020 is similar to banks in [Jung et al. \(2021\)](#).

## 5.2 Transition CRISK and marginal CRISK

Panel B of [Figure 5](#) shows the transition CRISK of the large U.S. life insurers. In contrast to banks in [Jung et al. \(2021\)](#), insurers' CRISKS were stable during the GFC and 2019-2020 when fossil fuel energy prices collapsed.

Panel B of [Figure 6](#) displays the transition marginal CRISK of life insurers in the U.S.. The marginal CRISK of insurers and banks are similar, close to zero for most of the time, and went up during 2019-2020, reaching more than \$10 billion in 2020. The range of insurer marginal CRISK scaled by market capitalization ranges between -66% to +31%, and this is comparable to those of banks (-41% to +33%). Due to the size effect, banks' marginal CRISK can reach \$ 120 billion while the maximum of insurers is less than \$ 15 billion.

## 5.3 Transition CRISK Decomposition

To gain insights into the factors contributing to the increase in transition CRISK in 2020, we decompose CRISK into three components according to [Equation 11](#). Panel B of [Table 2](#) shows the contribution of three components. On average, the risk (i.e., increase in climate beta) contributed 59% and the equity deterioration contributed 29% to the change in CRISK during 2020.

# 6 Insurers' Systemic Climate Risk Exposure

To analyze the systemic climate risk exposure of insurers, we compute the aggregate CRISK and the aggregate marginal CRISK of the top ten life and P&C insurers in the U.S. For CRISK, we truncate the insurers' CRISK and keep only the positive values, assuming that it is unlikely for an insurer with excess capital reserves would transfer (subsidize) its equity to

an undercapitalized insurer. For marginal CRISK, we sum up the insurers' marginal CRISK without adjustment, to focus on the effect of climate stress, isolated from the leverage effect.

Figure 9 displays the aggregate physical and transition CRISK, respectively. We find that the aggregate transition CRISK of insurers reached more than \$ 180 billion at the end of 2020, but declined to under \$ 150 billion at the end of 2021. Although this amount in dollars is smaller in comparison to banks, whose CRISK rose by approximately \$ 500 billion, the proportionate impact of CRISK on individual institutions, when scaled by market capitalization (28%), is similar to that of banks (38%).

Figure 10 displays the aggregate physical and transition marginal CRISK, respectively. During the sample period, insurers' aggregate physical marginal CRISK ranges from \$ 4 billion to \$ 19 billion, corresponding to 3% to 15% of their market cap. In terms of transition risk, insurers' aggregate marginal CRISK fluctuated from \$ -40 billion to \$ 80 billion, equivalent to approximately -35% to +27% of their market capitalization. Overall, the impact of transition risk on insurers appears to be more meaningful than the impact of physical risk.

Compared to the aggregate marginal CRISK of financial firms, including banks, broker-dealers, and insurance companies computed by Jung et al. (2021), insurers accounted for less than 20% of the aggregate marginal CRISK in the U.S. in 2020 but the proportion reached more than 40% at the end of 2021, suggesting that insurance sector may be facing higher levels of vulnerability in terms of transition CRISK compared to other segments of the financial industry.

## 7 Validation

### 7.1 Insurers' Physical Climate Beta and their Liability Exposure

In this section, we validate our methodology by comparing P&C insurers' physical climate beta, estimated from equation (7), with their *policy portfolio climate beta*, reflecting their portfolio of insurance policies.



To conduct this test, we first measure the physical climate risk of each county by employing municipal bond returns, as previous studies (Auh et al., 2022, e.g.) show that physical climate risk is priced in the municipal bond market. To account for the infrequent trading of municipal bonds, we focus on counties with a sufficient number of bond transactions (at least 10 times per quarter)<sup>17</sup>, and we analyze returns on a monthly frequency. Then, we compute the average of all municipal bond returns within the same county weighted by issue amount and trading interval, following the approach of Auh et al. (2022). Once county-level monthly returns on municipal bonds are obtained, we estimate the physical climate beta for each county using equation 7 on a monthly frequency.

To aggregate county-level physical climate beta to state-level physical climate beta, we focus on the positive climate betas and counties with high climate risk exposure to capture the asymmetric payoff to insurers. Insurers are more likely to experience losses from unexpected claims related to severe weather events in risky counties (associated with positive climate betas), while they do not have a corresponding advantage or significant gains from policies in areas with negative climate betas. Therefore, we retain counties with positive climate beta and aggregate them at the state level by calculating the 99th percentile of the climate beta of municipal bonds across all counties within the state.

After obtaining the state-level physical climate beta estimates, we construct a panel of policy portfolio climate beta by computing the weighted average climate beta for each insurer, where the weight is the DPE exposure of an insurer  $i$  to the corresponding state  $j$ :

$$\text{Policy Portfolio Physical Climate Beta}_{i,t} = \sum_{j \in J} w_{j,t} \beta_{j,t}^{\text{Physical}} \quad (13)$$

where the weight  $w_j$  is the DPE share in state  $j$ .  $\beta_j^{\text{Physical}}$  denotes the physical climate beta of state  $j$ .

Figure 7 shows that the market-based physical climate beta and the policy portfolio

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<sup>17</sup>This results in a sample of 295 counties.

climate beta are aligned. We formally test this with the following OLS specification:

$$\beta_{it}^{Physical} = a + b \text{ Policy Portfolio Physical Climate Beta}_{it} + \text{Insurer Controls} + \delta_i + \varepsilon_{it} \quad (14)$$

The dependent variable,  $\beta_{it}^{Physical}$  is insurer  $i$ 's time-averaged daily climate transition beta for each year. [Table 3](#) shows the result. Column (2) includes insurer control variables, size and leverage. Size is the log of total assets. Leverage is defined as 1 plus its book value of liabilities divided by its market value of equity. Standard errors are clustered at the insurer level. We find that  $b$  is positive and significant in both specifications.

## 7.2 Insurers' Transition Climate Beta and their Asset Holdings

In this section, we test whether insurers' exposure to transition risk, proxied by transition climate beta, aligns with insurers' asset holdings. To test this, we focus on life insurers' bond holdings because their equity holdings tend to be small, which can be partly explained by the high capital requirements on equities ([Kojien and Yogo, 2023](#)). First, we construct a panel of bond portfolio climate beta by computing the weighted average climate beta for each insurer where the weight is the proportion of bond holding in the respective industry and each investment is assigned the climate beta of the respective industry:

$$\text{Bond Portfolio Transition Climate Beta}_i = \sum_{j \in J} w_j \beta_j^{Transition} \quad (15)$$

where the weight,  $w_j$  is the proportion of investment made to the respective industry  $j$ .  $\beta_j^{Transition}$  denotes the transition climate beta of industry  $j$ , and it is computed as the value-weighted average climate beta of firms in each 3-digit NAICS industry. The industry climate betas are computed based on all listed firms in the U.S. following [Jung et al. \(2021\)](#). [Figure 8](#) shows that the market-based transition climate beta and the bond portfolio climate beta are

aligned. We formally test this with the following OLS specification:

$$\beta_{it}^{Transition} = a + b \text{ Bond Portfolio Transition Climate Beta}_{it} + \text{Insurer Controls} + \delta_i + \varepsilon_{it} \quad (16)$$

The dependent variable,  $\beta_{it}^{Transition}$  is insurer  $i$ 's time-averaged daily climate transition beta for each year. Insurer control variables include size and leverage, defined the same as in the previous subsection. [Table 4](#) shows the result. Column (2) includes insurer control variables. Standard errors are clustered at the insurer level. We find that  $b$  is positive and significant across both specifications, suggesting that insurers' exposure to transition risk is in line with their asset holdings.

## 8 Conclusion

We employ the CRISK framework proposed by [Jung et al. \(2021\)](#) to measure the climate risk exposure of life and P&C insurance companies in the U.S. Our approach involves developing physical risk factors based on portfolios of P&C insurers' stocks, taking into account each insurer's policy exposure to states associated with high physical climate risk. Additionally, we estimate the dynamic climate beta, which captures the stock return sensitivity of each insurer to the physical risk factor. By computing the expected capital shortfall of insurers under various climate stress scenarios, we further quantify the potential financial implications of climate risk.

In terms of transition risk for life insurers, we observe a notable increase in their transition climate beta during the 2019-2020 fossil fuel price collapse. The aggregate transition CRISK for life insurers in the U.S. also significantly rose by more than \$ 150 billion, equivalent to around 28% of their market cap. Excluding concurrent undercapitalization, the marginal CRISK attributed solely to climate stress increased by more than \$ 85 billion during the same period.

In terms of physical risk for P&C insurers, we find that the top ten P&C insurers mostly

had negative CRISK values (excess reserves), indicating no sign of potential systemic undercapitalization under physical climate stress. As of the end of 2020, their aggregate marginal CRISK stood at \$ 15 billion, equivalent to approximately 7% of their market cap.

Empirical validation of the transition climate risk factor and climate beta estimates is conducted using granular data on insurers' asset holdings and the industry exposure in those holdings. We find that the market-based transition climate beta reflects insurers' bond portfolio composition. Insurers with a higher proportion of their corporate bond holdings in industries that are more affected by transition climate risks are more exposed to transition climate risk compared to those with a lower allocation in such industries.

On the physical climate risk side, We validate our method by examining insurers' policy exposure in each state and the corresponding state-level physical risk. Our findings indicate that the market-based physical climate beta reflects insurers' policy portfolio composition. Insurers with a greater proportion of policies in states facing higher physical climate risks exhibit higher exposure to physical climate risk, while those with a lower allocation in such states have lower exposure.

