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2017 Coastal Master Plan

Attachment C2-4: Tropical Storm Intensity and Frequency

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement and enforce a comprehensive coastal protection and restoration master plan.

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Executive Summary

Tropical storms pervade all aspects of the Louisiana Coastal Protection and Restoration Authority's (CPRA) 2017 Coastal Master Plan modeling initiative. Potential changes in tropical storm frequency and intensity during the next 50 years, in part caused by natural climatic fluctuations but also by global warming, must be considered in order to fully capture the future threat of damages caused by hurricanes across the coast. All of the landscape models to be utilized for the 2017 Coastal Master Plan will be capable of efficiently simulating 50-year time periods and predicting project effects at a basin scale, given a specific set of storm characteristics and parameters for which they are intended to withstand. As such, an accurate measure of the frequency and intensity of tropical storms for the region is vital for all modeling systems.

Based upon the detailed literature review and professional judgment, adjustments in potential tropical storm intensity and frequency were made through year 50, with increases in overall intensity and decreases in overall frequency. The spatial and temporal considerations also provided insight into the vulnerability of specific areas within the CPRA region.

The updated historical record provided clear evidence of an increasing trend in tropical storm intensity since 1980. A review of the teleconnections between global and regional climate systems with tropical storm intensity and frequency showed a distinct relationship with phases of the El Niño Southern Oscillation (ENSO) and Louisiana hurricane strikes. This combined knowledge will aid the planning process, including the consideration of future scenarios.

Due to the complex interactions of global and regional climate forcings, uncertainty surrounding future emissions and warming scenarios, and the limited historical record, estimates for future tropical storm frequency and intensity build off of a robust collection of literature to determine plausible ranges of potential change. Eight ambitious modeling efforts project potential changes in tropical storm intensity using central pressure deficit, wind speed, and power dissipation index (PDI). The plausible range of tropical storm intensity by year 50 provided by these documents was a 4% to 23% increase in intensity, measured by central pressure deficit. The plausible range of future tropical storm frequency was split into two categories: all tropical storms and major hurricanes. All tropical storms showed a decrease of 28% to approximately 0%, while major hurricanes showed an increase in frequency of 13% to 83%. These figures were based on projections of Atlantic Basin changes only, although studies analyzing potential changes in the Pacific and global basins were noted. A detailed review of the models considered for selecting the ranges, as well as a brief literature review and justification for setting the range, are available within each section of this document.

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List of Abbreviations

ACE	Annual Accumulated Duration
AMO	Atlantic Multidecadal Oscillation
C	Celsius
CAPE	Convective Available Potential Energy
CLARA	Coastal Louisiana Risk Assessment
CMIP	Coupled Model Intercomparison Projects
CO_2	Carbon Dioxide
CPRA	Coastal Protection and Restoration Authority
ENSO	El Niño Southern Oscillation
GCM	Global Climate Model
H	Hurricane
hPa	Hectopascal
hr	Hour
IPCC	Intergovernmental Panel on Climate Change
km	Kilometer
kt	Knot
mbar	Millibar
MH	Major Hurricane
MPIv	Maximum Potential Intensity for Velocity
PDI	Power Dissipation Index
SST	Sea Surface Temperature
TS	Tropical Storm
WCPR	World Climate Research Program
WRF	Weather Research and Forecasting

1.0 Introduction

Tropical storms pose multiple risks to coastal communities in Louisiana, like storm surge flooding, wetland loss, and high wind damages. A recently developed tropical hazard index, the combined measure of all tropical storms to hit a specific location, found that southeast Louisiana was the most at-risk region on the Gulf coast for hurricane strikes from 1901-2005 (Keim et al., 2006). Accounting for potential changes in storm intensity and frequency during the next 50 years is vital for the Coastal Protection and Restoration Authority (CPRA) in modeling the effectiveness of coastal protection and restoration projects. This report builds on the findings of the 2012 Coastal Master Plan, focusing on new literature, but also updates to the historical record of tropical storm behavior. The findings of this study suggest considerable increases in tropical storm intensity, marginal changes in the frequency of weaker tropical storms, and significant increases in the frequency of major hurricanes (Category 3-5) could occur by 2065.

Projections of changes in future hurricane intensity were measured in wind speed and barometric pressure (mbar), and the frequency of all tropical storm and major hurricane events, as determined by the literature provided in this review. Changes in frequency were gauged by the number of tropical storms forming in the Atlantic Basin and by the proportion of major hurricanes. Because of the varied terminology used to describe tropical storm intensity, the following terminology will be used throughout this document:

- Tropical storm (TS): includes all tropical waves, tropical depressions, tropical storms, and hurricanes of all intensities on the Saffir-Simpson[1] scale
- Hurricane (H): a developed hurricane with minimum winds of 74 mph (64 kt, 119 km/hr), including all categories on the Saffir-Simpson scale (1-5), but excluding tropical storms and tropical depressions.
- Major hurricane (MH): hurricanes that reach maximum sustained 1-minute surface winds of at least 111 mph (96 kt, 178 km/hr). This is the equivalent of Category 3, 4, and 5 on the Saffir-Simpson scale.

