Increase in insurance losses caused by North Atlantic hurricanes in a warmer climate

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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 reinsurance industry globally. We leverage insurance loss data and stochastic modeling to investigate the impacts of projected changes in hurricane climatology on the insurance industry, for +2°C and +4°C warming scenarios. We find that, relative to the historical baseline 1950-2022, expected changes in wind speed and rainfall may increase hurricane losses by $5\% - 15\%$ (+2°C) and $10\% - 30\%$ (+4°C), with greater impacts at lower return periods than in the tail. The historical 100-year loss event may therefore be exceeded on average every 80 years (+2°C) and 70 years (+4°C). The expected changes in average annual loss are projected to be 10% (+2°C) and 15% (+4°C), with the largest relative increase attributable to precipitation-induced losses. Under the extreme SSP5-8.5 scenario, the expected loss inflation due to climate change is thus on the order of 0.5% per annum.

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, 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 [Lin et al., 2012, Woodruff et al., 2013, Wahl et al., 2015, Balaguru et al., 2016, Garner et al., 2017, Sarhadi et al., 2024]. Frequency distributions of projected changes in hurricane physical properties for a +2°C warming scenario were compiled based on results from a large number of modeling studies [Knutson et al., 2020]. The median projected changes in hurricane climatology suggest a 14% decrease in hurricane frequency, a 10% increase in the fraction of hurricanes reaching major intensities (category 4 and 5), and a 15% increase in hurricane-induced precipitation. The uncertainties around these projections are however significant, as not all studies agree on sign and magnitude of future changes.

Previous studies have also investigated the dependency of economic losses on hurricane wind, precipitation, and storm surge by combining hazard and damage information [Murnane and Elsner, 2012, Czajkowski et al., 2017, Tonn and Czajkowski, 2022, Estrada et al., 2015]. The expected hurricane intensification due to global warming is likely to have a significant impact on economic losses [Bjarnadottir et al., 2011, Emanuel, 2011, Raible et al., 2012, Rosowsky, 2021] with a potential increase in the average annual loss by 14% in a $+2°$C warming scenario [Jewson, 2023a]. Moreover, the projected increase in hurricane precipitation in the RCP8.5 scenario may lead to an increase in freshwater losses by up to 30% at the end of the century, with greater impacts in the Gulf region [Lin and Cha, 2021]. However, the impacts of climate change on hurricane-induced 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 probability distribution of projected changes in North Atlantic hurricane intensity and precipitation for the $+2°$C and $+4°$C warming scenarios [Knutson et al., 2020, Jewson, 2021].

We find that the median projected changes in hurricane climatology may increase event losses by $5\%-15\%$ in a $+2°$C scenario and by $10\% - 30\%$ in a $+4°$C scenario, with greater impacts on high-frequency, low-severity loss events. It follows that the 100-year insured loss in the historical baseline (approximately USD 220 billion) could have return periods of approximately 80 and 70 years in the $+2°$C and $+4°$C scenarios, respectively. Moreover, a $+2°$C global warming could lead to a median change in average annual loss (AAL) on the order of 10%, whereas a $+4°$C global warming could cause a 15% median 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 assess the uncertainties around these results by sampling from the probability distributions of projected changes in hurricane climatology. 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 Results

We first generate a stochastic eventset for the historical baseline (1950-2022) using the event frequency and loss probability distributions obtained from the compiled historical dataset (Figure 1) in our bootstrapping methodlogy (see Methods for details). The resulting loss exceedance frequency curves (Figures 2a and 2b) help us to better quantify the return periods of the costliest historical events in the current climate. 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 50 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.

We then investigate the impacts of global warming by applying the median projected changes in event frequency and wind-, storm surge-, and precipitation-driven losses (see Methods for details). We find that the 100-year occurrence loss in the historical baseline (USD 220 billion) could have return periods of approximately 80 years in the $+2°$C scenario and 70 years in the $+4°$C scenario (Figure 3a). Similarly, the historical 50-year occurrence loss (USD 150 billion) is projected to have return periods of approximately

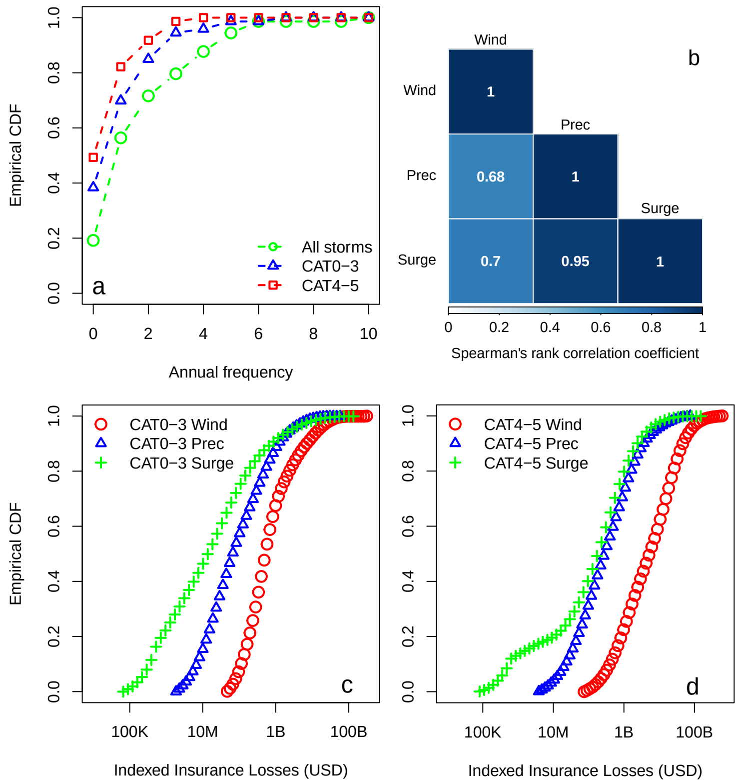

Figure 1: **Frequency and severity distributions of historical hurricanes.** a) Empirical cumulative distribution functions (CDF) of the annual frequencies of hurricanes, major hurricanes, and all storms. b) Spearman's rank correlation coefficients among the wind-, precipitation-, and storm surge losses 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].