In conclusion, this study enhances our understanding of the climate risk exposure of life and property and casualty insurers in the U.S. We find that transition risk can have a significant impact, while physical risk has a relatively lower impact on insurers' capital shortfall and risk sensitivities. Looking beyond this paper, fruitful directions for future research include exploring insurers' responses to physical and transition climate shocks, specifically focusing on their adjustments in policy pricing and quantity. This line of research will provide further insights into insurers' risk management strategies and their efforts to address the financial implications of climate change.

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# Tables

Table 1: Top 10 Insurer Summary Statistics

<i>Panel A: P&amp;C Insurers Summary Statistics</i>						
Ticker	Insurer	Mktcap	Asset	Equity	RSE (%)	Concentration
ALL	Allstate	10.17	11.74	9.93	29.21	0.066
TRV	Travelers	10.10	11.40	9.88	15.76	0.049
PGR	Progressive	9.79	10.07	8.79	3.92	0.157
HIG	Hartford	9.64	12.24	9.63	27.45	0.051
CNA	CNA Financial	9.02	10.99	9.28	25.24	0.049
CINF	Cincinnati Financial	8.97	9.76	8.75	3.61	0.082
MKL	Markel	8.58	9.58	8.17	27.70	0.050
AIZ	Assurant	8.52	10.30	8.43	26.02	0.053
WRB	WR Berkley	8.51	9.67	8.10	8.77	0.045
ORI	Old Republic	8.31	9.55	8.30	18.40	0.122

<i>Panel B: Life Insurers Summary Statistics</i>						
Ticker	Insurer	Mktcap	Asset	Equity	Brown Share(%)	Brown Exposure(%)
MET	MetLife	10.52	13.25	10.61	17.20	4.74
PRU	Prudential	10.32	13.26	10.40	13.72	4.36
AFL	Aflac	10.08	11.37	9.38	11.83	4.48
CI	Cigna	9.86	11.11	9.09	13.99	4.34
HIG	Hartford	9.64	12.24	9.63	11.86	4.20
AMP	Ameriprise	9.62	11.78	8.96	18.34	5.21
LNC	Lincoln National	9.19	12.14	9.30	15.59	4.66
VOYA	Voya Financial	8.95	12.19	9.39	12.56	4.53
GL	Globe	8.70	9.76	8.28	19.46	5.17
RGA	Reinsurance	8.30	10.20	8.29	12.74	4.39

**Note:** Panel A shows the summary statistics of P&C insurers. *RSE* (Risky State Exposure) represents the share of direct premiums earned in risky states (California, Florida, and Texas) for each insurer in each year during the sample period of 2000-2021. Panel B shows the summary statistics of life/health insurers. The Brown Share represents the ratio of the fair value of corporate bonds within brown industries to the total fair value of corporate bonds held by each insurer in each year during the same sample period. We identified brown industries as Coal Mining (NAICS Industry 2121), Gas Mining (NAICS Industry 211130), Gas utilities (NAICS Industry 2212), and Electric utilities (NAICS Industry 2211). According to [Jorgenson et al. \(2018\)](#), their estimated drop in industry output under a severe carbon tax scenario (\$50 tax, 5% growth rate) are 33.8%, 15.7%, 15.4%, and 12.4%, respectively. *Brown Exposure* is the proportion of insurer *i*'s corporate bond portfolio value that would be lost if a severe carbon tax policy (\$50 growing at 5% annually) gets implemented. Specifically, it is calculated as:  $Brown\ Exposure_{i,t} = \sum_{j \in J} w_{i,j,t} Markdown_j$  where  $w_{i,j,t}$  is the proportion of insurer *i*'s corporate bond invested in industry *j* at time *t*,  $Markdown_j$  is the drop in the output of industry *j* under the carbon tax. *Market cap*, *Asset*, and *Equity* are in log.

Table 2: CRISK Decomposition

<i>Panel A: P&amp;C Insurers CRISK</i>						
Ticker	CRISK(t-1)	CRISK(t)	dCRISK	dDEBT	dEQUITY	dRISK
PGR	-31.85	-51.55	-19.70	0.39	-13.86	-6.23
TRV	-22.79	-22.05	0.75	0.31	-0.17	0.61
ALL	-22.94	-21.25	1.69	0.04	2.56	-0.91
HIG	-13.75	-9.43	4.32	0.03	3.51	0.79
MKL	-11.30	-9.58	1.73	0.11	1.30	0.32
CINF	-12.81	-10.16	2.65	0.10	2.55	-0.00
WRB	-8.81	-7.95	0.86	0.16	0.70	0.00
CNA	-5.89	-4.64	1.25	0.19	1.29	-0.24
AIZ	-3.57	-3.74	-0.17	-0.03	-0.05	-0.09
ORI	-4.08	-3.51	0.57	0.06	0.63	-0.12
Top 10			-6.05	1.37	-1.54	-5.88
<i>Panel B: Life Insurers CRISK</i>						
Ticker	CRISK(t-1)	CRISK(t)	dCRISK	dDEBT	dEQUITY	dRISK
CI	-59.99	-59.47	0.51	0.15	1.04	-0.68
MET	15.50	30.09	14.59	2.62	3.34	8.63
AFL	-30.84	-9.40	21.44	0.30	6.38	14.75
PRU	37.01	49.98	12.97	2.03	4.49	6.46
AMP	-5.66	-3.85	1.81	0.66	-1.38	2.52
HIG	-14.66	-6.91	7.74	0.03	3.28	4.43
GL	-8.36	-4.97	3.39	0.11	1.11	2.17
LNC	18.35	21.80	3.45	1.68	0.95	0.82
RGA:US	-3.61	1.14	4.75	0.37	1.65	2.73
VOYA	5.99	7.90	1.92	0.41	0.58	0.92
Top 10			72.57	8.36	21.45	42.76

**Note:** CRISK(t) is the insurer's physical or transition CRISK at the end of 2020, and CRISK(t-1) is CRISK at the end of year 2019.  $dCRISK = CRISK(t) - CRISK(t-1)$  is the change in CRISK during 2020. dDEBT is the contribution of the firm's debt to CRISK. dEQUITY is the contribution of the firm's equity on CRISK. dRISK is the contribution of increase in volatility or correlation to CRISK. All amounts are in billion dollars.

Table 3: P&amp;C Insurer Climate Beta and Policy Portfolio Climate Beta

	(1) Climate Beta	(2) Climate Beta
Policy Portfolio Climate Beta	0.152*** (0.043)	0.106** (0.043)
Size		-0.037*** (0.008)
Leverage		0.010*** (0.002)
N	279	279
$R^2$	2.80	13.9

**Note:** This table shows results from regression 14. Standard errors in parentheses are clustered at the insurer level. Annual data from 2005 to 2020 for all P&C insurers in the U.S.. Significance levels: \*\*\*  $p < 0.01$ ; \*\*  $p < 0.05$ ; \*  $p < 0.1$ .

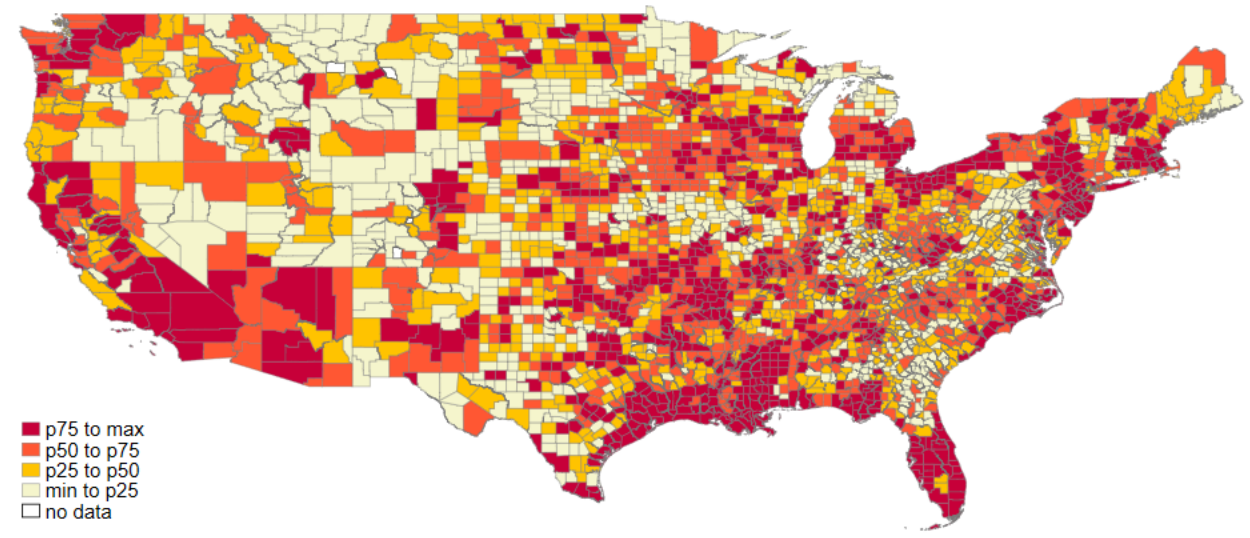
Table 4: Life Insurer Climate Beta and Bond Portfolio Climate Beta

	(1) Climate Beta	(2) Climate Beta
Bond Portfolio Climate Beta	0.950*** (0.236)	1.090*** (0.225)
Size		-0.012 (0.008)
Leverage		0.006*** (0.001)
N	292	292
$R^2$	7.57	23.2

**Note:** This table shows results from regression 16. Standard errors in parentheses are clustered at the insurer level. Annual data from 2000 to 2020 for all life insurers in the U.S.. Significance levels: \*\*\*  $p < 0.01$ ; \*\*  $p < 0.05$ ; \*  $p < 0.1$ .

