Hurricane Risk Management Strategies for Insurers in a Changing Climate

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Abstract

The insurance sector is among the earliest private sector industries to see substantial losses associated with climate change, and the risk signals embedded in insurance premiums could be a key driver for how climate adaptation decisions are made by individuals and communities. Therefore, risk assessments made in the insurance sector are critical for determining how the built environment responds to and rebuilds from natural disasters, and how society prices in the changes in disaster risk associated with climate change. Catastrophe models are the key tool the insurance community can use to bridge the gap between climate models and the extreme events that are the primary way in which society experiences climate change. The following discussion provides concrete suggestions for extending established catastrophe risk management practices to incorporate emerging climate risks. Incorporating climate change into hurricane risk management requires risk managers to 1. Explore catastrophe and climate model sensitivity to inputs in the built environment, 2. Divide hurricane risk by subperil so risk management strategies can be tailored to variable levels of uncertainty, and 3. Translate climate impacts into metrics that tie directly to decision-making and business outcomes. Each of these steps also highlights opportunities for collaboration between the insurance sector and scientific community. The general strategy of assessing sensitivity to model inputs, tailoring risk management strategies to the level of uncertainty in the hazard, and producing outputs that are useful for end users is broadly applicable for climate data services across a wide variety of sectors.

Keywords: Insurance, Climate, Catastrophe Modeling, Hurricane, Risk Management

Catastrophe Models: A key tool for linking climate change to risk

Insurance industry disaster risk is generally managed through tools known as catastrophe models. Catastrophe models were widely adopted in the aftermath of Hurricane Andrew making landfall in Florida in 1992, and further solidified following the Northridge earthquake in California in 1994. Because the most extreme events are not frequent enough to apply standard actuarial techniques with a basis in statistical theory of large sample sizes, these models offer a powerful tool to fill out gaps in historical coverage for rare and extreme events. Historical records of disasters are heterogeneous in time and space, and even lengthy historical records are typically insufficient to characterize events in the 100-250 year return period range commonly assessed in the insurance industry. Even where historical records are available, they might have impacted a building stock that was materially different from what exists today, with many fewer buildings in areas at high risk than is the case today, paired with older building codes that would not reflect a current view of damage potential. Catastrophe models allow insurers to assess the risk of plausible events that may not be in the historical record and capture the effects of changes in exposed building stock over time.

Catastrophe models vary somewhat in form, but generally come with the same four basic components. Catastrophe models take in exposure as an input, in the form of a database representing the locations that an insurer covers in its policies, describing their location, occupancy (such as single-family residential, or a commercial office building), construction type (wood frame, steel), age, and other details of how the structure was built. The physical environment is modeled through a hazard module, which is an event set of thousands of years of hypothetical events, including tropical cyclones, earthquakes, floods, wildfires, etc. The hazard and exposure feed into a vulnerability module, which builds a relationship between the level of hazard and type of building – for example, the percent damage that a single-family wood frame home will experience at a given wind speed in a hurricane. Vulnerability typically reflects a combination of engineering expertise and tuning to historical losses. Lastly, the amount of damage produced by the vulnerability component is fed into a financial model, which applies insurance policy terms like deductibles and limits.

Catastrophe models do not attempt to capture the same types of events as a typical climate model. While climate models are best at producing average projected changes in large scale patterns over long time periods, catastrophe models are designed to capture low frequency/high severity hazards in the tail of a probability distribution in single year increments at high spatial resolution. To capture extreme tails of the hazard distribution, catastrophe models blend physical modeling with statistical sampling of hazard parameters derived from the historical record, such as number of storms, genesis locations, or storm trajectory by latitude/longitude (Hall and Jewson 2007). Monte Carlo simulation of storm characteristics is computationally cheap compared with the high resolution physical climate models needed to represent extreme events like hurricanes, enabling catastrophe models to produce tens or hundreds of thousands of years of simulated disasters to realistically reflect rare but high impact events.

Although insurers have long been broadly aware of climate risk from an enterprise risk and regulatory standpoint, the catastrophe modeling tools that are most commonly used in daily decision-making and that feed into risk appetite reflect a snapshot of risk at a particular time. Since catastrophe models are drawn from a statistical distribution built from historical data, they are inherently designed for short-term climate impacts. At present, they do not explicitly incorporate most forms of forward-looking climate risk.

The statistical distributions of events used to build a catastrophe model become less and less representative of potential risk with climate projections that are further in the future, where events may happen that are outside the distribution of historical experience. However, climate model skill in attributing climate change impacts to extreme events tends to increase for most hazards further in the future, as external forcing continues to increase relative to internal natural variability. Therefore, leveraging these complementary tools in combination can help to highlight how climate change could impact extreme events, and how changes in extreme events might play out in societal impacts and economic losses.

Although the most common catastrophe models are designed for the insurance sector, there are academic models that capture at least some components of the catastrophe models used in the insurance sector. Hazard models are the most common, such as the Columbia HAZard Model (Lee et al. 2018) and Synthetic Tropical cyclOne geneRation Model (STORM) (Bloemendaal et al. 2020). However, the hazard and vulnerability components of a catastrophe model that are used to produce a loss are not fully independent. With two unknown variables for any given loss (hazard and vulnerability), the solution to produce that loss is not unique. Two models could produce the exact same loss for an event, with one arriving at that estimate through a higher assumption of hazard but a lower assumption of vulnerability, and the other producing a lower amount of hazard but higher vulnerability. Therefore, catastrophe models need to be carefully ground-truthed using observational data on wind and storm surge footprints, as well as engineering studies that link particular wind speeds to a proportion of damage.