45 and 40 years in the +2°C and +4°C climate scenarios, respectively. The results further suggest that the median changes in hurricane climatology may increase occurrence losses by 5% − 15% in the +2°C scenario and 10% − 30% in the +4°C scenario, with a greater impact at low return periods than in the tail (Figure 3b). We observe a similar dependency on the return period with respect to changes in aggregate annual losses (see Supplementary Notes 4). Moreover, major hurricanes will likely account for a much larger fraction of the aggregate annual losses. Critically, the contribution from hurricanes of category 4 and 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°C and +4°C warming scenarios (orange and red circles in Figure 3c).

The median changes in hurricane climatology may cause the average annual loss (AAL) to increase from USD 21.8 billion in the historical baseline to USD 23.9 billion (+10%) and USD 25.3 billion (+15%) in the +2°C and +4°C scenarios, respectively (Figure 4a). The AAL breakdown by hazard for each climate scenario suggests that the hurricane wind AAL increases from USD 19.5 billion to USD 21.1 billion (+8%) and USD 22.1 billion (+13%), the freshwater AAL from USD 1.4 billion to USD 1.8 billion (+26%) and USD 2.2 billion (+55%), and the storm surge AAL from USD 960 million to USD 1.03 billion (+8%). 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 (see percentage contributions in Figure 4b). We further find that the contribution of major hurricanes (category 4 and 5) to the AAL increases from USD 19.0 billion to USD 21.2 billion (+11%) and USD 23.0 billion (+21%), whereas the contribution of hurricanes with lower intensities (category 0 to 3) decreases from USD 2.9 billion to USD 2.7 billion (−7%) and USD 2.4 billion (−17%) (Figure 4a). This is expected, given that the median projections of storm intensity call for a decrease in the average frequency of low-intensity hurricanes.

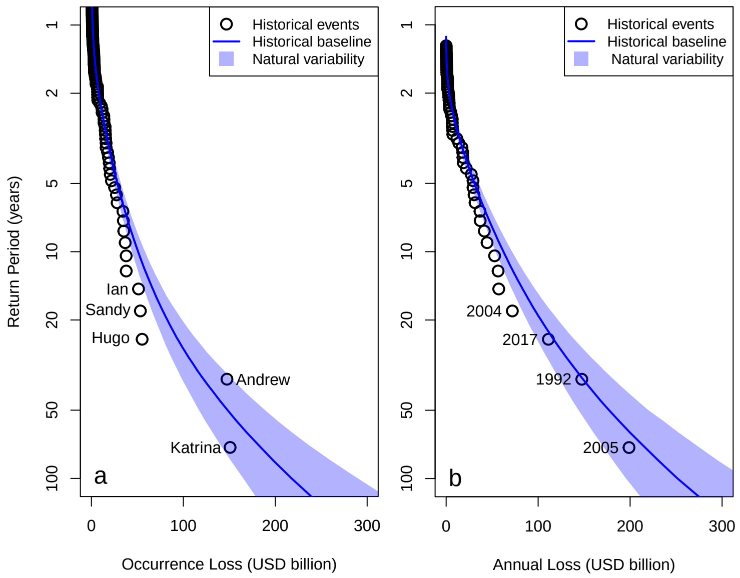

Figure 2: **Loss exceedance frequencies in the historical baseline (1950-2022).** a) Occurrence loss and b) annual loss exceedance frequencies obtained from the compiled hurricane loss dataset (black circles) and estimated via bootstrapping (blue lines). To quantify natural variability (shaded blue areas) we divided the $10,000$-year stochastic event set into 100 subsets and used them to calculate the 80% loss inter-quantile range at different return periods.

We finally assess the uncertainty around our loss projections by propagating the uncertainty underlying the hurricane climatology projections. We estimate that the 80% inter-quantile ranges of the future 100-year occurrence loss are USD $180 - 250$ billion in a $+2°C$ scenario and USD $160 - 290$ billion in a $+4°C$ scenario (horizontal bars in Figure 3a). Similarly, the 80% inter-quantile ranges of the future 50-year occurrence loss are USD $110 - 180$ billion in the $+2°C$ scenario and USD $100 - 210$ billion in the $+4°C$ scenario. Furthermore, the 80% inter-quantile ranges of the future AAL are USD $16 - 27$ billion in a $+2°C$ scenario and USD $14 - 35$ billion in a $+4°C$ scenario (vertical black bars in Figure 4a).

3 Discussion

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 recent projections of changes in hurricane climatology. 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.

Our results indicate that the insurance losses associated with North Atlantic hurricanes will likely increase due to global warming. Note that we obtain similar loss projections when using Verisk's stochastic event set of North Atlantic hurricanes [Verisk Extreme Event Solutions, 2021] in place of the compiled historical dataset (see Supplementary Notes 5), which corroborates the results of this analysis. 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. The average annual loss of major hurricanes (category 4 and 5) is expected to increase, whereas that of lower intensity hurricanes (category 0 to 3) could decrease. This follows from assuming a potential increase in the proportion of major hurricanes but an unchanged storm frequency. Note that, if we additionally account for the projected changes in future storm frequency, the median US property insurance losses are expected to decrease (see Supplementary Notes 6). However, scientific confidence around hurricane frequency projections is low and further research is necessary to

