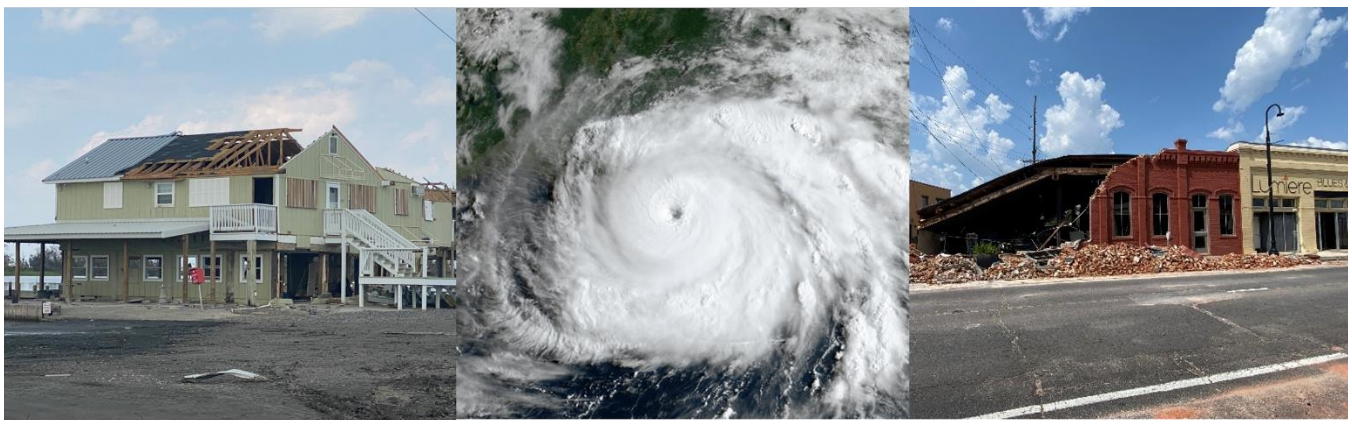
KCC WHITE PAPER

Climate Change Impacts on Hurricanes and Insured Wind Losses



November 2021

The Innovation and Technology Leader in Catastrophe Risk Modeling

Document Date

November 2021

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White Paper Highlights

(Re)insurers are now able to explicitly account for climate change in their risk-based decisions if the catastrophe models they use for pricing, underwriting, and portfolio management incorporate the impacts of climate change to date and provide credible views of potential future impacts. In order to make informed decisions, (re)insurers require clear information on the extent climate change has been reflected in their current catastrophe models and how the best available science on climate trends can be quantified in future scenario models.

This white paper explains climate change impacts on hurricanes, illustrates the portion of climate change that has already been observed relative to future projections, and quantifies what this means for insured wind losses. Highlights of this white paper include:

- The average global temperature has already increased by 1.1°C relative to the 1850 to 1900 average.
- Tropical cyclone intensity has increased with the warming climate, leading to a shift toward a higher proportion of major hurricanes—Category 3-5 on the Saffir-Simpson scale.
- This shift in hurricane intensity has likely already led to an increase in insured losses of about 11 percent above what the loss potential would have been in the absence of climate change.
- Global temperatures are projected to increase by an additional 0.4 to 1.3°C by 2050 depending on the emissions scenario.
- Average annual hurricane wind losses will increase an additional 10 to 19 percent by 2050 depending on the emissions scenario, but the increases will be larger for the lower return period losses on the Exceedance Probability (EP) curves and slightly less for the high return period losses.

Introduction

In recent years, a consensus has formed within the scientific community that the warming climate has led to increased tropical cyclone intensity. While the total number of tropical cyclones has not changed significantly, the global proportion of major hurricanes—tropical cyclones that register as Category 3-5 intensity on the Saffir-Simpson scale—has increased over the past several decades. This trend is projected to continue into the future with the magnitude of the increase driven by future increases in global temperatures.

Hurricanes are categorized by their extreme, damaging wind speeds and can also lead to extensive damage through flooding, both coastal flooding from storm surge and inland flooding from excessive rainfall. Each of these three perils—wind, storm surge, and inland flooding—has a unique physical response to global climate change. Winds increase with warming sea-surface temperatures (SSTs), storm surge is augmented by rising sea levels, and precipitation rates increase in response to warming air temperatures.

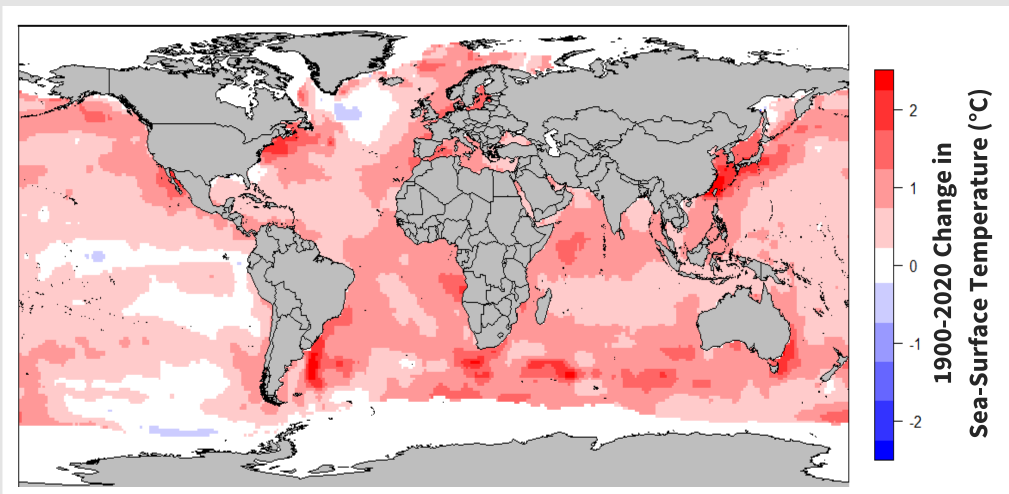
The KCC US Hurricane Reference Model Version 3.0 incorporates the impacts of climate change on these physical responses and provides insured losses from all three hurricane perils given a warming climate. The effects of climate change—both past and future—on the wind peril, with a specific focus on the North Atlantic basin, are described in this white paper.