Tying the hazard and vulnerability modules together has historically limited the development of academic or public sector catastrophe models, as private sector companies have access to insurance claims data that are generally not publicly accessible, as well as combined scientific and engineering expertise that is difficult to replicate in the academic space. Ongoing work to develop open source or publicly available catastrophe models could help to spread the risk insights that are accessible in the insurance industry to a broader set of end users in the public and private sectors. For example, catastrophe models only capture direct physical damage to the insurable built environment – they are not yet able to capture broader societal impacts such as transition risk, detailed supply chain impacts, or climate-driven migration or social upheaval, all valuable potential contributions from participants beyond the insurance industry.

For the purposes of this discussion, the risk analysis methodology will focus on North Atlantic hurricane risk, although much of what follows is applicable to other tropical cyclone basins as well. The hurricane hazards highlighted are not intended to be comprehensive, but rather representative of how hazards may interact with the built environment.

Three recommendations for risk modelers

The following sections will break down three key considerations to advance meaningful and actionable climate risk analytics within the framework of insurance risk management.

1. Exposure: Explore sensitivity of climate-driven losses to inputs from the built environment.
2. Hazard: Quantify scientific confidence and impact by subperil.
3. Translating climate data for decision-makers.

Each of these considerations highlights opportunities for leveraging catastrophe models to capture economic and societal impacts of climate change on hurricane risk. However, each recommendation also has space for further improvement with better tools and advances in the basic science. Therefore, each section is followed by a “Research Opportunities” subheading, showing key data or analytical gaps that are an opportunity to improve quantification of the societal impacts of hurricanes in a changing climate.

Recommendation 1 – Exposure: Explore sensitivity of climate-driven losses to inputs from the built environment

Climate hazards do not occur in a vacuum - they can only become disasters when they intersect with an impacted community. Catastrophe models are particularly adept at capturing the impact of climate hazards on the built environment, which may be subject to changes in risk that do not scale linearly with the change in hazard. However, this means that assessing climate impacts requires stringent data collection processes on exposure inputs, or the resulting modeled impacts will not be meaningful.

Modeling water risk in the built environment

Several of the most immediately changing hurricane subperils, such as storm surge and inland rainfall, are making hurricane damage wetter. This poses a particular challenge for risk modelers, since water perils require a much finer degree of detail on exposed properties to produce meaningful views of risk compared with more developed hazards like wind and earthquake. Wind risk, for example, is relatively forgiving of minor errors in modeling the location of a building, as the average risk from wind does not vary particularly dramatically at small spatial scales along the coast. Flood risk, however, may vary widely even within a single building parcel, and minor errors in location can easily cause properties to be modeled in the middle of retention basins or roadside ditches, leading to dramatic overestimates in risk. For this reason, modeling “climate risk” often requires substantial investments in improved data about exposed building locations in a book of business, long before examining any changes in physical hazard. Advances in geocoding and capturing important building characteristics like basements and building elevation can dramatically improve the realism of modeling hurricane-driven water risks like surge and inland rainfall.

Furthermore, at the scale of metropolitan areas, hurricane flood risk may not be distributed equitably. Redlining was a historical discriminatory practice that deemed communities populated by racial and ethnic minorities, and particularly Black communities, to be a bad financial risk. Communities that experienced redlining are disproportionately located in areas of higher flood hazard (Katz 2021). The practice of redlining systematically reduced property values as well, since it limited access to mortgages and related financing, limiting the tax base for investments in flood defenses like stormwater drainage infrastructure. After a disaster has occurred, homeowners are more likely to receive post-disaster funding to rebuild, both through federal and insurance assistance - this homeownership bias exacerbates unequal disaster impacts in communities with a higher proportion of renters (Fussell 2015). Climate-related water risks may only compound this historical inequality, potentially leading to a pattern of “climate gentrification” where only the wealthy have the resources to harden their homes, lobby for defensive infrastructure, and rebuild after major disasters. Investments in capturing socioeconomic data for use in physical risk models (Tedesco et al. 2021) can help to predict where such impacts are likely, highlighting communities that would benefit from additional investment in protective measures.

Spatial distribution of hazard vs. built environment

Even in the absence of changes in event frequency, risk and losses may change if different areas are exposed to hurricane risk in the future. A prime example of where this may play out is through poleward migration. There is at least some suggestion that migration of storms toward higher latitudes may be occurring in the historical record in some basins (Kossin et al. 2014), which is most likely to be occurring beyond an extent explainable by natural variability in the North Pacific basin (Knutson et al. 2019). This pattern may be driven by a change in tropical cyclone genesis location (Daloz and Camargo 2018), which could theoretically lead to declines in risk at very low latitudes. However, mid-latitude metropolitan areas may see increases in risk whether poleward migration comes from migrating genesis locations or an expansion in the parts of the ocean with sea surface temperatures warm enough to support tropical cyclones.

Moving stronger storms over regions whose building codes were designed based on historical wind return periods can increase losses through higher building vulnerability, independent of any changes in storm frequency. Building codes and enforcement are not standardized and vary widely from state to state, but in general, more northerly states are less likely to design for tropical cyclone wind risk. Even absent these building code considerations, exposing mid-latitude metropolitan areas like New York and Boston to hurricane risk, when these events have been historically rare, may substantially change the population that could be exposed to hurricane risk in the future.

