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Insured U.S. Hurricane Loss Under a 2°C Warmer Climate

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Abstract

Tropical cyclones, known as hurricanes in the North Atlantic, are a significant hazard for eastern North American, and Caribbean coastlines. The frequency and intensity of tropical cyclones in the North Atlantic has been observed to fluctuate between the 1970s and the 2020s. This has been a consequence of short- (e.g. El Niño Southern Oscillation), and longer-term climatic variability (Atlantic Multidecadal Oscillation (AMO)/atmospheric sulphate change) and anthropogenic-caused warming of the climate. A key question for at-risk communities and insurers therefore is how continued anthropogenic warming of the climate will impact tropical cyclone characteristics during the 21st Century. To understand the impacts of climate change on a given natural hazard, insurers commonly use exploratory scenarios. Here, we use a +2°C above pre-industrial climate scenario to analyse possible changes to insured losses from a present-day baseline due to tropical cyclones in the contiguous U.S. In this scenario, insured Average Annual Losses (AAL) are shown to increase by ~40% and the 1-in-200 Aggregate Exceedance Probability (AEP) loss by 26%. The scenario analysis also shows that the impacts are spatially variable, with the greatest relative impacts on the eastern seaboard. These results suggest building codes applied in Gulf Coast states should be applied at higher latitudes to mitigate current and future impacts of climate change.

1. Introduction

Historically, insured losses in the U.S. have been dominated by those generated from tropical cyclones, known as hurricanes in the North Atlantic. Indeed, tropical cyclones make up eight of the 10 costliest natural disasters in terms of insured loss between 1900 and 2023 globally (Aon, 2024). Insurer insolvency caused by these events, i.e. there were 11 insolvencies alone from Hurricane Andrew in 1992, have driven innovation in terms of catastrophe model development and exposure management (Grossi *et al*.., 2005). They have also led to innovation from a (re)insurance market structure perspective. Catastrophe bonds are now widely traded providing extra market capacity and retrocession cover to reinsurers, and risk is now more widely diversified. However, potential changes in tropical cyclone risk associated with continuing anthropogenic climate warming and financial shocks associated with more intense and more frequent landfalls, remains a dominant concern among insurance regulators and communities, which depend on this protection (Hindle & Lighthill Risk Network, 2023; Hereid, 2022). Quantifying the change in risk associated with anthropogenic induced climate change is therefore key to assessing future insurance market dynamics and societal mitigation of climate change impacts.

1.1. Climate change stress tests

Climate change impacts on natural hazards have been an increasing concern for both (re)insurers and those that regulate these markets. Regulators have therefore been carrying out increasing numbers of climate change stress tests in order to understand the resilience/exposure of financial institutions to climate driven 'shocks'. For example, the 2021 Climate Biennial Exploratory Scenario (CBES) run by the Bank of England included the risk to U.K. financial institutions from changes in tropical cyclone activity and the associated large financial shocks (Bank of England, 2022), whilst the International Association of Insurance Supervisors launched a second consultation in November 2023. These scenarios, whilst time consuming for those institutions undertaking them, are important to understand the exposure position of individual institutions and to inform regulators of potential sector vulnerabilities. They also have an important role to play in raising awareness among internal corporation decision makers. However, these scenarios can often be overly generalised, i.e. a portfolio of fixed assets (mortgages) will be impacted differently to an annually renewing reinsurance portfolio. These scenarios also often include arbitrary timescales, which mean that they are not necessarily the most useful for understanding immediate/short-term exposures to climate change impacts at individual institutions. The development and operationalisation of climate change scenarios within (re)insurance companies, which reflect their exposures and are informed by the latest defensible scientific research, should therefore represent a key component of ongoing exposure management and decision making.

Climate change scenarios commonly follow two approaches. The first, as was used in the CBES exercise, is to use emission pathway scenarios and prescribed dates. For CBES, two time horizons were chosen, 2030 and 2050, and three emission scenarios (see Figure 1). These were equivalent to 1.8°C and 3.3°C in 2050, roughly in line with RCP6.0 and RCP8.5 (Figure 1). The alternative approach is to use temperature change scenarios, i.e. 1.5°C, or 2°C above pre-industrial climate. This latter approach maintains the advantages of the emission pathway scenarios in terms of alignment with different decision-making horizons, i.e. short-, medium-, and long-term. However, temperature scenarios also have the advantage of greater flexibility, i.e. they can be adjusted to reflect recent observed trends in global temperatures, and they also align better with the 2015 Paris Agreement targets.

Yet, even development of scenarios using temperatures are often limited by the available data which are used to define the change in environmental characteristics. This is particularly evident given that much of the published literature focuses on more extreme scenarios (e.g. RCP8.5), at longer time horizons (e.g., 2100) to enhance the signal-to-noise ratio.

In this article, we show the impacts of further warming of the climate to 2°C above pre-industrial temperatures on tropical cyclone frequency in the North Atlantic and potential insured losses above present-day climate (defined to be 1.1°C above pre-industrial climate). To achieve this, we use a third party climate change dataset provided by Reask. We show that quantifying regional impacts are critical to understanding long-term changes in risk from tropical cyclones in the U.S.