# Figures

Figure 1: Natural Disaster Data Descriptive Statistics



Panel A: SHEL DUS Summary Statistics

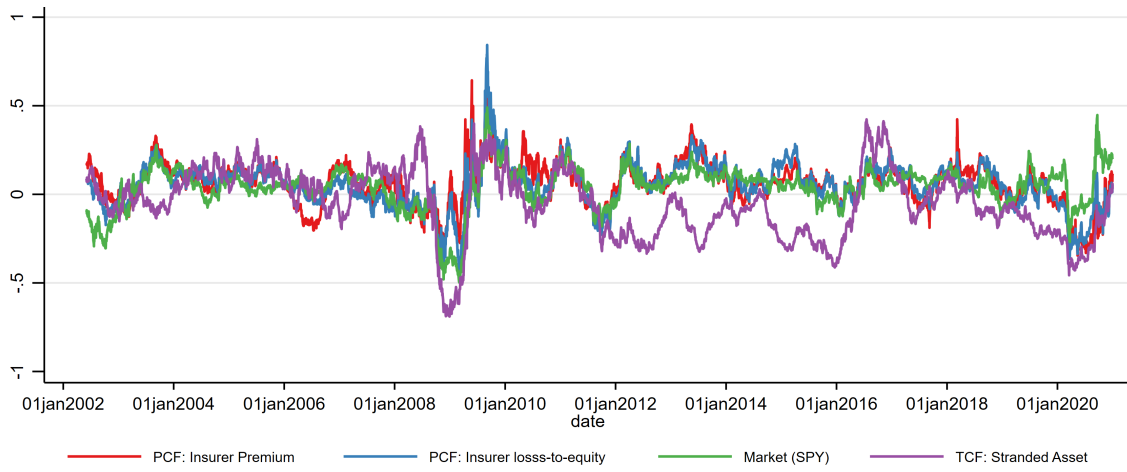
Hazard	Average(Billions \$)	Std	Median(Billions \$)	Max(Billions \$)
Hurricane	23,557	77,612	31	470,925
Flooding	9,456	51,986	714	565,212
Severe Storm	2,477	6,958	621	73,136
Winter	1,788	4,117	327	33,512
Wildfire	1,695	13,810	36	194,262
Drought	564	1,443	31	9,087
Coast	47	173	1	1,355
Heat	14	27	1	108

Panel B: Billion Dollar Summary Statistics

Harzard	Duration (Days)	Loss (Billions \$)	Average Loss(Billions \$)	Deaths
Hurricane	4	28,557	8,216	156
Drought	289	10,056	1,437	46
Wildfire	181	7,052	1,008	23
Winter	5	4,028	785	32
Flooding	21	3,729	780	13
Severe Storm	3	2,386	958	10

**Note:** The map shows the county distribution of SHEL DUS average property damage. Panel A shows the summary statistics of SHEL DUS country-level property damage data. Panel B shows the summary statistics of Billion Dollar Natural Disasters. Loss is the average total loss across events. The average loss is the average loss per day. We keep only the first 7 days for hazards that last for more than 7 days when calculating the average loss. The sample period of both the map and the table is 2000-2022.

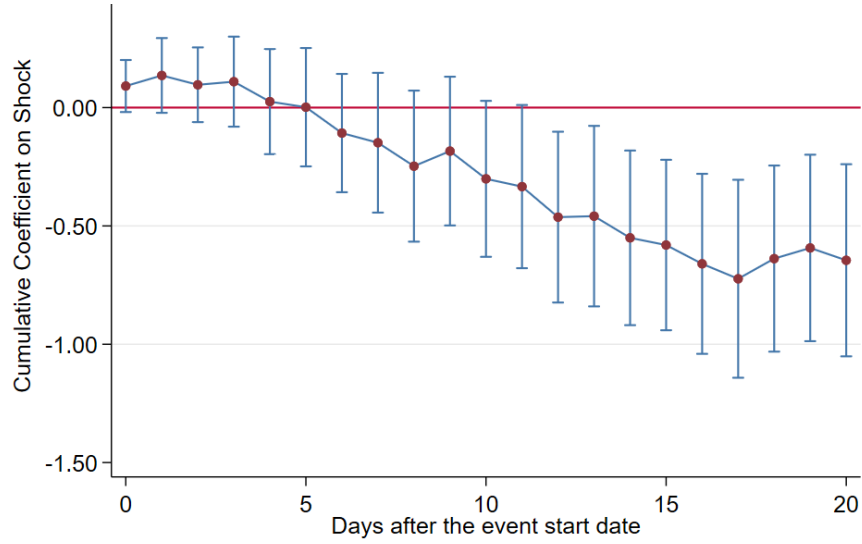
Figure 2: 6-Month Cumulative Returns



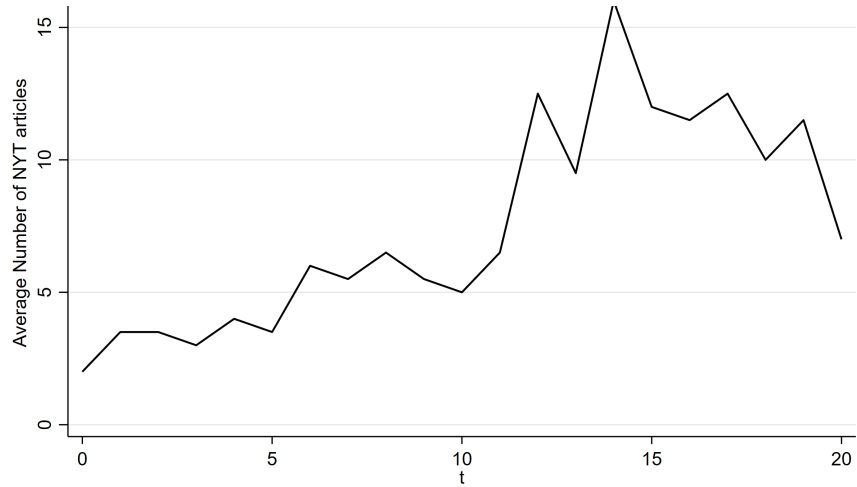
**Note:** 6-month cumulative returns of the market portfolio (SPY), transition risk factor (stranded asset factor), and physical risk factor (insurer premium factor and insurer loss-to-equity factor).

Figure 3: Responses around Natural Disaster Events

(a) Insurer Premium Factor Responses



(b) NYT News Responses

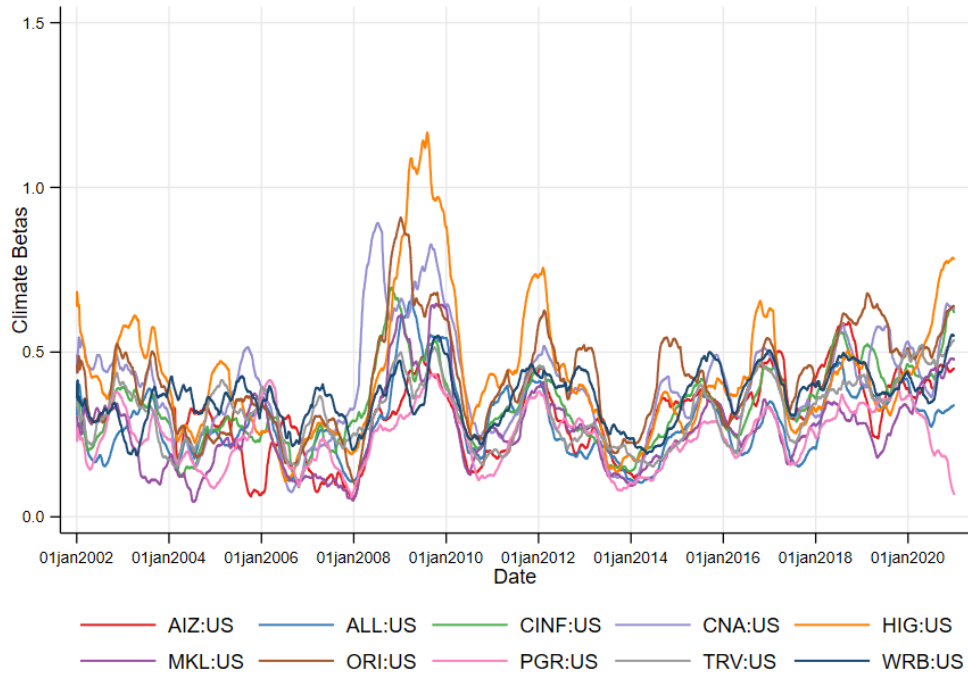


**Note:** Panel A shows the Cumulative coefficient  $\gamma$  on  $shock_t$  in  $PCF_t = \alpha + \sum_{n=0}^{20} \gamma_n shock_{t-n} + MKT_t + \epsilon_t$ .  $shock_t$  takes the value of 1 if it was the start date of a natural disaster event, and a value of 0 if there was no disaster on day  $t$ . Each physical risk factor series is standardized by its volatility. The standard errors are Newey-West adjusted and the band shows 95% confidence interval. Panel B displays the frequency of mentions of “hurricane” in NYT articles following a hurricane. The start date of the event is represented as  $t=0$ . The average number of mentions is calculated across the most significant hurricanes (95th percentile of all hurricanes generated loss). We focus on these large hurricanes due to their heightened public attention and assumed greater impact on the market.