Critical thresholds

Even where hazards are smoothly varying over time, the intersection between hazard and the built environment may lead to sharp discontinuities in risk. Hurricane Sandy highlighted the cascading impacts that ensue when a hazard intersects with critical pieces of infrastructure, as when

Sandy's storm surge entered the New York City subway system and took the storm's impact from damaging to catastrophic. Every metropolitan area has a point when damage becomes massively disruptive - whether it is public transit like New York, a critical piece of the power grid (also inundated in New York during Sandy, causing the blackout in lower Manhattan), or the point when a downtown center is inundated. For coastal cities in particular, storm surge sitting on top of sea level rise brings many of these pieces of critical infrastructure closer to this range of risk. Without explicit defensive measures, cities may find that infrastructure designed to be defended against a 1 in 100 or 1 in 250 year return period storm surge may actually be impacted by the 1 in 50 or 1 in 30 year storm surge in the future. Different pieces of infrastructure may have different levels of risk tolerance – for example, a municipality is likely to be more comfortable with a road being occasionally inundated compared with a nuclear plant. However, mapping and quantifying the risk to critical facilities is a key component of preparing communities for future extreme events.

Exposure research opportunities

1. Publicly available exposure data

The insurance sector has access to a rich resource of data about the built environment, both through individual portfolios of business that they write, as well as "industry exposure" datasets produced by catastrophe modeling companies. However, this data has some notable limitations. Most importantly, it is expensive to build and maintain, so it is generally proprietary and expensive to license. Detailed data about the built environment is necessary for quantifying costs of increased hazard, but the granularity of public datasets is generally not sufficient to capture high gradient hazards like flood, and it lacks an ability to distinguish critical infrastructure. Investments in public data available to the research community would fill a critical gap in quantifying economic impacts of climate change.

Defining economic costs of extreme hazards like hurricanes is particularly critical in a policy environment where decisions about mitigation and adaptation pathways are at least partially based on the expected economic costs of climate change. Extreme hazards are a key driver of economic loss, but they are minimally captured in the economic models widely used in the financial sector to model transition risk, which could lead to underestimation of the long-term costs of climate change on society.

2. Tools to capture detailed exposure characteristics

Hurricane water subperils, as well as other high-resolution hazards like inland flood and wildfire, require highly detailed information about the built environment to produce meaningful model results. Investments in remote sensing and machine learning to better identify details like building footprints and first floor elevations are critical to meaningfully incorporate emerging climate hazards into the risk models used throughout the insurance sector. This is an active area of private sector investment, but it is also an area where academic researchers could contribute meaningfully to managing climate risk.

3. Economic effects of physical risk on exposure values and investments

Forward-looking views of physical risk require projections of future exposures, along with the usual forecasts of physical hazards. However, physical hazards may have impacts on property values, which can complicate and materially affect the expected cost of extreme events like hurricanes. Coastal flood is a key example of the complexity of assessing changes in future economic risks from hurricanes, with knock-on implications for both catastrophe and transition risk modeling.

Coastal flood risk is not only composed of storm surge from hurricanes. For a given location, sea level rise manifests first through changes in coastal flood event frequencies, beginning with extreme hurricane surge events, and eventually moving through routine high tide flooding to complete inundation. Sunny day or “nuisance” flooding, high-frequency flooding driven by high tides combined with sea level rise, does not fall within the traditional purview of hurricane catastrophe models, although it can be exacerbated by bypassing hurricanes. However, the mechanism of stacking high tide events on top of current and future sea level rise scenarios works much the same way as storm surge in a catastrophe model. While often treated separately, storm surge and other types of coastal flood actually represent a continuum of coastal hazard, which may intersect in ways that could drive larger-scale climate risks.

While individual losses are small compared with storm surge, high frequency coastal flooding events may have systematic risk potential due to their impact on property values. Structures that experience routine flooding may be harder to sell, and ultimately lose value or grow in value more slowly than their lower-risk neighbors (Keys and Mulder 2020), as damages accumulate and insurance premiums rise from repeated claims. Since property values determine the amount of property taxes collected, this may limit a critical potential funding source for future coastal flood defenses. Coastal states that lack income tax, like Florida and Texas, have fewer obvious local funding sources if coastal property tax bases were to be impacted by a local decline in property values.

Property value risk is an area where insurers may be impacted on both sides of their balance sheet – in physical hazards driven by their portfolios of insured risks, as well as economic hazards within their investments. Municipal bonds, investments in the mortgage market, and other investments tied to a clear physical location could potentially see areas of clash, where a large hurricane could hypothetically trigger losses both from direct physical damage, as well as longer-term slowing or reversal of investment returns concentrated in the same location. While investments are chosen with a certain level of risk appetite for an economic shock, climate-driven financial risk has a different timeline for recovery than traditional economic shocks – unlike a recession, sea level is not expected to retreat globally for centuries or more, so some assets may not be recoverable. However, with a few exceptions like those noted above, investments typically have limited information about the physical locations of their facilities, a critical data gap for incorporating hazard assessments for extreme events like hurricanes into an investment portfolio.

Despite its importance for societal impacts of hurricanes, the interaction between nuisance flooding and storm surges, particularly regarding socio-economic risk, is comparatively understudied. For example, is a major storm surge event more likely to cause widespread mortgage defaults if the community has already been stressed by nuisance floods depressing property values? The interaction between high frequency and low frequency coastal flood events is also currently not generally incorporated into catastrophe modeling, suggesting a potential avenue for collaboration between the climate modeling, catastrophe modeling, and economic literature.

Recommendation 2 – Hazard: Quantify scientific confidence and impact by subperil

For a complex hazard like hurricanes, the question, "how does climate change affect hurricane risk?" is so broad as to be virtually meaningless. Within the framework of climate modeling, hurricanes are comparatively small scale and extreme events, so the science remains in flux for some aspects of the hazard. However, some characteristics of hurricanes have seen clear, immediate impacts in the current climate. Rather than attempting to roll hazards with wildly variable levels of uncertainty together, it is useful to break apart hurricanes into their associated subperils and apply different risk management strategies based on their corresponding scientific confidence and materiality of impact.