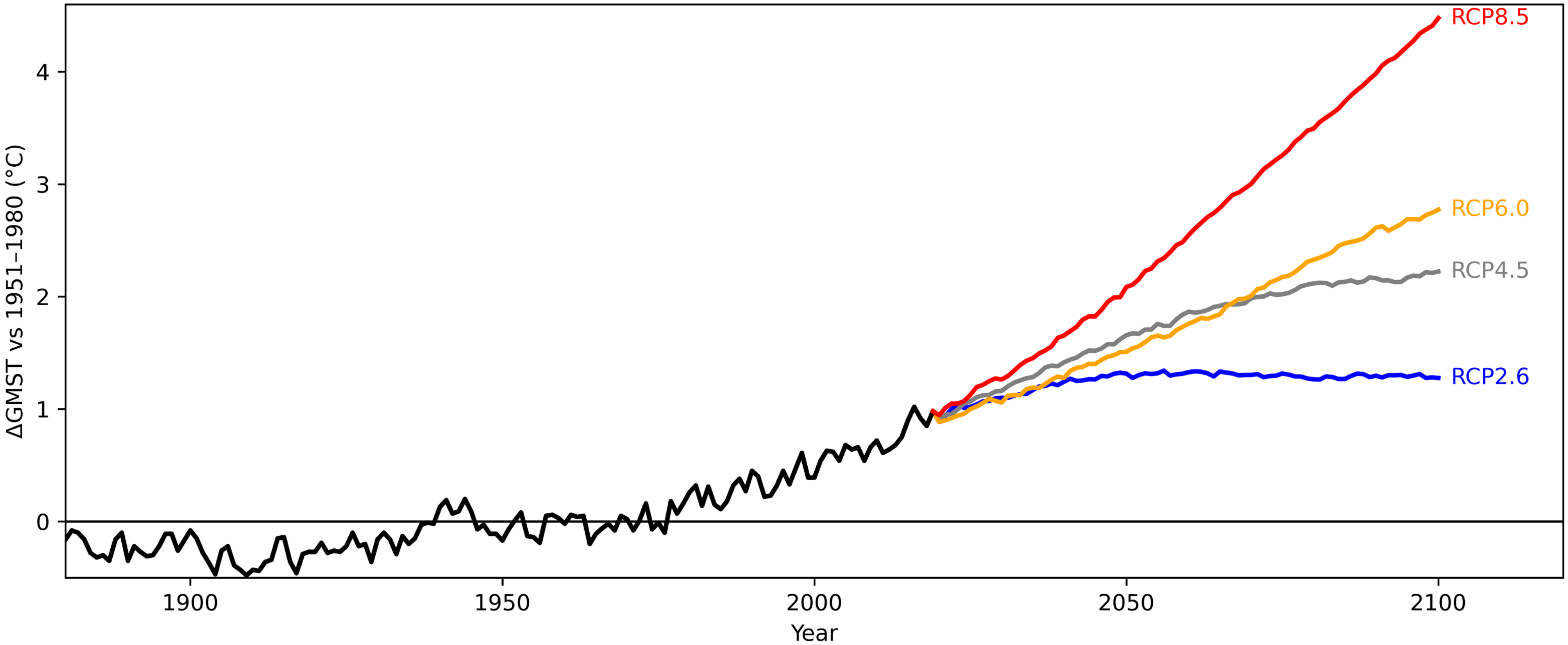

Figure 1: *Global mean change in surface temperatures compared to 1851-1900 and projected change under different emissions scenarios. Reconstructed from data derived from IPCC 6th Assessment Report (IPCC, 2023).*

2. Scenario development

Climate change impact scenarios are commonly developed using published academic and government institutional literature (Knutson, *et al*. 2020; Klotzbach, *et al*. 2022; Emanuel 2021a; O'Neill, *et al*. 2020; Arnell and Gosling 2016). However, as many catastrophe risk practitioners appreciate, for tropical cyclone scenario development, using this data can be challenging for a number of reasons, particularly for tropical cyclones (Jewson, 2022).

First, literature is commonly focused on basin-wide activity rather than landfalls (Emanuel 2021b; Knutson, *et al*. 2020). From a risk perspective, if more intense hurricanes develop but remain over the ocean, is this change a concern for local communities? Changes in basin frequency therefore must be translated to changes in landfalls in order to be of relevance to the insurance industry and disaster specialists (Jewson, 2023b, Camargo and Wing, 2021).

Second, it is difficult to precisely identify changes in how intensity characteristics change across the basin, i.e. is the whole distribution of intensities/wind speeds shifting, or are we likely to see just lower intensity (Category 2) tropical cyclones becoming major tropical cyclones (Category 3+) (Elsner, 2020). It is also unclear from these studies whether events, which reach greater intensities, are able to maintain their strength to landfall or whether intensification and decay happen more rapidly (Bhatia *et al*., 2019).

Third, model vendors rarely make their basin-wide event catalogue available, i.e. events which do not make landfall as well as those that do. It is therefore difficult to translate basin-wide changes in tropical cyclone characteristics directly to landfalls. Combined, these elements make catastrophe model adjustments from basin-wide changes in activity difficult, particularly as sufficient granularity to understand local changes in landfall characteristics is rarely available. This latter point is of particular concern to (re)insurers, due to their focus on areas of high exposure.

Acknowledging many of these issues and drawing on lessons learnt from CBES, MS Amlin developed a number of climate change impact scenarios for North Atlantic tropical cyclones by partnering with Reask in order to analyse potential changes in insured losses. This partnership enabled MS Amlin to analyse changes in cyclogenesis, i.e. the development of tropical cyclones relative to present-day climate, as well as changes in landfall frequency/severity in different regions of the North Atlantic under different temperature scenarios.

Reask provided MS Amlin with regional rates of change in landfall rate for different intensities of tropical cyclone for a 2°C climate compared to the present-day climate (defined as 1.1°C above pre-industrial) using their Unified Tropical Cyclone model (Loridan and Bruneau, 2024). For the contiguous U.S., the coastline was divided up into 12 separate regions from Texas, to the Northeast. The U.S. Gulf of Mexico coastline was divided up into 1) Texas; 2) Louisiana; 3) Mississippi, Alabama, and the Florida Panhandle; and 4) west Florida. The U.S. east coast comprise: 1) southeast Florida; 2) northeast Florida; 3) Georgia; 4) South Carolina; 5) North Carolina south of Cape Hatteras; 6) North Carolina north of Cape Hatteras to New Jersey; 7) New Jersey to Rhode Island; and 8) Northeast. The provided data was for each of these regions and for each category of tropical cyclone. This data was then used to adjust MS Amlin's simulated 100,000 year view of landfall rates for the U.S., which is based on Moody's (a third party catastrophe model vendor) medium -term rates and has been validated to be an appropriate representation of the present-day climate.

2.1. Event set adjustment

The MS Amlin event catalogue, appropriate for a 1.1°C warmer climate than pre-industrial levels, was adjusted using the Reask rate changes provided for a 2°C warmer than pre-industrial climate. Reask provided MS Amlin with ensemble outputs enabling analysis to be conducted for different percentiles of predicted change. For this analysis the median of the ensemble runs was chosen. Adjustments to the original MS Amlin event catalogue were made according to the following steps as defined by Jewson (2023a):-

First, the original simulated event set was divided up into individual landfall regions according to the regions which were defined in the Reask dataset. Individual events were assigned according to their maximum intensity landfall and were deemed appropriate as the Reask landfall rate changes were calculated using the same method. For example, if Hurricane Katrina had been present in the event set it would have only been considered for the purposes of the adjustment as a Category 3 tropical cyclone making landfall in Louisiana. This is due to Katrina making landfall in southeast Florida as a Category 1 tropical cyclone and a Category 3, the maximum intensity landfall, in Louisiana. This provided us with the total number of events of each category making landfall in each region under the 1.1°C present-day climate.

Second, the additional number of landfalls required for a given region were calculated, based on the Reask rate adjustments. For example, for northeast Florida, if the landfall rate for Category 4 tropical cyclones under the current climate was 5,000 per 100,000 years and a 25% increase was expected under a 2°C climate, the new 2°C climate event set would have 6,250 events over the 100,000 year simulation.

