Impacts of global warming on hurricane-driven insurance losses in the United States

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Abstract

North Atlantic hurricanes are a major driver of property losses in the United States and a critical peril for the insurance industry on a global scale. Despite the growing scientific consensus around the potential impacts of global warming on North Atlantic hurricanes, the implications for the insurance industry are still largely unquantified. We address this question by drawing on 70 years of historical hurricane data, including wind-, precipitation-, and storm surge-driven losses to the US property insurance industry. We condition this historical dataset to generate stochastic event sets for the 2- and 4-degree warming scenarios in accordance with the 2021 IPCC projections. We find that global warming may increase insured losses by up to 25%, with greater impacts at lower return periods than in the tail. The 100-year loss scenario in the historical baseline may be exceeded on average every 80 years in a warmer climate. Furthermore, the average annual insurance loss may increase by 12% to 16%, with the largest relative increase attributable to precipitation-induced losses. These results provide us with a concrete base to assess the relevance of global warming in relation to other important insurance loss drivers, such as economic inflation, litigation, and exposure growth.

1 Introduction

North Atlantic hurricanes are the most devastating weather events in the United States and rank as one of the major loss drivers for the global insurance industry. Since 1970, North Atlantic hurricanes have accounted for nearly 30% of the yearly global insured property losses [Banerjee et al., 2023]. However, this percentage has increased significantly in recent years, given the growing concentration of assets along the entire East and Gulf coasts of the United States, as well as due to the impacts of climate variability and global warming.

While hurricanes are complex weather phenomena, they require only four main ingredients to form and strengthen: moist air, warm ocean water, a pre-existing disturbance such as a thunderstorm, and low wind shear. It is well known that natural climate variability affects these weather variables, and thus exerts a fundamental control over the number of hurricanes forming in the North Atlantic basin. There is also reason to believe that some of the above-mentioned "ingredients" may become more readily available in a warmer climate. For instance, water vapor supply to the atmosphere may become more efficient due to increased evaporation rates from a warmer ocean surface. Furthermore, as the atmosphere continues to heat up, hurricanes may be able to hold a larger amount of water vapor. Even though significant trends in hurricane frequency and intensity have not yet materialized [Vecchi et al., 2021, Aryal et al., 2018], the scientific community has a medium to high confidence that climate change will lead to more intense hurricane winds [Knutson and Tuleya, 2004, Knutson et al., 2010, 2013, 2020, 2022, Walsh et al., 2016, 2019] and rainfall rates [Scoccimarro et al., 2014, Villarini et al., 2014]. Moreover, the more intense hurricane winds will likely provoke higher storm surge, exacerbating the impact of sea level rise on coastal flooding [Balaguru et al., 2016, Garner et al., 2017, Lin et al., 2012, Wahl et al., 2015, Woodruff et al., 2013]. The 2021 Intergovernmental Panel on Climate Change [Arias et al., 2021] reviewed all relevant scientific advances and reported with high confidence that global warming will increase the likelihood of hurricanes reaching major intensities (CAT4-5) by 10% and 20% in the 2- and 4-degree warming scenarios, respectively, while the hurricane-induced precipitation will increase by 11% and 28%.

Previous studies have investigated the dependency of insurance claims on hurricane wind, precipitation, and storm surge by combining hazard, exposure, and vulnerability information [Bjarnadottir et al., 2011, Bouwer, 2011, Czajkowski et al., 2017, Estrada et al., 2015, Lin and Cha, 2021, Raible et al., 2012, Rosowsky, 2021, Emanuel, 2011, Murnane and Elsner, 2012]. However, the impacts of climate change on hurricane insurance losses in the United States are still largely unclear, particularly with respect to the combined effects of wind, precipitation, and storm surge hazards.

Here, we draw on more than 70 years of historical data to quantify the potential impacts of a warmer climate on property insurance losses from North Atlantic hurricanes. Specifically, we combine the NOAA hurricane dataset (HURDAT2) with detailed insurance loss information from the Property Claim Services (PCS) and the National Flood Insurance Program (NFIP) to compile wind, precipitation, and storm surge losses for nearly 150 historical hurricanes in the contiguous United States. Using a bootstrapping technique, we generate stochastic event sets that embed the projected changes in hurricane intensity and precipitation reported in the 2021 IPCC report for the 2- and 4-degree warming scenarios.

Our results indicate that occurrence and aggregate annual insured losses may increase by up to 25% at low return periods and up to 10% in the tail. We find that today's 100-year insured loss scenario (approximately USD 200 billion) could have a return period of approximately 80 years in the warmer climate scenarios. Moreover, a 2-degree global warming could lead to a change in average annual loss (AAL) on the order of 12%, whereas a 4-degree global warming could cause a 16% increase in AAL. The contribution to the AAL from precipitation-driven losses may show an even larger percentage increase than those from wind and storm surge losses. We finally discuss the relevance of these results in relation to the potential increase in AAL driven by other major drivers of insurance losses, such as economic inflation, social inflation, and exposure growth.

2 Datasets

To investigate the potential impact of global warming on insurance losses from North Atlantic hurricanes, we rely on three main datasets: 1) the HURDAT2 dataset providing detailed information on all hurricanes that made landfall in the United States since 1851 including their lifetime maximum intensity category; 2) the PCS insurance industry dataset of property losses detailing all US insurance losses caused by hurricanes since 1950; 3) the NFIP claims dataset listing all paid property flood claims since 1979 and distinguishing between storm surge- and precipitation-related damage. We combine these three datasets to compile a table of nearly 150 North Atlantic storms that caused insurance losses in the US from 1950 to 2022 (see Figure S1 in the supporting information), listing the maximum lifetime storm intensity and the breakdown into wind-, precipitation-, and storm surge-related loss contributions. Note that we use the maximum lifetime storm intensity, rather than the landfall intensity, as this is the intensity measure referred to in the 2021 IPCC projections. Consistently with previous studies [Jewson, 2023], we assume that when the IPCC projections suggest that CAT4-5 storms will increase in frequency, landfalling storms that previously reached CAT4-5 intensity will also increase in frequency, whatever their intensity at landfall. We describe each dataset below in more detail and explain the data processing methodology that was implemented.