High-confidence perils, like increases in storm surge inundation, are explicitly included in catastrophe models in the current climate, and could be added in near-term (5-10 year) time steps that are relevant for underwriting, pricing, and portfolio planning. For lower-confidence perils, like hurricane frequency, an exploratory approach that examines how much the hazard would have to change to affect the business (rather than proscribed time-based scenarios) is more useful for planning purposes, and allows the organization to assess when and if action would be needed.

Water subperils

Storm surge

Storm surge is the clearest and most immediate impact of climate change on tropical cyclone risk. While the question of whether the component of the surge caused by the storm itself is changing remains open (Grinsted et al. 2012), sea level rise provides a higher platform for every incoming storm surge (Knutson et al. 2020), increasing both depth and the inland extent of the surge inundation footprint. The impact of sea level rise is compounded by the locations of major concentrations of exposure, which are often cities built on deltas that subside naturally, and in some cases whose subsidence is enhanced by factors like groundwater withdrawals (Nicholls et al. 2021).

Catastrophe models are built using sea levels that are close to those of the present day, so this climate-related trend is explicitly included in modeled loss results. However, forward-looking sea level rise scenarios, particularly projecting out into the medium term where portfolio optimization decisions are made, are in comparatively early stages of development, and are not consistently included in model results from many of the largest catastrophe model vendors.

At the time scales that are most important for decision-makers in the insurance sector (up to 2050 at the latest), uncertainties in sea level rise even among a wide range of emissions scenarios are comparatively small, ranging from median [likely] global mean sea level rise by 2046-2065 of 0.24m [0.17-0.32m] in RCP 2.6 to 0.30m [0.22-0.38m] in RCP 8.5 (Intergovernmental Panel on Climate Change 2014). While projecting global mean sea level changes down to the local scale required for catastrophe modeling is more challenging, the emergence of gridded products like that produced by NOAA in the US (Sweet 2017) makes it possible to produce reasonably localized sea level projections. Capturing this regional level of detail is critical for interpreting changes in storm surge risk over time, as individual cities do not experience global mean sea level change. For example, portions of the US East Coast are experiencing sea level rise that is 50% or more above the global mean, predominantly but not exclusively driven by post-glacial isostatic rebound (Piecuch et al. 2018).

Catastrophe model results highlight the impact that climate change can have on tropical cyclone subperils, even within the historical record. A study led by Lloyd’s in the aftermath of Hurricane Sandy found that the amount of sea level rise since 1950 had increased ground up losses by 30% in the New York metropolitan area (Maynard et al. 2014). Similarly, this modeling framework can be used to assign economic losses to the anthropogenic portion of sea level rise from historical storm surge events

(Strauss et al. 2021). Increases in loss are not limited to the increase in storm surge depth; higher storm surges also lead to greater inland extents of storm surge footprints, with the greatest increase in extent on low, flat coastlines. Consequently, loss increases may not be linear, but rather may have step functions as surge footprints are able to reach major concentrations of buildings or critical exposure that would have stayed dry with a lower baseline sea level. With adjustments for sea level rise, catastrophe models could be valuable tools to highlight these critical discontinuities in loss potential.

Rainfall-Induced Flooding

Hurricane rainfall is generally expected to intensify with climate change. The Clausius-Clapeyron equation shows a ~7% increase in the moisture that the atmosphere could potentially hold with every 1˚C temperature increase. Therefore, a warmer atmosphere itself provides a potential mechanism to enhance hurricane rainfall. Rainfall increases could also hypothetically be enhanced by stalling or other dynamical factors, as was the case for Hurricane Harvey over Houston and Hurricane Florence in the Carolinas (van Oldenborgh et al. 2017; Emanuel 2017a; Wang et al. 2018). Rain damage may not necessarily correlate well with wind damage, as major inland rainfall events have also been driven by tropical storms (Tropical Storm Allison, 2001 in Houston) and unnamed but near-tropical circulations (Baton Rouge flooding, 2016). This effect is enhanced along parts of the Gulf Coast by the "brown ocean" effect, allowing storms to maintain their structure, and at times even form, while over land (Andersen and Shepherd 2014).

Rainfall impacts may also be enhanced by their intersection with the built environment. For example, Hurricane Harvey produced the greatest amount of rainfall for a US tropical cyclone in records going back to the 1880s, with seven rainfall stations breaking the prior record held by Hurricane Hiki in Hawaii in 1950 (Blake and Zelinsky 2018). This could be thought of as particularly unlucky, to have such a historic event happen right over Houston, the fifth-largest metropolitan area in the United States (United States Census Bureau 2021). Alternatively, it could be interpreted that the record US tropical cyclone rainfall event and dramatic flood impacts happened in Harvey specifically *because* it happened to occur over such a large metropolitan area.

A variety of methods have been proposed to enhance rainfall over metropolitan areas, including surface roughness provided by buildings (Zhang et al. 2018) and local aerosol pollution (Pan et al. 2020). Similarly, impervious surfaces like buildings, roads, and parking lots can enhance flood risk by limiting avenues for rainfall to drain into the ground, forcing it to behave as overland flow instead and compounding the impact of increased rainfall on flood behavior (Sebastian et al. 2019).

