

Task 2: Climate Variability and Change in Mobile, Alabama



Impacts of Climate Change and Variability on
Transportation Systems and Infrastructure

The Gulf Coast Study, Phase 2

Climate Variability and Change in Mobile, Alabama Final Report, Task 2

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June 2013 Update

The following revisions were made in June 2013: Additional information was added on pages 130, 159, 164, 168, 192, 324, and 325 to provide further information about the sea level rise and storm surge analyses. In addition, the exposure statistics presented in Tables 3, 4, 20, 25, 47, 54, and 55 and accompanying text were revised to reflect refined GIS information developed under Task 3.

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Executive Summary

1. Introduction and Background

1.1. Overview of Gulf Coast Project

Despite increasing confidence in global climate change projections in recent years, projections of climate effects at local scales remains scarce. Location-specific risks to transportation systems imposed by changes in climate are not yet well known. However, consideration of these long-term factors are highly relevant for infrastructure components, such as rail lines, highways, bridges, and ports, that are expected to provide service for up to 100 years.

To better understand climate change impacts on transportation infrastructure and to identify potential adaptation strategies, the U.S. Department of Transportation (USDOT) is conducting a comprehensive multiphase study of climate change impacts in the Central Gulf Coast region. This region was selected as the study's focal point due to its dense population and complex network of transportation infrastructure, as well as its critical economic role in the import and export of oil, gas, and other goods. The study is funded by the USDOT Center for Climate Change and Environmental Forecasting and managed by FHWA.

The Gulf Coast Study has two distinct study periods: Phase 1 (2003 to 2008) examined the impacts of climate change on transportation infrastructure at a regional scale; and Phase 2 (underway) is focusing on a smaller region, enhancing regional decision makers' ability to understand potential impacts on specific critical components of infrastructure, and to start evaluating adaptation options.

1.1.1. Gulf Coast, Phase 1 (Completed)

In the first phase, USDOT had four main objectives: (1) to gather data critical for analyzing the impacts of climate change on transportation infrastructure; (2) to determine whether climate data could be valuable in assessing vulnerability of infrastructure in the region; (3) to identify and implement an assessment approach; and (4) to then develop an overview of the potential impacts on infrastructure. The Phase 1 study utilized historical data on weather events, recent climate data, and projected changes in climate for the coming century.

Phase 1 study results indicate that the Gulf Coast region is particularly susceptible to climate change over the 21st century. Some of the changes projected for the region include the following:

- Sea level is likely to rise in the region by at least 1 foot (0.3 meters), and by as much as 6 to 7 feet (2 meters) in some parts of the study area.
- Major storms could increase in intensity by at least 10%.

- Storms of at least Category 3 intensity (sustained winds of 111+ miles per hour (179 kilometers per hour) & storm surge of 9+ feet (about 3 meters)) are projected to increase in frequency.
- Annual average precipitation could either increase or decrease (varying by climate model), but precipitation event intensity is likely to increase over the next century.
- The average annual temperature is likely to increase by at least 2.7°F (+/- 1.8°F) (1.5°C +/- 1°C) over the next 50 years.
- The numbers of days above 90°F (32°C) and 100°F (38°C) are both projected to increase; days over 90°F (32°C) could increase by 50%.

The implications of projected changes in climate for regional transportation systems are significant. Increasing temperatures are likely to require modifications to system materials and maintenance. Increased severity of precipitation events could exacerbate incidents of flash flooding, threatening the stability of soils and foundational materials. The combined effects of land subsidence and absolute sea level rise (SLR) could permanently inundate existing infrastructure. Finally, an increase in severity of tropical storms could have significant impacts on coastal infrastructure. Damages due to storm surge, winds, and flying debris can be catastrophic, as has been seen with previous hurricanes.

1.1.2. Gulf Coast, Phase 2 (Underway)

While Phase 1 took a broad look at the entire Central Gulf Coast region (between Galveston, Texas and Mobile, Alabama) with a ‘big picture’ view of the climate-related challenges facing infrastructure, Phase 2 is focusing on a single Metropolitan Planning Organization (MPO) region around Mobile, Alabama. The purpose of this phase is to evaluate which transportation infrastructure components are most critical to economic and societal function, and assess the vulnerability of these components to weather events and long-term changes in climate. Phase 2 will also develop tools and approaches that the Mobile MPO and other public and private system operators can use to determine which systems need to be protected, and how best to protect them. Through this study, USDOT intends to create a process that can be replicated in other MPO regions.

Phase 2 is broken down into the following tasks:

- Task 1: Identify critical transportation assets in Mobile
- Task 2: Develop climate information
- Task 3: Determine vulnerability of critical assets
- Task 4: Develop risk management tool(s)
- Task 5: Coordinate with planning authorities and the public
- Task 6: Disseminate and publish results

This report discusses the methodology and results from Task 2.

1.2. Overview of Task 2

This report, the Task 2 report, lays the climate data foundation upon which a vulnerability assessment will be conducted in the next task. In future steps of the project, a vulnerability screen will be conducted along with an assessment of the highly critical assets identified previously under Task 1, as reported in the Task 1 final report *Assessing Infrastructure for Criticality in Mobile, AL*.¹

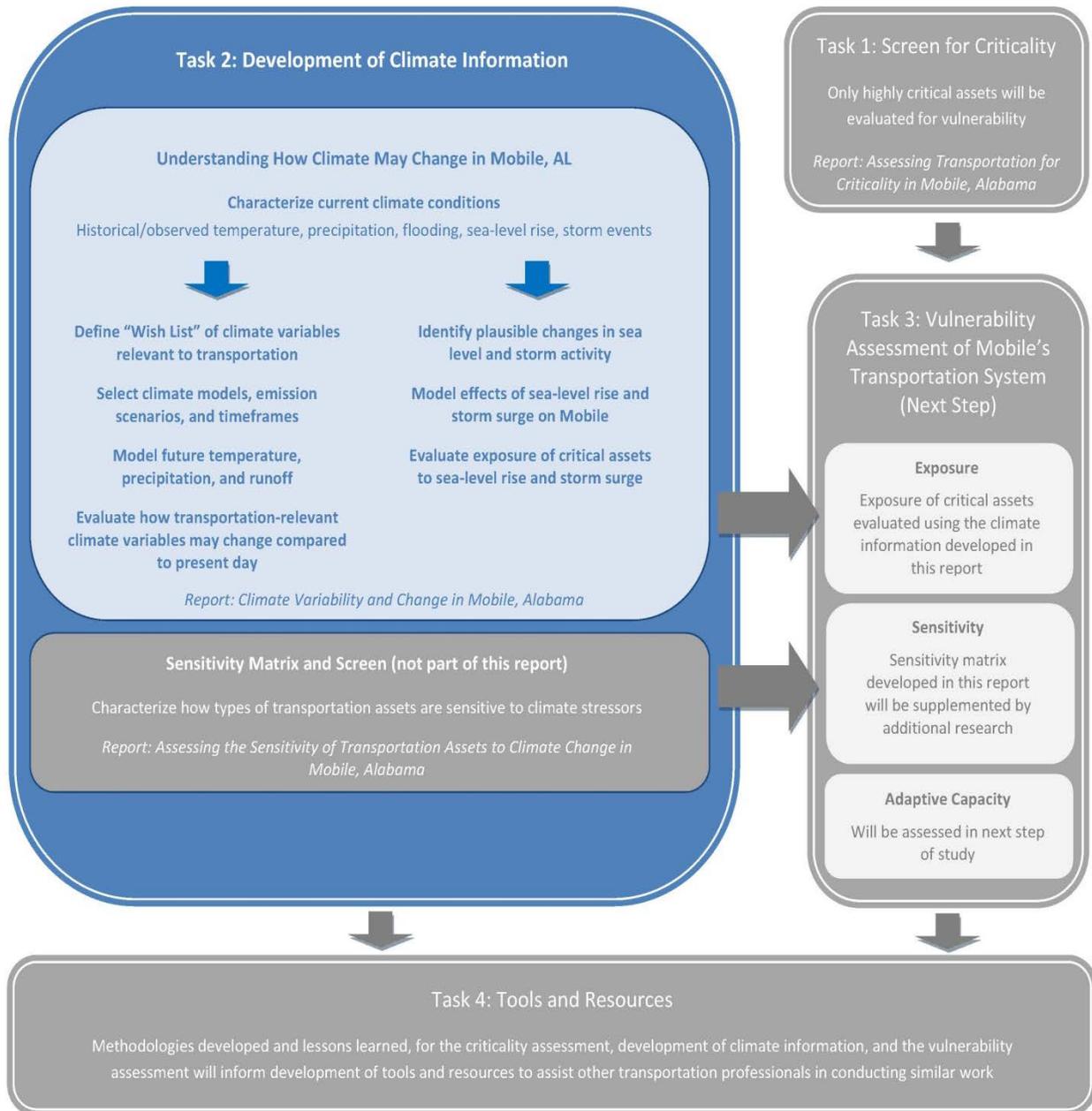
This report explores potential changes in five primary climate variables: temperature, precipitation, streamflow, sea level rise, and storm surge in Mobile, AL, the location selected as the study area for Phase 2. To do so, Task 2 characterizes the current climate conditions in Mobile, and then uses downscaled climate projection data, as well as sea level rise and storm surge modeling, to develop plausible climate futures. The climate information discussed in this report will be used to assess how the transportation system in Mobile might be affected by climate change.

Although this report does focus on Mobile, AL, the processes developed under this Task can be replicated by other transportation organizations across the country. The ultimate goal of this report is to not just identify how climate could change in Mobile, but also to develop robust methodologies, and identify existing datasets and tools, for developing these plausible climate futures. Furthermore, the work conducted under Task 2 will help inform the development of tools and resources to make these types of analyses easier for transportation agencies. To that end, the process of Task 2 is just as important as the results. Section 8 provides a discussion of how the lessons learned and information developed under Task 2 will be used in other products for different audiences.

Figure 1 below illustrates the components of this report and how they fit within the overall Gulf Coast Phase 2 project.

¹ Available at http://www.fhwa.dot.gov/hep/climate/gulf_coast_study/phase_2/index.cfm

Figure 1: Roadmap for Phase 2 of the Gulf Coast Project



Note: The components covered by this report are indicated with blue shading. The gray shading indicates other components of the Phase 2 study that are covered under other tasks and reports.

1.3. Report Roadmap

The main body of this report is organized by climate variable, with one section dedicated to each of the following variables:

- Temperature
- Precipitation

- Streamflow
- Sea level rise
- Storm events

Within each of those sections, this report first characterizes the current climate situation in Mobile, AL, and then discusses potential climate futures. Both the methodology used and the results of the analyses are presented. In addition to the key findings of the analysis, each section includes a discussion on the general implications of the potential climate futures for the transportation sector. The specific impacts that the climate projections may have on particular transportation assets in Mobile will be investigated in the next stage of this project.

The final section of this report includes a discussion of how the information developed in this report will be used for later activities under this project, and how it will inform the work of activities beyond this project.

2. Setting the Stage for Climate Research

2.1. Selection of Climate Variables

Task 2 included an assessment of the climate variables that have the greatest potential to impact transportation assets and operations: temperature, precipitation, streamflow, sea level rise, and storm surge. Wind was also calculated as part of the storm surge modeling, although it was not a specific focus of this study.²

An important part of this work was determining the appropriate format for communicating results for each climate variable. For example, this report goes beyond a generic exploration of projected changes in “temperature”, looking instead at specific changes to both long-term averages (e.g., change in average annual temperature or average monthly temperature) as well as short-term extreme events (e.g., number of days above 95°F (35°C)). The decisions on the format used to express climate information were vital in making this work relevant to the transportation community. Attention was focused on identifying the climate effects that have the most potential to have an impact on transportation. The appropriate formats used for a transportation perspective may be quite different than the formats appropriate for other sectors, such as human health, ecosystem services, or other economic sectors.

2.2. Methodology Overview

For each climate variable, this report first characterized the current (or recent historical) situation in Mobile, and then evaluated how that variable could change based on published literature, prevailing assumptions of future emissions of greenhouse gases, and a variety of modeled data. Table 1 provides an overview of the methods used in this report.

² There are other climate and weather effects that can be affected by climate change, and that may even have the potential to affect transportation, but were not included in this study because their anticipated effect on transportation is relatively low, or because of resource or technical limitations.

Table 1: Overview of Analytical Methods Used

Climate Variable	Methods Used to Analyze Current/Historical Situation	Methods Used to Develop Future Projections	Methods Used to Evaluate Exposure under Potential Future Scenarios*
Temperature	Historical data from 5 NOAA GHCN weather stations in the Mobile Region. The start of the data record varied by station, ranging from 1915 to 1956. Data was collected through September 2010 for all stations.	Downscaled daily global climate model data for B1, A2, and A1FI emission scenarios. Timeframes: 1980-2009 (hist.), 2010-2039 (near), 2040-2069 (mid), and 2070- 2099 (long)	To be addressed in Task 3 (vulnerability assessment)
Precipitation	Historical data from 5 GHCN weather stations in the Mobile region. The start of the data record varied by station, ranging from 1912 to 1956. Data was collected through September 2010 for all stations.	Downscaled daily global climate model data for B1, A2, and A1FI scenarios, 1980-2099 Timeframes: 1980-2009 (hist.), 2010-2039 (near), 2040-2069 (mid), and 2070- 2099 (long)	To be addressed in Task 3 (vulnerability assessment)
Streamflow	Historical data from five stream gages in the Mobile region through the USGS Surface Water Database. The start of the discharge data record varied by station, ranging from 1951 to 1995. Data was through September 2010 for all stations.	Modeled using USGS modified Thornwaite monthly water balance model, fed by projected temperature and precipitation Timeframes: 2010-2039 (near), 2040-2069 (mid), and 2070- 2099 (long)	To be addressed in Task 3 (vulnerability assessment)
Sea Level Rise	Historical data collected from two NOAA tidal gages. Dauphin Island data were available from 1966-2009. Pensacola data were from available from 1924-2009.	Review of recent scientific literature	GIS mapping of inundation areas, assuming 30 cm (by 2050),and 75 cm and 200 cm (by 2100) of global sea level rise, and accounting for local subsidence and uplift

Climate Variable	Methods Used to Analyze Current/Historical Situation	Methods Used to Develop Future Projections	Methods Used to Evaluate Exposure under Potential Future Scenarios*
Storms and Storm Surge	Case study analysis; storms selected through discussion with local experts and literature review	Review of recent scientific literature	Use of ADCIRC and STWAVE models to simulate two historical hurricanes (Georges and Katrina) assuming different levels of intensity and sea level rise

* A review of the scientific literature helped in the selection of plausible scenarios of sea level rise, and then mapping was used to show how Mobile would be inundated under those scenarios. Similarly, the scientific literature and discussions among the research team and with local stakeholders aided in the selection of storm scenarios, and mapping was used to show the inundation of Mobile under those scenarios.

2.3. Dealing with Uncertainty

Information provided on future climate in this report represents plausible *projections*, but not *predictions*. The information developed was based on a variety of assumptions, including the rate at which greenhouse gases are emitted into the future. The assumptions are based on recent and widely-accepted knowledge within the scientific community; however, there is a certain degree of uncertainty surrounding these assumptions. There is also uncertainty inherent in the various models that lay the basis of the analyses. Furthermore, there is natural variability in climate, which causes, for example, some winters to be much colder than the previous winter, or for some years to be wetter than others.

The climate futures described in this report are all plausible, but are not certain to occur. Additionally, none of the projections are considered more likely to occur than the others. The uncertainty around each of these components should be considered when conducting vulnerability assessments and implementing risk reduction measures. There are various techniques used to address uncertainty, including probabilistic approaches to quantify uncertainty, modeling various emission scenarios to produce a wide range of future possibilities, comparing present-day model results with observations, and engaging expert judgment to express uncertainty based on level of agreement and amount of evidence.

3. Temperature

3.1. Observed Temperature

Located on the United States' Gulf Coast, Mobile, Alabama is characterized by a very warm climate, with temperatures typically ranging from the high-50s to high-70s Fahrenheit. Overall, average annual temperatures have been relatively constant over the past 50 years in the Mobile region. While average annual temperatures have remained relatively constant, average minimum temperatures in March and September have decreased over the past century.

Table 2 summarizes the average value for several different temperature variables, 1912 to 2009.³

Table 2: Historical (1912 to 2009) Average for Temperature Variables

Temperature Variable	Historical Average (1912-2009)
Average annual temperatures	
Average annual mean temperature	66.9°F
Average annual minimum temperature	56.1°F
Average annual maximum temperature	77.5°F
Hot and Cold Days	
Hottest day of the year	97.9°F
Number of days above 95°F	12 days
Coldest day of the year	19.3°F
Number of days below freezing	23 days
Summer and Winter Temperatures	
Average Maximum Summer Temperature	90.0°F
Average Mean Summer Temperature	80.5°F
Average Minimum Winter Temperature	41.7°F
Average Mean Winter Temperature	52.5°F

3.2. Projected Temperature

3.2.1. Methodology

Climate projections of temperature were statistically downscaled from a number of models and analyzed to project how annual, seasonal, and monthly-average weather conditions, specific weather thresholds, and extreme conditions relevant to Mobile, Alabama, may change in the future.

³ Historical temperature was evaluated using observed data from five National Oceanic and Atmospheric Administration (NOAA) Global Historical Climatology Network (GHCN) stations in the Mobile region.

Projections were modeled for each of the following emission scenarios and time frames:

- Emission scenarios
 - Low-emission scenario (B1)
 - Moderately high-emission scenario (A2)
 - High-emission scenario (A1FI)
- Time frames
 - Near-term (2010 to 2039)
 - Mid-century (2040 to 2069)
 - End-of-century (2070 to 2099)

To account for local influences, large-scale global climate model data were downscaled to individual local observation stations in the Mobile region. Projections of daily maximum and minimum temperatures were statistically downscaled from up to ten climate models housed in the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP3) multimodel data set. This downscaling produced climate projections for each emission scenario and time frame, relative to one climate baseline (1980 to 2009).

To focus the study on climate projections that represent a robust projected change from baseline conditions, a statistical test (a paired t-test) was used to identify significant ($p < 0.05$) changes, i.e., climate projections that are statistically different from simulations of today's climate. This test helps identify which of the climate projections show a significant amount of change.

3.2.2. Key Findings

General

Temperature is projected to increase over time. The farther out in time, the greater the amount of temperature increase.

Overall, the amount of temperature increase is directly proportional to the increase in emissions—that is, the high (A1FI) emission scenario is associated with greater overall temperature increases than the low (B1) emission scenario. However, the increase in seasonal and monthly means is more variable across the emission scenarios. For example, under the low (B1) and moderately high (A2) emission scenarios, seasonal average temperatures are projected to increase the most in the fall season, with monthly average temperatures increasing the most in October. Under the high (A1FI) emission scenario, seasonal average temperatures are projected to increase the most in the summer season, with monthly average temperatures still increasing the most in October. As emissions increase there may be a tendency for peak warming to shift from fall to summer seasons.

Average Annual Temperatures

Average annual maximum, minimum, and mean temperatures are projected to increase significantly. Average annual mean temperatures increase steadily with each 30-year time period, by approximately 1°F (0.6°C), 2°F (1°C), and 3°F (2°C) for the low (B1), moderately high (A2), and high (A1FI) emission scenarios, respectively. Minimum temperatures are projected to increase more than maximum temperatures.

By the end-of-century, average annual mean temperature may increase to 70.5°F (21.4°C) under the low (B1) emission scenario, 73.8°F (23.2°C) under the moderately-high (A2) emission scenario, and 74.8°F (23.8°C) under the high (A1FI) emission scenario. Average annual maximum temperatures are projected to increase to as high as 84°F (29°C) by the end-of-century under the high (A1FI) emission scenario.

Seasonal and Monthly Mean Temperatures

Average seasonal and monthly mean temperatures are projected to increase significantly.⁴ The largest average seasonal mean temperature increases are projected to occur in the fall (particularly in October) and are largely dependent on changes in average minimum temperatures. The range of daily temperatures is projected to decrease. Lower temperatures benefit pavement and other infrastructure from reduced softening or expansion of materials, which are correlated with high temperatures. However, as the range of daily temperatures decreases, there may be less cooling relief overnight.

Extreme Temperature Events

The number of heat events above 95°F (35°C) and 100°F (38°C) are projected to increase dramatically. By mid-century, projections indicate there will be 2 to 5.5 additional weeks above 95°F (35°C). By end-of-century, projections indicate there will be 3 to 11 additional weeks above 95°F (35°C). The number of days above 105°F (41°C) and 110°F (43°C) are not projected to change significantly.

The length of the longest heat wave (defined as consecutive days over 95°F (35°C)) is also projected to increase. By mid-century, the longest heat wave is projected to lengthen by about 1 to 2 weeks. By end-of-century, the longest heat wave is projected to lengthen by between 1 week and 1 month.

The average coldest four days in winter are projected to be nearly 3 to 6°F (2 to 3°C) warmer by end-of-century. Projections of the coldest day of the year suggest that the extreme cold day in a 30-year time period will warm substantially more than the average cold day in the same time period.

⁴ “Significant” changes were identified using a statistical test (a paired t-test). See Appendix C.3.2 for a description of the paired t-test.

3.3. Implications for Transportation

These projected changes in temperature have some notable implications for transportation infrastructure and services. In general, higher temperatures result in more rapid deterioration of pavements that could require changes in repair and maintenance schedules (although in the longer term, newer and more durable pavement designs could reduce this impact). In addition, longer growing seasons due to longer periods of warmer temperatures could require more attention to mowing in rights of way, thus affecting maintenance budgets. An increase in the duration and frequency of extreme temperature events can result in increased buckling of rail and rutting and shoving of pavement. These impacts could be exacerbated by reduced potential for cooling relief overnight for pavement and other infrastructure. Excessive heat can contribute to equipment failures and more frequent vehicle breakdowns. Energy requirements for air conditioning of buildings, equipment, transit facilities, and freight are likely to increase. Ports, in particular, may see increases in energy costs to meet air conditioning and refrigeration requirements.

Extreme heat events also have health and safety implications for transportation agency personnel. In particular, maintenance and construction schedules may need to be adjusted to avoid health risks to workers. Further, the costs of ensuring the comfort and safety of passengers – particularly of train and bus travelers – are likely to increase.

The implications of the temperature findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

4. Precipitation

4.1. Observed Precipitation

Based on observed data from five observation stations, total annual precipitation in Mobile averaged 65.3 inches (165.9 centimeters) from 1912 to 2009. This makes Mobile one of the rainiest cities in the United States. Annual precipitation can vary by as much as 13.4 inches (34 centimeters) or 20%. Total annual precipitation has not changed significantly over the past century.

The maximum 24-hour precipitation event recorded each year has fluctuated over the historical record, exhibiting no significant trends. Precipitation associated with the average maximum 24-hour precipitation event across all stations from 1912 to 2009 was 5.2 inches (13.2 centimeters).

Precipitation amounts tend to be evenly distributed throughout the year, with July being the rainiest month and October being the driest. Over the historical period, monthly precipitation has increased significantly over the past century in January, October, and November. Summer precipitation has also exhibited an increasing trend.

4.2. Projected Precipitation

4.2.1. Methodology

Precipitation projections for Mobile were statistically downscaled using the same methodology as was used for temperature projections (see Section 3.2). Statistically downscaled data were analyzed to project changes in annual, seasonal, and monthly-average weather conditions, specific weather thresholds, and extreme conditions relevant to the study area.

4.2.2. Key Findings

General

Total annual precipitation is not projected to change significantly in the near-term, regardless of emission scenario. By mid- and end-of-century, total annual precipitation is projected to increase under the low (B1) emission scenario. Under the moderately-high (A2) and high (A1FI) scenarios, annual precipitation totals are projected to remain statistically similar to the baseline.

Seasonal and Monthly Precipitation

With very few exceptions, future seasonal and monthly precipitation totals are not projected to differ significantly from current climate conditions. Under the low (B1) emission scenario, winter precipitation is projected to increase significantly in the near-term and by mid-century, and fall precipitation under the low emission scenario is projected to increase significantly by mid-century.

Precipitation Events

Maximum seasonal three-day precipitation is projected to increase across all seasons, emission scenarios, and time frames, though not all increases are statistically significant.

For all time periods under all emission scenarios, precipitation during high-probability/low-impact 24-hour storms is projected to increase by 1 to 3 inches (3 to 8 centimeters), an increase of more than 60%. Meanwhile, precipitation during low-probability/high-impact 24-hour storms is projected to increase by 4 to 8 inches (10 to 20 centimeters), an increase of more than 65%. This suggests extreme storms will become more intense and potentially damaging.

Under the low (B1) and moderately-high (A2) emission scenarios, the storms experienced today across all return intervals are projected to occur more frequently in the future.

Two-day and four-day precipitation events that are currently uncommon in the Mobile region will become more frequent by mid- and end-of-century, particularly under the low (B1) and moderately-high (A2) emission scenarios. The precipitation associated with these events is projected to increase significantly over time under all emission scenarios.

4.3. Implications for Transportation

While minor changes in the total annual levels of precipitation are not likely to affect transportation, increases in the magnitude and frequency of precipitation events can have significant local impacts. These include the near-term consequences of heavy downpours as well as the longer-term damages associated with these events. More frequent and intense heavy precipitation events can cause flooding, mudslides, landslides, soil erosion, and result in high levels of soil moisture. These hazards can cause immediate damage during a rainfall event, necessitating emergency response. They also can undermine the structural integrity and maintenance of roads, bridges, drainage systems, and tunnels, necessitating more frequent repairs and reconstruction. The design of culverts and water receiving areas in vulnerable locations may need to accommodate greater capacity than current designs. Interestingly, an intense rain event after a period of very dry conditions can cause as much damage to assets and services as an intense rain event following a period of very wet conditions. In the first case, the dry ground cannot absorb the water quickly enough and it runs off or pools, while in the second case, the ground is already saturated and cannot absorb additional precipitation, so the water again runs off or pools.

Flooding can render a route temporarily impassable, and require maintenance to clear mud and debris. The connectivity of intermodal systems – including goods movement to and from ports – can be disrupted even if short segments of roadways are flooded. Severe precipitation can cause delays in air travel as aircraft are grounded or rerouted. Transportation agencies may need to fortify their emergency management and traffic management capabilities in anticipation of more frequent instances of heavy rainfall and associated response measures.

While these impacts are not new to transportation agencies, the frequency and severity of these problems are likely to increase as the incidence of extreme precipitation events rises. Managing damage and service disruption in real time may take more agency resources and require new communication channels and coordination protocols. Transportation agencies may need to consider preventive adaptation measures to increase the resilience of infrastructure (e.g., through design, operational improvements, and/or altered maintenance practices) and to prepare for additional emergency response needs associated with projected changes in precipitation patterns.

The implications of the precipitation findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

5. Streamflow

5.1. Observed Streamflow

Based on observed data from five stream gage sites in Mobile County, there is large variability in year-to-year peak streamflow events in the Mobile region. Over the past 58 years, annual peak streamflow at Chickasaw Creek has demonstrated a positive (increasing), but statistically insignificant, trend.

For the past 20 years, all Mobile area stream gage locations have demonstrated a similar pattern of annual mean stream discharge, similar to the pattern of annual peak streamflow. Average annual discharge at Chickasaw Creek from 1952 to 2010 has not changed significantly, suggesting the general characteristics affecting annual discharge have not changed.

Monthly mean discharge in the Mobile area is highest from February to April and lowest from October to November.

5.2. Projected Streamflow

5.2.1. Methodology

Monthly streamflow projections were developed using a monthly water balance model (WBM) driven by Mobile-specific information. The model estimates monthly runoff, evapotranspiration, and soil moisture within a basin or sub-basin using user-provided monthly precipitation and temperature data. The model was calibrated using streamflow data from three stream gage sites and meteorological data from the Coden and Mobile observations stations. The monthly runoff projections were translated to monthly discharge projections using the basin area for each stream gage.

5.2.2. Key Findings

During the summer months, monthly stream discharge is projected to decrease while actual evapotranspiration is projected to increase. During much of the winter and early spring months, monthly stream discharge is projected to increase.

Soil moisture is projected to decrease during the summer, particularly by the end of the century.

5.3. Implications for Transportation

It is unclear whether the projected changes in streamflow and soil moisture will have any significant impact on the vulnerability of transportation in Mobile. The impact of these changes will be evaluated in the Task 3 vulnerability assessment.

More generally, the transportation implications of changing streamflow patterns are similar to those resulting from severe precipitation events, discussed above. Streamflow changes are likely

to have the most significant effects on roadways, but may also impact rail lines; landside operations at ports; and facilities at airports, bus stations, and train terminals. Changes in seasonal and monthly hydrology could require consideration of wetland performance. Erosion patterns may also be affected, necessitating more frequent maintenance and changes in vegetation management.

The implications of the streamflow findings detailed in this report on transportation assets and services in Mobile will be investigated in more detail in the next task of this study (Task 3: Vulnerability Screen and Assessment). At this point, additional analysis may be done to consider the effects on peak flow events, which can affect performance of culverts, ditches, and water runoff collection and treatment systems.

6. Sea Level Rise

6.1. Observed Sea Level Rise

Sea levels have been rising in the Mobile area. Based on observed data between 1966 and 2006, local sea level⁵ near Dauphin Island, Alabama rose approximately 0.12 inches (0.30 centimeters) per year while relative sea level in nearby Pensacola, Florida rose approximately 0.08 inches (0.20 centimeters) per year.

6.2. Projected Sea Level Rise

6.2.1. Methodology

To characterize future sea level rise in Mobile, a literature review of state-of-the-science studies was conducted to understand how global sea levels could change in the future. The estimates in the literature vary, and it is not possible to definitively say the extent to which the sea level will rise; however, using the range of projected changes in global sea level, three plausible global sea level futures were selected: 0.3 meters (1.0 foot) by 2050, 0.75 meters (2.5 feet) by 2100, and 2.0 meters (6.6 feet) by 2100.

These global sea level rise levels were then adjusted for local land subsidence and uplift rates in the Mobile area to determine the local sea level rise in Mobile. Then, a Geographic Information System (GIS) was used to map the inundation of Mobile County under each of these sea level rise scenarios, which include the vertical land surface change and the global sea level rise (GSLR) for 2050 and 2100.⁶ The analysis does not take into account vertical protective structures such as sea walls and levees, nor does it take into account pumping systems, since there are relatively few such structures and systems in Mobile County.

6.2.2. Key Findings

The analysis indicates modest subsidence over most, but not all of southeastern Mobile County, which will amplify the impact of projected global sea level rise. The magnitude of the rates of subsidence in Mobile County is generally expected to be less than the magnitude of global sea level rise. In turn, the amount of land inundated by sea level rise in the study region is expected to be much less than that temporarily inundated by hurricanes that occasionally strike the area.

The scenario of 0.3 meters (1.0 foot) of global sea level rise by 2050 could inundate the lowest lying land in the Mobile region. These areas include wetlands associated with some of the creeks that feed into Mobile Bay, as well as low-lying areas such as Gaillard Island, Terrapin Island,

⁵ Local sea level rise is due to local or regional factors such as land uplift and subsidence from shifting local tectonics and changes in the amount of fluid in sediment pores; sedimentation and erosion adding or subtracting the amount of sediment at a particular location; gravitational changes; changes in oceanic and atmospheric circulation patterns; and changes in ocean density due to changes in salinity and temperature, in addition to global sea level rise.

⁶ Potential inundation due to long-term sea level rise is presented relative to Mean Higher High Water.

and parts of Dauphin Island. This level of inundation implies that short-term surges in water elevation due to relatively minor storms could lead to over-washing of the lowest lying coastal roads.

The scenario of 0.75 meters (2.5 feet) of global sea level rise by 2100 would exacerbate the impacts noted for the 0.3 meters scenario. Under this scenario, extensive flooding could occur across most of the wetlands at the head of the Bay and as far north as the wetlands to the east of Satsuma. The exposure of the area’s roads and rail to short-term storm-related flooding will increase. The area at risk of flooding under this scenario would include low-lying areas north of downtown, west of the CSX rail yard, and east of Route 45.

Under the scenario of 2.0 meters (6.6 feet) of global sea level rise by 2100, coastal inundation would significantly shift the southern Mobile County shoreline northward and would inundate most of Dauphin Island. While parts of Dauphin Island are at an elevation above 2.0 meters (6.6 feet), these areas would still likely be at significant exposure to storm surge and may not survive severe storms. Sea level rise under this scenario would also lead to inundation of some of the lowest downtown and port waterfront areas.

6.3. Implications for Transportation

Sea level rise can permanently inundate certain coastal assets, rendering them unusable without adaptive measures. With the exception of ports, Mobile’s critical transportation assets, as detailed in Task 1, are minimally exposed to sea level rise in the low- and mid-range scenarios of 0.30 meters (1 foot) and 0.75 meters (2.5 feet) of global sea level rise, respectively. In these scenarios, only 0 to 5% of critical assets of each mode are exposed. Under the high-range scenario of 2.0 meters (6.6 feet) of global sea level rise, exposure of critical assets of each mode ranges from 3 to 92%. A summary of the inundation of critical transportation assets is provided in Table 3.

Table 3: Percent of Critical Transportation Assets Inundated under Each Sea Level Rise Scenario

Sea Level Rise Scenario	Roads (miles)	Rail (miles)	Pipelines (miles)	Ports (#)	Transit Facilities	Mobile Downtown Airport (mi ²)*
0.3 meters by 2050	4%	1%	1%	46%	0%	1%
0.75 meters by 2100	5%	2%	2%	69%	0%	2%
2.0 meters by 2100	13%	20%	3%	92%	50%	3%

*The other highly critical airport, Mobile Regional Airport, is not inundated under any sea level rise scenarios. Inundation of small segments of coastal infrastructure can have broader implications if those segments are critical to the connectivity of the overall system. Further, coastal assets that are not fully inundated could be affected by rises in sea level. For example, higher sea levels can

increase the amount of shoreline erosion, thereby threatening coastal assets. Furthermore, higher groundwater levels can adversely affect pavement subgrade stability and stormwater system performance.

The interaction between sea level rise and storm surge is a critical consideration. Sea level rise exacerbates the vulnerability of infrastructure to storm surge, as higher water levels permit storm surge to travel farther into the County.

In addition to the direct effects of sea level rise on transportation infrastructure, the ecological impacts of sea level rise may have implications for transportation. The inundation of wetlands, for example, can destroy wetland mitigation efforts in which transportation agencies have invested. Further, inundation of natural coastal areas reduces the amount of ecological barriers - wetlands and marshes that absorb energy from tropical storms and hurricanes – that serve as buffer zones protecting populated areas.

Sea level rise is expected to be gradual, allowing time for assets to be protected or relocated. Dikes and levees, for example, can help protect transportation assets, and many assets can be completely relocated over time. However, such adaptive measures may require significant long-term planning and financial resources.

More information on the implications of the sea level rise findings detailed in this report as they relate to Mobile-specific transportation assets and services will be provided in the next task of this study (Task 3: Vulnerability Screen and Assessment).

7. Storm Events

7.1. Observed Storm Events

A variety of storm events affect Mobile including summer-time air-mass thunderstorms, tropical storms and hurricanes, and mid-latitude storms which may cause severe thunderstorms and/or heavy rains.

Mobile experiences frequent severe thunderstorms in the spring and fall, often accompanied by tornadoes. Key ingredients for these storms include a strong jet stream and warm, moist surface air.

Alabama experiences a storm originating in the tropics (e.g., tropical storm or hurricane) approximately every 1.5 years. Hurricanes strike the state about every 7.5 years, with a direct hit by a hurricane occurring approximately every 16 years.

These storm events can be destructive, causing flooding, downed power lines, and other infrastructure damage. To better understand the characteristics of recent extreme storms in Mobile, a case study analysis was conducted. The case studies provide an understanding of the current weather hazards that affect transportation planning and design. The case study analysis identified the key ingredients responsible for fueling each storm, serving as a basis for understanding how changes in climate may alter these ingredients and thereby influence future storm development. Information on reported damage from each storm was also recorded in the case studies; this information will help inform the vulnerability assessment in later stages of the project.

7.2. Projected Storm Events

7.2.1. Methodology

In this study, information on future storm events focused on projected changes in hurricane activity. Projected changes in hurricanes were developed using two techniques:

- A literature review
- A storm surge scenario analysis

A literature review was conducted to investigate scientific projections of storm-related atmospheric phenomena known to be important for storm development in Mobile. For example, this literature review investigated projected changes in the frequency and intensity of tropical storms and hurricanes.

A scenario-based analysis of storm surge from hurricanes was also conducted; this analysis sought to answer two main questions:

- What are the implications of a moderate hurricane striking the region under a scenario of increased sea level?
- What are the implications of a strike by a larger hurricane than the region has experienced in recent history?

To answer these questions, the storm surge inundation from 11 storm scenarios was modeled. These 11 scenarios were developed using Hurricane Georges and Hurricane Katrina—two damaging storms that affected Mobile in recent history—as base storms, and then adjusting certain characteristics of the storm parameters to simulate what could happen under alternate conditions. For the Georges simulations, all three sea level rise scenarios were examined. For the Katrina simulations, the modeling considered different adjustments, including shifting the path of Katrina so that it hit Mobile directly, intensifying the storm, and adding in 0.75 meters (2.5 feet) of sea level rise.

Simulations of storm-induced water levels (i.e., storm surge) were performed using the ADvanced CIRCulation model (ADCIRC). The ADCIRC storm simulations were driven by meteorological forcing data extracted from six-hour advisory forecast and observation reports issued by the NOAA National Hurricane Center (NHC). The wave characteristics accompanying each of the storm surge scenarios were simulated using STeady State spectral WAVE (STWAVE).

7.2.2. Key Findings

Literature Review Findings

The literature review suggests that Mobile may experience less mid-latitude cyclonic activity (e.g., severe thunderstorms) as the jet stream moves northward in response to a warming climate, but that this decrease in activity may be compensated by an increase in the intensity and/or frequency of extreme localized convective activity.

Based on the literature, it is difficult to predict the impacts of climate change on tropical cyclone activity as increasing vertical wind shear would reduce the development of tropical cyclones, while increasing sea surface temperatures could increase their intensification. Though this is an active area of debate among scientists, a scientific consensus report suggests that the future may bring a reduction in the frequency of hurricanes but an increased intensity of those hurricanes that do form.

Storm Surge Analysis Findings

The general magnitude of flooding from storm surge, even by the “natural,” unadjusted Hurricanes Georges and Katrina, exceeds the inundation from even the most extreme sea level scenario (2 meters) considered in this report. In other words, the land area temporarily affected by the surge from even moderate hurricanes is greater than the land area affected by the upper bounds of likely sea level rise over the 21st century. Flooded areas under these natural storm

scenarios include all of the coastal wetlands in Mobile County; low-lying areas along the waterfront and ports; as well as Gaillard Island, Terrapin Island, and nearly all of Dauphin Island.

The analysis of a strike by a larger hurricane than the region has experienced in recent history produced significantly increased storm surge. If Hurricane Katrina both shifted so that it hit Mobile directly and sustained its maximum wind speed through landfall, the surge at the Mobile Docks is estimated at 27.65 feet (8.38 meters). In this case, nearly all of the land to the east of I-65 would become flooded. Moreover, waves could affect structures more than 10 meters above sea level, including the downtown airport runways and hangars. In the most intense scenario (“shifted” Katrina, 0.75m SLR, MaxWind), the surge at Mobile Docks is estimated at 31.02 feet (9.40 meters) and the inundation impacts would be correspondingly greater.

Relatively speaking, sea level rise made a modest impact on the degree of inundation. Increased intensification of storms appears to be a much more significant driver in terms of amount of land inundated. However, inundation from sea level rise is permanent and affects groundwater levels, causing lasting effects. In contrast, inundation from storm surge, though damaging, tends to be temporary and repairable.

See Table 54 and Table 55 in Appendix D.9 for supplemental statistics of transportation modes inundated under these scenarios, including number of transit stops, miles of evacuation routes, and other metrics.

7.3. Implications for Transportation

Storm surge can have very significant impacts on transportation systems, rendering them unusable for the duration of the surge (lasting several hours or more). Critical facilities – including roads, bridges, rail lines, airports and ports – may be unusable, or exhibit reduced capacity, even after the waters recede due to damage to transportation assets, supporting infrastructure (e.g., utilities and telecommunications), or access routes. Damage can range from debris removal to complete destruction of certain assets. The direct costs of clean up, repair, and replacement can be high, and the secondary implications of disrupted transportation networks and supply chains can have widespread impacts on community life, and on the local and regional economy.

Table 4 shows the percent of critical transportation assets inundated under each storm surge scenario. Based on fractional extent of exposure, critical port facilities are most exposed to storm surge, with 92% to 100% of critical port facilities inundated, depending on the scenario. Critical rail lines are also highly exposed due to their coastal location, with 57% to 80% of critical rail-miles inundated. In contrast to the port facilities, pipelines have the lowest fractional extent of exposure, with 3% to 16% of pipeline-miles exposed.

Exposure varies for critical roadways. In the lowest surge scenario, 27% of the critical roadway length is exposed, whereas in the most extreme scenario, 75% of the critical roadway length is exposed. Importantly, even in the lowest scenario, many of the key evacuation routes are affected.

One of the two critical transit facilities, the GM&O Transportation Center, is inundated under all storm scenarios. Of the two critical airports, only Mobile Downtown Airport is inundated under any of the storm surge scenarios. Under the lowest storm surge scenario, 4% of the airport’s surface area is inundated. Under the highest storm surge scenario, the entire airport is inundated. Only when the track of Katrina is shifted would key aspects of the airport’s operations be exposed to inundation.

Table 4: Percent of Critical Transportation Assets Inundated under Each Storm Scenario

Storm Scenario*	Roads (miles)	Rail (miles)	Pipelines (miles)	Ports (#)	Transit Facilities**	Mobile Downtown Airport (mi ²)
Georges-Natural	27%	57%	3%	92%	50%	4%
Georges-Natural-30cm SLR	28%	59%	3%	92%	50%	5%
Katrina-Natural	28%	60%	3%	92%	50%	5%
Georges-Natural-75cm SLR	30%	62%	6%	92%	50%	7%
Katrina-Natural-75cm SLR	33%	66%	10%	92%	50%	9%
Katrina-Shift	46%	72%	12%	92%	50%	65%
Georges-Natural-200cm SLR	40%	68%	12%	92%	50%	15%
Katrina-Shift-75cm SLR	55%	74%	13%	96%	50%	90%
Katrina-Shift-ReducedPress-75cm SLR	60%	76%	13%	96%	50%	98%
Katrina-Shift-MaxWind	67%	78%	15%	100%	50%	100%
Katrina-Shift-MaxWind-75cm SLR	75%	80%	16%	100%	50%	100%

*Scenarios are presented in the order of least to greatest inundation of critical roads.

** Only two transit facilities were identified as critical. The GM&O facility downtown is inundated under all storm scenarios, while the Beltline facility is not inundated under any, leading to a 50% exposure statistic for all scenarios.

The *extent* of inundation of critical transportation assets from storm surge is much greater than exposure from long-term sea level rise. While potentially highly destructive, the *duration* of the exposure to surge is limited, whereas sea level rise is more likely to be gradual and more

widespread. Sea level rise compounds the severity of storm surge. The prospect of more frequent and more extreme storm events increases the adaptation burden on transportation.

Additional information on the implications of the storm surge findings detailed in this report on Mobile-specific transportation assets and services will be provided in the next task of this study (Task 3: Vulnerability Screen and Assessment).

8. Applications of the Information in this Report

8.1. Assessing Vulnerability in Mobile

The climate information developed in this report will inform a climate change vulnerability assessment.

Looking at the transportation assets deemed “Highly Critical” in the first task of Phase 2 of the Gulf Coast Study, the *exposure* to future climate effects will be considered, using the climate information developed in this report. Then, *sensitivity* of assets to those exposures will be considered.

Adaptive capacity will also be addressed during the vulnerability assessment, but was not addressed in this report.

Together, the evaluation of exposure, sensitivity, and adaptive capacity of the critical transportation assets will provide insight into the larger scale vulnerabilities of Mobile’s transportation system to climate change. The study aims to both identify highly vulnerable assets on an individual level, as well as develop an overarching understanding of the vulnerabilities of the transportation system as a whole.

Understanding Vulnerability

Vulnerability = $f(\text{exposure, sensitivity, adaptive capacity})$

- *Vulnerability* is the degree to which an asset is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes
- *Exposure* is the nature and degree to which an asset is exposed to significant climatic variations;
- *Sensitivity* is the degree to which an asset is affected, either adversely or beneficially, by climate-related stimuli
- *Adaptive capacity** is the ability of a system (or asset) to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences

Source: IPCC, 2001

* “Resilience” is sometimes used interchangeably with the term “adaptive capacity;” but is also used in the adaptation literature as a term related to, but distinct from, adaptive capacity; and sometimes as a concept representing the opposite of vulnerability. To avoid the confusion associated with the term “resilience,” this study exclusively uses the term “adaptive capacity.”

8.2. Informing Similar Work Elsewhere

There are a number of other transportation climate change vulnerability assessments underway across the nation. As this work is among the earliest and most in-depth, the findings and lessons learned may help inform those efforts going forward.

For example, the USDOT has recently funded two sets of climate change vulnerability assessment pilots. The Federal Highway Administration (FHWA) funded the first set of five pilots. The pilot studies were designed to test and improve a draft framework for conducting vulnerability assessments of transportation assets and services, with a primary focus on highway assets. The Federal Transit Administration (FTA) is funding a second set of pilots aimed at

transit assets and services. These pilot studies will build upon lessons learned through the FHWA pilots and findings in Phase 2 of this study.

There are a number of organizations and partnerships underway in the Gulf Coast area that are aimed at understanding the impacts of climate change to Gulf Coast communities, and promoting ways to increase the resiliency of the communities. The project team is actively engaging with these organizations to encourage information sharing and to leverage local knowledge.

Finally, an important goal of Phase 2 of the Gulf Coast Study is to develop tools and resources that will assist MPOs generally and other transportation agencies in conducting additional analyses. The processes and lessons learned throughout this report will help inform development of these resources. The tools and resources ultimately developed under this project will reduce the barriers to conducting similar analyses at local scales across the US.

Climate Variability and Change in Mobile, Alabama

1. Introduction and Background

1.1. Overview of Gulf Coast Project

Despite increasing confidence in global climate change projections in recent years, projections of climate effects at local scales remains scarce. Location-specific risks to transportation systems imposed by changes in climate are not yet well known. However, consideration of these long-term factors are highly relevant for infrastructure components, such as rail lines, highways, bridges, and ports, that are expected to provide service for up to 100 years.

To better understand climate change impacts on transportation infrastructure and to identify potential adaptation strategies, the U.S. Department of Transportation’s Center for Climate Change and Environmental Forecasting is conducting a comprehensive, multiphase study of climate change impacts on transportation in the Central Gulf Coast region. This study, formally known as *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study* (hereafter, “the Gulf Coast Study”), is the first such study of its magnitude in the United States and represents an important benchmark in the understanding of what constitutes an effective transportation system adaptation planning effort.