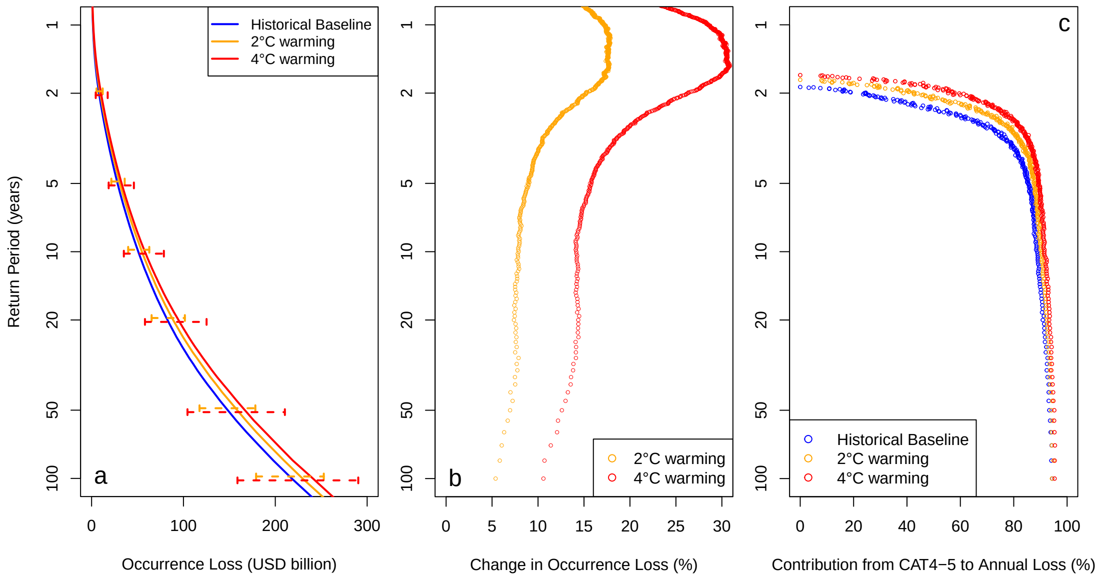

Figure 3: **Loss exceedance frequencies in future climate scenarios.** a) Exceedance frequencies of occurrence losses for the historical baseline (blue line), +2°C warming scenario (orange line), and the +4°C warming scenario (red line). For the climate change scenarios, solid lines represent losses resulting from median projected changes in hurricane climatology, whereas horizontal dashed bars represent the 80% inter-quantile ranges of the projected losses estimated by propagating the uncertainty in hurricane climatology projections. b) Relative change in median occurrence losses, with respect to the historical baseline, for the +2°C (orange circles) and +4°C (red circles) warming scenarios. c) Contribution from major hurricanes (category 4 and 5) to the aggregate annual losses at the corresponding return periods, for the historical baseline (blue circles) and future climate scenarios (orange and red circles).

assess the implications for property insurance losses.

There are some important sources of uncertainty underlying our results. Firstly, we have shown that the uncertainty propagating from hurricane climatology projections may lead to a wide range of potential outcomes for future hurricane losses. Secondly, not all potential impacts of global warming on hurricane physical properties have been included in our analysis. These include potential changes in the size and forward moving speed of hurricanes, as well as the geographic variability in storm tracks. Lastly, 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. It is also noteworthy that we did not account for the potential impact of sea level rise on future property insurance losses, given that this is unrelated to changes in hurricane climatology. Previous studies have suggested that sea level rise alone may increase flood hazard more significantly than changes in hurricane-induced precipitation and storm surge. Even if a receding shoreline could be accompanied by a gradual displacement of the exposed properties inland or mitigated by improved coastal defenses, it is likely that the compound effects of storm surge and higher sea-level will cause further inland seawater penetration than at present.

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], +2°C and +4°C warming with respect to our historical baseline (1950 - 2022) are unlikely to materialize before 2050 and 2080, respectively, even under the most extreme SSP5-8.5 scenario. It follows from our results that the expected AAL increase due to climate change is on the order of 0.5% per annum, with a 90% probability of not exceeding 0.8% 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].

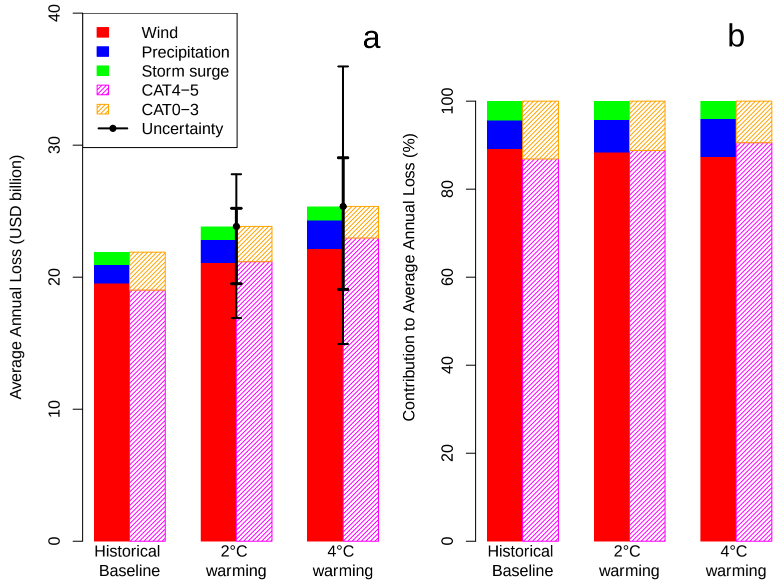

Figure 4: **Impact of climate change on the average annual loss (AAL).** a) Breakdown of the total AAL into contributions from the wind losses (red bars), freshwater losses (blue bars), storm surge losses (green bars), major hurricanes (category 4 and 5, hatched magenta bars), and hurricanes (category 0 to 3, hatched orange bars), for the historical baseline and future climate scenarios. b) Same as in a), but showing percentage contributions instead of absolute contributions. Vertical black bars represent the 50% inter-quantile ranges (thicker black lines) and 80% inter-quantile ranges (thinner black lines) of the AAL projections, estimated by propagating the uncertainty in hurricane climatology projections.