This white paper explains the scientific theory behind increasing tropical cyclone intensity along with how recent data analyses are now confirming the theory. It also illustrates how the KCC US Hurricane Reference Model Version 3.0 incorporates climate change to date and provides future climate scenarios for 2025, 2030, and 2050.

Climate Change Impacts on Tropical Cyclone Activity: The Theoretical Basis

There is a strong theoretical basis for expecting an increase in the most intense tropical cyclones in a warmer global climate. Warm SSTs provide energy to developing hurricanes over open water, acting as "fuel" for the hurricane "engine". This energy is provided to the hurricane in the form of increased heat and evaporation from the ocean's surface.

Climate change has caused an observable increase in global SSTs, including in the tropics where tropical cyclones typically form. Warming SSTs are not uniform across ocean basins, however, as some areas have warmed faster and some slower than the global trend as the map below shows.



Trend in observed sea-surface temperatures (1900-2020).

SSTs off the eastern coasts of nearly all continents have been warming faster due to shifts in western boundary currents. These are strong midlatitude ocean currents that exist along the western edges of each ocean basin, carrying warmer tropical waters along the coast from the equator towards higher latitudes. Observations indicate that these currents have intensified or shifted toward higher latitudes, leading to SST trends that outpace the global mean trend.

On average, global SSTs have warmed by 0.9°C since 1900, but there is geographic variability in the trends by basin.

Off the northeastern coast of the United States and in the waters surrounding Japan, for example, SSTs have increased nearly 2.5ºC, well above the global SST trend. In contrast, over the high latitudes of the North Atlantic, SSTs have warmed slower or even decreased in response to melting glaciers, which supply cooler waters to the ocean south of Greenland.

Recent studies have also demonstrated an overall weakening of the large-scale Atlantic currents that cycle warmer water northward from the tropics into the North Atlantic. These factors have contributed to a slower overall warming trend in some areas of the tropical North Atlantic, despite the intensification in western boundary currents.

The tropical Atlantic and Gulf of Mexico, where Atlantic hurricane formation and intensification primarily occur, have warmed about 0.5ºC since 1900, indicating the response in North Atlantic hurricane intensities to climate change could differ from the global average.

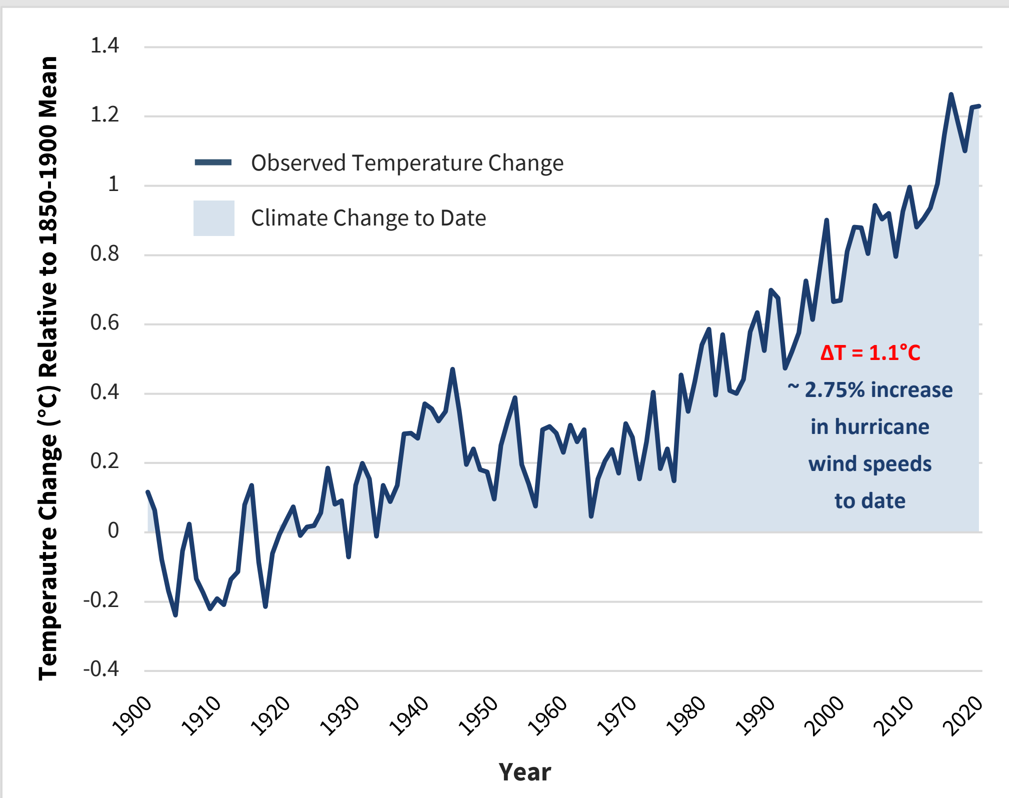
While the intensities of hurricanes increase in response to warming SSTs, the overall frequency of hurricanes depends more on aspects of the atmospheric environment, including the stability of the atmosphere, the vertical wind shear, and the amount of moisture in the mid-levels of the atmosphere. Trends in some of these factors due to climate change act to promote tropical cyclone formation while others work against it, and global datasets and model output do not generally agree on the recent trends.