The Gulf Coast Study was initiated to better understand climate change impacts on transportation infrastructure and to identify potential adaptation strategies. The Gulf Coast region was selected as the focal point due to its dense population and complex network of transportation infrastructure, as well as its critical economic role in the import and export of oil, gas, and other goods. The study is funded by the USDOT Center for Climate Change and Environmental Forecasting and managed by FHWA. The U.S. Geological Survey (USGS) has provided support for much of the climate science work. The Gulf Coast Study includes two phases:

- **Phase 1** (2008) – During Phase 1, USDOT partnered with the USGS and the U.S. Climate Change Science Program to investigate potential climate change risks and impacts on coastal ports, road, air, rail, and public transit systems in the region from Mobile, Alabama to Houston/Galveston, Texas. The study assessed likely changes in temperature and precipitation patterns, sea level rise, and increasing severity and frequency of tropical storms. The assessment concluded that storms could increase in intensity by at least 10%, hurricanes of at least Category 3 intensity are likely to increase in frequency, average annual temperatures are expected to rise by at least 2.7°F (1.5°C) over the next 50 years, the number of days over 90°F (32°C) could increase by 50%, and local sea level could increase by at least 1 foot (30 centimeters) (and in many areas more) by 2050 raising the specter of

widespread inundation. Phase 1 then explored how these changes could impact transportation systems. It found that a local sea level rise of four feet would permanently inundate 27% of the Gulf Coast region’s roads, 9% of its railways, and 72% of its ports; higher temperatures would likely lead to more rapid deterioration of infrastructure and higher maintenance costs; more intense precipitation events could overwhelm drainage systems and cause damage and delays; and increased hurricane intensity coupled with sea level rise would pose a significant threat to infrastructure. Additional information is available in the Task 1 final report, *Assessing Infrastructure for Criticality in Mobile, AL*.⁷

- **Phase 2** (currently underway) – The purpose of Phase 2 is to provide a more detailed assessment of the vulnerability of the most critical components of the transportation system to weather events and long-term changes in climate. This work is being conducted on a single metropolitan area—the Mobile, AL region (see box)—with the intention of making the processes used in the study replicable to other areas. USDOT is conducting Phase 2 in partnership with the Mobile Metropolitan Planning Organization, part of the South Alabama Regional Planning Commission (SARPC).

Phase 2 includes the following tasks:

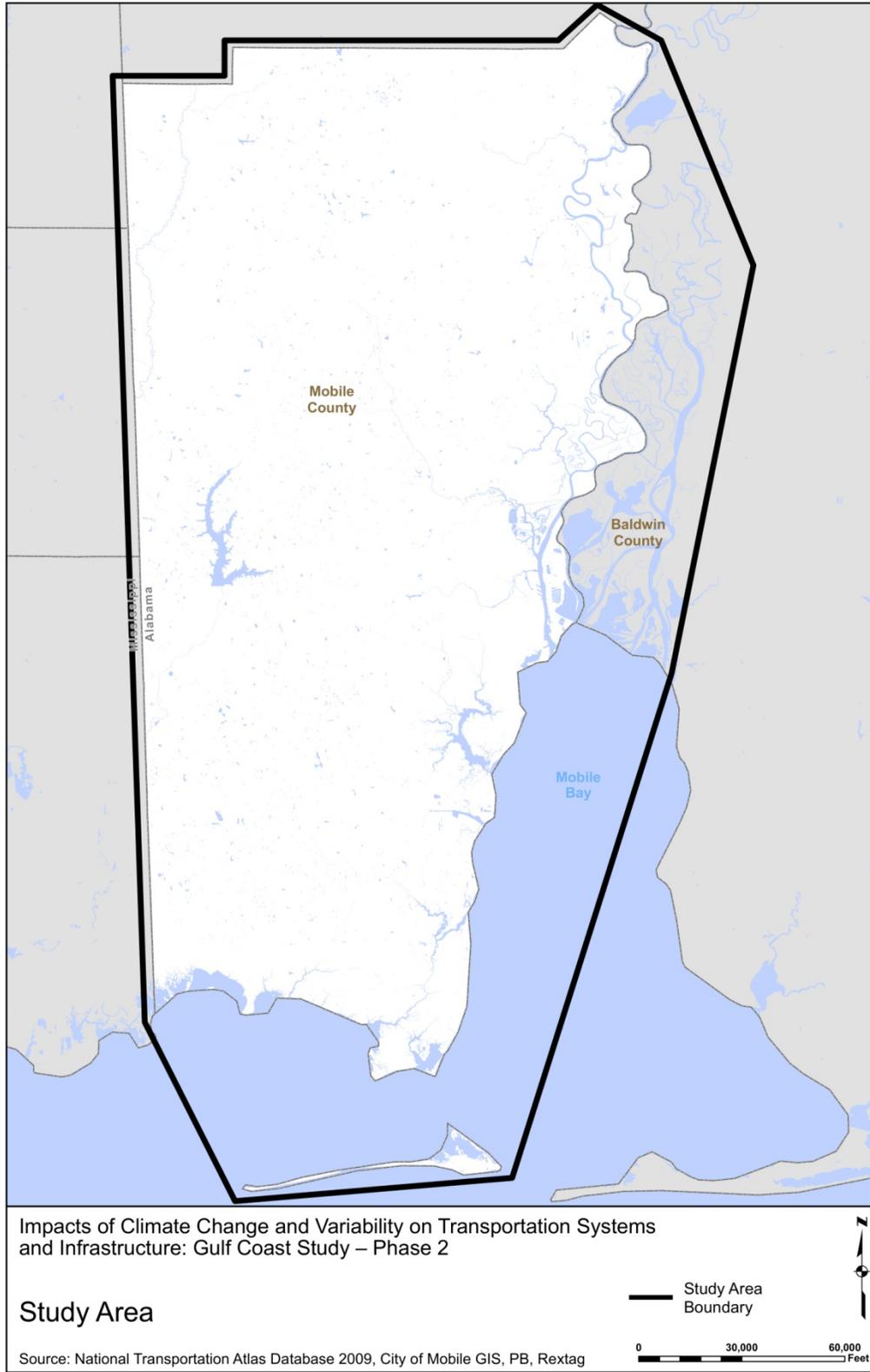
- Task 1: Identify critical transportation assets.
- Task 2: Develop climate information and assess sensitivity of assets to climate stressors.
- Task 3: Determine the vulnerability for key links and assets.
- Task 4: Develop and apply detailed risk management tools.
- Task 5: Coordinate with local planning authorities and the public on the process and implications of the analysis.
- Task 6: Publish and disseminate the lessons learned.

Phase 2 Study Area

While Phase 1 took a broad look at the entire Central Gulf Coast region (between Houston/Galveston, Texas and Mobile, Alabama) with a ‘big picture’ view of the climate-related challenges facing infrastructure, the current effort in Phase 2 focuses on Mobile, Alabama. The area of the study includes Mobile County (including Dauphin Island) and the crossings of Mobile Bay to the east to landfall in Baldwin County (Figure 2).

⁷ Available at: http://www.fhwa.dot.gov/hep/climate/gulf_coast_study/phase_2/index.cfm.

Figure 2: Study Area



1.1.1. Gulf Coast, Phase 1: Results

In the first phase, USDOT had four main objectives: (1) to gather data critical for analyzing the impacts of climate change on transportation infrastructure; (2) to determine whether climate data could be valuable in assessing vulnerability of infrastructure in the region; (3) to identify and implement an assessment approach; and (4) to then develop an overview of the potential impacts on infrastructure. The Phase 1 study utilized historical data on weather events, recent climate data, and projected changes in climate for the coming century.

Phase 1 study results indicate that the Gulf Coast region is particularly susceptible to climate change over the 21st century. Some of the changes projected for the region include the following:⁸

- Sea level is likely to rise in the region by at least 1 foot (0.3 meters), and by as much as 6 to 7 feet (2 meters) in some parts of the study area.
- As the sea surface temperature of the Atlantic and Gulf of Mexico increase, hurricanes will be more likely to form and become more destructive potential. Major storms could increase in intensity by at least 10%.
- Storms of at least Category 3 intensity (sustained winds of 111+ miles per hour (179 kilometers per hour) & storm surge of 9+ feet (about 3 meters)) are projected to increase in frequency. Depending on the characteristics of a given storm, facilities at or below 30 feet (9 meters) could be subject to storm surge.
- Annual average precipitation could either increase or decrease (varying by climate model), but precipitation event intensity is likely to increase over the next century.
- The average annual temperature is likely to increase by at least 2.7°F (+/- 1.8°F) (1.5°C +/- 1°C) over the next 50 years. Extreme high temperatures are also expected to increase, with the number of days above 90°F (32°C) and 100°F (38°C) are both projected to increase; days over 90°F (32°C) could increase by 50%.

The implications of projected changes in climate for regional transportation systems are significant. Increasing temperatures are likely to require modifications to system materials, maintenance, and operations. Increased severity of precipitation events could cause more flooding, threatening the stability of soils and foundational materials, stressing the capacity of drainage systems, and disrupting operations. The combined effects of land subsidence and absolute sea level rise (SLR) could permanently inundate existing infrastructure, including 27% of major roads, 9% of rail lines, and 72% of ports (depending on sea level rise scenarios, and excluding protective structures). Finally, an increase in severity of tropical storms could have significant impacts on coastal infrastructure. Damages due to storm surge, winds and flying debris can be catastrophic, disrupting service and causing costly damage to infrastructure.

⁸ USCCSP 2008a.

1.1.2. Gulf Coast, Phase 2: Overview of Tasks

While Phase 1 took a broad look at the entire Central Gulf Coast region (between Galveston, TX and Mobile, AL) with a ‘big picture’ view of the climate-related challenges facing infrastructure, Phase 2 is focusing on a single Metropolitan Planning Organization (MPO) region around Mobile, Alabama.

The purpose of this phase is to evaluate which transportation infrastructure components are most critical to economic and societal function, and assess the vulnerability of these components to weather events and long-term changes in climate. Phase 2 will also develop tools and approaches that the Mobile MPO and other public and private system operators can use to determine which systems need to be protected, and how best to protect them. Through this study, USDOT intends to create a process that can be replicated in other MPO regions.

Phase 2 is divided into the tasks below. The first three tasks form the basis of a vulnerability screen and assessment of the Mobile transportation system, while the other tasks focus on tool development, coordination with stakeholders, and communication of project results.

- **Task 1: Identify critical transportation assets in Mobile.** This task (completed) served as a first level screen for the vulnerability assessment, by identifying which transportation assets are highly critical to Mobile. The results were published in the report *Assessing Transportation for Criticality in Mobile, Alabama*.
- **Task 2: Develop climate information.** Task 2 (covered in this report) focuses on characterizing how temperature, precipitation, streamflow, sea level, and storms and storm surge in Mobile could change due to climate change. This task also investigated the sensitivities of different transportation assets to each of these climate stressors, which is discussed in the companion report *Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama*.
- **Task 3: Determine vulnerability of critical assets.** This task will evaluate how the highly critical assets identified in Task 1 could be vulnerable to the climate information developed under Task 2. This task will seek to develop a clearer understanding of the key vulnerabilities of Mobile’s transportation system due to climate change.
- **Task 4: Develop risk management tool(s).** Based on the findings and lessons learned during the first three tasks, Task 4 will develop tools and resources to assist other transportation agencies in conducting similar assessments and in managing their identified risks.
- **Task 5: Coordinate with planning authorities and the public.** Ongoing throughout the project, this task focuses on engaging key local transportation stakeholders, as well as members of the public.
- **Task 6: Disseminate and publish results.** There will be a final synthesis report that covers all of Phase 2, as well as associated presentations of the findings.

1.2. Overview of Task 2

This report, the Task 2 report, lays the climate data foundation upon which a vulnerability assessment will be conducted in the next task. In future steps of the project, a vulnerability screen will be conducted along with an assessment of the highly critical assets identified previously under Task 1, as reported in the Task 1 final report *Assessing Infrastructure for Criticality in Mobile, AL*.⁹

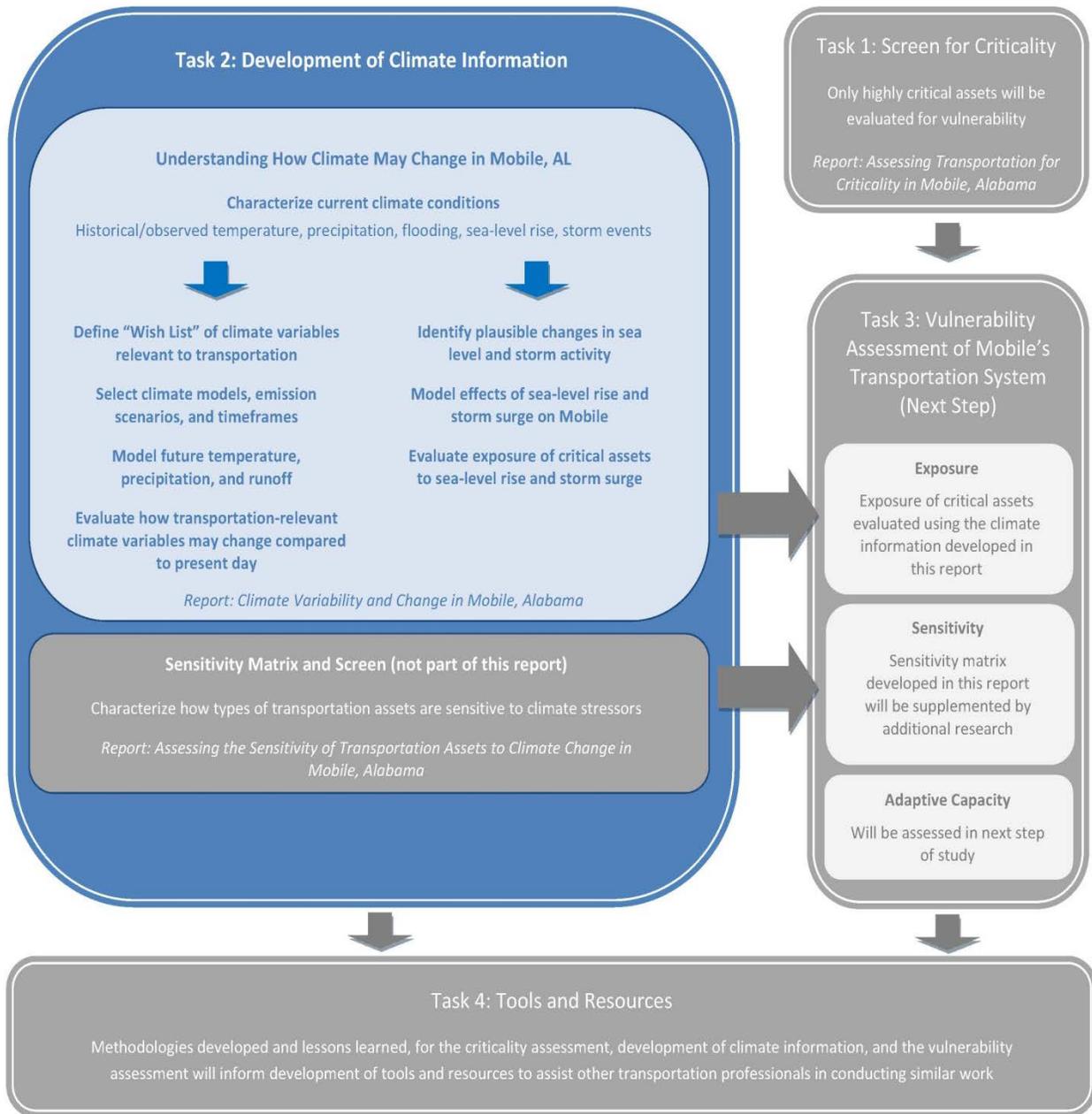
This report explores potential changes in five primary climate variables: temperature, precipitation, streamflow, sea level rise, and storm surge in Mobile, Alabama, the location selected as the study area for Phase 2. To do so, Task 2 characterizes the current climate conditions in Mobile, and then uses downscaled climate projection data, as well as sea level rise and storm surge modeling, to develop plausible climate futures. The climate information discussed in this report will be used to assess how the transportation system in Mobile might be affected by climate change.

Although this report does focus on Mobile, Alabama, the processes developed under this Task can be replicated by other transportation organizations across the country. The ultimate goal of this report is to not just identify how climate could change in Mobile, but also to develop robust methodologies, and identify existing datasets and tools, for developing these plausible climate futures. Furthermore, the work conducted under Task 2 will help inform the development of tools and resources to make these types of analyses easier for transportation agencies. To that end, the methodology of Task 2 is equally important as the results. Section 8 provides a discussion of how the lessons learned and information developed under Task 2 will be used in other products for different audiences.

Figure 3 below illustrates the components of this report and how they fit within the overall Gulf Coast Phase 2 project.

⁹ Available at http://www.fhwa.dot.gov/hep/climate/gulf_coast_study/phase_2/index.cfm

Figure 3: Roadmap for Phase 2 of the Gulf Coast Project



Note: The components covered by this report are indicated with blue shading. The gray shading indicates other components of the Phase 2 study that are covered under other tasks and reports.

1.3. Report Roadmap

The main body of this report is organized by climate variable, with one section dedicated to each of the following variables:

- Temperature
- Precipitation
- Streamflow
- Sea Level Rise
- Storm events

Within each of those sections, this report first characterizes the current climate in Mobile, AL, and then discusses potential climate futures. As noted previously, the approach is considered just as important as the results, to help serve as a resource for other agencies planning similar assessments. Therefore, both the methodology used and the results of the analyses are presented. Detailed information on the methodology and results are presented in the report Appendices. In addition to the key findings of the analysis, each section includes a discussion on the implications of the potential climate futures for the transportation sector.

The final section of this report includes a discussion of how the information developed in this report will be used for later activities under this project, and how it will inform the work of activities beyond this project.

2. Setting the Stage for Climate Research

Task 2 included an assessment of the climate variables that have the greatest potential to impact transportation assets and operations: temperature, precipitation, streamflow, sea level rise, and storm surge. Wind was also calculated as part of the storm surge modeling, although it was not a specific focus of this study.¹⁰

2.1. Selection of Climate Variables

To identify the climate variables that are most relevant to transportation, transportation planners, transportation engineers, and climate scientists collaboratively developed a list of all relevant variables that impact the region's transportation. This list was refined based on the following considerations:

- Does the environmental variable affect Mobile's transportation system?
- Is there a well-known model that simulates projections of the variable?
- Do the benefits of using the results in a risk assessment justify the effort necessary to develop projections of the variable?

The variables range in temporal scale from monthly, seasonal, and annual averages to specific events and hazards. For more information about how environmental variables were selected, see Appendix B.2. Ultimately, it was decided that this study would focus on projections of temperature (changes in average conditions and extreme events), precipitation (changes in average conditions and extreme events), streamflow, sea level rise, and storm events (including storm surge).

An important part of this work was determining the appropriate format for communicating results for each climate variable. For example, this report goes beyond a generic exploration of projected changes in "temperature", looking instead at specific changes to both long-term gradual changes (e.g., change in average annual temperature or average monthly temperature) as well as short-term extreme events (e.g., number of days above 95°F (35°C)). The decisions on the format used to express climate information were vital in making this work relevant to the transportation community. Great care was taken to identify the climate effects that have the potential to impact transportation. The appropriate formats used for a transportation perspective may be quite different than the formats appropriate to other economic sectors, human health, or ecosystem services.

¹⁰ There are other climate and weather effects that can be affected by climate change, and that may even have the potential to affect transportation, but were not included in this study because their anticipated effect on transportation is relatively low, or because of resource or technical limitations.

2.2. Methodology Overview

For each climate variable, this report first characterized the current (or recent historical) situation in Mobile, and then evaluated how that variable could change based on published literature, prevailing assumptions of future emissions of greenhouse gases, and a variety of modeled data. Table 5 provides an overview of the methods used in this report.

Table 5: Overview of Analytical Methods Used

Climate Variable	Methods Used to Analyze Current/Historical Situation	Methods Used to Develop Future Projections	Methods Used to Evaluate Exposure under Potential Future Scenarios*
Temperature	Historical data from 5 NOAA GHCN weather stations in the Mobile Region. The start of the data record varied by station, ranging from 1915 to 1956. Data was collected through September 2010 for all stations.	Downscaled daily global climate model data for B1, A2, and A1FI emission scenarios. ¹¹ Timeframes: 1980-2009 (hist.), 2010-2039 (near), 2040-2069 (mid), and 2070- 2099 (long)	To be addressed in Task 3 (vulnerability assessment)
Precipitation	Historical data from 5 GHCN weather stations in the Mobile region. The start of the data record varied by station, ranging from 1912 to 1956. Data was collected through September 2010 for all stations.	Downscaled daily global climate model data for B1, A2, and A1FI scenarios, 1980-2099. ¹² Timeframes: 1980-2009 (hist.), 2010-2039 (near), 2040-2069 (mid), and 2070- 2099 (long)	To be addressed in Task 3 (vulnerability assessment)
Streamflow	Historical data from five stream gages in the Mobile region through the USGS Surface Water Database. The start of the discharge data record varied by station, ranging from 1951 to 1995. Data was through September 2010 for all stations.	Modeled using USGS modified Thornwaite monthly water balance model, fed by projected temperature and precipitation. Timeframes: 2010-2039 (near), 2040-2069 (mid), and 2070- 2099 (long)	To be addressed in Task 3 (vulnerability assessment)

¹¹ Downscaled daily global climate model data was provided by Dr. Katharine Hayhoe of Texas Tech.

¹² Downscaled daily global climate model data was provided by Dr. Katharine Hayhoe of Texas Tech.

Climate Variable	Methods Used to Analyze Current/Historical Situation	Methods Used to Develop Future Projections	Methods Used to Evaluate Exposure under Potential Future Scenarios*
Sea Level Rise	Historical data collected from two NOAA tidal gages. Dauphin Island data were available from 1966-2009. Pensacola data were from available from 1924-2009.	Review of recent scientific literature	GIS mapping of inundation areas, assuming 30 cm (by 2050), and 75 cm and 200 cm (by 2100) of global sea level rise, and accounting for local subsidence and uplift
Storms and Storm Surge	Case study analysis; storms selected through discussion with local experts and literature review	Review of recent scientific literature	Use of ADCIRC and STWAVE models to simulate two historical hurricanes (Georges and Katrina) assuming different levels of intensity and sea level rise

* A review of the scientific literature helped in the selection of plausible scenarios of sea level rise, and then mapping was used to show how Mobile would be inundated under those scenarios. Similarly, the scientific literature and discussions among the research team and with local stakeholders aided in the selection of storm scenarios, and mapping was used to show the inundation of Mobile under those scenarios.

2.3. Dealing with Uncertainty

The future climate information developed for this report represents plausible *projections*, but not *predictions*. Modeling the climate system poses a number of challenges. There are three main sources of uncertainty in climate model simulations¹³:

- **Natural variability** (the unpredictable nature of the climate system)
- **Scenario uncertainty** (the ability to project future societal choices including energy use)
- **Model uncertainty** (the ability to accurately model the Earth’s many complex processes)

The relative contribution of each uncertainty component to the climate model simulation’s overall uncertainty varies with time horizon, spatial scale, and temporal scale. Most notably, scenario uncertainty is relatively minimal in the near-term but is currently the greatest contribution to total uncertainty by end-of-century.¹⁴ The model uncertainty represents a large

¹³ Hawkins and Sutton, 2009; Mote et al., 2010; Ray et al., 2008

¹⁴ IPCC, 2007; Hawkins and Sutton, 2009

portion of the total uncertainty throughout the time period, and is a dominant contributor by near-term and mid-century.¹⁵ Meanwhile, natural variability is a significant contributor to total uncertainty in the near-term, but becomes much less significant by end-of-century.¹⁶ The relative contribution of each uncertainty component also varies with spatial and temporal scale.¹⁷ Natural variability becomes a greater source of uncertainty at finer scales.¹⁸ This is one reason why incorporating downscaled projections expands the potential uncertainty in climate projections.¹⁹ As our understanding of global and local processes continues to improve, the level of uncertainty, particularly at finer scales, may be reduced.²⁰

The uncertainty around each of these components should be considered when conducting vulnerability assessments, making decisions, and implementing policies. In this study, a number of uncertainties are qualitatively addressed:

- Scenario uncertainty is intrinsically incorporated in the study design by providing projections driven by three different emission scenarios: ‘low’ (B1), ‘moderately-high’ (A2), and ‘high’ (A1FI). Using these emission scenarios is a way to explore the range of plausible projections, though it is quite possible that actual emissions in the 21st century will be above this range.
- Model uncertainty is indirectly characterized, to some extent, by comparing projections across a number of climate models.

In addition, this study incorporates an additional layer of uncertainty by using statistically downscaled temperature and precipitation projections. Downscaling of climate model projections allows scientists to incorporate local conditions, such as the effect of local topography or prevailing sea breezes, by tailoring larger-scale climate model results to a finer-scale analysis.²¹ However, using downscaled data introduces an additional degree of model uncertainty and natural variability into the projections that is not quantified here.²² Statistical downscaling further assumes that the relationship between today’s observed data and modeled data remains stationary with time.²³

For more information on uncertainty in climate model projections,²⁴ see Appendix C.2.3.

¹⁵ Hawkins and Sutton, 2009

¹⁶ Hawkins and Sutton, 2009

¹⁷ Hawkins and Sutton, 2009; Mote et al., 2010; IPCC, 2010

¹⁸ Hawkins and Sutton, 2009; Mote et al., 2010

¹⁹ Hawkins and Sutton, 2009; IPCC 2010

²⁰ Hawkins and Sutton, 2009; Ray et al., 2008

²¹ Ray et al., 2008

²² Hawkins and Sutton, 2009

²³ Ray et al., 2008

²⁴ IPCC 2010

3. Temperature

Temperature can affect transportation infrastructure in many ways and is a key consideration in many transportation designs, maintenance schedules, and operation budgets. Most importantly, extreme temperature events can damage transportation infrastructure.²⁵ Depending on the severity and duration of an extreme temperature event, bridges, pavement, vehicles, and construction activity are at risk.²⁶ For example, thermal expansion of paved surfaces can cause infrastructure degradation.²⁷

This section presents the methodology and key findings for several analyses related to observed and projected temperature.

- Section 3.1 describes two analyses of observed temperature.²⁸ First, data from five stations in the Mobile region were used to describe and characterize historical and present-day climate. Second, the same data were used for a trend analysis to identify any trends in temperature over the past 50 years. These analyses are intended to better characterize the local climate in Mobile and to better understand the information used to inform current transportation planning and transportation engineering designs. Note that these analyses based on observed data did not serve as the baseline for the analyses of projected changes. However, the observed data were used to downscale projections to the Mobile region.
- Section 3.2 describes the analysis of projected temperature. Changes in average and extreme temperatures were estimated using daily downscaled projections²⁹ from up to 10 climate models, under three emission scenarios and for three future time periods as compared to a model-simulated baseline period (1980 to 2009). A statistical test was used to identify those projections that were considered significantly different from the simulated baseline climate.
- Section 3.3 identifies several potential implications for transportation.

Additional detail about the temperature analyses is available in the appendices.

- Appendix B.1 describes the historical changes in temperature in Mobile in the context of climate change at the global, national, and regional scale.
- Appendix B.2 describes how specific temperature variables were chosen for consideration in this study.
- Appendix C.1 provides a diagram describing the temperature data available for each observation station.

²⁵ NRC, 2008; USCCSP, 2008a

²⁶ NRC, 2008; USCCSP, 2008a

²⁷ NRC, 2008

²⁸ Historical data was provided by Dr. Katharine Hayhoe of Texas Tech, who also conducted the temperature trend analysis.

²⁹ Daily downscaled projections were provided by Dr. Katharine Hayhoe of Texas Tech,

- Appendix C.2 provides background information on climate models, describes the uncertainty associated with climate projections, and explains the approach used to identify optimum modeling criteria to inform transportation vulnerability assessments.
- Appendix C.3 provides a detailed description of the temperature projections methodology.
- Appendix C.4 provides a high-level investigation of how the end-of-century temperature projections vary by climate model and emission scenario.
- Appendix C.5 provides summary tables for the projected temperature analysis, including the results of a test for significance.
- Appendix E.1 provides tables of the climate model ensemble mean by station location, time period, and emission scenario for the projected temperature analysis.

3.1. Observed Temperature

Observed temperature records for Mobile were analyzed to describe historical and present-day climate conditions in the region.

3.1.1. Methodology

This section describes the methodology used to analyze observed temperature data in the Mobile region.

Historical data from five National Oceanic and Atmospheric Administration (NOAA) Global Historical Climatology Network (GHCN) stations in the Mobile region were analyzed to investigate existing climatic trends and baseline conditions.³⁰ Two of the stations (Codens and Mobile Airport) are located in Mobile County and three of the stations are located in neighboring Baldwin County (see Figure 4).³¹ Table 6 summarizes the data available for each station and identifies any gaps in the record. Temperature observations at the Baldwin County stations began between 1915 and 1924, giving these stations the longest record of temperature measurements. Temperature observations at the Mobile County stations began between 1948 and 1956.

³⁰ Dr. Katharine Hayhoe of Texas Tech provided the historical data (see Hayhoe and Stoner 2012 for a discussion of data quality and additional data filtering).

³¹ The GHCN dataset was sufficient as it was important to: (1) have daily data for event analysis, and (2) to use a consistent set of data when comparing against the climate projections later in this report. Had these two factors not been important, the homogeneity adjusted data in the USHCN would have been considered. The USHCN data provide monthly and seasonal data (<http://www.ncdc.noaa.gov/oa/climate/research/ushcn/>). <http://www.ncdc.noaa.gov/oa/climate/research/ushcn/>), as recommended per communication with Dr. Tom Peterson of NOAA, with careful consideration in treatment of the data gaps existing in the record. Hence, the USHCN data set has no data gaps. To determine what impact the daily data gaps that exist in the GHCN data may have had, monthly and seasonal averages using the GHCN data set were compared against the USHCN data set for the one location in common (Fairhope). This comparison indicated no noticeable differences, suggesting the daily data gaps in Fairhope observational record have minimal impact on the monthly and seasonal averages.

Figure 4: Map of GHCN Stations

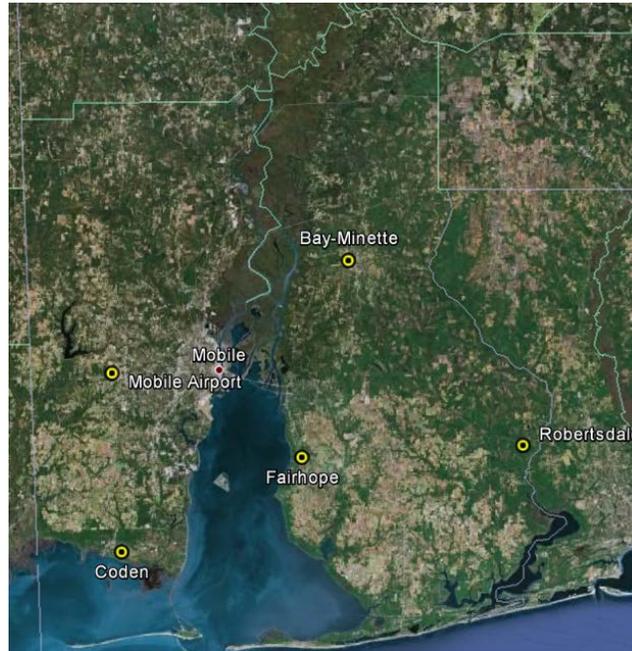


Table 6: Mobile Area GHCN Station Temperature Data Summary

Station	Station ID#	County	Temp. Start of Data Collection	Temp. Data Gaps*
Bay-Minette	USC00010583	Baldwin	1915	1931, 1937-1941
Coden	USC00011803	Mobile	1956	1985-1988
Fairhope	USC00012813	Baldwin	1918	-
Mobile Airport	USC00015478	Mobile	1948	-
Robertsdale	USC00016988	Baldwin	1924	1926-1934

* Gaps defined as over 80% of data points missing for the year

** Missing minimum temperature only

Each station records daily minimum and daily maximum temperatures. Daily mean temperature was estimated by averaging the daily minimum and maximum temperatures.³² Monthly, seasonal, and annual minimum, maximum, and mean temperature averages were produced using the daily data for both the historical record (1912 to 2009), where data were available, and the present-day climate period (1980 to 2009). This present-day climate period (1980 to 2009)

³² The estimates of mean annual temperature were calculated by Dr. Katharine Hayhoe.

corresponds to the baseline climate period adopted for the climate projections. A Mann Kendall trend analysis was used to identify statistically significant changes in annual and monthly minimum, maximum, and mean temperatures from 1961 to 2009.³³ Additional analyses were conducted to illustrate historical and present-day conditions of temperature extremes.

3.1.2. Key Findings

This section describes key findings from the analysis of observed temperatures. Key findings are presented for annual, seasonal, and monthly temperatures, and temperature extremes.

Annual Temperatures

The Mobile region stations have experienced similar patterns in temperature over time, collectively demonstrating no regional statistically significant ($p < 0.10$) trends in annual temperatures over the twentieth century.³⁴ Averaging across all stations and all years, 1912 to 2009, the average annual temperatures were as follows³⁵:

- Average annual **mean temperature**: 66.9°F (19.4°C)
- Average annual **minimum temperature**: 56.1°F (13.4°C)
- Average annual **maximum temperature**: 77.5°F (25.3°C)

The Coden station tends to be the coolest of the five stations, with an average observed mean temperature of 66°F (18.9°C), or approximately 0.8°F (0.4°C) lower than the five-station average.

Table 7, Table 8, and Table 9 provide the average annual minimum, maximum, and mean temperature, respectively, for each station over both the full station record (see Table 6 for each

Key Findings for Temperature Trends

- Average annual maximum temperature in the Mobile region from 1912-2009 was 78°F (25°C), with the hottest monthly temperature experienced in July at 90°F (32°C).
- Overall, average annual temperatures have not changed significantly in the Mobile region.
- Average maximum and mean temperatures in March and September have decreased significantly in the Mobile region.
- Average annual maximum temperatures have decreased significantly at three of the GHCN stations.
- The number of days per year below freezing ranged from 6 days in 1921 to 43 days in 1978 and averaged 23 days over the entire historical record.

³³ The results of the Mann Kendall trend analysis for the historical record were provided by Dr. Katharine Hayhoe.

³⁴ Statistical significance at $p < 0.10$ represents a confidence interval level of 90%. The trend for each station was considered when determining if a regional trend was noted (i.e., all five stations needed to agree). The “p-value” is a test statistic that suggests whether a significant change in temperature has occurred over the time period considered. A p-value of below 10% is less than a one-in-10 chance that the difference observed over time is due to chance. The smaller the p-value, the less likely it is that the trend observed is due to chance (e.g., a p-value of 5% is a one-in-20 chance that the trend observed is due to chance).

³⁵ The averaging for the region provides a means to effectively communicate local changes and provides a larger sample size to support the findings than based on simply one location alone. Averaging across all stations and years for regional average annual temperatures may skew the data towards the locations with the most complete and longest data record. A check was conducted, and it was determined that an artificial trend did not appear that could be associated with any one station.

station’s full record), the most recent climate period (1980-2009)³⁶, and the historical record used to inform the trend analysis (1961-2010).³⁷ The tables also provide the standard deviation (SD) of the temperature values across the time series. The SD values indicate how much variability exists in the data. A large SD as a proportion of the mean indicates a large amount of variability in the historical values, while a smaller SD indicates that the values do not vary considerably over the time period. The Coden and Robertsdale stations seem to experience the greatest temperature variability. It is not known if this variability is, in fact, due observational error.

The fourth column for each station in Table 7, Table 8, and Table 9 notes whether there has been a statistically significant increase or decrease in temperature from 1961 to 2010.³⁸ Temperatures have not changed consistently in the Mobile region. The most consistent trend found is that average annual maximum temperatures have decreased significantly ($p < 0.01$) at three of the GHCN stations, though no trend was observed at the Fairhope and Mobile stations. These findings are fairly consistent with observations in the Southeast (see Appendix B.1 for more information).

The only temperature variables that have shown regionally consistent statistically significant trends over the data record are the average maximum and mean temperatures for March and September, which have decreased significantly ($p < 0.01$) at all five GHCN stations.

Table 7: Average Annual Minimum Temperature (°F) and Variability (Δ°F) for Each Station

Station	Full Station Record [†]	1980-2009	1961-2010	Historical Trend?
Bay-Minette	56.5 (1.7)	56.5 (0.8)	56.4 (1.1)	decreasing***
Coden	55.5 (4.2)	54.7 (5.2)	55.6 (4.3)	no trend
Fairhope	57.3 (1.4)	56.9 (0.9)	56.9 (0.9)	no trend
Mobile	57.4 (1.0)	57.1 (0.9)	57.4 (1.0)	no trend
Robertsdale	54.0 (5.6)	55.5 (1.4)	55.3 (1.4)	decreasing**
Average	56.1 (2.8)	56.1 (1.8)	56.3 (1.7)	

[†]Full Station Record is detailed in Table 6

*Statistically significant at the: *90% Confidence Level, **95% Confidence Level, ***99% Confidence Level

Note: The standard deviation representing variability across the time period is provided in the parenthesis. Mann Kendall results exploring historical trend from 1961 to 2010 are provided courtesy of Dr. Hayhoe and Dr. Stoner of Texas Tech.

³⁶ Temperature averages provided in Table 3, 4, and 5 for the 1980-2009 time period are based on the observational data. This time period is consistent with the baseline time period used later in the temperature projections piece (e.g., the baseline 1980-2009 climate model simulations).

³⁷ The 1961 to 2010 analysis is based on full data except as noted previously and is for a partially complete 2010 year (does not include October, November, and December).

³⁸ Hayhoe and Stoner (2012) tested significance using the non-parametric Mann-Kendall analysis. See Hayhoe and Stoner (2012) for a full discussion of the Mann-Kendall analysis methodology.

Table 8: Average Annual Maximum Temperature (°F) and Variability (Δ°F) for Each Station

Station	Full Station Record [†]	1980-2009	1961-2010	Historical Trend?
Bay-Minette	77.8 (1.8)	77.3 (1.1)	77.4 (1.0)	decreasing***
Coden	76.5 (3.2)	75.1 (3.5)	76.4 (3.2)	no trend
Fairhope	77.8 (1.7)	77.4 (1.2)	77.4 (1.2)	decreasing**
Mobile	77.5 (1.0)	77.5 (1.0)	77.6 (1.0)	no trend
Robertsdale	77.9 (1.9)	77.5 (1.4)	77.6 (1.3)	decreasing*
Average	77.5 (1.9)	77.0 (1.6)	77.3 (1.5)	

[†]Full Station Record is detailed in Table 6

*Statistically significant at the: *90% Confidence Level, **95% Confidence Level, ***99% Confidence Level

Note: The standard deviation representing variability across the time period is provided in the parenthesis. Mann Kendall results exploring historical trend from 1961 to 2010 are provided courtesy of Dr. Hayhoe and Dr. Stoner.

Table 9: Average Annual Mean Temperature (°F) and Variability (Δ°F) for Each Station

Station	Full Station Record [†]	1980-2009	1961-2010	Historical Trend?
Bay-Minette	67.1 (1.7)	66.9 (0.8)	66.9 (0.9)	decreasing***
Coden	66.0 (3.7)	64.9 (4.2)	66.0 (3.8)	no trend
Fairhope	67.4 (1.4)	67.1 (0.9)	67.1 (0.9)	decreasing**
Mobile	67.4 (0.9)	67.3 (0.8)	67.5 (0.9)	no trend
Robertsdale	66.7 (1.6)	66.5 (1.3)	66.4 (1.2)	decreasing**
Average	66.9 (1.9)	66.5 (1.6)	66.8 (1.5)	

[†]Full Station Record is detailed in Table 6

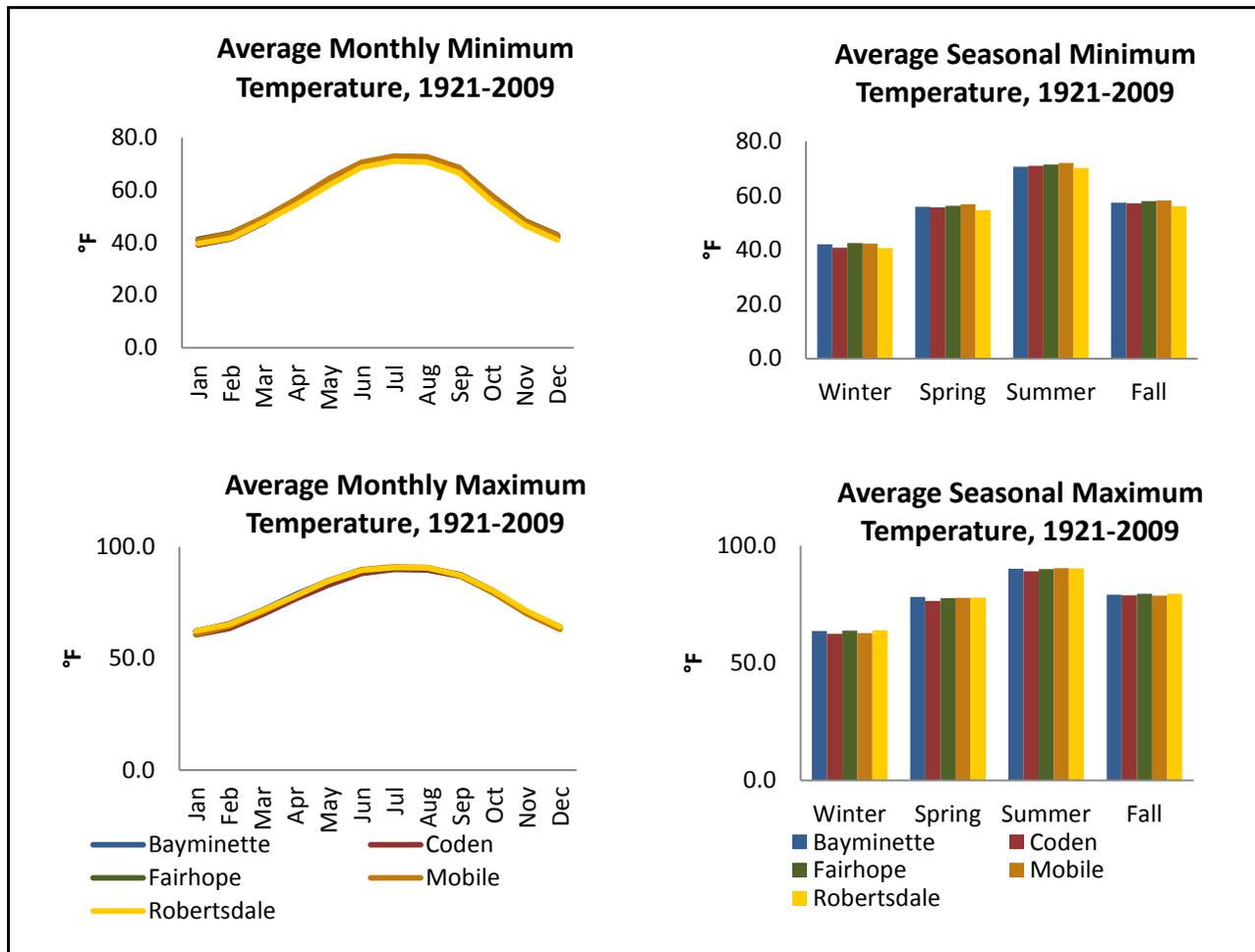
*Statistically significant at the: *90% Confidence Level, **95% Confidence Level, ***99% Confidence Level

Note: The standard deviation representing variability across the time periods is provided in the parenthesis. Mann Kendall results exploring historical trend from 1961 to 2010 are provided courtesy of Dr. Hayhoe and Dr. Stoner.

Seasonal and Monthly Temperatures

Figure 5 illustrates the average monthly and seasonal minimum and maximum temperatures across the historical record for each GHCN station. Average monthly mean temperatures range between 51°F (11°C) in January, the coldest month, and 81.2°F (27.3°C) in July, the warmest. This figure demonstrates there is more variability by month and season than by station location.

Figure 5: Average Monthly and Seasonal Minimum and Maximum Temperatures (°F), 1921-2009

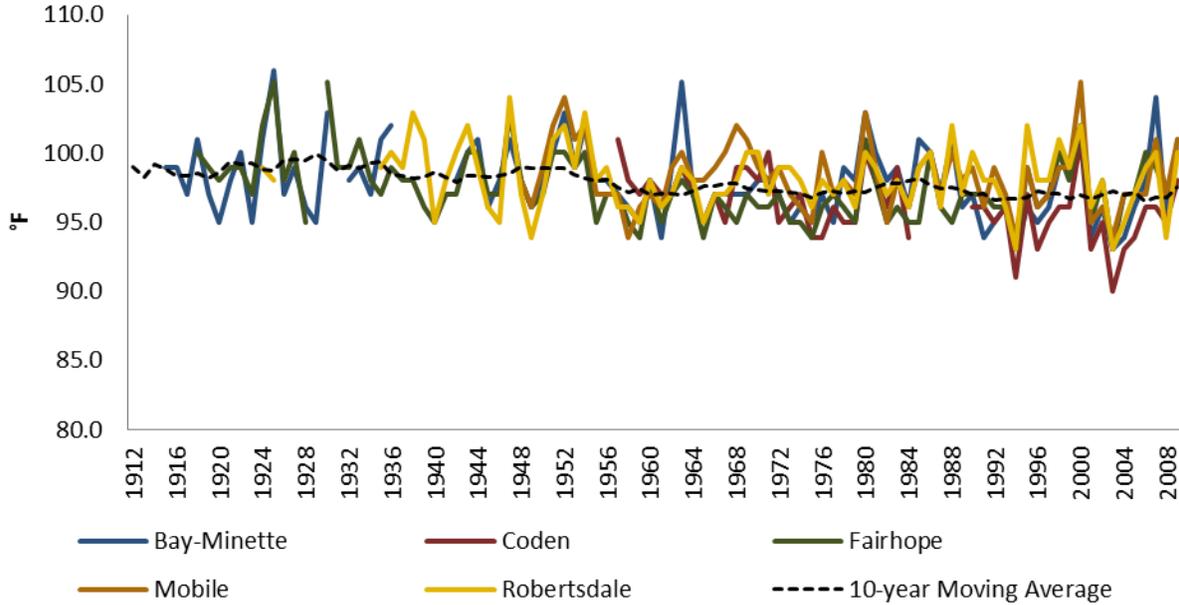


Temperature Extremes

Temperature extremes have similarly demonstrated no significant changes over the historical data record. The highest recorded temperature was 106°F (41.1°C), recorded in 1925 at the Bay-Minette station. Averaged across all five stations, the hottest day of the year has ranged between 93°F (34°C) and 104°F (40°C), recorded in 2003 and 1930, respectively. The hottest day of the

year has fluctuated around an average of nearly 98°F (37°C), exhibiting no significant linear trend upward or downward over the data record (see Figure 6).³⁹

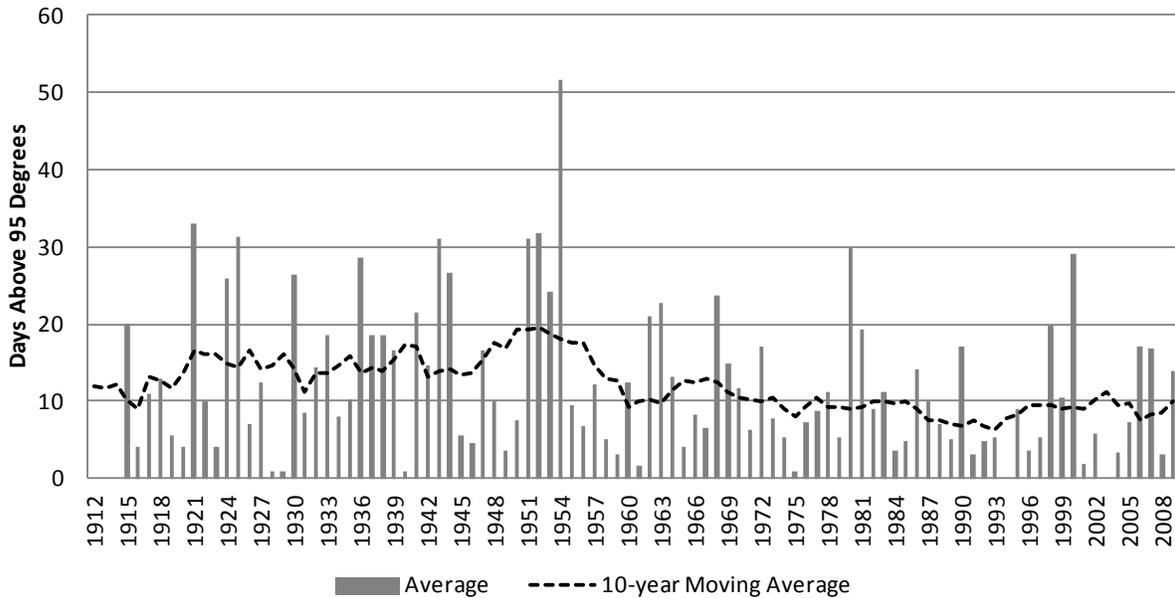
Figure 6: Hottest Day of the Year (°F)



The number of days per year above 95°F (35°C) (see Figure 7) has shown a significant ($p < 0.1$) decrease over the data record at three of the five GHCN stations from 1961 to 2009.

