Understanding Past, Present, and Future Tropical Cyclone Activity

Jacob Carstens[1], Christopher Uejio[2], and Allison Wing[1]

[1]Department of Earth, Ocean, and Atmospheric Science, Florida State University, Tallahassee, FL
[2]Department of Geography, Florida State University, Tallahassee, FL

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Abstract

This paper presents an overview of the current state of the science on the relationship between climate change and hurricane activity, with an emphasis on the Atlantic basin. Various hazards associated with hurricanes are discussed, including wind, rain, and storm surge. Confidence attribution involves a combination of an observed trend in the historical record, an explanation for that trend rooted in theory, and explainable agreement among climate model projections. Each of these components are discussed for each hurricane-related hazard or characteristic, including confidence levels and current limitations in understanding.

Key messages:

1. Coastal flooding from storm surge is expected to increase regardless of changes in storm intensity due to future sea level rise (high confidence).
2. There is agreement between theory and model projections that flooding rain associated with hurricanes will become more hazardous. It is more difficult to evaluate historical trends in hurricane rainfall, but a notable trend of slower-moving storms has recently emerged.
3. While the mean intensity of hurricanes has not changed significantly in the past, warmer oceans raise the ceiling for intensity. A larger proportion of storms have reached major hurricane (Category 3-5) strength in recent years, along with an increase in rapid intensification events.
4. The locations where hurricanes reach their peak intensity has shifted away from the equator poleward and toward the west, or closer to land in the Atlantic basin, with other regional changes in hurricane tracks observed. Theoretical explanations for this behavior are a topic of ongoing research.
5. There is relatively low confidence in projections of future tropical cyclone frequency, and work is ongoing to understand what sets the global number of tropical cyclones each year.

1. INTRODUCTION

Tropical cyclones (TCs) are among the most impactful weather phenomena on Earth. Forming in tropical and subtropical oceans, they pose several societal hazards, particularly along coastlines. TCs frequently impact Florida, primarily during the Atlantic Ocean's hurricane season from June to November. Notable examples of hurricanes to directly affect Florida in recent years include Irma (2017), Michael (2018), and Sally (2020), each causing significant damage through intense winds and flooding. While our ability to forecast TC formation, track, and intensity have improved substantially in the past several decades, it is critical to further build our understanding of the relationship between TC activity and climate change, particularly as coastal population and infrastructure continue to increase. To contextualize our discussion on the impact of climate change on TCs, we begin with a brief description of TC structure and hazards, as well as environments that favor TC development.

a) TC Definition, Structure, and Hazards

A tropical cyclone (TC) is defined by the World Meteorological Organization as: "A warm-core non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center." In this definition, "warm core" refers to a center which is often much warmer than its surrounding environment, especially in the middle and upper troposphere. "Non-frontal" refers to the lack of a large scale horizontal temperature contrast (cold and warm fronts) as seen at higher latitudes. "Synoptic-scale" weather systems are those spanning hundreds of miles, hinting at the important note that TC impacts are often wide-reaching, well beyond their centers of circulation. TC is a term that encompasses hurricanes (or typhoons in the Northwest Pacific Ocean), tropical storms, and tropical depressions.

Perhaps the most visually striking feature of a mature TC is its eye in the center, consisting of relatively dry, cloud-free air, little wind, and minimum pressure. Surrounding this is the eyewall, a region of intense rain and strongest winds on the order of 10-50 miles away from the center of circulation. While winds gradually weaken at farther radii from the eyewall, gale force winds in excess of 40 mph are common dozens, or even hundreds, of miles from the center. Outside the eyewall, most precipitation occurs in the form of spiral rainbands, which are capable of producing locally intense rain and winds. An example of this structure is outlined in Figure 1.

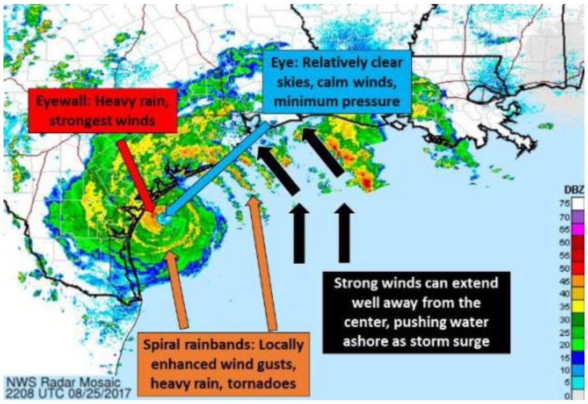

Figure 1: Outline of mature tropical cyclone structure on radar, using the example of Hurricane Harvey (2017). Image from NOAA.