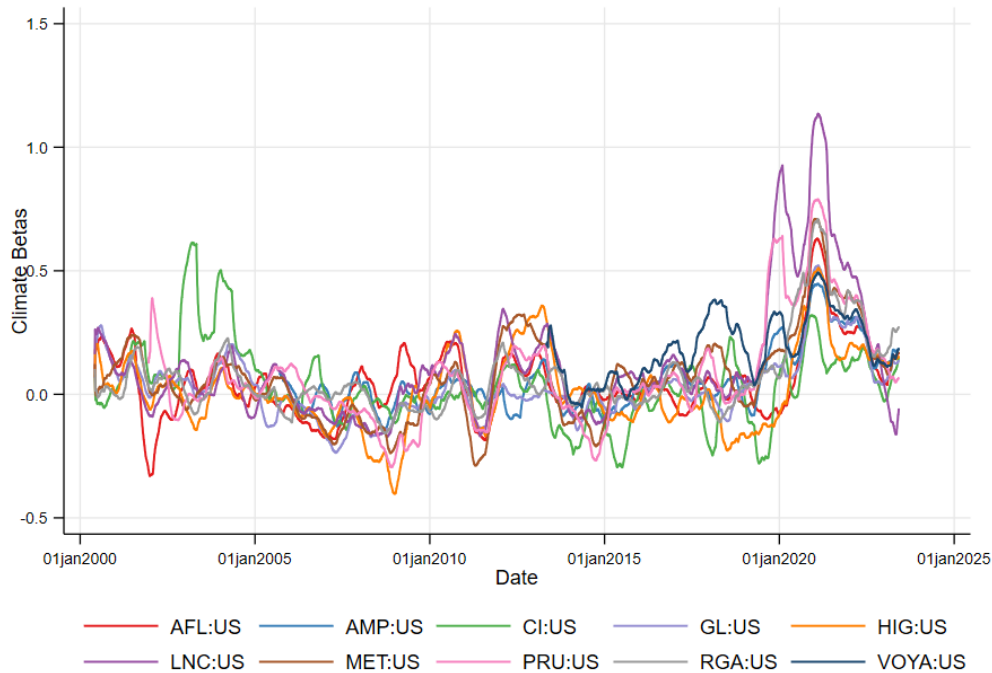


Figure 4: Climate Beta

(a) Physical Climate Beta of P&C Insurers in the U.S.



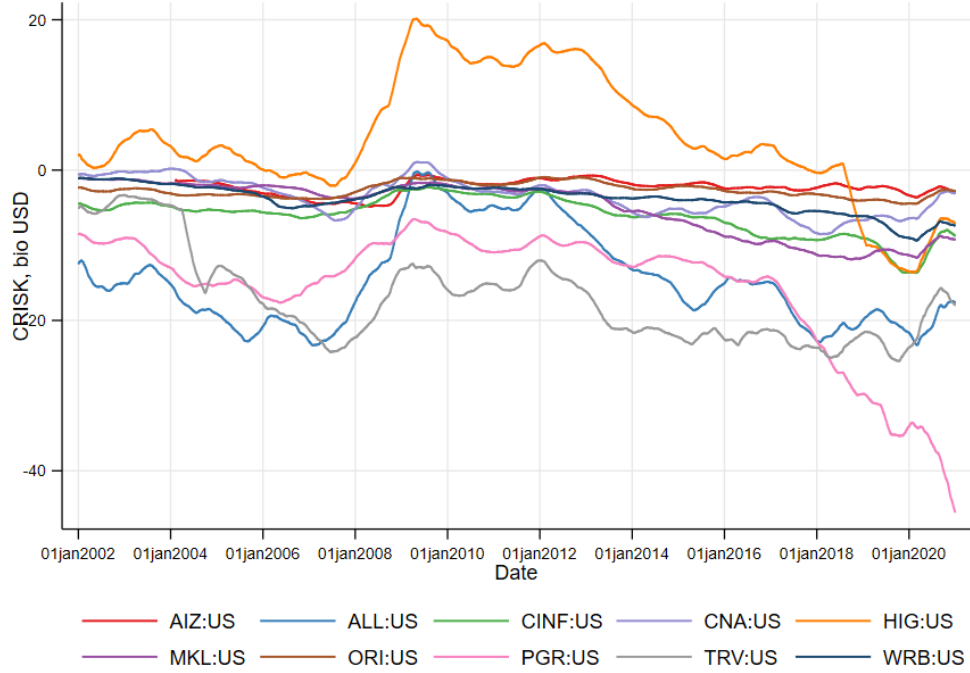
(b) Transition Climate Beta of Life Insurers in the U.S.



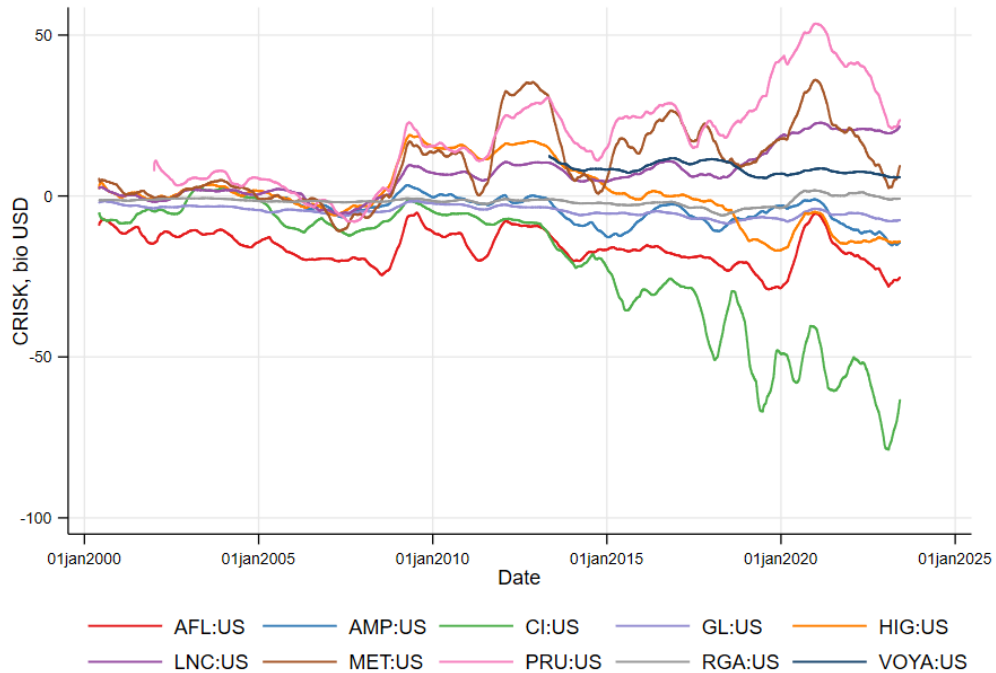
**Note:** Panel A displays the climate beta of P&C insurers in the U.S.. The sample insurers are the top large P&C insurers in the U.S. in Table 1. The sample period is from January 2002 to December 2020. Panel B exhibits the climate beta of life insurers in the U.S.. The sample insurers are the top large life insurers in Table 1. The sample period is from June 2000 to December 2021.

Figure 5: CRISK

(a) Physical CRISK of P&C Insurers in the U.S.



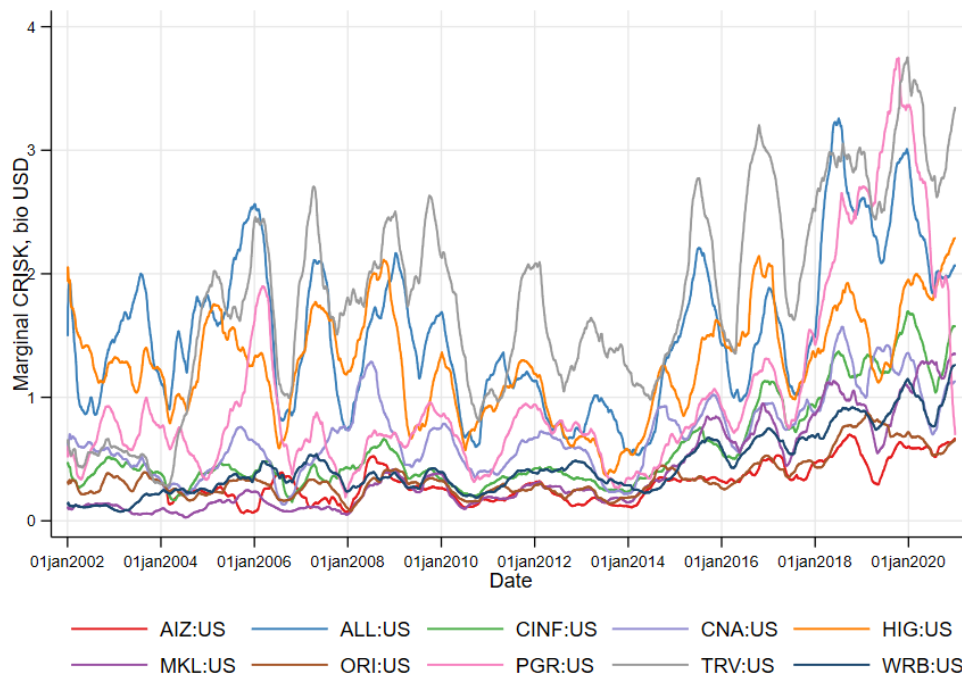
(b) Transition CRISK of Life Insurers in the U.S.