Third, events were randomly sampled, based on tropical cyclone category, from the original event set, and then randomly prescribed a year of occurrence. Each event selection was made independently, and therefore the same event could be assigned to occur more than once in the adjusted event set. The underlying event set was held static whilst sampled events were added. This meant that the original distribution of events did not change (Jewson, 2023a).

Last, the resampling process was then repeated. This was done in order to achieve convergence of results and thus test whether the resampled event set had any underlying biases in it. This process was also completed using a U.S. wide adjustment rate provided by Reask, with the intention of demonstrating the impacts of using regional/continental scale adjustments.

The nationwide event set adjustment was conducted in the same way. However, for this adjustment it only considered the U.S. wide adjustment in rates for each tropical cyclone category.

2.2. Methodological uncertainties

A number of deficiencies should be acknowledged, which could impact the relative results and the shape of the climate scenario loss curve. First, it does not account for tropical cyclone clustering or the impacts of short- to medium-term climate cycles, such as the El Niño Southern Oscillation (ENSO), when sampled events are added to the event set. This is justified on the basis that it is unclear in the original event set data which years reflect different ENSO phases. It is also unclear in the rate adjustment dataset how the relative rates of change for different ENSO phases would respond under a 2°C warmer climate. The fact ENSO was not accounted for in the adjustment means that longer return period losses are being underpredicted from a loss perspective, as clustering associated with different ENSO phases adds events disproportionately to specific years, i.e. La Niña impacted years.

Second, there is still uncertainty as to the likely impact of a 2°C above pre-industrial climate on the relative frequencies of El Niño and La Niña events (see Vecchi and Wittenberg, 2010). ENSO phases/characteristics have been predicted to intensify with increasing global temperatures (Fredriksen, *et al*. 2020; Yun, *et al*. 2021; Lin, et al. 2020; Cai, *et al*. 2021). The extent of the impacted areas is also expected to increase (Chand, *et al.* 2017; Lin, *et al.* 2020). Other studies have also suggested that the relative occurrence of different phases of ENSO may change under a warmer climate. For example, Wang *et al*. (2023) suggested that more multi-year La Niña events may occur as the climate warms. Changes to one or all of these characteristics would likely impact the interannual variability of tropical cyclone development in the North Atlantic.

Third, the event set adjustment was made based on regional tropical cyclone maximum intensities. Historically, events have been seen to make multiple landfalls in different regions (e.g. hurricanes Andrew and Katrina), or in the same region (hurricanes Nicole and Gordon); see Figure 2 for examples of multiple landfall tracks. Climate change has the potential to make each landfall more intense or may allow greater re-intensification before the second landfall. These changes remain challenging to incorporate into any climate change adjustment as the adjustment event set is bound by the original end set characteristics, i.e. we are unable to adjust the intensity of one or both of the landfalls of a given event.

Fourth, the adjustment methodology remains coarse in terms of how tropical cyclone intensity is considered. The provided data and original event set only allows a frequency adjustment based on the Saffir Simpson Hurricane Wind Scale category. An alternative adjustment could be based around changing the distribution of modelled windspeeds at landfall. Given the relationship between wind speed and sustained damage, a windspeed specific adjustment could provide even greater insight into how risk could change under a warmer climate. Indeed, even under the present-day climate there is an uncertainty as to the peak windspeeds of landfalling tropical cyclones which are therefore rounded to the nearest 5 knots.