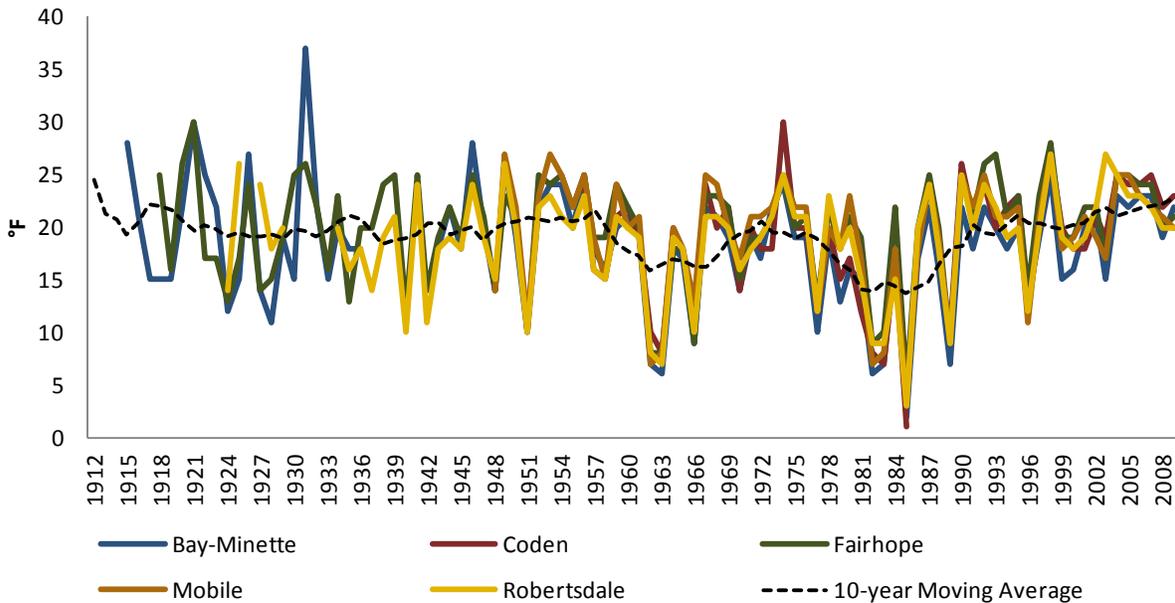
³⁹ The 10-year moving average is provided for each figure. As the five stations provide varying data records, the moving average from 1920 to 1960 is based on Bay-Minette and Fairhope station data, and the moving average after 1960 is an average across all five station data. An additional screening was applied to the observation data to remove any years where the hottest day of the year was observed to be more than three standard deviations from the long-term average.

Figure 7: Number of Days per Year above 95°F



As illustrated in Figure 8, the average coldest day of the year across the entire record and station locations was 19°F (-7°C). The coldest daily minimum temperature on record was 2.8°F (-16.2°C) in 1985. Over the past 30 years, the coldest day of the year for the Mobile region has become warmer, after reaching a historic low in the early 1980s.

Figure 8: Coldest Day of the Year



The number of days per year below freezing, averaged across all stations, ranged from 6 days in 1921 to 43 days in 1978 (see Figure 9) and averaged 23 days over the entire historical record.

Since 1960, the region has experienced an increase in the number of days below freezing compared to the first half of the century.

Figure 9: Number of Days per Year below Freezing

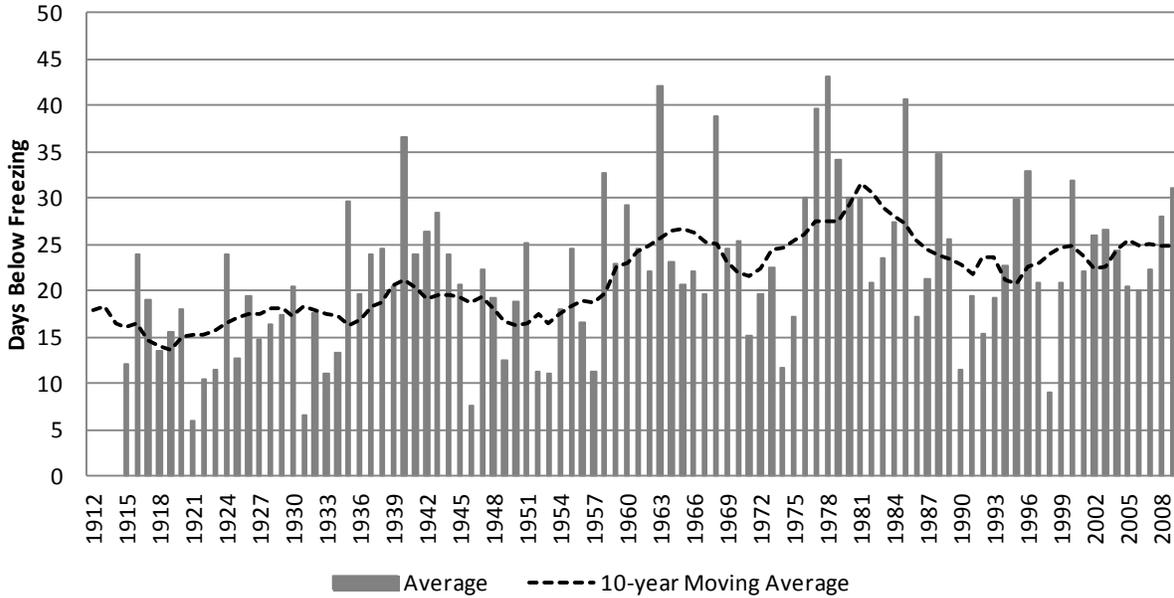


Table 10 provides a summary of the present-day (1980 to 2009) averages for the temperature variables, based on observed data. This table serves as a comparison for the projected temperature discussion in Section 3.2 (see Table 12 for a description of how these variables were developed).

Table 10: Present-day Averages for Temperature Variables, based on Observed Data

Temperature Event	1980-2009	Temperature Event	1980-2009
Number of days above 95°F	10 days	Number of consecutive days above 95°F	4 days
Number of days above 100°F	0.6 days	Number of consecutive days above 100°F	0.4 days
Number of days above 105°F	0 days	Number of consecutive days above 105°F	0 days
Number of days above 110°F	0 days	Number of consecutive days above 110°F	0 days
50 th percentile of the hottest day	96.8°F	Hottest week of the year	94.4°F

Temperature Event	1980-2009	Temperature Event	1980-2009
95 th percentile of the hottest day	101.3°F	Warmest four days in summer	100.8°F
Maximum hottest day	102.8°F		

3.2. Projected Temperature

Climate projections of temperature were statistically downscaled from a number of models and analyzed to project how annual, seasonal, and monthly-average temperature conditions; specific temperature thresholds; and extreme conditions relevant to Mobile, Alabama, may change in the future.

3.2.1. Methodology

This section describes the methodology used to estimate projected temperature changes using daily statistically downscaled climate data from up to ten climate models under three emission scenarios. Additional detail is provided in Appendix C.3.

Climate Models and Emission Scenarios

To capture a range of possible futures, a low emission scenario (B1), a moderately-high emission scenario (A2), and a high emission scenario (A1FI) were selected for a scenario-based analysis of future climate. A summary of the downscaled climate data is provided here (see Hayhoe and Stoner (2012) for a detailed description of the downscaling methodology and validation results).⁴⁰

Projections of daily temperature for Mobile were statistically downscaled from climate model data housed in the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP3) multi-model data set.⁴¹ Climate models in the WCRP CMIP3 database were selected based on the following three criteria:

- Climate models must be “well established” and shown to adequately reproduce key features of the atmosphere and ocean systems.
- The climate model ensemble should represent the IPCC’s range of uncertainty in climate sensitivity.⁴²
- Climate models must provide adequate available data with continuous daily temperature for at least two of the three emission scenarios used in this study (A1FI, A2, and B1).⁴³

⁴⁰ The statistically downscaled projections were provided by Dr. Katharine Hayhoe and Dr. Anne Stoner through an interagency agreement between FHWA and USGS (see Hayhoe and Stoner (2012) for a detailed analysis and summary of the methodology and results). The WCRP CMIP3 data set can be found at <http://esg.llnl.gov:8080/index.jsp>. For purposes of this study, climate model is used synonymously with global climate model (GCMs).

⁴¹ The WCRP CMIP3 data set was used to inform the findings of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). This database will be replaced with the WCRP CMIP5 data set that is currently being developed by the climate community and whose findings will be summarized in the IPCC Fifth Assessment Report (AR5) scheduled to be published in September 2013. The methodologies and tools developed in this report are transferable to the new data set.

⁴² Note that the models which simulate the hottest temperature response to a doubling of CO₂ concentrations (i.e., highest climate sensitivity) are not included in this assessment.

Ten climate models, described in Table 11, met these criteria. Their projections of daily minimum temperature and daily maximum temperature were downloaded for each emission scenario for the years 1960 to 2099.⁴⁴

Table 11: The Climate Models Used in This Study (Adapted from Hayhoe and Stoner (2012))

Climate Model Name	Origin	Atmospheric Resolution (horizontal and vertical)	Climate Sensitivity (°C)	Emission Scenario		
				B1	A2	A1FI
BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway	1.9° x 1.9° 31 levels	N/A	✓	✓	
CCSM3	National Center for Atmospheric Research, USA	1.4° x 1.4° 26 levels	2.7	✓	✓	✓
CGCM3 (T47)	Canadian Centre for Climate Modeling and Analysis, Canada	2.8° x 2.8° 31 levels	3.4	✓	✓	
CGCM3 (T63)		1.9° x 1.9° 31 levels	3.4	✓	✓	
CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques, France	1.9° x 1.9° 45 levels	N/A	✓	✓	
ECHAM5/MPI-OM	Max Planck Institute for Meteorology, Germany	1.9° x 1.9° 31 levels	3.4	✓	✓	
GFDL-CM2.0	U.S. Department of Commerce/ National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), USA	2.0° x 2.5° 24 levels	2.9	✓	✓	
GFDL-CM2.1		2.0° x 2.5° 24 levels	3.4	✓	✓	✓
PCM	National Center for Atmospheric Research, USA	2.8° x 2.8° 26 levels	2.1	✓	✓	✓
UKMO-Hadcm3	Hadley Centre for Climate Prediction and Research/Met Office, UK	2.5° x 3.75° 19 levels	3.3	✓	✓	✓

To account for local influences, the large-scale climate data was downscaled to the locations of individual local observation stations (see Figure 4).⁴⁵ The Asynchronous Regional Regression

⁴³ Hayhoe and Stoner, 2012.

⁴⁴ All ten models had projections for the B1 and A2 emission scenarios. Only four of the models as noted in Table 11 had projections for the A1FI emission scenario.

Model (ARRM) method of statistical downscaling was used because it is capable of downscaling at daily timescales.⁴⁶ To learn more about the downscaling methodology, see Appendix C.2.5 and Hayhoe and Stoner (2012).

Temperature Averages and Events

Table 12 provides a list of the temperature-related weather hazards and climatic averages that are investigated in this study. All of the variables can be directly estimated using the daily downscaled temperature data. These average changes and events were identified and deemed useful by:

- Discussions among local transportation engineers and planners about how local transportation infrastructure, maintenance, and operations in Mobile are impacted by today’s weather hazards,
- An extensive literature review and conversations with local transportation officials, summarized in the *Assessing Sensitivity* report, and
- Meetings of transportation infrastructure engineers, federal transportation planners, and climate scientists.

Only some of these variables provide robust, quantitative results appropriate for quantitatively-based decisions. In Table 12, asterisks denote the variables and percentiles that do not provide robust quantitative results (per communication with Dr. Hayhoe) and their use should be limited to qualitatively informing the impact assessment. In general, these asterisks denote cases where extreme events are based on a small sample size (e.g., 5th percentile of high daily maximum temperature is based on only 30 data points). In contrast, temperature projections based on a large sample size are considered robust (e.g., average annual temperature is based on 365 days of data per year and averaged across 30 years for a total of more than 10,000 data points).

Table 12: Temperature Variables Developed for this Study

Variable	Transportation Mode	Methodology
Annual, seasonal, and monthly average minimum, maximum, and mean temperature for each 30-year time period	Airports (runway design)	For each 30-year period, the daily minimum, maximum, and mean temperature corresponding to each month, season, or year were averaged for each station location, climate model, and emission scenario. Then, the 30-year average was determined for each station location, climate model, and emission scenario. Averages and standard deviations were then calculated across climate models for each station location and emission scenario. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region.

⁴⁵ Downscaling of the global climate model simulations was conducted by Dr. Katharine Hayhoe.

⁴⁶ Hayhoe and Stoner, 2012.

Variable	Transportation Mode	Methodology
<p>5th*, 50th and 95th*percentile of high daily maximum temperature and the warmest day of the year for each 30-year time period</p>	<p>Rail (AREMA rail design, buildings)</p>	<p>For each 30-year period, the daily maximum temperature for each year was identified. This resulted in a total of 30 data points in each time period for each climate model, station location, and emission scenario. The mean, 50th, and 95th percentile levels were estimated from this set of 30 data points applying a quantile distribution and then averaged across climate models for each station location and emission scenario. The warmest day in summer for the 30-year period was estimated in the same way. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region.</p>
<p>Seasonal and annual number of days and maximum consecutive days of maximum temperatures at or above 95°F, 100°F, 105°F, and 110°F during each 30-year time period</p>	<p>Civil, Geotech, Pavement</p>	<p>For each 30-year period, the number of days where the maximum temperature was at or above 95°F, 100°F, 105°F, and 110°F was counted for each year. This resulted in 30 data points in each time period (one for each year), for each climate model, station location, and emission scenario. The 30 data points were averaged to estimate the annual number of days at or above each high temperature threshold for each climate model, station location, and emission scenario. The mean and standard deviation was then determined across the climate models for each station location and emission scenario. The process was repeated to obtain seasonal projections. The maximum consecutive days of high temperature for each threshold was likewise calculated. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region.</p>

Variable	Transportation Mode	Methodology
<p>Mean; 5th*, 25th, 50th, 75th, and 95th* percentile; and minimum value for the average minimum air temperature over four consecutive days in winter and the average maximum temperature over four consecutive days in summer for each 30-year time period</p>	<p>Bridge, Rail</p>	<p>For each winter in the 30-year period, the average of the minimum air temperature for any four consecutive days was estimated for each climate model projection, emission scenario, and location. The 5th, 25th, 50th, 75th, and 95th percentile; mean; and coldest period across the 30 data points was estimated for each climate model, emission scenario, and location applying a quantile distribution. For each summer in the 30-year period, the average of the maximum air temperature for any four consecutive days was estimated for each year, ultimately providing the 5th, 25th, 50th, 75th, 95th percentile; mean; and hottest period across the 30 data points for each climate model, emission scenario, and location. The average across climate models for each location was determined, and then averaged across station locations to provide an average for the Mobile region.</p>
<p>The average, 1st*, 5th *, 10th, and 50th percentile of the coldest day of the year during each 30-yr time period</p>	<p>Multi (pavement design)</p>	<p>Using the daily minimum temperatures, the coldest minimum temperature for each year was identified for each climate model, emission scenario, and station location. Across the 30 data points for each time period, the mean, 1st, 5th, 10th, and 50th percentile was calculated by applying a quantile distribution for each climate model, emission scenario, and station location. The average across climate models for each location was determined, and then averaged across station locations to provide an average for the Mobile region.</p>
<p>Maximum 7-day average air temperature per year with the % probability of occurrence during each 30-yr period (mean, 50th, 90th, 95th*, 99th*percentile) for each 30-yr time period</p>	<p>Multi (pavement design - asphalt)</p>	<p>Using the daily maximum temperature, the maximum 7-day average temperature for each year was determined. This produced a total of 30 data points in each time period, for each climate model, emission scenario, and station location. Across the 30 data points, the mean, 50th, 90th, 95th, and 99th percentile was estimated by applying a quantile distribution for each climate model, emission scenario, and station location. The average across climate models for each location was determined, and then averaged across station locations to provide an average for the Mobile region.</p>

The statistically downscaled climate model results were provided for each emission scenario, for each of the five station locations, and for the baseline and projected time frames (1980 to 2009, 2010 to 2039, 2040 to 2069, and 2070 to 2099). For each station location, the results were then

averaged across the statistically downscaled climate models to produce a climate model ensemble average (the average projection across all climate models for a given emission scenario and time period).⁴⁷ The projected change for each temperature average, threshold, and extreme was calculated by comparing the climate model ensemble average projections to the climate model ensemble average baseline (“simulated baseline”) of 1980 to 2009.⁴⁸

Identification of Statistically Significant Climate Projections

This study produced an enormous amount of climate projections across station locations, emission scenarios, and time periods. For a complete database of the climate projections by emission scenario, location, and time period, see Appendix E.1.

To focus the study on climate projections that represent a statistically significant projected change from the simulated baseline conditions, a statistical test (a paired t-test) was used to identify significant ($p < 0.05$) changes, i.e., climate projections that are statistically different from simulations of the baseline climate (1980 to 2009). See Appendix C.3.2 for a description of the paired t-test.

For the purposes of this study, only the variables that demonstrate a statistically significant change at *all five* station locations are considered to demonstrate statistically significant differences for the region.

3.2.2. Key Findings

This section presents the results of the projected temperature analysis, including a discussion of:

- Average annual minimum, maximum, and mean temperatures
- Average seasonal and monthly minimum, maximum, and mean temperatures
- Extreme temperature events

Temperature is projected to increase over time as greenhouse gas concentrations in the Earth’s atmosphere continue to increase. The farther out in time, the greater the amount of temperature increase. Overall, the amount of temperature increase is directly proportional to the increase in emissions—that is, the high (A1FI) emission scenario is associated with greater overall temperature increases than the low (B1) emission scenario.

The increase in seasonal and monthly means is more variable across the emission scenarios. For example, under the low (B1) and moderately-high (A2) emission scenarios, seasonal average temperatures are projected to increase the most in the fall season, with monthly average temperatures increasing the most in October. Under the high (A1FI) emission scenario, seasonal average temperatures are projected to increase the most in the summer season, with monthly

⁴⁷ Since there are 10 GCMs providing results for the A2 and B1 emission scenarios, the uncertainty estimates include ranges of one standard deviation from the mean based on the set of all relevant climate model simulations. Since only four GCMs provide results for the A1FI emission scenario, the uncertainty estimates are a coarser range of model results described by the minimum and maximum GCM values.

⁴⁸ The climate model simulations of 1980 to 2009 are similar but not identical to the observations of 1980 to 2009 discussed in section 2.1.1.

average temperatures still increasing the most in October. As emissions increase there may be a tendency for peak warming to shift from fall to summer seasons.

Explanation of Box Plots

Throughout this report, the projected changes in environmental variables are illustrated by box plots. Each box on the plot shows the mean (represented by the line separating the two types of shading) and variability¹ (represented by the box height) of climate projections for each time period and emission scenario, averaged across all five stations and the climate model ensemble. The “simulated baseline”¹ is the average temperature simulated from 1980 to 2009, as modeled by all downscaled climate models and averaged across emission scenarios and station locations.

Tables including more detail about the projected changes are available in Appendix C.5.

Average Annual Temperatures

Key Findings for Average Annual Temperatures

- Average maximum, minimum, and mean temperatures are projected to increase significantly in each time period under all emission scenarios.
- Average mean temperatures increase steadily with each 30-year time period by approximately 1°F (0.6°C), 2°F (1°C), and 3°F (2°C) for the low (B1), moderately-high (A2), and high (A1FI) emission scenarios, respectively.
- Minimum temperatures are projected to increase more than maximum temperatures.

Average annual maximum, minimum, and mean temperatures averaged across each of the time periods are projected to increase significantly ($p < 0.05$) for all emission scenarios. Figure 10 illustrates how average annual mean temperatures are projected to increase over time in the Mobile region as a function of emission scenario and time period.

Figure 10: Projected Average Mean Temperature (°F)

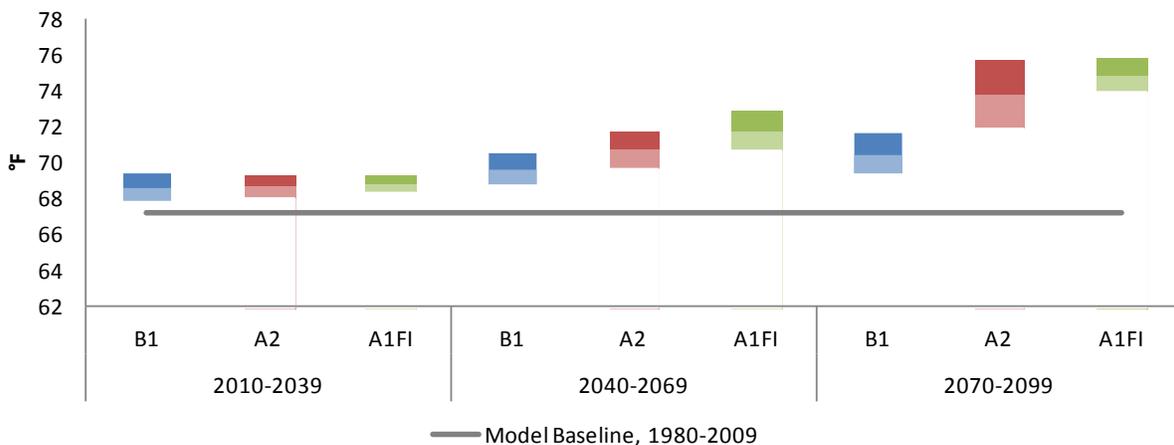


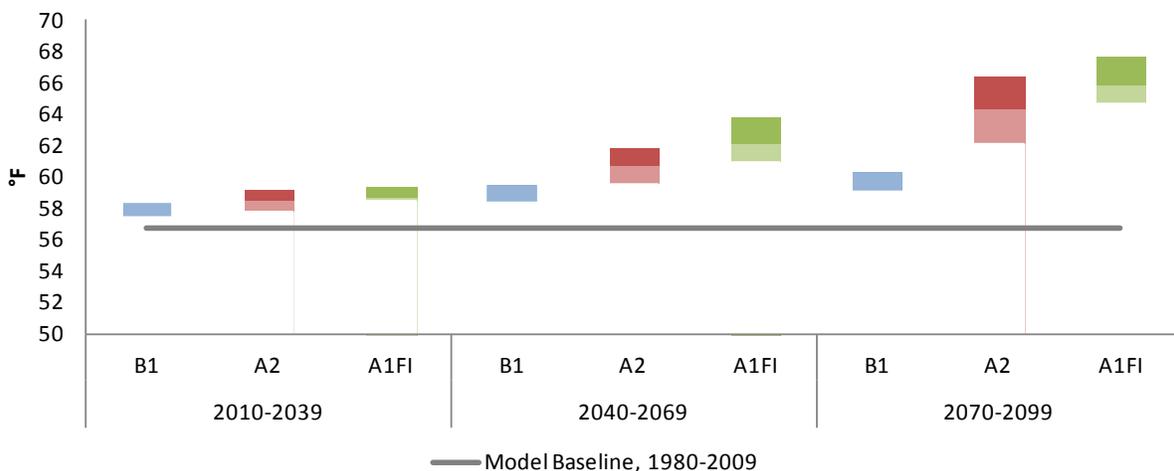
Figure 10 also illustrates that the variability of the temperature projections increases with time (variability is indicated by the range of projections across both climate models and station locations).⁴⁹ This figure shows that though temperature increases in the near-term are similar under all three emission scenarios, a distinct pattern based on emission scenario emerges by mid-century and end-of-century. By mid-century, average annual mean temperatures are projected to increase 2.4°F (1.3°C), 3.5°F (1.9°C), and 4.6°F (2.6°C) above modeled baseline for the low (B1), moderately-high (A2), and high (A1FI) emission scenarios, respectively. By end-of-century, average annual mean temperatures are projected to increase by 3.2°F (1.8°C), 6.6°F (3.7°C), and 7.7°F (4.3°C) above modeled baseline, for the low (B1), moderately-high (A2), and high (A1FI) emission scenarios, respectively. A noticeable pattern suggests average annual mean temperatures steadily increase with each 30-year time period by approximately 1°F (0.6°C), 2°F (1°C), and 3°F (2°C) for the low (B1), moderately-high (A2), and high (A1FI) emission scenarios, respectively.

The average annual mean temperature observed over the past 30 years (1980-2009) in the Mobile region was about 67°F (19°C). By the end-of-century, this may increase to 70.5°F (21.4°C) under the low (B1) emission scenario, 73.8°F (23.2°C) under the moderately-high (A2) emission scenario, and 74.8°F (23.8°C) under the high (A1FI) emission scenario.

Average annual maximum temperatures are projected to increase from 78°F (26°C) at baseline to as high as 84°F (29°C) by the end-of-century under the high (A1FI) emission scenario.

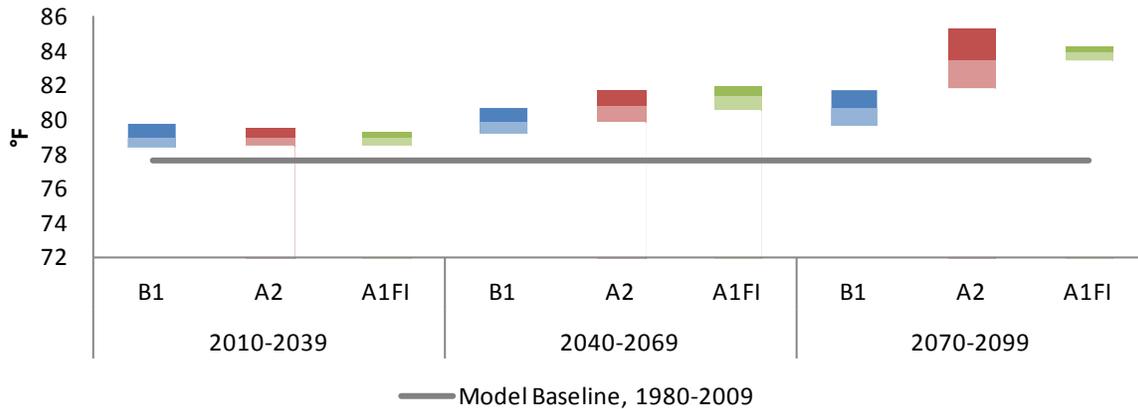
Figure 11 and Figure 12 show that minimum temperatures are projected to increase more than maximum temperatures. This suggests that the diurnal temperature range will reduce with time.

Figure 11: Projected Average Minimum Temperature (°F)



⁴⁹ The trends were found to be consistent across all five stations.

Figure 12: Projected Average Maximum Temperature (°F)



Key findings for average annual temperature increases relative to simulated baseline (1980-2009) are as follows:

- In the near-term (2010-2039):
 - Projections associated with the low (B1) and moderately-high (A2) emission scenarios indicate average annual mean, minimum, and maximum temperatures will increase 1.4°F (0.8°C), 1.6°F (0.9°C), and 1.3°F (0.7°C), respectively.
 - Projections associated with the high (A1FI) emission scenario indicate the average annual minimum temperature will increase more, thereby affecting the average annual mean temperature. Under this scenario, average annual mean, minimum, and maximum temperatures are projected to increase by 1.7°F (0.9°C), 2.0°F (1.1°C), and 1.3°F (0.7°C), respectively.
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, the average annual mean, minimum, and maximum temperatures are projected to increase 2.4°F (1.3°C), 2.6°F (1.4°C), and 2.2°F (1.2°C), respectively, which represents an approximately 1°F (0.6°C) increase from the near-term projections.
 - Under the moderately-high (A2) emission scenario, the average annual mean, minimum, and maximum temperatures are projected to increase 3.5°F (1.9°C), 3.9°F (2.2°C), and 3.1°F (1.7°C), respectively, which represents an approximately 2°F (1°C) increase from the near-term projections.
 - Under the high (A1FI) emission scenario, the average annual mean, minimum, and maximum temperatures are projected to increase 4.6°F (2.6°C), 5.5°F (3.1°C), and 3.8°F (2.1°C), respectively, which represents an approximately 3°F (2°C) increase from the near-term projections.

- By end-of-century (2070-2099):
 - Average annual temperature projections associated with the low (B1) emission scenario increase by approximately 3°F (2°C), or about 1°F (0.6°C) from mid-century projections.
 - Average annual temperature projections associated with the moderately-high (A2) emission scenario increase by 5.8 to 7.5°F (3.2 to 4.2°C), or about 2°F (1°C) from mid-century projections.
 - Average annual temperature projections associated with the moderately high (A2) emission scenario increase by 6.3°F (3.5°C), or about 3°F (2°C) from mid-century projections.

Season Definitions

Winter = December, January, February

Spring = March, April, May

Summer = June, July, August

Fall = September, October, November

Average Seasonal and Monthly Temperatures

Key Findings for Average Seasonal and Monthly Temperatures

- Average seasonal and monthly mean temperatures are projected to increase significantly for all emission scenarios and time periods.
- The largest average seasonal mean temperature increases are projected to occur in the fall (particularly in October) and are largely dependent on the timing of the substantial increases in average minimum temperatures.
- The range of daily temperatures is projected to decrease. This might benefit pavement and other infrastructure, but the level of projected temperatures may result in less cooling relief overnight.

Average seasonal and monthly mean temperatures are also projected to increase significantly for all emission scenarios and time periods. Projected changes in seasonal and monthly average mean temperatures are driven largely by the projected changes in average minimum temperatures.

Under the low (B1) and moderately-high (A2) emission scenarios, seasonal average temperatures are projected to increase the most in the fall season. Monthly average temperatures are projected to increase the most in October.

Under the high (A1FI) emission scenario, seasonal average temperatures are projected to increase the most in the summer season. Monthly average temperatures are still projected to increase the most in October.

Projections suggest that the average seasonal and monthly diurnal temperature range may decrease, particularly for temperature projections associated with the moderately-high (A2) and high (A1FI) emission scenarios.

Key findings for seasonal and monthly temperature increases relative to simulated baseline (1980 to 2009) are as follows:

- In the near-term (2010 to 2039):
 - Projected changes in average seasonal mean, maximum, and minimum temperatures are relatively consistent across emission scenarios and seasons. Temperatures are projected to increase relatively modestly, by about 1 to 2°F (0.6 to 1°C). Fall is projected to experience a slightly larger warming in minimum temperatures compared to the other seasons.
 - Projected average monthly mean, maximum, and minimum temperatures do not exhibit much variability across emission scenarios and months.
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, average maximum and mean temperature changes vary by less than 1°F (0.6°C) across seasons. The greatest increase (2.6°F (1.4°C) in maximum temperature and 2.9°F (1.6°C) in mean temperature) is projected in the fall. Average minimum temperatures vary by about 1.0°F (0.6°C) across seasons. The greatest increase in minimum temperature (3.2°F (1.8°C)) is projected in the fall and peaks in November.
 - Under the moderately-high (A2) emission scenario, average maximum and mean temperatures vary by about 1°F (0.6°C) across seasons. The greatest increase (about 3.5°F (1.9°C) in maximum temperature and 4.2°F (2.3°C) in mean temperature) is projected in the fall. Average minimum temperatures vary by about 1.7°F (0.9°C) across seasons. The greatest increase in minimum temperature (4.9°F or 2.8°C) is projected for the fall and peaks in October.
 - Under the high (A1FI) emission scenario, average maximum and mean temperatures vary by as much as 2°F (1°C) across seasons. The greatest increase (about 4.2°F (2.3°C) in maximum temperature and 5.5°F (3.1°C) in mean temperature) is projected for the summer. Average minimum temperatures vary by about 1.7°F (0.9°C) across seasons. The greatest increase in minimum temperature (6.9°F or 3.8°C) is projected for summer, though October is still projected to experience the greatest monthly increase.

Figure 13: Change in Average Seasonal Mean Temperature, Averaged Across Climate Models and Station Locations for Mid-Century (2040-2069) Relative to Baseline (1980-2009)

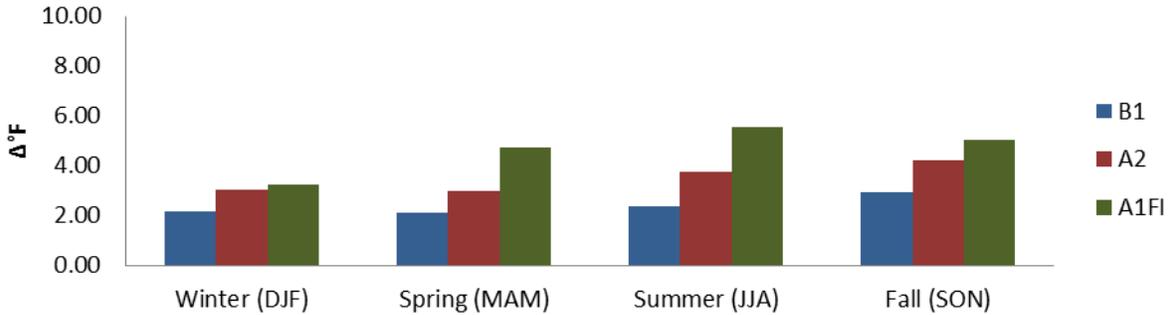
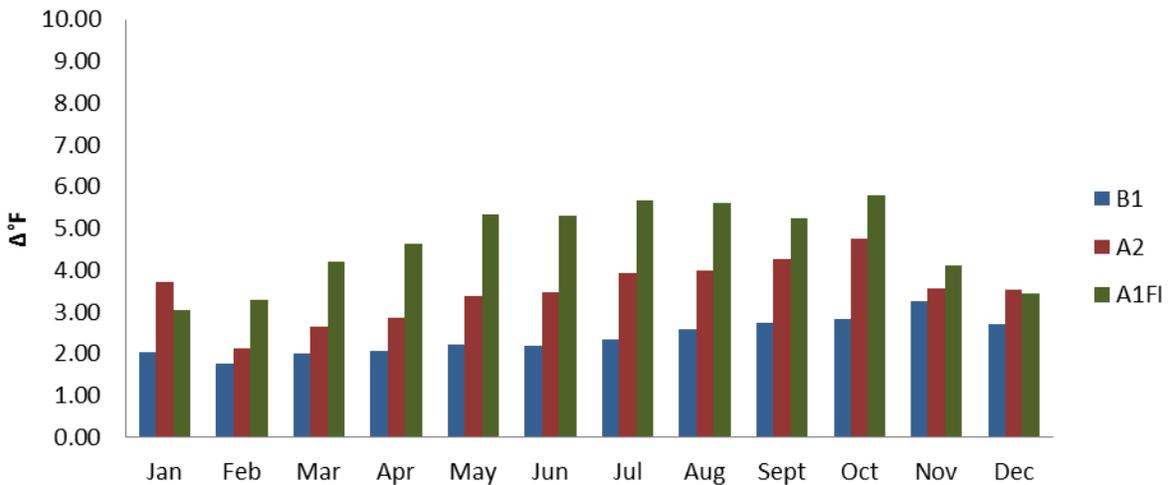


Figure 14: Projected Change in Average Monthly Mean Temperature, Averaged Across Climate Models and Station Locations for Mid-Century (2040-2069) Relative to Baseline (1980-2009)



■ By end-of-century (2070-2099):

- Under the low (B1) emission scenario, temperature increases would continue to peak in the fall. Average mean temperature is projected to increase by 4.3°F (2.4°C) in the month of October.
- Under the moderately-high (A2) emission scenario, temperature increases would continue to peak in the fall. Average mean temperature is projected to increase by 8.9°F (4.9°C) in the month of October. In the summer and fall months, average minimum temperatures are projected to increase by nearly 3°F (2°C) more than average maximum temperatures. Projected increases in mean monthly minimum temperatures range from 4.7°F (2.6°C) in February to 10.6°F (5.9°C) in October.
- Under the high (A1FI) emission scenario, seasonal temperature increases are projected to peak during the summer, though the greatest monthly temperature increase is projected in October. Projected increases in mean monthly minimum temperatures range from 5.2°F (2.9°C) in February to 12.0°F (6.7°C) in October, with summer months increasing by

about 11°F (6.1°C) or more. The mean monthly maximum temperatures are projected to increase more modestly, with projected increases ranging from 5.3°F (2.9°C) in February to 7.1°F (3.9°C) in May.

Figure 15: Change in Average Seasonal Mean Temperature, Averaged Across Climate Models and Station Locations for End-of-Century (2070-2099) Relative to Baseline (1980-2009)

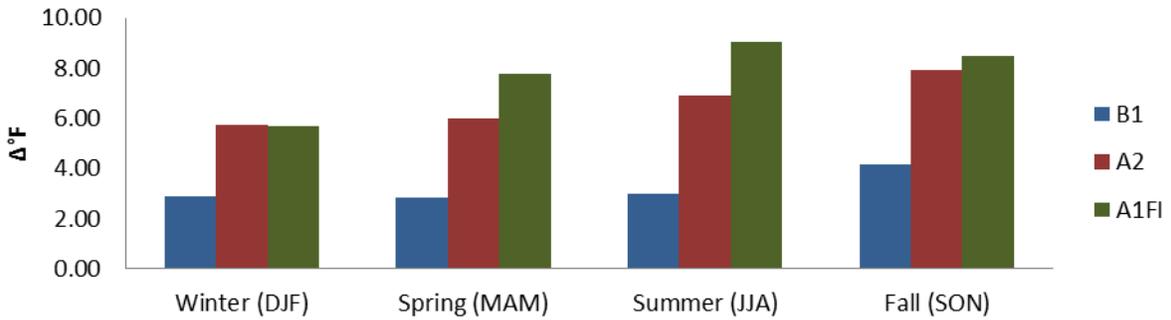


Figure 16: Projected Change in Average Monthly Mean Temperature, Averaged Across Climate Models and Station Locations for End-of-Century (2070-2099) Relative to Baseline (1980-2009)

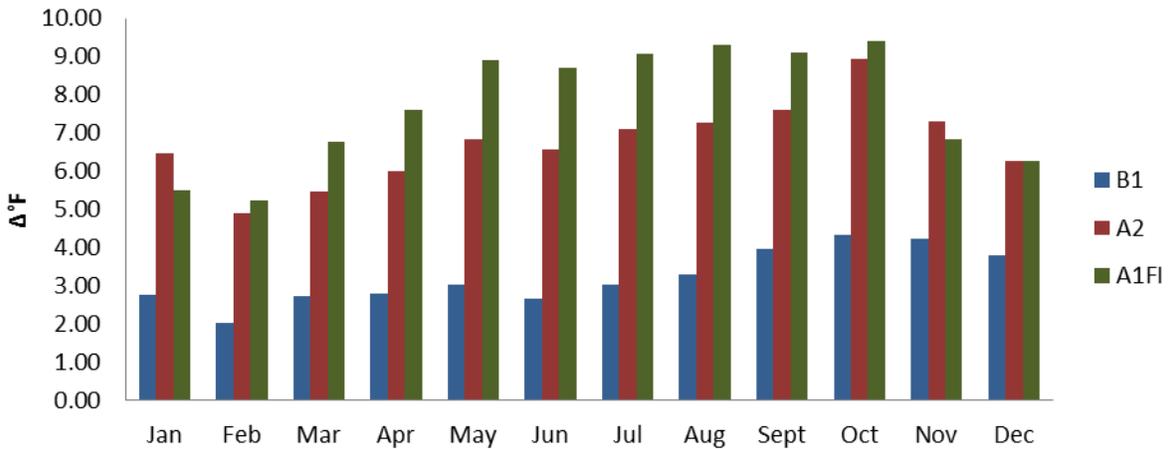
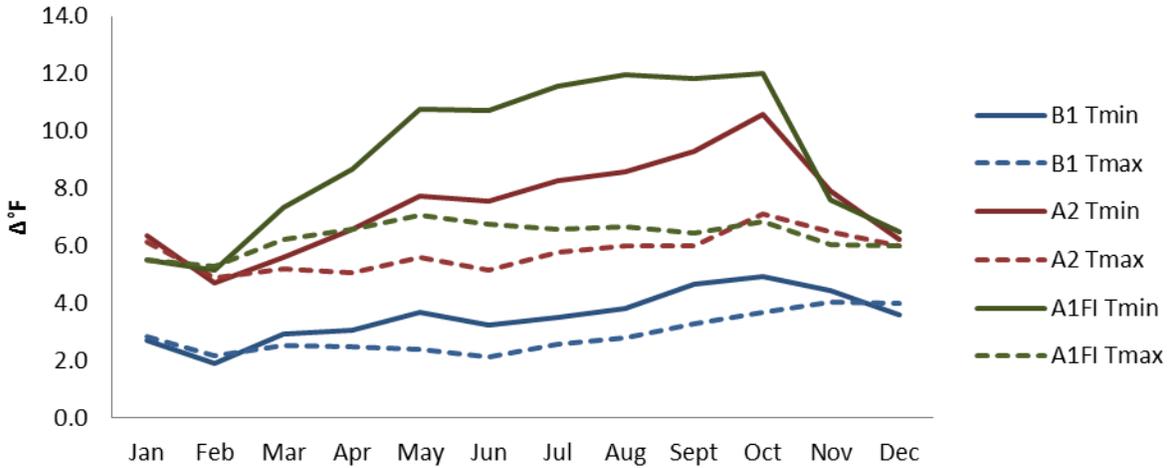


Figure 17: Projected Change in Average Monthly Minimum and Maximum Temperatures, Averaged Across Climate Models and Station Locations for End-of-Century (2070-2099) Relative to Baseline (1980-2009)



A common theme across these projections is that the range between minimum and maximum temperatures is projected to decrease over time (see Figure 17). A decrease in the range of daily temperatures may benefit pavement and other infrastructure, but the level of projected temperatures under the future scenarios implies that there may be less cooling relief overnight.

Extreme Temperature Events

Key Findings for Extreme Temperature Events

- The number of heat events above 95°F (35°C) and 100°F (38°C) are projected to increase dramatically, indicating:
 - By mid-century, an additional 2 to 5.5 weeks above 95°F (35°C).
 - By end-of-century, an additional 3 to 11 weeks above 95°F (35°C).
- The number of heat events above 105°F (41°C) and 110°F (43°C) are not projected to change significantly.
- The number of consecutive days over 95°F (35°C) (i.e., a heat wave) is also projected to increase in length, indicating:
 - By mid-century, an increase of about 1 to 2 weeks in the length of the longest heat wave.
 - By end-of-century, an increase of about 1 week to 1 month in the longest heat wave.
- The average coldest four days in winter are projected to increase by nearly 3 to 6°F (1.7 to 3.3°C) by end-of-century.

The discussion of extreme temperature events are divided into two sections: extreme heat and extreme cold. See Table 10 for the present-day (1980 to 2009) averages for the temperature variables, based on observed data.

Extreme Heat

The discussion of extreme heat is further divided into two sections: hot days and hot periods.

Hot days

This section presents the projected change for the following variables:

- Number of hot days above 95°F (35°C), 100°F (38°C), 105°F (41°C), and 110°F (43°C)
- Number of consecutive days above 95°F (35°C) (called heat events), 100°F (38°C), 105°F (41°C), and 110°F (43°C)
- 50th and 95th percentile and maximum hottest day

These variables were derived from maximum temperature and averaged across the downscaled climate model and station location for each emission scenario and future time period (see Table 12 for a description of the how each of these variables were calculated).

From 1980 to 2009, the hottest temperature of the year in the Mobile region averaged nearly 103°F (39°C). This high temperature is very unusual, as Mobile only experiences an average of 9 to 10 days per year above 95°F (35°C) and less than one day per year above 100°F (38°C). The duration of heat events (i.e., number of consecutive days when the daily maximum temperature is above 95°F (35°C)) averaged almost four days per year.

The number of days above 95°F (35°C) and 100°F (38°C) is projected to increase significantly. However, there was no significant projected change in the number of days above 105°F (41°C) or 110°F (43°C) (currently zero – see Table 10). Only the end-of-century moderately-high (A2) and high (A1FI) emission scenarios project an average 1 to 2 days of temperatures above 105°F (41°C). Figure 18 and Figure 19 show the dramatic projected increases in the number of hot days.

By mid-century, the number of days above 95°F (35°C) is projected to increase by two weeks under the low (B1) emission scenario and by a month or more under the moderately-high (A2) and high (A1FI) emission scenarios. This represents an approximately four-fold increase over baseline.

By end-of-century, the number of days above 95°F (35°C) is projected to increase by three weeks under the low (B1) emission scenario and by two months or more under the moderately-high (A2) and high (A1FI) emission scenarios. This represents a nine-fold increase in the number of days over 95°F (35°C) under the A1FI scenario by end-of-century.