1.1 Updated Historical Trends

The ability to monitor and project hurricanes with a high degree of accuracy has only been developed since the beginning of hurricane flight monitoring in the 1940s, and later with the satellite era (1970s onward), which makes hindcasting and assessments of long-term trends extremely limited. Historical and instrumental records of tropical storms date back to the 1800s, with paleoclimate data extending even further back in time. However, proxy data is a poor tool for analyzing tropical storm trends over such long durations. What is known of the historical trends of tropical storms is that they are highly dependent on the natural cycles of the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO; IPCC, 2013). When considering increases in tropical storm activity during the last few centuries, it is important to note that records of pre-instrumental data are limited to only the most devastating landfalling hurricanes.

[1] The Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained wind speed. This scale estimates potential property damage. Hurricanes reaching Category 3 and higher are considered major hurricanes because of their potential for significant loss of life and damage. Category 1 and 2 storms are still dangerous, however, and require preventative measures.

Villarini and Vecchi (2012) identified an increasing trend of tropical storm frequency driven by radiative forcing during the first half of twentieth century. However, the trend became ambiguous for the entire twentieth century overall (Villarini & Vecchi, 2012). Emanuel (2005) has shown that since 1949 the annual accumulated duration (ACE) of North Atlantic and Western North Pacific storms that impact the east coast has increased by about 60%, and in the same period the average wind speed has increased by 50%. ACE is an approximation of the wind energy used by a tropical system over its lifetime and is calculated for every 6-hour period. Concurrently, major hurricanes have doubled in proportion, although globally the total number of hurricanes has remained approximately the same. Particularly in the North Atlantic, a strong correlation between increasing sea surface temperature (SST) has been observed simultaneously with a significant increase in tropical storm duration and frequency (Arpe & Leroy, 2007; Emanuel, 2005, 2007; Webster et al., 2005).

The Third U.S. National Climate Assessment (2014) showed that the intensity, frequency, and duration of North Atlantic tropical storms, as well as the frequency of major hurricanes (Category 3-5), have all increased since the early 1980s. In addition, Kossin et al. (2013) found an increasing trend of tropical storm intensity in the North Atlantic during the period 1982-2009. Those results are supported by Holland and Bruyere (2013), who found an increasing trend in the proportion of Category 4-5 hurricanes of 40% per degree Celsius SST rise that is directly attributed to anthropogenic global warming. For perspective, the Intergovernmental Panel on Climate Change (IPCC, 2013) and U.S. National Climate Assessment (2014) projected a combined range of 1.5° to 3.5° SST increase by 2100, or an additional 60% to 140% increase in the proportion of MH based on Holland and Bruyere (2013).

The most recent increases in hurricane activity coincided with a SST shift to a warm AMO, caused by natural variability, and accelerated by heat retention of the upper and deep oceans caused by global warming (IPCC, 2013). The literature cited in this report has examined potential changes in hurricane intensity and frequency caused by both natural variability and human-induced climate change.

1.2 Teleconnections

Tropical storms are powered by interlinked regional and global climate mechanisms, or teleconnections. Teleconnections are defined by a positive or negative correlation between meteorological processes that can occur over a long distance. For example, tropical storms are twice as likely to strike Louisiana in a La Niña year, or the ENSO during a "cool" phase (IPCC, 2013; Table 1), ENSO describes a SST change in the Pacific Ocean from warm (El Niño) to cool (La Niña). "Neutral" describes a phase that is neither warm nor cool, but within the average range between phases. For the entire Gulf coast, hurricane strikes are most likely during a strong La Niña phase, with a 93% chance of a hurricane landfall and 72% chance of a major hurricane landfall during those years, based on data from the last century (Table 2). Other global and regional processes, like the AMO, also greatly impact the intensity and frequency of tropical storms, as well as their tracks (Klotzbach, 2011; Table 3).

There is a rapidly growing body of research concerning the regional and global teleconnections between climate systems and ENSO in a warming world. Borlace and Cai (2013) found increasing amplitude of ENSO cycles since the late twentieth century, but paleoclimate data show that the fluctuation in amplitude may be within the range of natural variability. While the links between mean climate and ENSO amplitude are still unclear, models of the teleconnections of systems influencing ENSO show that ENSO is sensitive to CO_2 concentrations (Stevenson et al., 2011). Additionally, global warming is projected to impact both the mean state of the tropical Pacific, which drives ENSO, and non-linearities observed in the ENSO record

(Boucharel et al., 2011). Those findings are supported by Gergis and Fowler (2008), who found that 30% of ENSO variance since 1525 occurred after 1940.

Table 1: Louisiana annual impact probability during ENSO phases (Klotzbach, 2011).

