AIR Hurricane Model for the United States

Accounting for Climate Change

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Revision History

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September 17, 2020	Initial publication.

Table of Contents

List of Figures

Accounting for Climate Change

Climate change affects extreme weather events. To account for these effects, AIR incorporates the current and near-current climate into its catastrophe models. For the AIR Hurricane Model for the United States, AIR researched how hurricane wind, storm surge, and precipitation-induced flood events have changed and will change to understand how the AIR model captures these trends.

Detecting and attributing climate change impacts on various weather phenomena is a relatively young branch of climate science that is growing in demand and sophistication. Attribution confidence depends on many factors, including:

- how robustly climate models simulate impacts;
- whether the climate models agree with each other;
- whether there is a detectable trend in the historical data that agrees qualitatively with the modeled future result;
- how well we can physically connect and understand the modeled or observed effect on climate.

Figure 1 shows the relative degree of confidence scientists have in ascribing climate change impacts to individual weather events. Temperature phenomena are most confidently assessed because of the direct physical connection between increasing carbon dioxide (and other greenhouse gases) and a warming atmosphere.

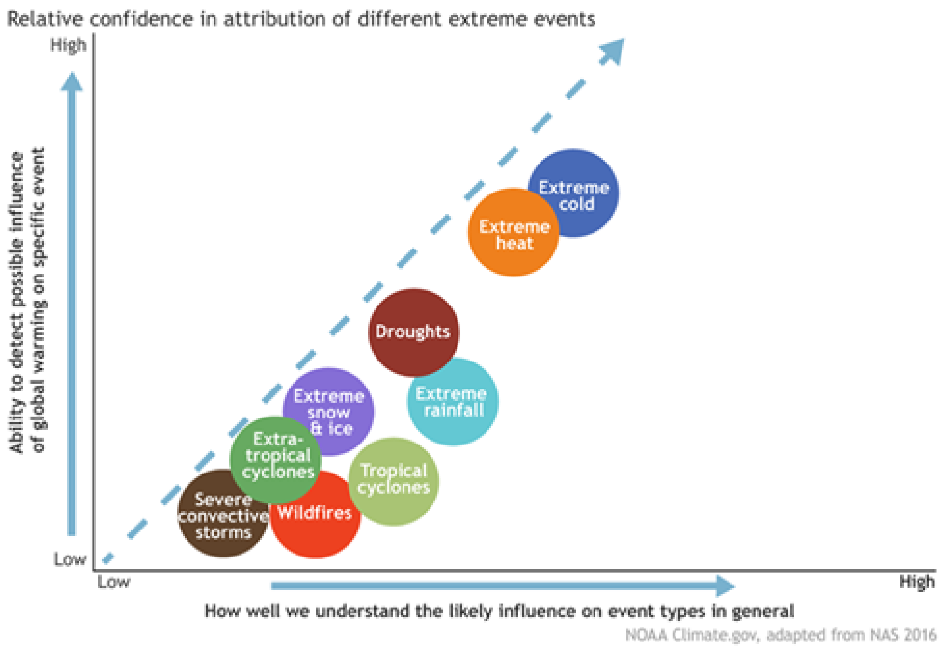

Figure 1. Relative degree of confidence that climate change is impacting various weather phenomena. (Source: NOAA climate.gov)

There is less confidence that climate change is impacting tropical cyclones relative to some other types of weather phenomena (such as extreme heat/cold). Reasons for this low confidence include:

- the relative infrequent occurrence;
- a historical record with changes in observational uncertainty over time;
- the inherently nonlinear physics driving these events.

Extreme rainfall, a peril often associated with tropical cyclones, is confidently understood. A well-known theoretical relationship, the Clausius-Clapeyron equation, states that the amount of water vapor the atmosphere can contain increases with increasing air temperature. Thus, as the atmosphere warms, its moisture content can increase, which can result in heavier rainfall rates.

Climate change is expected to have a notable impact on hurricane activity worldwide by later in the 21st century (Knutson et al. 2020). Analysis of global climate model projections indicate that future climate change will yield an increase in the proportion of Category 4 and 5 hurricanes, as well as an overall decrease in the total number of tropical cyclones. The projections vary across ocean basins and by study, as seen in Figure 2.

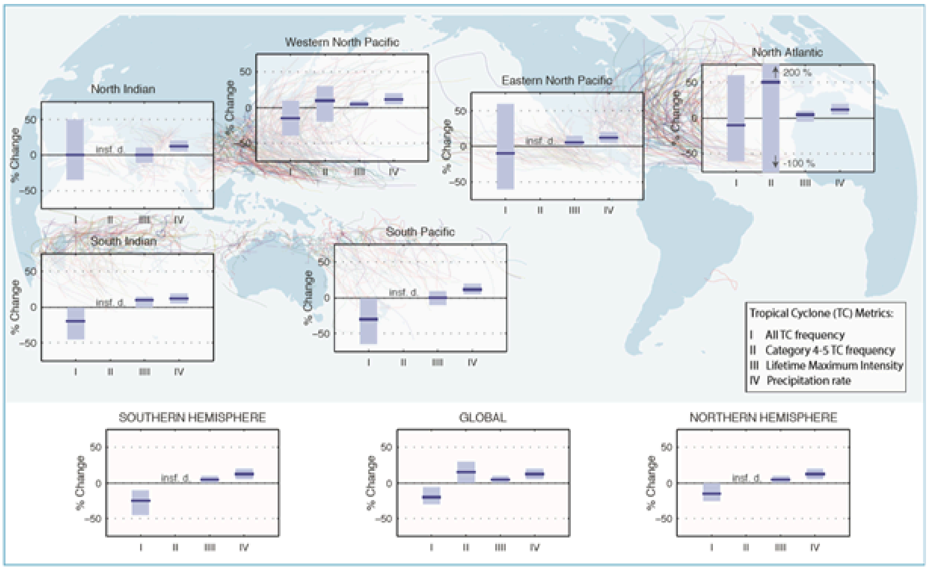

Figure 2. Projected changes in tropical cyclone statistics. All values represent expected percent change in the average over the period 2081–2100 relative to 2000–2019 under a moderate emissions scenario, based on expert judgment and after subjective normalization of the model projections. For each metric plotted (see map legend), the solid blue line is the best estimate of the expected percentage change, and the shaded bar provides the 67% (likely) confidence interval for this value (note that this interval ranges from -100% to +200% for the annual frequency of Category 4 and 5 hurricanes in the North Atlantic). Where a metric is not plotted, there are insufficient data (denoted “insf.d.”) available to complete an assessment. A random selection of historical storm tracks overlies each region of tropical cyclone activity. (Source: Fig. TS.26, IPCC, 2013)

While global climate modeling studies provide the best estimates of future impacts on tropical cyclone activity, the more relevant challenge for catastrophe risk modeling is quantifying the effects of climate change that has occurred already on current tropical cyclone risk. The rest of this chapter describes how the AIR Hurricane Model for the United States accounts for climate change. The first section provides global and region-specific historical evidence of climate change, using a combination of literature review and internal AIR research. The second section explains how the development of the AIR Hurricane Model for the United States and its stochastic catalogs reflects the recent climate. Finally, the third section presents validation of the AIR Hurricane Model for the United States representation of recent climate conditions against observed data.

Historical Trends

Despite the complex nature of tropical cyclones and other challenging aspects of interpreting the data record, several studies (e.g., Rahmstorf et al. 2018 and Figure 3 below) show significant increases in the recent frequency of high-intensity hurricanes, with uncertain but plausible estimates on the order of several hundred percent for Category 5 storms.