TCs present multiple hazards, especially to coastal regions such as those in Florida. Hazards include damaging winds, which can exceed 150 mph in the strongest hurricanes, but generally pose risks across a wider area beyond the eyewall. Water is the most deadly and damaging hazard – ocean water pushed inland by wind causes coastal storm surge flooding, and extreme rainfall can cause inland flooding. Slow-moving TCs can produce multiple feet of rain in some cases, while flooding from storm surge may extend well inland depending on factors such as TC intensity, ocean bathymetry, and land topography. Tornadoes are also common in landfalling TCs, regardless of the intensity of the TC, due to local wind shear (a change in wind speed and/or direction with height) generated by the TC circulation. Hurricane Ivan, which affected the western Florida Panhandle in 2004, spawned approximately 120 tornadoes as it traversed the eastern United States. In addition, TC-induced tornadoes are often more difficult to forecast compared to those generated from supercell thunderstorms, in part due to their nature to generate and dissipate quickly.

TCs differ from the extratropical cyclones of middle and high latitudes in where they draw their energy from. TCs are fueled by fluxes of heat and moisture from the ocean surface, while extratropical cyclones are driven by horizontal temperature and density contrasts in the atmosphere. Subtropical cyclones are somewhat of a hybrid between these two, often drawing energy from both sources and having a less pronounced warm core than a traditional TC. The fact that TCs are fueled by oceanic heat naturally motivate the question of how climate change and warming oceans have affected them[19]. The remainder of this paper will review our understanding of the TC-climate connection, including observed trends in TC statistics and future projections. Before that discussion, an introduction to different observational and modeling techniques used to collect information on TCs is presented next.

b) Gathering Data on TCs

The growing field of paleotempestology[56] informs us about the TCs of past climates using deposits of sediments in coastal regions[3,7], oxygen isotopic ratios of hurricane precipitation, tree rings, and coral[13,14]. These tools allow us to analyze TC activity hundreds to thousands of years before the present, as well as the variability of TC activity in past climates. This information can provide a valuable analog to compare against our currently changing climate, and can be combined with numerical modeling to draw more robust conclusions. However, these methods cannot distinguish trends, basin-wide variability, or tracks, because they only focus on a specific geographic location[1].

Early direct observations of tropical cyclones were either taken by land-based weather observing stations in cases of landfalling storms, or by ships. From these observations, databases have been developed such as HURDAT, which estimate the locations, maximum sustained winds, and minimum central pressures of TCs at 6-hour intervals[30]. While this dataset extends as far back as the mid-19th century, several uncertainties and gaps in the data complicate trend analysis[45,50]. Issues include improvements to observational systems over time[20,31], the likelihood that some TCs in the early time period were missed altogether, and likely underestimation of intensity for storms over open water, where there are sparse observations.

Among the most robust methods of observing TCs is aircraft reconnaissance, which was performed for the first time in 1943. Dozens of missions are conducted annually, predominantly in the Atlantic basin, to collect data on TCs that pose a threat to land, and for scientific research. In the Atlantic, two different types of missions are generally conducted – upper-air flights to gather data in the storm's surrounding environment, and lower-level flights to collect data inside the storm, including its eye and eyewall. Several meteorological instruments are onboard the aircraft, including Doppler radars. In addition, "dropsondes" released from the aircraft measure meteorological variables such as temperature, wind, pressure, and humidity as they descend to the ocean surface. Aircraft reconnaissance provides the most detailed data on TCs over the ocean, which is fed directly into forecast models and used to assess and forecast intensity, track, and hazards. However, due to limited funding and instrumentation, relatively few missions are conducted in other parts of the world.

The most readily-available tool for observing TCs is satellites. Since the advent of weather satellites in the 1960s, technology has advanced significantly, and coverage of the global tropics using geostationary satellites (those remaining over a fixed location on Earth in its orbit) has improved. The available satellite data record is most comprehensive in the Atlantic and Pacific Oceans, now covered by GOES-16 and GOES-17 (United States) and Himawari-8 (Japan). Deficiencies in coverage over the Indian Ocean were resolved in the 1980s and 1990s, leading to data collection over a time period more sufficient for trend analysis[28].