As a result, the consensus among scientists is that there has been no trend in tropical cyclone frequency due to climate change.

Quantifying Climate Change Impacts

According to the scientific consensus, we have already seen a 1.1°C increase in global surface temperature including both land *and* ocean when compared to the 1850-1900 average, which is slightly higher than the 0.9°C trend in global SSTs. SSTs tend to warm more slowly than land temperature due to the higher heat capacity of water relative to land and the ocean's ability to counteract the warming with increased evaporation.

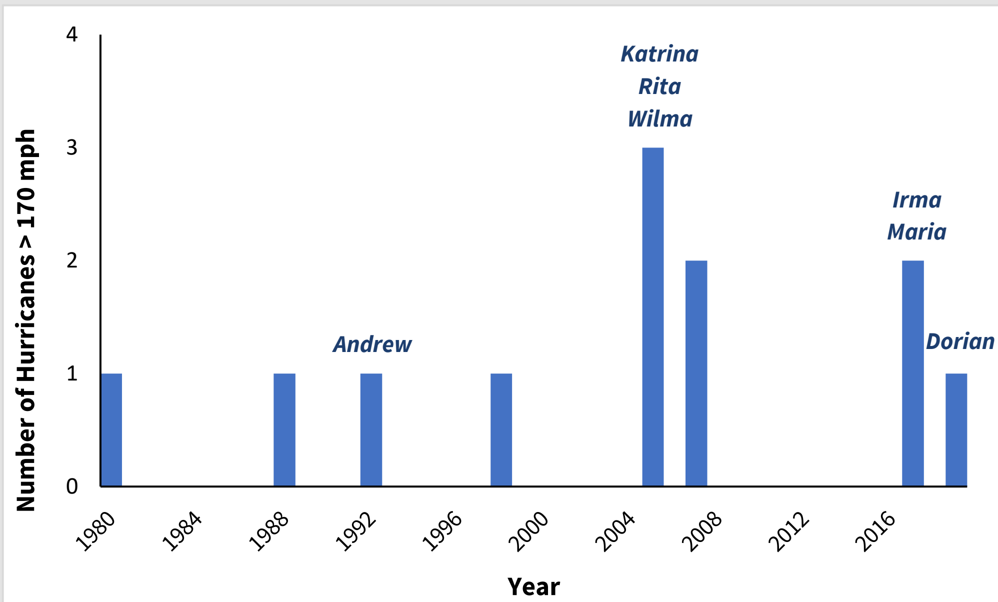
The most recent report, AR6, from the Intergovernmental Panel on Climate Change (IPCC) states that a global surface temperature increase of 1°C likely leads to a 2.5 percent increase in hurricane wind speeds. This implies that global hurricane intensity may have already increased up to 2.75 percent due to warming global temperatures since 1900.



IPCC AR6 observations of global surface temperature change.

Because the force applied by wind on structures increases exponentially with the wind speed, insured property losses respond non-linearly to an increase in hurricane intensity. Sensitivity studies show that a two percent increase in wind speeds leads to a 10 to 12 percent increase in losses, for example.

There is observational evidence of an increase in hurricane intensities in the North Atlantic basin. For example, there have been eight hurricanes with peak wind speeds exceeding 170 mph in the past 20 years, but only four during the preceding two decades. Recent intense hurricanes in the North Atlantic include several landfalling storms, such as Katrina, Irma, and Dorian. Dorian made landfall in the Caribbean at its peak intensity while other intense hurricanes weakened prior to landfall.

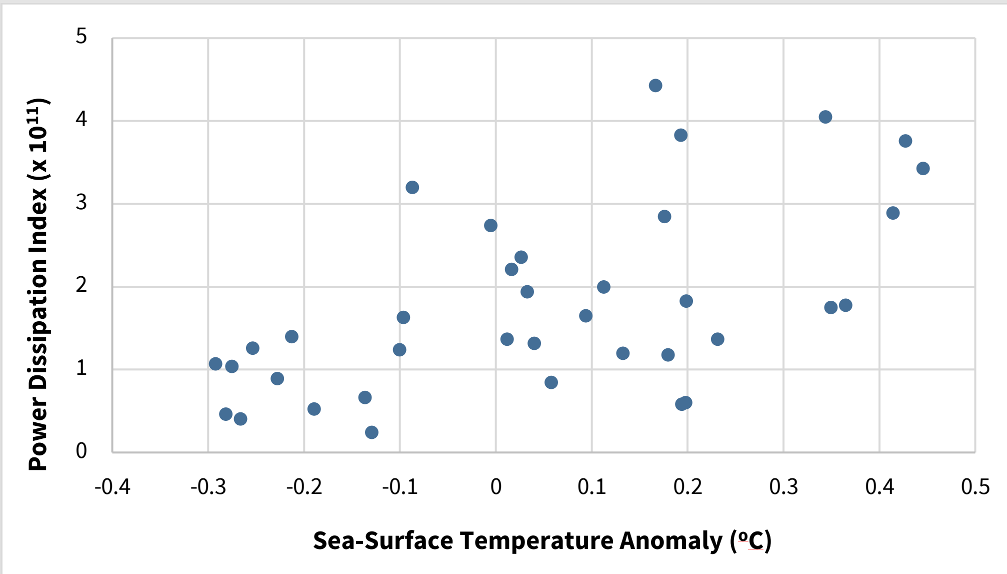


Occurrences of intense Category 5 hurricanes with peak wind speed >170 mph.