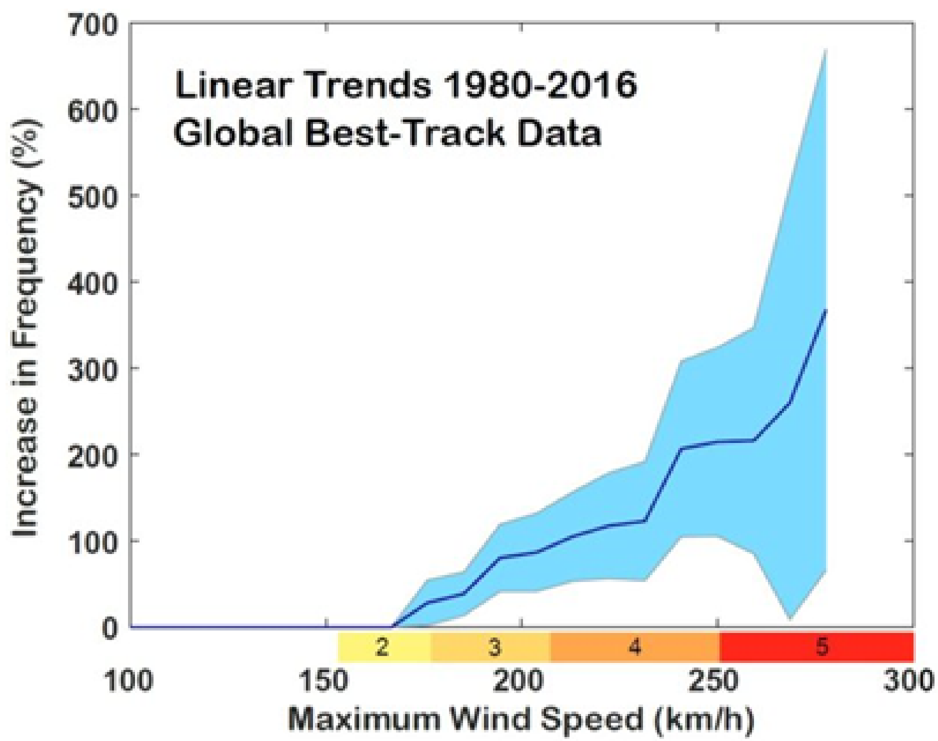

Figure 3. Recent increases in tropical cyclone frequency by Saffir-Simpson Hurricane Wind Scale. (Graph source: Kerry Emanuel, MIT. Creative Commons License CC BY-SA 3.0: https://creativecommons.org/licenses/by-sa/3.0/)

Some studies have found evidence for other increased aspects of Atlantic Basin activity, especially when focusing on the last several decades (e.g., Murakami et al. 2020, Kossin et al. 2020). These studies have found that some of the strongest observed North Atlantic hurricanes have maintained their intensity for unprecedented amounts of time. For example, Hurricane Irma in 2017 remained at or above Category 4 intensity for a record-breaking 85 consecutive hours while over the Caribbean and Hurricane Dorian in 2019 remained a Category 5 storm for approximately 40 hours.

Annual Landfall Frequency

Estimates of hurricane risk require a longer-term perspective to allow for robust sample sizes of these rare events. Since the emphasis in catastrophe modeling is on loss, it is appropriate to consider trends in metrics that are applicable to loss. For example, hurricane landfall activity is more relevant than activity over the full North Atlantic Ocean basin. Thus, AIR researchers examined both the total number of hurricanes and the number of major hurricanes that made landfall in the U.S. from 1900 to 2018 (Figure 4). Major hurricanes are defined by the minimum central pressure-based Saffir-Simpson hurricane scale as tropical cyclones with a minimum central pressure of less than 965 mb. Using this definition, the well-documented major hurricane landfall drought in the United States between 2005 and 2017 is not evident in the figure. However, similar studies have noted that this drought was based on a somewhat arbitrary 100-kt maximum sustained surface windspeed threshold (Hart et al. 2016), which is slightly greater than the 96-kt threshold used to define a major hurricane based on the Saffir-Simpson Hurricane Wind Scale.

The green and blue dotted lines in Figure 4 represent linear trendlines fit to the annual total hurricane and major hurricane frequencies over the specified time periods, respectively. It is evident by the slopes of these trendlines that no statistically significant trend (increase or decrease) has occurred in hurricane or in major hurricane landfall frequency over time.

Experts tend to agree that the U.S. hurricane landfall record is nearly complete back to 1900, although there may be some counting errors associated with determining whether a storm made landfall at hurricane or major hurricane strength. Even though the ability to accurately measure sea level pressure has existed for several hundred years, techniques to infer the minimum central pressure have evolved over the years. The latest techniques have been implemented as part of the forensic process to update historical storms in NOAA's National Hurricane Center's (NHC's) Atlantic hurricane database (Atlantic HURDAT2).

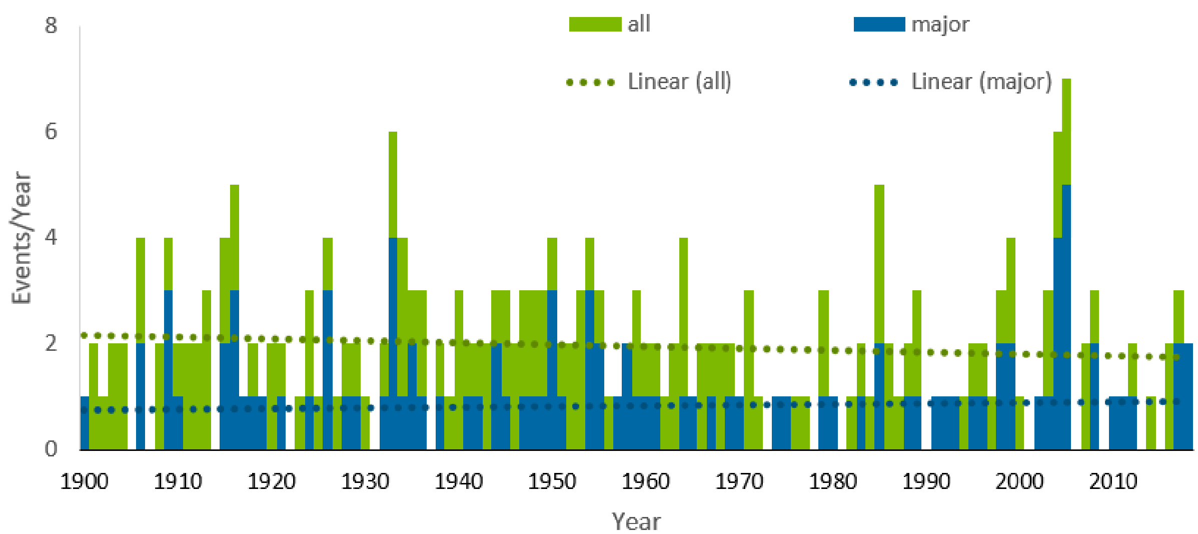

Figure 4. Frequency distribution (i.e. events/year) of all hurricanes (defined by a minimum central pressure (Cp) < 1000 mb; green bars) and all major hurricanes (defined by a Cp < 965 mb; blue bars) that made landfall in the U.S. from 1900-2018. Their corresponding trendlines are plotted in green and blue dotted lines, respectively. NOAA NHC's HURDAT2 data are used in this analysis.