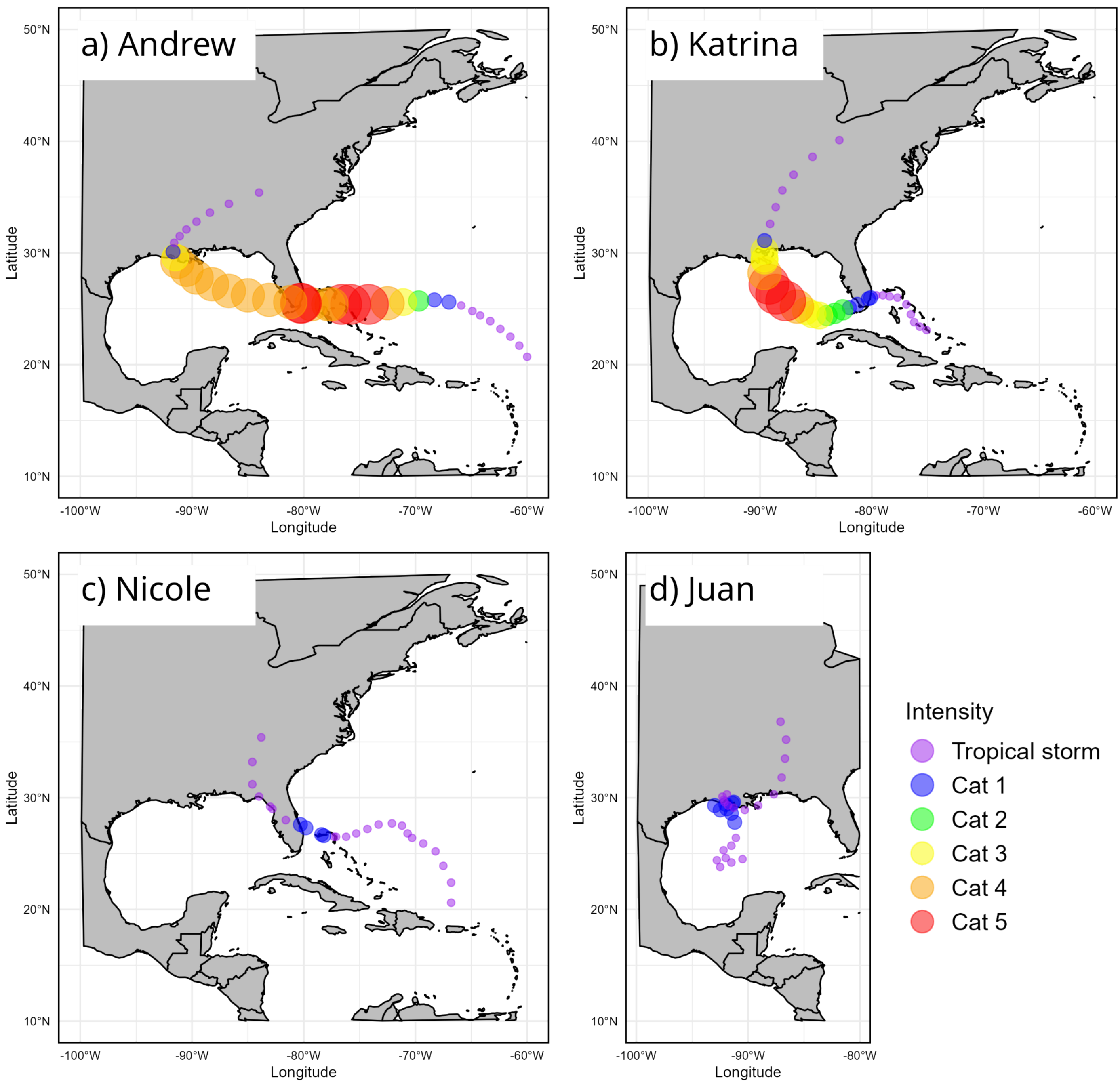

Figure 2: *Examples of multiple landfall tracks from historical observations in HURDAT2. a) Hurricane Andrew (1992) made landfall as a Category 5 tropical cyclone in Florida and a Category 3 tropical cyclone in Louisiana. b) Hurricane Katrina (2005) made landfall as a Category 1 tropical cyclone in Florida and a Category 3 tropical cyclone in Louisiana. c) Hurricane Nicole (2022) made landfall as a Category 1 tropical cyclone and a tropical storm in Florida. d) Hurricane Juan (1985) made landfall twice as a Category 1 tropical cyclone in Louisiana and once as a tropical storm.*

3. Results

3.1. Climate change and landfall risk

Under a 2°C above pre-industrial climate, the Reask model suggests an increase in the frequency of landfalls of tropical cyclones for the U.S. This is driven primarily by changes in sea surface temperatures and vertical windshear in the North Atlantic, which are input into the Reask model from CESM2 outputs. The CESM2 inputs for the 2°C scenario suggest sea surface temperatures are warmer offshore West Africa in the main development region for Atlantic tropical cyclones and along the U.S. east coast (Figure 3b). This is coupled with lower vertical windshear in the same region off West Africa and along the U.S. coastline (Figure 3a). These inputs into the Reask tropical cyclone model are consistent with other climate model outputs from CMIP5 and CMIP6 (Ting, *et al*. 2019; Vecchi and Soden, 2007) and are more favourable to tropical cyclone development maintenance. The incursion of warmer water poleward is particularly noteworthy, as this allows Atlantic tropical cyclones to maintain their intensity for longer and to higher latitudes altering local risk profiles.

Figure 4 shows the change in return period for tropical cyclone peak windspeeds of a 2°C warming scenario relative to present-day for the contiguous U.S. as a whole. It shows that the return period change of the lowest (Category 1 and 2) intensity landfalls is relatively small. This is a consequence of low intensity landfalling events being relatively common, and the relative increase in low intensity events not driving large change in landfall rate. However, large reductions in return period are seen for categories four and above. This is particularly true for Category 5 events, which make landfall relatively infrequently in the contiguous U.S.

Figure 5 shows the impact in terms of average annual loss (AAL) of a 2°C warming scenario relative to present-day. Figure 5a shows the change in AAL associated with a nationwide adjustment. Figure 5b shows the change in AAL associated with a regional adjustment. Focusing on Figure 5b, the greatest increases in AAL are seen along the east coast of the U.S., particularly around the mid-Atlantic and northeast regions. This is driven both by more frequent weaker tropical cyclones (Category 1s and 2s) making landfall, but also increases in the rate of major (Category 3+) tropical cyclone landfalls (see Figure 4). However, it must be noted that the absolute numbers of major hurricanes making landfall here in this scenario are far lower than the number seen along the Gulf coasts. For the Gulf Coast regions and east Florida, small relative increases in the number of events expected under the 2°C warming scenario result in much larger changes in the absolute numbers of major hurricanes making landfall. Yet, this does not result in large relative changes in insured losses.

3.2. Landfall risk change and insured losses

From an insured loss perspective, the MS Amlin 2°C climate change scenario estimates that the U.S. wide AAL would increase by ~42% from present-day when a U.S. wide adjustment for landfalling hurricanes was applied (Table 1). This is reduced slightly when a regional landfall adjustment is used to ~39%. Analysis of the differences in these AALs showed that they were caused by a combination of slightly different numbers of landfalling hurricanes, and regional adjustments resulting in more hurricanes making landfall in regions with lower total insured values. At the 1-in-200 Aggregate Exceedance Probability (AEP) the difference in insured loss drops to 25% for the U.S. wide adjustment and only 26% for the regionalised adjustment.

To put a 39% increase in losses in perspective we consider historical losses from 1990 to 2023. According to Gallagher Re, the total insured loss from tropical cyclones in the contiguous U.S. from 1990 to 2023 was US$556 billion (Gallagher Re, 2024). Normalised to 2023 U.S. dollar values, this translates to an AAL of US$16.6 billion. However, if we exclude the years of the statistically unlikely major hurricane drought from 2006 to 2016 (Hall and Hereid 2015), the AAL rises to ~US$22.4 billion. An increase of 39% to these historical losses would have resulted in an AAL of US$31.2 billion. This figure is intended to be instructive of the scale of the increase in risk from present-day climate to a 2°C above pre-industrial climate. Indeed, a repeat of the 1990 to 2023 tropical cyclone season today would result in significantly higher insured losses as a consequence of exposure growth, sea-level rise, and a climate ~0.5°C warmer than 1990.