Satellite imagery provides information on TCs including dynamic and thermodynamic environments, structural integrity, and where regions of intense rainfall might occur, among others. For example, Dvorak[9] used cloud patterns associated with TCs to estimate their intensity. This technique has been improved over the years[44] and has become an integral tool in assessing TC intensity in real time, particularly in basins without consistent aircraft reconnaissance. However, satellite-based estimates of TC intensity remain imperfect compared to in situ (direct) measurements[28].

c) Development of Modeling Techniques

With advances in computing ability over the past several decades, knowledge and forecasting of TCs has accelerated with the help of numerical models, including reanalysis datasets[16,49]. Reanalyses are models meant to simulate past weather using a blend of historical atmospheric and oceanic observations, and solutions of predictive equations for variables like temperature, humidity, etc. governed by theory. Reanalyses have improved over time to better capture the observed frequency and variability of TC activity around the world, and are widely used in research studies, though challenges still exist to capture TC characteristics with full accuracy.

The development of global climate models (GCMs) capable of simulating TCs has enabled projections of TC activity hundreds of years into the future. Newer GCMs generally have resolutions of 25-50 km (~0.25°-0.5° of latitude), and may be run in several configurations. Similar to reanalyses, GCMs struggle to capture some characteristics of TCs, which will be discussed in more detail in the final section. However, the ability of GCMs to simulate the global number and distribution of TCs has improved, making them an increasingly useful tool[4,60,62].

High-resolution modeling, while limited to short time scales, can capture interactions on small scales that factor into TC development. This includes the explicit simulation of clouds and precipitation, which GCMs and reanalyses are unable to explicitly produce. As such, these high-resolution models are particularly useful for understanding TC formation and intensification[5,37,43,61]. Given that our understanding of these processes remains somewhat lacking, advances here could help to develop theory "upscale" – that is, to use our understanding of TCs on small spatial and temporal scales to improve our confidence in large-scale climate projections.

2. RECENT RESEARCH PROGRESS

This section presents a hazard-by-hazard assessment of our current understanding of the relationship between TCs and climate change. We address observed trends in hazards, expected future changes, and confidence in each. Results are presented in descending order of confidence, starting from hazards for which the meteorological community is most certain of observed trends and/or projected changes.

Effective attribution of changes in TC hazards to climate change requires three components: trends in historical observations via statistical analysis, consistent future projection using GCMs, and well-constrained theory that is able to explain these observed changes and expectations. This review will discuss each component, summarized in Table 1 at the end of this section.

a) Flooding

Coastal Flooding: The most confident projection regarding tropical cyclone hazards, particularly relevant to the Florida coast, is storm surge flooding. Even in the absence of changes to TC intensity, frequency, etc., flooding from storm surge is expected to increase simply due to sea level rise[35]. The risk of coastal flooding will increase in general, including calm weather flooding such as that from high tides. Observed evidence for this is already present in South Florida, in the form of King Tides in the Miami area. As greenhouse gas emissions increase globally, ocean temperatures increase, sea ice coverage at high latitudes decreases, and sea levels rise (Figure 2). This is consistent across observations, theory, and modeling, which alone should motivate improvements to coastal infrastructure with flooding risks in mind, especially from TCs.

Inland Flooding: Along with storm surge flooding, there is high confident that flooding rains will also increase with future TCs[23]. A warmer atmosphere is capable of holding an exponentially increasing amount of water vapor via the Clausius-Clapeyron equation, a fundamental thermodynamic relation. Intuitively, increased moisture content increases the potential for extreme rainfall.

Modeling studies are consistent with this theoretical expectation, projecting increases in TC rain rates on the order of 10% for every 1 °C of warming[24]. Distinct trends have not appeared in the observational record of TC rainfall to this point, likely due to challenges in rainfall data collection. However, recent Atlantic storms such as Harvey (2017)[57] and Florence (2018)[48] point to the likelihood of this risk increasing in the future.

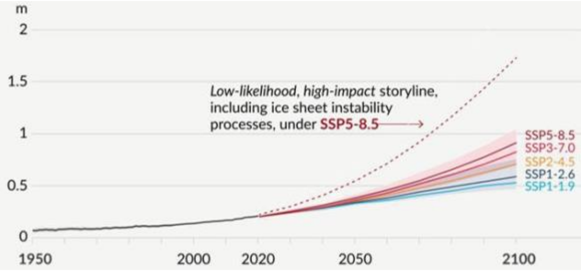

Figure 2: Observed changes and future projections of sea level, from the IPCC 6th Assessment Report (AR6).