As this Houston example shows, cities are in the position of being uniquely exposed to enhanced hurricane rainfall risk. Increased rainfall inputs are expected from warmer air and sea surface temperatures, with potential further enhancements specifically in tropical systems. The presence of a city may itself enhance local precipitation. And impervious cover prevents rainwater from absorbing into the ground, leading to overland flow into rivers and other drainage networks. All of this is happening where populations exposed to hurricane risk are the most concentrated. This puts cities at an uncomfortable confluence of compounding climate and exposure-driven hurricane flood hazard, so they would greatly benefit from more sophisticated risk modeling.

Although historically not captured explicitly in catastrophe models in the US, hurricane rainfall is a subperil that gained particular interest in the aftermath of Hurricane Harvey, and is now more broadly incorporated into hazard modeling. However, given the complexity of a peril that is changing via climate-driven hazard impacts, land use impacts, and whose loss history reflects a blend of public sector (mostly residential flood losses, in the National Flood Insurance Program) and private sector (larger commercial flood losses), this is an emerging hazard in the catastrophe modeling community that will likely continue to evolve as climate impacts and attribution continue to solidify.

Compound flood

Many major coastal metropolitan areas are located along estuaries or deltas that are susceptible to both riverine flood and coastal flood risk. A tropical cyclone can drive both risks occurring at the same time, with storm surge running up waterways and preventing river waters from draining as quickly, paired with intense inland rainfall enhancing river flood at the same time. Therefore, although the return period of a flood height can be calculated independently for coastal and river floods, best practice would account for the strong correlation between these perils in coastal areas that are exposed to storm surges. Furthermore, compounding riverine and coastal flood events will be exacerbated by sea level rise (Moftakhari et al. 2017). The science of compound hazards is comparatively immature, and it presents an opportunity to quantify risk in areas where human exposure and impacts are particularly high. Capturing this correlated hazard footprint is an area that is under development at many catastrophe modeling vendors.

Wind subperil

Wind frequency

Changes in hurricane frequency and intensity due to climate change are a key question posed by regulatory bodies, which partially reflects the fact that this is a problem which catastrophe models are ideally suited to address. The hazard portion of a catastrophe model is a database of hypothetical events and their associated frequencies, which may be constant or vary by event, to produce a hazard distribution that matches the historical record. Manually adjusting the frequencies of these events, or resimulating event catalogs by resampling, is a comparatively straightforward exercise that allows for exploring a range of frequency and intensity change scenarios.

Unfortunately, frequency is one of the areas of hurricane science where immediate climate-related impacts are least clear. Even at a global scale, there is credible disagreement even on the direction of potential frequency changes, much less the magnitude of those changes (Knutson et al. 2020; Lee et al. 2020). In the insurance industry, tropical cyclone risk is not managed at the global scale, but rather based on landfall frequencies at the country scale. In the case of the US, landfall frequencies are further downscaled to a regional scale, with loss tolerances designed to maintain capital adequacy around specific regions like the US Gulf or Northeast. Projecting future changes in frequency of hurricane landfalls at the scale of a few states at sub-decadal time scales lies well beyond the current state of climate science.

Wind intensity

Much like frequency changes, catastrophe models are suitable tools to assess the impacts in changes in intensity. Across a large stochastic catalog of hypothetical events, intensity changes can be alternatively interpreted as a change in frequency. For example, a 5% increase in the intensity of a 100mph hurricane could instead be thought of as an increase in the frequency of 105mph events, shifting the entire probability distribution of hurricane intensities towards stronger events.

Changes in intensity are less useful without an understanding of how that change is distributed across the spectrum of storms. Intensity changes are often reported as a mean change across all storms, either globally or within individual basins (Knutson et al. 2020). But an increase in intensity concentrated in low category storms would have a very different loss distribution than a similar change among stronger storms - building codes along the coast typically are designed to protect at least against weaker storms, but lower category storms are much more frequent than more intense ones. Catastrophe models could assess competing influences on loss with a change in intensity distribution, but a flat change across all storms may be less applicable to risk management.

Wind risk management strategies

The limited forward-looking skill in hurricane frequency projections and comparative lack of detail in intensity projections pose a challenge to risk modelers. Even when the scientific community can make reasonable frequency projections for global tropical cyclone activity, that skill typically declines when extrapolated to a single basin. And importantly, basin activity does not cause property damage – landfall statistics are the ultimate measure of real wind risk to an insured portfolio. However, these limitations do not mean that insurers lack tools to manage future hurricane wind perils.

A key consideration for insurers involves assessing which parts of the historical record should be included when determining *current* frequency distributions. In the North Atlantic hurricane basin, much of this debate centers on the application of a correction to account for Atlantic multidecadal variability, a pattern which strongly influences hurricane activity via increased sea surface temperatures, decreased sea level pressure, and reduced vertical wind shear in the tropical Atlantic (Goldenberg et al. 2001), and which is correlated with greatly increased frequency of major hurricanes (Klotzbach et al. 2015), but may not actually represent a physical oscillation with any predictive skill (Waite et al. 2020; Mann et al. 2021). Catastrophe models have the option to represent hurricane frequencies associated with the positive phase of the AMO, such as by producing medium-term forecasts or conditioning frequencies on observational periods in the same AMO phase rather than the full historical record, but usage of these views would be complicated if the Atlantic multidecadal variability lacks forward-looking skill.

Accounting for the degree of historical human influence on hurricane frequency is controversial as well. Sea surface temperatures are unlikely to return to their preindustrial state any time in the near future, but does removing older storms limit the view of internal variability? In the Atlantic, the 1960s-1980s experienced a low number of hurricanes, but was this driven by anthropogenic aerosol pollution (Murakami et al. 2020) that is not expected to return? Even if reasonable projections of basin-scale event frequency can be made, can we disentangle the influence of sub-basin processes like wind shear patterns, which may materially modify landfalls (Kossin 2017) in ways that may not stay consistent with future climate change (Ting et al. 2019)? Quantifying the climate change impacts that have already occurred through the last century is key for understanding what baseline to use for current and future wind risk.