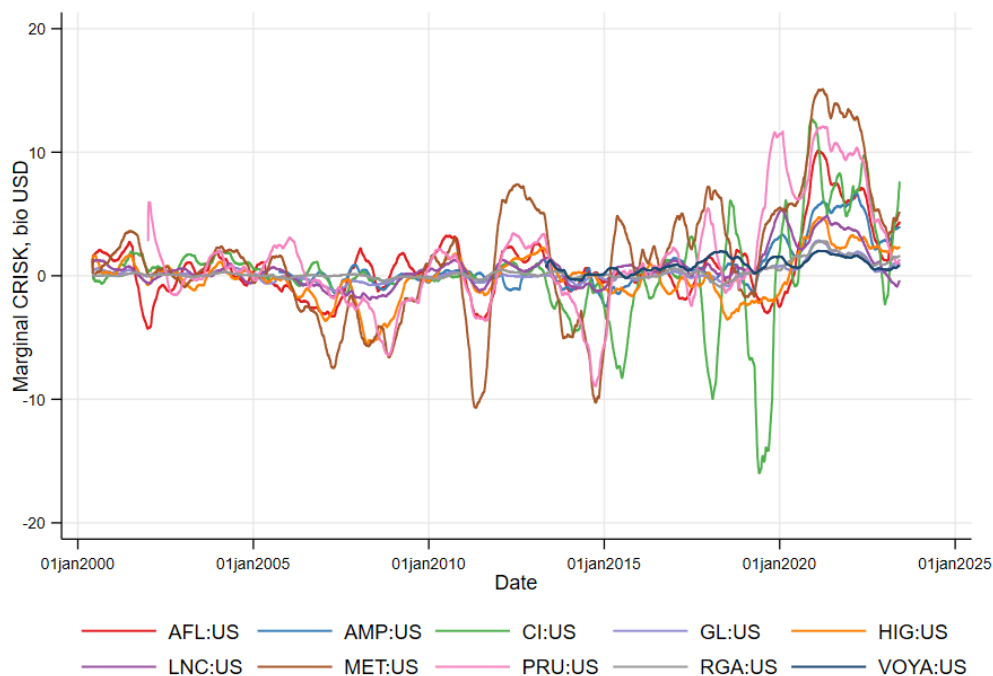
**Note:** Panel A displays the physical CRISK of P&C insurers in the U.S.. The sample insurers are the top large P&C insurers in Table 1. The sample period is from January 2002 to December 2020. Panel B exhibits the transition CRISK of life insurers in the U.S.. The sample insurers are the top large life insurers in Table 1. The sample period is from June 2000 to December 2021.

Figure 6: Marginal CRISK

(a) Physical Marginal CRISK of P&C Insurers in the U.S.

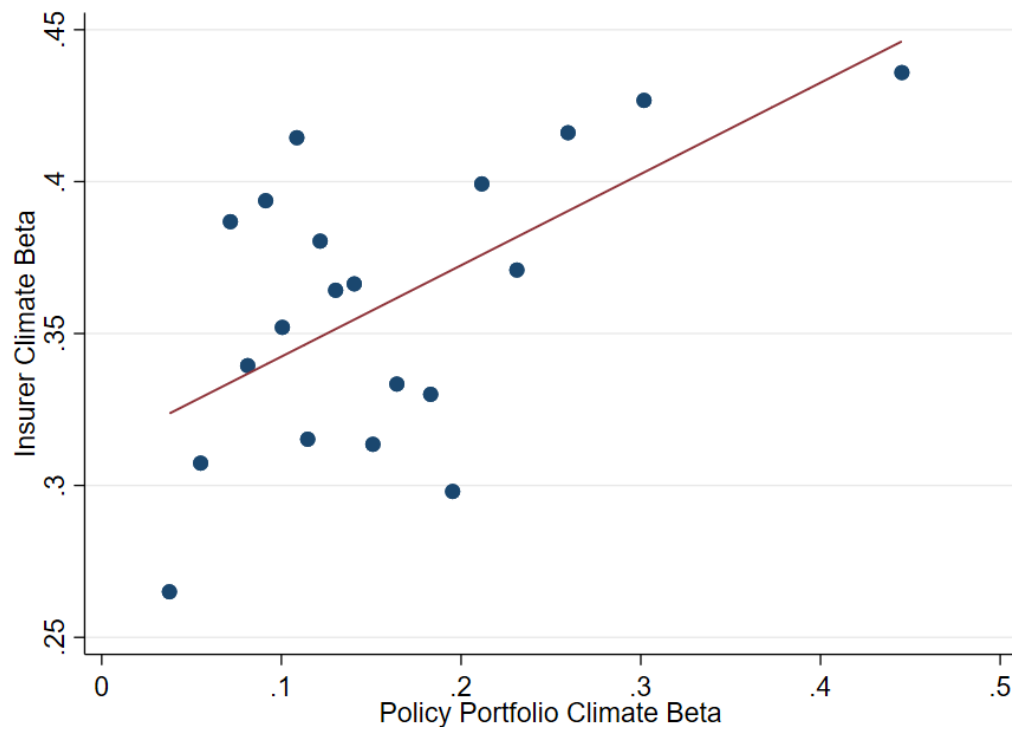


(b) Transition Marginal CRISK of Life Insurers in the U.S.



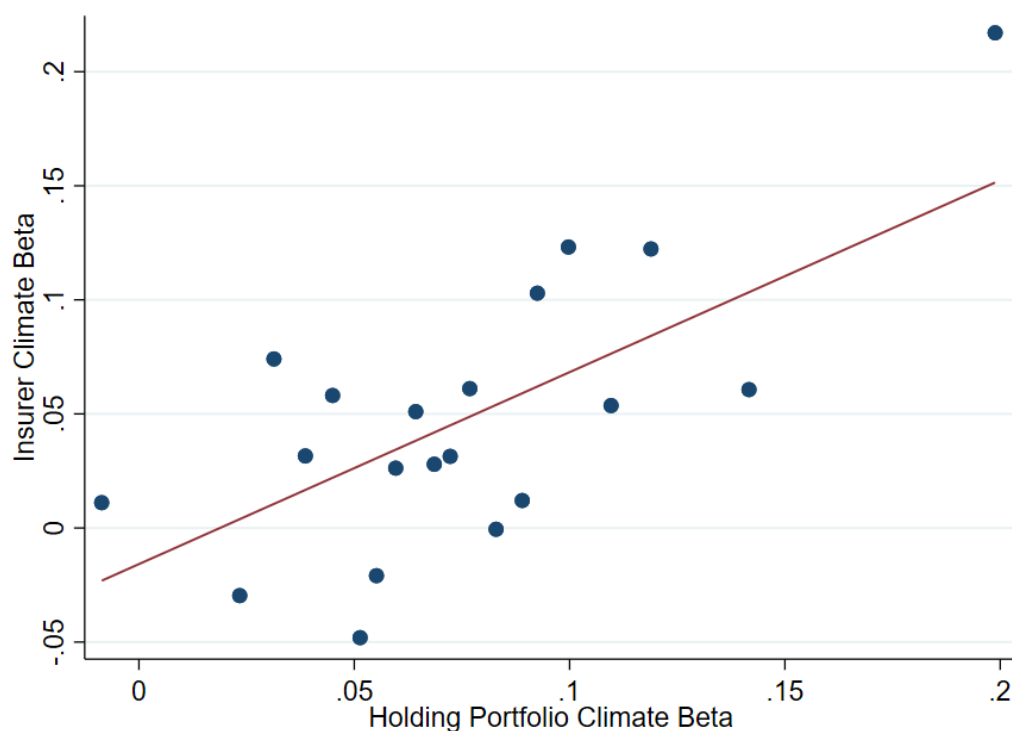
**Note:** Panel A displays the physical marginal CRISK of P&C insurers in the U.S.. The sample insurers are the top large P&C insurers in Table 1. The sample period is from January 2002 to December 2020. Panel B exhibits the transition marginal CRISK of life insurers in the U.S.. The sample insurers are the top large life insurers in Table 1. The sample period is from June 2000 to December 2021.

Figure 7: Correlation between Physical Climate Beta and Policy Portfolio Beta



**Note:** Binned scatter plot of insurer physical climate beta and policy portfolio climate beta without controls and fixed effects, based on annual data from 2005 to 2019 for listed P&C Insurers in the U.S.