Storm Intensity

AIR researchers examined the effect of climate change on tropical cyclone intensity in the United States by analyzing the average annual minimum recorded central pressure of U.S. landfalling tropical cyclones that reached at least tropical storm intensity since 1900. As shown in Figure 5, there is no statistically significant intensity trend from 1900 to 2018 (discontinuous green line). From 1979 to 2018, which corresponds to the high-resolution satellite era (Velden et al. 2017), however, there is a decrease in average tropical storm and hurricane minimum central pressure of around 18 mb over that 40-year period (blue dashed line). This decrease, with a p-value of 0.043, calculated using the Mann-Kendall test (Mann 1945, Kendall 1975, Gilbert 1987), is below the 0.05 p-value threshold often used to determine statistical significance. However, this trend may not be entirely attributable to climate change because other shorter periods, such as 1940-1960 and 1960-1980, show decreasing or increasing trends, respectively.

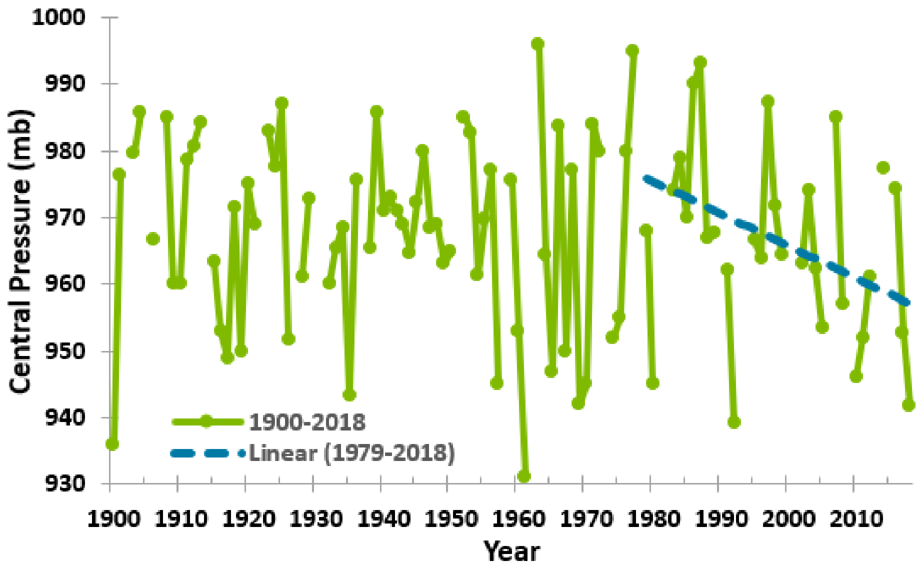

Figure 5. Time series of U.S. landfalling tropical storm and hurricane average annual minimum central pressure recorded from 1900 to 2018 (discontinuous green line). Note that isolated green points indicate adjacent years that exhibited no landfalls. The associated linear trendline fit to the data from 1979 to 2018 is plotted as the blue dashed line. NOAA NHC's HURDAT2 data are used in this analysis.

The year-to-year behavior of tropical storm and hurricane landfall frequency and intensity suggests that climate variability may play a greater role than climate change. For example, it is well known that the El Niño/Southern Oscillation (ENSO) phenomenon, which operates on time scales of 3 to 8 years, and the Atlantic Multidecadal Oscillation (AMO; also known as the Atlantic Multidecadal Variability (AMV)), which has operated on time scales of 50 or more years, can have strong influences on hurricane behavior over the full North Atlantic Ocean basin and at landfall. ENSO influences hurricane activity over the North Atlantic basin by increasing shear over the main development region during its positive phase (i.e. during El Niño events). AMO influences activity through anomalous sea surface temperatures (SSTs). Figure 6 shows how these climate signals have influenced U.S. hurricane landfall behavior from 1900 to 2018. The plotted variable is the multivariate ENSO Index (MEI) and is a composite of 5 variables that reflect ENSO behavior[1]. A positive MEI corresponds to El Niño and a negative one to La Niña. Chi-squared tests show statistically significant differences between distributions of both hurricane frequency and intensity at landfall for MEI+/- years.

[1] https://psl.noaa.gov/enso/mei

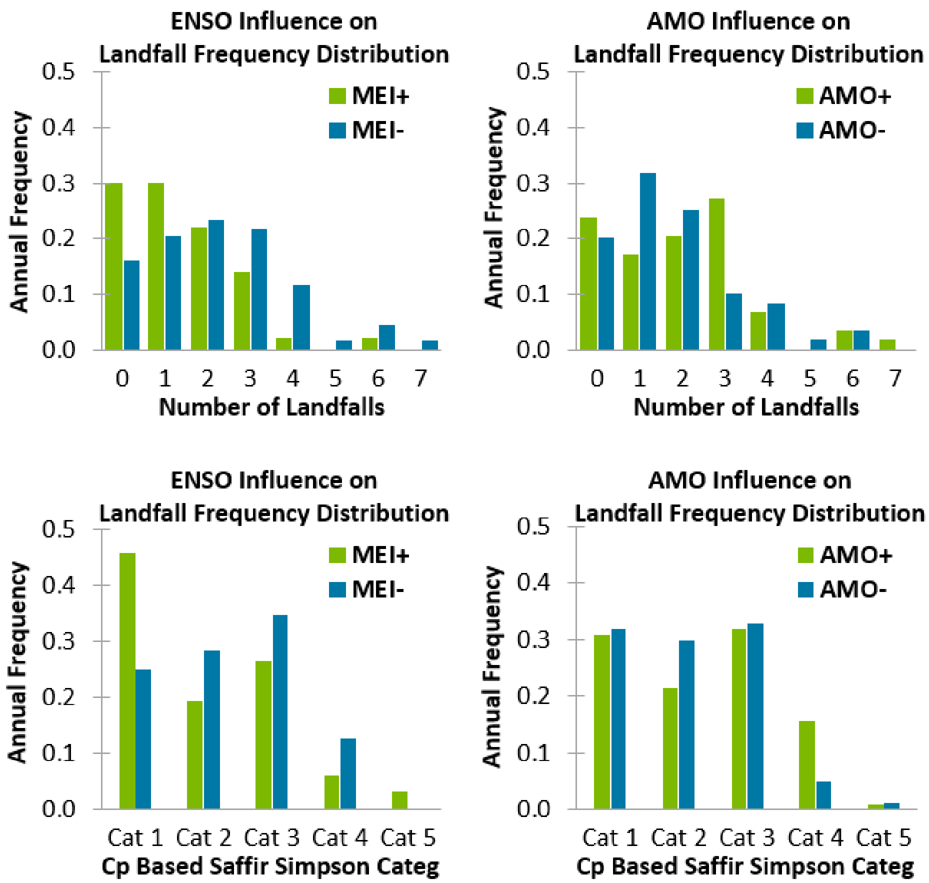

Figure 6. Annual U.S. hurricane landfall frequency distributions by yearly number of landfalls (upper row) and by Saffir-Simpson hurricane intensity category (as defined by minimum central pressure (Cp); lower row). Positive (+) and negative (-) phases (green and blue bars, respectively) of the Multivariate ENSO Index (MEI) and the Atlantic Multidecadal Oscillation (AMO) are shown in the left and right columns, respectively.