Academic studies of hurricanes in the North Atlantic and other ocean basins tell a similar story. Elsner et al. (2008), for example, identified a global increase in the highest wind speed intensities using satellite-derived wind speed data, but identified large variations in the intensity trend across individual basins.

One of the first analyses of trends in North Atlantic hurricanes, Emanuel (2005), made use of a metric of intensity called the Power Dissipation Index (PDI). The PDI, which is proportional to the cube of the maximum wind speed in a hurricane, is a direct measure of overall hurricane intensity and can be applied to a single event or used to summarize the amount of hurricane activity in an entire season.

The Emanuel study further demonstrated that increased PDI has a direct relationship to warming surface temperatures. KCC scientists confirmed this in the plot below, showing PDI in the North Atlantic Basin is observed to be generally higher when surface temperatures, specifically SSTs, are warmer.



Positive relationship between North Atlantic basin June-October SST and PDI. Each dot represents an individual year.

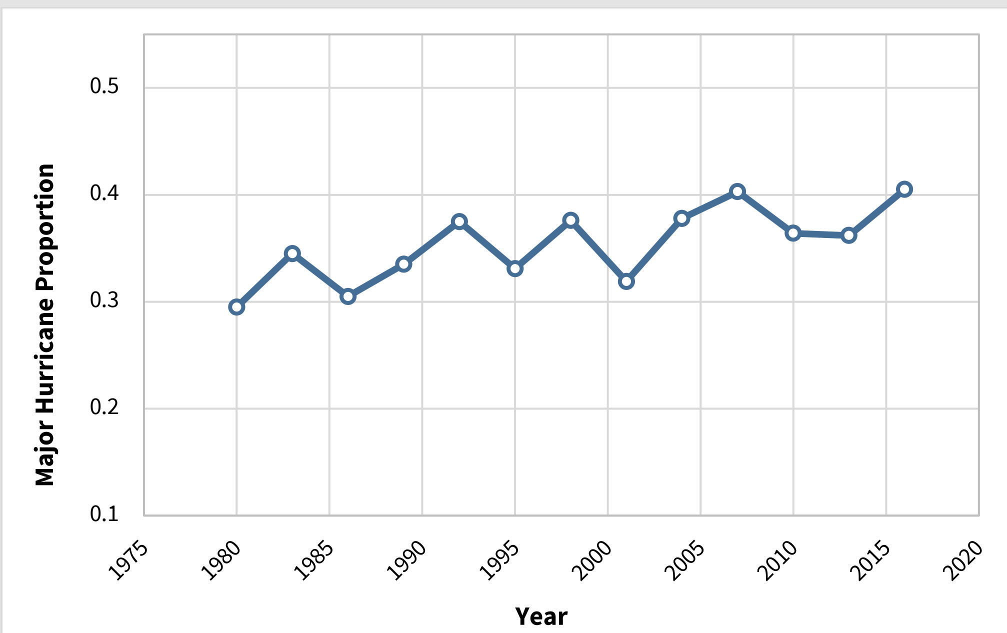
The relationship between SSTs and hurricane intensity has been well studied, but detecting and *quantifying* the changes in hurricane intensity using observational data has been challenging due to the short length of global data records and the large amount of year-to-year variability in hurricane activity. The Hurricane Satellite dataset (HURSAT) now includes data from a time period of nearly 40 years, improving scientists' ability to test the effects of climate change on hurricane intensity.

HURSAT consists of location and intensity information estimated using the Advanced Dvorak Technique for the lifetimes of all tropical cyclones in all basins. This method involves estimating intensity from differences in cloud-top temperatures, which can be measured remotely, meaning that the length of record is limited only by the availability of geo-stationary satellite data, going back to the late 1970s.

Importantly, HURSAT data have been estimated for all tropical basins using a consistent methodology. This allows for analysis of climate change impacts on hurricanes on a global scale, reducing the influence of trends in hurricane activity within individual basins which can result from natural atmospheric cycles, e.g. the Atlantic Multi-decadal Oscillation (AMO) and El Nino-Southern Oscillation (ENSO). With the expanded data record, the warming climate signal in hurricane severity has started to emerge in the global HURSAT dataset.