Although a consensus on future changes in frequency is lacking, modeling is more consistent in predictions for the most intense storms - generally producing an increase in the proportion of the most intense storms (Category 4-5 storms or Category 3-5, depending on the study), with an increase in absolute number in all but those models where an overwhelming decline in total storm number overwhelms the increasing proportion of stronger storms (Knutson et al. 2020). Furthermore, there is evidence that this trend is appearing even in recent historical records in the Atlantic (Kossin et al. 2020), which may reflect a blend of natural and climate variability, but places the change within the time frame that is most relevant for insurance analytics.

While major hurricanes make up a small fraction of total storms, they contribute disproportionately to damage and loss. Estimates that account for inflation, population, and growth of wealth arrive at roughly 80% of all US hurricane losses coming from storms of Category 3 or above, even though they only account for about a third of US landfalls (much of the remainder comes from surge-heavy storms like Hurricanes Sandy and Ike). Similarly, the most intense Category 4 and above storms, which produce ~10% of US landfalls, are responsible for roughly half of all US hurricane losses (Weinkle et al. 2018). Furthermore, as the US population continues to concentrate in major coastal cities that are exposed to wind risk, losses will be compounded irrespective of any underlying climate trends. For insurers concerned about capital adequacy and near-term climate impacts, it is clear that climate sensitivity testing should focus on changes in high category hurricanes, where the science is comparatively clearer, and where changes in frequency can drive the largest potential impacts in losses.

The impact of large losses from major hurricanes on the US property insurance market is clearly visible in the Rate on Line index maintained by the broker Guy Carpenter (Guy Carpenter 2020). After a substantial spike in market prices for US property risk following the extremely active 2004-05 Atlantic hurricane seasons, there was a long decline that coincided with the US major hurricane drought (Hall and Hereid 2015). Market prices did not consistently reverse their trajectory until after the US major hurricane drought was broken in the 2017 Atlantic hurricane season.

These market fluctuations likely have a variety of causes, including a recency bias on the part of decision-makers. An increase in available capital competing for premium dollars, due to a lack of events requiring claims payments, was particularly important in the reinsurance and insurance-linked securities markets. There are disputes about how to define a major hurricane drought (Hart et al. 2016), and pressure may be a more consistent representation of a storm's damage potential than wind speed (Klotzbach et al. 2020), but however a major storm is defined, the comparative lull of the most intense US hurricane wind events clearly was associated with a long-term fluctuation in the US property insurance market. This substantial market impact was driven by a gap in intense hurricanes that likely occurred by chance, but changes in the background frequency of major hurricanes could change the odds that such a drought could recur in the future.

Changes in hurricane wind risk may threaten insurers from an operational and claims handling perspective as well. Rapid intensification is a particular threat, since it makes hurricane forecasting unusually difficult, is a key driver of major hurricanes (Lee et al. 2016), and may worsen with future climate change (Emanuel 2017b, Bhatia et al. 2019). From the perspective of a building, it doesn't matter how quickly a hurricane intensifies – damage is determined by the intensity of the local wind field. However, major insurers use track and intensity forecasts to position teams of claims adjusters in advance of a storm, and may bring in external contractors for repairs if the local labor market is unlikely to be able to be sufficient to support post-event rebuilding. Lack of predictive skill in rapid intensification may cause claims teams to underestimate the needed response, slowing claims handling or recovery due to underestimated pre-deployment. If the events that cause the most economic damage are the least predictable, that should be reflected in how insurers prepare to respond immediately before and after a hurricane makes landfall.

Hazard research opportunities

1. Localizing water impacts

Risk managers are charged with managing water risks at the spatial scale of individual locations. This means that spatially-averaged climate impacts on water hazards, like global sea level rise on storm surges, are less useful than detailed spatial projections. Gridded sea level products are starting to fill that gap. However, adding storm surge on top should ideally not behave like a bathtub, but rather reflect the changing hydrodynamics of surge with a new baseline, to better capture inland surge inundation.

As noted in the rainfall section, there is also some evidence for important impacts on hazard related to the presence of the built environment, such as extent of impervious cover. Cities pose the greatest potential for risk accumulation in a single event, so capturing these local-scale impacts on hazard is important to correctly represent risk where the exposed population is the largest.

2. Deeper understanding of tail wind impacts

As noted above, the highest intensity storms drive the overwhelming majority of economic losses from hurricanes in the US. However, the most extreme storms are also the most difficult to represent in climate models, making this a critical research target to quantify the most societally impactful risk.

3. Thinking beyond frequency

A variety of emerging research topics on wind risk have been proposed for hurricanes, including changes in rapid intensification (Emanuel 2017b), inland decay rates (Li and Chakraborty 2020), and track changes (Shuai and Ralf 2021). Many of these risks would have material impacts on property and life and safety risk without touching the frequency or severity of overall hurricane counts. Splitting hurricane risk by subperil highlights these emerging hurricane risk management topics, and although confidence is currently low, further research could help to explore ways that hurricanes may produce societal impacts in a more sophisticated way than simply checking if there will be more hurricanes or fewer.

4. Explicitly modeling impacts of green infrastructure on hazard

Catastrophe models have opportunities for enhancement that could make them more effective partners in climate adaptation. For example, interest has grown in recent years in "green infrastructure" to build coastal flood defenses against storm surge that utilize ecosystem services from mangroves, marshes, oyster banks, and the like to minimize surge damage. There is some evidence that these ecosystem services can produce material reductions in storm surge damage and losses, at times with clearly quantified economic benefits defined in the scientific literature (Narayan et al. 2017; del Valle et al. 2020; Reguero et al. 2021), but there are opportunities to further explore cost-benefit tradeoffs between mobile coastal wetlands compared with hard infrastructure like seawalls, which catastrophe models could be well-suited to address.