The AMO Index reflects the anomalous SST conditions over the North Atlantic Ocean. A positive index indicates warmer than normal conditions and a negative index indicates cooler than normal SST conditions. Chi-squared tests show that there are no statistically significant differences between hurricane landfall intensity distributions for AMO+/- years for all landfall intensities. When focusing on major hurricane landfalls, however, the correlation between decadally-averaged values of AMO and decadal counts of major landfalling hurricanes is quite high (0.9; Figure 7). It is important to note that the influence of climate variability on hurricane landfall frequency and intensity does not refute the existence of climate change or any impacts climate change may be having on these characteristics. Rather, its signature may be relatively weak compared to those from internal climate influences.

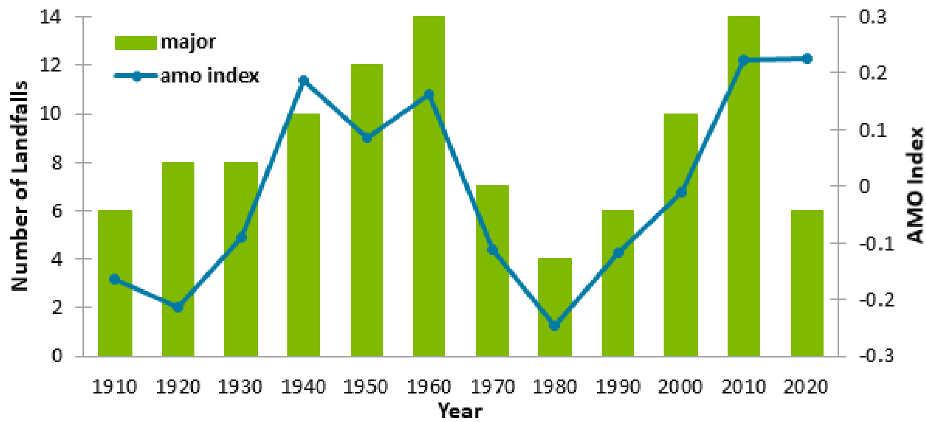

Figure 7. Time series of the number of U.S. major landfalling hurricanes, by decade (green bars) and decadally-averaged AMO Index (blue line). Horizontal axis labels are such that 1910 includes activity from 1900-1909, for example.

Forward Speed

Recent studies have found about a 10% decrease in average annual hurricane forward speed over most ocean basins and a 15-25% decrease over adjacent land masses since around 1950 (Kossin 2018). While some of these trends are statistically significant, and physical theory suggests the environmental winds that steer hurricanes are expected to slow down in a warming atmosphere, Global Climate Models (GCMs) do not all predict this result. Therefore, there is little confidence that these trends in hurricane translational speed are the result of climate change (Knutson et al. 2019).

AIR scientists analyzed the average annual forward speed of U.S. hurricanes at landfall from 1900 to 2018 (Figure 8). Results from this internal analysis show no statistically significant trend, however, some ranges of high variability in forward speed are evident between 1950 and 1975. Some degree of variability should be expected in a time series developed from small sample sizes, especially in cases where a particular year is an average of only one or a few landfalling storms. This variability is consistent with the lack of scientific community climate change consensus, and it underscores the even deeper uncertainty of any risk related to changes in hurricane forward speed. In addition, in comparing the distribution of landfalling hurricane forward speed for ME +/- and AMO +/- years, AIR researchers found no statistically significant differences (not shown).

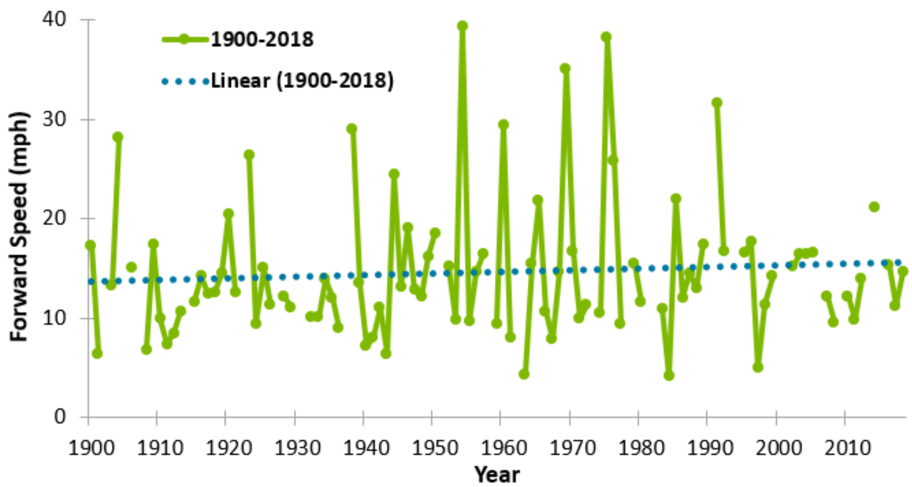

Figure 8. Time series of U.S. hurricane average annual forward speed at landfall for the period from 1900 to 2018 (discontinuous green line). Note that isolated green points mean adjacent years exhibited no landfalls. The associated linear trendline fit to the data is plotted as a blue dotted line. NOAA NHC's HURDAT2 data are used in this analysis.

Precipitation

Recent studies have examined the effect of climate change on tropical cyclone-induced precipitation amounts. Since a warmer atmosphere can contain more water vapor (Clausius-Clapeyron equation), a warmer atmosphere would correspondingly accelerate or amplify the hydrologic cycle, all else being equal. In fact, studies have found that tropical cyclone rainfall amounts have been increasing globally for several years (Kunkel et al. 2010, Lau et al. 2012, Chang et al. 2013). For example, Kunkel et al. (2010) provides a detailed long-term analysis of precipitation associated with tropical cyclone activity over the United States since 1890 and found statistically significant increases in rainfall amounts over many decades.

More recently, Risser and Wehner (2017) and van Oldenborgh et al. (2017) analyzed extreme precipitation, including rainfall produced by tropical cyclones in the Gulf of Mexico region. They estimated the change in return periods of extreme precipitation events over the last century using rain gauge, radar, and model data. While their analyses included approximately 30% extreme precipitation events that are not associated with tropical cyclones, both studies showed a clear upward trend in the frequency of extreme precipitation, and both ascribed this trend mainly to anthropogenic climate change. Their results agreed with those from Emanuel (2017), who estimated the trend in model-simulated return periods of extreme precipitation events associated with tropical cyclones near Houston using a modeling approach described in Feldmann (2019).

AIR's internal analysis of precipitation trends in the United States shows continued, if not accelerating, increases in hurricane-induced precipitation amounts over time. Figure 9 shows average annual observed hurricane-induced precipitation amounts across the U.S. for the first and second halves of the high-resolution satellite period (left and right images, respectively). The observed values are a blend of information from various platforms.

It is apparent from Figure 9 that the second half of the high-resolution satellite era is characterized by significantly more precipitation than the first half. Specifically, the "hot spots" in Texas (from Hurricane Harvey in 2017) and in North Carolina (from Hurricane Florence in 2018 and Hurricane Floyd in 1999) are clear reminders of very wet rather recent events. Additionally, there are higher amounts of hurricane-induced precipitation along many coastal locations, which also extend farther inland in the most recent period as compared to the first half of the high-resolution satellite era. Comparison of values between the two images in Figure 9 indicates increases of more than 100% in some locations.