What Harvey and Florence also share is their slow translation speed. Recent studies have noted a trend toward slower-moving TCs in the observational record[17,29]. Storms that slow or stall near landfall pose an even greater flooding risk, both from storm surge and rainfall. This is simply because the TC's intense winds and rain remain over a given region for a longer time period. Hurricane Sally (2020) was a recent example in Florida, bringing feet of rainfall to the western Panhandle and notably destroying the Pensacola Bay Bridge. Despite the observed trend toward slower moving storms, model projections and theory are less confident. To a first order, TC motion is dictated by steering from environmental winds. Slower moving TCs would thus most likely be caused by weaker environmental steering winds, such as the easterly trade winds in tropical oceans. Hypotheses exist as to why the trade winds might weaken, but remain under debate[15,33,54]. Nonetheless, theoretical increases in TC rain rate and observed downward trends in translation speed provide a confident projection that the risk of extreme rainfall with TCs will increase with warming.

b) Intensity

Other confident projections in future TC activity relate to intensity (the strength of the winds). TC intensity, especially that of the strongest storms, is expected to increase with warming. This projected increase, agreed upon by nearly all model projections[54], is well supported by theory. Potential intensity (PI)[11] captures the theoretical maximum intensity (speed limit) a TC can attain in its present environment. This limit depends on the difference between sea surface and atmospheric temperatures and is based on conceptualizing the TC as a Carnot heat engine. In the conceptual model (Figure 3), air flowing inward towards the TC at the warm surface extracts energy from the oceans, which is then converted by the TC "heat engine" to power the winds. A warmer ocean surface provides more fuel and favors more intense TCs. PI is projected to increase by roughly 8 m/s for each 1°C SST increase.

To date, little trend in mean TC intensity has been observed globally in the historical record, though there is basin-to-basin variability. However, the proportion of TCs reaching major hurricane strength (Category 3 or higher, or 111+ mph, on the Saffir-Simpson Hurricane Wind Scale) has increased in the last several decades[10,21,25,59], as has the intensity of the strongest storms. This trend is particularly important, as the most intense TCs inherently pose the greatest societal risk. Uncertainties in the historical record limit our ability to unambiguously attribute these trends to climate change, but this trend is consistent with expectations from theory and model projections that indicate the shift toward more intense storms will continue with further warming[22,51].

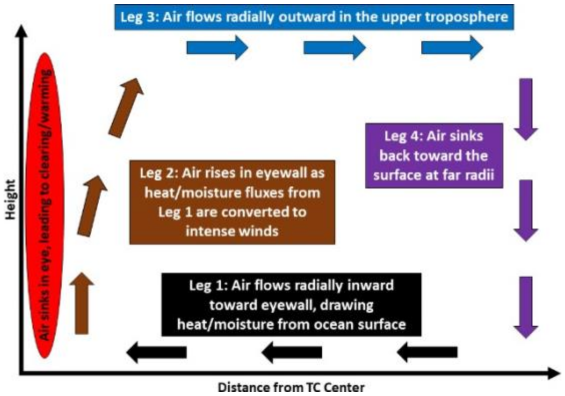

Figure 3: Description of TC as a Carnot heat engine. The eye is indicated by the red circle, while brown arrows indicate rising motion in the eyewall.

Also notable is the occurrence of rapid intensification (RI), defined as an increase in maximum sustained winds of at least 35 mph in a 24-hour period. The 2020 Atlantic Hurricane Season featured a record-tying 10 storms that underwent RI. These included Laura, Sally, and Zeta, all of which made landfall along the United States Gulf Coast at their peak intensities. Given the first-order role of ocean temperatures on TC intensity, the frequency of environments supporting RI is expected to increase with warming[2,46], though distinct trends in observations are difficult to uncover. Rapid intensification is particularly threatening to populations for multiple reasons. First, our ability to forecast RI events lags behind general TC intensity forecasting. Also, RI near landfall provides little lead time for communities to prepare or evacuate, likely amplifying societal impacts. Work is ongoing to improve our understanding of the small-scale physics leading to RI, as our knowledge of the large-scale environments supporting it is stronger.

c) Tracks

In addition to trends toward slower-moving TCs, spatial shifts in the locations where TCs reach their lifetime maximum intensity (LMI) have also been found in observations. Wang and Toumi[58] note a general east to west shift in the location of LMI across several basins (including the Atlantic), which results in LMI occurring closer to land in recent decades. This would amplify all TC risks to coastal regions. Some GCM projections also suggest a shift in TC tracks closer to land masses at the western ends of ocean basins[41]. However, further research is necessary, including the development of theoretical explanations for this behavior.