2.1 HURDAT2 Dataset

The HURDAT2 dataset [Landsea and Franklin, 2013] originates from the National Hurricane Center's Atlantic Hurricane Database Re-analysis Project, that aims to extend and revise the original North Atlantic hurricane database (or HURDAT). Going back to 1851 and revisiting storms from more recent years, information on tropical cyclones is corrected and augmented using an enhanced collection of historical meteorological data in the context of today's scientific understanding of hurricanes and analysis techniques. The HURDAT2 dataset contains information obtained at six-hour intervals on the location, maximum winds, central pressure, and (since 2004) size of all known tropical and subtropical cyclones. We filtered the dataset to retain only the storms that caused insured losses in the United States, that is, those that made landfall or neared the US East and Gulf coasts. For each of these storms, we record the maximum lifetime sustained wind speed and map it to the maximum lifetime category (CAT0: below 63 kn; CAT1: 64-82 kn; CAT2: 83-95 kn; CAT3: 96-112 kn; CAT4: 113-136 kn; CAT5: above 137 kn).

2.2 PCS Dataset

PCS is the claims reporting organization unit of Verisk's Insurance Services Offices and is the internationally recognized source for compiling and reporting estimates of catastrophic insured property losses in the US since 1950. Reporting is based on information provided by insurance companies affected by a catastrophe event. PCS estimates include covered insurance losses from personal property, vehicle, and commercial property policies. Those policies cover real property, contents, time-element losses (e.g., business interruption and additional living expenses), vehicles, boats, and property under certain inland marine and specialty policies. PCS also typically includes losses insured by state wind pools, joint underwriting associations, and certain other residual market mechanisms. Note that PCS hurricane loss estimates do not include the flood claims paid by the NFIP, which we account for separately. For this study, we use the PCS FlatCat dataset [Property Claim Services, 2023] that provides the catastrophe serial numbers, dates of occurrence, states affected, types of perils, and loss estimates. We further index all past hurricane losses to account for economic inflation and growth in insurance penetration, population, and wealth per capita. Following the method of Barthel and Neumayer [2012], we perform the indexation based on the yearly values of US Gross Domestic Product (GDP) deflator [The World Bank, 2023] and US property insurance gross premium as reported by the Organization for Economic Co-operation and Development [Organisation for Economic Co-operation and Development, 2023], which yield an average indexation factor of 7% per annum. This leads to an indexed average annual loss of USD 21.7 billion for insured hurricane losses in the US, which is in line with recent estimates [Verisk, 2023]. Note that the North Atlantic hurricane losses reported by PCS include flood losses that fall under private insurance policies. However, PCS does not include flood losses covered by the NFIP or losses that fall under the NFIP's Write Your Own (WYO) Program. Because the market share of private flood insurance in the US is estimated to be as low as 5%, we use the PCS hurricane losses to quantify exclusively the loss contribution from wind damage.

2.3 NFIP Dataset

Flooding is a major source of loss to individuals and businesses in the United States, and private insurers have historically been unable to provide flood insurance to homeowners at affordable rates. The NFIP was created in 1968 to reduce flood losses through flood hazard identification, floodplain management including supporting flood mitigation projects, and providing insurance protection. Through the NFIP, the Federal Emergency Management Agency (FEMA) offers insurance coverage for building structures as well as for contents and personal property within the buildings to eligible and insurable properties. Since 1983, insurance companies participating in FEMA's Write Your Own (WYO) program also offer flood insurance through the NFIP. The NFIP dataset is openly accessible through the OpenFEMA portal [Federal Emergency Management Agency, 2023] and provides details on more than 2 million NFIP claims transactions since 1979, including the damage class (river overflow, rainfall accumulation, tidal water overflow, erosion, landslide, subsidence, sinkholes) and denoting the catastrophe event associated with the claim. We aggregate these damage classes into three more comprehensive loss classes, namely precipitation, storm surge, and other losses. Specifically, we associate tidal water overflow to storm surge losses; river, lake, rainfall, and alluvial fan overflow claims to precipitation losses; the remaining damage classes, which are less relevant for the purpose of this study, are assigned to other losses. We finally calculate the NFIP losses for each hurricane and loss class by summing all corresponding claims. The original NFIP losses are indexed to 2022 using the same methodology applied to the PCS insured hurricane losses.

3 Hurricane projections for future climate scenarios

The 2021 IPCC report provides climate change projections on key physical properties of North Atlantic hurricanes for the 2- and 4-degree warming scenarios. The findings of the IPCC report are summarized hereafter including some relevant implications for insurance claims. We also list the key projections in Table S1 in the supporting information.

- Hurricane intensity: Hurricane peak wind speeds will very likely increase in the North Atlantic with global warming [Knutson et al., 2020]. As a result, the proportion of major hurricanes (CAT4-5) is projected to increase, approximately by 13% and 20% in the 2- and 4-degree warming scenarios. Accordingly, we increase the sampling probability of major hurricanes from 40% (as calculated from the historical dataset) to 44% (2-degree warming) and 48% (4-degree warming) when creating stochastic events sets for these future climate conditions. It follows that the sampling probability of minor hurricanes (CAT0-3) decreases from 60% (historical dataset) to 56% and 52% in the 2- and 4-degree warming scenarios.
- Hurricane frequency: Climate studies have projected diverse and sometimes inconsistent changes in hurricane frequency in the North Atlantic, both in sign and magnitude. This disparity and the difficulty in explaining the mechanisms behind the different model responses emphasize the lack of process understanding of future changes in tropical cyclogenesis. Given the lack of confidence in the projected impact of global warming on hurricane frequency, we assume no changes in the frequency distribution for the purpose of this study.
- Hurricane precipitation: There is medium-to-high confidence that hurricane-induced rainfall will increase with global warming. The rate of increase per degree of warming is approximately 7%, that is, close to the rate of water vapor increase at constant relative humidity. Thus, the projected increase in rainfall amounts is approximately 14% and 28% for the 2- and 4-degree warming scenarios, respectively. This might cause larger flood depths and flood footprints, leading to a larger number of flood claims and to a larger average paid claim amount. The impact of increased flood depth on the number of flood insurance claims was assessed by Czajkowski et al. [2017] who estimated an increase of approximately 0.85% in the number of affected policies per percentage increase in flood depth. Furthermore, the results by Tonn and Czajkowski [2022] indicate that the average paid claim increases by 0.15% per percentage increase in flood depth. By combining these results, we estimate that the flood insurance losses may increase by approximately 13% to 27% in the 2- and 4-degree warming scenarios (see the supporting information for additional details).
- Storm surge: There are reasons to believe that an increase in hurricane intensities might lead to a corresponding increase in storm surge, as stronger winds can push water farther inland from the shoreline. Research on the subject has mostly focused on local impacts, such as the coast of New York City [Garner et al., 2017, Sarhadi et al., 2024], and can hardly be extrapolated to the entire East and Gulf coasts. In this study, the potential increase in insurance losses caused by more severe storm surge is implicitly accounted for in the future climate event sets owing to the larger proportion of major hurricanes, which are associated with higher flood claims. It is important to note that in this study we do not compound the impacts of global warming on storm surge and sea level rise, as the latter is unrelated to any changes in the physical properties of hurricanes. We further discuss the potential role of sea level rise in the closing section.