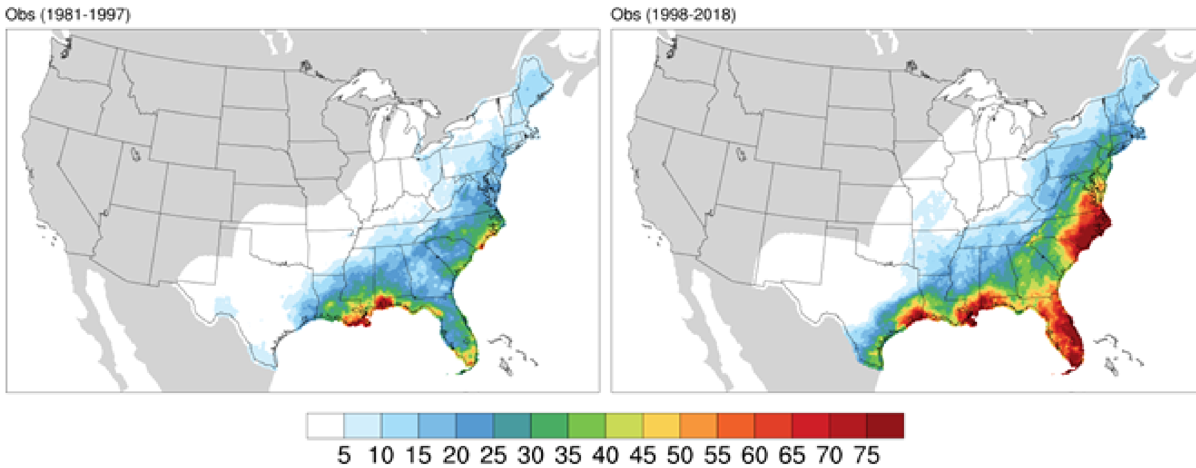

Figure 9. Average annual hurricane-induced precipitation amounts (in mm) from 1981–1997 (left) and from 1998-2018 (right) for the United States.

Despite the clear evidence of increased rainfall from tropical cyclones, understanding the causes is not as straightforward. For example, in addition to the aforementioned contributions to increased rainfall (e.g., decreased forward speed, increased intensity (Lonfat et al. 2004), and increased atmospheric moisture), there could be an overall increase in the number of events and/or different storm trajectories that result in more precipitation days per event impacting some regions. A comparison of the number of landfalling hurricanes during the 1981-1997 period to the 1998-2018 period in Figure 4 indicates more storms made landfall in this later period (43 in 21 years, or ~2.0 storms per year) than in the earlier period (26 in 17 years, or ~1.5 storms per year). The number of days by time period and location was not tracked for Figure 9.

An alternate way to evaluate the possibility of a climate change signal associated with tropical cyclone precipitation is to examine whether the wettest storms are getting wetter. Figure 10 shows a comparison of frequency distributions (left image) and box-and-whisker plots of maximum precipitation (right image) of the named tropical cyclone (of tropical depression intensity or higher) that generated the highest precipitation point total in each year during the 1959-1988 and 1989-2018 thirty-year time periods. The frequency distribution graph on the left shows that the number of years associated with lower maximum precipitation amounts (<20 inches) is similar for the two time periods. In fact, the two distributions are similar except that the more recent (1989-2018) time period has a broader range of precipitation totals than the earlier (1959-1988) time period.

A comparison of the box-and-whisker plots in Figure 10 indicates that both the median of and the variability in tropical cyclone maximum precipitation amounts have increased over the more recent historical time period shown (1989-2018). These results suggest an increase in precipitation amounts and variability with time and are expected from a climate change perspective. However, further analysis indicates that the increases in both the median and variability values are statistically insignificant. The precipitation component of the AIR Hurricane Model for the United States has been calibrated to the data from this more recent data period.

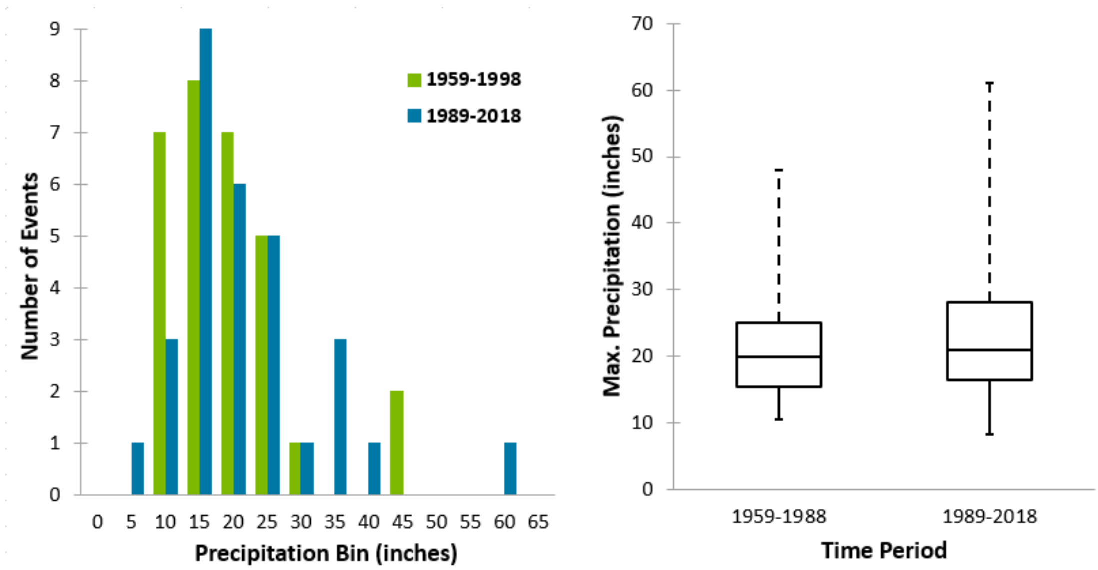

Figure 10. Two different perspectives on the historical distribution of maximum precipitating tropical cyclone events (that reach tropical depression intensity or higher) by year. Left panel: Number of events that fell within a given precipitation total bin during the 1959-1988 (green bars) and 1989-2018 (blue bars) 30-year time periods. Right panel: Median (black horizontal line inside the box), 25th and 75th percentiles (black box bounds) and 5th and 95th percentiles (black horizontal lines outside the box) for the same time periods.

Storm Surge and Sea Level

An important aspect of hurricane activity is storm surge. Storm surge is impacted by sea level changes due to climate change and other long-term processes. Figure 11 shows the average annual rate of sea level rise (SLR) at selected coastal stations using at least 30 years of data. Sea level rise from climate change has been occurring from melting glaciers and from thermal expansion due to rising ocean water temperatures. The global average rate of SLR from these two sources is 1.7-1.8 mm/yr (Church et al. 2011). The variations in sea level trends shown in Figure 11 primarily reflect differences in rates and sources of vertical land motion (Wöppelmann and Marcos, 2016) that result from tectonic motion, soil compaction, glacial isostatic adjustment, and changes in the water table (e.g., from increased human consumption of water). A slowing of the Gulf Stream has also resulted in some large changes in relative sea level rise along the east coast of the United States (Ezer et al. 2013). Climate change projections indicate that sea level will continue to rise due to climate change over the next decade at a global average rate of 2-3 mm/yr (IPCC 2013).