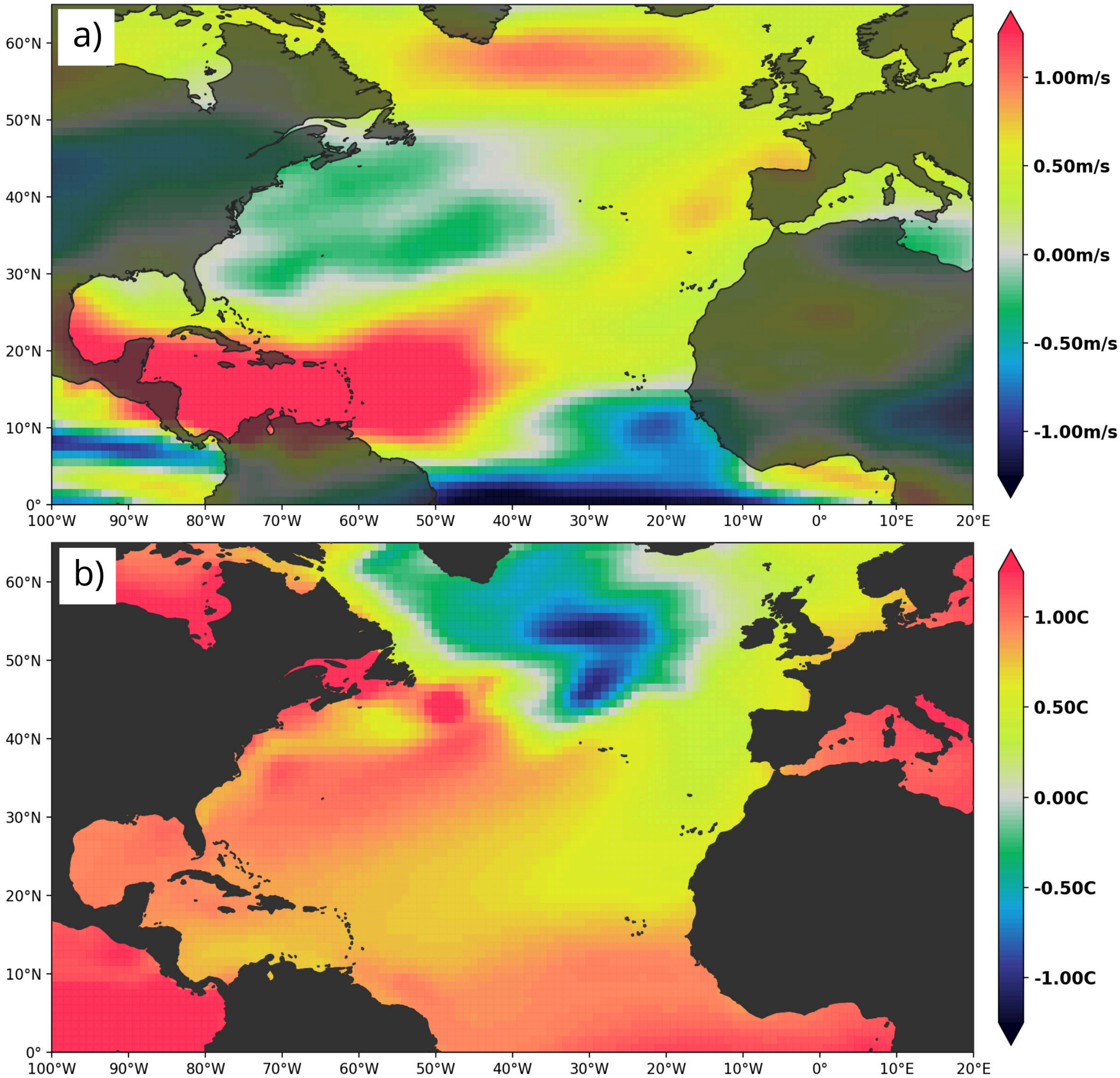

Figure 3: *Climatic anomalies which occur under the 2°C scenario provided by Reask. a) Vertical wind shear anomalies. b) Sea surface temperature anomalies. Both environmental variables have strong controls on hurricane genesis and development.*

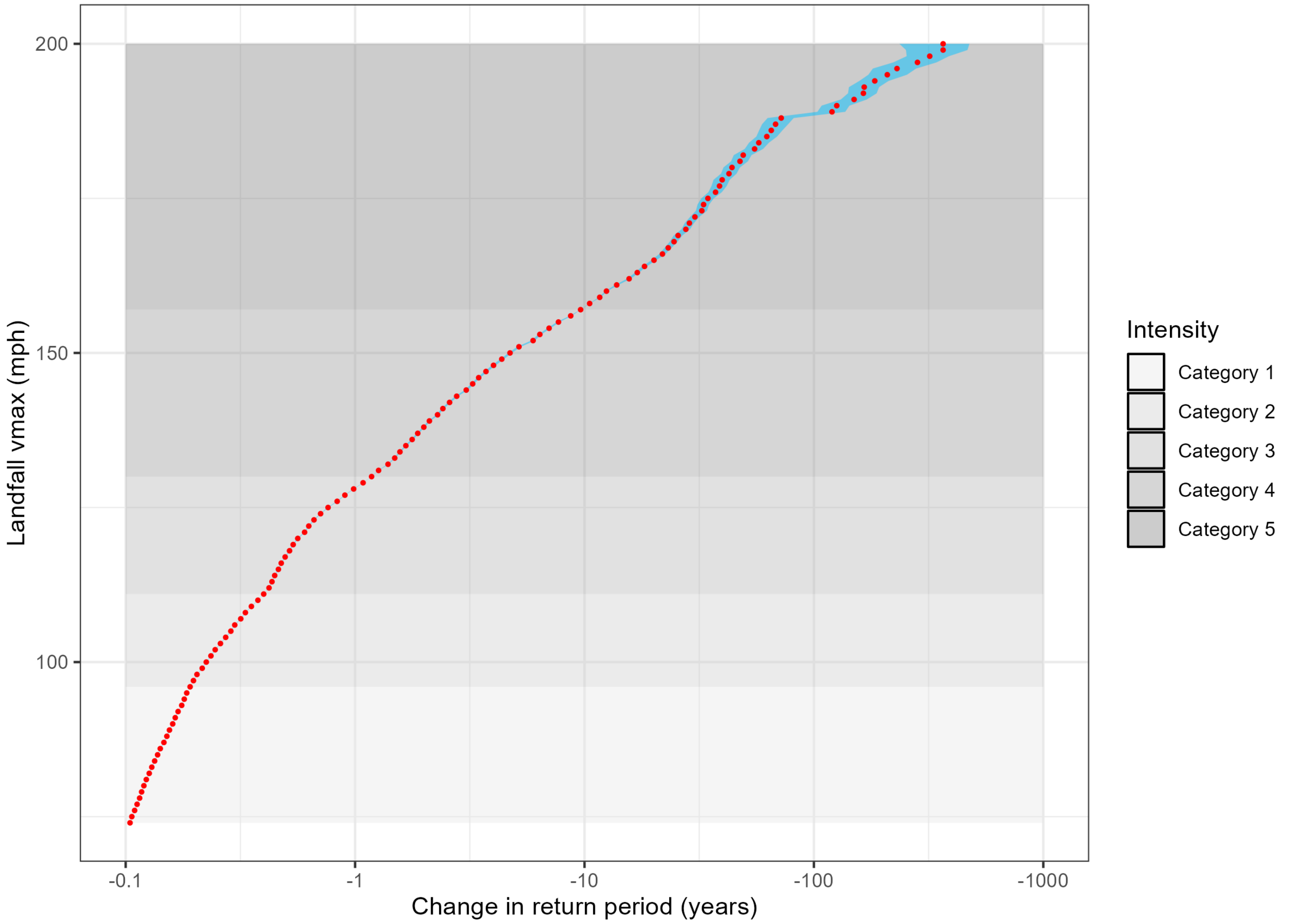

Figure 4: *Change in return period for tropical cyclones with a given maximum windspeed at landfall (Landfall vmax) between the present-day climate event set and the 2°C warming scenario. Red points show the mean change over 1,000 sampled runs. Blue shading shows the range of changes in return period over the sampled runs.*