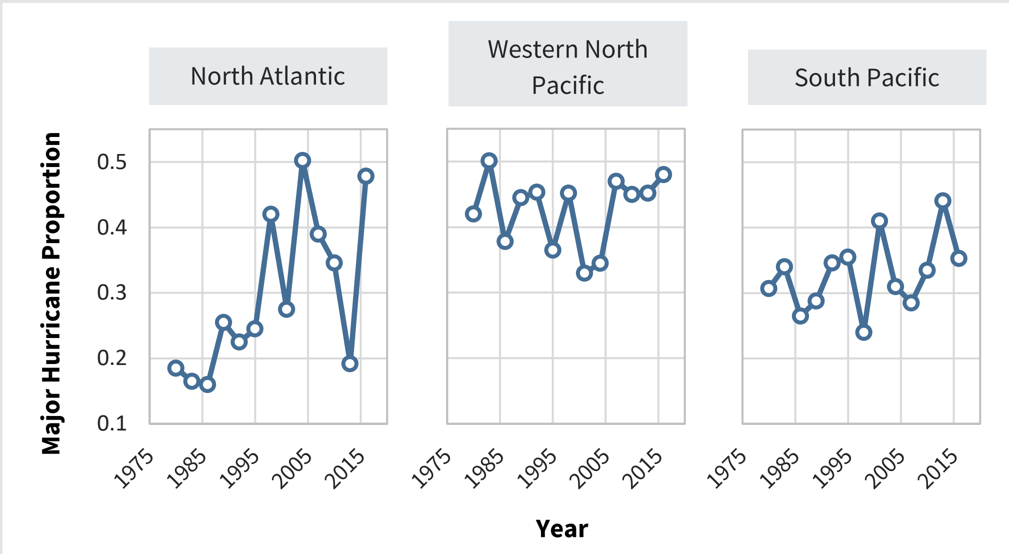
Kossin et al. (2020) used HURSAT data to analyze the historical trend in global hurricane intensity back to 1980 (see plot below). Their analysis identified a shift towards higher hurricane intensity over the past several decades. The global shift can be understood as an increase in the proportion of major hurricanes at the expense of the weaker storms.

More specifically, scientists have found an increase in the proportion of hurricanes that reach major hurricane intensity (Category 3-5) and a relative decrease in the number of weaker (Category 1-2) hurricanes.



Global proportion of major hurricanes (Category 3-5) in observed data, adapted from Kossin et al (2020). Each dot represents a three year average.

While 40 years of data is sufficient to have increased confidence in the global hurricane intensity trends, there is greater uncertainty in individual basin trends, as the plot below demonstrates.



Proportion of major hurricanes (Category 3-5) in observed data for North Atlantic, Western North Pacific, and South Pacific basins, adapted from Kossin et al (2020). Each dot represents a three year average.

For the North Atlantic basin specifically, the shift to the warm phase of AMO in the mid-1990s influenced an increase in the proportion of major North Atlantic hurricanes. The effects of natural variability, such as the AMO, make it difficult to separate the comparatively long-term trends of *global* climate change from *basin-specific* multi-decadal oscillations.

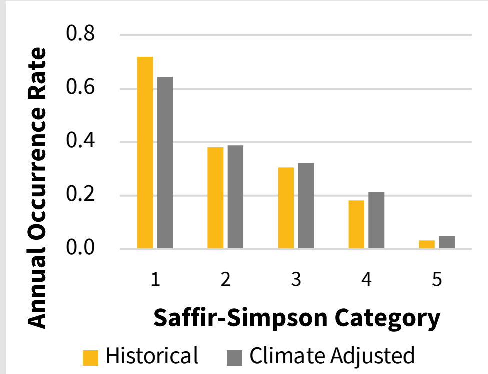
To construct a catalog of US landfalling hurricanes that accounts for climate change to date, KCC scientists used the global trend calculated from the HURSAT data so the signal of climate change can be isolated from the basin-specific, natural climate oscillations. The global trend is quantified by applying quantile regression analysis to the HURSAT dataset. Quantile regression measures trends in the proportion of hurricanes in different intensity bins, revealing the wind speeds that are changing the most and least.

In accordance with the results of the quantile regression analysis, the maximum sustained winds for historical storms are adjusted to the higher intensities they would reach if they had all occurred in the current climate. The process is similar to trending past losses to what they would be today to account for inflation and population growth.

The proportion of major landfalling hurricanes in the US since 1900 increases from 32 percent using the unadjusted historical data to 36 percent when global climate trends are taken into account.

Proportion of Landfalling Hurricanes

	Non-Major	Major
Historical	68%	32%
Adjusted for global climate trends	64%	36%



Proportions of major and non-major landfalling hurricanes for the historical data versus a catalog adjusted for global climate trends.

While the HURSAT dataset includes a long enough period of record to detect a statistically significant trend in hurricane intensities, substantial uncertainty still exists surrounding the exact magnitude of the increase and how individual basins have responded to past climate trends. In consideration of this uncertainty and the observation that trends in the North Atlantic may be less pronounced than the global trend, the KCC US Hurricane Reference Model Version 3.0 incorporates a blended view of the pure historical and the climate adjusted catalogs.

The impact on insured losses is about an 11 percent increase relative to a model based purely on the historical data.

KCC scientists believe this is a credible view of insured losses that should form the foundation for current risk management decisions.

Implementing Future Climate Change Scenarios

The KCC US Hurricane Reference Model already accounts for the shift in hurricane intensity and resulting increase in insured losses caused by climate change to date. Updates to the model will continue to capture the evolving changes in the climate. Additionally, KCC scientists have created several catalogs reflecting various future time periods and emissions scenarios.