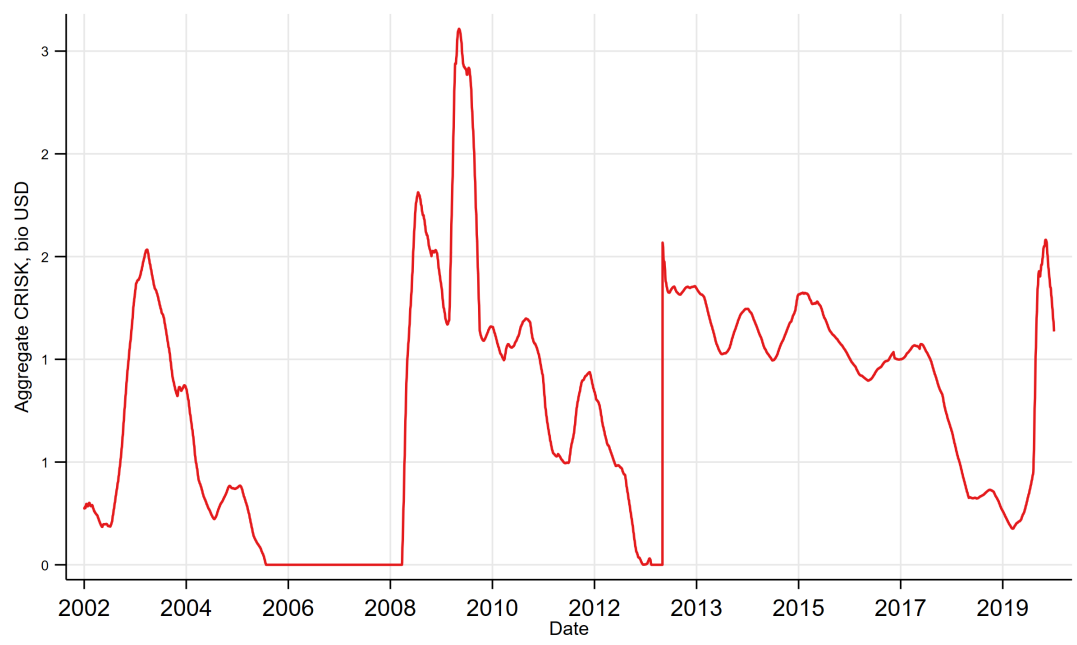
Figure 8: Correlation between Transition Climate Beta and Bond Portfolio Beta



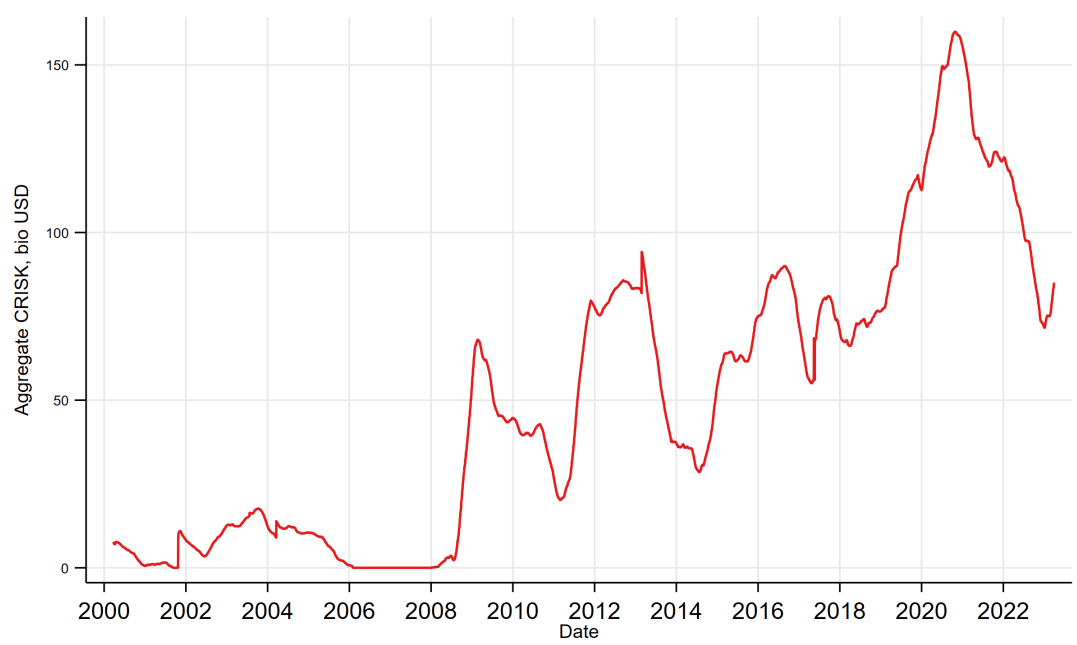
**Note:** Binned scatter plot of insurer transition climate beta and bond portfolio climate beta without controls and fixed effects, based on annual data from 2000 to 2020 for listed Life Insurers in the U.S..

Figure 9: Aggregate CRISK of US

(a) Physical CRISK



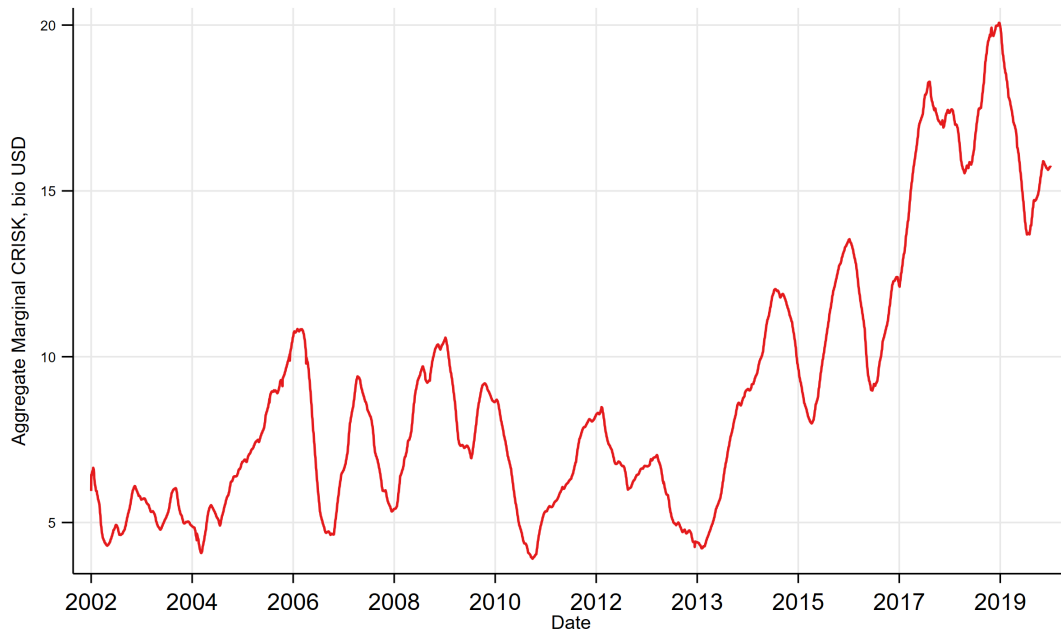
(b) Transition CRISK



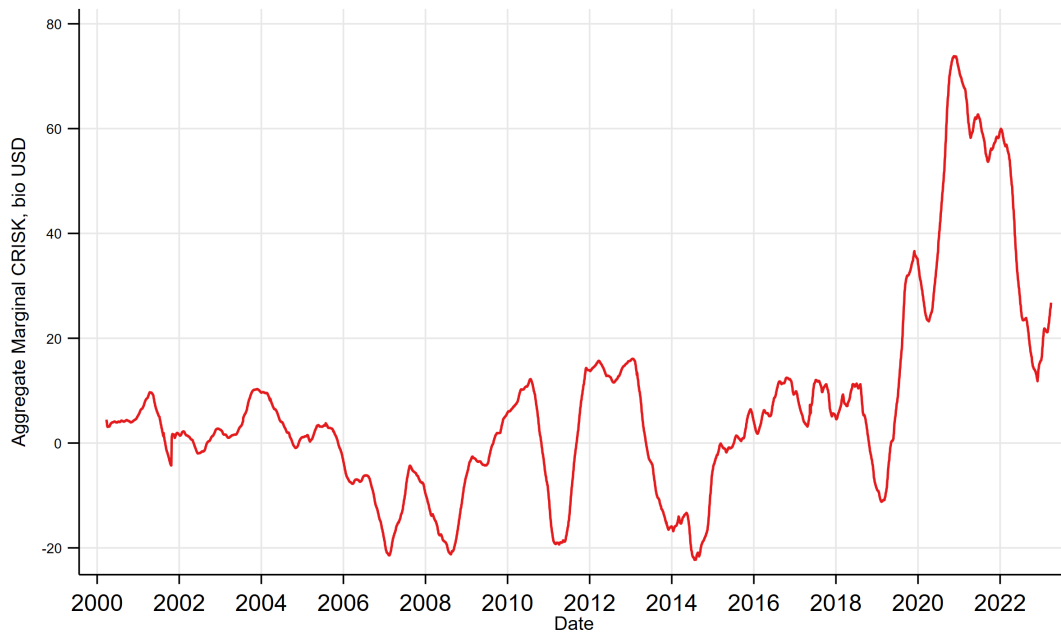
**Note:** Panel A displays the aggregate physical CRISK of US. The sample insurers are the top large P&C insurers in Table 1. The sample period is from January 2002 to December 2020. Panel B exhibits the aggregate transition CRISK of US. The sample insurers are the top large life insurers in Table 1. The sample period is from June 2000 to December 2021.

Figure 10: Aggregate Marginal CRISK of US

(a) Physical Marginal CRISK



(b) Transition Marginal CRISK



**Note:** Panel A displays the aggregate physical marginal CRISK of US. The sample insurers are the top large P&C insurers in Table 1. The sample period is from January 2002 to December 2020. Panel B exhibits the aggregate transition marginal CRISK of US. The sample insurers are the top large life insurers in Table 1. The sample period is from June 2000 to December 2021.