	El Niño: Hurricane	**El Niño: MH**	**Neutral: Hurricane**	**Neutral: MH**	**La Niña: Hurricane**	**La Niña: MH**
Probability of impact (%)	25	13	26	12	34	11

Table 2: Gulf coast annual impact probability during El Niño, Neutral, and La Niña phases (Klotzbach, 2011).

ENSO Phase	**Hurricane**	**Major Hurricane**
El Niño	44	22
Neutral	60	29
La Niña	78	42
Strong El Niño	49	18
Strong La Niña	93	72

Table 3: Gulf coast annual impact probability during ENSO and AMO phases (Klotzbach, 2011).

Negative AMO:	**Hurricane**	**Major Hurricane**
El Niño	31	12
Neutral	60	31
La Niña	82	47
Positive AMO:	Hurricane	Major Hurricane
El Niño	56	37
Neutral	61	27
La Niña	74	37

Increases in lower tropospheric absolute vorticity, mid-tropospheric relative humidity, and Emanuel's (1995) hurricane maximum potential intensity for velocity (MPIv) have also been linked to increased hurricane activity (Vecchi & Soden, 2007). Vertical wind shear, another important component of hurricane formation and strength, is also likely to increase (Vecchi &

Soden, 2007). Wind shear inhibits tropical storm development and reduces the wind intensity of developed systems. Still, the single most influential factor of tropical storm intensity and, to a lesser extent, frequency, is SST. From Trepanier (2014): "As the oceans' surfaces increase in temperature, the maximum intensity for hurricanes is expected to increase most significantly over the Gulf of Mexico, the Caribbean Sea, and the western Atlantic."

2.0 Hurricane Intensity

Figures from eight recent academic publications were used to determine a plausible range of hurricane intensity from 2015-2065. While more than 50 articles were reviewed for the range, only eight presented high-resolution data for central pressure and wind speed within the timeframe. Those papers which did not provide figures for the total range or did not consider changes in central pressure were used as supporting documents for the Risk Assessment modeling team in determining ranges of future hurricane intensity. A summary of all of the models evaluated for the range of future hurricane intensity changes can be found in Table 4.

In basic atmospheric theory, a storm's intensity increases with higher SSTs (Emanuel, 1987; Emanuel, 2007; Emanuel et al., 2007). In a review of predictive models, Knutson et al. (2010) found that storms were becoming more intense globally as a result of rising SSTs, experiencing an increase in wind speeds of up to 11%.

The plausible range of future hurricane intensity was selected based on modeling resolution, timeframe, study location, and methodology. Six of the eight models used for the intensity range used the World Climate Research Program (WCPR) Coupled Model Intercomparison Projects (CMIP) data, downscaled from the IPCC's 200 km resolution to 2, 6, 9, or 18 km resolution. The two versions of the IPCC CMIP project (CMIP3 and CMIP5) were used under varying future temperature conditions, including the A1B scenario which is a moderate rise in temperature based on future greenhouse gas emissions. CMIP3 was the first collection of models used for the 2007 IPCC report. The downscaled CMIP5 projections, the most recent compilation from WCRP, divides its tropical storm projections into early (2016-2035) and late (2081-2100) twenty-first century time slices, taking historical data from 1981-2010 and changing the conditions to those projected under the future SST scenarios.

The use of local SST versus relative Atlantic SST or global SST yielded significantly different results in PDI; for example, Emanuel (2013) found that 2° C warming of the tropical Atlantic would result in a 300% increase in PDI using local SST, whereas Villarini and Vecchi (2013) found relatively smaller (± 60%) changes in PDI through 2100 using relative SST. Swanson (2008) found that Atlantic PDI is also correlated to indices of Atlantic SST relative to tropical mean SST. These two correlations led to projections of future Atlantic hurricane activity where the former correlation indicates a large increase in Atlantic activity and the latter suggests a minimal increase in Atlantic PDI (Knutson, 2013).

2.1 Units for Assessing Changes in Intensity

Four units of measurement were considered for determining the plausible range of future hurricane intensity: mean maximum central pressure drop, central pressure deficit, maximum wind speed, and power dissipation index (PDI). Emanuel et al. (2013) found that barometric pressure was a better indicator of hurricane damage (cost in billions) than wind speed, and that a 1% reduction in barometric pressure resulted in a doubling of storm damage, and a 20% increase in wind speed also doubled storm damages. Since tropical storms in the Coastal

Louisiana Risk Assessment (CLARA) model are varied based on minimum central pressure, each of the four units of measurement were adjusted to reflect changes in the simulated hurricane intensity.