There are other potentially relevant hurricane properties, such as storm track, translational speed, and storm size, whose projected changes in future climate scenarios are highly uncertain. The projections for hurricane tracks in the North Atlantic vary considerably among available studies, although the general expectation is that the location of maximum intensity might shift poleward in a warmer climate. Hurricane translational speeds may potentially reduce outside the tropics, but at more local scales there could be an acceleration of the storms. As for hurricane size, a plausible storm-widening mechanism can be envisaged, whereby the outward inclination of the eye wall with height could lead to larger eyewall area in combination with a higher tropopause. However, given the high uncertainty and lack of confidence in these projections, we assume no change in the hurricane tracks, translational speeds, nor size for the purpose of this study.

4 Bootstrapping methodology

The compiled historical event dataset and the 2021 IPCC hurricane projections are then used to construct stochastic event sets for future climate scenarios. For any given simulation year in the stochastic set, we sample the number of events as

$$n = F_n^{-1}(u), \tag{1}$$

where n is the yearly number of events, F_n is the empirical event frequency CDF that we estimate from the historical event set (green curve in Figure 1a), and u is a random number uniformly distributed between 0 and 1. We then divide the number of events n into number of hurricanes n_h and major hurricanes n_m, such that $n_h + n_m = n$ and

$$n_h = \sum_i^n 1 - \mathcal{L}(u_i; P_m), \tag{2}$$

$$n_m = \sum_i^n \mathcal{L}(u_i; P_m). \tag{3}$$

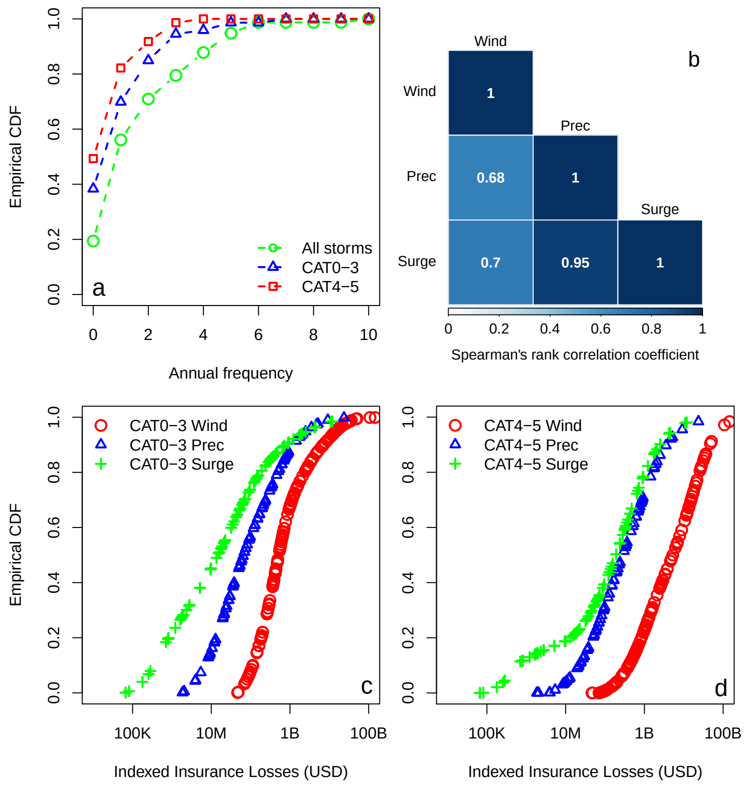

Figure 1: **Empirical statistics computed from the compiled dataset of historical events.** a) Empirical cumulative distribution functions (CDF) of the annual frequencies of hurricanes, major hurricanes, and all storms. b) Spearman's rank correlation coefficients among the wind-, precipitation-, and storm surge losses in the historical eventset. c) Empirical CDFs of the wind-, precipitation-, and storm surge-driven losses for hurricanes and d) major hurricanes, smoothed with a log-transformed kernel density function [Jones et al., 2018].

In equations (2) and (3), P_m is the proportion of hurricanes reaching major intensity in the climate scenario of interest (first row in Table S1 in the supporting information), u_i, $i = 1, ;n$ are uniformly distributed random numbers between 0 and 1, and $\mathcal{L}(u_i; P_m)$ is a logical operator such that

$$\begin{cases} \mathcal{L}\left(u_i; P_m\right) = 1 \text{ if } u_i \leq P_m \\ \mathcal{L}\left(u_i; P_m\right) = 0 \text{ if } u_i > P_m \end{cases} \tag{4}$$

We finally calculate the insurance losses for all events by sampling their wind, precipitation, and storm surge contributions for the climate scenario of interest. For this purpose, we need to account for the statistical correlations between the different loss contributions, as higher wind losses are often accompanied by higher flood losses (see Figure 1b for the Spearman's correlation coefficients). We perform a multivariate random sampling of the three loss contributions by sampling from a Gaussian copula:

1. we transform the wind, precipitation, and storm surge losses in our historical dataset into standard normal variates using quantile mapping.
2. we calculate the 3×3 covariance matrix $\mathbf{\Sigma}$ of the normal-transformed wind, precipitation, and storm surge losses.
3. we generate a multivariate normal sample, of dimension $3 \times n$, $\mathbf{z} = \mathbf{D} \cdot \mathbf{x}$, where $\mathbf{D}$ is the Cholesky decomposition of $\mathbf{\Sigma}$ and $\mathbf{x}$ is a univariate standard normal sample. Each element of $\mathbf{z}$ is associated with either a hurricane or a major hurricane.
4. we back-transform the multivariate normal sample $\mathbf{z}$ into the corresponding wind, precipitation, and storm surge losses for hurricanes ($\mathbf{w}_h$, $\mathbf{p}_h$, and $\mathbf{s}_h$) and major hurricanes ($\mathbf{w}_m$, $\mathbf{p}_m$, and $\mathbf{s}_m$) using quantile mapping

$$\begin{cases} \mathbf{w}_h = F_{h,w}^{-1}\left(\mathcal{N}\left(\mathbf{z}_1\right)\right) \\ \mathbf{p}_h = F_{h,p}^{-1}\left(\mathcal{N}\left(\mathbf{z}_2\right)\right) \\ \mathbf{s}_h = F_{h,s}^{-1}\left(\mathcal{N}\left(\mathbf{z}_3\right)\right) \end{cases} \tag{5}$$

$$\begin{cases} \mathbf{w}_m = F_{m,w}^{-1}\left(\mathcal{N}\left(\mathbf{z}_1\right)\right) \\ \mathbf{p}_m = F_{m,p}^{-1}\left(\mathcal{N}\left(\mathbf{z}_2\right)\right) \\ \mathbf{s}_m = F_{m,s}^{-1}\left(\mathcal{N}\left(\mathbf{z}_3\right)\right) \end{cases} \tag{6}$$

In equations (5) and (6), $F_{h,w}$, $F_{h,p}$, and $F_{h,s}$ are the empirical CDFs of wind, precipitation, and storm surge losses for hurricanes (Figure 1c), which we estimate from the historical hurricane dataset. Similarly, $F_{m,w}$, $F_{m,p}$, and $F_{m,s}$ are the empirical CDFs for major hurricane losses (Figure 1d). Furthermore, $\mathcal{N}$ is the standard normal CDF. Note that, when sampling events for future climate scenarios, the precipitation losses $\mathbf{p}_h$ and $\mathbf{p}_m$ are inflated by the corresponding projection factors (second row in Table S1 in the supporting information).

We repeat the calculations described in equations (1) to (6) for a number $N_y = 500$ of simulation years to generate a stochastic event set. This allows us to quantify the return periods of insurance losses beyond those that can be inferred from the 70 years of historical data. Furthermore, we generate a number $N = 10000$ of different stochastic event sets (each one containing N_y years of simulations) to calculate robust estimates of key statistics, such as median loss values and inter-quantile ranges at different return periods.

5 Results

We first verify that our methodology can reproduce the loss exceedance frequencies as observed in the historical dataset. For this purpose, we generate a stochastic eventset for the historical baseline (1950-2022) using the hurricane frequency and loss probability distributions estimated from the historical dataset. The results, presented in Figures 2a and 2b, show good agreement with the return periods calculated for the historical losses. The stochastic exceedance frequency curve also helps us to better quantify the return periods of the costliest historical events. For instance, our results suggest that an event loss of USD 150 billion (Hurricane Katrina and Hurricane Andrew indexed to 2022) has a return period of approximately 60 years, whereas an event loss of USD 50 billion (Hurricane Ian, Hurricane

Sandy, and Hurricane Hugo indexed to 2022) has a return period of approximately 10 years. On an annual aggregate basis, the costliest year exhibiting an industry loss of USD 200 billion (hurricane season 2005 indexed to 2022) has a return period of 70 years, whereas the second costliest year resulting in an industry loss of USD 150 billion (hurricane season 1992 indexed to 2022) appears to have a return period of approximately 40 years.

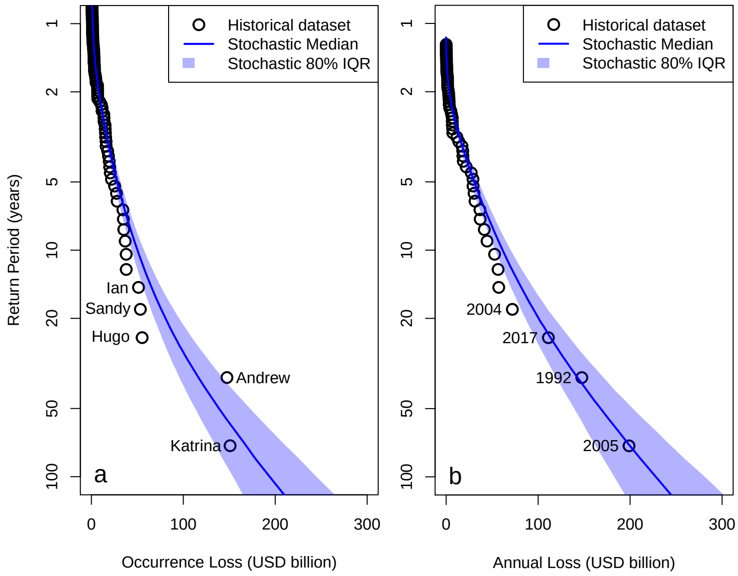

Figure 2: **Loss exceedance probabilities in the historical baseline (1950-2022).** a) Occurrence losses and b) annual losses exceedance probabilities obtained from the compiled hurricane loss dataset (black circles) and estimated via bootstrapping (the solid blue line indicates the median and shaded area indicates the 80% inter-quantile range).

We then investigate the impacts of global warming by applying the prescribed projections to the probability distributions of event frequency and wind-, storm surge-, and precipitation-driven losses. We find that the 100-year occurrence loss in the historical baseline (USD 200 billion) could have a return period of approximately 80 years in the warmer climate scenarios (Figure 3a). Similarly, the 50-year occurrence loss (USD 140 billion) is projected to have a return period of approximately 40 years. The results suggest that climate change is likely to increase occurrence losses by 5% to 25%, with a greater impact at low return periods than in the tail (Figure 3b). We observe similar results with respect to aggregate annual losses (see Figure S3 in the supporting information). Moreover, major hurricanes will likely account for a much larger fraction of the aggregate annual losses. Critically, the median contribution from CAT4-5 to the 2-year return period annual loss, which is approximately 10% in the historical baseline (blue circles in Figure 3c), is projected to be in the range of 50% to 60% in the 2- and 4-degree warming scenarios (orange and red circles in Figure 3c).