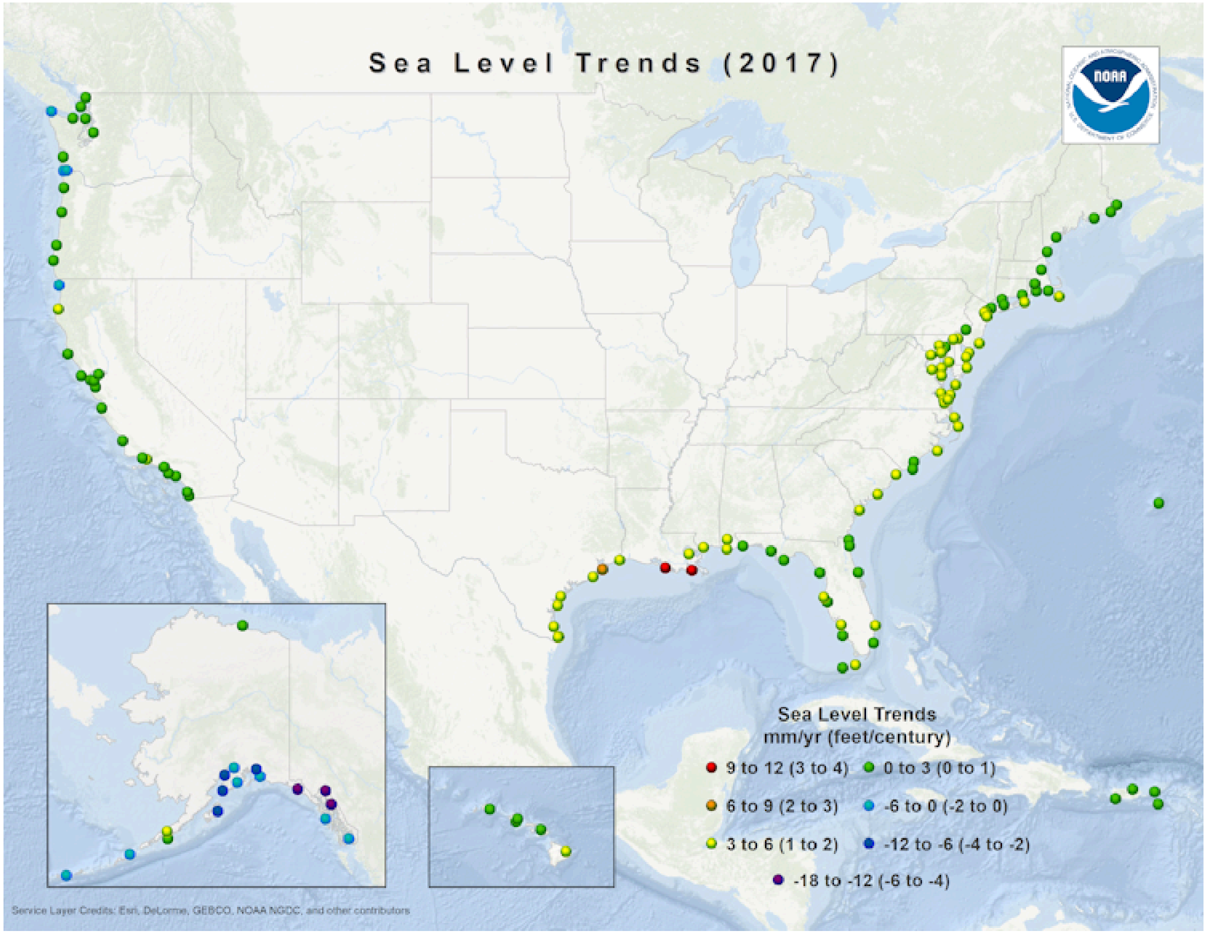

Figure 11. Trends in relative sea level rise for selected stations. Source: NOAA

Additional Hurricane Characteristics

Other trends in hurricane activity and the influence climate change and other long-term processes have on these trends, such as track and storm size metrics, are harder to evaluate. Previous studies (e.g., Kossin et al. 2014) have documented poleward migrations of the latitude of lifetime maximum intensity. Globally, there has been about a 0.5-degree poleward shift in either hemisphere but with considerable inter-basin variability. For example, results were inconclusive over the North Atlantic Ocean Basin. Knaff et al. (2014) examined satellite-derived data for possible trends in wind field diameter over the period from 1978 to 2011 but did not find any statistically significant results, globally or over individual ocean basins. Limitations in data and unclear guidance from climate models contribute to that difficulty and accordingly, hurricane track and storm size metrics are not considered for this analysis.

In summary, based on both a review of peer-reviewed published literature and AIR's internal investigations, no statistically significant evidence of climate change impact on hurricane landfall frequency, intensity, or forward speed can be identified. Overall, hurricane behavior appears to be influenced significantly by natural variability. Additionally, the trends that have been identified exist most robustly over the last twenty years, which is too short of a time period to attribute behavior to climate change, especially given the known influences of natural forcing. Changes in hurricane-induced precipitation exist over a longer time period (1981-2018) and can be understood within the context of climate change, although climate variability over this time period has also likely played a role. AIR's findings described in this section are supported by Knutson et al. (2019). In addition, a summary of the degree(s) of confidence for these hurricane characteristics is available in Knutson et al. (2019).

Model and Catalog Development

The primary data source used to develop the AIR Hurricane Model for the United States is the NOAA National Hurricane Center's (NHC's) HURDAT2 Best Track data from 1900 to 2017. AIR's stochastic catalog was updated in 2019 to reflect changes made to the HURDAT2 dataset. Hurricane frequencies were adjusted slightly along some coastal landfall (LF) segments over Florida. No additional changes were made to preferentially weight more recent data or to adjust data from earlier time periods in order to synthetically account for potential absences or shortcomings. While the architecture of the catalog has remained essentially unchanged since 2009, it remains a robust representation of near-term hurricane climatology in the United States.

In developing the AIR Hurricane Model for the United States, the HURDAT2 data were treated with equal weight throughout the historical interval. Landfall and over-land hurricane activity were modeled using data beginning in 1900. For over-water portions of tracks, e.g., as hurricanes approach or depart U.S. landmasses, over-basin information beginning in 1950 was used. This implementation resulted in a stochastic catalog that reflects the long term mean hurricane activity and the variability about the mean beginning in 1900. Modeled hurricane characteristics include landfall frequency, intensity, forward speed, and precipitation.

Stability is an important aspect of any catastrophe model, as is its ability to reflect the current climate. Since ocean warmth is critical in the thermodynamics of hurricane genesis, development, and evolution, an indicator of basin-wide SST conditions (e.g., the AMO index) should be considered when assessing hurricane climate state. As shown previously, the correlation between the AMO index and U.S. landfalling major hurricane frequency is high.

Current warm ocean conditions indicate a positive AMO index. However, there is still significant uncertainty in the relative contributions that internal and external mechanisms have on elevated Atlantic SSTs (Zhang et al. 2019). While extrapolation of the current phase and various studies (e.g., Frajka-Williams et al. 2017) would indicate the possibility of a return to neutral or even negative conditions in the next 5 to 10 years, there is much speculation about what kind of variability the coming years may exhibit in surface Atlantic warmth due to anthropogenic climate change. Ocean uptake of the rapidly-increasing surface warmth or freshwater flux from melting ice sheets at a location critical to the dynamics of the Atlantic Meridional Overturning Circulation (AMOC) could result in stable or increasing SSTs (Liu et al. 2019b). The AMOC is the zonally (west-to-east) integrated component of surface and deep currents in the Atlantic Ocean. It is characterized by a northward flow of warm, salty water in the upper layers of the Atlantic, and a southward flow of colder, deep waters that are part of the thermohaline circulation (Buckley and Marshall 2016). Many scientists believe the AMOC is a significant contributor to the AMO and general Atlantic Multidecadal Variability (AMV). Due to the uncertainty regarding mechanisms that contribute to higher Atlantic SSTs and how higher SSTs, and other possible interactions, influence hurricane activity, AIR continues to weigh the full range of historical data across positive and negative AMO states equally to cover the spectrum of possibilities in the near future.