Figure 18: Projected Number of Days per Year above 95°F

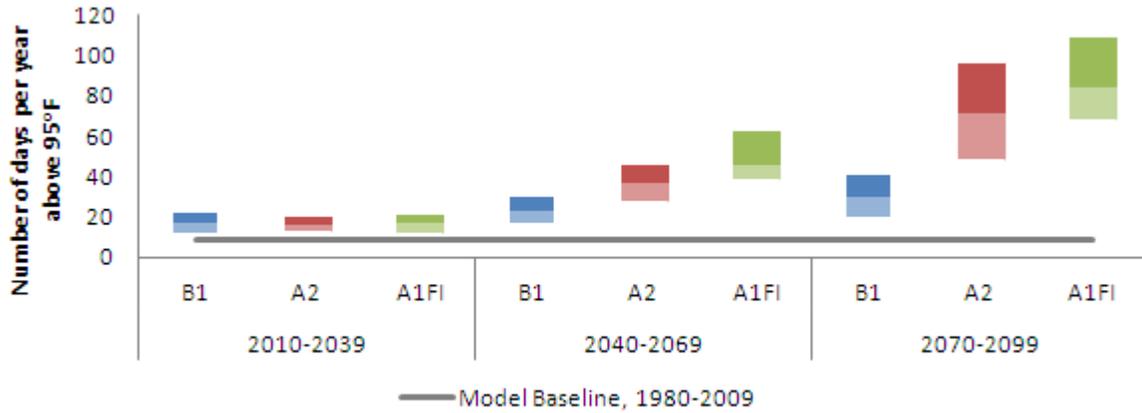


Figure 19: Projected Number of Days per Year above 100°F

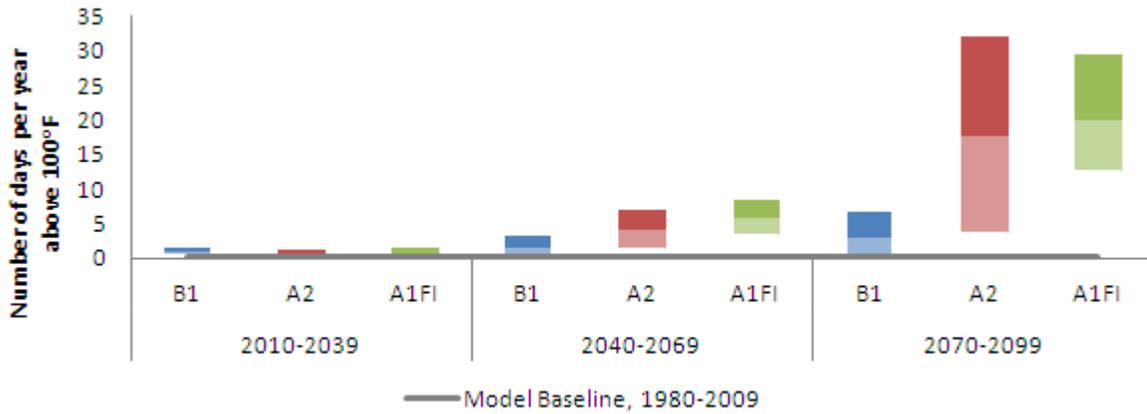


Figure 20 and Figure 21 show the increase in the maximum number of consecutive days over 95°F (35°C) and 100°F (38°C). These figures suggest that heat events will last longer in the future.

Figure 20: Projections of the Longest Number of Consecutive Days per Year above 95°F

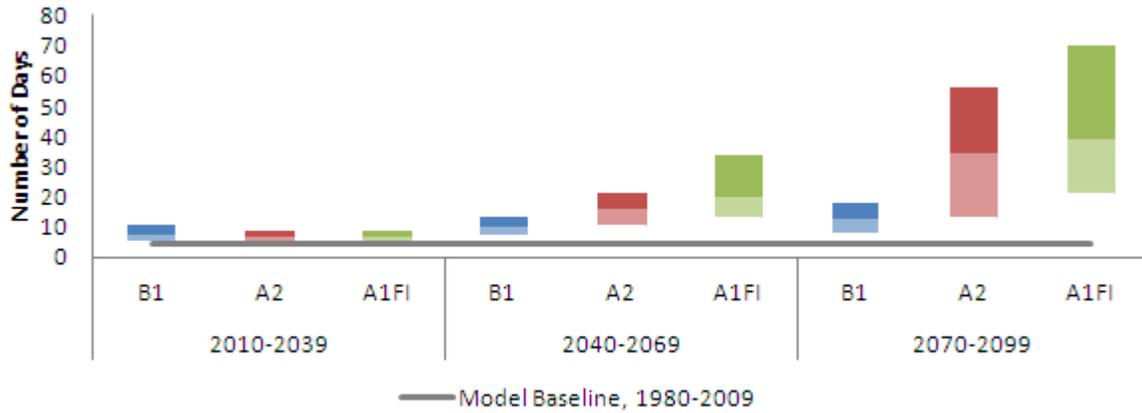


Figure 21: Projections of the Longest Number of Consecutive Days per Year above 100°F

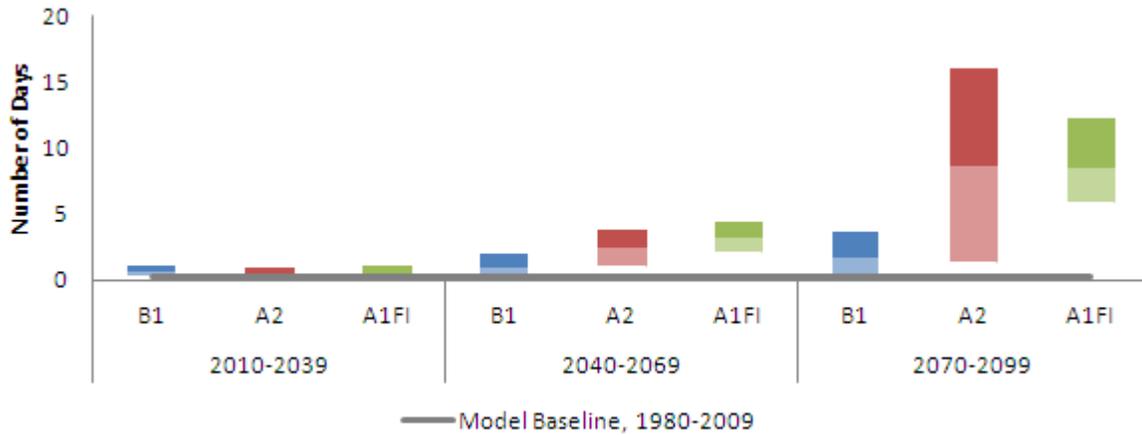


Figure 22 and Figure 23 illustrate percentiles of temperature for the hottest day of the year by time period and emission scenario. As with other temperature metrics, the temperature of the hottest day of the year is projected to increase with time and emissions. Variability in projections across climate models and observation stations also increases over time. The maximum hottest temperature projected by end-of-century is 109.3°F (42.9°C), under the A1FI emission scenario.

Figure 22: Hottest Day of the Year, Mid-Century (2040-2069)

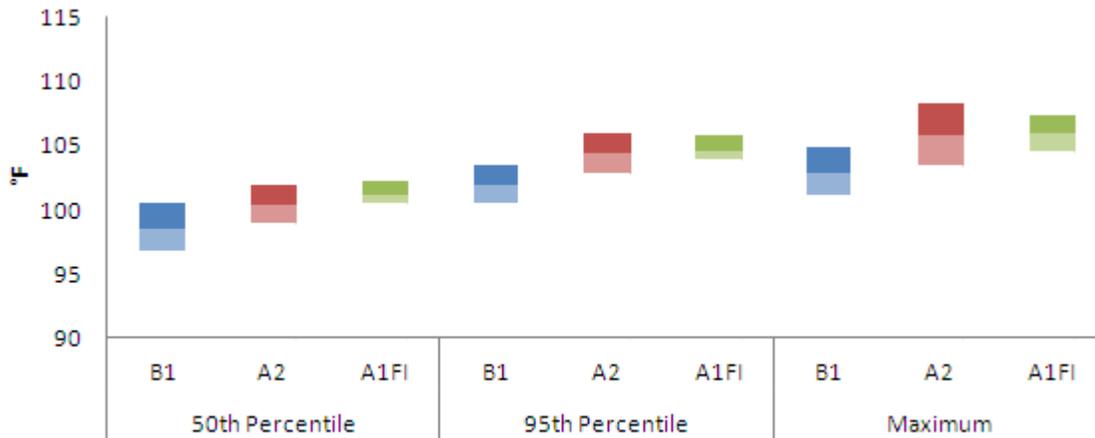
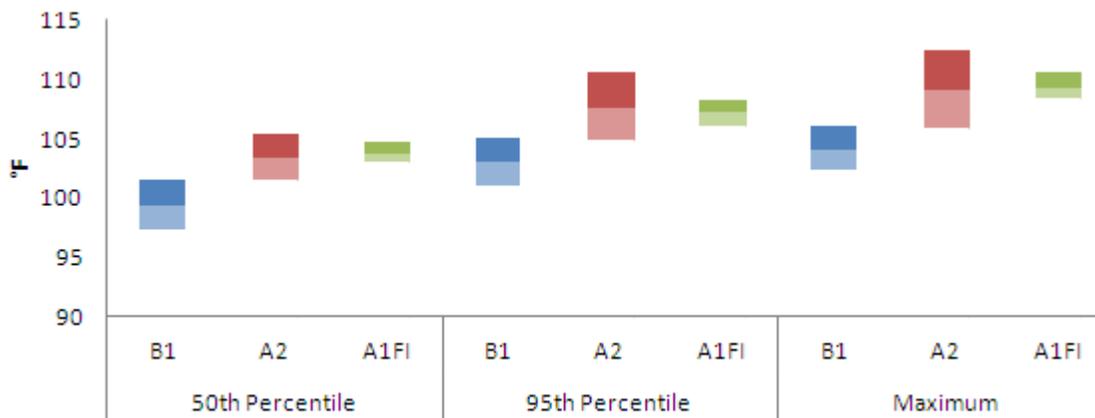


Figure 23: Hottest Day of the Year, End-of-Century (2070-2099)



Key findings for projected increases in the number of days above a given threshold relative to simulated baseline (1980-2009) are as follows (see Table 10 for present-day conditions observed in the Mobile region from 1980 to 2009):

■ Near-term (2010-2039):

- The number of days per year above 95°F (35°C) is projected to nearly double in the near-term to a projected average of about 15 to 17 days across emission scenarios. Under the low (B1) and moderately-high (A2) emission scenarios, the number of summer days above 95°F (35°C) is projected to significantly increase by nearly 6 days.
- Under the high (A1FI) emission scenario, the number of summer days above 95°F (35°C) is projected to significantly increase by about 8 days.

■ By mid-century (2040-2069):

- Under the low (B1) emission scenario, projections suggest 12 additional summer days above 95°F (35°C). The number of consecutive days above 95°F (35°C) is projected to increase by more than 5 days.
 - Under the moderately-high (A2) emission scenario, projections suggest 23 additional summer days above 95°F (35°C) and 4 additional summer days above 100°F (38°C). The longest heat event (where temperatures are above 95°F (35°C) across consecutive days) is projected to increase in the summer by nearly 11 days. The longest heat event in the fall is projected to lengthen by 2.6 days.
 - Under the high (A1FI) emission scenario, projections suggest 32 additional summer days with temperatures surpassing 95°F (35°C). The longest heat event is projected to last two additional weeks.
- By end-of-century (2070-2099):
- Under the low (B1) emission scenario, projections suggest about 17 additional summer days with temperatures above 95°F (35°C). The longest heat event is projected to last over a week longer than under baseline conditions.
 - Under the moderately-high (A2) emission scenario, projections suggest 45 additional summer days with temperatures surpassing 95°F (35°C) and approximately 14 additional days surpassing 100°F (38°C). The longest heat event is projected to last more than 26 consecutive days longer than under baseline conditions. The heat is projected to extend into both spring and fall with an additional 5 spring days and 13 fall days above 95°F (35°C), and more of these days occurring consecutively by 4 and 8 days, respectively.
 - Under the high (A1FI) emission scenario, projections suggest 56 additional summer days with temperatures surpassing 95°F (35°C) and about 17 additional days surpassing 100°F (38°C). The longest heat event is projected to last more than 31 days longer and an intense heat event (where temperatures are above 100°F (38°C)) is projected to last more than a week longer than under baseline conditions. The heat is projected to extend into the fall with an additional 13 days above 95°F (35°C), an additional 2 days above 100°F (38°C), and the longest heat event lasting over 8 days longer than before.

The figures above demonstrate the spread of estimates across the climate models for each emission scenario. The greatest spread is associated with the moderately-high (A2) emission scenario, which is determined from ten climate models. The spread associated with the high (A1FI) emission scenario is artificially small in comparison, as it is only determined from four climate models.

Hot Periods

This section presents the projected change for the following variables:

- Hottest week of the year

- Warmest four days in summer
- Warmest summer in 30 years

These variables were derived from maximum temperature and averaged across the downscaled climate model and station location for each emission scenario and future time period (see Table 12 for a description of the how each of these variables were calculated).

Projected temperature was also analyzed for the hottest week of the year, the warmest four days in summer, and the warmest summer in 30 years. Figure 24 shows probability curves of the warmest summer simulated for each time period and for each emission scenario. It illustrates how temperatures are projected to shift (e.g., the area under the curve illustrates how likely the temperature is projected to occur).⁵⁰ The curves demonstrate how the average summer temperature may change, reflected by the top of the bell-shaped curve. The curves also demonstrate how the extremely cold or extremely warm summer average temperature may change, reflected by the tails of the curve.

Key findings for these projections relative to simulated baseline (1980-2009) are as follows:

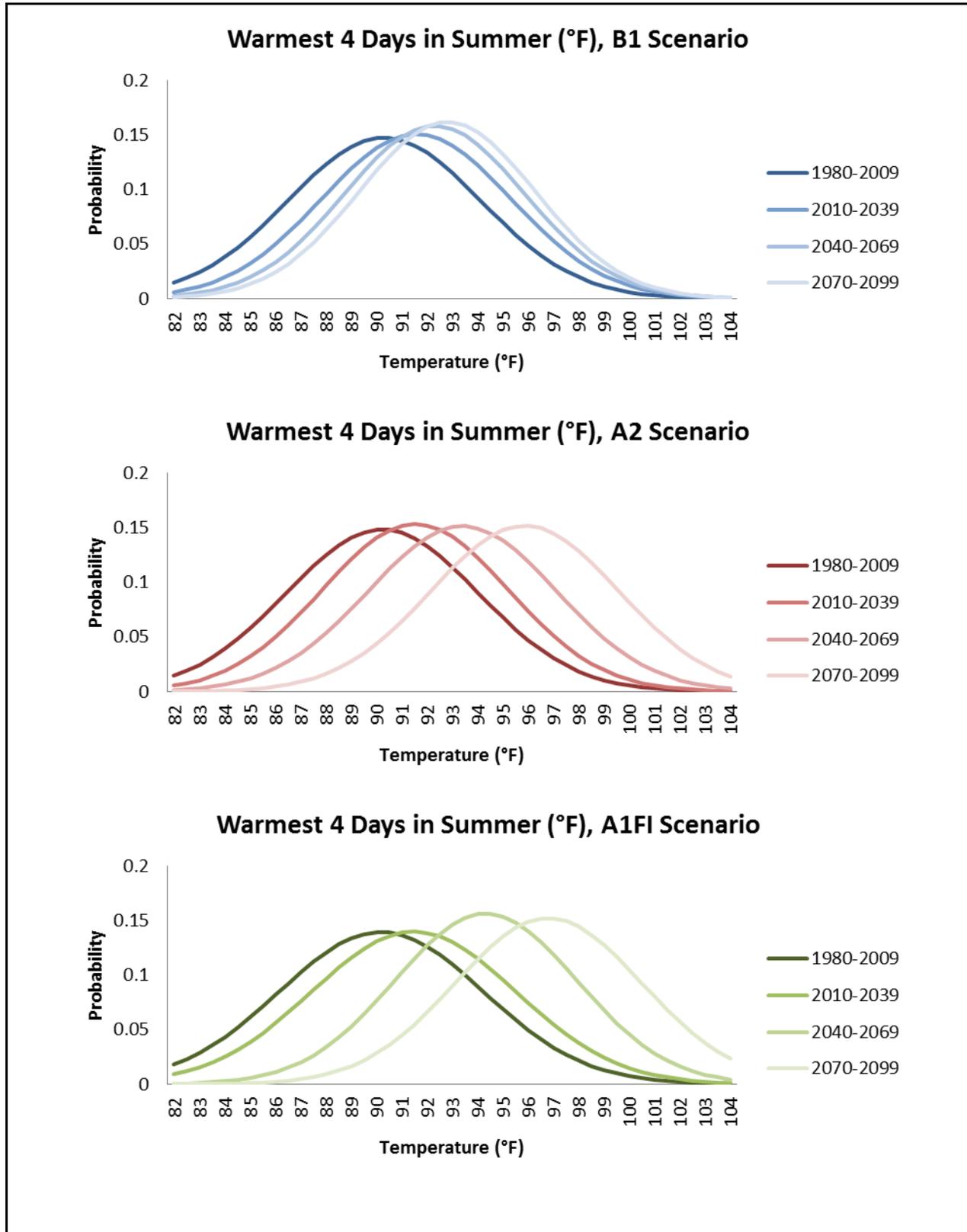
- In the near-term (2010-2039):
 - Temperatures during the hottest week of the year and the warmest days in summer are projected to modestly increase by about 1 to 1.8°F (0.6 to 1.0°C) across all emission scenarios. Only the warmest summer under the low (B1) emission scenario is projected to experience a significant warming of about 2°F (1°C).
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, the hottest week of the year and the warmest four days in summer are projected to warm by about 2°F (1°C). The temperature of the warmest summer is projected to increase by about 1.5°F (0.8°C).
 - Under the moderately-high (A2) emission scenario, the hottest week of the year is projected to warm by about 3.6°F (2.0°C) and the warmest four days in summer are projected to warm by about 3.2°F (1.8°C). The warmest summer is projected to warm by about 3.5°F (1.9°C).
 - Under the high (A1FI) emission scenario, the hottest week of the year is projected to warm by about 4.3°F (2.4°C) and the warmest four days in summer are projected to warm by about 4.1°F (2.3°C). The temperature of the warmest summer is projected to increase by 3.7°F (2.1°C).
- By end-of-century (2070-2099):

⁵⁰ These plots were developed by fitting a standard Gaussian distribution using the values provided for the 5%-, 25%-, 50%-, 75%-, 90%-, and 95%-percentile for the warmest summer.

- Under the low (B1) emission scenario, the warmest summer is projected to warm by 2.7°F (1.5°C) and the warmest four days in summer are projected to warm by 2.5°F (1.4°C).
- Under the moderately-high (A2) emission scenario, the warmest summer is projected to be 7°F (4°C) warmer.
- Under the high (A1FI) emission scenario, the warmest summer is projected to be 7.6°F (4.2°C) warmer.

Figure 24 illustrates the change in the distribution of the warmest four days in summer over time for each emission scenario. The tails of the projections represent the coldest and hottest warmest four days in summer for each time period and, given the uncertainty in the tails, should be considered representative of *possible* extreme values; meanwhile, the peak of the curve represents the average warmest four days in summer. Projections under the low (B1) emission scenario suggest a shift to warmer conditions. Projections associated with the moderately-high (A2) and high (A1FI) emission scenarios suggest that the probability of the warmest four days of summer to become hotter over the 30-year period will increase dramatically over time compared to baseline conditions.

Figure 24: Warmest 4 Days in Summer, Projections by Emission Scenario Averaged Across Climate Models and Station Locations Relative to Model Baseline (1980-2009)



Extreme Cold

This section presents the projected change for the following variables:

- Average coldest four days in winter
- Coldest day of the year

These variables were derived from minimum temperature and averaged across the downscaled climate model and station location for each emission scenario and future time period (see Table 12 for a description of the how each of these variables were calculated).

Along with increases in the temperature, frequency, and duration of heat events, the Mobile region is projected to experience significant decreases in the occurrence of cold temperatures.

Winter temperatures are projected to warm, such that the average coldest four days in winter are projected to be nearly 3°F (2°C) warmer by the end of the century under the low (B1) emission scenario, and nearly 6°F (3°C) warmer under the moderately-high (A2) and high (A1FI) emission scenarios.

The coldest day of the year in the baseline period averaged 19°F (-7°C) in the Mobile region. The coldest day is projected to warm significantly over time, with the average coldest day ranging from 21 to 22°F (-6 to -5.6°C) at mid-century (see Figure 25), and ranging from 21 to 25°F (-6 to -3.9°C) at end-of-century (see Figure 26), depending on emission scenarios. Projections of the coldest day of the year suggest that the extreme cold day in a 30-year time period will warm substantially more than the average cold day in the same time period. The climate model projections, however, show high variability when projecting the lowest temperature of the year.

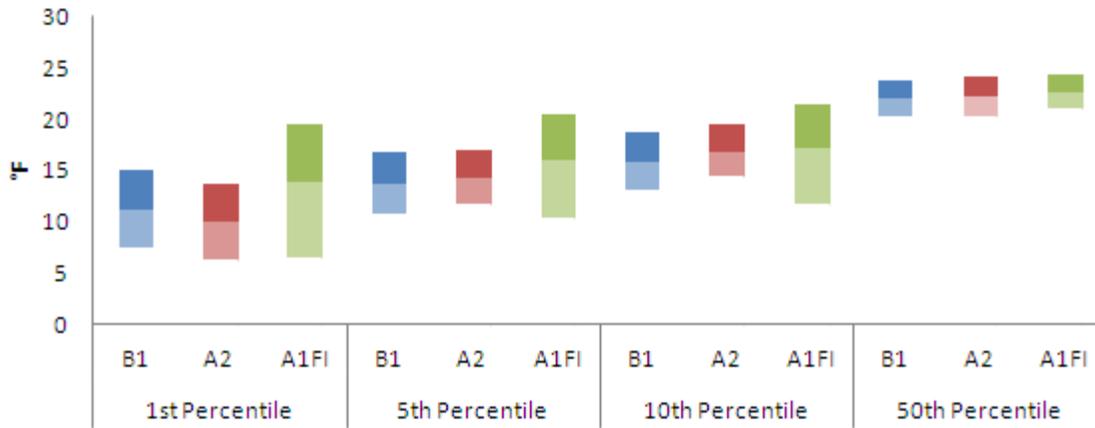
Key findings for extreme cold relative to simulated baseline (1980-2009) are as follows:

- In the near-term (2010-2039):
 - The projections of the coldest four days in winter do not vary considerably across emission scenarios or percentiles, increasing 0.9 to 1.5°F (0.5 to 0.8°C). The coldest winter in 30-years does not change significantly.
 - Projections of the mean coldest day of the year under the moderately-high (A2) emission scenario suggest an increase in temperatures of 1.6°F (0.9°C), while high (A1FI) emission scenario projections suggest an increase in temperatures of about 5.7°F (3.2°C). Note that this projection is not significant under the low (B1) emission scenario.
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, the 50th percentile of the coldest day of the year is projected to warm by 2.3°F (1.3°C) compared to a 4°F (2.2°C) warming for the 5th percentile. The coldest four days in winter are projected to warm by about 2°F (1°C). The

coldest winter experienced within a thirty year period is projected to increase in temperature by 4.2°F (2.3°C).

- Under the moderately-high (A2) emission scenario, the 50th percentile of the coldest day of the year is projected to warm by 2.7°F (1.5°C) compared to a 5.2°F (2.9°C) warming for the 5th percentile. The coldest four days in winter are projected to warm by about 3°F (2°C).
- Under the high (A1FI) emission scenario, the 50th percentile of the coldest day of the year is projected to warm by 3.8°F (2.1°C) compared to a 8.5°F (4.7°C) warming for the 5th percentile. The coldest four days in winter are projected to increase in temperature by about 3°F (2°C).

Figure 25: Coldest Day of the Year (°F), Mid-Century (2040-2069)



- By end-of-century (2070-2099):
 - Under the low (B1) emission scenario, the 50th percentile of the coldest day of the year is projected to warm by 2.2°F (1.2°C) compared to a 3.1°F (1.7°C) warming for the 5th percentile. The coldest four days in winter are projected to increase in temperature by about 3°F (2°C).
 - Under the moderately-high (A2) emission scenario, the 50th percentile of the coldest day of the year is projected to warm by 5.6°F (3.1°C) compared to a 9.0°F (5.0°C) warming for the 5th percentile. The coldest four days in winter are projected to warm by about 6°F (3°C). The coldest winter experienced within a 30-year period is projected to warm by 8.9°F (4.9°C).
 - Under the high (A1FI) emission scenario, the 50th percentile of the coldest day of the year is projected to warm by 6.0°F (3.3°C) compared to a 11.0°F (6.1°C) warming for the 5th

percentile. The coldest four days in winter are projected to increase in temperature by about 6°F (3°C).

Figure 26: Coldest Day of the Year (°F), End-of-Century (2069-2099)

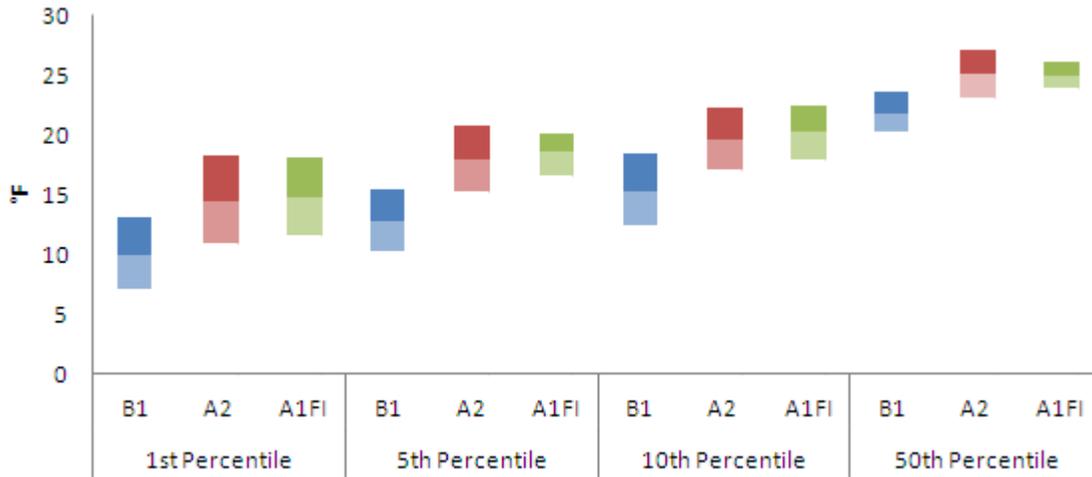
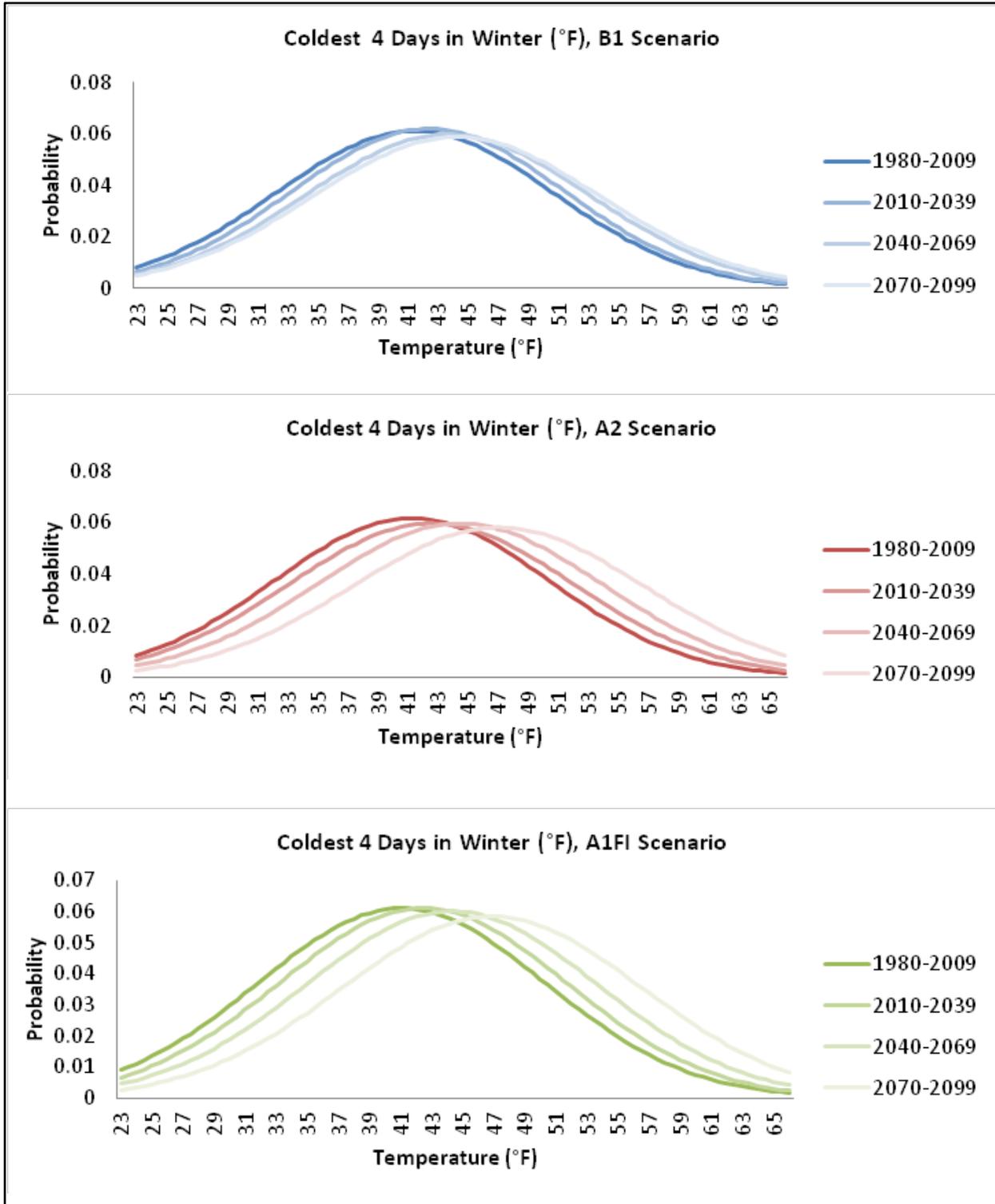


Figure 27 shows how the coldest four days in winter in each time period is projected to become warmer under all emission scenarios. Given the uncertainty in the tails of the projections, the shifts in these extremes should be used cautiously when informing transportation planning. The mean temperature of the coldest four days in winter increases under all emission scenarios and time periods. Unlike the projections of the warmest four days in summer, the shape of the curves tends to remain somewhat consistent over time. The coldest four days in winter observed from 1980 to 2009 averaged 41°F (5°C). By end-of-century, the coldest four days in winter is projected to average 44 to 47°F (7 to 8°C), depending on emission scenario.

Figure 27: Coldest 4 Days in Winter, Projections by Emission Scenario Averaged Across Climate Models and Station Locations Relative to Baseline (1980-2009)



3.3. Implications for Transportation

These projected changes in temperature have some notable implications for transportation infrastructure and services. In general, higher temperatures result in more rapid deterioration of pavements that could require changes in repair and maintenance schedules (although in the longer term, newer and more durable pavement designs could reduce this impact). In addition, longer growing seasons due to longer periods of warmer temperatures could require more attention to mowing in rights of way, thus affecting maintenance budgets. An increase in the duration and frequency of extreme temperature events can result in increased buckling of rail and rutting and shoving of pavement. These impacts could be exacerbated by reduced potential for cooling relief overnight for pavement and other infrastructure. Excessive heat can contribute to equipment failures and more frequent vehicle breakdowns. Energy requirements for air conditioning of buildings, equipment, transit facilities, and freight are likely to increase. Ports, in particular, may see increases in energy costs to meet air conditioning and refrigeration requirements.

Extreme heat events also have health and safety implications for transportation agency personnel. In particular, maintenance and construction schedules may need to be adjusted to avoid health risks to workers. Further, the costs of ensuring the comfort and safety of passengers – particularly of train and bus travelers – are likely to increase.

The implications of the temperature findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

4. Precipitation

Increases in precipitation or drought events can significantly affect transportation infrastructure and are an important consideration in the design, operation, and maintenance of the transportation system. For example, heavy precipitation events can cause flooding, mudslides, landslides, soil erosion, and adversely high levels of soil moisture. These hazards directly affect the structural integrity and maintenance of roads, bridges, drainage systems, and tunnels.

This section presents the methodology and key findings for several analyses related to observed and projected precipitation.

- Section 4.1 describes two analyses of observed precipitation.⁵¹ First, data from five stations in the Mobile region were used to describe and characterize historical and present-day precipitation. Second, the same data were used for a trend analysis to identify any trends in precipitation over the past 50 years. These analyses are intended to better characterize the local climate in Mobile and to better understand the information used to inform current transportation planning and transportation engineering designs. Note that these analyses based on observed data did not serve as the baseline for the analyses of projected changes, however, the observed data were used to downscale projections to the Mobile region.
- Section 4.2 describes the analysis of projected precipitation. Changes in total and extreme precipitation were estimated using daily downscaled precipitation⁵² projections from up to ten climate models, under three emission scenarios and for three future time periods as compared to a model-simulated baseline period (1980 to 2009). A statistical test was used to identify those projections that were considered significantly different from the simulated baseline.
- Section 4.3 identifies several potential implications of changes in precipitation for transportation.

Additional detail about the precipitation analyses is available in the appendices.

- Appendix B.1 describes historical changes in precipitation in Mobile in the context of climate change at the global, national, and regional scale.
- Appendix B.2 describes how specific precipitation variables were chosen for consideration in this study.
- Appendix C.1 provides a diagram describing the precipitation data available for each observation station.
- Appendix C.2 provides background information on climate models, describes the uncertainty associated with climate projections, and explains the approach used to identify optimum modeling criteria to inform transportation vulnerability assessments.

⁵¹ Historical data was provided by Dr. Katharine Hayhoe of Texas Tech, who also conducted the precipitation trend analysis.

⁵² Daily downscaled projections were provided by Dr. Katharine Hayhoe of Texas Tech.

- Appendix C.3 provides a detailed description of the precipitation projections methodology.
- Appendix C.4 provides a high-level investigation of how the end-of-century precipitation projections vary by climate model and emission scenario.
- Appendix C.6 provides summary tables for the projected precipitation analysis, including the results of a test for significance.
- Appendix E.2 provides tables of the climate model ensemble mean by station location, time period, and emission scenario for the projected precipitation analysis.

4.1. Observed Precipitation

Observed precipitation records for Mobile were analyzed to describe historical and current climate conditions in the region.

4.1.1. Methodology

This section describes the methodology used to analyze observed precipitation data in the Mobile region.

Historical data from the five NOAA GHCN stations (see Figure 4) in the Mobile region were analyzed to investigate existing climatic trends and baseline conditions.⁵³ Table 13 summarizes the data available for each station and identifies any gaps in the record.

Table 13: Mobile Area GHCN Station Precipitation Data Summary

Station	Station ID#	County	Precip. Start of Data Collection	Precip. Data Gaps*
Bay-Minette	USC00010583	Baldwin	1914	1931, 1937-1941
Coden	USC00011803	Mobile	1956	1975, 1985-1988
Fairhope	USC00012813	Baldwin	1918	-
Mobile Airport	USC00015478	Mobile	1948	-
Robertsdale	USC00016988	Baldwin	1912	-

* Gaps defined as over 80% of data points missing for the year

** Missing minimum temperature only

Each station records total daily precipitation. This study uses observed daily precipitation to represent 24-hour precipitation events. In Alabama, winter storms tend to last at least one day or

⁵³ Dr. Katharine Hayhoe provided the historical data (see Hayhoe and Stoner 2012 for a discussion of data quality and additional data filtering).

longer, while summer storms tend to last less than a few hours.⁵⁴ This suggests that the heaviest 24-hour precipitation event during winter may be split between two consecutive days of measurements, while the heaviest 24-hour precipitation event during summer would likely be captured by daily measurements.

To get monthly, seasonal, and annual averages, the daily data by month, season, and year were averaged across the historical record (1912 to 2009), where data were available. In addition, averages for the present-day climate period (1980 to 2009) were calculated. Daily precipitation totals were summed by month, season, and year, and then averaged for the entire historical record (1912-2009) and present-day climate period (1980-2009).⁵⁵

4.1.2. Key Findings

Key Findings for Historical Precipitation in the Mobile Region

- Historically, total annual precipitation in Mobile averages 65.3 inches (165.9 cm). Annual precipitation can vary by as much as 13.4 inches (34.0 centimeters) or 20% of average.
- Total annual precipitation has not changed significantly over the past 50 years.
- The maximum 24-hour precipitation event recorded each year has fluctuated over the historical record, exhibiting no significant trends.
- Monthly precipitation has increased significantly over the past 50 years in January, October, and November.

This section describes key findings from the analysis of observed precipitation.

As with temperature, precipitation patterns demonstrate similar ranges and trends over time across all five stations. While some stations show anomalous dips in precipitation totals, this is likely due to incomplete data, instrument error, or recording error for that year. Figure 28 illustrates total annual precipitation for each station. Averaging across all stations and years, annual precipitation in Mobile was 65.3 inches (165.9 centimeters). Year-to-year variability suggests annual rainfall can vary by as much as 13.4 inches (34.0 centimeters) (20%). This greater variability in the precipitation record compared to the temperature record is expected, as precipitation is more heavily influenced by small-scale phenomena (e.g., coastal breezes).

⁵⁴ Durrans and Brown

⁵⁵ Annual precipitation totals that were more than three standard deviations from the mean of the observation record were considered erroneous and removed from the analysis.

Figure 28: Annual Precipitation (inches)

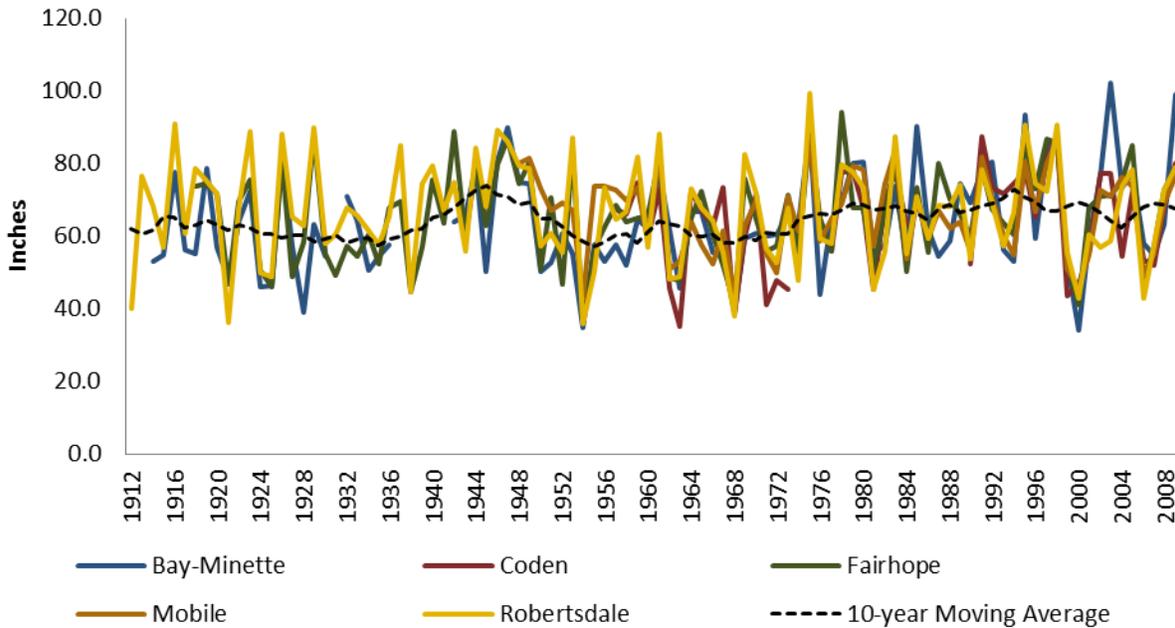


Table 14 provides annual precipitation for each station over both the full station record (see Table 13 for each station’s full record),⁵⁶ the present-day climate period (1980 to 2009), and the historical record used to inform the trend analysis (1961 to 2010).⁵⁷ The table also notes the standard deviation, or the amount of variability, in the data. The table shows relatively consistent average annual precipitation levels from station-to-station and from period-to-period. The only significant trend observed in the annual precipitation is at the Bay-Minette station, where precipitation demonstrates an increasing trend.

⁵⁶ The full record available was used to compute the “full station record” (see Table 3). An analysis was conducted to determine if the data gaps would affect the long-term precipitation as recommended by Dr. Kelly Redmond of the Western Regional Climate Center. A station with the most complete data record, Fairhope, had existing data removed from its record to replicate the station with the least complete data record, Coden. The removal of these days did not affect the Fairhope station average totals. Hence, it was determined that the full record available for each station, respectively, would provide the best estimated precipitation average totals.

⁵⁷ The 1961 to 2010 analysis is based on full data except as noted previously and is for a partially complete 2010 year (does not include October, November, and December).

Table 14: Average Annual Precipitation Totals (inches), Mean (SD)

Station	Full Station Record	1980-2009	1961-2010	Historical Trend?
Bay-Minette	63.2 (14.0)	69.1 (16.1)	66.0 (15.0)	increasing*
Coden	63.1 (13.8)	67.1 (13.4)	63.8 (14.2.3)	no trend
Fairhope	65.0 (13.1)	68.0 (12.3)	66.2 (13.0)	no trend
Mobile	65.2 (11.2)	66.7 (11.3)	64.9 (11.5)	no trend
Robertsdale	66.1 (14.2)	66.3 (12.9)	65.4 (14.1)	no trend
Average	67.4 (13.2)	63.1 (15.4)	65.3 (13.6)	

*Statistically significant at the: *90% Confidence Level, **95% Confidence Level, ***99% Confidence Level

Note: The standard deviation representing variability across the time period is provided in parentheses. Mann Kendall results exploring historical trend are also provided.

Precipitation associated with the maximum 24-hour precipitation event recorded each year has fluctuated over the historical record, exhibiting no significant trends. Historically, precipitation during the maximum annual 24-hour precipitation event in the Mobile region has ranged between 1.3 inches (3.3 centimeters) at Bay-Minette in 1931 to 17.5 inches (44.5 centimeters) at Robertsdale in 1917. Averaged across all stations, precipitation associated with the maximum 24-hour precipitation event has ranged between 2.4 inches (6.1 centimeters) in 1938 and 14 inches (35.6 centimeters) in 1917. Precipitation associated with the average maximum 24-hour precipitation event across all stations from 1912 to 2009 was 5.2 inches (13.2 centimeters) (see Figure 29). A few extreme precipitation events can be traced to a hurricane event.⁵⁸ This suggests future changes in high precipitation return periods are likely to be partially driven by changes in hurricane activity. This figure may underestimate actual maximum precipitation due to gage failures that can occur during periods of heavy rainfall.⁵⁹

⁵⁸ Hurricane Katrina is not the most extreme precipitation event in 2005. The measured daily precipitation totals for Hurricane Katrina range from 1.2 inches to 3.25 inches on August 29 and August 30, 2005 across the five observation stations.

⁵⁹ Durrans and Brown

Figure 29: Maximum 24-Hour Precipitation Events Recorded Each Year (inches)

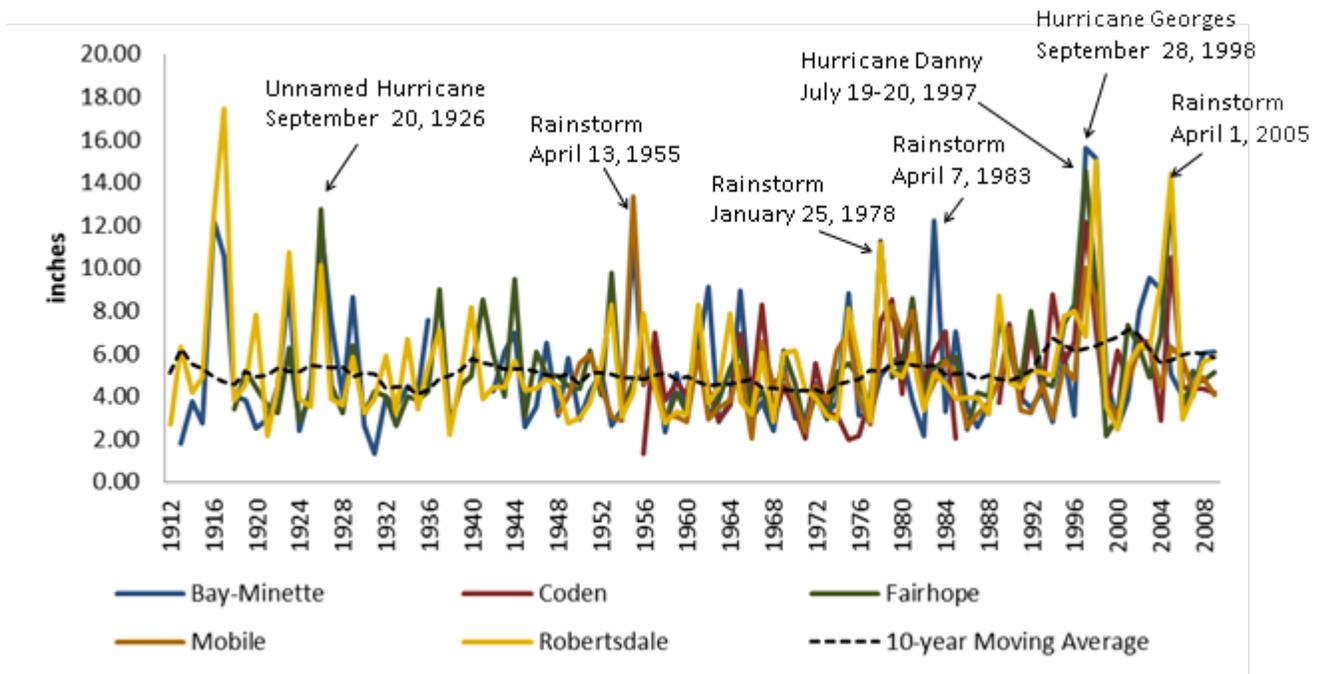


Figure 30 and Figure 31 illustrate seasonal and monthly precipitation, respectively, for each GHCN station in the Mobile region, 1912 to 2009. All stations demonstrate a similar distribution of precipitation over the year. The summer is the wettest season. July is the wettest month with approximately 8.1 inches (20.6 centimeters) of rainfall. October is the driest month, with approximately 3.7 inches (9.4 centimeters) of rainfall. Over the historical record, monthly precipitation has increased significantly ($p < 0.10$) at all five stations in January, October, and November. Summer precipitation has increased significantly at all five stations.