4 Conclusions

In conclusion, the impact of global warming in isolation from changes in the building stock is likely going to increase property losses from North Atlantic hurricanes in the United States. The results presented in this study may provide useful guidelines to assess the need for climate adaptation and mitigation policies in regions prone to wind or flood damage. While private and public insurers 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, as well as a stronger focus on limiting exposure concentrations along the East and Gulf coasts.

5 Methods

5.1 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 private 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, listing the maximum lifetime storm intensity and the breakdown into wind-, precipitation-, and storm surge-related loss contributions (see Supplementary Notes 1 for additional details). Note that we use the maximum lifetime storm intensity, rather than the landfall intensity, as this is the intensity measure referred to in hurricane climatology projections [Knutson et al., 2020]. We assume that when the climate impact projections suggest that category 4 and 5 storms will increase in frequency, landfalling storms that previously reached category 4 and 5 intensity will also increase in frequency, whatever their intensity at landfall [Wang and Toumi, 2018, Jewson, 2023b]. For example, Hurricane Katrina is recorded as category 5 even though it made landfall as category 3. We describe each dataset below in more detail and explain the data processing methodology that was implemented.

- HURDAT2 dataset: This dataset originates from the National Hurricane Center's Atlantic Hurricane Database Re-analysis Project [Landsea and Franklin, 2013], that aims to extend and revise the original North Atlantic hurricane database. 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 (category 0: below 63 kn; category 1: 64-82 kn; category 2: 83-95 kn; category 3: 96-112 kn; category 4: 113-136 kn; category 5: above 137 kn).
- PCS dataset: To quantify hurricane loss contributions from wind damage we use the PCS Catastrophe History Reporter [Property Claim Services, 2023], a Verisk commercial product providing industry loss information at state-level resolution for the US since 1950, including catastrophe serial numbers, dates of occurrence, states affected, types of perils, and wind-induced loss estimates. We index all past hurricane losses to 2022 to account for economic inflation and growth in insurance penetration, population, and wealth per-capita [Barthel and Neumayer, 2012, Weinkle et al., 2018]. For this purpose, we combine the yearly values of US Gross Domestic Product (GDP) deflator [The World Bank, 2023] and US property insurance gross premium [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 this indexation methodology does not account for spatial variations in urban development and changes in vulnerability, such as improvements to flood defenses and building codes.
- NFIP dataset: This dataset is openly accessible through the OpenFEMA portal [Federal Emergency Management Agency, 2023] and provides details on more than 2 million flood claims transactions in the US 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 only retain claims associated with hurricane events (accounting for approximately 73% of the total NFIP losses) and aggregate the original damage classes into three more comprehensive 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.

5.2 Hurricane climatology projections

For the +2°C warming scenario, we use frequency distributions of projected changes in hurricane physical properties compiled from results of several independent studies [Knutson et al., 2020]. We then extrapolate these frequency distributions to the +4°C warming scenario using an exponential scaling of the global mean surface temperature, as described in [Jewson, 2021] (see equation 1 in the Supplementary Information). The median changes in hurricane climatology are summarized hereafter including some relevant implications for insurance claims. We provide in Supplementary Notes 3 the full frequency distributions of projected changes, which we use to assess the uncertainty around the impacts on property insurance losses

- 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 median increase in the proportion of major hurricanes (category 4 and 5) is projected to be 9% and 19% in the +2°C and +4°C warming scenarios. Accordingly, we increase the sampling probability of major hurricanes from

40% (as calculated from the historical dataset) to 44% (+2°C) and 48% (+4°C) when creating stochastic events sets for these future climate conditions. It follows that the sampling probability of minor hurricanes (category 0 to 3) decreases from 60% (historical dataset) to 56% and 52% in the +2°C and +4°C warming scenarios. Note that the definition of major hurricanes in this study differs from that of the National Hurricane Center, which also includes tropical storms of category 3.

- 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. The large variability in model responses results in a wide distribution of projected changes, with median values of −14% and −27% in the +2°C and +4°C warming scenarios, respectively. 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 the main analysis (see Supplementary Notes 6 for the analysis including potential changes in hurricane frequencies).

- 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 believed to be approximately 7%, that is, close to the rate of water vapor increase at constant relative humidity, although some recent research has called this rate into question [Tu et al., 2021, Wei et al., 2022]. The median projected changes in hurricane-induced rainfall are approximately 16% and 34% in the +2°C and +4°C warming scenarios, respectively [Knutson et al., 2020, Jewson, 2021] (see Supplementary Figure 3 for the full probability distributions). This may cause larger flood depths and flood footprints, leading to a larger number of flood claims and to larger average claim amounts. Based on previous studies on the impact of flood depth on the number and average amount of insurance claims in the United States [Czajkowski et al., 2017, Tonn and Czajkowski, 2022] we estimated an increase of approximately 0.85% in the number of affected policies and an increase of 0.15% in the average paid claim per percentage increase in flood depth. By combining these results, we estimate that the flood insurance losses may experience a median increase of approximately 16% and 35% in the +2°C and +4°C warming scenarios (see Supplementary Notes 2 for additional details on these calculations). These projections are consistent with previous model-based estimates for the Southeast United States [Lin and Cha, 2021].

- Storm surge: There are reasons to believe that an increase in hurricane intensities may 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. 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 hurricane climatology.

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 may 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.