AIR offers an alternative view of risk via the Warm Sea Surface Temperature (WSST) stochastic catalog. This catalog further conditions the standard stochastic catalog based on an index derived from the warm North Atlantic Ocean basin years. Details of the methodology behind WSST catalog development are provided in Climatological Influences on Hurricane Activity: The AIR Warm SST Conditioned Catalog, available on the AIR Client Portal. This catalog uses the same landfall data since 1900 but extracts the additional sensitivity to landfall frequency, especially to that of major hurricanes.

To model the rainfall patterns of hurricanes, AIR created a new precipitation catalog that closely resembles precipitation from hurricanes and other weather systems. The AIR Hurricane Model for the United States provides a realistic view of the precipitation hazard by blending its existing general circulation model (GCM) coupled to the numerical prediction (NWP) model with its new precipitation simulation and with the existing catalog's tracks. For each stochastic year, any environmental precipitation produced by non-hurricane weather systems along a simulated hurricane track is replaced by the simulated hurricane precipitation. The blending process is done smoothly so that there are no jumps between the modeled hurricane precipitation field and the surrounding environmental precipitation. Data from historical hurricanes captured in the gridded reanalysis from 1979 through recent seasons were used to construct and calibrate this model component (including Hurricane Harvey in 2017 and Hurricane Florence in 2018).

To model the storm surge component, NOAA's National Tidal Datum Epoch is used (1983-2001), with a correction to the static initial water level to improve validation of storm surge from modern landfalling hurricanes during the 2000s and 2010s. Since long-term sea level rise along the U.S. East and Gulf Coasts from the time of these landfalling hurricanes to the present day is at most 1-2 inches, the storm surge model accounts for the current state of the sea level for the purposes of modern-day risk analysis.

Model Validation

The AIR Hurricane Model for the United States has been validated against recent hurricane landfall frequency, intensity, duration, forward speed, and rainfall observations to show that AIR's stochastic catalog still reflects the most recent hurricane climatology. For this validation, the recent historical record is defined as 1995 to 2018. This period was chosen because it is almost as long as a canonical climate period (typically 30 years) and it encompasses the current positive AMO Index phase. Since the AMO has been in a positive phase over the last 20 years and it is not clear when it will end, and because the goal of a catastrophe model is not only to reflect the climate from the recent past but also that over the next five to ten years, this time period is the most relevant period to use for evaluation. Note that AIR used the standard catalog as opposed to the WSST catalog for these validations. Using the standard catalog is a more stringent test, as it has been developed using data from all years as opposed to the WSST catalog, which only includes data for years when the AMO was in a positive (i.e. warm) phase.

Annual Landfall Frequency

Figure 12 compares the AIR-modeled and observed (1995-2018) average annual U.S. hurricane landfall frequencies by Saffir-Simpson Hurricane Intensity Category (based on minimum central pressure (Cp)). As seen in the figure, the relatively higher observed Category 3 and 4 hurricane landfall frequencies are expected because the AMO has been in a positive phase during this analysis period. Despite the visible differences across the intensity categories, a chi-square test and a two-sample Kolmogorov-Smirnov (K-S) test show that the observed and AIR-modeled distribution differences are statistically insignificant. Thus, AIR's standard stochastic catalog robustly represents U.S. landfalling hurricane activity for all strengths of the AMO observed thus far. Additionally, given that the AMO is more likely to decline rather than increase over the next 5-10 years, the catalog will likely remain a robust representation of activity for the near future.

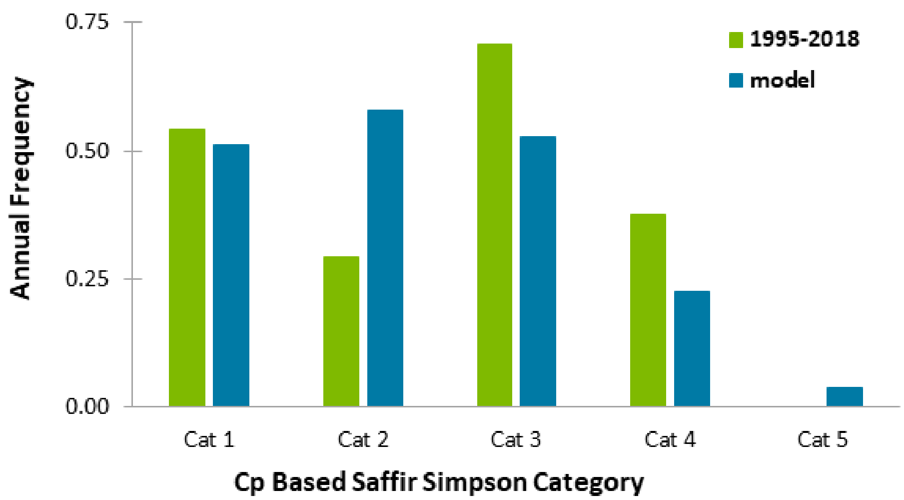

Figure 12. Comparison of the 1995-2018 observed (green bars) and AIR-modeled (blue bars) average annual U.S. hurricane landfall frequencies by Saffir-Simpson Hurricane Intensity Category (as defined by minimum central pressure (Cp)).

Regional-specific versions of the analysis shown in Figure 12 are not very useful due to the relatively short climate period used in this analysis. However, such regional graphics using the full historical record show very good agreement between the AIR-modeled and observed average annual hurricane landfall frequencies.

Storm Intensity

It is difficult to fully evaluate whether the modeled hurricane intensity is capturing the behavior of the recent climate beyond what is shown in Figure 12 without including what has happened over the longer-term record. For example, the landfall central pressure of Hurricane Michael (2018) of 920.34 mb was the third lowest landfall central pressure recorded in U.S. history since 1900. The two lowest values were from the Labor Day storm in 1935 (892 mb) and Hurricane Camille in 1969 (904 mb). Thus, Hurricane Michael was close to a 40-year storm from a landfalling central pressure standpoint. Some uncertainty exists in this return period because it was calculated using a relative brief historical record (i.e. 1900-2018). However, from a model standpoint, this 40-year return period landfalling central pressure is 914 mb +/- 8 mb based on bootstrapping 120-year samples from the 10,000-year catalog.

Forward Speed

As presented in the "Historical Trends" section of this chapter, AIR's analysis did not show any statistically significant increase or decrease in U.S. landfalling hurricane forward speed overall. Beginning in the mid-1990's, however, historical data exhibit both relatively low forward speeds and low variability in forward speed of U.S. landfalling hurricanes. These recent trends underscore the importance of examining how well AIR's Hurricane Model for the United States captures the most recently observed values. Figure 13 compares the AIR-modeled and 1995-2018 observed U.S. landfalling hurricane forward speed frequency distributions using several different forward speed bins. Results from a two-sample K-S Test indicate these two distributions are statistically similar and, hence, recent forward speed trends are well represented in the AIR Hurricane Model for the United States.