Figure 30: Average Seasonal Precipitation Totals (inches), 1912-2009

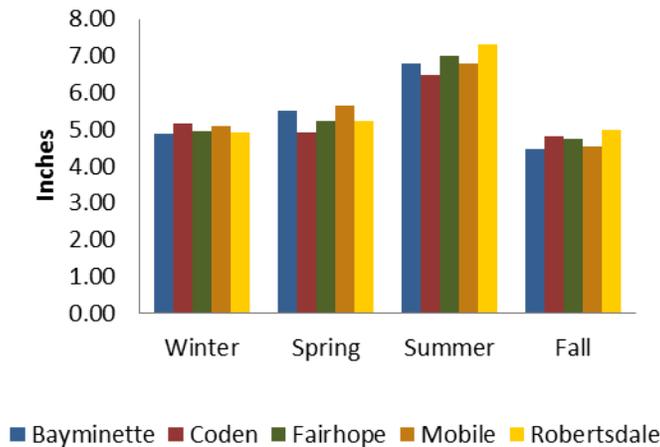


Figure 31: Average Monthly Precipitation Totals (inches), 1912-2009

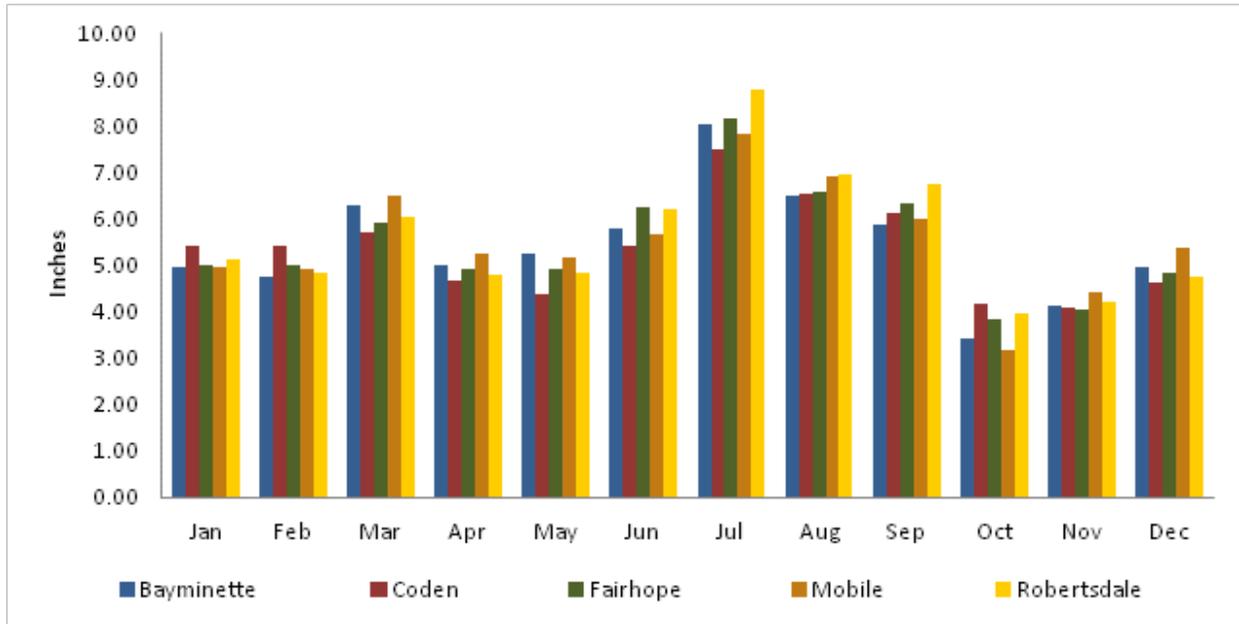


Table 15 provides a summary of the present-day (1980 to 2009) averages for the precipitation variables, based on observed data. This table serves as a comparison for the projected precipitation discussion in Section 4.2 (see Table 16 for a description of how these variables were developed).

Table 15: Present-day Averages for Precipitation Variables, Based on Observed Data

Precipitation Event	1980-2009	Precipitation Event	1980-2009
Maximum 3-Day Winter Precipitation	15.3 inches	1% exceedance probability for the 2-Day Storm Event	5.5 inches
Maximum 3-Day Spring Precipitation	15.7 inches	1% exceedance probability for the 4-Day Storm Event	6.9 inches
Maximum 3-Day Summer Precipitation	20.2 inches		
Maximum 3-Day Fall Precipitation	14.2 inches		

4.2. Projected Precipitation

This section describes the methodology and key findings for the analysis of future precipitation in the Mobile region.

4.2.1. Methodology

Precipitation projections for Mobile were statistically downscaled using the same methodology as was used for temperature projections. This methodology is described in detail in Section 3.2. See Appendix C.3 for detailed methodology specific to the precipitation variables. Projected precipitation was estimated using daily downscaled daily precipitation data from up to ten climate models (see Table 11) under three emission scenarios (B1, A2, A1FI). Note that climate models do not simulate regional precipitation as well as regional temperature due to the higher spatial and temporal variability associated with precipitation.⁶⁰

Table 16 provides a list of the precipitation-related weather hazards and climatic averages that are investigated in this study. The methods used

to develop these datasets vary by precipitation variable. For example, the 24-hour precipitation projections are developed by applying a Gumbel extreme value distribution (which is traditionally used for this purpose) to annual duration data to obtain the probability of a precipitation event occurring in a given year (see textbox entitled, “Storm Event Probabilities”).⁶¹ Other precipitation variables are developed by applying a quantile distribution to the 30-year simulation; this procedure is not intended to extrapolate beyond the 30-year dataset (e.g., this distribution will not provide the precipitation of an event that has a 1% chance of occurring in any given year). In Table 16, asterisks denote the variables and percentiles that do not provide robust quantitative results (per communication with Dr. Katharine Hayhoe) and their use should be limited to qualitatively informing the impact assessment. In general, these asterisks denote cases where extreme events are based on a small sample size—e.g., the 24-hr precipitation event with a 0.2% chance of occurring per year (i.e., a 1-in-500-year event) is based on fitting a theoretical

Terminology

Threshold—A critical value that may create difficulties for an asset when exceeded.

Probability of Occurrence—The chance an event will occur in a given time period.

Exceedance Probability—The probability that a threshold will be met or exceeded within a given time period.

Return Period-- Average length of time between events of similar magnitude and direction.

Percentile—The percentage of the observations that fall below a given threshold.

⁶⁰ For days in the 1980 to 2009 record with low amounts of precipitation, the local precipitation simulations tend to underestimate observed data by 5% to 15%. For days with the highest amounts of precipitation (i.e., for the 99th percentile of precipitation), the local precipitation simulations tend to overestimate observed data by 20% to 30%. (Hayhoe and Stoner, 2012)

⁶¹ The 24-hour exceedance probabilities described in Hayhoe and Stoner (2012) are derived by applying a quantile distribution to the annual duration of maximum 24-hour precipitation events over each 30-year period; hence, those results describe a different analysis than that provided in this report.

distribution curve to only 30 data points and extrapolating to the tails of the curve. In contrast, precipitation projections based on a large sample size are considered robust—e.g., the two-day storm event with a 0.2% chance of occurring within the 30-year period is based on a running two-day sum over the entire 30-year period for a total of more than 10,000 data points.

Table 16: Precipitation Variables Developed for the Study

Variable	Transportation Mode	Methodology
Annual, seasonal, and monthly total precipitation for each 30-year time period	Multi (pavement design)	Daily precipitation corresponding to each month, season, or year was summed for each year, station location, climate model, and emission scenario. Then the 30-year average of each sum was determined. Averages and standard deviations were calculated across climate models for each station location and emission scenario. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region.
Precipitation for 24-hour period with a 0.2%*, 1%*, 2%, 5%, 10%, 20%, and 50% probability of occurrence per year	Multi (drainage, liquid storage)	The day with the maximum total daily precipitation for each year was found for each emission scenario, climate model, and station location. This produced a total of 30 data points for each time period. Across the 30 data points, the daily precipitation representing each probability of occurrence was estimated for each emission scenario, climate model, and station location by applying a Gumbel extreme value distribution. Averages and standard deviations were calculated across climate models for each station location and emission scenario. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region.

Variable	Transportation Mode	Methodology
<p>Occurrence of precipitation for 24-hour period based on today's 0.2%*, 1%*, 2%, 5%, 10%, 20%, and 50% probability of occurrence per year</p>	<p>Multi (drainage)</p>	<p>For the 1980 to 2009 time period, the value of the occurrence probabilities using the maximum total daily precipitation was identified using the results of the variable above for each climate model, emission scenario, and station location. For each of the future time periods, the day with the maximum total daily precipitation for each year was found for each emission scenario, climate model, and station location. This produced a total of 30 data points. Across these 30 data points, the occurrence probabilities were determined by applying a Gumbel extreme value distribution. These fitted distributions provided the new probabilities associated with the historical value of each baseline occurrence probabilities. Averages and standard deviations were calculated across climate models for each station location and emission scenario. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region.</p>
<p>Exceedance probability of precipitation across four consecutive days for each 30-year period: 0.2%, 1%, 2%, 5%, 10%, 20%, 50%; Exceedance probability of precipitation across two consecutive days for each 30-year period: 0.2%, 1%, 2%, 5%, 10%, 20%, 50%</p>	<p>Pipeline</p>	<p>For each time period, a sum of daily precipitation was calculated for every four consecutive days. This produced a total of 10,950 data points. The data was ranked from high to low, and the exceedance probabilities of 0.2%, 1%, 2%, 5%, 10%, 20%, and 50% were then determined for each climate model, emission scenario, and station location by applying a quantile distribution. Averages and standard deviations were calculated across climate models for each station location and emission scenario. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region. This was repeated for the two-day exceedance probabilities.</p>

Variable	Transportation Mode	Methodology
Largest three-day total precipitation each season	Multi	The maximum three-day total precipitation for each season was identified for each year. This produced 30 data points for each of the four seasons. The 30 data points were averaged to produce the average maximum three-day total for each season. For purposes of discussion, the results were averaged across station locations to produce an average for the Mobile region

*Variables and percentiles that do not provide robust quantitative results (per communication with Dr. Katharine Hayhoe). Their use should be limited to qualitatively informing the impact assessment.

4.2.2. Key Findings

Overall, there is a high degree of variability in the precipitation results. Only certain projections show significant change from simulated baseline conditions and many variables (such as total annual precipitation) are not projected to change significantly. Generally, the variability across downscaled climate models is much greater for projections of precipitation than it is for projections of temperature. Findings suggest that total annual precipitation may not change significantly but the timing of that precipitation may change.

The amount of projected change in precipitation was not proportional to the projected change in emissions. The most notable changes in annual precipitation occurred under the low (B1) emission scenario, including an increase of nearly 7 inches (17.8 centimeters) by mid-century and 8.4 inches (21.3 centimeters) by end-of-century. Meanwhile, projections under the moderately-high (A2) and high (A1FI) emission scenarios do not demonstrate a significant change from simulated baseline conditions for any future time period.

The sections below present the results of the projected precipitation analysis, including a discussion of:

- Average annual precipitation
- Average seasonal and monthly precipitation
- Precipitation events

Tables including more detail about the projected changes are available in Appendix E.2.

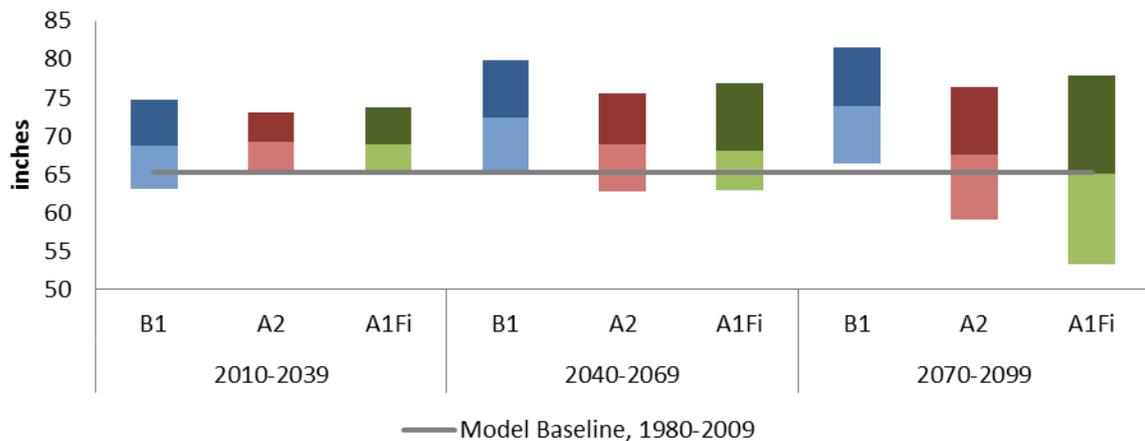
Average Annual Precipitation

Key Findings for Annual Average Precipitation

- Total annual precipitation is not projected to change significantly in the near-term, regardless of emission scenario.
- By mid- and end-of-century, total annual precipitation is projected to increase under the low (B1) emission scenario. Under the moderately-high (A2) and high (A1Fi) emission scenarios, annual precipitation totals are projected to remain statistically similar to the baseline.

Only two projections for total annual precipitation are considered statistically significantly different from the simulated baseline. Under the low (B1) emission scenario, total annual precipitation is projected to increase 6.9 inches (17.5 centimeters) by mid-century and 8.4 inches (21.3 centimeters) by end-of-century. Figure 32 illustrates how total annual precipitation is projected to change over time in the Mobile region, as a function of emission scenario. As illustrated in the figure, the projected changes indicate that total annual precipitation under the three emission scenarios will be similar to the simulated baseline, particularly when variability is taken into account.

Figure 32: Projections of Total Annual Precipitation



The uncertainty associated with the climate model ensemble mean grows with time, which suggests some disagreement between climate models in the magnitude and direction of projected changes in precipitation. In general, precipitation changes are more notable at the seasonal and monthly scale. In other words, total annual precipitation may not change dramatically, but the timing of precipitation may shift.

Key findings for projected change in total annual precipitation relative to simulated baseline (1980-2009) are as follows:

- In the near-term (2010-2039):
 - There are no significant changes in total annual precipitation.
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, total annual precipitation is projected to increase by 6.9 inches (17.5 centimeters).
- By end-of-century (2070-2099):
 - Under the low (B1) emission scenario, total annual precipitation is projected to increase by 8.4 inches (21.3 centimeters).

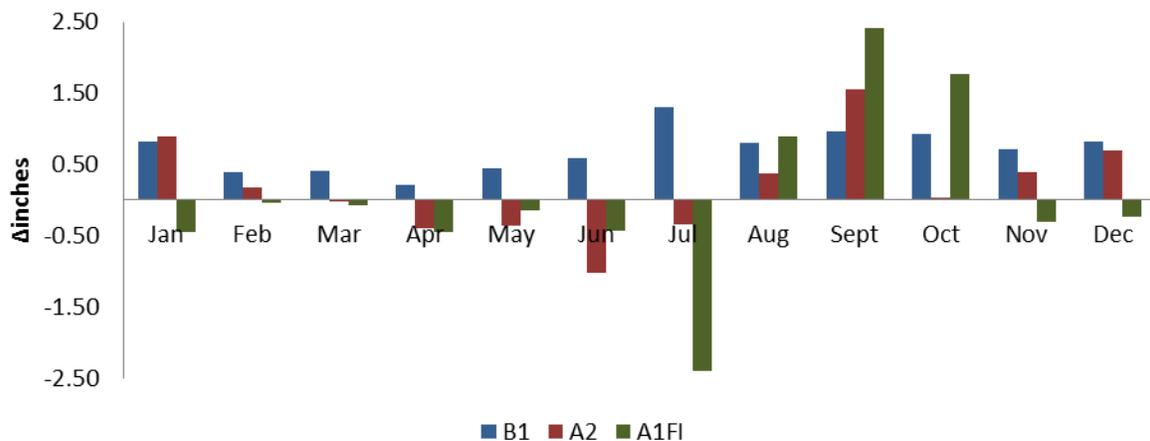
Seasonal and Monthly Average Precipitation

Key Findings for Average Seasonal and Monthly Precipitation

- With very few exceptions, future seasonal and monthly precipitation totals are not projected to differ significantly from current climate conditions, regardless of time period or emission scenario.

Very few projections for seasonal and monthly precipitation demonstrate statistically significant changes from the simulated baseline. Under the low (B1) emission scenario, winter precipitation is projected to increase significantly both in the near-term and by mid-century, by 1.6 and 1.7 inches (4.1 and 4.3 centimeters), respectively. Meanwhile, fall precipitation under the low emission scenario is projected to increase 2.2 inches (5.6 centimeters) by mid-century. Figure 33 illustrates the projected total monthly precipitation of the climate model ensemble at the end-of-century, as a function of emission scenario.

Figure 33: Projected End-of-Century Change in Total Monthly Precipitation, Averaged Across Climate Models and Station Locations and Relative to Simulated Baseline (1980-2009)



Key findings for the projected change in total seasonal and monthly precipitation relative to simulated baseline (1980-2009) are as follows:

- In the near-term (2010-2039):
 - Under the low (B1) emission scenario, total winter precipitation is projected to increase by 1.6 inches (4.1 centimeters).
 - Under the high (A1FI) emission scenario, total September precipitation is projected to increase by 1.3 inches (3.3 centimeters).
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, the winter and fall seasons are projected to experience an additional 1.7 and 2.2 inches (4.3 and 5.6 centimeters) of precipitation, respectively. October is projected to experience an additional 0.6 inches (1.5 centimeters) of precipitation.
- By end-of-century (2070-2099):
 - There are no statistically significant seasonal or monthly changes in total precipitation projected for the end-of-century.

Precipitation Events

Key Findings for Precipitation Events

- Maximum seasonal three-day precipitation is projected to increase across all seasons, emission scenarios, and time frames, though not all increases are statistically significant.
- For all time periods, precipitation during high-probability/low-impact 24-hour storms is projected to increase by 1 to 3 inches (3 to 8 centimeters). Meanwhile, precipitation during low-probability/high-impact 24-hour storms is projected to increase by 4 to 8 inches (10 to 20 centimeters). This suggests extreme storms will become more intense and potentially damaging.
- Under the low (B1) and moderately-high (A2) emission scenarios, the storms experienced today across all return intervals are projected to occur more frequently in the future.
- Two-day and four-day precipitation events that are currently uncommon in the Mobile region will become more frequent by mid- and end-of-century, particularly under the low (B1) and moderately-high (A2) emission scenarios. The precipitation associated with these events is projected to increase significantly over time under all emission scenarios.

Precipitation events covered in this section include:

- Seasonal Three-Day Precipitation Events
- 24-Hour Precipitation Events
- Two-Day and Four-Day Precipitation Events

Note that climate models may underestimate changes in precipitation events. This is because climate models tend to produce rainfall events that are less intense than observations, in part due to the models' low spatial resolution (see textbox titled, "Underestimating Precipitation Events").⁶² However, as discussed in the methodology section above, the simulated precipitation events for baseline conditions (1980 to 2009) tended to be overestimated compared to observations.

Underestimating Precipitation Events

Scientists have relatively high confidence in the ability of climate models to simulate changes in mid-latitude storms and jet streams. However, climate models may not do a good job of capturing precipitation events in the Mobile region, particularly extreme events such as 1-in-100-year events (i.e., 1% probability of occurring in any given year). In part, this is because tropical storms and hurricanes may represent a sizeable portion of extreme storms in the area, and small-sized tropical storms and hurricanes are not reliably simulated by climate models. Other events, such as summertime convective thunderstorms, are too small in scale to be well represented and require the use of parameterization schemes. Overall, future changes of the very extreme storms that are developed from model projections (i.e., changes in 1% and 0.2% probability of occurrence) are very uncertain.

Seasonal Three-Day Precipitation Events

Maximum seasonal three-day precipitation is projected to increase across all seasons, emission scenarios, and time frames. However, not all increases are statistically significant.

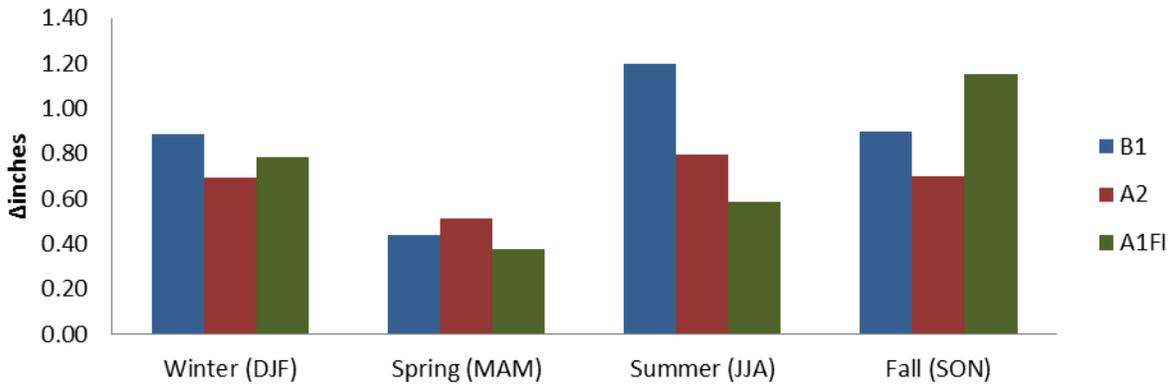
Under the low (B1) emission scenario, projected increases are statistically significant in the winter in the near-term; in the winter, summer, and fall by mid-century; and in the winter and fall by end-of century. Under the moderately-high (A2) emission scenario, only the projected increase in winter by the end-of-century is statistically significant.

Key findings for projected change in seasonal three-day precipitation events relative to simulated baseline (1980-2009) are as follows:

- In the near-term (2010-2039):
 - Under the low (B1) emission scenario, maximum three-day precipitation in the winter is projected to increase by 0.9 inches (2.3 centimeters).
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, maximum three-day precipitation is projected to increase by 0.9 inches (2.3 centimeters) in both the winter and the fall. Maximum three-day precipitation in the summer is projected to increase by 1.2 inches (3.0 centimeters).

⁶² USCCSP, 2008c

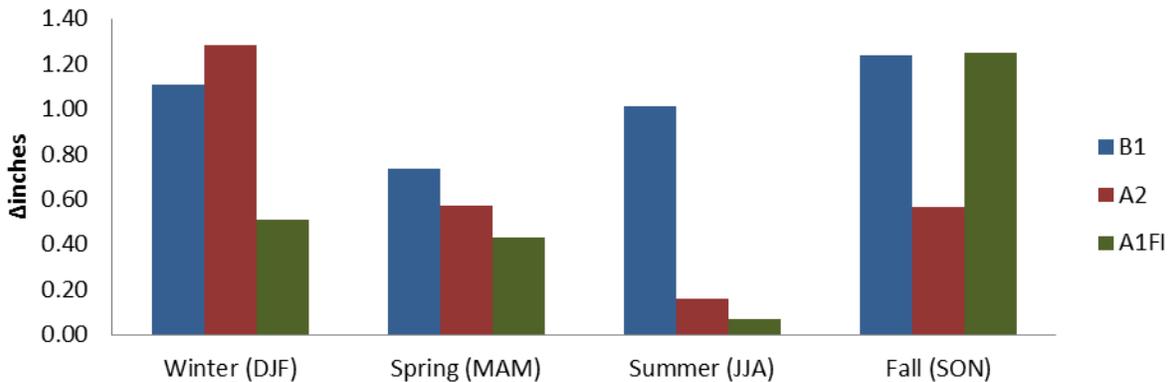
Figure 34: Projected Change in Maximum Three-Day Precipitation, from Baseline (1980-2009) to Mid-Century (2040-2069)



■ By end-of-century (2070-2099):

- Under the low (B1) emission scenario, maximum three-day precipitation in the winter is projected to increase by 1.1 inches (2.8 centimeters). Maximum three-day precipitation in the fall is projected to increase by 1.2 inches (3.0 centimeters).
- Under the moderately-high (A2) emission scenario, maximum three-day precipitation in the winter is projected to increase by 1.3 inches (3.3 centimeters).

Figure 35: Projected Change in Maximum Three-Day Precipitation from Baseline (1980-2009) to End-of-Century (2070-2099)



24-Hour Precipitation Events

The frequency and magnitude of 24-hour precipitation events are projected to increase significantly in the future under both the low (B1) and moderately-high (A2) emission scenarios (see textbox titled, “Storm Event Probabilities” for definition of storm events).⁶³ The projections of storm events with low probability are less robust than other projections due to the small sample from which they are drawn. Additional research is needed to investigate the patterns suggested here for the storm events with a 1% or 0.2% chance of occurring in any given year. This section provides additional detail on the components contributing to the projected change in

⁶³ Daily precipitation data was used as a substitute for 24-hour precipitation.

low probability storm events.

Storm Event Probabilities

Storm events, defined by 24-hour total precipitation, are classified by their likelihood of occurrence in any given year. For example, a storm with a 20% probability has a 20% chance of occurring in any given year and is likely to occur about once every five years. Based on the model simulations, a 20% storm in Mobile corresponds to a storm with 6.7 inches (17.0 centimeters) of precipitation. Projections of these storm event probabilities were developed by fitting a Gumbel Extreme Value distribution to 30 years of data for each time period and extrapolating to the distribution tails for the extreme values. This method mirrors the approach currently applied when working with observed data. For use in impact assessments, it is the projected change compared to today’s observations that is considered.

24-Hour Precipitation Events for 1980-2009				
Probability (% chance of occurrence in any given year)	Period of Occurrence	Based on Observations		Baseline Model Simulations ^c
		Alabama Atlas ^a	TP 40 NOAA ATLAS ^b	
0.2%	500 years	13.6 inches	<i>Not Available</i>	14.4 inches
1%	100 years	11.8 inches	13 inches	11.8 inches
2%	50 years	10.4 inches	11 inches	10.6 inches
5%	20 years	9.2 inches	10 inches	9.1 inches
10%	10 years	6.5 inches	9 inches	7.9 inches
20%	5 years	5.4 inches	7.5 inches	6.7 inches
50%	2 years	3.9 inches	5.5 inches	4.8 inches

^a This database provides information on extreme rainfall for Alabama by applying a Gumbel Extreme Value distribution to over 10,738 station-years of record representing varying time periods, temporal resolution, and locations around the state; the values provided in this table are for Mobile, Alabama (Durrans and Brown, TRB Paper No. 01-0125).

^b This technical paper provides contour maps of extreme precipitation events for the continental United States based observation data from 1940 to 1958. These values were derived based on the empirical data for the period of occurrences of 2 to 10 years, and applying a Gumbel procedure for the period of occurrences greater than 20 years (Hershfield 1961).

^c To investigate how the precipitation events based on the simulated baseline (1980-2009) might represent precipitation events based on a longer period of record, precipitation observations at all five stations for the Mobile region were used to compare present-day climate (1980-2009) to the entire historical record. The results suggest the present-day record is representative of the historical record with similar percentages of occurrence for each bin of maximum precipitation per year (bins were: 0 to 3 inches, 3 to 6 inches, 6 to 9 inches, 9 to 10 inches, 10 to 11 inches, and greater than 11 inches). A pattern was noticeable where the present-day climate had slightly less occurrences of rain below 6 inches and slightly more occurrences of rain above 6 inches.

As part of this analysis, model simulations of 24-hour precipitation events from 1980 to 2009 were compared to historical observations to investigate the accuracy of the downscaled climate model simulations. This investigation indicates that the 24-hour precipitation events simulations are not likely to replicate the timing and magnitude of every observed event. However, the simulations are likely to replicate the nature of the precipitation events over an entire 30-year time period.⁶⁴

For example, Figure 36 presents the maximum 24-hour precipitation event for each year from 1980 to 2099 as simulated by a single downscaled climate model, GFDLCM2.0, at the Bay-Minette location under the low (B1) emission scenario. For this time period, the simulation captures similar magnitude and variability as the events recorded at Bay-Minette (see Figure 29). Under this simulation, a number of extreme precipitation events are projected to occur towards the end of the century.

Figure 36: Simulated Maximum 24-Hour Precipitation Events of a Downscaled Climate Model under the Lower (B1) Emission Scenario at Bay-Minette (inches)

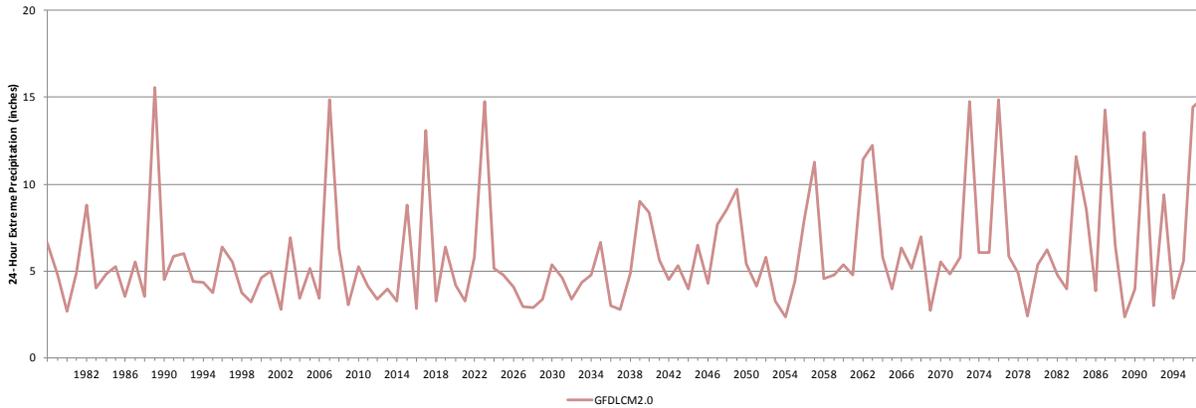
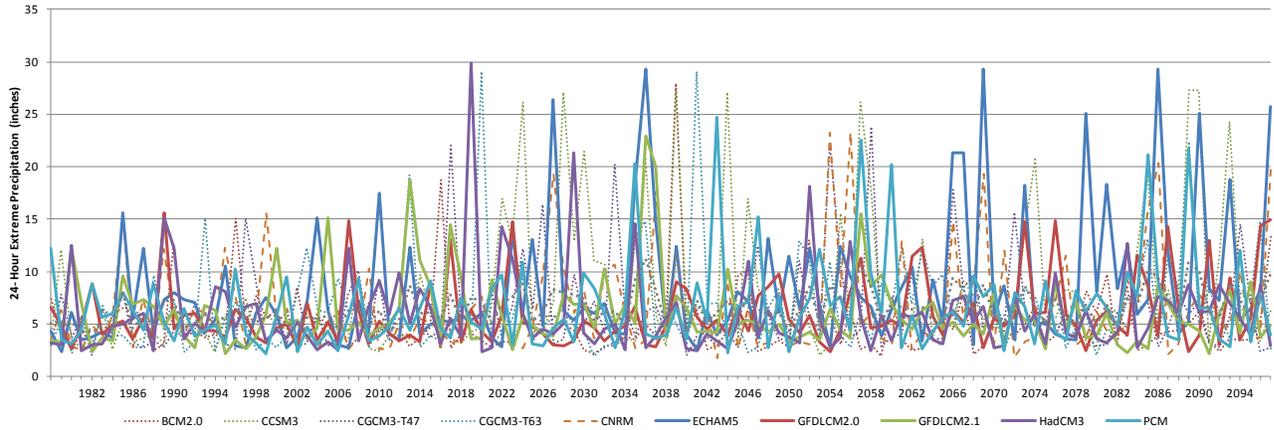


Figure 37 presents the maximum 24-hour precipitation events for each year from 1980 to 2099 as simulated by all 10 climate models at Bay-Minette under the low (B1) emission scenario. This figure indicates that downscaled maximum 24-hour precipitation events increase substantially in intensity after about 2015. This noticeable increase is particularly evident when comparing the baseline simulations (1980 to 2009) to the projected simulations (2010 to 2099).

Figure 37 also demonstrates the variability across climate models. For example, some models simulate extreme precipitation events in the near-term while other models simulate extreme precipitation events towards the end-of-century. The projected changes in extreme 24-hour precipitation events presented in this section are based on averages of the collection of climate model simulations, where each distinct simulation was fitted to a Gumbel extreme value distribution (see Table 16).

⁶⁴ The observed data represent all forms of extreme precipitation events that affect Mobile, such as mid-latitude storms, tropical storms and hurricanes, and summer-time thunderstorms. Though climate simulations do not capture tropical storms and hurricanes, the statistical downscaling is based on observation data that does. Projections of extreme precipitation events represent an area of large uncertainty.

Figure 37: Simulated Maximum 24-Hour Precipitation Events of Downscaled Climate Models under the Lower (B1) Emission Scenario at Bay-Minette (inches)



For all time periods, precipitation associated with high-probability/low-impact storms (e.g., a storm with a 50% probability of occurrence in any given year) is projected to increase by 1 to 3 inches (3 to 8 centimeters). Meanwhile, precipitation associated with low-probability/high-impact storms (e.g., a storm with a 1% probability of occurrence in any given year) is projected to increase more, by up to 4 to 8 inches (10 to 20 centimeters). This suggests extreme storms will become more intense and potentially damaging.

By mid-century, precipitation associated with a 1% probability of occurrence is projected to increase by 4.9 inches (12.4 centimeters) under both the low (B1) and moderately-high (A2) emission scenarios. By the end of the century, precipitation associated with a 1% probability of occurrence is projected to increase by 6.0 inches (15.2 centimeters) under the moderately-high (A2) emission scenario. Figure 38 illustrates the projected change in precipitation totals for storms with a 1% probability of occurrence. Please see Appendix E.2 for tables of projected changes under all emission scenarios, for all time periods, and all storm event probabilities.

Stationarity Versus Non-Stationarity

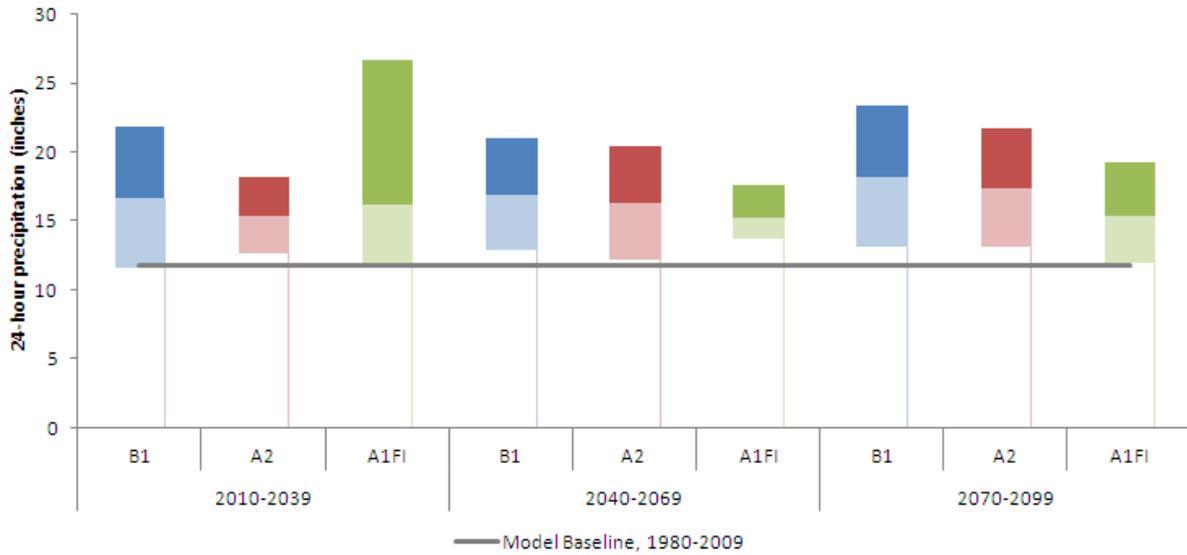
“Stationarity” assumes that while weather varies, the climate mean does not change over time. Infrastructure is currently designed under this assumption. However, changes observed in the hydroclimatic record suggest that “stationarity is dead.” This is due to factors including humans changing the natural landscape and greenhouse gas emissions affecting climate.

“Non-stationarity” is already evident in climate observations and can be accounted for by extreme value analyses. However, there is much debate amongst scientists on how best to account for non-stationarity. Two key requirements to adequately account for non-stationarity are:

- long-term observation records
- implementation of a framework that captures the temporal evolution of the data

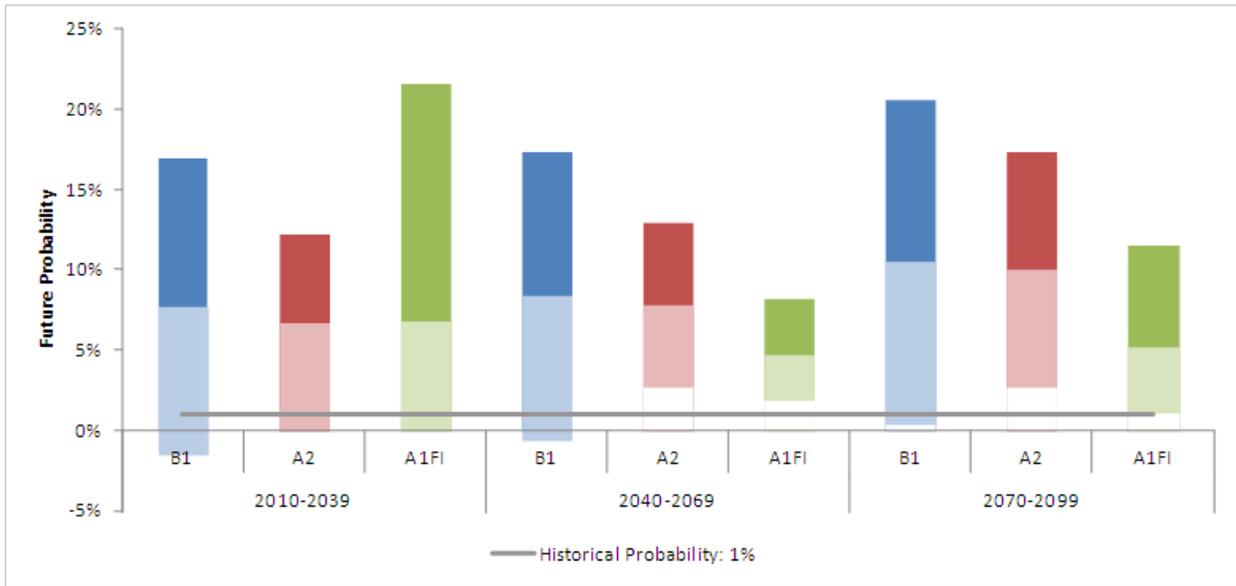
Although this is an area characterized by significant uncertainty, climate projections suggest that it would not be prudent to design infrastructure assuming stationarity.

Figure 38: Projected Precipitation Totals for a Storm with a 1% Probability of Occurrence



In addition, under the low (B1) and moderately-high (A2) emission scenarios, storms experienced today across all return intervals are projected to be more likely to occur. For example, a storm with a 1% probability of occurrence, defined as approximately 12 inches (30 centimeters) of rainfall in 24 hours, is projected to increase up to 6 inches (15 centimeters) by the end of the century under both scenarios. Figure 39 illustrates the projected change in probability of historic storms with a 1% probability of occurrence. This figure illustrates that a storm with approximately 12 inches (30 centimeters) of rainfall in 24 hours is projected to increase in frequency by the end of the century to have roughly a 10% probability of occurring in any given year. Please see Appendix E.2 for tables of projected changes under all emission scenarios, for all time periods, and all storm event probabilities.

Figure 39: Projected Probability of the Historical Storm that has a 1% Probability of Occurrence



Key findings for projected change in 24-hour precipitation events relative to simulated baseline (1980-2009) are as follows (note that the 24-hour precipitation events described here do not include events associated with tropical cyclonic activity):

■ In the near-term (2010-2039):

- Under the low (B1) emission scenario, the precipitation associated with a storm with a 0.2% probability of occurrence is projected to increase from about 14 inches (36 centimeters) to more than 20 inches (51 centimeters). The precipitation associated with a storm with a 1% probability of occurrence is projected to increase from about 12 to 16.5 inches (30 to 42 centimeters). Heavy 24-hour precipitation events are also projected to become more common—events with a 20% chance of occurring today are projected to have about a 36% chance of occurring. Extreme events with a 1% and 0.2% chance of occurring today are projected to have a 7.7% and 3.8% chance of occurring, respectively.
- Under the moderately-high (A2) emission scenario, the precipitation associated with a storm with a 0.2% probability of occurrence is projected to increase from about 14 inches (36 centimeters) to more than 19 inches (48 centimeters). The precipitation associated with a storm with a 1% probability of occurrence is projected to increase from about 11 to 15 inches (28 to 38 centimeters). Heavy 24-hour precipitation events are projected to become more common—events with a 20% chance of occurring today are projected to have about a 37% chance of occurring. Extreme events with a 1% and 0.2% chance of occurring today are projected to have a 6.7% and 2.8% chance of occurring, respectively.

- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, the projected changes in the magnitude and frequency of 24-hour precipitation events are similar to the projected changes in the near-term (discussed above). In addition, high-probability/low-impact 24-hour events are projected to become even more common—events with a 50% chance and 20% chance of occurring today are projected to have about a 66% and 40% chance of occurring, respectively.
 - Under the moderately-high (A2) emission scenario, the projected changes in the magnitude and frequency of 24-hour precipitation events are somewhat greater than the near-term projections and closely mirror those discussed above for the low (B1) emission scenario.
- By end-of-century (2070-2099):
 - Under the low (B1) emission scenario, high-probability/low-impact 24-hour precipitation events are projected to increase in both magnitude and frequency. The projected changes in low-probability/high-impact 24-hour precipitation events are not statistically significant. This is likely due to the variability across climate models.
 - Under the moderately-high (A2) emission scenario, projected changes in the magnitude and frequency of low-probability/high-impact events are statistically significant. The precipitation associated with an event with a 0.2% probability of occurrence is projected to increase by about 8 inches (20 centimeters). The precipitation associated with an event with a 1% probability of occurrence is projected to increase by about 6 inches (15 centimeters). The probability of the storms with a 1% and 0.2% probability of occurrence is projected to increase by 4.5% and 9.0%, respectively. The magnitude and frequency of high-probability/low-impact events are also projected to increase. The precipitation associated with a storm with a 10% probability of occurrence is projected to increase by 3 inches (8 centimeters). The precipitation associated with a storm with a 50% probability of occurring is projected to increase by about 1.4 inches (3.6 centimeters). Historical storms are also projected to be more likely to occur—the probability of a storm with a 10% probability of occurrence in any given year is projected to increase to almost 31% and the probability of a storm with a 50% chance of occurrence in any given year is projected to increase to almost 67%.

Two-Day and Four-Day Precipitation Events⁶⁵

Rainfall during maximum two-day and four-day precipitation events is projected to increase significantly by mid- and end-of-century under all emission scenarios. The projections associated

⁶⁵ The peak four-day precipitation event identifies longer lasting storms which may be impacted by a strong slow-moving mid-latitude storm. These results are constrained to events occurring within each thirty year period but are statistically robust given the large number of data points used in the analysis. See previous section for methodology description, and Hayhoe and Stoner (2012) for description of the quantile distribution applied to obtain the exceedance probabilities. These results do not reflect annual return periods as that requires analyzing just the maximum event for each year in the time period.

with the low (B1) emission scenario show the most significant changes from baseline conditions, but there are also some significant projected changes associated with the moderately-high (A2) and high (A1FI) emission scenarios. Projected changes in total precipitation for two-day and four-day precipitation events with a 1% exceedance probability are shown in Figure 40 and Figure 41, respectively.

Figure 40: Projected Total Precipitation for Two-Day Precipitation Events with a 1% Exceedance Probability

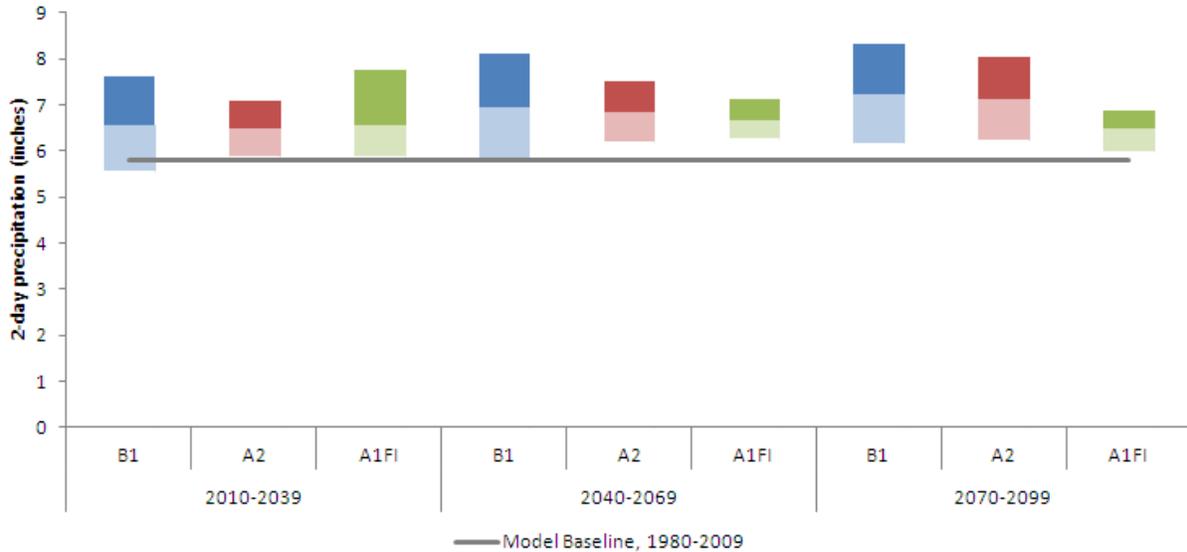


Figure 41: Projected Total Precipitation for Four-Day Precipitation Events with a 1% Exceedance Probability



Two-day and four-day precipitation events that are currently uncommon in the Mobile region are projected to become more frequent by mid-century and end-of-century (near-term projections suggest very little significant change from baseline conditions).

Key findings for projected changes in two-day and four-day precipitation events relative to simulated baseline (1980-2009) are as follows:

- In the near-term (2010-2039):
 - Under the moderately-high (A2) emission scenario, the precipitation associated with four-day precipitation events with 0.2% and 5% exceedance probabilities is projected to increase by 3.9 and 0.3 inches (9.9 and 0.8 centimeters), respectively. The precipitation associated with two-day precipitation events with a 0.2% exceedance probability is projected to increase by 3.3 inches (8.4 centimeters).
- By mid-century (2040-2069):
 - Under the low (B1) emission scenario, statistically significant changes are projected for four-day precipitation events with 0.2%, 1%, 2%, 5%, and 10% exceedance probabilities and two-day precipitation events with 1%, 2%, 5%, and 10% exceedance probabilities. The precipitation associated with four-day precipitation events with exceedance probabilities of 0.2% and 5% is projected to increase by 4.8 and 0.5 inches (12.2 and 1.3 centimeters), respectively. The precipitation associated with two-day precipitation events with a 0.2% exceedance probability is projected to increase by 3.9 inches (9.9 centimeters).
 - Under the moderately-high (A2) emission scenario, statistically significant changes are projected for four-day precipitation events with 1%, 2%, 5%, and 10% exceedance probabilities and two-day precipitation events with 1%, 2%, 5%, 10%, and 20% exceedance probabilities. The precipitation associated with four-day precipitation events with 1% and 5% exceedance probabilities is projected to increase by 1.3 and 0.4 inches (3.3 and 1.0 centimeters), respectively. The precipitation associated with two-day precipitation events with a 1% exceedance probability is projected to increase by 1.0 inches (2.5 centimeters).
 - Under the high (A1FI) emission scenario, statistically significant changes are projected for four-day and two-day precipitation events with 1% and 2% exceedance probabilities. The precipitation associated with four-day precipitation events with 1% and 2% exceedance probabilities is projected to increase by 1.4 and 1.0 inches (3.6 and 2.5 centimeters), respectively. The precipitation associated with two-day precipitation events with 1% and 2% exceedance probabilities is projected to increase by 1.0 and 0.6 inches (2.5 and 1.5 centimeters), respectively.