Observations have also revealed a poleward shift in the latitude of LMI across several basins[26,27]. This may suggest an increased risk for intense TC impacts at higher latitudes less accustomed to TCs, such as the United States Mid-Atlantic coast. Hypotheses for this shift relate to the expansion of the mean meridional overturning circulation in the tropics, otherwise known as the Hadley circulation. Expansion of this circulation leads to a poleward shift of its descending branch, which corresponds to subtropical high pressure regions. Subtropical highs are fundamental in steering TCs, so a poleward shift of them would likely allow more TCs to move toward higher latitudes. Like east-west shifts in the location of LMI, some modeling studies suggest a continuation of this trend[27], but confidence remains limited until more modeling and theoretical progress is made[42].

d) Formation

Confidence is most limited in projections and understanding of TC frequency[38,39]. About 80-90 TCs form per year globally, a number which has held largely steady over time with very little trends[18]. Our understanding remains poor as to why this is the case – why there are not 8 or 800 TCs per year, for instance[52]. Despite decades of research into the physics of TC formation, both from modeling and observational data, a universally accepted theory has not yet been developed[8,36,47]. It is likely that our confidence in the physical mechanisms causing TCs to form must improve to develop a larger-scale climate theory for TC number.

Given these difficulties in theory and observations, one might also expect future modeling projections to struggle to reach a consensus. Indeed, this is the case, as GCMs conflict on future trends in TC frequency more than on the other characteristics previously discussed. Much of the early work on TC frequency projected little changes with warming, or a modest decrease[6,53]. As higher-resolution models have been developed in recent years, this outcome is still suggested by many GCMs. However, some newer models and other modeling techniques have begun to suggest increases in TC frequency as well[2,13,64,65], at least in specific ocean basins[32,40]. This model disagreement compounds with the lack of theoretical understanding or observed trends. Simply stated, we do not yet know how TC frequency will change. Reasons for these complications, and important caveats regarding other risk assessments, will be discussed next.

HAZARD	THEORY	OBS	MODELS
Coastal Flooding	Strong	Strong	Strong
Inland Flooding	Strong	Medium	Strong
Winds	Strong	Medium	Strong
Track	Medium	Medium	Medium
Frequency	Weak	Weak	Weak

Table 1: Summary of confidence in various tropical cyclone characteristics.

3. CHALLENGES/FUTURE WORK

While substantial progress has been made to understand the impacts of climate change on TCs, there are several significant obstacles to overcome. These affect each component required to perform effective attribution: observations, models, and theories.

To build confidence in observed trends in various TC characteristics, decades of future data will likely be necessary. First and foremost, we are likely missing many storms entirely from the period before satellite coverage was widespread. Various correction schemes have been developed in an attempt to account for these unobserved storms, but are largely empirical in nature. In addition, the Satellite Era is not without heterogeneity. Satellite coverage over the Indian Ocean was problematic until the 1990s, and gradual improvements in technology have improved our ability to track TCs relative to 50 years ago. Each of these factors complicates trend analysis, especially in TC frequency.

Another hurdle to navigate in observations is the role of interannual and multidecadal variability on TC activity[34,55,63]. For example, there is observed variability in Atlantic Ocean temperatures and TC frequency on time scales of 20-40 years, though the cause of this is debated. Both natural and anthropogenic forcing may contribute. A cool period of Atlantic temperatures from the 1960s-1990s corresponded to a period of reduced TC activity, which reversed around 1995. In addition, modes of variability in one basin often affect activity in another, such as the role of El Nino-Southern Oscillation (ENSO) on Atlantic TCs.

Models form much of the foundation of our future projections, especially when theory and observations lag behind. However, models also have limitations, especially related to horizontal resolution. To perform simulations spanning dozens to hundreds of years, GCMs operate on a coarse grid which fails to resolve many small-scale processes integral to TCs. Instead, models often rely on parameterizations, tools to approximate a variable such as precipitation given some set of large-scale conditions. As a result, GCMs tend to underestimate TC intensity, since the strongest winds are in the poorly-resolved inner core. In addition, GCMs portray other TC characteristics quite differently based on their configuration – choice of physics packages and parameterizations, warming scenarios, coupling to an ocean model, etc. For these reasons, we usually study a large ensemble of models rather than one individual case when possible, to best inform us of a range of different possibilities. Model depiction of TCs is steadily improving, but still has potential for further advances.

Along with development of model and observational datasets, work is ongoing to improve our fundamental knowledge and theory of TCs. Arguably the most pressing question currently is what sets the global frequency of TCs, and how this might change. Other areas being addressed include the physics of TC formation, small-scale processes leading to intensification, and the environments and storm characteristics that favor rapid intensification. Continued work in each will improve forecast quality and warning communication in the short term, while also informing our models and future projections on climatic time scales.

Several recent storms hint at the TC risks that climate change is likely to enhance moving forward. This topic is of great importance to the meteorological community, with a growing number of scientists seeking to improve our knowledge in the public interest. With rapid population and infrastructure growth along the coasts over the past several decades – growth which will very likely continue – this research continues to become more imperative each year.

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