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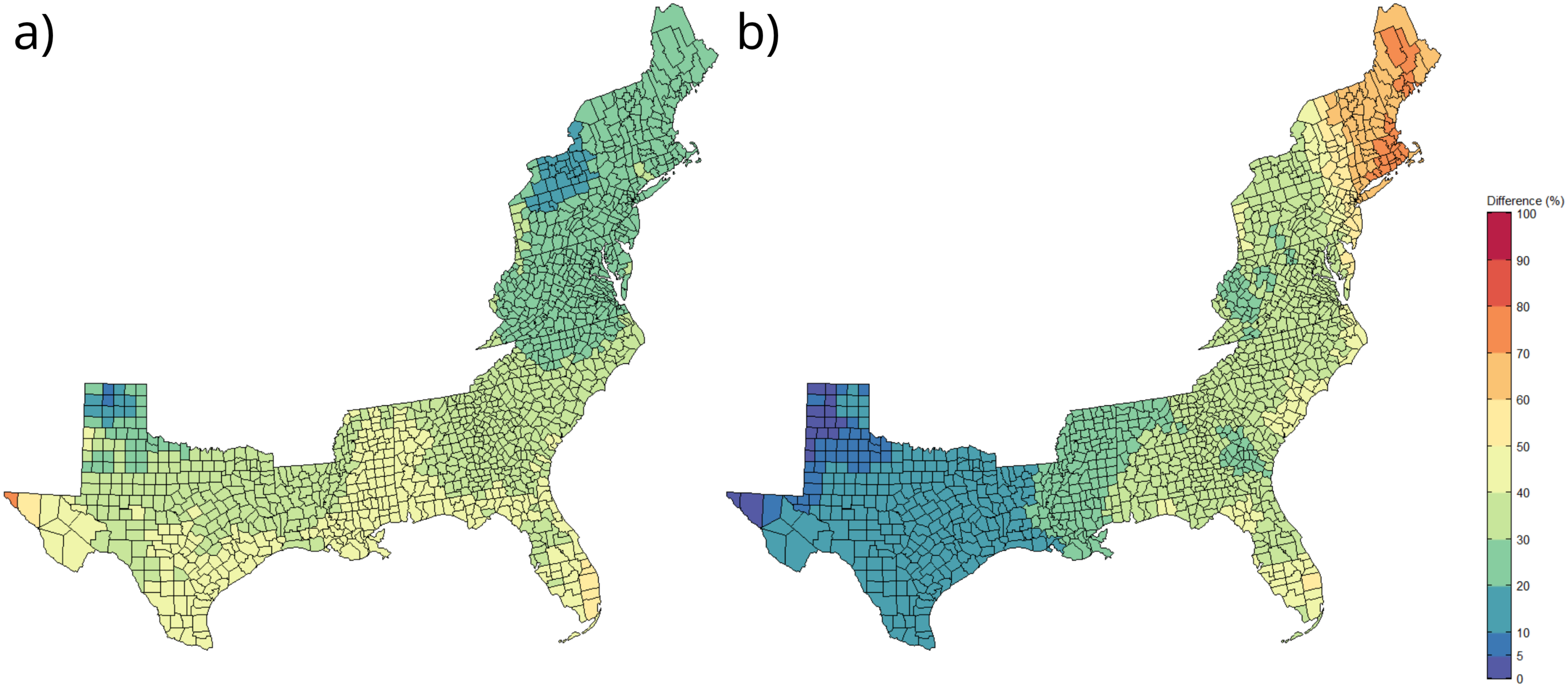

Figure 5: *Change in average annual loss (AAL) under a 2°C warmer climate scenario compared to present-day using; a) a nationwide adjustment to landfall rates; b) regional adjustments to landfall rates.*

Table 1: Changes to insured losses under a 2°C warmer than pre-industrial climate relative to the present-day climate.

Landfall adjustment method	Change relative to the present-day insured loss	
	Annual average loss (AAL)	1-in-200 AEP
U.S. wide	+42%	+25%
Regional	+39%	+26%

3.3. Regional insured losses

Regional changes in the number of landfalls of different tropical cyclone intensities are translated into change in expected AAL using the regional tropical cyclone adjustment rates (Table 2). Changes in AAL are shown to be the largest in the Mid-Atlantic and Northeast regions and reflect the larger (relative) increases in tropical cyclone landfalls projected here (see Figure 5). However, it is important to acknowledge that many of these states generate small AALs compared to other regions of the U.S. The two states which make it into the top 10 in terms of modelled AAL are New York and Florida. Both these states have high values of insured exposures, but Florida also suffers from frequent tropical cyclone landfalls due to its southerly latitude. Under the 2°C above pre-industrial climate scenario, both experience large relative increases in terms of their AALs. The Florida AAL increases by 44%, whilst the New York AAL increases by 64%. For Florida, which experiences the greatest number of landfalls under present-day climate, this is a consequence of small rate changes resulting in large numbers of additional events making landfall. For New York, this is caused by large rate changes greatly increasing the average rate of landfalls experienced.

3.4. National and regional loss curve adjustments

The MS Amlin 2°C climate scenario adjustments show the largest changes at short return periods (see Figure 6). This is a common feature of frequency/severity adjustments to catastrophe model catalogues that others have also noted (Rye, 2023; Jewson, 2021). It is an open research question, the extent to which tail risk under a warmer climate is adequately captured. Yet, when the responses of AEP curves are considered regionally after the regional level adjustment has been applied, useful information can still be extracted from such scenario analyses. The relative responses for Texas and the Carolinas in Figure 6 clearly show distinct differences. The size of changes across the AEP curves for the Carolinas far exceeds either those for Texas or the contiguous U.S. as a whole. Relative changes in modelled losses for the Carolinas are double those for the contiguous U.S. and more than doubled those projected for Texas. As return periods increase, the relative changes for the Carolinas are more comparable with those of the U.S. as a whole, but are much larger than those for Texas (about triple the size).

The implication of these results is that insurers do not face equal risk from climate change impacts on tropical cyclone characteristics. They show that regional carriers potentially could experience very different loss outcomes compared to national carriers or reinsurers (grey in Figure 6). Another key finding of this study is a projected reduction in years without a landfall. The years without a contiguous U.S. landfall sees a reduction of 30%. This partly explains the large increase in losses at the shortest return periods. It also means that without an adjustment in pricing and potentially risk selection, exposure to large landfall year numbers and commensurate losses, e.g. 2005, increases.