- By end-of-century (2070-2099):
 - Under the low (B1) emission scenario, statistically significant changes are projected for four-day and two-day precipitation events with 0.2%, 1%, 2%, 5%, 10%, and 20% exceedance probabilities. The precipitation associated with four-day precipitation events with 0.2% and 5% exceedance probabilities is projected to increase by 4.8 and 0.6 inches (12.2 and 1.5 centimeters), respectively. The projected change is similar to that projected for the mid-century time period. The precipitation associated with two-day events that have a 0.2% exceedance probability is projected to increase by 4.6 inches (11.7 centimeters).
 - Under the moderately-high (A2) emission scenario, statistically significant changes are projected for four-day precipitation events with 0.2%, 1%, 2%, and 5% exceedance probabilities and two-day precipitation events with 0.2%, 1%, and 2% exceedance probabilities. The precipitation associated with four-day precipitation events with 1% and 5% exceedance probabilities is projected to increase by 1.7 and 0.5 inches (4.3 and 1.3 centimeters), respectively. The precipitation associated with two-day precipitation events with a 1% exceedance probability is projected to increase by 1.3 inches (3.3 centimeters).
 - Under the high (A1FI) emission scenario, statistically significant changes are projected for four-day precipitation events with 1%, 2%, and 5% exceedance probabilities and two-day precipitation events with 2% exceedance probability. The precipitation associated with four-day precipitation events with 1% and 2% exceedance probabilities is projected to increase by 1.2 and 0.9 inches (3.0 and 2.3 centimeters), respectively. The precipitation associated with two-day precipitation events with a 2% exceedance probability is projected to increase by 0.5 inches (1.3 centimeters), respectively.

4.3. Implications for Transportation

While minor changes in the total annual levels of precipitation are not likely to affect transportation, increases in the magnitude and frequency of precipitation events can have significant local impacts. These include the near-term consequences of heavy downpours as well as the longer-term damages associated with these events. More frequent and intense heavy precipitation events can cause flooding, mudslides, landslides, soil erosion, and result in high levels of soil moisture. These hazards can cause immediate damage during a rainfall event, necessitating emergency response. They also can undermine the structural integrity and maintenance of roads, bridges, drainage systems, and tunnels, necessitating more frequent repairs and reconstruction. The design of culverts and water receiving areas in vulnerable locations may need to accommodate a greater capacity than current design practice. Interestingly, an intense rain event after a period of very dry conditions can cause as much or more damage to assets and services as an intense rain event following a period of very wet conditions. In the first case, the dry ground cannot absorb the water quickly enough and it runs off or pools, while in the second case, the ground is already saturated and the additional precipitation runs off or pools.

Flooding can render a route temporarily impassable, and require maintenance to clear mud and debris. The connectivity of intermodal systems – including goods movement to and from ports - can be disrupted even if short segments of roadways are flooded. Severe precipitation can cause delays in air travel as aircraft are grounded or rerouted. Transportation agencies may need to fortify their emergency management and traffic management capabilities in anticipation of more frequent instances of heavy rainfall and associated response measures.

While these impacts are not new to transportation agencies, the frequency and severity of these problems are likely to increase as the incidence of extreme precipitation events rises. Managing damage and service disruption in real time may take more agency resources and require new communication channels and coordination protocols. Preventive adaptation measures may be considered to increase the resilience of infrastructure (e.g., through design, operational improvements, and/or altered maintenance practices) and to prepare for additional emergency response associated with projected changes in precipitation patterns.

The implications of the precipitation findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

5. Streamflow

Transportation planners and engineers rely on streamflow properties measured at specific stream gage stations to estimate the magnitude and frequency of floods. Flooding is an important factor to consider in the design of bridges, culverts, highway embankments, dams, and other hydraulic structures near streams.⁶⁶ Flooding affects a number of human systems, and can have detrimental impacts on transportation infrastructure, disrupting and damaging transportation systems. In some cases, increased runoff and discharge may also be associated with increased scour of bridge piers, which can potentially make bridges unsafe for use.

This section presents the methodology and key findings for several analyses related to observed and projected changes in streamflow. This section discusses environmental variables that directly inform present-day decisions of transportation planners and engineers in Mobile.

- Section 5.1 describes the analysis of observed annual peak streamflow, annual and monthly stream discharge, and regional flood frequency based on observed data from five USGS stream gage sites. A discussion of soil moisture is also provided. These analyses are intended to better characterize local conditions in Mobile and to better understand the information used to inform current transportation planning and transportation engineering designs.
- Section 5.2 describes the analysis of projected monthly streamflow based on a monthly water balance model driven by Mobile-specific information. The projected change in average monthly streamflow may also affect the impact of future peak streamflow, particularly for events associated with short return intervals.⁶⁷ Section 5.2 also describes projected changes in monthly evapotranspiration and soil moisture. These analyses describe plausible future changes in the environment and the potential impacts on relevant transportation stressors such as wetland performance; however, they will not provide information on impacts influenced by peak flow rates.
- Section 5.2.3 identifies several potential implications of changes in streamflow properties for transportation.

Additional detail about the streamflow analyses is available in the appendices.

- Appendix C.7 describes in detail the methodology used to select stream gages for the historical streamflow analysis.
- Appendix C.8 provides a detailed description of the streamflow projections methodology.
- Appendix C.9 provides additional summary tables and figures for the projected streamflow analysis.

⁶⁶USGS, 2004; USGS, 2010a

⁶⁷ Changes in extreme peak streamflow will be investigated during the risk assessment on an as needed basis.

5.1. Observed Streamflow

5.1.1. Methodology

This section describes the methodology used to analyze observed streamflow data in the Mobile region. For more detailed information, see Appendix C.8.

Five USGS stream gage sites located in and around Mobile County were selected and analyzed for this study. Stream gages provide localized data that transportation planners and engineers can use in the design of bridges, culverts, dams, and other transportation infrastructure.⁶⁸

Data came from the USGS Surface-Water database of stream gage data. This database provides streamflow properties at over 24,000 sites across the United States.⁶⁹ Though the USGS stream gage database provides important local information and useful flood frequency statistics, very few sites provide a long enough record to investigate long-term trends (i.e., how peak streamflow has changed over the twentieth century).

Stream gages from within this database were selected to provide a representative range of basin characteristics and stream sizes. The selection criteria are outlined in Figure 42. The selection criteria identified three stream gage sites for the analysis: Chickasaw Creek, Crooked Creek, and Hamilton Creek. Two sites did not meet the criteria but were included due to their unique location, size, and basin characteristics: Mobile River and Fowl River. Table 17 summarizes the streamflow and discharge data available for the five selected sites. Mean stream discharge data was provided by USGS using daily mean time-series at each gage site. This historical data is available on a daily, monthly, and annual basis. For the purpose of this analysis, monthly and annual data were utilized to provide monthly and annual present-day conditions.

Definition of Streamflow Characteristics

Surface runoff is the portion of precipitation that doesn't infiltrate the ground or evaporate, but flows across land surfaces into surface streams or water bodies (mm).

Discharge is defined as outflow, and can be applied to a variety of locations, ranging from discharge from a pipe to discharge across a section of a stream. Discharge is typically expressed as a volume rate (e.g., cubic feet per second).

Streamflow is a specific type of discharge that occurs in a natural channel (cubic feet per second).

Flooding occurs when streamflow gets high enough to overtop stream banks.

Sources: USGS, 2011f; USGS, 2011g

⁶⁸ USGS, 2007

⁶⁹ USGS Surface-Water database, available at <http://waterdata.usgs.gov/usa/nwis/sw>

Figure 42: Flowchart Describing the Stream Gage Selection Process

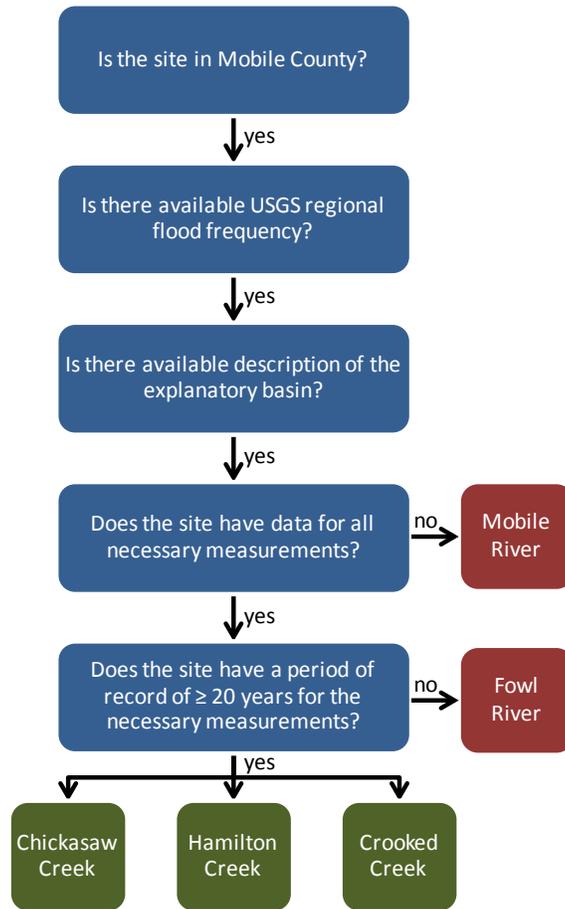


Table 17: Streamflow and Discharge Data Available for Selected Mobile County Stream Gage Stations

Site	Site #	Characteristics	Annual Peak Streamflow		Monthly Mean Discharge		Annual Mean Discharge	
			Start	End	Start	End	Monthly	Annual
Chickasaw Creek ⁷⁰	02471001	Large stream; 125 mi ² drainage area	5/1952	5/2010	10/1951	9/2010	1952	2010
Mobile River ⁷¹	02470630	Large river; 44,000 mi ² drainage area	4/1951	2/2004	X	X	X	X
Fowl River ⁷²	02471078	Urban stream; 16.5 mi ² drainage area	4/1995	1/2010	3/1995	9/2010	1995	2010
Crooked Creek ⁷³	02479980	Small rural stream; 8 mi ² drainage area	1/1991	1/2010	6/1990	9/2010	1990	2010
Hamilton Creek ⁷⁴	02480002	Small urban stream; 8 mi ² drainage area	5/1991	1/2010	6/1990	9/2010	1990	2010

Figure 43 shows a map of Mobile County and the individual stream gage stations used in this study.

⁷⁰ USGS, 2011a
⁷¹ USGS, 2011d
⁷² USGS, 2011b
⁷³ USGS, 2011c
⁷⁴ USGS, 2011e

Figure 43: Selected Stream Gage Sites in the Mobile Region



USGS data from these five stream gage sites were used to analyze annual peak streamflow, as well as annual and monthly mean stream discharge. The Mann Kendall trend analysis was used to investigate whether there was a statistically significant positive or negative trend in the Chickasaw Creek annual peak streamflow (the only stream gage site with a long-term period of record). In addition, a series of USGS reports published between 2004 and 2010 provided an analysis of regional flood frequency of urban and rural streams in Alabama.⁷⁵

⁷⁵ USGS, 2004; USGS, 2010. These reports fit a Pearson Type III distribution to the logarithm of annual peak streamflow to obtain flood magnitudes.

5.1.2. Key Findings

Key Findings for Historical Streamflow and Flooding

- There is large variability in year-to-year peak streamflow events.
- Annual peak streamflow at Chickasaw Creek has demonstrated a positive (increasing), but statistically insignificant, trend over the past 58 years.
- For the past 20 years, all Mobile area stream gage locations demonstrate a similar pattern of annual mean stream discharge, similar to the pattern of annual peak streamflow.
- Average annual discharge at Chickasaw Creek from 1952-2010 has not changed significantly, suggesting the general characteristics affecting annual discharge have not have changed.
- Monthly mean discharge in the Mobile area is highest from February to April and lowest from October to November.

Streamflow is heavily influenced by physical and topographical factors, including elevation and slope, drainage patterns and barriers (natural or man-made), and reservoirs that prevent runoff from continuing downstream. In Mobile County, flooding caused by heavy precipitation events is influenced by the flow and channel changes in the Mobile River, which drains almost two-thirds of Alabama, and is fed by the Alabama River to the east and Tombigbee to the west (see Figure 44). The elevation of land across Alabama tends to slope to the south and west.⁷⁶ The southern portion of Alabama, including Mobile County, is a coastal plain.⁷⁷

⁷⁶ USGS, 2004

⁷⁷ This coastal plain ranges in elevation from sea level to 1,000 ft above National Geodetic Vertical Datum (NGVD) of 1929.

Figure 44: Map of the Mobile-Alabama-Coosa River⁷⁸

Streamflow in Mobile County is also affected by storm surge. As freshwater in the river basin travels downstream to the coast, it can collide with a surge of saltwater traveling up the estuary, causing the river to back up. This event can be caused by the natural fluctuations of the tides or exacerbated by a storm.

⁷⁸ Evans, 2009

Factors Affecting Streamflow

Streamflow is a function of the volume of water in the stream, the speed at which water flows, and the size of the stream channel. It is also dependent on runoff. The amount, intensity, duration, and distribution of precipitation events all impact streamflow. Soil saturation from earlier precipitation events also plays a role. For example, if the ground is still wet from a previous rain event, the soil will be less able to absorb excess water and more likely to cause runoff.

Meteorological Factors Affecting Runoff/Streamflow	Physical Characteristics Affecting Runoff/Streamflow
<ul style="list-style-type: none"> ■ Type of precipitation (e.g., rain, snow, sleet) ■ Rainfall intensity ■ Rainfall amount ■ Rainfall duration ■ Distribution of rainfall over the watershed(s) ■ Direction of storm movement ■ Prior precipitation and resulting soil moisture ■ Other meteorological and climatic conditions that affect evapotranspiration, such as temperature, wind, relative humidity, and season 	<ul style="list-style-type: none"> ■ Land use ■ Vegetation ■ Soil type ■ Drainage area ■ Basin shape ■ Elevation ■ Slope ■ Ponds, lakes, reservoirs, sinks, or other similar features in the basin, which prevent or alter runoff from continuing downstream ■ Direction of orientation ■ Drainage network patterns ■ Presence of built structures ■ Topography

Sources: USGS, 2011f; USGS, 2011g

Over the 20th century, much of the United States has not experienced a significant change in high levels of peak streamflow.⁷⁹ This is consistent with the findings for Mobile. This section presents key findings for Mobile based on observed data at the five selected stream gage sites. The findings are presented in three categories:

- Regional Flood Frequency
- Annual Peak Streamflow
- Annual and Monthly Mean Stream Discharge
- Soil Moisture

⁷⁹ Pielke et al., 1999

Regional Flood Frequency

Flood frequencies for Alabama provide transportation planners with vital information for designing transportation infrastructure. The accuracy of these frequencies is dependent on the amount of stream gage data available, the accuracy of those data, changes in land-use that impact the river drainage area, climate, and how well the theoretical distribution fits the stream gage data.⁸⁰ A series of USGS reports published between 2004 and 2010 provide regional flood frequency analyses of urban and rural streams in Alabama.⁸¹

Table 18 describes flood magnitudes based on annual peak streamflows for several different recurrence intervals. For example, a “Q2” recurrence interval has a 50% probability of occurring in any given year (i.e., a 2 year event). The “Q500” recurrence interval is an extreme flood that has a 0.2% probability of occurring in any given year (i.e., a 500-year event).

Table 18: Peak Discharge (cfs) for Recurrence Intervals by Stream Gage Site

Site	Years of Data	Peak discharge for recurrence interval in years (cfs)							
		Q2	Q5	Q10	Q25	Q50	Q100	Q200	Q500
Chickasaw Creek	51	4,450	8,840	12,900	19,600	25,800	33,400	42,300	56,800
Mobile River	52	278,000	352,000	397,000	450,000	487,000	522,000	556,000	600,000
Fowl River	13	1,590	3,600	5,540	8,770	11,800	15,500	19,800	26,700
Hamilton Creek	17	930	1,910	2,720	3,940	4,960	6,070	7,280	9,040
Crooked Creek	13	685	1,180	1,590	2,200	2,740	3,350	4,040	5,090

Annual Peak Streamflow

Figure 45 illustrates annual peak streamflow at the five selected stream gage sites in Mobile County from 1990 to 2010. This figure demonstrates how often peak streamflow has reached or exceeded levels representative of floods of varying recurrence intervals. Over the past 20 years, all sites have surpassed the Q5 and Q10 recurrence intervals. Chickasaw Creek, Crooked Creek, and Mobile River have reached an annual peak streamflow representative of the Q25 recurrence interval, while no sites have exceeded this threshold.

The Mobile River site demonstrates the greatest annual peak streamflow with an average of about 300,000 cubic feet (9,000 cubic meters) per second. The Chickasaw Creek site reports the

⁸⁰ USGS, 2010b [General Information Product 106, available at <http://pubs.usgs.gov/gip/106/pdf/100-year-flood-handout-042610.pdf>]

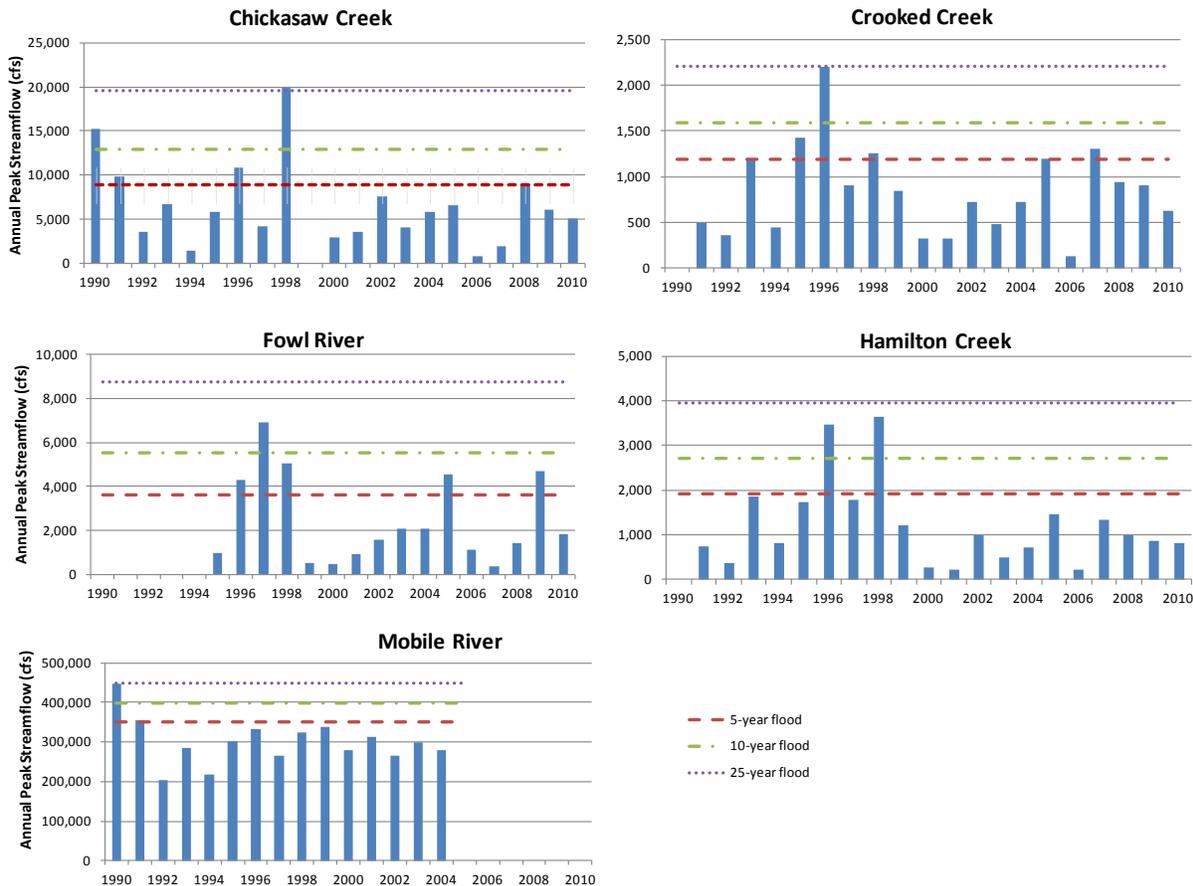
⁸¹ USGS, 2004; USGS, 2010a

next highest average of 6,600 cubic feet (198 cubic meters) per second. The remaining three sites had average annual peak streamflows ranging from about 800 to 2,400 cubic feet (24 to 72 cubic meters) per second. All sites, except Mobile River, show similar patterns of peak streamflow with high levels in the mid to late 1990s, and unusually low levels in 2006. Hurricane Georges, which struck the southeast in 1998, is responsible for peak flows at Chickasaw Creek and Hamilton Creek. Overall, the sites demonstrate large variability in year-to-year peak streamflow events.

The Chickasaw Creek site provides historical context with a longer period of record (58 years), beginning in 1952. The average annual peak streamflow based on its full record is slightly lower than the average from 1990 to 2010, at 6,287 cubic feet (189 cubic meters) per second. A trend analysis suggests a positive (increasing), but statistically insignificant, trend.⁸²

Figure 45: Annual Peak Streamflow (cfs) Measured at Stream Gage Sites in Mobile County, AL, 1990-2010

The horizontal lines represent the Q5, Q10, and Q25 recurrence intervals specific to each stream gage site.



⁸² The Mann Kendall trend analysis was used to investigate whether a statistically significant positive or negative trend occurred in the Chickasaw Creek annual peak streamflow. The analysis found no significant trend (i.e., tau correlation coefficient of approximately 0.05 with a p value of approximately 0.5).

Annual and Monthly Mean Stream Discharge

Annual and monthly mean stream discharge indicate the overall conditions for each stream, important for understanding the general conditions in the Mobile region (e.g., is there significant variability from year-to-year or seasons with high mean discharge?). These conditions impact transportation planners when considering assets or operations sensitive to overall regional “sogginess” or drought.

Annual mean stream discharge data for four sites is illustrated in Figure 46 (this information was not available for the stream gage located at Mobile River). Over the past 20 years, all stream gage locations show a similar pattern of annual mean discharge. This pattern includes higher annual mean discharge in 1998 and 2005 and lower annual mean discharge from 2000 to 2002 and 2006 to 2007.

Unlike the peak streamflow comparison, the average annual mean stream discharge at Chickasaw Creek from 1952 to 2010 is approximately the same as the average from 1990 to 2010. This suggests that the general characteristics affecting annual discharge (e.g., annual precipitation, land use) have not changed over time. The trend analysis also found no statistically significant change.⁸³

⁸³ The Mann Kendall trend analysis was used to investigate whether a statistically significant positive (wetter) or negative (drier) trend was noticed in the Chickasaw Creek annual mean discharge period of record from 1952 to 2010. The analysis found no significant trend (i.e., tau correlation coefficient is -0.007 with a p value of 0.94).

Figure 46: Annual Mean Discharge (cfs) Measured at Four Stream Gage Sites in Mobile County, 1990-2010

The red line indicates the overall mean across the entire time series, while the shaded gray area represents one standard deviation above and below the mean.

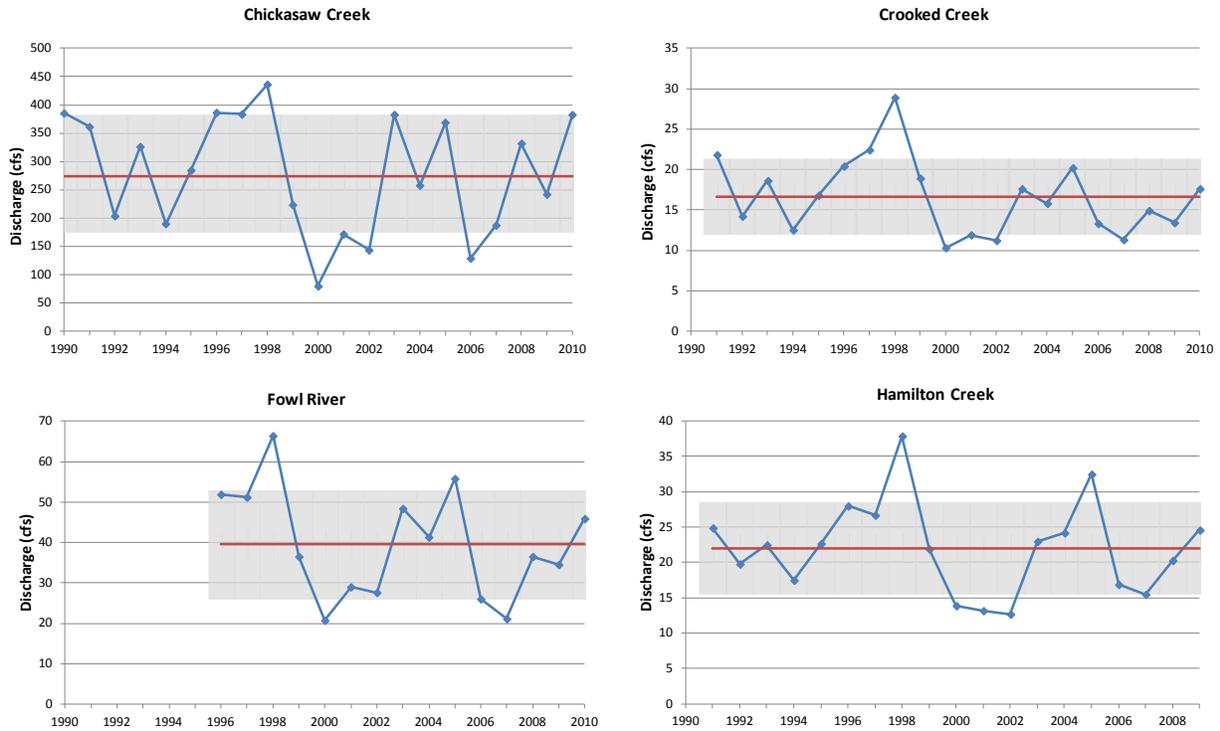


Figure 47 illustrates the monthly mean discharge averaged from 1990 to 2009 for four sites, as data were available. Though precipitation is greatest during the summer, the monthly discharge data patterns show that streamflow tends to be highest from February to April and lowest from October to November.⁸⁴

The high monthly discharge data from February to April corresponds to Alabama’s “flash flood” season, which can occur during late winter or early spring when vegetation is dormant, the ground is cold (sometimes frozen), and cooler temperatures reduce evaporation rates.⁸⁵ During this time, a heavy precipitation event can induce flooding. The flood waters tend to begin in northern Alabama and flow southerly over several days until reaching the Gulf of Mexico.⁸⁶

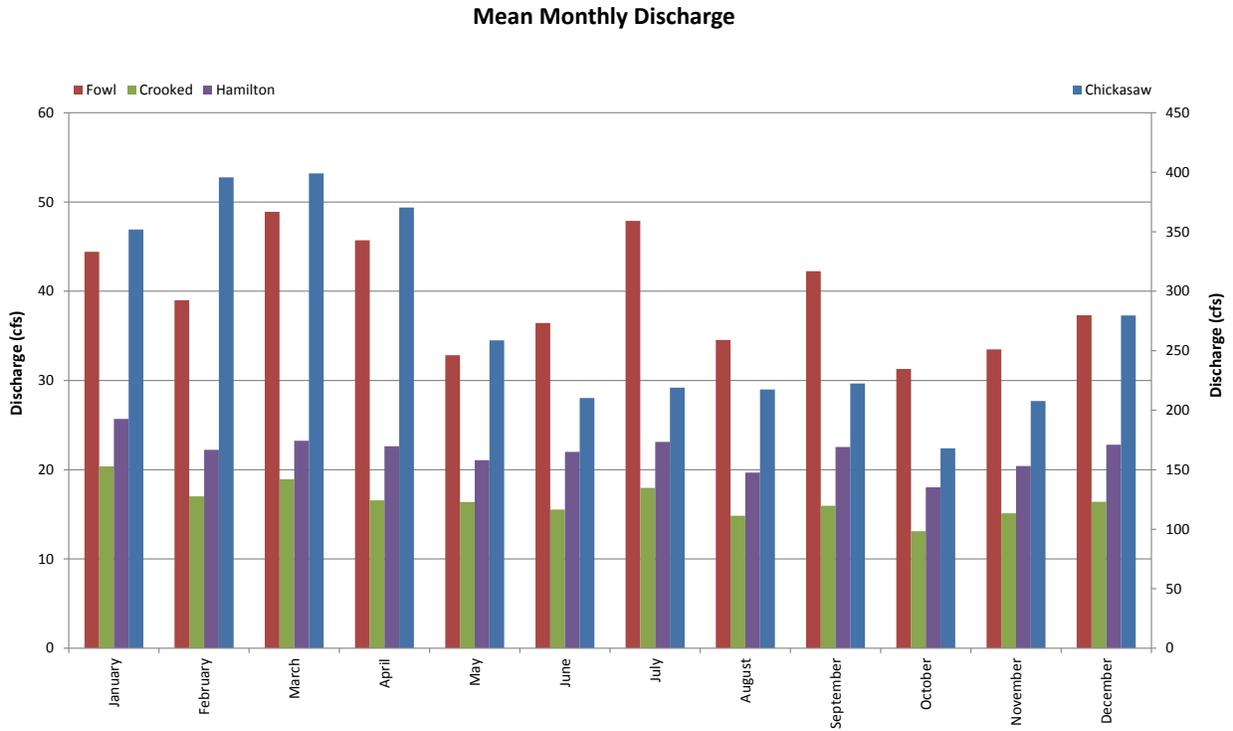
⁸⁴ This is consistent with the runoff discussion published in USGS (2010a).

⁸⁵ Evans, 2009

⁸⁶ Evans, 2009. Also noted that some but not all Alabama river systems have flood controls or reservoirs.

Figure 47: Average Monthly Mean Discharge (cfs) Measured at Four Stream Gage Sites across Mobile County for Data Available from 1990 to 2009

Due to the significantly higher range in values for the Chickasaw stream gage, the Chickasaw data is on a secondary axis.

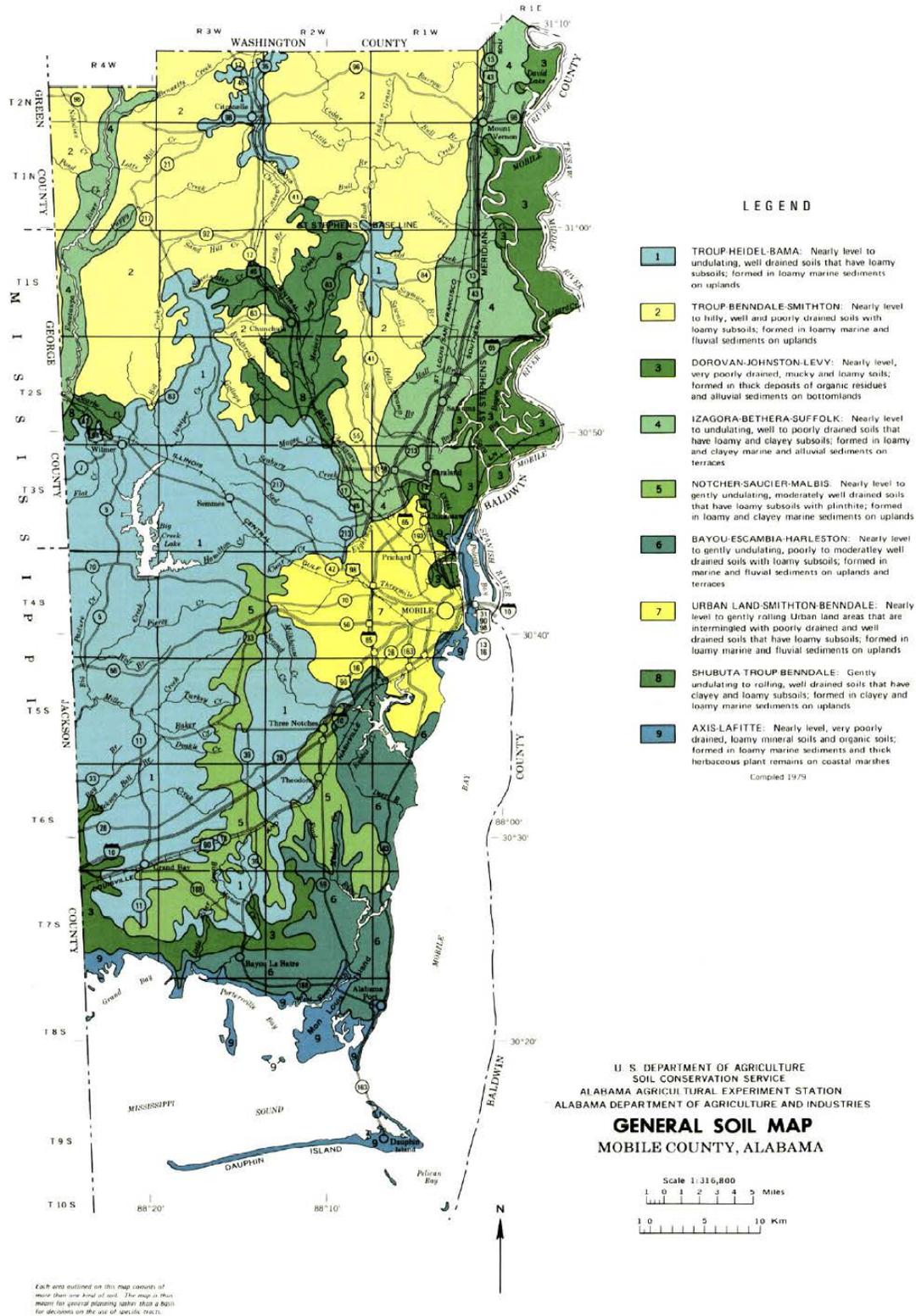


Soil Moisture

Soil types in Mobile County impact how quickly precipitation runs off the surface or is absorbed by the soil. Figure 48 provides a description of the soils found in Mobile.⁸⁷

⁸⁷ USDA, 2002

Figure 48: Soil Map for Mobile County, Alabama



5.2. Projected Streamflow

5.2.1. Methodology

This section describes the analysis of projected monthly streamflow based on a monthly water balance model driven by Mobile-specific information. These projections inform how monthly hydrological properties may change in the future, which could affect transportation stressors such as wetland performance; however, they will not provide information on impacts influenced by peak flow rates.

Monthly projections were developed for an artificial basin using the USGS' modified Thornwaite monthly water balance model (WBM) driven by Mobile-specific information.⁸⁸ This model estimates monthly runoff, evapotranspiration, and soil moisture within a basin or sub-basin using user-provided monthly precipitation and temperature data. The monthly runoff projections were translated to monthly discharge projections using the basin area for each stream gage. The model assumes:

- A portion of precipitation immediately becomes runoff (termed the “direct runoff factor”). This portion is determined by the model user.
- A portion of precipitation infiltrates into the soil and is stored (termed the “soil moisture”). This portion is determined by the model user.
- A portion of precipitation evaporates back into the atmosphere (termed “evapotranspiration”). This portion is a function of temperature.
- Any remaining precipitation is multiplied by a user-defined runoff factor which determines how much of the remaining precipitation becomes additional runoff and how much is considered surplus that gets carried over to the next month.

Optimum values for the user-defined parameters were determined for Mobile using runoff data from three stream gage sites and meteorological data from the Coden and Mobile observations stations (see Appendix C.8 for detailed discussion of the methodology and calibration results).

Once calibrated for Mobile, the WBM was run with the climate model baseline simulations and compared against the stream gage monthly mean discharge values. These runs show that the model underestimates monthly discharge compared to stream gage monthly discharge. In addition, the WBM does not capture the extreme daily peaks of discharge and has the most difficulty accurately portraying fall monthly runoff. The test runs indicate that the projected streamflow may best represent changes at Chickasaw Creek.

⁸⁸ http://wi.water.usgs.gov/Soil_Water_Balance/index.html

5.2.2. Key Findings

Key Findings for Streamflow Projections

- Monthly stream discharge is projected to decrease during the summer months, while actual evapotranspiration is projected to increase.
- Monthly stream discharge is projected to increase in January, February, and March.
- Soil moisture is projected to become drier during the summer, particularly by the end of the century.

This section presents the results of the projected streamflow analysis, including a discussion of:

- Monthly Stream Discharge
- Soil Moisture

Monthly Stream Discharge

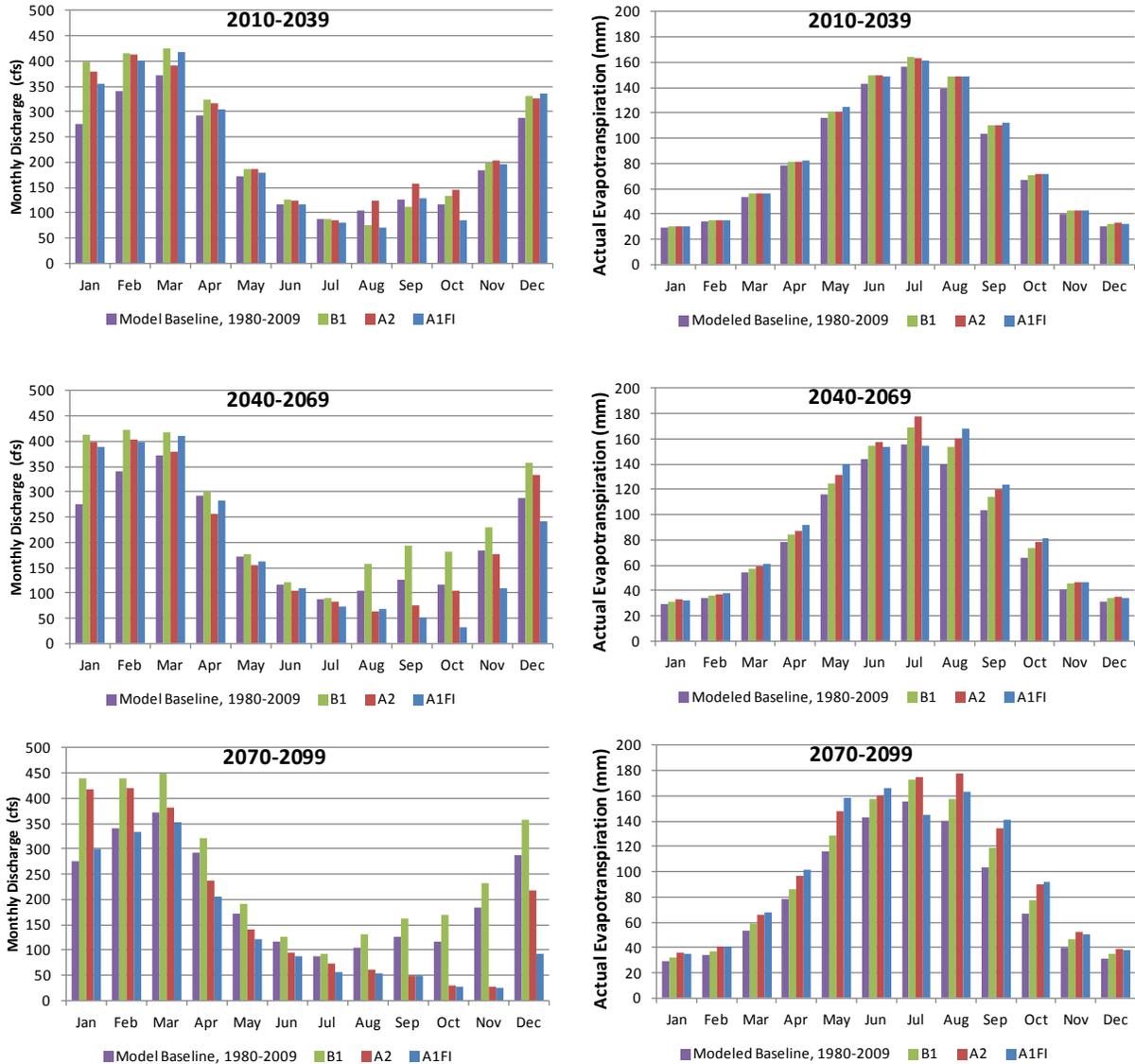
The results of the projected streamflow analysis for Chickasaw Creek are presented here (see Figure 49). Appendix C.9 contains the results for Hamilton Creek and Crooked Creek, which demonstrate similar patterns in projected monthly stream discharge.

Monthly stream discharge is projected to increase across much of the winter and early spring months, regardless of emission scenario and time period. However, there are noticeable differences in monthly discharge projections by emission scenario. By end-of-century, January discharge at Chickasaw Creek is projected to increase by as much as 23.9 cubic feet (0.7 cubic meters) per second under the high (A1FI) emission scenario and 160.5 cubic feet (4.8 cubic meters) per second under the low (B1) emission scenario.

Under the moderately-high (A2) and high (A1FI) emission scenarios, monthly discharge during much of the year (April through December) is projected to decrease substantially compared to baseline. This projected decrease in discharge is coupled with a projected increase in monthly evapotranspiration (i.e., evaporation from ground surfaces and plants), which is reflective of the projected warmer temperatures. The combination of these two projections suggests soil moisture may be drier over much of the year compared to baseline conditions.

Under the low (B1) emission scenario, monthly discharge and evapotranspiration are projected to increase compared to baseline across all months.

Figure 49: Modeled Baseline and Projected Monthly Streamflow Discharge (ft³/sec) for Chickasaw Creek and Actual Evapotranspiration (mm) by Time Period and Emission Scenario



Soil Moisture

Soil moisture is affected by changes in both monthly streamflow and evapotranspiration, and is defined as the amount of water stored in the soil (mm).⁸⁹ Projections of soil moisture suggest that summer months will become increasingly dry under the moderately-high (A2) and high (A1FI) emission scenarios over time (see Figure 50). Drier conditions traditionally experienced during the summer months are projected to extend into late spring and through the fall. The low (B1) emission scenario does not demonstrate large differences from simulated baseline conditions.

⁸⁹ The monthly water balance model assumes as the soil becomes drier, water is increasingly difficult to remove from the soil and less is available for actual evapotranspiration.

These results suggest large changes in summertime soil moisture under the moderately-high (A2) emission scenario by end-of-century and under the high (A1FI) emission scenario by both mid-century and end-of-century. In the upcoming vulnerability assessment under Task 3, soil moisture capacity projected by the WBM may be used to drive hydrologic modeling to estimate event-driven changes in projected streamflow and to establish changes in long-term soil conditions.

Figure 50: Modeled Soil Moisture (mm) by Time Period and Emission Scenario



5.2.3. Implications for Transportation

The transportation implications of changing streamflow patterns are similar to those resulting from severe precipitation events, discussed above. Streamflow changes are likely to have the most significant effects on roadways, but may also impact rail lines; landside operations at ports; and facilities at airports, bus stations and train terminals. Changes in seasonal and monthly hydrology could require consideration of wetland performance. Erosion patterns may also be affected, necessitating more frequent maintenance and changes in vegetation management. Under the next task of this project (Task 3: Vulnerability Screen and Assessment), additional analysis may be done to consider the effects on peak flow events, which can affect performance of culverts, ditches, and water runoff collection and treatment systems.

The implications of the streamflow findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

6. Sea Level Rise

Sea level rise can permanently inundate coastal transportation assets damaging infrastructure, leading to corrosion, and potentially rendering certain coastal infrastructure unusable without adaptation actions. Rises in sea level can also magnify the surge associated with storm events. Storm surges can cause immediate flooding and both horizontal and vertical coastal erosion.⁹⁰ Damage to transportation infrastructure can be caused by the force of the water and from collisions with debris.⁹¹ Impacts from storm surge are discussed in greater detail in Section 7.

Over the 20th century, global average sea-level has risen by a total of 6.7 inches (0.17 meters) with recent observations suggesting an accelerated increase in the average rate of sea level rise.⁹² Along most of the Atlantic and Gulf coasts, relative sea-level has risen at a rate of 0.8 to 1.2 inches (2.0 to 3.0 centimeters) per decade during the 20th century. Along the Louisiana coast, relative sea level has risen at an even faster rate of a few inches per decade, due to relatively rapid land subsidence.⁹³

As sea-level rises, the zone impacted by erosion and damage from inundation, storm surges, and waves expands inland. Since the 1970s, half of coastal Mississippi and Texas has experienced shoreline erosion of 8.5 to 10.2 feet (2.6 to 3.1 meters) per year.⁹⁴ Louisiana has experienced even more significant erosion of 39 feet (12 meters) per year.⁹⁵

In this section, the methodology for evaluating observed sea level measurements for the Mobile region and sea level rise projections is provided followed by a description of key findings.

- Section 6.1 describes the analysis of observed sea level rise, based on data from two regional stations.
- Section 6.2 describes the analysis of future sea level rise. This analysis included a literature review of state-of-the-science studies to identify global sea level rise scenarios. These scenarios were adjusted for local subsidence and uplift to inform in-depth inundation mapping. This section discusses key findings and shows maps that overlay each sea level rise scenario on top of the critical assets defined in Task 1 of the Gulf Coast study.
- Section 6.3 discusses the implications of these findings on transportation.

Additional detail about the sea level rise analyses is available in the appendices.

- Appendix D.1 describes the factors that can contribute to relative sea level rise, but that are not considered in the Mobile sea level rise analysis.

⁹⁰ NRC, 2008; USCCSP, 2008a

⁹¹ NRC, 2008; USCCSP, 2008a

⁹² IPCC, 2007a; DOT FHWA, 2010; National Science and Technology Council, 2008

⁹³ National Science and Technology Council, 2008.

⁹⁴ Nicholls et al., 2007

⁹⁵ Nicholls et al, 2007

- Appendix D.2 describes in detail the methodology to estimate subsidence and uplift.⁹⁶
- Appendix D.3 provides the vertical land surface rates for the benchmark surveys and corresponding InSAR Data in Mobile and Baldwin Counties.
- Appendix D.4 provides supplementary exposure statistics from the Mobile sea level rise scenario analysis.
- Appendix D.5 describes caveats, gaps, and replicability of the future sea level rise analysis.

6.1. Observed Sea Level Rise

This section describes the analysis of observed sea level rise based on observed data.