Catastrophe models in their present state are designed to reflect a snapshot of risk at a single point in time, so leveraging the time-varying development of coastal flood risk presents an opportunity to blend the strengths of both climate and catastrophe models. By quantifying expected annual losses associated with storm surges under different defense assumptions, a catastrophe model coupled with a probability distribution of sea level rise out of a climate model could put an explicit price tag on the choice of an effective but inflexible piece of gray infrastructure like a seawall, compared with a coastal ecosystem that perhaps does not stop every surge, but can dynamically respond to changing sea levels. Without such tools, hard coastal defense projects like seawalls that make sense with current sea levels cannot be sufficiently compared with mobile ecosystems like marshes, which may migrate inland without human intervention assuming no inland obstructions.

Similarly, a common way that cities attempt to reduce the impacts of increased extreme rainfall (from hurricanes or otherwise) is via green stormwater management – building in green spaces, rain gardens, and other strategies to reduce impervious surfaces, absorb excess rainfall, and minimize flood peaks. Despite clear benefits to flood risk, with knock-on improvements in groundwater storage and other ecosystem services (Prudencio and Null 2018), catastrophe models generally lack the ability to explicitly give credit for the risk reduction produced by these activities, which could perversely disincentivize this key adaptation strategy, since local spending on risk reduction would not lead to a corresponding reduction in modeled loss impacts.

Recommendation 3 – Translating climate data for decision-makers

Time horizon

There has been a longstanding disconnect between the timing required to make decisions in a business environment in comparison with the time frames that generally receive the most attention in the scientific literature. The scientific community often focuses on the ~2050-2100 time frame, where climate impacts are more likely to have emerged from natural variability. At this time scale, anthropogenic forcing is large relative to natural variability, making trends and impacts on extreme events clearer. Conversely, the insurance business wants to know what to expect for the upcoming year, to correspond with the length of a standard insurance contract, up to perhaps a decade in the future, for its underwriting and portfolio management strategy. While insurers may do qualitative horizon-scanning exercises beyond this time frame to consider broader product strategy and emerging risks, quantitative risk assessment beyond the portfolio steering time frame have limited practical applicability in the insurance decision-making framework. This time frame is heavily impacted by interannual and decadal scale variability, where predictive skill in climate models is low, so at first glance it is difficult to give clear guidance. Similarly, seasonal and sub-seasonal forecasting is available that relies heavily on climate features like El Niño/La Niña, but for contracts that are written to cover an entire year, the relative benefit to insurance companies of adjusting their risk appetite to match a forecast at the current level of forecast skill is marginal (Emanuel et al. 2012).

However, this view does not consider that the models used to manage risk are built using historical data. While recent events are included in regular catastrophe model updates, these models also include events from past decades that occurred in a climate that will not return within the next century. A key potential space to incorporate climate risk comes from understanding how much change in hazard has already occurred relative to a historical dataset that may span up to the last 50-100 years. Trends in extreme hazards like hurricanes represent a complex mix of internal natural variability, potentially short-term external forcings like aerosol pollution, and long-term anthropogenic climate change, so disentangling the influence of each for various hurricane subperils would help risk managers to account for trends in historical data while preserving as much of the distribution of natural variability as possible. For example, catastrophe models are not limited to only using storm surges within the last few years, even though sea levels have risen throughout the full historical record. By extracting the component of historical storm tides that came from wind only, the full distribution of historical surge events is preserved, and then added on top of current sea levels. This explicitly accounts for known climate trends up to present while still leveraging the full variability present in over a century of historical data. In this sense, attribution exercises that quantify how much climate change has impacted individual recent storms or trends in events is highly valuable within the insurance sector, since they can then be explicitly modeled while preserving a historical statistical distribution that better captures decadal-scale natural climate variability.

Selecting an appropriate time horizon for risk assessment has also emerged as a concern for climate risk disclosure in the regulatory space. Different parts of the public and private sector have different risk tolerances and planning horizons. Insurers tend to focus on immediate and short-term quantitative climate impacts, because their risk is driven by extreme events like hurricanes, more than changes in mean conditions that are better understood at longer time periods. Infrastructure planners may also need to think about extreme events, such as when designing a seawall for future storm surges, but the design lifetime of a structure is much longer than an annual insurance contract, which can be adjusted dynamically as new climate risks emerge. Even within infrastructure planning, a nuclear power plant likely has a lower tolerance for a failure in hazard defenses than a local street. A risk management framework that includes (1) critically assessing the time scale at which material climate risks emerge, (2) cumulative tolerance for negative outcomes, and (3) the ability to adjust as the climate changes is a useful thought exercise for determining climate risk tolerance both within and outside of the insurance sector.

Within insurance, the short-term, quantitative assessment of climate risk can be supplemented by longer term, qualitative analysis of emerging risks and mitigation that are poorly captured in current tools. For example, it is likely that building codes will continue to improve in the face of more destructive hurricanes, but predicting the timing and magnitude of these reductions in building vulnerability is not currently possible, lowering the skill of long-term projections in hurricane economic losses. These differing levels of skill at different time horizons must also be clearly articulated in the regulatory space, to avoid counterproductive or maladaptive decision-making driven by quantitative modeling at longer time horizons that exceed scientific knowledge.