# Appendix

## A.1 Tables

Table A.1: Summary Statistics of Factors

	Mean	St.Dev.	25th percentile	75th percentile	Count
Market (SPY)	0.0003	0.0123	-0.0041	0.0058	4784
PCF: Insurer Premium	0.0006	0.0170	-0.0072	0.0079	4784
PCF: Insurer Loss-to-Equity	0.0005	0.0163	-0.0063	0.0073	4784
TCF: Stranded Asset	-0.0005	0.0134	-0.0070	0.0068	4784

**Note:** The sample period is 2002-2020 and all factors are daily.

Table A.2: Correlation of Factors

	Market: SPY	PCF: Premium	PCF: Loss-to-Equity	TCF: Stranded
Market: SPY	1.00			
PCF: Insurer Premium	0.74	1.00		
PCF: Insurer Loss-to-Equity	0.78	0.90	1.00	
TCF: Stranded Factor	0.22	0.19	0.18	1.00

**Note:** The sample period is 2002-2020 and all factors are daily.

Table A.3: New York Times Articles on Hurricane Katrina

Date	Article Title
8/26/2005	A Blast of Rain but Little Damage as Hurricane Hits South Florida
8/27/2005	Hurricane Drenches Florida And Leaves Seven Dead
8/29/2005	Approaching Storm Slows Oil Output in Gulf of Mexico
8/29/2005	POWERFUL STORM THREATENS HAVOC ALONG GULF COAST
8/29/2005	With Few Warning Signs, an Unpredictable Behemoth Grew
8/29/2005	In Slot Machines' Silence, A Storm's Economic Cost
8/30/2005	Nature's Revenge
8/30/2005	Another Storm Casualty: Oil Prices
8/30/2005	Shares Rally as Oil Prices Pull Back From Early Surge
8/30/2005	Storms Vary With Cycles, Experts Say
8/30/2005	Escaping Feared Knockout Punch, Barely, New Orleans Is One Lucky Big Mess
8/30/2005	Guard Units' New Mission: From Combat To Flood Duty



8/30/2005 After Centuries of 'Controlling' Land, Gulf Residents Learn Who's Really the Boss

8/30/2005 HURRICANE SLAMS INTO GULF COAST; DOZENS ARE DEAD

8/30/2005 In Coastal City, Ruin All Around

8/30/2005 Insurers Estimate Damage at \$9 Billion, Among Costliest U.S. Storms on Record

8/31/2005 Navy Ships and Maritime Rescue Teams Are Sent to Region

8/31/2005 NEW ORLEANS IS INUNDATED AS 2 LEVEES FAIL; MUCH OF GULF COAST IS CRIPPLED; TOLL RISES

8/31/2005 New York City Looks South For Lessons a Storm Can Teach

8/31/2005 No Quick Fix for Gulf Oil Operations

8/31/2005 Payouts Hinge on the Cause of Damage

8/31/2005 The Misery Is Spread Equally

8/31/2005 Where Living at Nature's Mercy Had Always Seemed Worth the Risk

8/31/2005 Casino Owners Look Toward Rebuilding

8/31/2005 Damage to Economy Is Deep and Wide

8/31/2005 Disease and Coordination Vie as Major Challenges

8/31/2005 Face to Face With Death and Destruction in Biloxi

8/31/2005 Flooding Stops Presses and Broadcasts, So Journalists Turn to the Web

8/31/2005 Geography Complicates Levee Repair

8/31/2005 In Search of a Place to Sleep, and News of Home

8/31/2005 Life-or-Death Words of the Day in a Battered City: 'I Had to Get Out'

8/31/2005 Markets Assess Hurricane Damage, and Shares Fall

9/1/2005 Millions Said to Be Lacking Phone Service of Any Kind

9/1/2005 A City in Ruins: Americans Open Their Hearts

9/1/2005 Oil and Construction Issues Lead Shares Broadly Higher

9/1/2005 Administration Steps Up Actions, Adding Troops and Dispatching Medical Supplies

9/1/2005 Rows and Rows of Corpses, And Voices Choked With Sobs

9/1/2005 Searching for the Living, but Mostly Finding the Dead

9/1/2005 Television Finds Covering Area Hit by Storm Is Like Working in a War Zone

9/1/2005 Utility Workers Come From Afar to Help Their Brethren Start Restoring Service

9/1/2005 Waiting for a Leader

9/1/2005 Wall of Water Set a Record

9/1/2005 At Stadium, a Haven Quickly Becomes an Ordeal

9/1/2005 BUSH SEES LONG RECOVERY FOR NEW ORLEANS; 30,000 TROOPS  
IN LARGEST U.S. RELIEF EFFORT

9/1/2005 Deal Is Put Off For Louisiana Bank

9/1/2005 Economy's Pace Is Lowered a Bit

9/1/2005 Educators Offer Classrooms To Many Displaced Students

9/1/2005 GAS PRICES SURGE AS SUPPLY DROPS

9/1/2005 Hazards Contained in Waters Are Not as Toxic as Feared

9/1/2005 Intricate Flood Protection Long a Focus of Dispute

9/1/2005 Loved Ones Turn to Web For Searches In Flood Zone

9/2/2005 Mississippi's Morning After

9/2/2005 New Orleans Is Awaiting Deliverance

9/2/2005 Rotting Food, Dirty Water And Heat Add to Problems

9/2/2005 Spanning the Gulf

9/2/2005 The Man-Made Disaster

9/2/2005 They Saw It Coming

9/2/2005 A Can't-Do Government

9/2/2005 You Want How Much a Gallon?

9/2/2005 Anxious Liberal Groups Try to Rally Opposition Against Supreme Court Nom-  
inee

9/2/2005 As One City Is Emptying, Another Finds Itself Full

9/2/2005 A Desperate Search for Relief, and for Answers

9/2/2005 By Air or Car, Travel Is Complex

9/2/2005 Cameras Captured a Disaster But Now Focus on Suffering

9/2/2005 Conservation? It's Such A 70's Idea

9/2/2005 Democrats and Others Criticize White House's Response to Disaster

9/2/2005 DESPAIR AND LAWLESSNESS GRIP NEW ORLEANS AS THOUSANDS  
REMAIN STRANDED IN SQUALOR

9/2/2005 From Margins of Society to Center of the Tragedy

9/2/2005 Gazing at Breached Levees, Critics See Years of Missed Opportunities

9/2/2005 Government Saw Flood Risk but Not Levee Failure

9/2/2005 In a Multitude of Forms, the Offers of Help Pour In

9/3/2005 Newcomer Is Struggling to Lead a City in Ruins

9/3/2005 On Ruined Coast, the Desperate Cry Out for Loved Ones Still Lost

9/3/2005 Promises by Bush Amid the Tears

9/3/2005 Spotlight on a Hurricane, and Off the Mayoral Race

9/3/2005 Spot Shortages Of Gas Reported Around Country

9/3/2005 United States Of Shame  
 9/3/2005 Bus Full of Evacuees Crashes, Leaving 1 Dead and 17 Hurt  
 9/3/2005 Closed to Visitors  
 9/3/2005 First Estimate Puts Storm's Economic Toll at \$100 Billion  
 9/3/2005 Indictments and Statistics All Overwhelmed by Tragedy Down South  
 9/3/2005 In First Response to Crisis, Bush Strikes Off-Key Notes  
 9/3/2005 Job Growth Stepped Up Its Pace In August  
 9/3/2005 Katrina's Assault on Washington  
 9/3/2005 Lawmakers Criticize U.S. Response  
 9/3/2005 Military Dealt With Combination of Obstacles Before Reaching Victims  
 9/3/2005 MORE TROOPS AND AID REACH NEW ORLEANS; BUSH VISITS  
 AREA; CHAOTIC EXODUS CONTINUES  
 9/4/2005 Falluja Floods the Superdome  
 9/4/2005 Homeland Security Chief Defends Federal Response  
 9/4/2005 Katrina's Shock to the System  
 9/4/2005 Legislative Agenda Turned Upside Down by Hurricane  
 9/4/2005 Navy Turns to Halliburton For Help on Damaged Bases  
 9/4/2005 Police Quitting, Overwhelmed by Chaos  
 9/4/2005 Storm Is Devastating for Businesses in Gulf Area, but Its National Effect  
 Remains Muted  
 9/4/2005 Storm Will Have a Long-Term Emotional Effect on Some, Experts Say  
 9/4/2005 As Anxiety Over Storm Increases, Bush Tries to Quell Political Crisis  
 9/4/2005 The View From Abroad  
 9/4/2005 With Mayor on Roll and Minds on Gulf, Democrats Hone Final Tactics  
 9/4/2005 A Delicate Balance Is Undone in a Flash, and a Battered City Waits  
 9/4/2005 Bush Pledges More Troops as the Evacuation Grows  
 9/4/2005 Career-Maker For Williams As the Anchor At NBC  
 9/5/2005 Not Even Web Retailers Will Be Exempt From the Aftereffects of Katrina  
 9/5/2005 On the Gulf Coast, a Chance to Inspire Is Slipping Away  
 9/5/2005 Reporting, and Living Out, a Calamity  
 9/5/2005 Amid Criticism of Federal Efforts, Charges of Racism Are Lodged  
 9/5/2005 Amid the Ruins, Worshipers Pause to Pray and Receive Messages of Hope  
 9/5/2005 The Hurricane and Accountability  
 9/5/2005 The Pendulum Of Reporting On Katrina  
 9/5/2005 White House Enacts a Plan To Ease Political Damage  
 9/5/2005 A 'Weather Nerd' in Indiana Sent a Warning to the Mayor