5.3 Bootstrapping methodology

The compiled historical event dataset and the hurricane projections are used to construct stochastic event sets for present and future climate scenarios. For this purpose, we use an implementation of the classic frequency-severity technique commonly used in hurricane risk models [Jewson, 2023a]. The innovative aspect of this methodology lies in the breakdown of event losses by hazards (wind, precipitation, storm surge) and the simulation of their correlation structure. For any given simulation year in the stochastic set, we sample the number of events as

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

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 $n_{\mathrm{h}} + n_{\mathrm{m}} = n$ and

$$n_{\mathrm{h}} = \sum_{i}^{n} 1 - \mathcal{L}(u_i; P_{\mathrm{m}}), \tag{2}$$

$$n_{\mathrm{m}} = \sum_{i}^{n} \mathcal{L}(u_i; P_{\mathrm{m}}). \tag{3}$$

In equations (2) and (3), P_{m} is the proportion of hurricanes reaching major intensity in the climate scenario of interest (sampled from the probability distribution in Supplementary Figure 3a), u_i, $i = 1, \dot{;} n$ are uniformly distributed random numbers between 0 and 1, and $\mathcal{L}(u_i; P_{\mathrm{m}})$ is a logical operator such that

$$\begin{cases} \mathcal{L}(u_i; P_{\mathrm{m}}) = 1 \text{ if } u_i \leq P_{\mathrm{m}} \\ \mathcal{L}(u_i; P_{\mathrm{m}}) = 0 \text{ if } u_i > P_{\mathrm{m}} \end{cases} \tag{4}$$

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 $\boldsymbol{\Sigma}$ 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 $\boldsymbol{\Sigma}$ 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 ($\mathbf{w}_{\mathrm{h}}$, $\mathbf{p}_{\mathrm{h}}$, and $\mathbf{s}_{\mathrm{h}}$) and major hurricanes ($\mathbf{w}_{\mathrm{m}}$, $\mathbf{p}_{\mathrm{m}}$, and $\mathbf{s}_{\mathrm{m}}$) using quantile mapping

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

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

In equations (5) and (6), $\mathcal{N}$ is the standard normal CDF and $F_{\mathrm{h,w}}$, $F_{\mathrm{h,p}}$, and $F_{\mathrm{h,s}}$ are the empirical CDFs of wind, precipitation, and storm surge losses for hurricanes (Figure 1c), which we estimate from the historical hurricane dataset. Similarly, $F_{\mathrm{m,w}}$, $F_{\mathrm{m,p}}$, and $F_{\mathrm{m,s}}$ are the empirical CDFs for major hurricane losses (Figure 1d). To estimate losses with return periods longer the duration of the historical dataset (72 years), we augment the empirical CDFs using Verisk's North Atlantic hurricane model, as implemented in Touchstone Re v11.5, which provides us with 10,000 years of stochastic event losses to the US property insurance industry [Verisk Extreme Event Solutions, 2021]. Furthermore, $\mathcal{N}$ is the standard normal CDF. Note that, when sampling events for future climate scenarios, the precipitation losses $\mathbf{p}_{\mathrm{h}}$ and $\mathbf{p}_{\mathrm{m}}$ are inflated by the corresponding projection factors (sampled from the probability distribution in Supplementary Figure 3c).

We repeat the calculations described in equations (1) to (6) for $N_{\mathrm{y}} = 10,000$ 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 72 years of historical data. To assess the uncertainty propagating from the projected changes in hurricane climatology, we generate $N_{\mathrm{s}} = 100$ events sets, each one obtained by sampling from the probability distributions of future changes (see Supplementary Figure 3). This allows us to calculate key statistics, such as median loss values and inter-quantile ranges at different return periods.

Data Availability

All data presented in this manuscript and the code used to produce the results can be accessed at `https://data.mendeley.com/datasets/jbdsy2x7n5/2` [Comola, 2024].

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Competing interests

The authors declare no competing interests.

Author contributions

FC devised the project, designed the methodology, performed the computations, and wrote the manuscript. BM, HP, CB, and KS supervised the project. BM verified the analytical methods. All authors discussed the results and contributed to the final manuscript.

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Supplementary information for "Increase in insurance losses caused by North Atlantic hurricanes in a warmer climate"

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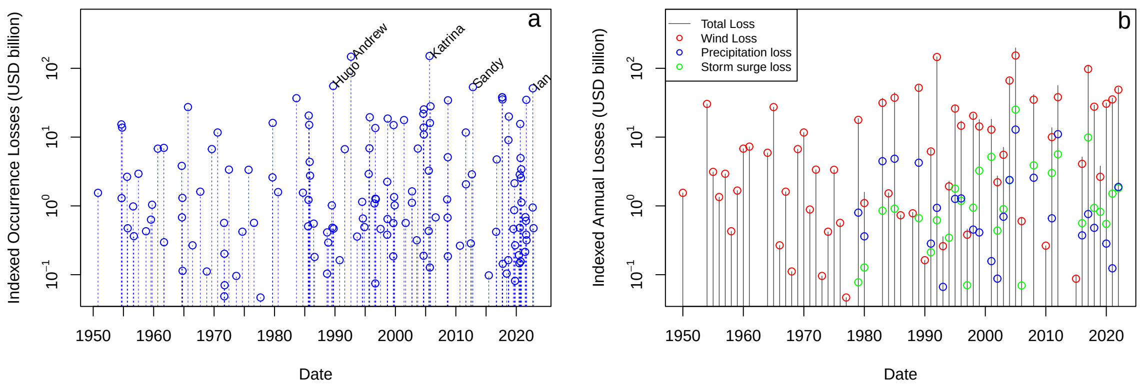
This document provides supplementary information on the following aspects:

- Supplementary Notes 1: The data sources of hurricane-induced US property insurance losses and the results of the indexation methodology.
- Supplementary Notes 2: Our approach for assessing the impacts of hurricane-induced precipitation on US property insurance losses.
- Supplementary Notes 3: The frequency distributions of projected changes in hurricane climatology for the 2°C and 4°C warming scenarios.
- Supplementary Notes 4: The projected increase in aggregate annual insured losses caused by hurricanes making landfall in the US.
- Supplementary Notes 5: The projected changes in occurrence losses obtained from applying the bootstrapping methodology to Verisk's North Atlantic hurricane model.
- Supplementary Notes 6: The projections for hurricane-induced property insurance losses obtained by accounting for potential changes in hurricane frequency.