6.1.1. Methodology

This section describes the methodology used to analyze observed sea level rise data in the Mobile region. The analysis of observed sea level is based on data from two regional stations. Data was collected from the NOAA Tides and Currents program for the Dauphin Island station⁹⁷ and the Pensacola, FL station.⁹⁸ Pensacola, FL is located about 60 miles (97 kilometers) from Mobile, AL, sea level data at Dauphin Island and Pensacola stations demonstrate similar trends of rising sea level over time. The Pensacola station was included as it provides a robust long-term data record from 1923 to present and is considered to be the most stable area along the Gulf.⁹⁹

6.1.2. Key Findings

This section describes key findings from the analysis of observed sea level rise.

Sea levels have been rising in the Mobile area.

Based on observed data from 1966 to 2006,

mean annual local sea level at Dauphin Island has increased 0.12 inches per year (2.98 millimeters/year) and mean annual local sea level at Pensacola has increased 0.08 inches per year (2.03 millimeters/year). For the entire Pensacola record (1923-2006), mean annual local sea level has risen at 0.084 inches/year (2.10 millimeters/year) (see Table 19). This locally observed rate of sea level rise is greater than the global average. Globally, sea level increased approximately 0.07 inches per year (1.7 mm/year) during the 20th century, and more than 0.14 inches per year (3.5 mm/year) since 1993.¹⁰⁰

Key Findings for Historical Sea Level Rise

- Sea level at Dauphin Island rose approximately 5.0 inches between 1966 and 2006 (i.e., 0.12 inches/year).

⁹⁶ Based on the preliminary analysis provided by K. Van Wilson, USGS.

⁹⁷ Station ID: 8735180.

⁹⁸ Station ID: 8729840.

⁹⁹ Personal communication with Dr. Scott Douglass of the University of South Alabama's Marine Sciences program.

¹⁰⁰ IPCC 2007a; NOAA 2012c

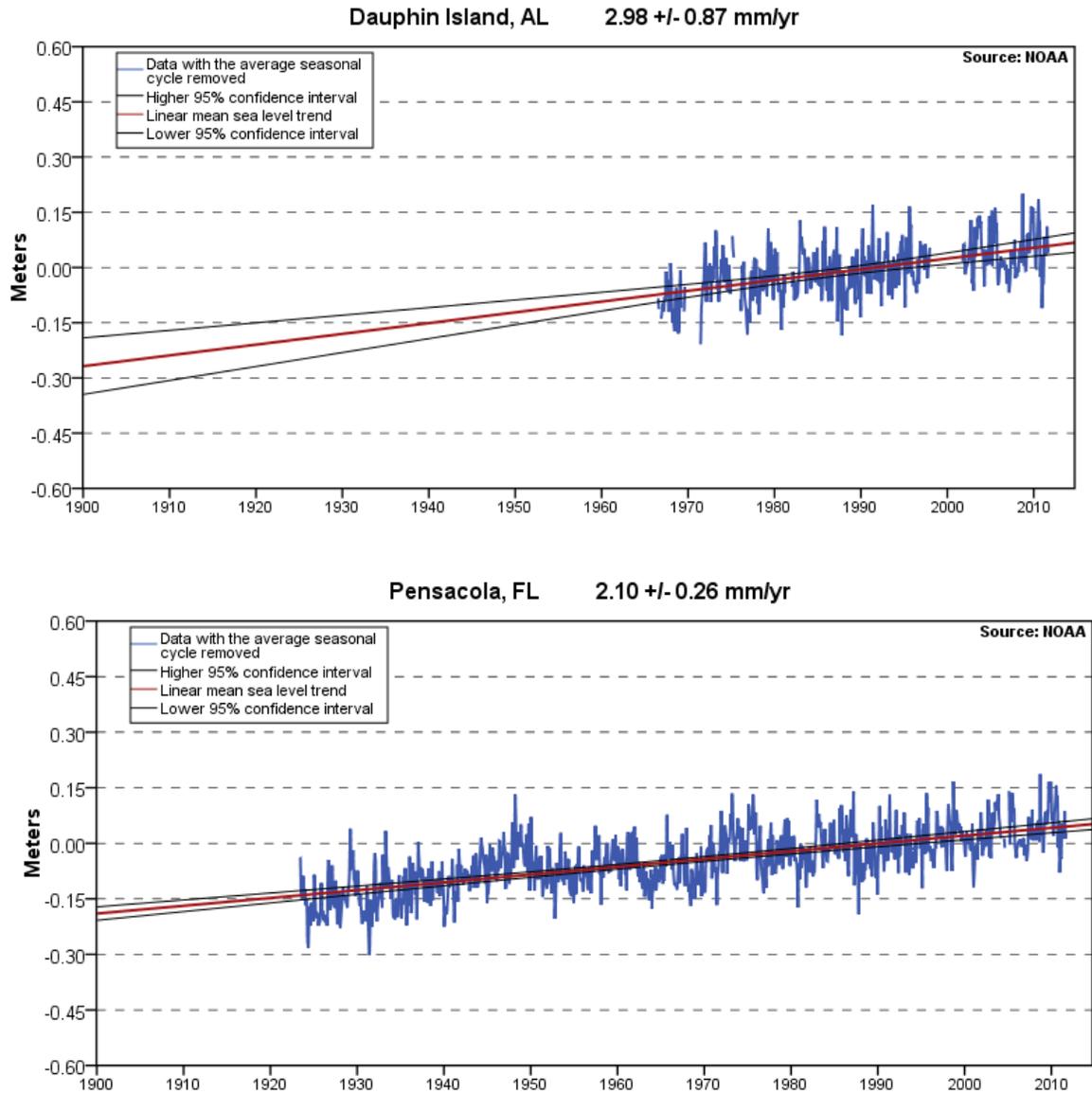
Table 19: Sea Level Rise at Dauphin Island and Pensacola Stations

Site	Time Period	
	1966 to 2006	1923 to 2006
Dauphin Island	0.12 inches/year	Not available
Pensacola	0.08 inches/year	0.084 inches/year

Figure 51 illustrates the change in annual mean local sea level for Dauphin Island and Pensacola. Annual mean local sea level was estimated from monthly mean sea level data records with regular seasonal fluctuations removed. The general trends in mean annual sea level over time are consistent between the two stations, with the rate at Dauphin Island approximately 0.04 inches/year greater than at Pensacola. If one assumes a GSLR of 0.071 inches/year, then the local influence on RSLR is approximately -0.012 inches/year at Pensacola and -0.047 inches/year at Dauphin Island.¹⁰¹

¹⁰¹ Based on a preliminary analysis by USGS provided to FHWA.

Figure 51: Change in the Annual Mean Local Sea level for Dauphin Island, Alabama and Pensacola, Florida



Variability in local sea level is affected by many factors (see Factors Affecting Local Sea Level Rise text box).¹⁰² Many of the peaks shown in this time series likely reflect the inter-annual variation in sea level due to global ocean phenomena such as the El Niño-Southern Oscillation (ENSO).¹⁰³ Peaks may also reflect unusual seasonal weather patterns (precipitation, temperature, and runoff), and years with increased storms and waves.¹⁰⁴ The long-term trend that is visible through the “noise” in the data record provides a baseline of relative sea level changes experienced to-date.

¹⁰² Thompson et al., 2008. Local sea level rise as discussed in the Climate Projections section of this report describes changes in sea level due to global sea level rise, uplift, and subsidence of land.

¹⁰³ Parker, 1992

¹⁰⁴ Ibid.

Factors Affecting Local Sea level Rise

Sea level rise (SLR) does not happen uniformly across the globe. Since this study is focused on the local scale, it is important to consider potential *local* sea level rise (LSLR) scenarios for Mobile, AL. There are a number of factors that contribute to changes in local sea level including:

- Global sea level rise (GSLR), or global-scale changes in the volume of water in the ocean;
- Uplift and subsidence of land from shifting local tectonics and changes in the amount of fluid in sediment pores;
- Sedimentation and erosion adding or subtracting the amount of sediment at a particular location;
- Gravitational changes;
- Changes in oceanic and atmospheric circulation patterns; and
- Changes in ocean density due to changes in salinity and temperature.

These latter five factors can vary at regional and/or local scales. In addition, inter-annual variability and episodic events such as storms and precipitation can affect year-to-year sea level.

6.2. Future Sea Level Rise

This section describes the methodology and key findings for the analysis of future sea level rise in the Mobile region.

6.2.1. Methodology

The approach first identified possible levels of global sea level, and then adjusted these levels based on local subsidence and uplift of land to estimate changes in relative sea level.

This approach relied on selection of multiple plausible future scenarios of sea level, as precise levels of sea level rise cannot be predicted. Increases in atmospheric greenhouse gas concentrations are linked to future changes in global sea level. However, there is a large amount of uncertainty associated with quantitatively estimating those changes. Therefore, a set of plausible sea level rise scenarios for Mobile, Alabama were explored. A scenario-based analysis is a standard approach in the face of “deep uncertainty” associated with environmental or other challenges relating to future conditions. The scenarios used in this analysis, which are reflective of the state-of-the-science, are not predictions. Rather, the scenarios represent conditions that may occur, thereby encompassing a representative range of possible future conditions.

Once global sea level rise scenarios were selected, they were adjusted to reflect local uplift and subsidence, and then state-of-the-art quantitative models were used to assess the inundation of Mobile under each scenario.

Two of the six factors affecting local sea level rise (see text box above) were considered in this study: global sea level rise and changes in local land elevation. These two factors are likely to

have a strong influence on local average sea level by the end of the century. Local sea level rise (LSLR) was estimated by simply adding the current rates of subsidence or uplift to each global sea level rise scenario.

The other four factors were not considered in this study because they were not considered to likely significantly impact the results, or due to resources constraints. For more information on why other factors were not considered, see Appendix D.1. This section describes the methodology used to characterize future sea level rise in Mobile. This analysis included a literature review and selection of global sea level rise scenarios, adjustment of those GSLR scenarios for local subsidence and uplift to estimate LSLR, and in-depth inundation mapping for each of the LSLR scenarios.

Literature Review and Selection of Global Sea level Rise Scenarios

To identify plausible future levels of global sea level, a literature review was conducted. The findings of this literature review are discussed below.

Climate change may increase global sea level through two dominant pathways: by the melting of land-based ice caps and glaciers and by thermal expansion of ocean waters due to increasing temperatures. By 2100, the IPCC projects an increase in sea level of 0.6 feet to 1.9 feet (0.18 to 0.59 meters) in response to rising temperatures. This projection accounts for thermal expansion and the melting of glaciers and ice caps but what is now recognized as a low rate of loss¹⁰⁵ for the ice sheets. However, satellite observations suggest ice sheets are already becoming affected and recent studies suggest that sea level rise could be much greater than projected by the IPCC in 2007.¹⁰⁶

According to the National Research Council, land ice loss is expected to accelerate as temperature increases, leading to a GSLR of 1.6 to 3.3 feet (0.5 to 1.0 meter) by 2100, with the possibility of up to 5.3 feet (1.6 meters).¹⁰⁷ This range is conservative compared to other recent studies that estimate sea level rise of up to 2.0 meters (6.6 feet) by 2100. Other estimates of sea level rise range from 2.6 to 6.6 feet (0.8 to 2.0 meters),¹⁰⁸ 1.6 to 4.6 feet (0.5 to 1.4 meters),¹⁰⁹ and 3.2 to 5.1 feet (0.97 to 1.56 meters).¹¹⁰ This large range is indicative of the considerable scientific uncertainty associated with estimating GSLR.

¹⁰⁵ Ice loss can be due to ice sliding directly into the ocean, from melting of the ice, and from direct evaporation of the ice into the atmosphere.

¹⁰⁶ A 20-year study funded by the National Aeronautics and Space Administration (NASA) suggests that ice sheets in Greenland and the Antarctic are melting at an increasing rate with each passing year. This trend is thought to be directly correlated with warmer summer temperatures. (Rignot et al., 2011; Gardner et al., 2011) Total losses from both ice sheets averaged roughly 475 billion metric tons (534 billion short tons) of ice each year, enough volume to increase average global sea levels by 1.3 millimeters (0.05 inch) per year. The same study proposes that if current ice sheet melting rates continue, average total sea level rise could reach 32 centimeters (12.6 inches) above current averages by 2050 from melting ice sheets, glacial ice caps, and thermal expansion. Another study projects mountain glaciers and ice caps around the world could lose up to 75 percent of their present ice volume by 2100. (Radic and Hock, 2011)

¹⁰⁷ NRC, 2010b

¹⁰⁸ Pfeffer et al., 2008

¹⁰⁹ Rahmstorf, 2007

¹¹⁰ Vermeer and Rahmstorf, 2009

These studies, viewed collectively, demonstrate both the large potential for sea level rise in the future and the large uncertainty associated with current understanding of ice dynamics.

Based on these recent estimates of global sea level rise, this study uses a sea level rise estimate that falls in the middle of the NRC estimates, i.e., 0.75 meters (2.5 feet) by 2100. Using the precautionary principle¹¹¹ as a guide, this study also explores the implications of sea level rise of 2 meters (6.6 feet) by 2100. In addition, the study considers a rise of 0.3 meters by 2050, which corresponds approximately to the scenario of 0.75 meters (2.5 feet) by 2100, assuming a linear trend. Due to the significant, aforementioned uncertainty, relative probabilities are not assigned to these values.

Global Sea Level Rise Scenarios Selected

- 0.3 meters by 2050
- 0.75 meters by 2100
- 2.0 meters by 2100

If, at a later date, the science indicates that GSLR may be above or below these values, the findings presented below are still useful. Different dates can be roughly assigned to each GSLR scenario. For example, if sea level rises much more slowly than anticipated, the 0.3 meter (1.0 foot) scenario could be assumed to occur in 2100.¹¹² Similarly, if sea level rises more rapidly than anticipated, the 0.75 meter (2.5 feet) scenario could be assumed to occur in 2050.¹¹³ The main caveat with doing so would be that the rates of subsidence/uplift would be mismatched with the years. However, subsidence/uplift in the study region is anticipated to have a less significant effect on SLR over the 21st century than other factors, so this mismatch would not constitute a major problem, and the use of these scenarios would still provide a general sense of the assets that would be exposed to LSLR.

Adjustments for Vertical Land Motion (Subsidence and Uplift)

The literature does not provide estimates of local sea level rise projections, specific to Mobile. Therefore, GSLR rates were modified to account for vertical land motion, as discussed below. As already noted, LSLR is determined not only by global changes in the ocean's volume, but also by local changes in land elevation due to geological plate movement, extraction of underground water and resources, and other factors. For example, if global sea level rises 0.1 meters, and the land elevation also rises 0.1 meters over the same time period, then the LSLR would be zero. Conversely, if the land were to subside by 0.3 feet (0.1 meters) while global sea level rose by 0.3 feet (0.1 meters), the LSLR would be 0.7 feet (0.2 meters).

Many areas of the Gulf coastal zone are subsiding due to geological faulting and compaction of sediment resulting in part from groundwater withdrawal.¹¹⁴ However, the rate of subsidence is

¹¹¹ Principle 15 of the Rio Declaration of 1992 states: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

¹¹² This scenario could manifest itself if there is little to no acceleration in the transfer of water from ice sheets to the ocean over the next century.

¹¹³ This scenario could manifest itself if the loss of ice sheets is at the upper end of what has been reported in the literature.

¹¹⁴ Dokka, 2006

not uniform. In some places, uplift is occurring (see below). To better evaluate the impacts of sea level rise, the US Geological Survey (USGS)¹¹⁵ assisted with an analysis of the added effects of vertical land motion to the GSLR scenarios, to provide a more accurate estimate of projected local sea level rise in Mobile.

USGS estimated subsidence and uplift rates using Interferometric Synthetic Aperture Radar (InSAR) data together with a series of stable survey benchmarks and tide gages. The approach is discussed in more detail in Appendix D.2. In summary, the InSAR data provided vertical movement data for most of the study area, while the benchmark data helped to augment the InSAR data outside the spatial domain of the InSAR data.¹¹⁶ InSAR data were used where possible, because they are spatially continuous and possess relatively high accuracy. A spatially complete data set of vertical motion from these two datasets was arithmetically added to a high resolution Digital Elevation Model based on LIDAR data¹¹⁷ to estimate the vertical position of the land surface out to 2050 and 2100.

Inundation Mapping

A Geographic Information System (GIS) was used to map all locations below the prescribed GSLR scenarios that are subject to potential inundation from LSLR.¹¹⁸ Then, GIS was used to overlay inundation under each of the sea level rise scenarios on top of the critical assets defined in Task 1 of the Gulf Coast Study. This analysis considered the bare earth elevation of assets—that is, the elevation of the land on which the assets sit. It did not consider the height of the assets themselves.

6.2.2. Key Findings

This section presents the results of the sea level rise analysis, including inundation maps for the three selected scenarios. The LSLR results shown here are relative to Mean Higher High Water (MHHW).

The analysis indicates modest subsidence over most, but not all of southeastern Mobile County, which will amplify the impact of projected global sea level rise.

Vertical change rates for the 75 benchmarks considered by USGS ranged from -0.08 to 0.02 inches per year¹¹⁹ (-1.9 to 0.5 millimeters per year) with a mean of -0.03 inches per year (-0.75

¹¹⁵ The analysis of vertical land motion was led by K. Van Wilson, USGS MS Water Science Center, 308 South Airport Road, Jackson, MS 39208. He gratefully acknowledges the following at the National Geodetic Survey who were very helpful in providing technical assistance and requested benchmark information: Denis Riordan, State Geodetic Advisor for Mississippi, Jackson, MS; Jim Harrington, State Geodetic Advisor for Alabama, Montgomery, AL; and Vasanthi Kammula, Chief, Project Analysis Branch, Silver Springs, MD. The author also acknowledges Zhong Lu, USGS, Cascades Volcano Observatory, Vancouver, WA, for his technical assistance in adjusting the InSAR data using the updated benchmark results. Original ERS-1/2 SAR data are copyrighted by the European Space Agency (ESA). Original ALOS/PALSAR data are copyrighted by the Japan Aerospace Exploration Agency (JAXA) and Japan Ministry of Economy, Trade and Industry (METI). More details about the USGS analysis are available from FHWA in the form of three technical reports that were submitted by USGS.

¹¹⁶ In the western-most areas of Mobile County and the western end of Dauphin Island, actual data values were extended outward into data voids to build the interpolation surface.

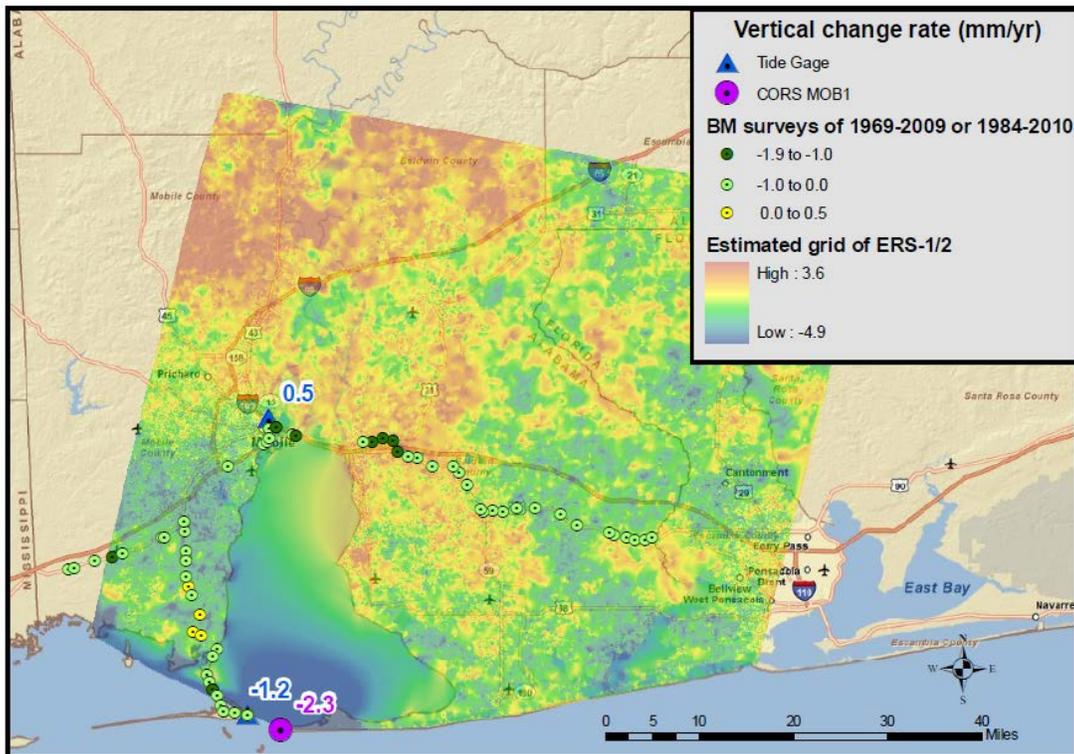
¹¹⁷ LIDAR data provided by the City of Mobile, 2010

¹¹⁸ A new file delineating the shoreline at high resolution was generated. This file was used in this analysis as well in the storm surge analysis.

¹¹⁹ In referring to vertical change rates, subsidence is expressed as a negative number, and uplift as a positive number.

millimeters per year) and a standard deviation of 0.02 inches per year (0.42 millimeters per year) (see Appendix D.2 for details). The 198,129 InSAR data points plotted in Figure 52¹²⁰ had vertical change rates ranging from -0.2 to 0.2 inches per year (-5.1 to 3.6 millimeters per year) with a mean of -0.02 inches per year (-0.60 millimeters per year) and standard deviation of 0.03 inches per year (0.82 millimeters per year). Due to the large number of InSAR data points, each individual value is not shown in this report (see Figure 52). Table 46 in Appendix D.3 provides the vertical land surface rates for benchmark surveys and corresponding InSAR data in Mobile and Baldwin counties.

Figure 52: Vertical Land Motion for Mobile and Baldwin



To place these vertical land surface change estimates into context, the maximum subsidence rate from the benchmark data (-1.9 millimeters per year) would produce a total subsidence of 0.17 meters (6.6 inches) by 2100. With the exception of Dauphin Island, which has the study area’s greatest subsidence rate, the contribution of subsidence and uplift to LSLR in Mobile County are relatively minor in relation to the effect of GSLR (e.g., the scenarios of 0.3 – 2.0 meters explored in this study).

Although the results presented here are preliminary, underlying analysis indicates that they are more accurate than prior analyses. However, it would be useful in subsequent scientific studies to check and revise these estimates as future benchmark survey data, Continuously Operating Reference Stations (CORS) data, and InSAR or other satellite data become available.

¹²⁰ Figure provided courtesy of Van Wilson, USGS.

Figure 53, Figure 54, and Figure 55 illustrate the inundation resulting from the three inundation scenarios. Under the scenario of 0.30 meters (1.0 foot) GSLR by 2050, LSLR inundates the lowest lying land in the Mobile region (see Figure 53). These areas include wetlands associated with some of the creeks that feed into Mobile Bay. This includes wetlands in the Chickasaw area, to the east of Tillman's corner, and near Fowl River, as well as the lowlands along the southern mainland coast of the county. Low-lying areas also include Gaillard Island, Terrapin Island, and parts of Dauphin Island. This level of inundation implies that short-term surges in water elevation due to relatively minor storms could lead to over-washing of the lowest lying coastal roads.

Under the scenario of 0.75 meters (2.5 feet) GSLR by 2100, LSLR exacerbates the impacts noted for the 0.3 meters (1.0 foot) scenario (see Figure 54). One particularly dramatic change is the extensive flooding that occurs across most of the wetlands at the head of the Bay and as far north as the wetlands to the east of Satsuma. However, this result hinges on the assumption of no change in vertical accretion¹²¹ by the wetland. Regardless, the exposure of the area's roads and rail to short-term storm-related flooding will increase since the still-water¹²² table will be closer to the elevation of current road surfaces.¹²³ The area at risk of flooding under this scenario would also include low-lying areas north of downtown, west of the CSX rail yard, and east of Route 45.

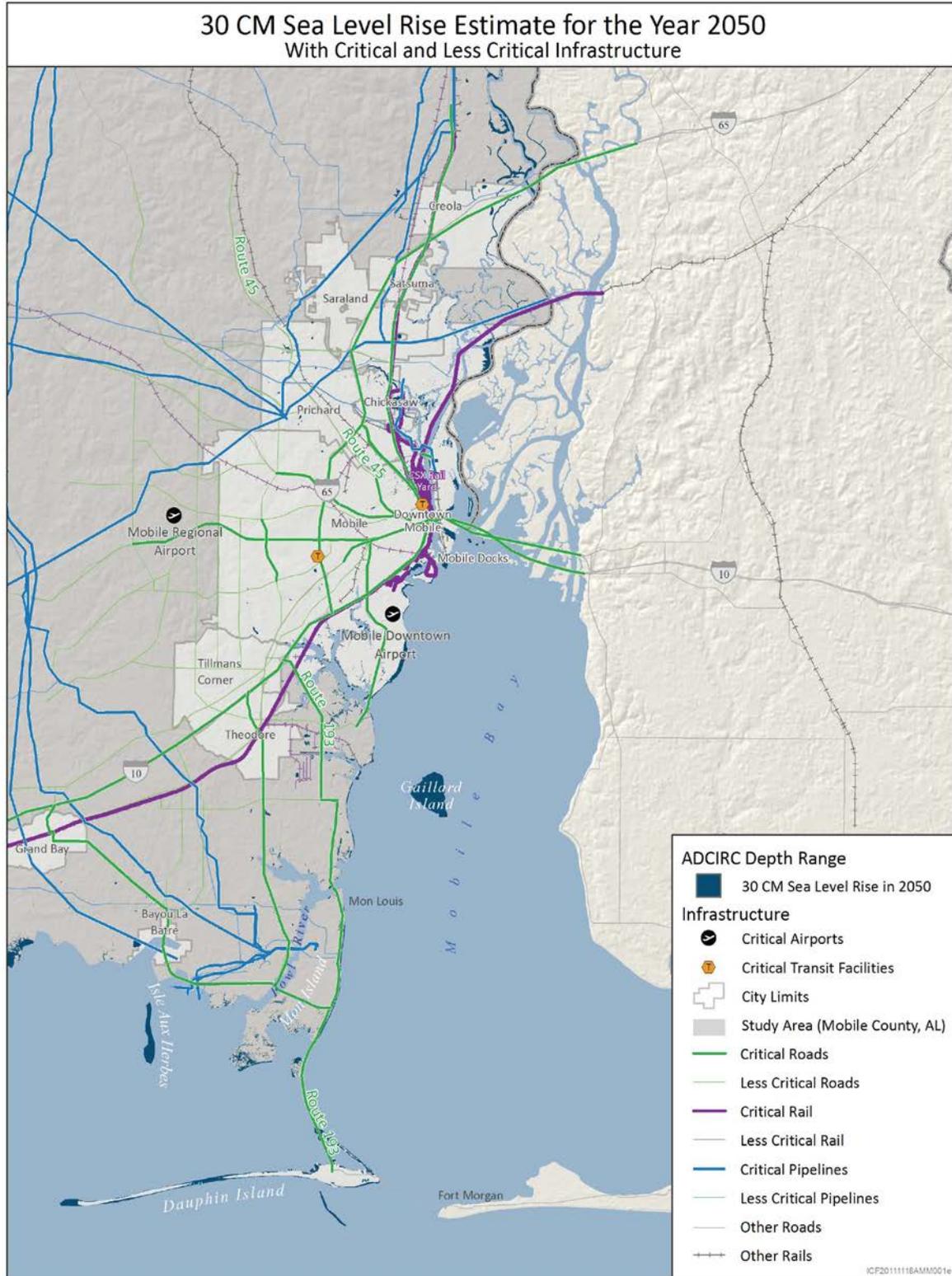
Inundation from sea level rise under the scenario of 2.0 meters (6.6 feet) GSLR by 2100 significantly shifts the southern Mobile County shoreline northward and inundates most of Dauphin Island (see Figure 55). This finding assumes no natural or human-generated vertical accretion. While parts of Dauphin Island are at an elevation above 2.0 meters (6.6 feet), these areas would still likely be at significant exposure to storm surge and may not survive severe storms. This scenario may also cause the shoreline to migrate north of I-65, if there is no vertical accretion from either natural or human sources. The approximately 0.8 inches per year (20 millimeters per year) rate of LSLR implied by this scenario would make it more difficult for natural vertical accretion to keep pace than under the 0.75 meter (2.5 feet) scenario. It would also lead to inundation of some of the lowest areas in the downtown and port waterfront.

¹²¹ Vertical accretion refers to the upward growth of the top level of sediment due to the accumulation of both inorganic sediment and organic matter.

¹²² The still-water level refers to the elevation of the water surface in the absence of waves.

¹²³ This vulnerability may be partially mitigated by increasing the elevation of road surfaces during the routine recapping of the asphalt roads in the area.

Figure 53: Potential Inundation with Global Sea level Rise of 0.3 meter by 2050 ¹²⁴



¹²⁴ Subsidence and uplift are accounted for in the three scenarios using InSAR and benchmark data, as described in the text.

Figure 54: Potential Inundation with Global Sea level Rise of 0.75 meter by 2100

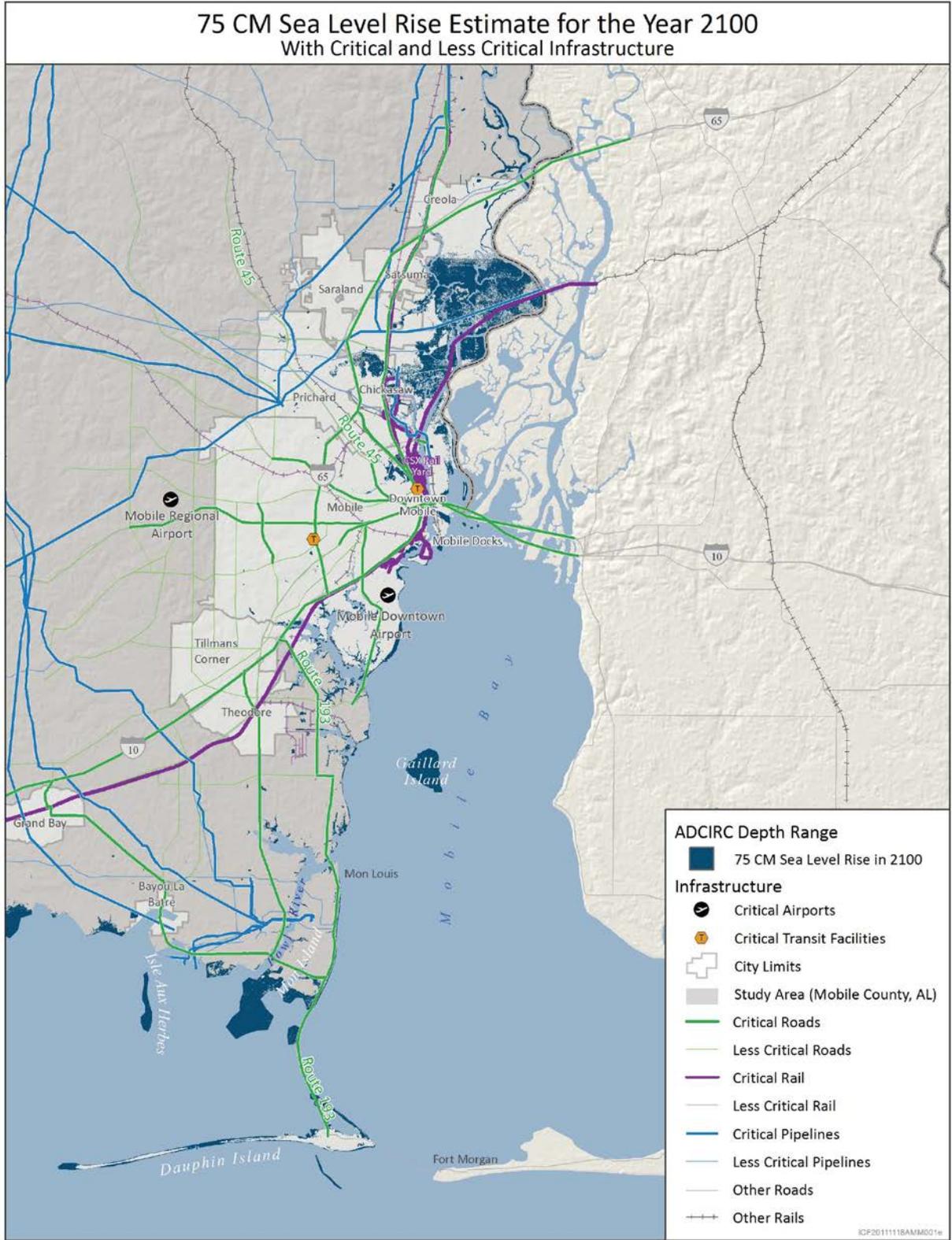
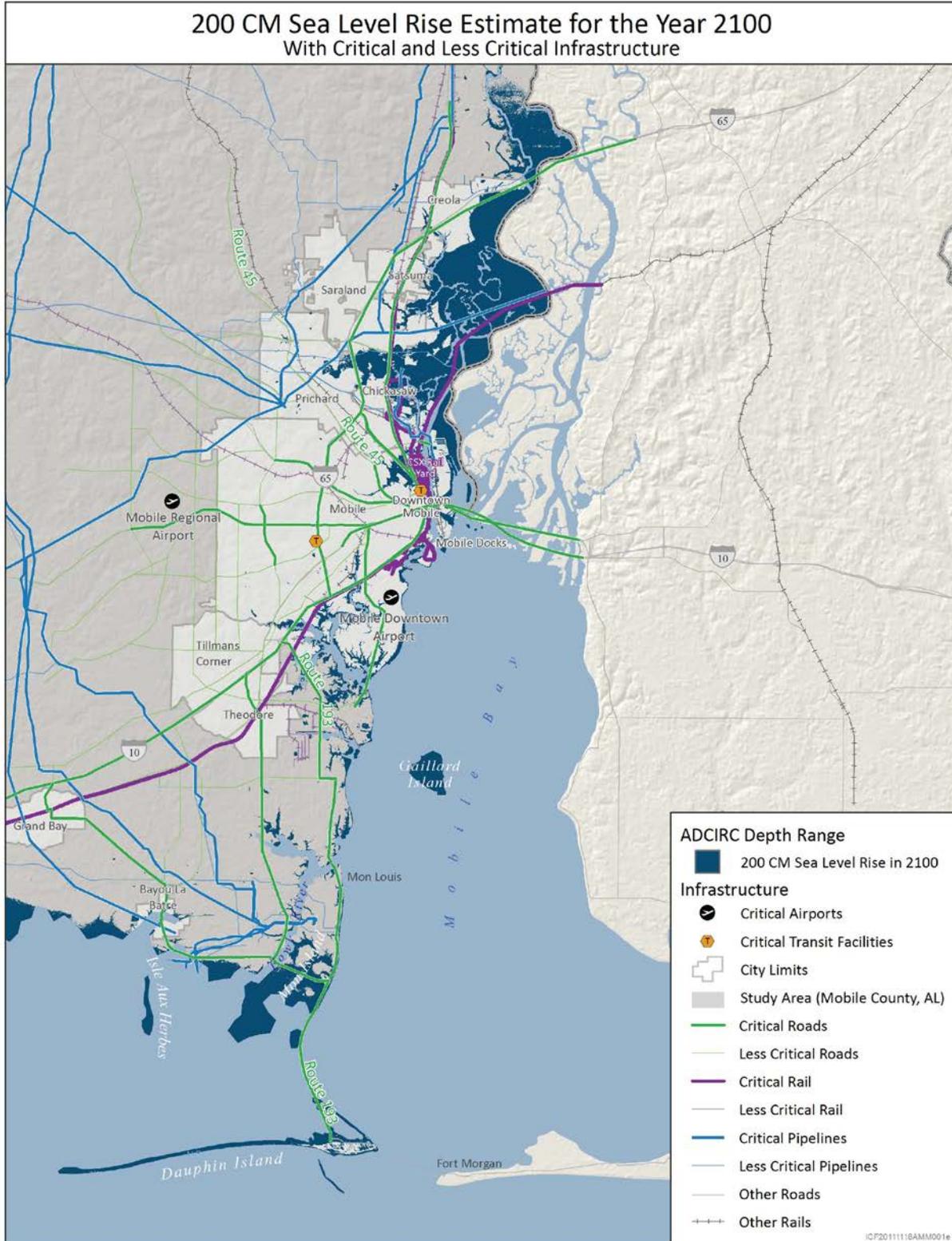


Figure 55: Potential Inundation with Global Sea level Rise of 2.0 meter by 2100



Caveats, Gaps, and Replicability

The approach to sea level rise mapping used here is appropriate for initial exposure assessment. However, several factors affecting sea level rise were not taken into account. For example, vertical addition or subtraction of sediment through coastal engineering, changes in the vertical accretion rate of wetlands, and small-scale protective barriers were not taken into account. For a more thorough account of the caveats, gaps, and replicability of this study, see Appendix D.5.

6.3. Implications for Transportation

Sea level rise can permanently inundate certain coastal assets, rendering them unusable without adaptive measures. Inundation of transportation assets was computed by overlaying the sea level rise estimates onto the elevation of each asset. A summary of the inundation of critical transportation assets is provided in Table 20. A more detailed summary is provided in Table 47 of Appendix D.4. Except for ports, Mobile's critical transportation assets are minimally exposed to sea level rise in the low- and mid-range scenarios of 0.30 meters (by 2050) and 0.75 meters (by 2100) of global sea level rise, respectively. In both of these scenarios, only 0 to 4% of critical assets of each mode are exposed. Under the highest scenario of 2.0 meters of sea level rise by 2100, transit have the highest fractional extent of exposure, with 50% of facilities exposed. Pipelines have the lowest fractional extent of exposure, with 3% of pipeline-miles exposed.

Across all sea level scenarios, critical roads and rails are most exposed linear assets to sea level rise in terms of the fractional extent of inundation. Exposure of critical roads ranges from 4% of linear extent inundated under the lowest sea level rise scenario up to 13% under the highest. The area's critical rail lines are similarly exposed to sea level rise, with 20% of kilometers exposed under the highest sea level rise scenario.

In contrast, pipelines have the lowest fractional extent of exposure to sea level rise for linear assets. One percent of critical pipeline-kilometers are exposed under the mid-range scenario, while 3% are exposed under the highest scenario.

Port facilities are significantly exposed to sea level rise, with 46% of the 26 critical ports exposed under the lowest scenario, and 92% exposed under the highest scenario.

One of the two critical transit facilities, the GM & O Transportation Center, is inundated under the highest sea level rise scenario.

Of the two critical airports, only Mobile Downtown Airport experiences any inundation under the sea level rise scenarios. One percent of the airport's area is inundated under the lowest scenario and 3% is inundated under the highest sea level rise scenario. These relatively minor effects impact wetlands at the edge of the airport.

Table 20: Critical Assets Inundated Under Each Sea level Rise Scenario

Scenario	Roads (miles)	Rail (miles)	Pipelines (miles)	Ports (#)	Transit Facilities (#)	Mobile Downtown Airport (mi ²)*
2050 0.3m	9 of 209 (4%)	2 of 196 (1%)	3 of 426 (1%)	12 of 26 (46%)	0 of 2 (0%)	0 of 3 (1%)
2100 0.75m	11 of 209 (5%)	2 of 196 (2%)	7 of 426 (2%)	18 of 26 (69%)	0 of 2 (0%)	0 of 3 (2%)
2100 2.0m	26 of 209 (13%)	40 of 196 (20%)	13 of 426 (3%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (3%)

Note: The “highly critical” asset list was revised after the criticality report was completed to include parts of CR188, CR59, and the Cochrane Bridge in response to comments received from local stakeholders. Therefore, the total km presented here may differ from that reported in the Criticality Assessment report.

Inundation of small segments of coastal infrastructure can have broader implications if those segments are critical to the connectivity of the overall system. Further, coastal assets that are not fully inundated could be affected by rises in sea level. For example, higher sea levels can increase the amount of shoreline erosion, thereby threatening coastal assets. Furthermore, higher groundwater levels can adversely affect pavement subgrade stability and stormwater system performance.

The interaction between sea level rise and storm surge is a critical consideration. Sea level rise exacerbates the vulnerability of infrastructure to storm surge, as higher water levels permit storm surge to travel farther into the County (described in detail in Section 7.2).

In addition to the direct effects of sea level rise on transportation infrastructure, the ecological impacts of sea level rise may have implications for transportation. The inundation of wetlands, for example, can destroy wetland mitigation efforts in which transportation agencies have invested. Further, inundation of natural coastal areas reduces the amount of ecological barriers—wetlands and marshes that absorb energy from extra-tropical storms¹²⁵ and hurricanes—that serve as buffer zones protecting populated areas.

Sea level rise is expected to be gradual, allowing time for assets to be protected or relocated. Dikes and levees, for example, can help protect transportation assets, and many assets can be completely relocated over time. However, such adaptive measures may require significant long-term planning and financial resources.

¹²⁵ Lacy and Hoover, 2011

The implications of the sea level rise findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

7. Storm Events

Severe storms, such as hurricanes, can have temporary, but unpredictable and highly damaging effects. These effects include temporary surges in sea level (lasting several days) that can inundate coastal areas, precipitation-induced flooding, strong wind, and waves, all potentially damaging to infrastructure. Hurricanes have had severe impacts on Mobile in the past. For example, in 1979, Hurricane Frederic caused approximately \$1.7 billion (1979 USD) in damage and wiped out sections of the causeway linking Dauphin Island to the mainland.¹²⁶

According to a scientific assessment from the U.S. Climate Change Science Program, “the power and frequency of Atlantic hurricanes have increased substantially in recent decades, though North American mainland land-falling hurricanes do not appear to have increased over the past century. ... There is evidence suggesting a human contribution to recent changes in hurricane activity as well as in storms outside the tropics. ... Hurricane wind speeds, rainfall intensity, and storm surge levels are likely to increase [in the future]”.¹²⁷ In other words, there are likely to be more large hurricanes in the future. However, due to the relatively infrequent nature of hurricanes it is difficult to identify when or whether such an increase would be detected in Mobile.

Other severe storms, such as mid-latitude storms and thunderstorms, can also produce significant rain and cause severe damage. The damage associated with these storms has increased over time, in part, due to the growth in population and infrastructure.¹²⁸ According to a scientific assessment from the National Academy of Science, “Changes in major storm events are of interest both because a significant fraction of total U.S. precipitation is associated with storm events and because storms often bring wind, storm surges, tornadoes, and other threats. ... Extratropical storms, including snowstorms, have moved northward in both the North Pacific and North Atlantic, but the body of work analyzing current and projected future changes in the frequency and intensity of these storms is somewhat inconclusive. Historical data for thunderstorms and tornadoes are insufficient to determine if changes have occurred.”¹²⁹ Projecting changes in mid-latitude storms and thunderstorms is an area of active research; the main findings relevant to Mobile, Alabama are presented here.

In this section, the methodology for evaluating observed storm events in the Mobile region and storm event projections is provided followed by a description of key findings.

- Section 7.1 describes the characterization of observed storm events, including discussion of five representative storm events as case studies. The case studies identify and characterize the extreme events that impact the study area. This provides an understanding of the current weather hazards that affect transportation planning and design. The case studies also identify

¹²⁶ USACE, 1981

¹²⁷ Karl et al., 2008

¹²⁸ Ross and Lott, 2003

¹²⁹ NRC, 2010a

key environmental phenomena that were crucial for developing the extreme storm. This is useful for then understanding how these extreme storms may change in the future. Information on reported damage from each storm was also recorded in the case studies; this information will help inform the vulnerability assessment in later stages of the project.

- Section 7.2 describes the analysis of future storm events. This analysis included a literature review of studies projecting how storm-producing atmospheric phenomena may change and a scenario- and model-based analysis of hurricane storm surge.
- Section 7.3 discusses the implications of these findings on transportation.

Additional detail about the storm event analyses is available in the appendices.

- Appendix D.6 provides detailed summaries of the five historical storm event case studies.
- Appendix D.7 describes projected changes in U.S. and global storm events.
- Appendix D.8 describes in detail the methodology for the scenario-based storm surge analysis.
- Appendix D.9 provides supplementary exposure statistics for the hurricane storm surge scenario analysis.
- Appendix D.10 describes caveats, gaps, and replicability of the storm surge analysis.

7.1. Observed Storm Events

This section discusses the types of storms that Mobile experiences, and investigates five representative storm events that have previously occurred in Mobile. These case study storms provide context for understanding the impacts that past storms have had on Mobile's transportation assets and services. This section also highlights the meteorological conditions, such as the placement of the jet stream, that were important in the development of each storm event. Section 7.2 discusses how these key meteorological conditions may change in the future, providing context as to how these case study storms could change in the future.

7.1.1. Methodology

Mobile, Alabama experiences a large variety of storm events. To help characterize historical storm events in the Mobile region, the National Weather Service (NWS) office in Mobile provided a list of recent local storm events (this study focuses on those events occurring from 1995 onward). The list consisted of 18 mid-latitude storms and thunderstorms (i.e., storms other than tropical storms or hurricanes) and 16 tropical storm and hurricane events. The list was supplemented by a targeted literature search to determine if additional research was available that could enhance the analysis.

The NWS list and literature search results were used to characterize the types of storms occurring in Mobile, as well as the meteorological conditions leading to and experienced during them. The list was then used to develop a representative set of case studies to investigate local storm events.

To select storms for case studies, the storm events were first organized by storm type and level of impact to ensure that the analysis covered the variety of storm events that affect Mobile. Each storm was then evaluated based on:

- (1) Whether the storm was a good representation of the types of storms that hit Mobile,
- (2) Whether sufficient information was readily available to develop a case study, and
- (3) Whether the storm type was likely to occur under future projections.

Five storm events were selected for case studies. These events include:

- A severe thunderstorm/tornado event
- A hailstorm event
- A heavy rain event
- Two hurricanes. Section 7.2 analyzes these selected hurricanes, complementing the case studies presented here.

Storm event data for the case studies were collected from a number of sources.

- Meteorological data came from the National Weather Service’s Cooperative Observer Program (CO-OP), which are available through the National Climatic Data Center.¹³⁰
- Streamflow data came from the United States Geological Survey’s (USGS) National Streamflow Information Program.¹³¹
- Tidal data came from NOAA CO-OP stations.¹³²

A literature survey was then conducted for each storm event to provide additional information on storm analysis, damage information, and general meteorological conditions contributing to storm development and/or intensification.

The mid-latitude storms and thunderstorm case studies include:

- A brief discussion of storm development identifying key meteorological conditions;
- Storm event metrics including precipitation, discharge, temperature, wind, surface pressure, sea level, and storm surge; and

¹³⁰ Data analyzed from Mobile Regional Airport Land Surface COOP Station (COOP ID 015478) and the Mobile Land Surface COOP Station (COOP ID 015483).

¹³¹ Data analyzed from stream sites at Crooked Creek near Fairview (USGS 02479980), Chickasaw Creek near Kuskla (USGS 02471001), and Fowl River near Laurendine (USGS 02471078).

¹³² Data analyzed from tide stations at Dauphin Island (ID 8735180), Mobile State Docks (ID 8737048), and Pensacola, FL (ID 8729840).