2.1.1 Mean Maximum Central Pressure Drop

Two studies analyzed the change in mean maximum central pressure drop for measuring future storm intensity measured in millibars (mbar). Mousavi et al. (2010) projected central pressure drop in the Gulf of Mexico and North Atlantic basins for the period 2015-2065 with varied resolution, using SST increases ranging from 1° to 5° C. The model used two six-month average projections of changes in SST starting at year 2000 for the 2030s and 2080s, resulting in a central pressure intensification of 0.14 to 0.45 mbar per year. For year 25 and 50 of the 2017 Coastal Master Plan, Mousavi et al. (2010) found a mean maximum central pressure drop increase of +4 to +11 mbar and +7 to +23 mbar, respectively. As a percent, the range for years 25 and 50 are +4% to 10% and +6% to +20%, respectively. Kanada et al. (2013) simulated six MHs under A1B conditions for 2075-2099 and found a range of +4 to +27 hPa increase in central pressure drop, which is consistent with Mousavi et al. (2010). The range translated as a percent is +4% to +23% increase in the difference between environmental and tropical storm central pressure. Combined, the two papers provide a mean maximum central pressure drop increase of 3.5% to 23% by year 2065.

2.1.2 Central Pressure Deficit

Central pressure deficit is another way of describing the intensity of tropical storms. Central pressure deficit is a measure of the difference between the environmental pressure and the central pressure of the system, expressed as:

$$P_D = (p_R - p_o) \qquad (1)$$

where p_R is the environmental pressure (hPa), and p_0 the central pressure (hPa).

The range for increase in central pressure deficit, based on Knutson and Tuleya (2004), Hill and Lackman (2011), and Mallard et al. (2013), is +10% to +23%. Knutson and Tuleya (2004) examined the order of magnitude of hurricane sensitivity per degree Celsius SST warming. The results showed an increase of intensity range of 1% to 8% per degree Celsius SST warming, with a statistically-significant average of sensitivity of 4°C per degree warming. When considered against estimates of future SST rises, this figure translated to a range of +4% to +11% increase in central pressure deficit by 2065. Knutson and Tuleya (2011) later averaged a 14% increase in central pressure deficit based on downscaling at a higher resolution. Hill and Lackman (2011) used 6 km and 2 km resolution downscaling of the Weather Research and Forecasting (WRF) model to assess future changes in hurricane intensity. At the 6 km resolution, they found an increase of +9% to +12% in central pressure deficit. However, at the higher-resolution level, 2 km, the authors found a +11% to +19% increase in central pressure deficit. Mallard et al. (2013) found results very similar to Hill and Lackman (2011), for a total increase in central pressure deficit of +11% to +19%. Together, the three papers result in an increase of +4% to +19%. Those figures are consistent with the Mousavi et al. (2010) and Kanada et al. (2013) mean maximum central pressure drop figures above.

2.1.3 Maximum Wind Speed

The maximum sustained wind speed associated with a tropical storm is a common indicator of the intensity of the storm. Within a mature tropical storm, it is found within the eye wall at a distance defined as the radius of maximum wind. Maximum wind speed can also be related to central pressure (Takashi, 1939) by:

$$V_{max} = K^*(P_D)^{1/2} \quad (2)$$

where V_{max} is the maximum surface wind speed (kt) and K is a constant (K=16 based on Mcknown et al., 1952).

Knutson et al. (2013) used a downscaling approach of CMIP3 and CMIP5 data to determine potential increases in wind speed for 2001-2100 (A), 2016-2035 (B), and 2081-2100 (C) under A1B conditions. The results showed a mean increase of maximum wind speed of 6.7% (A), 3.8% (B), and 5.2% (C).

Using the equation from Takashi (1939) and constant from Mcknown et al. (1952), the plausible range for the CLARA model storms' central pressure would be +4% to +12%. The results of the wind speed to pressure calculation (Knutson et al., 2013) suggest a smaller range in plausible changes of in mean maximum central pressure drop, but are still consistent with the previous findings.

2.1.4 Power Dissipation Index (PDI)

PDI is an aggregate measure of hurricane activity in a single index. The PDI is highly correlated with tropical Atlantic SST (Emanuel, 2008). Two of the studies considered in this analysis used PDI as a measure of hurricane intensity. Vecchi et al. (2008) created a linear trend through 2100 of increasing PDI based on absolute and relative SST increases. It is important to note, however, the linear trends of PDI do not capture the inherent variability of ENSO and AMO cycles to the same degree the "time slice" models do. Villarini and Vecchi (2013) used downscaling of CMIP5 for 2016-2035 under low (A), moderate (B), and high-emission (C) scenarios as defined by the IPCC. While wind speed and pressure are highly correlated with PDI, the figures cannot be converted to direct change in pressure. Thus, these figures are used as supporting data to the previous models.

2.2 Range

Plausible range for tropical storm intensity change over 50 years: +4% to +23% increase in central pressure deficit.