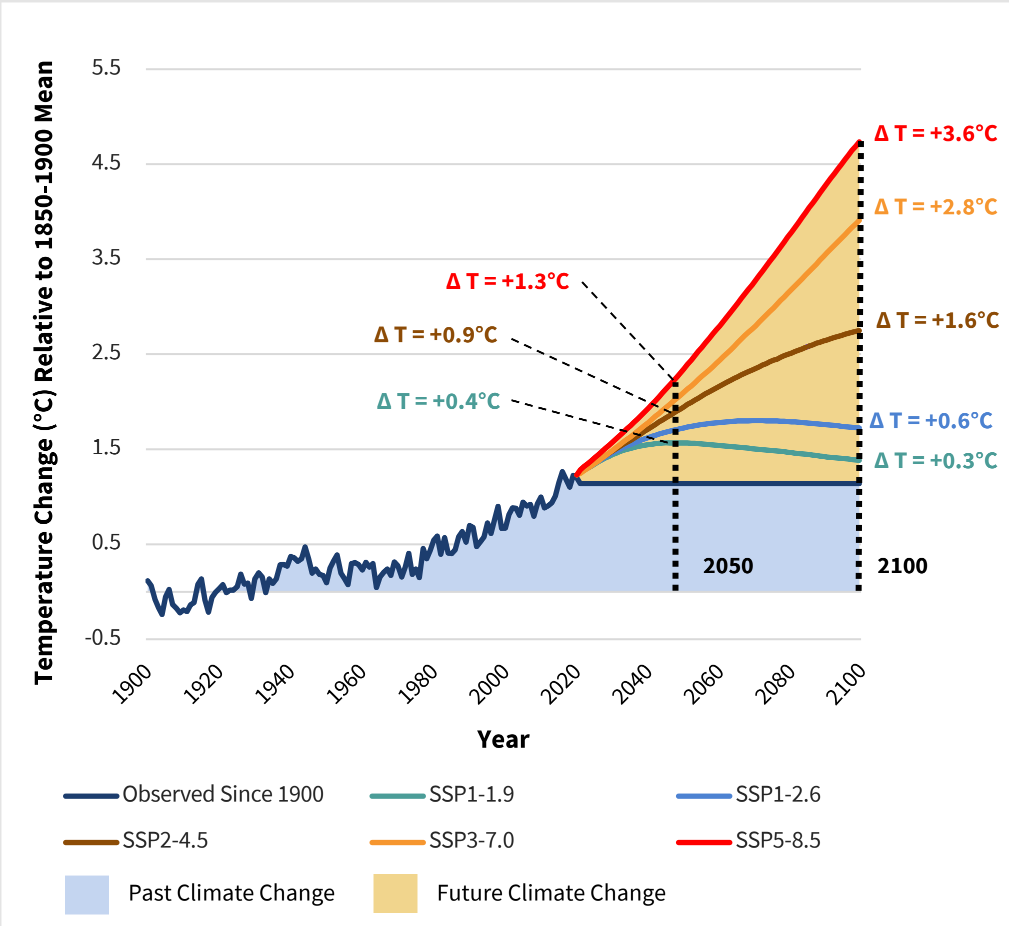
The amount of warming projected for the coming decades depends in large part on the future emissions of greenhouse gases which in turn depend on the actions of governments and societies. In the new AR6 report, the IPCC provided Shared Socioeconomic Pathways (SSPs) to represent potential future scenarios.

The SSP scenarios, outlined in the table below, represent future emissions scenarios based on socioeconomic change, with SSP1-1.9 representing the best-case scenario and SSP5-8.5 representing the worst-case scenario. The numbers in each scenario represent the radiative forcing in Watts-per-meters-squared (W/m^2) in the year 2100. Radiative forcing is a metric of the increased energy that accumulates in the Earth's atmosphere due to the greenhouse effect, which acts to warm the Earth's surface.

Scenario	Radiative Forcing (W/m^2)	SSP Assumptions
SSP1-1.9	1.9	Global shift toward environmentally sustainable economic growth. Significantly and rapidly reduced per capita energy consumption, reaching net zero emissions by 2050.
SSP1-2.6	2.6	Global shift to sustainability and emissions cut significantly to net zero by 2050, but at a slower rate than SSP1-1.9 leading to a larger radiative forcing.
SSP2-4.5	4.5	Largely business-as-usual with regard to technological advancements and economic growth, with slow progress toward sustainability goals.
SSP3-7.0	7.0	Increased global competition and a shift towards national security and resource stockpiling, leading to significant increase in emissions from modern level.
SSP5-8.5	8.5	Rapid global economic growth supported by heavy investment in fossil fuel energy.

Shared Socioeconomic Pathways (SSPs) provided in the IPCC AR6 report.