Supplementary Notes 1

As described in the main manuscript, we leverage PCS and NFIP data to compile a comprehensive event set of hurricane-driven US property insurance losses. 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 has followed a consistent methodology over time and 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 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. 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. 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. 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.



Supplementary Figure 1: **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 50 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).

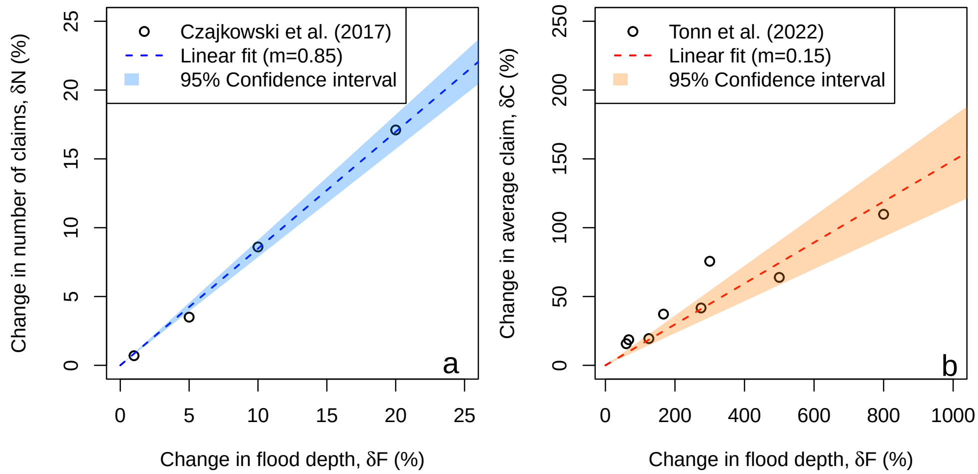
The original insured loss amounts have been indexed to 2022, accounting for yearly economic inflation and growth in insurance penetration, population, and wealth per capita [Barthel and Neumayer, 2012]. The resulting indexed losses from each tropical storm in the dataset are shown in Supplementary Figure 1a, whereas the aggregate annual losses are shown in Supplementary Figure 1b. 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.

Supplementary Notes 2

An increase in hurricane-induced precipitation 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 on 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 Supplementary Figure 2a, 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



Supplementary Figure 2: **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.

(Supplementary Figure 2b). 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 Knutson et al. [2020] provide 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 16% and 34%, the median projected changes for the 2- and 4-degree warming scenarios, may lead to an increase in flood insurance losses δL of approximately 16% and 35%, respectively.

Supplementary Notes 3

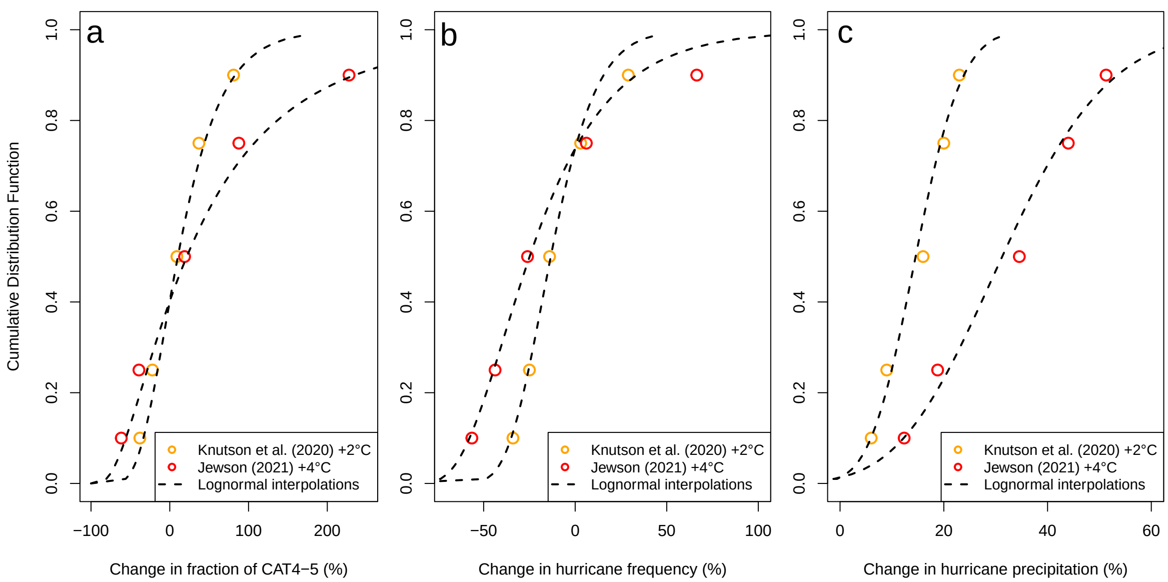
We perform an uncertainty propagation analysis to generate a probability distribution of changes in insurance losses from the probability distributions of changes in hurricane climatology. For the +2°C climate scenario, we rely on the distribution quantiles (10%, 25%, 50%, 75%, and 90%) of projected changes provided by Knutson et al. [2020], compiled from a large pool of independent studies (orange circles in Supplementary

Figure 3). For the +4°C climate scenario, we extrapolate the +2°C quantiles using the temperature scaling suggested by Jewson [2021]

$$C_T = \exp\left[\frac{1}{2}T\log\left(C_2+1\right)\right]-1, \quad (1)$$

where C_T is the projected change in the hurricane physical property of interest for an increase in global mean surface temperature of T-degrees ($4°C$ in this case, see red circles in Supplementary Figure 3), and C_2 is the projected increase of the same physical property for a +2°C climate scenario provided by Knutson et al. [2020].