2.3 Supporting Information for Selecting the Range

Knutson and Tuleya (2004) averaged a 14% increase in central pressure fall, a 6% increase in maximum surface wind speed, and an 18% increase in average precipitation within 100 km of the storm center. The model used an increase of up to 21% in convective available potential energy (CAPE; Knutson & Tuleya, 2004). Knutson and Tuleya (2004) estimated that for every degree Celsius SST increases, the order of magnitude of hurricane sensitivity is about 4%; for near-storm rainfall rates the increase was upwards of 12%. This change occurs for an idealized climate change scenario consisting of an 80-year increase of CO_2 at 1% compounded (which produces SST increases ranging from 0.88 to 2.48° C in the tropical storm basins in the CMIP3 models).

Vecchi et al. (2008) determined that by 2100 models project lower bound 5-year average hurricane intensity comparable to the intensity of the 2005 season. The upper bound of the model 5-year average exceeded the 2005 levels by more than a factor of 2. Other studies (e.g., Mousavi et al., 2010) showed that hurricane intensification increased 0.32 to 0.45 mbar per year, or 16 to 22.5 mbar, on average, by 2065. Mousavi et al. (2010) also found that over the one-day period around the peak surge, at all study locations, hurricane surge increased 10% to 15% per 10 mbar of central pressure drop.

Hill and Lackmann (2011) used high-resolution simulations to compare the period 2090-2099 to 1990-1999 over the western half of the Atlantic "Main Development Region", and concluded that there may be a 12% to 16% increase in central pressure deficit between the two time periods.

Villarini and Vecchi (2012) applied a statistical model to outputs from 17 global climate models (GCMs) produced under CMIP5 to project that mean PDI values over 2016-2035 may be 20% larger than the corresponding PDI values during 1986-2005, and the multi-model mean PDI values over 2046-2065 may be between 50% and 75% larger than the values documented for the reference period of 1986-2005.

Knutson et al. (2013) showed that the lifetime-maximum hurricane intensity may increase by 4% to 6% for CMIP3 and CMIP5 ensembles for late twenty-first century (2081-2100). Knutson et al. (2013) also examined the geographical distribution of storm tracks of a warmer world, looking specifically at track changes of Category 4 and 5 storms. The authors found that the occurrence of Category 4 and 5 storms increased in the Gulf of Mexico region. In addition, for tropical storms with winds exceeding 65 m/s-1, which occur on average once per decade, Knutson et al. found a fivefold increase (one every two years).

Emanuel (2013) showed that the PDI of all tropical storms may increase by as much as 45% during the twenty-first century. In contrast to other studies which generally indicate a decline in frequency, he attributed nearly half of the increase in intensity to the increase of tropical storm frequency (Emanuel, 2013). Emanuel (2011) also found that annual U.S. tropical storm accumulated damage would increase by about $6 billion by 2065, with annual damages increasing 100% per year, on average.

Mallard et al. (2013) simulated the 2005 and 2009 hurricane seasons under future A1B scenarios (est. year 2100) and found minimum central pressure reductions between 11% and 19%, along with increases in near-storm rainfall between 10% and 30%, depending on the emission scenario used. The 6 km ensembles simulated a greater percentage of tropical storms with a central pressure deeper than 960 hPa. Past studies have generally found that intensity is increased by the use of higher resolution (e.g., Gentry & Lackmann, 2010).

Models analyzed in the fifth IPCC report (2013), ranging from 100 km to 9 km resolution, also showed a likely increase of tropical storm peak winds. More specifically, models projected an additional 3% to 5% increase in wind speed per degree Celsius increase of tropical SST. The studies also projected an increase in near-storm precipitation by as much as 30% (IPCC, 2013).

Table 4: Summary of resources used for analyzing changes in tropical storm intensity.

Source	Summary	Measure	Resolution	Region	Timeframe	Change
Knutson and Tuleya (2004)	CO_2-Induced Warming on Simulated Hurricane Intensity	Central Pressure Deficit	9 km	Global	2004-2084	+14%
Vecchi et al. (2008)	Analysis of PDI with absolute and relative SST increases	PDI anomalies		Atlantic	2015 (A), 2025 (B), 2035(C), 2045 (D), 2055 (E), 2065 (F)	+2.5% (A), 3% (B), 3.6% (C), 4.3% (D), 5.2% (E), 6.5%(F)
Mousavi et al. (2010)	Mean 6-month average projections of change in SST for A1B, B1 and A1F1	Mean maximum central pressure drop	Highly varied	Atlantic	2015-2065	16 to 22.5 mbar
Hill and Lackmann (2011)	Analysis of A1B, A2, B1 scenarios mean results from IPCC AR4 report	Central Pressure Deficit	2 km and 6 km	Atlantic	2090-2099	+9% to +19%
Villarini and Vecchi (2013)	Downscaling of CMIP5 for RCP2.6 (A), RCP4.5 (B), and RCP8.5 (C)	PDI		Atlantic	2016-2035	+10% (A), +17% (B), +23% (C)
Knutson et al. (2013)	Dynamical downscaling CMIP3 (A) and CMIP5(B and C)	Max. wind speed	9 km and 18 km	Atlantic	2001-2100 (A), 2016-2035 (B), 2081-2100 (C)	+6.7% (A), +3.8% (B), +5.2% (C)
Mallard et al. (2013)	Downscaling ensemble models and isolating thermodynamics using A1B	Mean maximum central pressure drop	6 km and 18 km	Atlantic	2100	+11% to +19%
Kanada et al. (2013)	Analysis of 6 simulated major hurricanes using A1B and AGCM20	Mean maximum central pressure drop	20 km	Global	2075-2099	+4 to +27 hPa