Table 2: Top 10 states in terms of changes to average annual loss under the 2°C warmer than pre-industrial climate.

State	Change in average annual loss relative to the present-day insured loss	Rank of state average annual losses under present-day climate	Rank of state average annual losses under 2°C climate change scenario
Rhode Island	+71%	14	14
Massachusetts	+71%	8	7
New Hampshire	+70%	19	19
Maine	+69%	18	18
Connecticut	+68%	13	12
New York	+64%	4	4
Vermont	+64%	21	21
New Jersey	+55%	9	9
Delaware	+47%	17	17
Florida	+44%	1	1

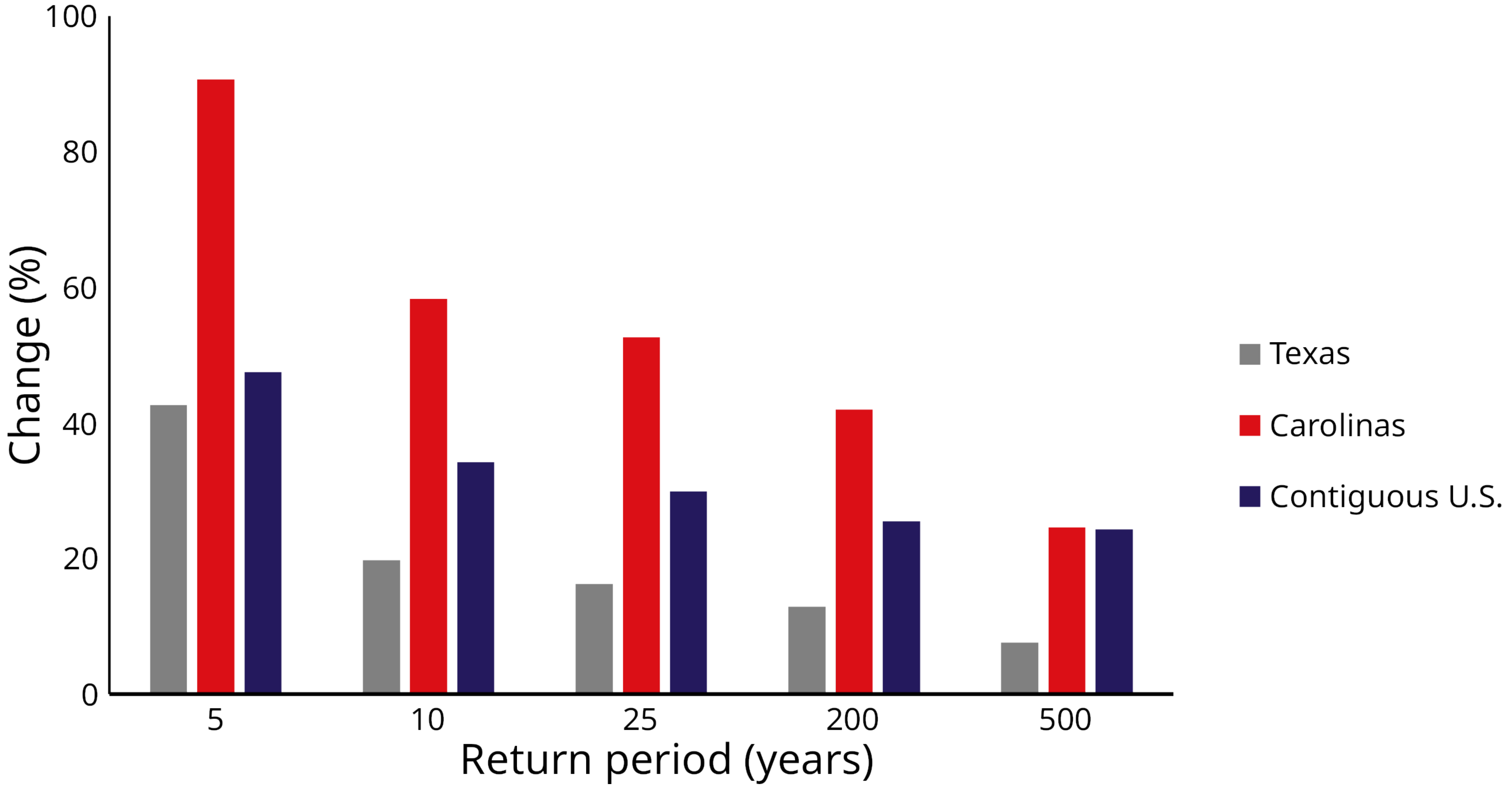

Figure 6: *Change in AEP insured losses under a 2°C warming scenario for two regions and the U.S. across a range of return periods.*

4. Discussion

4.1. National vs. regional adjustments

Basin-wide cyclogenesis statistics or continental landfall statistics are commonly used to adjust catastrophe model event sets. However, such adjustments are bound by the underlying event catalogue, which is intended to be representative of present-day landfall risk characteristics. For example, if 70% of Category 3 landfalls are expected in the Gulf of Mexico under present-day climate, then this proportion will be approximately maintained if a continental-wide adjustment is used and event selection occurs randomly. Using regional changes in landfall rate can overcome this issue, allowing the user greater flexibility to adjust the shape of the event distribution and improving the user's analysis of changing risk. The contrasts between using a nationwide adjustment and a regional adjustment can be seen in Figure 6.

Given the clear advantages of regional over national level adjustments, should local level adjustments be considered? In this study, regional level adjustments were possible due to the Reask model outputs being amalgamated across defined regions, i.e. Texas. However, catastrophe models commonly consider landfall gates as their means of capturing landfall rates. Landfall gates are normally defined as 50 – 100 km lines, over which a tropical cyclone must pass in order to be deemed that it has made landfall. Adjustments could therefore be made at the 50 – 100 km spatial scale. Such adjustments would appear advantageous as they would enable the user to understand changes in landfall risk impacted areas of high exposure. Yet, adjustments of this granularity may produce a sense of false confidence in results for non-experts interpreting the outputs of such scenarios. This is a consequence of climate models still commonly only having grid resolutions at ≥100 km (Ziehn, *et al.* 2020; Danabasoglu, *et al.* 2020; Sellar, *et al.* 2019). It is therefore unlikely, given that many models fail to easily resolve weather systems, such as tropical cyclones, that they can confidently prescribe which side of a 50 km gate a tropical cyclone passes and how this changes under a warmer climate scenario. At the spatial scale of an individual gate the challenge in terms of the adjustment is therefore one of signal versus noise. Such analyses should therefore be used to stress test (re)insurance portfolios rather than used to inform precise representations of changing risk.