Risk metrics

Climate risk has often been treated as a type of emerging risk within the insurance sector, with a focus on exploratory scenarios that are designed to highlight potential impacts across different parts of the business (underwriting, investments, regulatory risk, etc.). While such scenarios are valuable in assessing broad-scale, interconnected risks at longer time scales, they have limited utility in active decision-making. A hypothetical scenario with a 50% increase in major hurricanes may appear alarming to a risk manager, but without a clear and short-term time frame for when such a change could be expected, it is difficult to justify making immediate adjustments to a portfolio of risks.

More valuable information from a risk management perspective comes when climate risk is translated to use the same risk metrics that are used in portfolio steering. This "normative approach" designs climate sensitivity tests around common business goals like profitability or maintaining sufficient capital (Rye et al. 2021). Rather than framing climate testing as an assessment of business impacts for a given amount of climate change, this approach allows risk managers to the question around, and instead run negative stress tests to determine what level of climate impact would be sufficient to affect the risk appetite of the business.

The insurance industry uses a wide range of metrics to plan for risk appetite, but some of the most common are tail risk metrics, expected losses, historical events, and extreme disaster scenarios (Rye et al. 2021). Tail metrics might include probable maximum loss (PML), a representative large loss at a low expected frequency such as a 100 year or 250 year return period, or tail value at risk (TVaR), the average of all losses above a given return period. In the insurance industry, tail metrics are often used to assess capital sufficiency, to ensure that enough reserves are held to pay claims after large events, and they are key drivers of an organization's risk tolerance. Expected loss, or average annual loss (AAL), is the amount of loss that occurs each year on average over a long period of time, which insurers must cover with premium revenue to maintain long-term profitability. Historical events and extreme disaster scenarios both represent known loss values, which can be used as standalone scenarios, or companies can use frequency to assess risk tolerance - for example, how often the company could sustain a Hurricane Andrew-level loss, or a Category 3 hurricane in New York City.

The value of a climate management approach driven by traditional risk metrics is that it drives climate risk into the language used by risk managers across the insurance industry. Climate science is no longer limited to the domain of scientific technical experts. As climate impacts move further into the broader society, the role of translation - tracking and understanding the rapidly evolving scientific literature, contextualizing the level of uncertainty, and turning climate hazards into decision-relevant metrics - will spread further into more climate-affected industries. Insurance offers an opportunity to set a clear example for how to turn science into decision-relevant data for practitioners throughout the economy.

Translating impacts research opportunities

1. Hazard assessment at a wider range of time horizons

Decision-makers on the ground who will be directly impacted by climate change, be it insurance companies, city planners, commercial risk managers, or homeowners taking out a mortgage, do not have the luxury of waiting until 2100, when climate forcings are large enough to see clear signals emerge far beyond natural variability. Particularly for rare events like hurricanes, even large trends can take decades to emerge from historical records that feature substantial multidecadal variability, as has been the case in the literature looking at historical trends in major hurricanes (Vecchi et al. 2021).

Therefore, the end-users of hurricane climate information would greatly benefit from added research activity in the messy present. This is not a call for seasonal or decadal forecasting, per se, but rather a more robust quantification of how much change seen to date is driven by anthropogenic forcing, compared with how much can be confidently attributed to natural variability.

2. Engagement with end-users on time horizons and metrics

This discussion highlights key time horizons and metrics that are widely used in the insurance sector, but other climate data end-users are likely to have different needs. Infrastructure or city planners may want to look 50-75 years in the future, and a mortgage holder may want to understand their cumulative flood risk over the next 30 years. The work of engaging with climate data services end-users is slow and has struggled to gain priority from an incentives standpoint (funding, advancing toward tenure, etc.). Enhanced interaction with social scientists may help improve communication and co-development of climate analytics between the academic, public, and private sectors (Findlater et al. 2021).

Conclusion

In this article, I have presented three recommendations for how to leverage the capabilities of catastrophe risk management for dealing with climate change impacts on hurricane risk:

1. Risk modelers need to bring more data about the built environment to the table to meaningfully model emerging climate risks, particularly for water subperils like storm surge and inland rainfall. The substantial gaps in capturing the built environment in the climate modeling space shines a bright light on one of the most important contributions that catastrophe models could make to capturing future societal impacts of climate-driven hurricane risk.

2. The unbundling of hurricane hazards into subperils that can be assessed for relative confidence in their intersection with broader climate trends offers a model that could be widely applied to other emerging climate hazards, like flood and wildfire risk. Where climate hazard confidence is higher, such as sea level rise, the near-term impacts on hurricane subperils like storm surge are clear enough that further dissecting of uncertainty will not fundamentally alter what is now a risk management and policy problem (Sobel 2021). However, lower confidence but high severity impacts like changes in hurricane frequency can be explored through sensitivity testing, and prioritized by their downstream societal and economic impacts.

3. Finally, incorporating climate science into catastrophe modeling is a clear case study highlighting the value of “climate translators” in the private sector. Calls for climate risk disclosure have leapfrogged the abilities of climate models (Fiedler et al. 2021), but that does not mean that climate models have nothing to offer the risk management community. Instead, emerging climate risks in hurricane risk management will require both climate scientists and catastrophe modelers to better understand the strengths and limitations of each other’s data and toolkits. Translating climate science into actionable information for end-users is critical across the public and private sectors to help society adapt to the inevitable climate challenges to come.

The entire economy will have to grapple with the ongoing impacts of changes in extreme events like hurricanes. Insurance risk managers can leverage their decades of experience in working with models designed to quantify society’s most extreme natural hazards, which will bring valuable leadership to the private sector response to climate change. The resources and expertise in the catastrophe risk management community are a key investment toward greater societal resilience in the face of climate change.

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