The average annual loss (AAL) increases from USD 20.7 billion (historical baseline) to USD 23.1 billion (+12%) and USD 24.0 billion (+16%) in the 2- and 4- degree warming scenarios (Figure 4a). The AAL breakdown by hazard for each climate scenario suggests that the hurricane wind AAL increases from USD 17.4 billion to USD 19.3 billion (+11%) and USD 19.8 billion (+14%), the freshwater AAL from USD 1.3 billion to USD 1.7 billion (+30%) and USD 1.9 billion (+46%), and the storm surge AAL from USD 900 million to USD 1 billion (+11%). This indicates that wind-related losses may experience the largest loss increase in absolute terms, whereas freshwater losses may experience the largest increase in relative terms. We further find that the contribution of major hurricanes (CAT4-5) to the AAL increases from USD 18.0 billion to USD 20.6 billion (+14%) and USD 21.7 billion (+27%), whereas the contribution of hurricanes with lower intensities (CAT0-3) decreases from USD 2.7 billion to USD 2.5 billion (−7%) and USD 2.3 billion (−15%) (Figure 4b). This trend is expected, given that our projections assume an decrease in the average frequency of CAT0-3 hurricanes. We summarized these results in Table S1 in the supporting information.

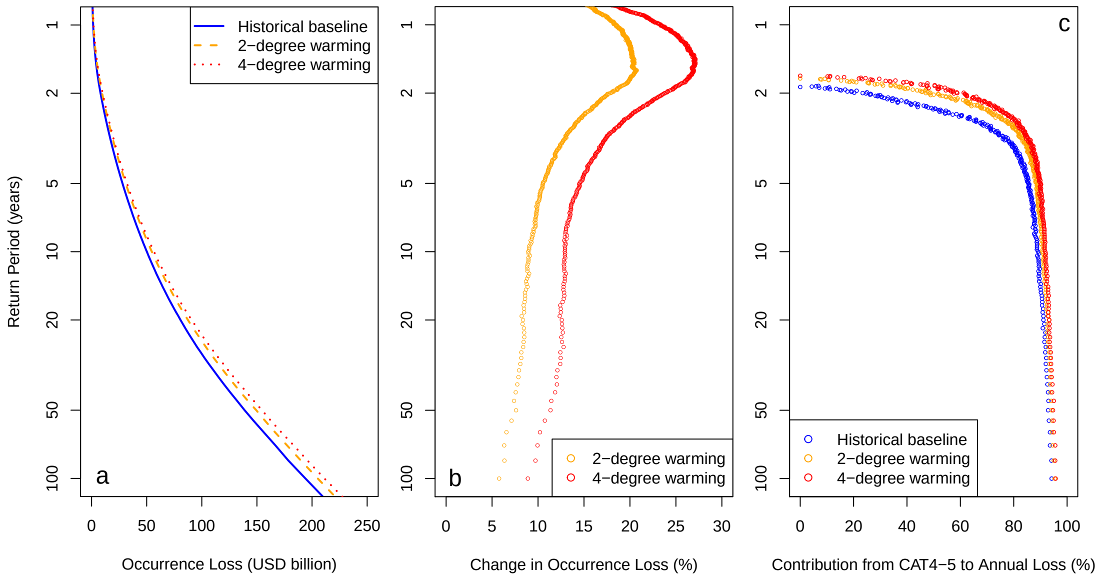

Figure 3: **Loss exceedance probabilities in future climate scenarios.** a) Occurrence loss exceedance probabilities for the historical baseline (solid blue line) and future climate scenarios (dashed orange line for 2-degree warming and dotted red line for 4-degree warming). The lines indicate the median values calculated from the bootstrapping. b) Relative change in occurrence losses with respect to the historical baseline, for the 2-degree (orange circles) and 4-degree (red circles) warming scenarios. c) Contribution from major hurricanes (CAT4-5) to the aggregate annual losses at the corresponding return periods, fur the historical baseline (blue circles) and future climate scenarios (orange and red circles). The circles indicate median values calculated from the bootstrapping.

6 Discussion and conclusions

Despite the growing scientific consensus on the potential impacts of global warming on the intensity and storm-induced precipitation of North Atlantic hurricanes, very little is known about the implications for the insurance industry. We addressed this question by compiling a comprehensive historical hurricane dataset, that is then used as a baseline to generate stochastic event sets for future climate scenarios in accordance with the 2021 IPCC projections. In doing so, we aimed at isolating the impact of climate change from other important insurance loss drivers, such as exposure growth, economic inflation, and social inflation. We found that both occurrence and annual aggregate insured losses may increase up to 25%, with greater impacts at low return periods than in the tail. Consequently, the 100-year historical loss scenario may be exceeded on average every 80 years in a warmer climate. Moreover, the average annual loss may increase by 12% and 16% in the 2- and 4-degree warming scenarios. Critically, precipitation-induced annual losses may show the largest relative increase due to the combined effects of increased precipitation and increased proportion of major hurricanes, which are often associated with larger losses from rain and flood. It is worth noting that the average annual loss of major hurricanes (CAT4-5) might significantly increase, whereas that of lower intensity hurricanes (CAT0-3) is expected to decrease. This follows from the 2021 IPCC projections that indicate an increase in the proportion of major hurricanes but a stable, if not slightly decreasing, overall storm frequency.