3.0 Tropical Storm Frequency

By late this century, models, on average, project a slight decrease in the annual number of tropical storms, but an increase in the number of major hurricanes (Category 3-5; Knutson et al., 2010) for the Atlantic Basin. The projected range of the future global frequency of tropical storms is considerably larger and less certain than the projections for future tropical storm intensity. A few years ago, the general consensus was that tropical storms were projected to either stay the same or slightly decrease in the future (Knutson et al., 2010). Knutson et al. (2010) reviewed tropical storm projections since 2006 and found that most high-resolution models projected a slight decrease in the frequency of globally averaged tropical storms (-20% to -27%) and a significant increase (+39% to +87%) in the frequency of major hurricanes.

However, a recent paper by Emanuel (2013) indicated that global tropical storm frequency may increase by as much as 40% by 2075, with most of the increases observed in the Pacific and Indian Ocean basins. Supporting Emanuel (2013), Bender et al. (2010) reproduced both high intensity storms (Category 3 and higher) as well as weaker storms in a warmed climate using an ensemble of 18 high-resolution models and found up to a 220% increase in the number of storms with wind speeds greater than 145 mph (Category 4 and 5). Specifically, Grinsted et al. (2013) projected that the frequency of Hurricane Katrina magnitude events would double with a temperature increase of 0.4° C.

The disagreement among published results concerning increasing or decreasing North Atlantic tropical storm trends in a warmer climate can be largely explained (close to half of the variance) in terms of the different SST projections (Atlantic minus tropical mean) of the different climate model projections (Villarini & Vecchi, 2012).

Continued and accelerated warming SSTs in the Gulf of Mexico could result in more frequent hurricanes in the Gulf (Dailey et al., 2009). Other studies suggest that tropical storm tracks in the North Atlantic may shift northwards in a warming climate, leading to fewer Gulf coast strikes (Colbert et al., 2011; Colbert et al., 2013). The spread of potential changes in hurricanes (summarized by Table 5) presents difficulties in considering the frequency of tropical storm strikes in Louisiana. The range for future hurricane frequency changes was selected from the eight papers (Table 6) with Atlantic Basin-specific projections within the 2065 timeframe of the master plan.

3.1 Range

Plausible range for hurricane frequency:

a) For all tropical storms, -28% to no change in frequency.
b) For major hurricanes, +13% to +83% change in frequency.

3.2 Supporting Information for Selecting the Range

Bengtsson et al. (2007) projected that the total number of Atlantic tropical storms will be reduced by 10% over the twenty-first century, while the number of storms with maximum wind speeds greater than approximately 112 mph (Category 3 or higher) will increase by at least 30%. Zhao (2009) tested the statistical relationship between tropical storms and an increase in CO_2 and found that global tropical storm frequency will decrease 11% to 20% under the condition of increasing CO_2 and increase in SST. Zhao also found that models consistently under-predict the number of projected Atlantic tropical storms when comparing modeled to observed seasonal and annual trends.

Dailey et al. (2009) evaluated the relationship of SSTs and tropical storm landfall risk. According to the analysis, under a warmer SST scenario, storm genesis in the northern Gulf of Mexico will increase, but the close proximity to land will likely not allow enough time for these storms to intensify before moving over land and dissipating. For weak tropical storms, there was a 14% increase in the frequency of tropical storms making landfall in the Gulf, but almost no discernible change in the frequency of stronger, hurricane-strength tropical storms in either warmer or cooler SST conditions (Dailey et al., 2009). Those results have been challenged by other models that found near-opposite results (e.g., Bender et al., 2010, Knutson et al., 2013, and Emanuel, 2013).

In Villarini (2010), frequency of north Atlantic tropical storms was modeled by a conditional Poisson distribution with a rate of occurrence parameter that is a function of tropical Atlantic and mean tropical SSTs. The results showed minor changes in the frequency of all tropical storms ranged from a slight decrease (2%) to a slight increase (4%).

In addition, a compilation from the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory was able to reproduce both high-intensity tropical storms (Category 3 and higher) as well as weaker storms in a warmed climate using an ensemble of 18 high-resolution models (Bender et al., 2010). Similar to the findings of Knutson et al. (2010), the models in the Bender et al. (2010) compilation projected a decrease in the overall frequency of all tropical storms and weaker hurricanes, and a doubling of major hurricanes globally. The ensemble-mean change in frequency for Category 4 and 5 hurricanes showed a 10% increase in frequency by decade, about 50% increase by 2065. The model averaged an increase of 11% for Category 4-5 hurricanes frequency per degree Celsius SST and a decrease of 7% in the proportion of Category 1-2 hurricanes.