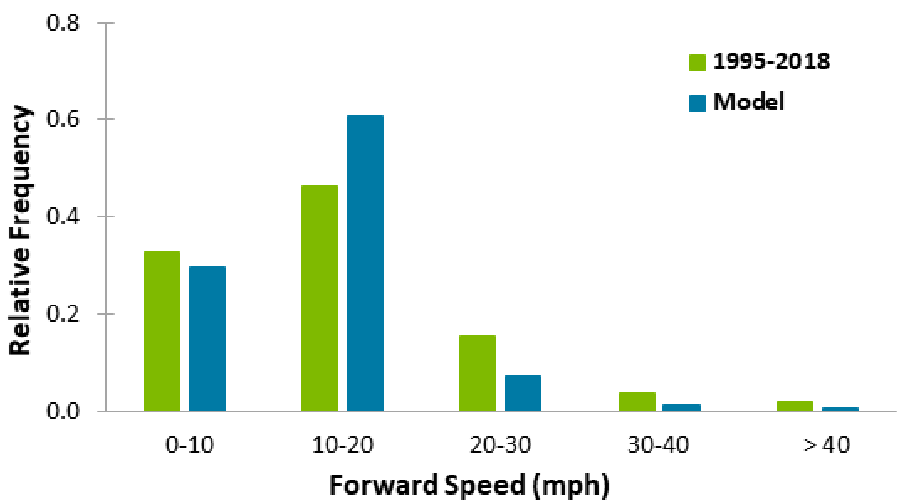

Figure 13. Comparison of the 1995-2018 observed (green bars) and AIR-modeled (blue bars) relative forward speed frequency distributions of U.S. hurricanes at landfall.

Shortly following the 2017 Atlantic hurricane season, AIR analyzed the apparent anomalous hurricane behavior that occurred in 2017 to determine how well AIR's stochastic catalog captured these events. Some examples of this behavior include: 1) two major hurricanes

(Harvey and Irma) making landfall in the U.S. within a 15-day period, 2) ten consecutive hurricanes of category 1 strength or higher, and 3) three consecutive category 4 hurricanes. Huang (2017) analyzed the likelihood of two consecutive major hurricane landfalls occurring within a 15-day period and found that AIR's stochastic catalog accurately represents this observed frequency (i.e. 4 times between 1950 and 2017). Sousounis and Huang (2018) evaluated additional 2017 Atlantic Ocean Basin hurricane behavior and found that AIR's stochastic catalog accurately represents the observed occurrence frequency of ten consecutive hurricanes and three consecutive Category 4 hurricanes. These studies demonstrate the AIR Hurricane Model for the United States' ability to accurately represent the current climate.

Precipitation

In general, comparing modeled tropical cyclone precipitation to observations is challenging because of differences in temporal and spatial resolution and the fact that observations do not identify precipitation amount by weather system type. Direct measurements from in-situ meteorological station rain gauges, as can be found in the Global Summary of the Day (GSOD) Data from the National Climatic Data Center, would be the first choice for a precipitation analysis. However, the GSOD data are incomplete, particularly for hurricane events, due to the destruction that results from the storm.

In order to compensate for the lack of direct in-situ meteorological station rain gauge measurements, gridded precipitation data are interpolated from remote sensing observational platforms, such as surface-based radars and orbiting satellites. By combining data from multiple sources, a comprehensive estimate of precipitation amounts in both space and time is achieved.

Figure 14 compares the AIR Hurricane Model for the United States' simulated average annual hurricane precipitation estimates to the observed average annual hurricane precipitation for the 1981-2018 and 1998-2018 time periods. The modeled precipitation was created using AIR's standard 100,000-year catalog.

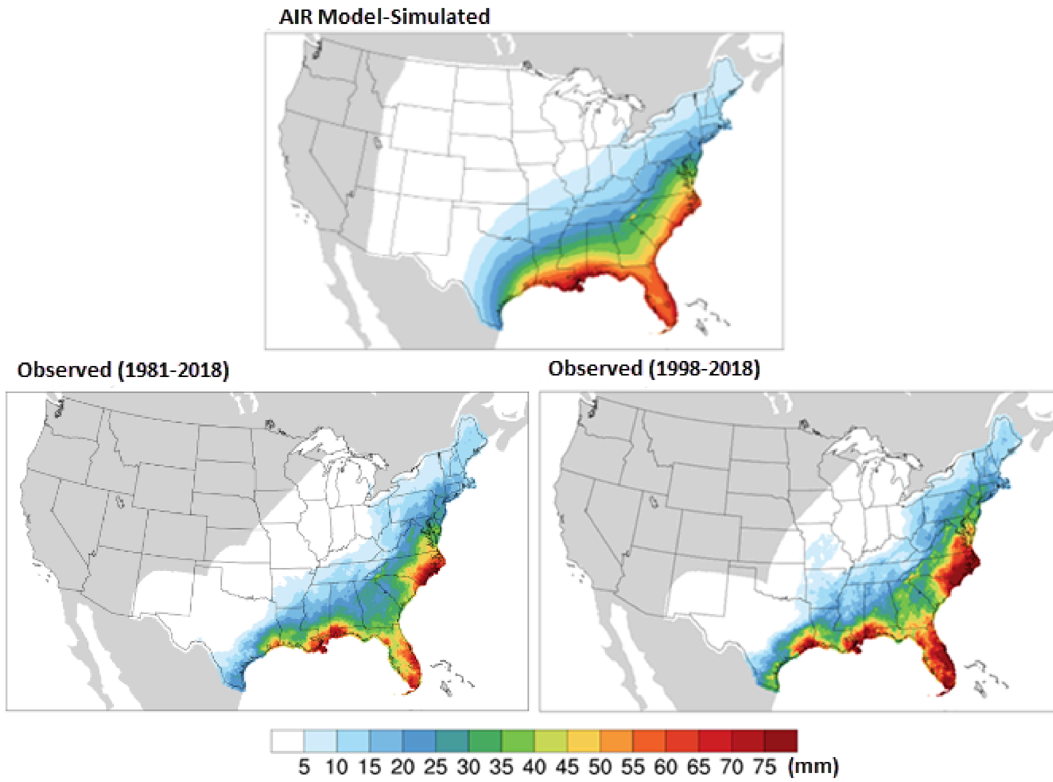

Figure 14. Comparison of AIR-simulated (top map) to the 1981-2018 and 1998-2018 observed (left and right bottom maps, respectively) average annual hurricane precipitation (mm). The simulated precipitation was created using the AIR 100,000-year stochastic catalog.

As seen in Figure 14, there is reasonable agreement between the AIR-modeled precipitation and the observed precipitation during both the last ~40 years and last ~20 years of observed data. In fact, the simulated average annual precipitation falls between the two observed time periods, which implies that the model result is weighted more towards the second half than to the mean of the entire ~40-year period. It is important to note that the entire ~40-year period may be the most appropriate recent climatological period to use for validation due to the influence of positive AMO on North Atlantic Ocean basin hurricane activity during the last ~20 years. AIR-modeled precipitation validation shown here (including validation for moderately extreme and extreme events and key historical hurricanes), demonstrate AIR's stochastic catalog's ability to accurately represent the current climate.

The AIR Hurricane Model for the United States continues to represent the current hurricane risk well. There are temporal trends in AIR-modeled hurricane frequency, intensity, forward speed, and precipitation, which are all consistent with those found in the published literature. The magnitudes of these trends, however, are relatively weak and are often not statistically significant. Increases in hurricane-induced precipitation amounts have occurred and can be understood within the context of climate change, however, the extent to which climate change plays a role is tough to determine. Due to the longer-term variabilities in SSTs, as demonstrated by the AMO Index, it is difficult to isolate the recent climate change contribution to hurricane activity over the United States, even though, in some instances, the physical understanding is consistent with the observed change. It is more important to capture the overall variability than to focus on large-amplitude, short-duration trends, especially given the uncertainty in how they may change over the next several years. Thus, the updated AIR Hurricane Model for the United States represents the current hurricane risk.

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