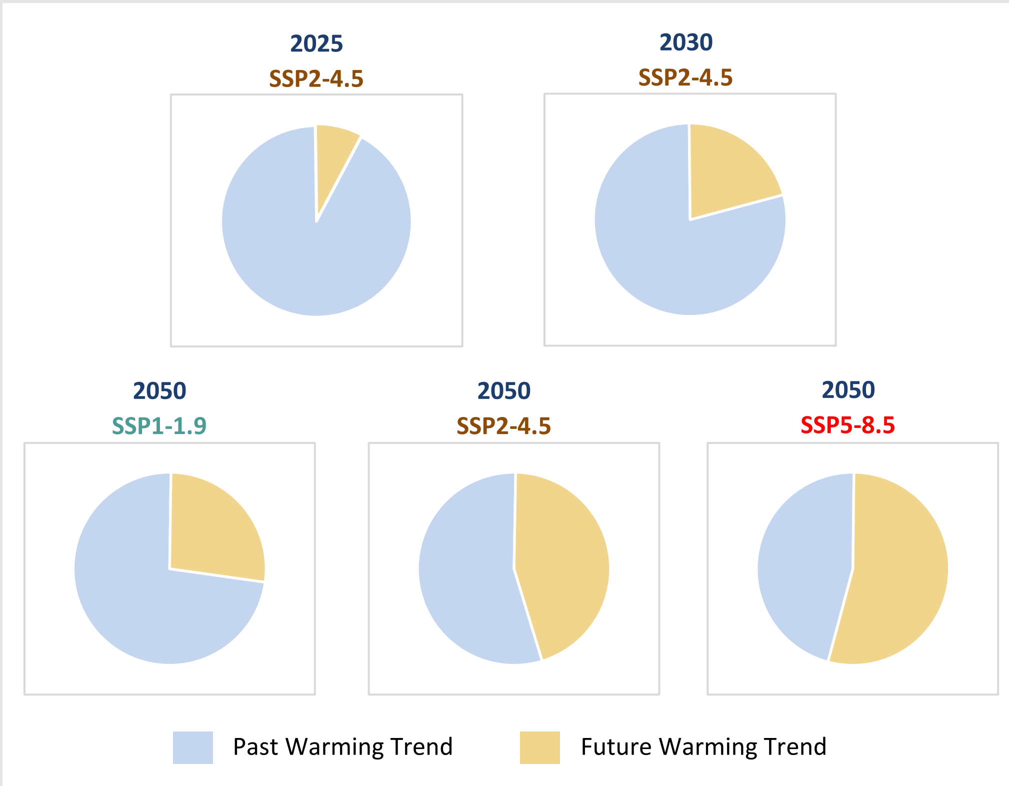
The resulting global surface temperature projections for each scenario relative to what has already been observed are demonstrated in the figure below. The projected future increases in global surface temperature are in addition to the observed 1.1°C trend through 2020.



Observations and IPCC AR6 projections of global surface temperature changes.

Temperatures are projected to warm between 0.4°C in the low emissions scenario and 1.3°C in the high emissions scenario between 2020 and 2050. After 2050, warming is projected to accelerate in the high emissions scenarios. Interestingly, the more optimistic SSP1-1.9 and SSP1-2.6 scenarios reach net zero emissions by 2050, which leads to a *reversal* in the warming trend by the late 21st century.

The relative proportions of past versus future climate change are presented in the figure below for three SSPs. In the low and middle emissions scenarios, past climate change comprises the majority of the projected warming between 1900 and 2050. Only in the SSP5-8.5 scenario does future warming between 2020 and 2050 outpace the warming that has already occurred since 1900.



Proportion of past versus future warming trends.

To project the impacts from the various scenarios on hurricane intensity, KCC scientists developed the Future Climate Catalogs (FCCs) based on three of the SSPs: best case (SSP1-1.9), middle-of-the-road (SSP2-4.5), and worst case (SSP5-8.5) emissions scenarios. The KCC FCCs were developed for 2025, 2030, and 2050 to provide decision makers with near- and long-term views of risk from climate change.

The table below illustrates the expected changes in temperature and hurricane wind speeds for the nine scenarios. Projected wind speed changes are consistent with the 2.5 percent increase in wind speeds per 1°C of global surface temperature warming, as per IPCC projections.

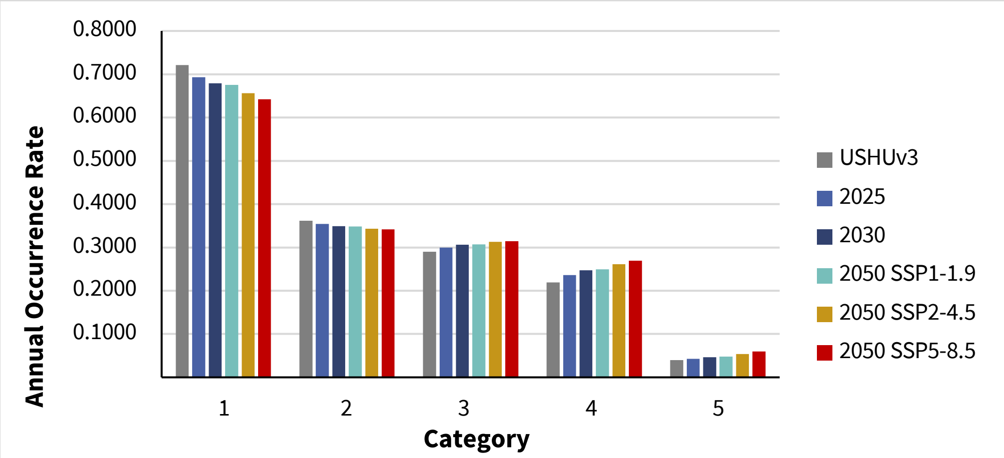
	Temperature Increase Relative to 2020 (°C)			Wind Speed Increase Relative to 2020 (%)		
	2025	2030	2050	2025	2030	2050
SSP1-1.9	0.1	0.3	0.4	0.25	0.75	1.00
SSP2-4.5	0.1	0.3	0.9	0.25	0.75	2.25
SSP5-8.5	0.2	0.5	1.3	0.50	1.25	3.25

IPCC AR6 projections of global surface temperature change and resulting increases in hurricane wind speeds relative to 2020.

While the degree of future warming is dependent on the emissions scenario, all cases project a continuation of rising temperatures and as a result, a continuation of the observed shift toward higher proportions of the more intense, major hurricanes.

To emulate this shift using the US Hurricane Reference Model Version 3.0 stochastic catalog, KCC scientists modeled the shift in intensities in the FCCs using projected increases in seasonal PDI for each scenario and timeframe. The projections of global temperature for the different scenarios do not diverge significantly until after 2030, meaning a single climate scenario is sufficient to represent each of the projected climates for 2025 and 2030.