There are some important sources of uncertainty underlying our results. Firstly, the potential impacts of global warming on some hurricane physical properties are not well understood, and were thus not included in our analyses. These include potential changes in the size and forward moving speed of hurricanes, as well as the geographic variability in storm tracks. Secondly, how future changes in hurricane precipitation may affect the number and size of insurance claims is still uncertain, due to the complexities underlying the hydrological and hydraulic processes involved in the rainfall-runoff transformation. Our projections of hurricane freshwater losses are thus preliminary and need to be corroborated by further research. Lastly, we did not account for the potential impact of sea level rise on future property insurance losses,

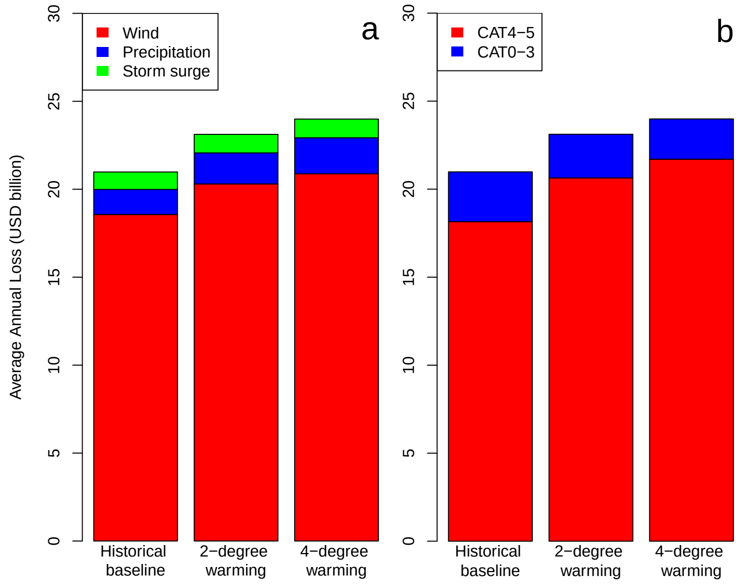

Figure 4: **Impact of climate change on the average annual loss (AAL).** a) Contributions from the wind losses (red bars), freshwater losses (blue bars), and storm surge losses (green bars) to the total AAL in the historical baseline and future climate scenarios. b) Contributions from major hurricanes (CAT4-5, red bars), and hurricanes (CAT0-3, blue bars) to the total AAL for the historical baseline and future climate scenarios.

given that this is unrelated to the physical properties of hurricanes. Even though sea level rise is likely to play a significant role in future storm surge losses, a receding shoreline should be accompanied by a gradual displacement of the exposed properties inland or mitigated by improved coastal defenses. A sensible assessment of the sea level rise contribution to storm surge losses thus also would need to account for possible exposure mitigation measures in coastal regions.

Despite these uncertainties, our results provide a solid foundation for assessing the impact of global warming on the US insurance industry in a wider context. According to the IPCC Sixth Assessment Report [Arias et al., 2021], a 2-degree warming might materialize between 2041-2060 under the (likely) SSP2-4.5 scenario, while a 4-degree warming might materialize between 2081-2100 under the (unlikely) SSP3-7.0 or (highly unlikely) SSP5-8.5 scenarios. If we consider the more likely SSP2-4.5 scenario, it follows from our results that climate change might drive an AAL increase smaller than 1% per annum. Such an increase is relatively small compared to other insurance loss drivers, such as economic inflation, social inflation, and exposure growth. For comparison, the compound loss loading factor from all these man-made drivers in the United States exceeded 10% in the single year 2022 [Briggs et al., 2022].

In conclusion, global warming is likely going to cause an increase in property losses from North Atlantic hurricanes in the United States. While the insurance and reinsurance industries should carefully assess the impacts of wetter and more intense hurricanes on their portfolios, an equal, if not larger, attention should be warranted to other pressing societal issues, including a stronger focus on realizing a more sustainable exposure growth along the East and Gulf coasts.

Acknowledgments

All data and scripts used to produce the results presented in this manuscript can be accessed at `https://data.mendeley.com/preview/jbdsy2x7n5?a=a82f9c12-b72f-4325-9aff-897fa38a2961`.

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Supporting information for “Impacts of global warming on hurricane-driven insurance losses in the United States”

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Introduction

This supporting material provides additional information on

- Our estimation of the US property insurance losses caused by hurricanes since 1950, indexed to 2022.
- Our approach for assessing the impact of global warming on US property insurance losses due to hurricane-driven precipitation.
- The projected increase in aggregate annual insured losses caused by hurricanes making landfall in the US.

S1 Indexed insurance industry hurricane losses

As described in the main manuscript, we leverage a variety of data sources to compile a comprehensive dataset of hurricane-driven property insurance losses in the United States since 1950. The original insured loss amounts have been indexed to 2022, accounting for yearly economic inflation and growth in insurance penetration, population, and wealth per capita [Barthel and Neumayer, 2012]. The resulting indexed losses from each tropical storm in the dataset are shown in Figure S1a, whereas the aggregate annual losses are shown in Figure S1b. Note that, because the NFIP claims dataset provides information on hurricane-induced flood losses starting from 1979, only wind-driven loss contributions are shown for hurricanes that occurred between 1950 and 1979.

S2 Relationship between flood insurance losses and hurricane-induced precipitation

An increase in hurricane-induced precipitation, as projected by the 2021 IPCC report, will likely cause larger flood footprints and, consequently, a larger number of flood insurance claims. In addition, an increase in precipitation may lead to deeper flood waters and thus to higher average claim amounts. Here, we draw on the results of previous studies investigating the statistical relationships among flood depth, number of flood claims, and average claim amounts to assess the potential impact of higher hurricane-driven precipitation and flood insurance losses.

Czajkowski et al. [2017] determined a statistical relationship between the increase in number of claims and the major flood insurance loss drivers, including flood depth. This allowed them to explore via a sensitivity analysis how changes in flood depth may impact insured property losses, assuming that other exposure and vulnerability factors remain the same (Table 2 in their paper). Their sensitivity analysis, shown in Figure

S2a, indicates a linear scaling $\delta N \propto \delta F$ between the increase in number of flood claims, δN, and the increase in flood depth, δF. The resulting proportionality coefficient is approximately 0.85 ± 0.06 (95% confidence interval).

The statistical relationship between the average freshwater insurance claim and hurricane flood depth was investigated by Tonn and Czajkowski [2022]. Therein, the authors presented the distribution of paid claim amounts by flood depth bins (Figure 6 in their paper). We use their results to establish the linear relationship $\delta C \propto \delta F$ between the increase in average claim amount, δC, and the increase in flood depth, δF (Figure S2b). The resulting proportionality coefficient is approximately 0.15 ± 0.03, where the uncertainty indicates the 95% confidence interval.