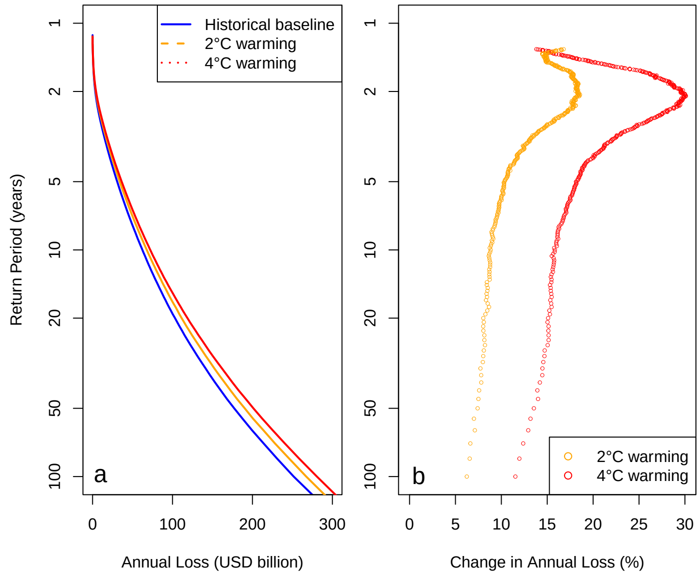
We perform a stochastic sampling of the projected changes using log-normal distributions, fitted to the distribution quantiles using a RMSE method (dashed black lines in Supplementary Figure 3). Note that the fraction of hurricanes that reach major intensities has an upper bound of 1, meaning that all tropical storms in a given year reach major intensities. Therefore, when sampling from the corresponding log-normal distribution (Supplementary Figure 3a), we discard all values that violate this constraint.



Supplementary Figure 3: **Probability distribution of the changes in hurricane climatology projected for the +2°C and +4°C warming scenarios**. a) Changes in the fraction of hurricanes reaching major intensities (category 4 and 5). b) Changes in the annual frequency of hurricanes of any category. c) Changes in hurricane-induced precipitation. Orange circles refer to the projections for a +2°C climate scenario, as provided in Knutson et al. [2020]. Red circles refer to the projections for a +4°C climate scenario, extrapolated from the +2°C scenario using the scaling by Jewson [2021]. The dashed black lines indicate the best fit log-normal interpolations.

Supplementary Notes 4

Supplementary Figure 4 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 annual losses (having return periods between 2 and 3 years) are the most impacted, with an increase in insured losses up to 20% in the 2-degree warming scenario and 30% in the 4-degree warming scenario. The loss increase is smaller, in the range of 5% to 15%, for the less frequent, more severe annual losses with return periods larger then 50 years.



Supplementary Figure 4: **Impact of climate change on aggregate annual losses.** a) Aggregate annual loss exceedance probabilities for the historical baseline (blue line) and future climate scenarios (orange line for 2-degree warming and red line for 4-degree warming) resulting from median projected changes in hurricane climatology. 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.

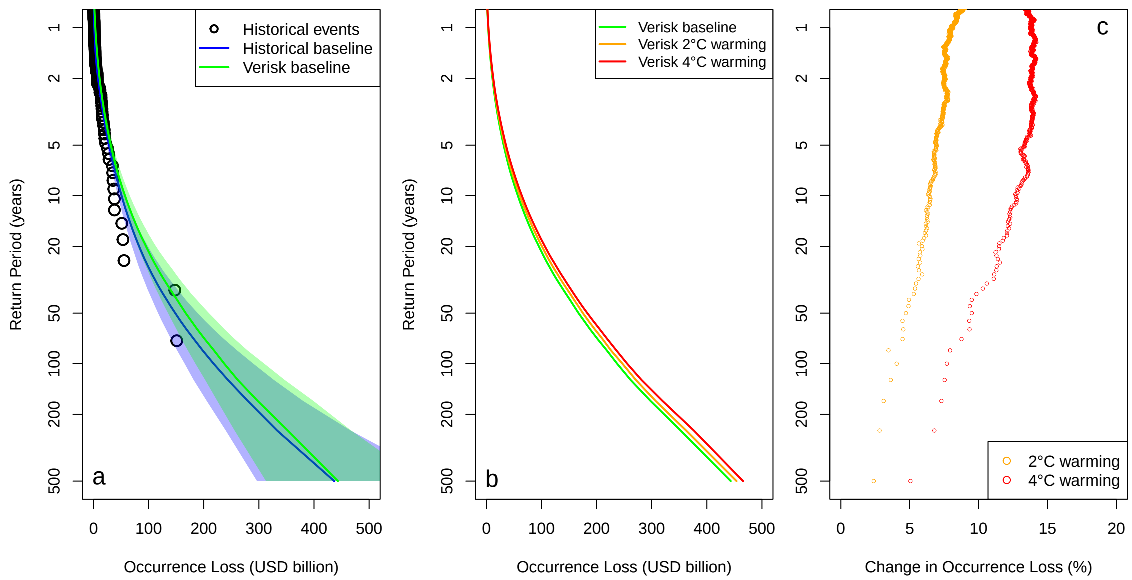
Supplementary Notes 5

Here, we apply our bootstrapping methodology using the event frequency and loss probability distributions derived from Verisk's stochastic event catalog of North Atlantic hurricanes, as implemented in TouchstoneRe v11.5 [Verisk Extreme Event Solutions, 2021]. This well known catastrophe model is commonly used for technical pricing of reinsurance contracts and insurance-linked securities. The stochastic catalog contains 10 thousand years of possible realizations of North Atlantic hurricanes and provides the corresponding US property insurance losses as-of end of 2022 by hazard type (wind, precipitation, and storm surge).