The 2050 timeframe is separated into the three SSPs to provide a full spectrum of climate change projections for the coming decades. When applied to the distributions of event wind speeds in the KCC US Hurricane Reference Model Version 3.0 (USHUv3), the projections lead to shifts in the model hurricane intensities as shown below.



Annual occurrence rate by Saffir-Simpson Category for each scenario.

With higher rates of major hurricanes in the FCCs, the set of possible events has expanded to account for new events that become probable under future warming climate. For example, a Category 5 hurricane with a large radius of maximum wind may have been too unlikely to be included in previous catalogs, but with a higher rate of Category 5 storms in a warming climate such an event could become frequent enough to warrant inclusion in a future climate catalog. Thousands of additional major hurricane events were added to the stochastic event set to expand the set of possible hurricanes in the KCC FCCs.

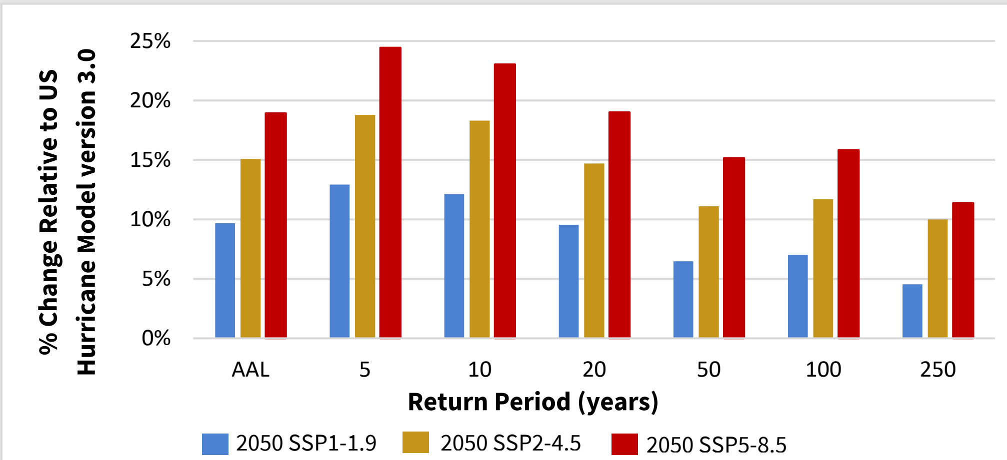
The proportion of major hurricanes in the 2025 FCC is about 36 percent, consistent with only a small change from the present-day baseline. Major hurricanes increase in proportion with each subsequent scenario, 37 percent by 2030 and up to 40 percent by 2050.

	Proportion of Major Hurricanes (%)		
	2025	**2030**	**2050**
SSP1-1.9	36	37	37
SSP2-4.5			39
SSP5-8.5			40

Proportion of major (Category 3-5) US landfalling hurricanes under various climate scenarios.

Impacts on Wind Loss Estimates

The graph below illustrates the impacts of the FCCs on the industry Exceedance Probability (EP) curve. Because climate change is causing a shift in hurricanes by intensity rather than a simple increase in frequencies of all intensities, the shapes of individual insurer and the industry curves are changing.



Percent increase in 2050 expected aggregate wind losses by return period in each FCC relative to KCC US Hurricane Reference Model Version 3.0.

Specifically, the lower return period losses are rising faster—on a percentage basis—than the longer return periods. The 1 in 5-year return period losses, for example, are projected to increase by almost 25 percent in the worst-case SSP5-8.5 scenario, while the 1 in 250-year return period losses increase by 11 percent.

The reason for the changing shape of the EP curve is clear. For the industry as a whole, for example, the 1 in 100-year hurricane loss is currently around $170 billion, but there are only two places along the coastline likely to experience that level of loss with a one percent probability—Miami and Galveston/Houston. A major hurricane striking New York City would also cause industry losses this high, but the probability of that occurring is much less than one percent.

On a probabilistic basis, opportunities for the "tail" losses are limited to specific locations. By contrast, an increasing frequency of major hurricanes all along the Gulf, Florida, and Southeast coastlines, and a lower proportion of weaker storms will increase the losses for many landfalling events all along the coast putting more upward pressure on the lower return period losses.

Summary and Conclusions

A scientific consensus has formed that tropical cyclone intensity is increasing due to global climate change. This is causing a shift in hurricane intensity away from the weak hurricanes and toward the more intense, major hurricanes rather than an overall increase in the frequency of tropical cyclones.

Global temperature has increased by 1.1°C since 1900 and is projected to increase another 0.4 to 1.3°C by 2050 depending on the emissions scenario. The KCC US Hurricane Reference Model Version 3.0 is based on a climate-adjusted catalog of US landfalling hurricanes that best represents the impacts of climate change to date. Insured wind losses are 11 percent higher today on average due to already observed climate change.

KCC scientists developed the KCC FCCs to provide (re)insurers with credible estimates of how future climate change will impact insured losses. Future increases in losses depend on the time horizon and emission scenarios. Insured loss potential has already increased by 11 percent, and future increases in AALs will likely range from 10 to 19 percent by 2050, with larger increases at the lower return periods.

The results presented in this white paper illustrate the expected increases in wind losses due to climate change. An upcoming KCC white paper will detail climate change impacts on inland and coastal flooding.

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