Knutson et al. (2013) projected that there will be a significant decrease (20%) in overall tropical storm frequency but a significant increase (45%) in the frequency of major hurricanes during early twenty-first century in the Atlantic Basin. Knutson et al. (2013) used multiple downscaling methods to examine future hurricane frequency at the Atlantic regional 50 km, 18 km, and 9 km grid. The ensemble analysis used a linear trend based on 1991-2008 tropical storm activity to project forward to 2100, then computed the difference between the 2081-2100 minus the 2001-2020 as climate change perturbation. The results from the regional model showed a 20% decrease in all Atlantic tropical storm frequency for the period 2016-2035. However, for the same period, the model showed an 83% increase in the global frequency of Category 4 or greater hurricanes. Knutson et al. (2013) also projected that during CMIP5 conditions, tropical storms shifted toward the Gulf of Mexico and Florida region, and concluded that 55% of the variance between models was due to statistical downscaling.

Mallard et al. (2013) simulated future hurricane frequency at 18 km and 6 km resolution in the Atlantic Basin using ensembles of monthly basin-scale simulations run with present-day initial boundaries conditions and then run again with future temperature and moisture conditions. This study showed significant decreases in the total number of annual hurricanes (28% for hurricanes and 18% for major hurricanes). Part of the variability between Mallard et al. (2013) and other models is the additional 10% CAPE configured in the modeling process. Mallard et al. (2013) increased CAPE in their assessment by 10% based on Hill and Lackmann et al. (2011), which resulted in fewer overall hurricanes. In an increasing CO_2 environment, reduced upward mass flux suppresses hurricane genesis. If SST continues to increase but greenhouse gas emissions stay fixed, increased moisture and static stability reduce upward motion (Mallard et al., 2013).

In contrast, Emanuel (2013) used downscaled climate models, which projected a total increase of tropical storm frequency in the range of 10% to 40% (Figure 1). Emanuel's study also captured spatial and seasonal variability based on ENSO and AMO cycles. The model ran 600 events per year globally for the period 1950-2100, then averaged the change in frequency of tropical storm by decade. The model assumed RCP8.5 conditions. Supporting Emanuel's research, researchers investigating historic storm patterns in the Northern Gulf of Mexico found an increase in the frequency of weak tropical storms if SSTs are raised (IPCC, 2013).

Murakami et al. (2014) used 10 MRI-AGCMs representing different versions (versions 3.1, 3.2, and 3.3), different resolutions (20, 60, 120, and 200 km mesh), and different cumulus convection schemes of the model. The analysis also indicates that projected future changes in the frequency of the occurrence of storms tend to be underestimated in the Atlantic (-53% bias). The ensemble-mean reanalysis for all tropical storms under A1B (A) , RCP4.5 (B), and RCP8.5 (C) scenarios found decreases of 12.8% (A), 18.1% (B), and 28.4% (C) by 2075-2099.

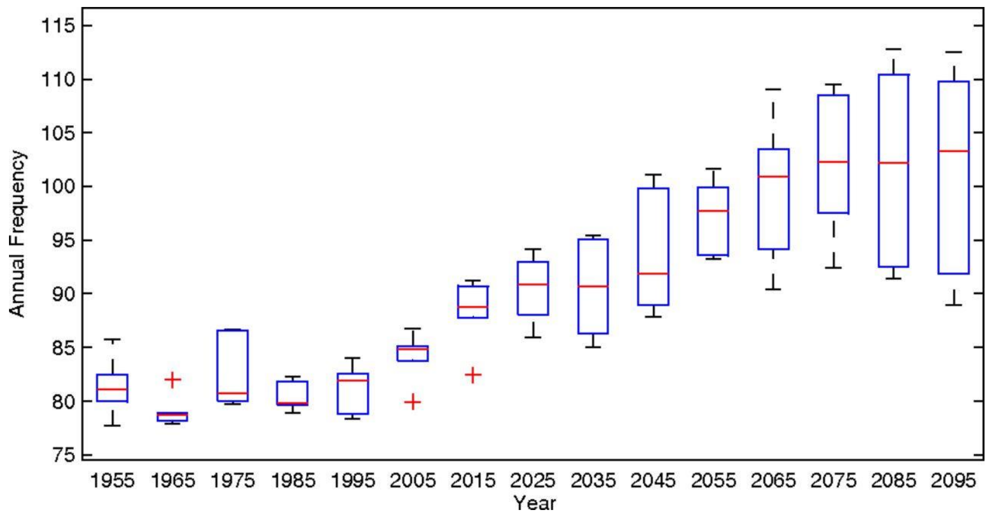

Figure 1: Global annual frequency of tropical storms averaged in 10-year blocks for the period 1950–2100, using historical simulations for the period 1950–2005 and the RCP8.5 scenario for the period 2006–2100 (Emanuel 2013).