The occurrence loss exceedance probabilities (OEP) obtained from the historical and Verisk's baselines are in good agreement (Supplementary Figure 5a), suggesting that the compiled historical event set provides accurate estimates of hurricane losses as of 2022. The climate change-conditioned OEPs of Verisk's stochastic catalog (Supplementary Figure 5b) suggest comparable loss increases to those observed in Figure 3b of the main manuscript, with greater changes at lower return periods than in the tail (Supplementary Figure 5c). Some discrepancies between these results and those presented in the main manuscript are visible at return periods shorter than 5 years, where the results based on Verisk's catalog suggest significantly smaller loss changes than those based on the historical eventset (Figure 3 in the main manuscript).

Supplementary Notes 6

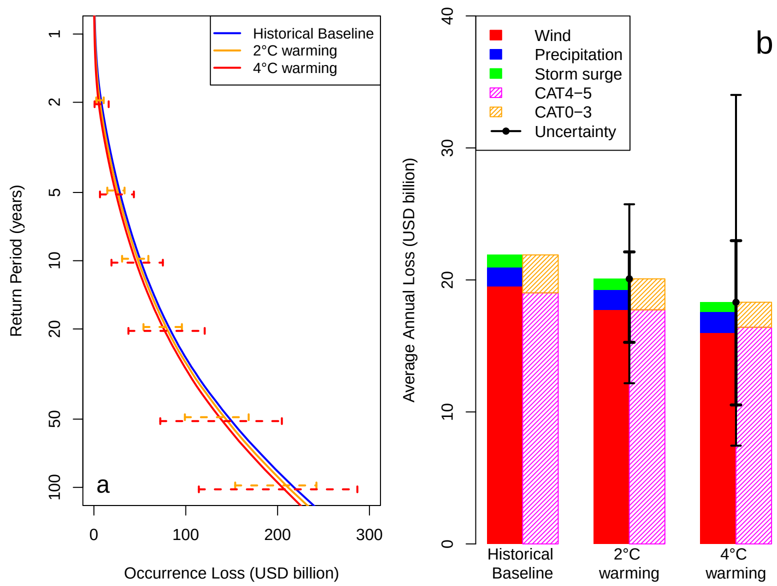
In the main manuscript, we neglected potential changes in hurricane frequency due to the high uncertainty of model results and insufficient physical understanding of the drivers. Here, we explore how changes in the total annual hurricane frequency may impact the US property insurance losses in combination with other changes in hurricane climatology, namely the proportion of major hurricanes and the intensification of hurricane-induced precipitation. For this purpose, we sample from the probability distribution of the hurricane frequency changes (Supplementary Figure 3b) and adjust the annual event frequency distribution



Supplementary Figure 5: **Occurrence loss exceedance probabilities (OEP) based on Verisk's stochastic hurricane catalog.** a) OEPs obtained from the historical baseline (blue line, median as in Figure 2a of the main manuscript), Verisk's baseline (green line, median), and historical eventset (black circles, as in Figure 2a of the main manuscript). Shaded areas represent natural variability, quantified as described in Figure 2 of the main manuscript. b) Climate change-conditioned Verisk's OEPs, obtained by applying the median projected changes in hurricane climatology to Verisk's stochastic catalog. The orange line represents the OEP for a +2°C scenario, while the red line represents the OEP for a +4°C scenario. c) Relative changes in the hurricane loss OEP with respect to the baseline, for the +2°C (orange circles) and +4°C (red circles) scenarios.

(Figure 1a in the main manuscript) to reflect a corresponding shift in the mean value.

The results indicate that a potential reduction in overall hurricane frequency may compensate the increase in hurricane intensity and precipitation. Consequently, the median US property insurance losses may show an opposite trend to what is shown the main manuscript, with slightly decreasing losses at all return periods (solid lines in Supplementary Figure 6a). The 80% inter-quantile ranges (horizontal bars), estimated by sampling from the full distributions, are wider than those shown in the main manuscript (horizontal bars in Figure 3a) owing to the additional uncertainty propagating from changes in overall hurricane frequency.



Supplementary Figure 6: **Future changes US property insurance losses including variations in hurricane frequency.** a) Exceedance probability curves of hurricane losses for the historical baseline (blue line), +2°C scenario (orange line), and +4°C scenario (red line). For future climate scenarios, solid lines represent losses resulting from median projected changes in hurricane climatology, whereas horizontal dashed lines represent the 80% inter-quantile ranges of projected losses estimated by propagating the uncertainty in hurricane climatology projections (Supplementary Figure 3). b) Average annual losses (AAL) in the historical baseline and future climate scenarios, with breakdown by hazard (red, blue, and green bars) and by intensity (hatched magenta and orange bars). Vertical black lines represent the 50% and 80% inter-quantile ranges of AAL projections for future climate scenarios, estimated by propagating the uncertainty in hurricane climatology projections.

The median average annual loss (AAL) is also projected to decrease by 8% and 16% in the +2°C and +4°C warming scenarios (Supplementary Figure 6b). Despite this reduction, the contribution to the AAL from precipitation-induced losses (blue bars) are projected to increase, with most of the reduction attributable to the wind- and storm surge contributions (red and green bars). Note that the AAL inter-quantile ranges (vertical black lines in Supplementary Figure 6b) are larger than those shown in Figure 4 of the main manuscript, due to the additional uncertainty propagating from potential changes in hurricane frequency.

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