The freshwater insurance losses for any hurricane event can be approximated as the product of the number of claims and the average paid claim. It follows that the increase in freshwater insurance losses can be expressed as $\delta L \approx (\delta N + 1)(\delta C + 1) - 1$. We can use the linear scaling derived above to then estimate the change in freshwater insurance losses as a function of the projected change in flood depth $\delta L \approx (0.85 \times \delta F + 1)(0.15 \times \delta F + 1) - 1$.

It is worth noting that the 2021 IPCC report provides projections for the increase in hurricane precipitation, rather than the ensuing flood depths. The relationship between the increase in precipitation and the increase in flood depth is generally non-trivial, especially given the complex hydrological and hydraulic processes involved in the rainfall-runoff transformation. For the purpose of this study, we assume that the projected increase in precipitation translates into an equal increase in flood depth, i.e., $\delta F \approx \delta P$. This may be a sensible approximation for so-called pluvial floods, generated by excessive rainfall that contributes almost entirely to water accumulation at the surface [Brauer et al., 2020]. Further research is however required to estimate the potential impacts on insurance losses for so-called fluvial floods, caused by embankment overflow.

From the above scaling analysis it follows that an increase in hurricane precipitation δP of approximately 14% and 28%, as projected by 2021 IPCC report for the 2- and 4-degree warming scenarios, may lead to an increase in flood insurance losses δL of approximately 13% and 27%, respectively.

S3 Projected changes in aggregate annual insurance losses

Figure S3 shows the potential changes in aggregate annual losses in the 2- and 4-degree warming scenarios, relative to the historical baseline. High-frequency, low-severity events (having return periods between 2 and 3 years) are the most impacted, with an increase in insured losses up to 18% in the 2-degree warming scenario and 25% in the 4-degree warming scenario. The loss increase is smaller, in the range of 5% to 10%, for the less frequent, more severe events with return periods larger then 50 years.

Table S1 summarizes the input parameters required for the stochastic sampling methodology, namely average proportion of CAT4-5 and change in precipitation-driven insured losses, and the key results of our study.

Table S1: **Summary of simulation parameters and key results.** List of input parameters (fraction of major hurricanes, change in precipitation-driven losses) and key results (5-, 20-, and 100-year event losses, average annual loss with breakdown into hazards and intensity categories) for the historical baseline (1950-2022) and each of the future climate scenarios.

	Historical baseline	**2-degree warming**	**4-degree warming**
Average proportion of CAT4-5	40%	44%	48%
Change in precipitation losses	-	+13%	+27%
5-year event loss (USD billion)	27.8	31.0	32.1
20-year event loss (USD billion)	79.8	87.4	90.8
100-year event loss (USD billion)	192.0	205.1	211.2
Total AAL (USD billion)	20.7	23.1	24.0
Wind AAL (USD billion)	17.4	19.3	19.8
Precipitation AAL (USD billion)	1.3	1.7	1.9
Storm surge AAL (USD billion)	0.9	1.0	1.0
CAT0-3 AAL (USD billion)	2.7	2.5	2.3
CAT4-5 AAL (USD billion)	18.0	20.6	21.7

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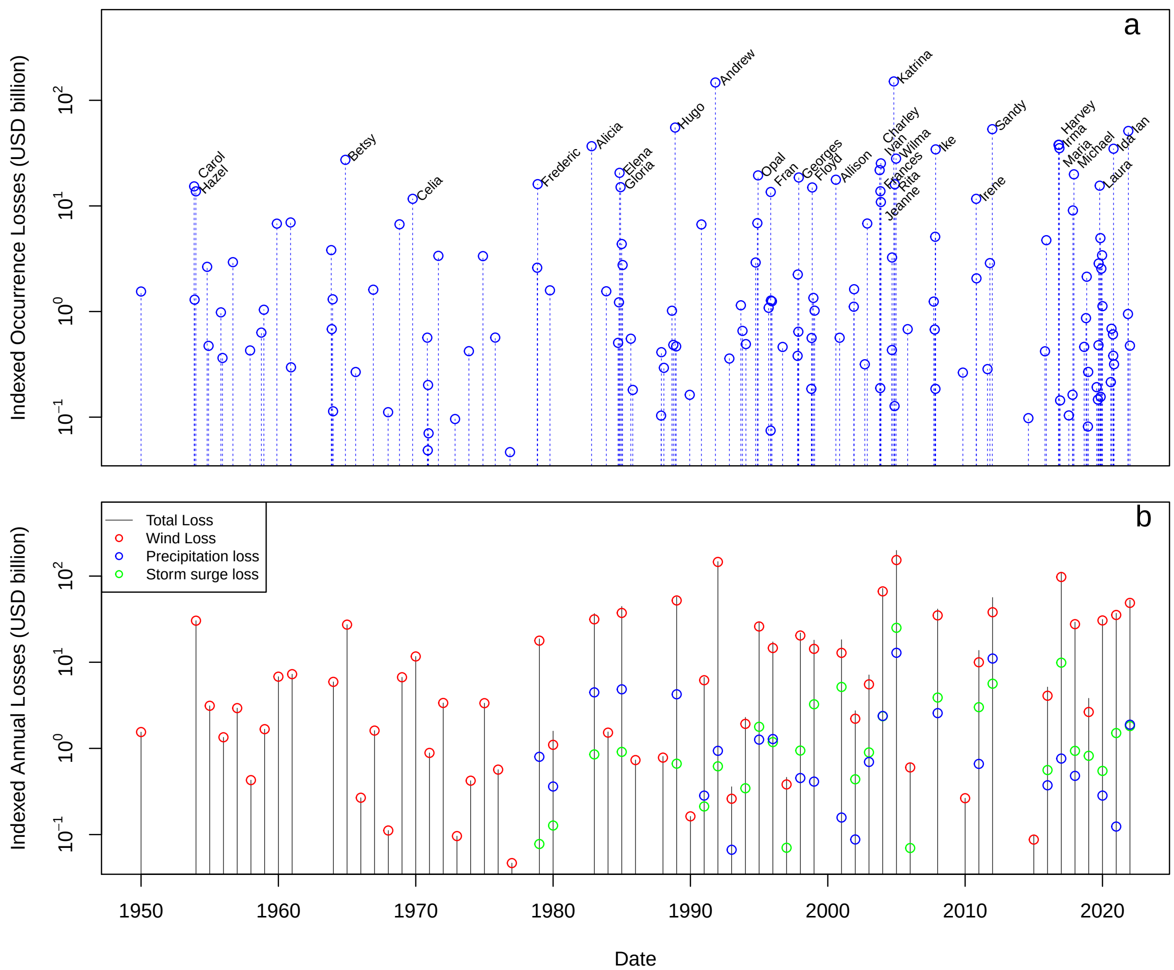