Table 5: Annual number of North Atlantic Basin tropical storms and major hurricanes based on the plausible range of future tropical storm frequency.

	1981-2010 Average	**Projected Average for 2015-2065**
All tropical storms (TS)	12.1	8.8 to 12.6
Major Hurricanes (MH)	2.7	3.1 to 8.6

Despite the contradictions on future tropical storm frequency world-wide, the majority of experts project that Atlantic tropical storm frequency will either slightly decrease or remain essentially unchanged in a warming environment, and the frequency of major hurricanes will increase dramatically. However, because it is likely that SSTs in the Gulf of Mexico will increase in the future (Bengtsson et al., 2007), it is possible that the frequency of tropical storm and weak hurricane landfalls will be enhanced regionally, although an impending shift to a cool AMO may counteract that effect (IPCC, 2013). The possible increase in overall frequency in the Gulf of Mexico is partly due to the fact that tropical storm landfalls along the Gulf coast are mainly from storms that form in the Gulf of Mexico but have inadequate opportunities to intensify before making landfall (Dailey et al., 2009).

Table 6. Summary of resources used for analyzing changes in tropical storm frequency.

Source	Methods Summary	Resolution	Region	Timeframe	Change (all TS)	Change (MH)
Bengtsson et al. (2007)	Reanalysis of A1B using 63 spectral nodes from 1860-2007	40 km	Atlantic	2080-2100	-10%	+30%
Zhao et al. (2009)	Simulated inter-annual variability of CMIP3 model with A1B scenario	50 km and 100 km	Atlantic	A1B conditions	-11% to -20%	+13% to +25%
Bender et al. (2010)	Downscaling using operational hurricane-prediction with CMIP3 18-model ensemble	18 km	Atlantic	2035 (A), 2065 (B), 2081-2099 (C)	-18% to -28% (C)	+20% (A), +50% (B), +80% to +220% (C)
Villarini and Vecchi (2012)	TC frequency averaged 2016-2035 minus 1986-2005 for RCP2.6, RCP4.5, and RCP8.5	50 km	Atlantic	2016-2035	+4%, -2%, and -1%	
Knutson et al. (2013)	Dynamical downscaling CMIP3 (A) and CMIP5(B and C)	9 km and 18 km	Atlantic	2001-2100 (A), 2016-2035 (B), 2081-2100 (C)	-27% (A), -20% (B), -23% (C)	+87% to +250%(A), +43% to 83%(B), +125% (C)
Mallard et al. (2013)	Downscaling ensemble models and isolating thermodynamics using A1B	6 km and 18 km	Atlantic	A1B conditions	-18% to -28%	
Emanuel (2013)	Downscaling CMIP5	6 km, 18 km, and 50 km	Global	1950-2100 (A), 2026-2035 (B), 2056-2065 (C)	+10% to +40% (A), +87% to +95%(B), +94% to +104% (C)	+40% (A)

Source	Methods Summary	Resolution	Region	Timeframe	Change (all TS)	Change (MH)
Murakami et al. (2014)	Ensemble-mean reanalysis for all TS under A1B (A) , RCP4.5 (B), and RCP8.5 (C)	20 km, 60 km, 120 km and 200 km	Atlantic	2075-2099	-12.8% (A), -18.1% (B), -28.4% (C)	

4.0 Conclusions

Although tropical storms may become fewer in total, they will likely become more intense in terms of wind speed, rainfall, and central pressure deficit. The PDI for tropical storms is expected to increase between 2% to 75% during the coming century. Louisiana will likely experience a decrease in the number of tropical depressions, tropical storms and Category 1 and 2 hurricanes, but an increase in the frequency of Category 3-5 hurricanes in the coming years.

This effect is likely already occurring and will likely increase in intensity in the next few decades. ENSO amplitude, or the warm and cool ocean-surface temperature deviation which affects hurricanes, is likely to increase as well, which would increase the likelihood of impact by a tropical storm by 5% to 35% on the Gulf coast for El Niño and La Niña years, respectively. ENSO operates on a two- to seven-year timeframe, though how the system has or will respond to anthropogenic global warming remains uncertain. One paper (Collins et al., 2004) suggested that climate change favors El Niño conditions on the order of one standard El Niño event per century in the 1% per year CO_2 increase scenario. A recent paper by Mei et al. (2013) found that hurricanes serve as climate modulators, and that increasing temperatures leading to increased hurricanes will, in turn, lead to warmer SSTs, in what could become a dangerous positive feedback loop. These findings were supported by Sriver et al. (2013). CPRA anticipates a range of plausible future conditions that considers a variety of research approaches and methods, all of which point toward more intense hurricanes in the next 50 years.

5.0 References

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