9/5/2005 BUSH PROMISES TO MOVE QUICKLY ON CHIEF JUSTICE  
 9/5/2005 Chaotic Week Leaves Bush Team on Defensive  
 9/5/2005 For Victims, News About Home Can Come From Strangers Online  
 9/5/2005 Fox Says U.S. Shares Blame For Problems Along Border  
 9/5/2005 Housing Boom May Continue After Storm, Experts Say  
 9/5/2005 Hurricane Response Becomes Issue in Mayor's Race  
 9/5/2005 In Tale of Two Families, a Chasm Between Haves and Have-Nots  
 9/5/2005 After Failures, Officials Play Blame Game  
 9/5/2005 Medical Team From Georgia, Trying to Provide Help, Hits Roadblocks Along  
 the Way  
 9/5/2005 New Orleans Begins a Search for Its Dead  
 9/6/2005 Mayoral Race Seems Recharged at Parade  
 9/6/2005 A Hospital Takes In The Tiniest Of Survivors  
 9/6/2005 Practicing Medicine In the Dark, On the Edge  
 9/6/2005 PRESIDENT NAMES ROBERTS AS CHOICE FOR CHIEF JUSTICE  
 9/6/2005 'Prison City' Shows a Hospitable Face to Refugees From New Orleans  
 9/6/2005 Residents Of a Parish Encountering Lost Dreams  
 9/6/2005 Scouring the Neighborhoods in a Personal Appeal to Holdouts  
 9/6/2005 The Larger Shame  
 9/6/2005 Thrown Off Schedule  
 9/6/2005 Utility Crews Help Turn Lights Back On in Parts of the Gulf Region  
 9/6/2005 With Some Now at Breaking Point, City's Officers Tell of Pain and Pressure  
 9/6/2005 Bush and the Lightning Nomination  
 9/6/2005 Bush Makes Return Visit; 2 Levees Secured  
 9/6/2005 Buying Time With Quick Action on the Court and a Second Trip to the South  
 9/6/2005 Carnival Forecasts Profit Cut From Katrina  
 9/6/2005 Clinton Is an Unexpected Partner in the Hurricane Effort  
 9/6/2005 Crawfish Etouffee Goes Into Exile  
 9/6/2005 Destruction on Mississippi River Delta Illustrates Danger of Life at Earth's  
 Edge  
 9/6/2005 Filling a Desperate Need for Shelter Begins With Cruise Ships and Proposals  
 9/6/2005 From the Air, Scientists Comb a Ruined Coastline for Clues and Lessons  
 9/6/2005 Her Hometown Destroyed, A Traveler Turns to a Blog  
 9/6/2005 High-Tech Flood Control, With Nature's Help  
 9/6/2005 Houston Finds Business Boon After Katrina  
 9/6/2005 In New Orleans, the Business Haves and Have-Nots

9/6/2005 Katrina and the Gas Pump

9/7/2005 Across Nation, Storm Victims Crowd Schools

9/7/2005 Osama and Katrina

9/7/2005 Pain Now, but Gain May Lie Ahead for Gulf Utility

9/7/2005 President of NBC News Announces His Resignation

9/7/2005 Putting Down New Roots on More Solid Ground

9/7/2005 School Routine Provides Welcome Change From Chaos

9/7/2005 Shares Up Sharply, Aided by Oil Price and Services Data

9/7/2005 Some Senators on Panel Ask Angry Questions About Gasoline Pricing and Profits

9/7/2005 Ad-Libbing Many Routes, Ships Return To the River

9/7/2005 Urban Evacuees Find Themselves Among Rural Mountains

9/7/2005 Urgent Warning Proved Prescient

9/7/2005 Bush Promises to Seek Answers To Failures of Hurricane Relief

9/7/2005 FLOODING RECEDES IN NEW ORLEANS; U.S. INQUIRY IS SET

9/7/2005 Gas Prices At Pumps Show Signs Of Easing

9/7/2005 Gonzales Is Mentioned in Court Remarks

9/7/2005 Haunted By Hesitation

9/7/2005 Hurricane's Toll Is Likely to Reshape Bush's Economic Agenda

9/7/2005 In Asia, Low Fuel Prices And Subsidies Lose Ground

9/7/2005 It's Not a 'Blame Game'

9/7/2005 A Sight or a Sound Can Bring 9/11 Flooding Back

9/7/2005 Miller Suffers a Setback Over Expenses

9/7/2005 Navy Pilots Who Rescued Victims Are Reprimanded

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**Note:** The titles of New York Times articles that have at least two sentences contain the word “hurricane” in the article from August 26, 2005 to September 7, 2005. Hurricane Katrina started on August 25, 2005 and ended on August 30, 2005.

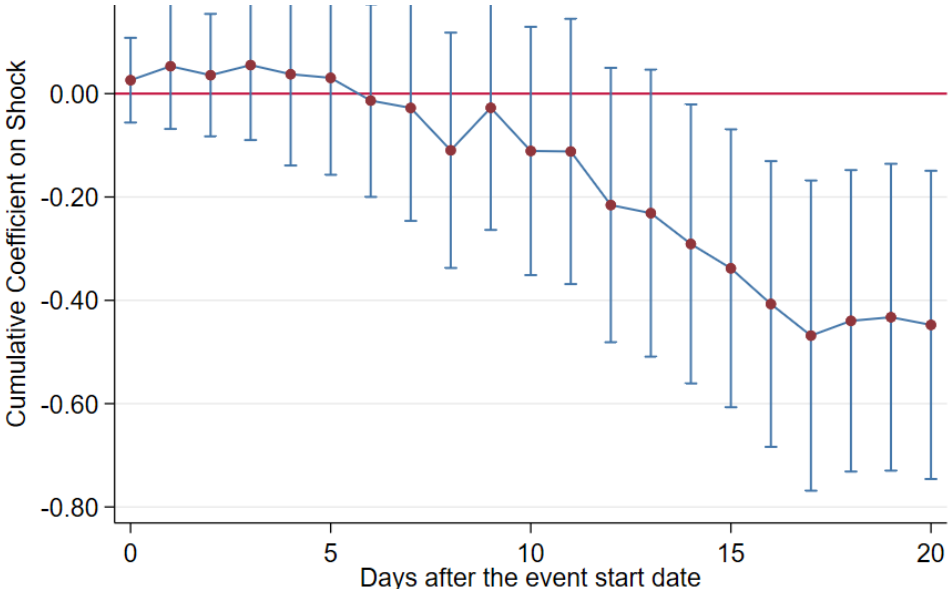
Table A.4: Drop in Industry Output for Carbon Tax and Growth Rate Scenarios in [Jorgenson et al. \(2018\)](#)

IGEM Industry	\$25 tax, 1% growth	\$25 tax, 5% growth	\$50 tax, 1% growth	\$50 tax, 5% growth
Agriculture	0.009	0.016	0.017	0.028
Oil mining	0.026	0.045	0.049	0.079
Gas mining	0.059	0.097	0.103	0.157
Coal mining	0.163	0.237	0.252	0.338
Nonenergy mining	0.016	0.028	0.028	0.046
Electric utilities	0.047	0.077	0.082	0.124
Gas utilities	0.049	0.087	0.092	0.154
Water and wastewater	0.016	0.026	0.028	0.046
Construction	0.010	0.018	0.018	0.030
Wood and paper	0.015	0.026	0.027	0.045
Nonmetal mineral products	0.022	0.039	0.040	0.068
Primary metals	0.022	0.038	0.040	0.066
Fabricated metal products	0.013	0.022	0.023	0.037
Machinery	0.014	0.024	0.025	0.040
Information technology equipment	0.008	0.013	0.013	0.022
Electrical equipment	0.009	0.015	0.015	0.025
Motor vehicles and parts	0.014	0.024	0.025	0.040
Other transportation equipment	0.006	0.011	0.012	0.019
Miscellaneous manufacturing	0.010	0.017	0.017	0.029
Food, beverage and tobacco	0.006	0.011	0.012	0.019
Textiles, apparel and leather	0.010	0.017	0.019	0.031
Printing and related activities	0.004	0.007	0.008	0.012
Petroleum and coal products	0.042	0.070	0.077	0.123
Chemicals, rubber and plastics	0.012	0.020	0.022	0.035
Wholesale trade	0.006	0.011	0.011	0.018
Retail trade	0.008	0.013	0.013	0.022
Transportation and warehousing	0.027	0.046	0.048	0.079
Publishing, broadcasting, telecommunications	0.005	0.009	0.010	0.015
Software & information technology services	0.008	0.014	0.014	0.023
Finance and insurance	0.006	0.010	0.011	0.017
Real estate and leasing	0.008	0.013	0.015	0.022
Business services	0.008	0.014	0.015	0.024
Educational services	-0.002	-0.004	-0.004	-0.007
Health care and social assistance	0.003	0.006	0.006	0.010
Accommodation and other services	0.007	0.011	0.012	0.020
Other government	0.001	0.001	0.001	0.002

**Note:** Estimates of decreases in industry output from Table 8 in [Jorgenson et al. \(2018\)](#). All scenarios here assume that the income from the tax is recycled as a lump sum dividend. Estimates are of decreases in industry output from 2015 until 2050.

## A.2 Figures

Figure A.1: Insurer Loss-to-Equity Factor Responses around Natural Disaster Events



**Note:** Cumulative coefficient  $\gamma$  on  $shock_t$  in  $PCF_t = \alpha + \sum_{n=0}^{20} \gamma_n shock_{t-n} + MKT_t + \epsilon_t$ .  $shock_t$  takes the value of 1 if it was the start date of a natural disaster event, and a value of 0 if there was no disaster on day  $t$ . Each physical risk factor series is standardized by its volatility. The standard errors are Newey-West adjusted and the band shows 95% confidence interval.