Figure S1: **Hurricane losses for the US property insurance industry since 1950.** a) Occurrence insured losses, including wind, freshwater, and storm surge contributions, indexed to 2022 using the methodology described in [Barthel and Neumayer, 2012]. The chart displays storm names for events having indexed insurance losses in excess of USD 10 billion. b) Total aggregate annual insured losses (black lines) with a breakdown into wind (red circles), precipitation (blue circles), and storm surge contributions (green circles).

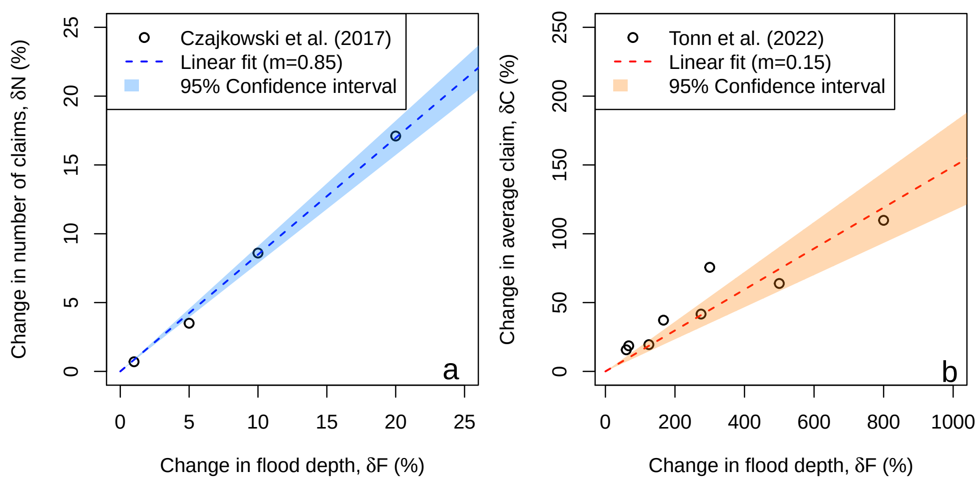

Figure S2: **Increase in flood insurance losses with flood depth.** a) Relationship between number of flood claims and flood depth based on data from Czajkowski et al. [2017] (black circles). The dashed blue line indicates the linear fit based on the least mean square error method, and the shaded blue area indicates the 95% confidence interval of the linear fit slope. b) Relationship between average insurance claim amount and flood depth. The circles show the data points from Tonn and Czajkowski [2022], the dashed red line indicates the linear fit based on the least mean square error method, and the shaded orange area depicts the 95% confidence interval of the linear fit slope.

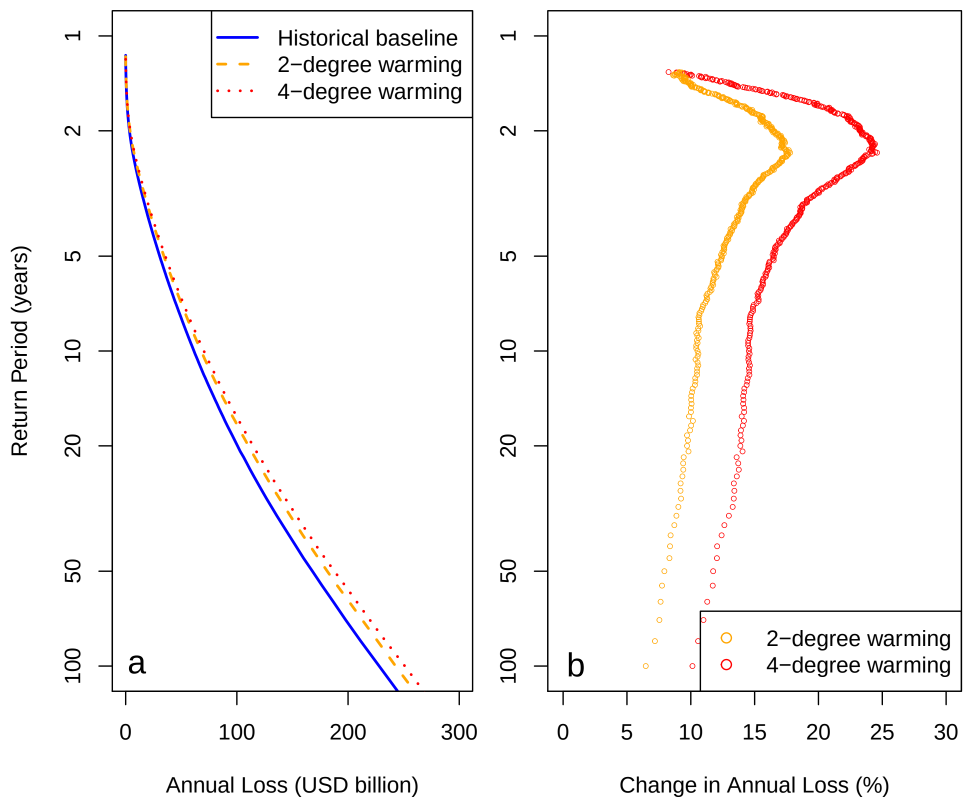

Figure S3: **Impact of climate change on aggregate annual losses.** a) Aggregate annual loss exceedance probabilities for the historical baseline (solid blue line) and future climate scenarios (dashed orange line for 2-degree warming and dotted red line for 4-degree warming). The lines indicate the median values calculated from the bootstrapping. b) Relative change in annual losses with respect to the historical baseline, for the 2-degree (orange circles) and 4-degree (red circles) warming scenarios.