4.2. Comparison with other climate change scenario studies

Academic and (re)insurance studies have produced estimates of the economic and insured loss estimates attributable to climate change, as well as scenarios of losses under different emission/heating pathways. Attribution studies provide estimates of the climate change impact on increased windspeeds (Clarke, *et al.* 2024) or precipitation rates observed (Reed and Wehner 2023; Frame, Wehner, *et al.* 2020) and their impact on economic or insured losses (Comola *et al.*, 2024). However, these only provide a guide as to the increasing role of climate change in increasing the severity of events. Biases in event selection exist as attribution studies generally focus on events where climate change is deemed to have a large impact, or where impacts on communities are severe. In contrast, climate change scenario impacts on tropical cyclone frequency/landfall numbers provide guidance about potential outcomes, but often generate conflicting results and/or large amounts of uncertainty (Jewson, 2023b; Fosu *et al*., 2024; Meiler *et al*., 2023; Knutson *et al.*, 2022; Toumi and Sparks, 2024).

Other similar climate change scenario studies have produced similar results to those reported in this study in terms of changes in landfalls (Knutson, *et al.* 2022; Fosu, *et al.* 2024; Mendelsohn, *et al*. 2012). When using column relative humidity to determine tropical cyclone seeding rate, Fosu *et al*. (2024) showed an increase in cyclogenesis for all tropical cyclone intensities, which translated into increased tropical cyclone landfall rates across the U.S. over the period 2030 – 2050. As with this study, the largest changes were observed on the eastern seaboard. Rates of change of different categories are relatively similar for lower intensity storms. However, for higher intensity, less frequent events, our data suggest a greater rate of change. This is especially true for regions such as the Southeast and Northeast. The rate in change of Category 4 and above tropical cyclones in both studies is greatly exceeded by Knutson *et al*. (2022) albeit the Knutson *et al*. study uses a smaller number of simulation years meaning this could be a function of sample length. It must be noted that some studies have shown landfall trends opposite to those discussed above. For example, Bengaluru *et al*. suggested a reduction in Northeast landfalls and increased rates of landfall in Florida and the Gulf of Mexico. Where trends in landfall frequency decline, this is commonly prescribed to be a feature of greater atmospheric stability reducing cyclogenesis or earlier recurving of tropical cyclone tracks.

From an insured loss perspective, the Fosu *et al*. (2024) study reports losses at 2040, where temperatures are slightly below 2°C above pre-industrial level. Using their more active seeding parameter, they report mean changes in AAL of between 20% and 25% across different CMIP6 inputs compared to 40% in this study. Indeed, the suggested AAL change in this study would sit in the upper quartile of modelled losses from the Fosu study. However, both studies show that the greatest impact on insured losses occurs at the shortest return periods and decreases as return periods increase. Beyond 2040, even as temperatures increase, the reduction in landfalls in the Gulf of Mexico in the Fosu *et al*. study results in changes in insured loss being suppressed. Combined with the change in landfall rate data, this similarly shows the dominant role that Florida and the Gulf states play in driving insured losses – given current insured exposures – as reduced landfall rates in the Gulf compensate for much higher landfall rates on the eastern seaboard.

4.3. Reducing the impacts of hurricanes in a warmer climate

The climate change scenario reported here makes a number of assumptions. It assumes that tropical cyclone landfall frequencies will continue to increase and uncertainty still exists on this topic (see discussion above). It also does not consider the potential impacts of changes in sea-level on storm surge or changes in tropical cyclone induced precipitation flooding. Both are likely to increase with further climate warming (Balaguru, Xu, *et al.* 2024). However, in the case of sea level change, the rate at which it is rising will continue to be highly spatially variable (Sweet, *et al.* 2022).

Insured losses presented are also based on a static insured market where insurance penetration remains at present-day levels and methods of mitigating the impacts of hurricanes do not change. Both assumptions are unlikely. Based on this analysis, as at-risk communities suffer increased losses and insured losses increase, insurance premiums will need to respond. If individuals are unwilling to take out coverage, or private (re)insurers are unwilling to accept increased volatility within their portfolio, pressure will increase on public or local governments to provide additional cover.

Without public insurance schemes or local government involvement, the insurance gap would be likely to grow under this scenario, further reducing community resilience (European Central Bank and European Insurance and Occupational Pensions Authority 2023). Indeed, research focusing on risks associated with seismic hazards has shown that community perceptions in some regions are that public bodies will step in to provide disaster relief and this has reduced the uptake of private insurance (Kelly, Bowen and McGillivary 2020). Reductions in private insurance take-up rates, either due to increased premium costs, or the development of the belief that public institutions will respond to help rebuild affected communities, will likely increase pressure on state finances as they respond to increased hurricane landfalls.

Mitigation measures are unlikely to remain static if landfall rates and intensities increase. However, unlike previous catastrophe events, enhancements should be put in place before, rather than after, events have occurred. Where more intense hurricanes are already common, e.g. Florida or Louisiana, strong building code enforcement should be in place. This should help to reduce the impacts of increased frequencies of landfalls. In areas where the most intense hurricanes are rare, i.e. along the eastern U.S. seaboard and particularly in the mid-Atlantic and Northeast – where only three major (Category 4+) landfalls have occurred since 1900 – building codes should be strengthened and be brought more in-line with states further south. Although likely to still be relatively rare, this should help mitigate the impacts of the projected increase in more intense hurricanes making landfall at increasingly high latitudes. Funding these changes is likely to be challenging. Retrofitting property to building codes more in-line with the risk that climate change represents will be extremely costly, whether this is through public intervention or through "build-back better" insurance cover post event. However, the minimum should be to enforce newly built property and infrastructure to meet standards appropriate to future risk.

5. Conclusions

Climate change scenarios are critical to understand potential insured and economic losses from changing natural hazard event characteristics, such as tropical cyclones in the North Atlantic. They also demonstrate the value of mitigating the impacts of anthropogenic climate change. This study has shown the increases in insured losses from a 2°C warmer than pre-industrial climate compared to a present-day climate (defined as 1.1°C above pre-industrial). The AAL for the U.S. increases by ~39% but that relative changes in risk for the contiguous U.S. is spatially variable. Although the absolute increase in the number of landfalling tropical cyclones would be greatest along the coasts of the Gulf states and Florida, while the greatest increase in relative landfalls occurs along the eastern seaboard. Preventative action, for example improving building codes or reducing further development in particularly high risk coastal locations, would reduce the impacts on local communities.

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