- A discussion of associated damages.

The hurricane case studies include:

- A brief discussion of storm track and intensification;
- Storm event metrics including precipitation, discharge, wind, central storm pressure, sea level, and storm surge; and
- A discussion of associated damages.

7.1.2. Key Findings

Key Findings for Historical Storms

- Mobile experiences frequent severe thunderstorms in the spring and fall, often accompanied by tornadoes. Key ingredients for these strong convective storms are a strong jet stream and warm, moist surface air.
- Mobile is also frequently affected by tropical storms and hurricanes, including 12 storms since 2000. Mobile receives a direct hit about once every 16 years.
- Storm events in Mobile can cause flooding, downed power lines, and other infrastructure damage.
- The Mobile Bay Causeway was completely inundated during both case study tropical storms (Hurricane Georges and Hurricane Katrina).

General Characterization

Prior to investigating specific case studies, storm event types in Mobile were characterized more generally, including the meteorological conditions leading to, and experienced during, each type of storm. Storm events in Mobile have been characterized into two types corresponding to the sections below: (1) mid-latitude storms and thunderstorms, and (2) tropical storms and hurricanes.

Mid-Latitude Storms and Thunderstorms

Mid-latitude storms and thunderstorms are a common occurrence in Mobile during the summer months. The southerly direction of the prevailing wind transports warm moist air from the Gulf of Mexico into southern Alabama. This warm moist air rises into the atmosphere, condenses, and creates air-mass thunderstorms.

In the summer, it is unusual for these air-mass thunderstorms to develop into severe thunderstorms. These thunderstorms occur locally and are missing a few key ingredients: wind shear; a strong trigger for significant uplift of warm, moist air; and divergence aloft. These summer air-mass thunderstorms are not associated with tornadoes.¹³³

¹³³ Tornadoes have been observed with severe weather such as severe thunderstorms and tropical cyclones.

In the spring and fall months, however, these key ingredients are available: a prevailing southerly wind providing a source of warm moist air, the periodic presence of cold fronts rolling into Alabama providing the necessary uplift mechanism, and, in some cases, the jet stream loops far into the southern United States providing significant divergence aloft. Severe thunderstorms tend to develop as much as 100 or more miles (160 or more kilometers) ahead of the cold front.¹³⁴

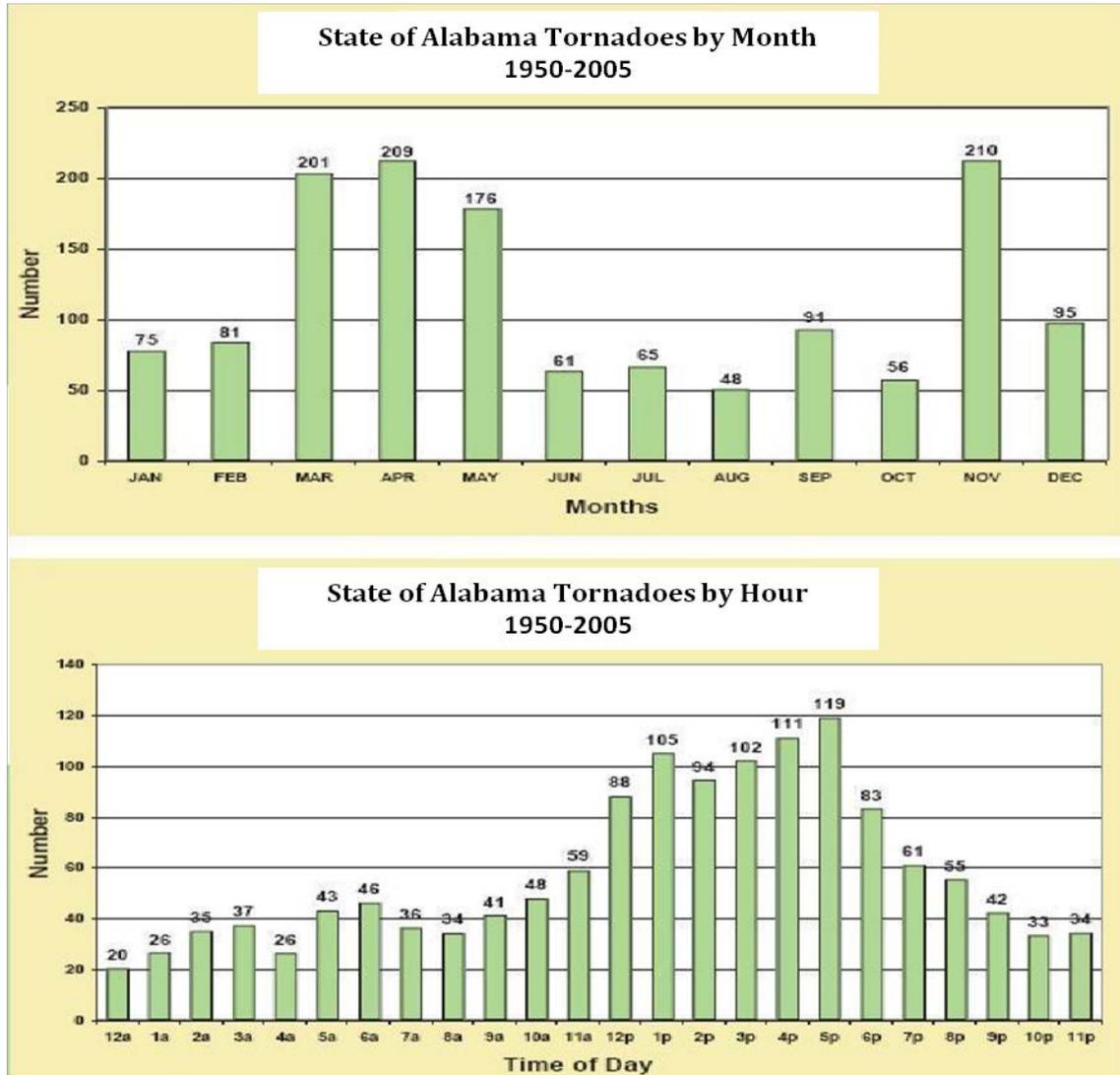
Severe spring thunderstorms are most common in March, April, and May between noon and 7:00PM, producing tornadoes, hail, and strong winds.¹³⁵ A second season of thunderstorms occurs in the fall, from late October through December with severe storms producing tornadoes. Tornadoes occur most often in November (see Figure 56). Hail may be present and, depending on the strength of the wind, may be particularly damaging. Table 21 presents a list of severe thunderstorms recently affecting Mobile.

¹³⁴ Williams, 1992

¹³⁵ Evans, 2009

Figure 56: Tornadoes by Month and Hour for the State of Alabama from 1950 to 2005

Source: RMS, 2009



The Role of the Jet Stream

The polar jet stream plays an important role in generating extreme storm events in Mobile, Alabama. The polar jet stream is a fast moving stream of air about 10,000 feet above the surface of the Earth, traveling from west to east across the United States. The jet stream occurs between cold northern Arctic air to the north and warm moist southern air to the south. Because storms draw much of their energy from temperature differences, this boundary between cold and warm air masses is a highly favorable location for storms. In addition, the jet stream acts as a source of vertical wind shear also highly favorable to storm development.

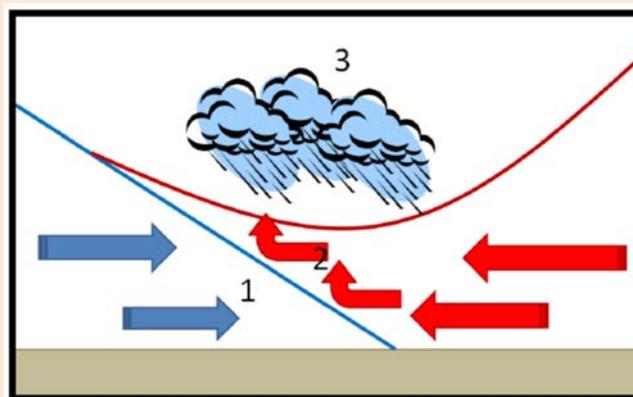
The polar jet stream can travel south towards Alabama from fall through winter and into early spring. The jet stream brings a cold front associated with a mid-latitude cyclone (or low pressure system) into Mobile about once per week. This cold front typically dominates the weather for several days and is replaced by cold sunny days until the next cold front comes in.

When the jet stream travels south, air masses steered by the moving mid-latitude cyclone enter Alabama. A warm, dry air mass enters first. Being denser than the prevailing warm, moist air from the Gulf of Mexico, the warm, dry air mass pushes the warm moist air aloft, creating instability. The cold air mass enters Alabama next. Because the cold air mass tends to travel faster than the warm air mass, the cold front pushes less-dense warm air up as it advances, causing a rapid uplift (see Figure below). This can result in a squall line of severe thunderstorms that can spawn tornadoes. A squall line can last 12 hours or more.

Within this squall line, a supercell can be generated. A supercell is a long-lasting thunderstorm that brings flash flooding, damaging hail, wind, and families of tornadoes. Supercells tend to develop in late-winter and spring. A 150-mile (240-kilometer) wide tornado line from the southwest corner of Alabama to the northeast corner is the most active in the region for tornadoes.

An Example of the Boundary between Cold and Warm Air Masses and the Resultant Convection

Source: RMS, 2009



An example of a boundary between cold and warm air masses and the resultant convection: (1) First, cold air moves into warmer air and cuts beneath it; (2) then, warm air is forced to rise and overtops the encroaching cold air; and (3) finally, rising air creates clouds and stormy conditions.

Table 21: Recent Severe Thunderstorm Events Affecting Mobile, Alabama

Winter	Spring	Fall
<ul style="list-style-type: none"> ■ McIntosh Tornado, January 10, 2009 ■ Northwest Florida, South Alabama Tornado Event, February 17, 2008 ■ Super Tuesday Tornado Outbreak, February 6, 2008 	<ul style="list-style-type: none"> ■ Northern Choctaw County, AL, April 27, 2011 ■ Tornado Outbreak, April 15, 2011 ■ Tornado Outbreak and Flash Flood Event, March 9, 2011 ■ Central Baldwin County Storms, March 27, 2009 ■ Millers Ferry Tornado, March 1, 2007 ■ Southwest Alabama Severe Thunderstorm Outbreak, March 12, 2001 ■ Leakesville, MS Hailstorm Event, March 5, 1998 	<ul style="list-style-type: none"> ■ Red Oak Tornado, October 8, 2008 ■ South Mobile County Tornado, October 22, 2007 ■ Tornado Outbreak, November 15, 2006 ■ Baldwin County, AL Tornado, November 27, 2004 ■ Central Gulf Coast Tornado Outbreak, October 13, 2001 ■ Pensacola Tornado, October 18, 2007

Source: NOAA NWS, Mobile Office

Several other seasonal, non-tropical storm events can affect Mobile, Alabama. These events include snow, severe winter thunderstorms, sleet, extreme heat, extreme cold, drought, and fog.

Due to Alabama’s temperate climate, snow is rare in Mobile. Snow generally occurs due to northern Arctic air entering Alabama and hitting the warm, moist Gulf air.¹³⁶ Thunder and lightning during a snow event generally indicates that a strong low pressure system is pulling warm air from the Gulf of Mexico over the cold air at the surface.¹³⁷

Recent Seasonal, Non-Tropical Storm Events Affecting Mobile, Alabama

- Heavy rainfall event, April 4-5, 2008
- Damaging winds, February 12, 2008
- Rare snow storm, January 19, 2008
- Gulf Coast hard freeze, December 5, 2006
- New Year Snow , January 1, 2002

Severe thunderstorms can also occur during the winter, as evidenced by the occurrence of tornadoes.

Freezing rain can occur during the winter months when surface temperatures are low and raindrops freeze on impact.¹³⁸

¹³⁶ The prevailing southerly wind over Mobile County transports warm moist air from the Gulf of Mexico.

¹³⁷ Evans, 2009

¹³⁸ Evans, 2009

Periods of extreme heat, extreme cold, or even drought¹³⁹ can occur in Alabama when a stationary front stays in the area. The stationary front can shift the prevailing wind direction so that moist air from the Gulf does not enter Alabama. This occurs most frequently in the winter.¹⁴⁰ Conversely, during the summer months, drought can occur in Mobile when a high pressure system remains in the area for weeks and blocks the warm moist air from the Gulf.¹⁴¹

Finally, advection fog can impact Mobile during the winter months. Dense advection fog occurs as warm, moist air from the Gulf of Mexico travels over cold land.¹⁴²

Tropical Storms and Hurricanes

In the list provided by the Mobile NWS office (see textbox), all of the summer storm events classified as extreme are tropical storms and hurricanes.¹⁴³ Though the Atlantic hurricane season runs from June 1 through November 30, hurricanes primarily affect Alabama in May, June, mid-September, October, and November.¹⁴⁴ Warm sea surface temperatures (SST) from the Gulf Stream crossing a section of the Gulf of Mexico increase the likelihood that tropical cyclones will intensify and occur. This occurred in 2005 with Hurricanes Katrina, Rita, Wilma, and others.¹⁴⁵ Once developed, about 25% of Gulf-Atlantic tropical cyclones hit the mainland. Multiple strikes can occur within a given season.¹⁴⁶

Over the twentieth century, Alabama experienced 17 direct hits from hurricanes, including Frederic (category 4) at Dauphin Island in 1979, Ivan (category 3) in 2004.¹⁴⁷ Figure 57 illustrates the hurricanes and tropical storm strikes

Recent Tropical Storms and Hurricanes Affecting Mobile, Alabama

- Tropical Storm Lee, September 4, 2011
- Tropical Storm Ida, November 10, 2009
- Hurricane Ike, September 13, 2008
- Hurricane Gustav, September 1, 2008
- Tropical Storm Fay, August 23, 2008
- Hurricane Katrina, August 2005
- Hurricane Dennis, July 2005
- Hurricane Cindy, July 7, 2005
- Tropical Storm Arlene, June 11, 2005
- Hurricane Ivan, September 2004
- Tropical Storm Barry, August 2001
- Tropical Storm Helene, September 2000
- Tropical Storm Hermine, September 1998
- Hurricane Georges, September 1998
- Hurricane Danny, July 1997
- Hurricane Opal, October 1995
- Hurricane Erin, August 1995

Source: NOAA NWS, Mobile Office

¹³⁹ The definition of drought is relative to the location (“abnormal dryness”).

¹⁴⁰ Evans, 2009

¹⁴¹ Ibid.

¹⁴² Lutgens and Tarbuck, 2007

¹⁴³ Mobile, Alabama regularly experiences localized “air-mass” thunderstorms during the summer months. Though these storms can be problematic to the operations of the transportation system, the local weather service does not classify these thunderstorms as extreme.

¹⁴⁴ Evans, 2009

¹⁴⁵ RMS, 2009

¹⁴⁶ Ibid.

¹⁴⁷ Evans, 2009; NOAA 2011g Historical Hurricane Tracks Tool; Chaney, P. 2007.

experienced in Mobile since 1980. Alabama experiences a storm¹⁴⁸ that originated in the tropics approximately every 1.5 years. Hurricanes impact Alabama about every 7.5 years.

Figure 57: Storm Tracks of Hurricanes and Tropical Storms that Have Impacted Mobile, Alabama over the Past 15 Years

Source: NOAA Historical Hurricane Tracks Tool (<http://csc-s-maps-q.csc.noaa.gov/hurricanes/viewer.html>)

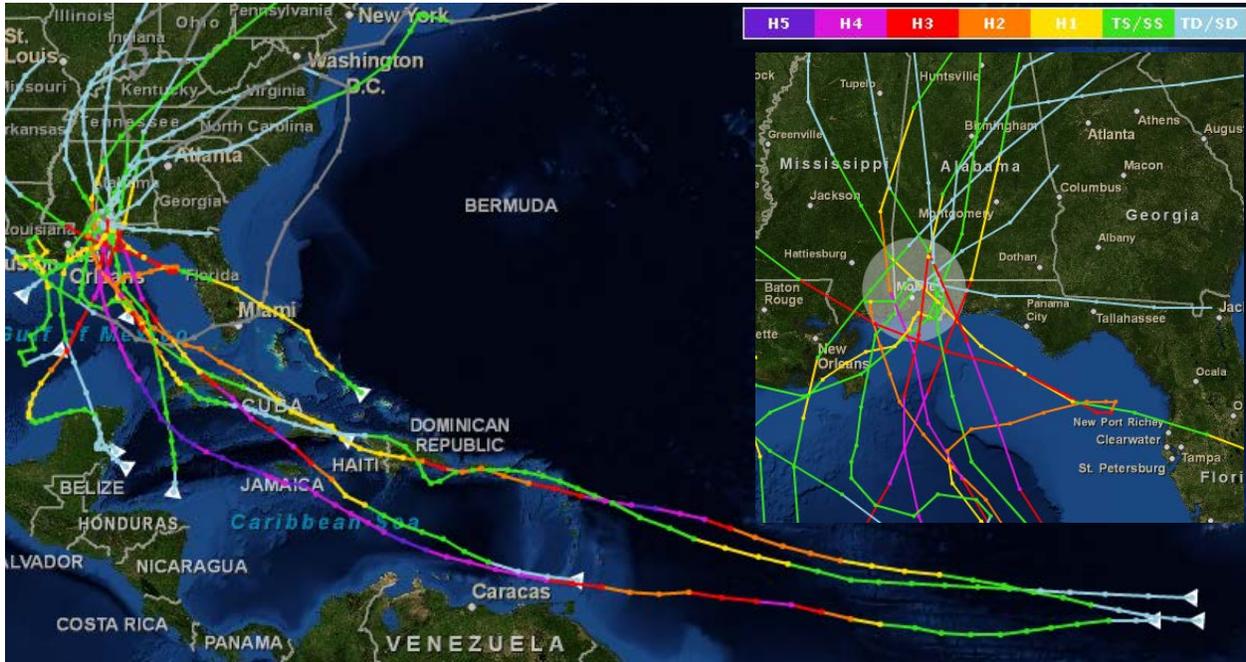
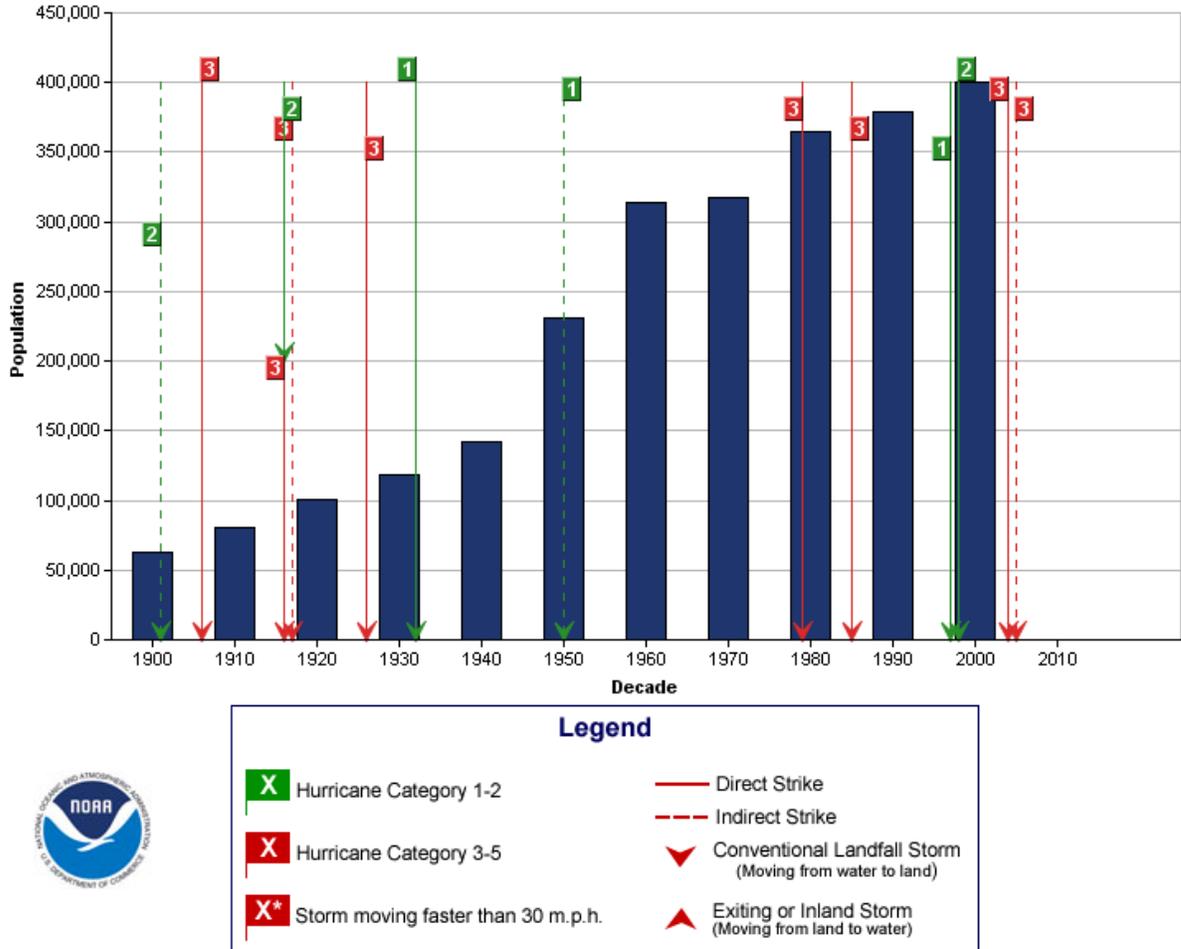


Figure 58 displays the timing of hurricane strikes in relationship to the population of Mobile County, Alabama. The hurricanes are marked by category number with green labels for category 1 and 2 hurricanes, and red labels for stronger hurricanes. The population of the county represented by the bars has increased substantially since 1900, increasing more than 50% from 1940 to 1960. A number of direct and indirect hurricane strikes occurred between two time periods: 1900 to 1930 and 1980 to 2000. The figure suggests more hurricane strikes have occurred in the past few decades (1980-2000) than during any previous twenty-year period in the twentieth century.

¹⁴⁸ Chaney, 2007

Figure 58: Hurricane Strikes vs. Population for Mobile, Alabama

Source: NOAA Historical Hurricane Tracks Tool (<http://csc-s-maps-q.csc.noaa.gov/hurricanes/viewer.html>)



Hurricane Strike Data: National Hurricane Center
 Population Data: U.S. Census Bureau

Storm surge associated with tropical storms and hurricanes can cause significant coastal damage. A recent study developed storm surge return periods for the U.S. Gulf Coast based on an analysis of available data and other information dating back to 1880.¹⁴⁹ A surge database, SURGEDAT, provides the results of this analysis. Table 22 summarizes the findings in SURGEDAT for Alabama and the western Florida Panhandle.

¹⁴⁹SURGEDAT divides the U.S. Gulf Coast into 10 regions. The data was constructed from 62 sources, including 28 Federal Government sources, numerous academic publications, and more than 3,000 pages of newspaper from 16 daily periodicals. For each region, the Southern Regional Climate Center (SRCC) linear regression method, a log-linear regression method, was utilized to estimate basin-wide and sub-regional surge water levels for the 10-year, 25-year, 50-year, and 100-year return periods. (Personal Communication with H.F. Needham, based on an analysis of data in Needham and Keim, 2011.)

Table 22. Storm Surge Return Periods for Alabama and Western Florida Panhandle¹⁵⁰

10-year	25-year	50-year	100-year
2.3 m (7.6 feet)	3.8 m (12.5 feet)	4.9 m (16.2 feet)	6.1 m (19.9 feet)

Case Studies

As discussed in the methodology section above, five different storm events were analyzed to identify the key characteristics of the storms and associated damages in Mobile. These storms represent a sampling of the different types of storms that Mobile experiences, including a thunderstorm and tornado event, a hailstorm, a heavy rain event, Hurricane Georges, and Hurricane Katrina. The case studies are summarized in detail in Appendix D.6. Abbreviated summaries are presented in this section.

Case Study 1: Severe Thunderstorms and Tornado Outbreak, November 15, 2006

Storm Development

Severe thunderstorms strong enough to produce six tornadoes struck the Mobile region on November 15, 2006.¹⁵¹ These thunderstorms developed due to a strong southerly jet stream aloft that steered a low pressure system into Alabama. Key meteorological conditions for this storm’s development were: (1) a strong jet stream aloft, (2) a surface cold front associated with a low pressure system, and (3) warm, moist surface air. As detailed earlier, this is a typical example of a severe storm event in Mobile, Alabama.

Storm Highlights

- Severe thunderstorms produced six tornadoes
- Wind gusted at over 50 mph
- Five flash warnings were issued
- Rain totaled up to 8 inches across the region
- Most rain fell in a 3-6 hour window

Storm Damage

Strong winds and tornadoes caused the majority of storm damage. Debris, fallen trees, and downed power lines blocked roadways. Flooding also impacted transportation infrastructure. The NWS estimates the storm’s six tornadoes caused \$0.5 million to \$1 million of damage.¹⁵²

Extreme Event Comparison

- **Observed 24-Hour Precipitation:** greater than a 2 year event
- **Observed Peak Discharge:** greater than a 2 year event
- **Observed Storm Surge:** less than a 10 year event

¹⁵⁰ Source: Personal Communication with H.F. Needham based on an analysis of data in Needham and Keim, 2011

¹⁵¹ NWS, 2009a. NWS Forecast office of Mobile/Pensacola analysis of this storm event.

¹⁵² Ibid.

Case Study 2: Severe Hailstorm, March 5, 1998

Storm Development

Thirteen severe thunderstorms developed in the Mobile region on March 5, 1998. The storms brought hail ranging from the size of a dime to the size of a baseball.¹⁵³ Key meteorological conditions leading to the storm's development include: (1) a strong west-to-east jet stream aloft, (2) cold, dry air in the middle layer of the atmosphere, (3) vertical wind shear, (4) strong potential for convective thunderstorms,¹⁵⁴ and (5) a high pressure system over Florida that brought warm, moist air into Alabama.

Storm Highlights

- Over 8 inches of rainfall in 15 hours

Storm Damage

This storm caused about \$60,000 of damage in the Leakesville area.¹⁵⁵ The severe hail chipped paint, dented house siding, stripped trees, destroyed satellite dishes,¹⁵⁶ and damaged vehicles.¹⁵⁷

Extreme Event Comparison

- **Observed 24-Hour Precipitation:** less than a 2 year event
- **Observed Peak Discharge:** less than a 2 year event
- **Observed Storm Surge:** less than a 10 year event

Case Study 3: Heavy Rain Event, April 4-5, 2008

Storm Development

On April 4, 2008 a line of intense storms moved east across central Alabama producing significant rainfall in the Mobile region. Key meteorological conditions leading to the storm include: (1) strong upper level north-to-south winds slowly steering a surface-level cold front into Mobile, (2) warm, moist air from the Gulf that was pulled into Mobile ahead of the cold front, (3) vertical wind shear,¹⁵⁸ and (4) a strong jet stream aloft.

Storm Highlights

- Severe hail 0.5 to 2 inches in diameter caused damage to houses and cars

¹⁵³NWS, 2009b. Forecast office of Mobile/Pensacola analysis of this storm event.

¹⁵⁴Ibid. Also evident was a 'dip' in the zonal air flow over Arkansas and Louisiana at 700 mb (air situated at 700 mb is between the surface and 500 mb).

¹⁵⁵ NWS, 2011b.

¹⁵⁶ Ibid.

¹⁵⁷ Ibid.

¹⁵⁸ NWS, 2011c.

Storm Damage

Heavy rain caused flooding in the streets of downtown Mobile, submerging vehicles,¹⁵⁹ and overwhelmed two wastewater pumping stations, causing over 13 million gallons (49 million liters) of sewage to spill into Mobile Bay.¹⁶⁰ The storm also downed trees and power lines, causing 7,600 homes to lose power.¹⁶¹ Across Alabama, resulting tornados damaged trees and buildings.

Extreme Event Comparison

- **Observed 24-Hour Precipitation:** approximately a 5 to 15 year event
- **Observed Peak Discharge:** less than a 2 year event
- **Observed Storm Surge:** less than a 10 year event

Case Study 4: Hurricane Georges, September 28, 1998

Storm Track and Intensification

Hurricane Georges began as a tropical depression on September 15, 1998, four hundred miles south-southwest of Cape Verde.¹⁶² As the storm traveled westward, it steadily intensified, developing into a tropical storm on September 16, reaching hurricane strength by September 17, and peaking on September 19, as a Category 4 storm with winds of 150 miles per hour (240 kilometers per hour).¹⁶³ Hurricane Georges caused damage in Puerto Rico, the Dominican Republic, Haiti, and Cuba, weakened at one point by the mountainous terrain of the Dominican Republic and Haiti.

Hurricane Georges entered the Gulf of Mexico on September 25, traveling north-northwest at an average speed of 11 miles per hour (18 kilometers per hour).¹⁶⁴ The storm began to strengthen as it moved into the warm waters of the Florida Straits moving in a west-northwest track. Sea surface temperatures in the Gulf near the track of Hurricane Georges were estimated to be 81.7°F (27.6°C).¹⁶⁵ This is close to the minimum sea surface temperatures of 82°F (28°C) typical for a storm to develop and maintain its strength.¹⁶⁶

¹⁵⁹ CNN, 2008

¹⁶⁰ Smith, 2008

¹⁶¹ Gordon, 2008

¹⁶² U.S. Army Corps of Engineers, 1999

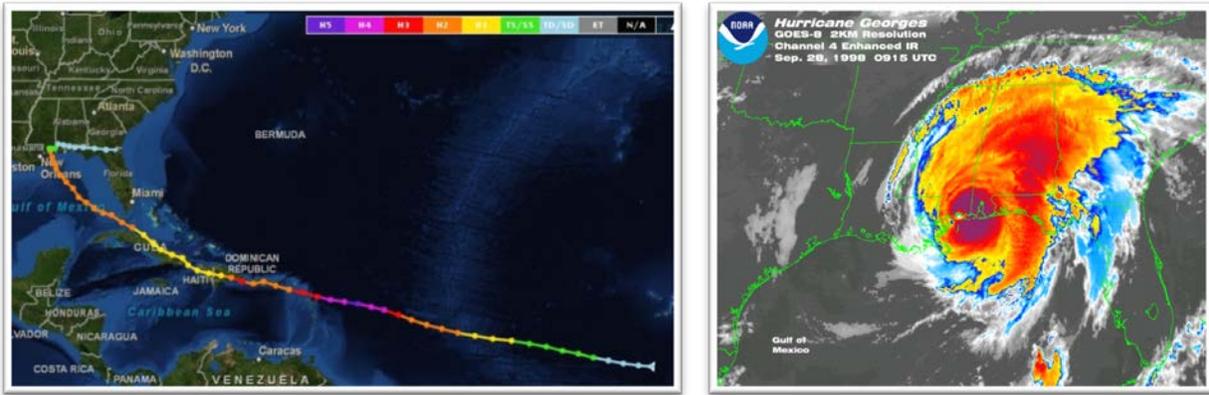
¹⁶³ Ibid.

¹⁶⁴ United States Department of the Interior, 2000

¹⁶⁵ Ibid. The sea surface temperatures were averaged from Sea-Viewing Wide field-of Sensor (seaWiFS) satellite data.

¹⁶⁶ NASA, 2003

Figure 59: Storm Track of Hurricane Georges (left) and Infrared Image of Georges (right)¹⁶⁷



Georges made U.S. landfall near Biloxi, Mississippi around 6:30 am on September 28 as a Category 2 storm. The storm moved slowly over land and reached Mobile in the early morning of September 29.¹⁶⁸ Because the storm moved so slowly, Alabama experienced significant torrential rains and coastal storm inundation.¹⁶⁹

Storm Damage

Hurricane Georges caused severe flooding along the Gulf Coast from Mississippi to Florida, including the Mobile region. Downtown Mobile was heavily flooded as a result of heavy precipitation and high storm surge. This resulted in inundated and blocked roadways. The Mobile Bay Causeway was fully inundated, disabling transportation across the bay between Mobile and Baldwin Counties.

Extreme Event Comparison

- **Observed 24-Hour Precipitation:** approximately a 10 year event
- **Observed Peak Discharge:** 25 year event
- **Observed Storm Surge:** above a 10 year event

Case Study 5: Hurricane Katrina, August 29, 2005

Storm Track and Intensification

Hurricane Katrina was one of the most destructive hurricanes to hit the United States.^{170,171} The storm formed from the combination of a tropical wave, an upper-level trough, and the mid-level

¹⁶⁷ Figure 59 shows Georges' storm track approaching the Gulf Coast, where the color denotes the storm's Saffir-Simpson intensity rating (NOAA, 2011g). The image at the right is an enhanced infrared image of Georges that provides an illustrative demonstration of the shape and activity of the storm soon after hitting land (NOAA, 2011h).

¹⁶⁸ Though Biloxi is just 60 miles from Mobile, they have different shoreline characteristics. Biloxi sits directly on the Gulf of Mexico, while Mobile is inset on Mobile Bay, with some barrier islands between the Gulf and the inlet. The differences may affect storm surge and so the locations are considered separately in this analysis.

¹⁶⁹ U.S. Army Corps of Engineers, 1999

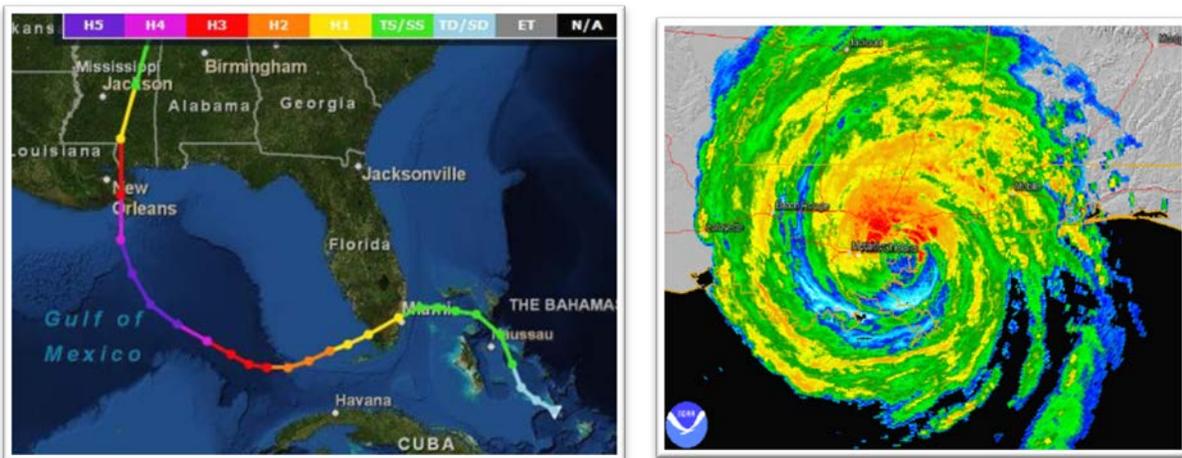
¹⁷⁰ NOAA, 2005a

¹⁷¹ NOAA, 2005b

remnants of Tropical Depression Ten.¹⁷² Hurricane Katrina began its early development on August 23 as a tropical depression about 175 miles (280 kilometers) southeast of Nassau, Bahamas.¹⁷³ On August 24, the tropical depression became a tropical storm as it moved towards the Bahamas.¹⁷⁴ In the early evening of August 25, the storm strengthened to a Category 1 hurricane with sustained winds of 80 miles per hour (128 kilometers per hour) before making landfall in Florida between Hallandale Beach and North Miami Beach.¹⁷⁵ Hurricane Katrina crossed the tip of Florida overnight and began to re-intensify over the warm Gulf waters (sea surface temperatures were 2°F to 4°F (1°C to 2°C) above normal).¹⁷⁶

From August 25 to August 31, Hurricane Katrina slowly turned north-northwest. As Hurricane Katrina moved again towards landfall, Katrina intensified due to upper atmosphere conditions, above-normal sea surface temperatures, and less-than-normal vertical wind shear. On August 28, Hurricane Katrina became a Category 5 hurricane with peak winds speeds near 175 miles per hour (280 kilometers per hour) and a central pressure of 902 millibars. The storm extended about 105 miles (168 kilometers) from its center, with tropical storm force winds extending out another 100 miles (160 kilometers).

Figure 60: Storm Track and Infrared Image of Hurricane Katrina



On the morning of August 29, Hurricane Katrina made landfall in Plaquemines Parish, Louisiana as a strong Category 3 hurricane with wind speeds of about 127 miles per hour (203 kilometers per hour) and a central pressure of 920 millibars. After returning back to sea, Hurricane Katrina made its final landfall near the Louisiana-Mississippi border with winds reported at near 121 miles per hour (194 kilometers per hour).

¹⁷² NOAA, 2005b

¹⁷³ Ibid.

¹⁷⁴ Ibid.

¹⁷⁵ Ibid.

¹⁷⁶ NOAA, 2005a

Storm Damage

Mobile County experienced significant damage from Hurricane Katrina, primarily in the form of coastal flooding and storm surge. Storm surge on Dauphin Island destroyed or damaged dozens of homes.¹⁷⁷ In the city of Mobile, flood depths of 11 to 12.5 feet (3.4 to 3.8 meters) caused severe inundation and incapacitation of most major roadways.¹⁷⁸ Downtown Mobile was entirely inundated, causing authorities to issue a dusk-to-dawn curfew. The Mobile Bay Causeway was fully inundated, disabling transport across the bay.¹⁷⁹ Katrina also caused debris damage from oil rigs in the Mobile area. Dauphin Island experienced damage from an offshore oil rig that washed up on the shore. An oil rig under construction along the Mobile River was dislodged and carried 1.5 miles (2.4 kilometers) north where it struck the Cochrane Bridge just north of downtown Mobile.¹⁸⁰

Extreme Event Comparison

- **Observed Precipitation:** less than a 2 year event
- **Observed Peak Discharge:** less than a 2 year event
- **Observed Storm Surge:** 25 year event

7.2. Projected Storm Events

An analysis of future storm events was conducted to evaluate how storms could change in the future, and how Mobile's transportation could be exposed to storm surge. This section describes the methodology and key findings for the analysis of future storm events in the Mobile region. The analysis of future storm events is presented in two sections, corresponding to the two analyses that were conducted:

- Literature Review of Changes in Storm-Producing Atmospheric Phenomena
- Scenario- and Model-Based Analysis of Hurricane Storm Surge and Waves

7.2.1. Literature Review of Changes in Storm-Producing Atmospheric Phenomena

A literature review was conducted to help inform understanding of how storms could change in the Mobile region in the future due to climate change.

Methodology

The analysis of historical storm events experienced in the Mobile region highlighted which atmospheric phenomena contributed to the severity of each storm event. To help to characterize future storm events, a literature review of studies projecting how these atmospheric phenomena may change was conducted. This review provides clues as to how the frequency, duration, and intensity of storm events in the Mobile region may change.

¹⁷⁷ FEMA, 2006a

¹⁷⁸ Ibid.

¹⁷⁹ Ibid.

¹⁸⁰ Knabb et al., 2006

Key Findings

Key Findings for Storm Event Literature Search

- Many studies suggest a poleward shift of the jet stream, which would reduce the frequency of some mid-latitude storms around Mobile.
- Intensity and/or frequency of extreme localized convective activity may increase.
- It is difficult to predict the impacts of climate change on hurricane activity due to conflicting changes in atmospheric phenomena.

This section presents key findings from the literature review of studies projecting how storm-related atmospheric phenomena affecting Mobile may change. The findings are presented in two parts: (1) severe thunderstorms and seasonal events, and (2) tropical storms and hurricanes. Appendix D.7 presents an overview of how storm events may change in the United States and globally.

Mid-latitude storms and thunderstorms

While studies project an overall increase in extra-tropical storm severity in the eastern United States,¹⁸¹ no studies were found that focused specifically on the Southeastern United States or the Mobile region. Therefore, future changes in Mobile storm events were investigated through studies that discuss how the atmospheric phenomena affecting the storm events may change.

- *Jet Stream.* The jet stream can steer and intensify severe thunderstorms affecting Mobile. Many studies suggest a poleward shift of the jet stream. This would result in a northward shift in the mid-latitude storm track and reduce the frequency of some mid-latitude storm activity around Mobile.¹⁸²
- *Convective Activity.* Scientists suggest that convective storms may increase in intensity due to increased atmospheric moisture content, and frequency due to increasing summer minimum temperatures.¹⁸³ Trapp et al. (2007)¹⁸⁴ projects an increase in the environmental conditions conducive to severe thunderstorms in the spring and summer in the Mobile area. For example, vertically integrated buoyant energy and specific humidity are projected to increase with minimal increase in vertical wind shear. For the Mobile region, Figure 61 illustrates the increase in the number of days of severe thunderstorm environment (NDSEV) from the 1962-1989 time period to the 2079-2099 time period for the spring months (up to 1 additional day) and summer months (more than 2 additional days).¹⁸⁵

¹⁸¹ Del Genio et al., 2007; Trapp et al., 2007 and 2009; Van Klooster et al., 2009

¹⁸² Archer and Caldeira, 2008; Frierson et al., 2007; Hu and Fu, 2007; Lorenz and DeWeaver, 2007; Lu et al., 2007; Ulbrich, 2009; Yin, 2005

¹⁸³ USCCSP, 2008a

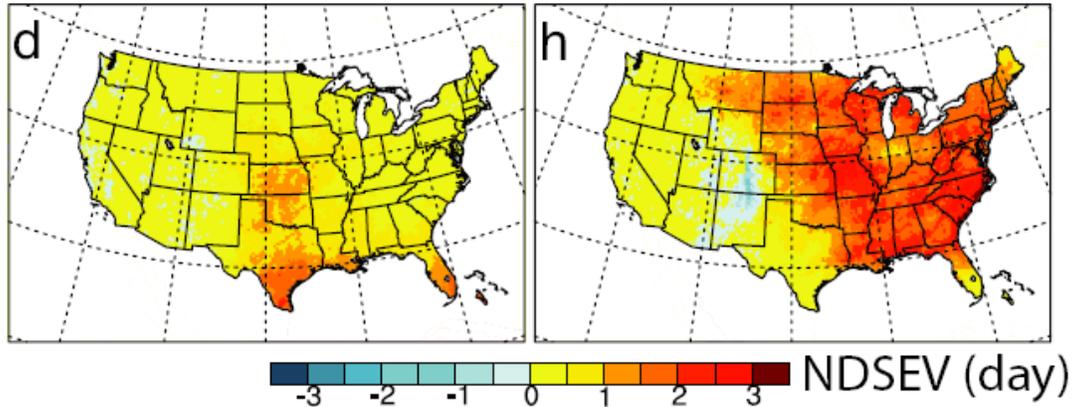
¹⁸⁴ The study provides projections of environmental conditions that support severe U.S. thunderstorms using a high resolution regional climate model under a moderately-high (A2) emission scenario.

¹⁸⁵ These findings were compared to simulations of three climate models, MPI ECHAM5, GFDL CM2.1, and NCAR CCM3. All models demonstrated a similar directional trend for the Mobile region; however, the increase in NDSEV did vary from approximately 1 day in summer simulated by NCAR CCM3 to more than 3 days simulated by MPI ECHAM5. Overall, the findings provided in this study suggest an increase in NDSEV but with some uncertainty across models regarding the magnitude of the increase.

These findings suggest that Mobile may experience less mid-latitude storm events as the jet stream moves north, but that this decrease in activity may be compensated by an increase in the intensity and/or frequency of extreme localized convective activity.

Figure 61: Change (1962-1989 to 2079-2099) in the Number of Days with Local Formation of Thunderstorms that Could Produce Significant Winds, Hail, and/or Tornadoes, for a Moderately-High (A2) Emission Scenario in Spring (d) and Summer (h)

Source: Trapp et al. 2007



Hurricanes and Tropical Storms

As discussed in FHWA (2010), there is some disagreement amongst scientists about how tropical storms and hurricanes may change in response to changes in climate. Further, it remains uncertain whether past changes in tropical storm activity were influenced by natural variability or human activity.¹⁸⁶ The development of these storms has been linked to the presence of two important factors: low vertical wind shear but high SST.¹⁸⁷

- *Vertical Wind Shear.*¹⁸⁸ Vertical wind shear in the tropical Atlantic Ocean is projected to increase, which would reduce the development of tropical storms and hurricanes that reach the Gulf.¹⁸⁹
- *Relative Sea Surface Temperature (SST).* Under a moderate (A1B) emission scenario, SSTs in the Gulf of Mexico are projected to significantly warm by the end of the century, which could lead to increased intensification of tropical storms and hurricanes entering the Gulf.¹⁹⁰

However, these two competing factors make it difficult for hurricane experts to conclusively agree on how hurricane activity may change.

The recent scientific consensus on hurricane activity suggests hurricanes may globally decrease in frequency but increase in intensity. This consensus suggests that the globally averaged intensity of storms originating in the tropics will increase by 2 to 11% by the end of the century

¹⁸⁶ Knutson et al., 2010; USCCSP, 2008c

¹⁸⁷ Bender et al., 2010; Garner et al., 2009; Vecchi and Soden, 2007

¹⁸⁸ Vertical wind shear refers to how much the wind changes in speed and direction with vertical height.

¹⁸⁹ Vecchi and Soden, 2007

¹⁹⁰ Muhling et al., 2011

but the globally averaged frequency will decrease by 6 to 34%.¹⁹¹ This suggests a future decrease in overall hurricane number, but an increase in the severity of the hurricanes that do develop. Peduzzi et al. (2012) found that over the next 20 years, the mortality risk associated with the projected changes in tropical storms and hurricane activity increases due to the increase in both the intensity of the storm and demographic pressures, despite the reduction in the frequency of these storms and the potential progression in development and governance.

7.2.2. Scenario- and Model-Based Analysis of Hurricane Storm Surge

A scenario-based analysis of storm surge from hurricanes was also conducted; this analysis sought to answer two main questions:

- What are the implications of a moderate hurricane striking the region under a scenario of increased sea level?
- What are the implications of a strike by a larger hurricane than the region has experienced in recent history?

Methodology

To answer these questions, the storm surge inundation from 11 plausible storm scenarios was modeled. These 11 scenarios were developed using Hurricane Georges and Hurricane Katrina—two damaging storms that affected Mobile in recent history—as base storms, and then adjusting certain characteristics of the storm parameters to simulate what could happen under alternate conditions. This scenario approach was used to manage the uncertainty in quantitatively estimating how increases in atmospheric greenhouse gas concentrations are linked to future changes in hurricane characteristics.¹⁹²

Environmental implications of the selected storm scenarios were assessed using state-of-the-art quantitative models. The scenario- and model- based analysis included the following steps:

- Selection of storm surge scenarios
- Advanced circulation modeling
- Advanced circulation model testing
- Wave modeling
- Exposure mapping

For more detail, see Appendix D.8.

¹⁹¹ Knutson et al., 2010

¹⁹² A scenario-based analysis is a standard approach in the face of “deep uncertainty” associated with environmental or other challenges relating to future conditions. The scenarios used in this analysis, which are reflective of the state-of-the-science, are not predictions. Rather, the scenarios represent conditions that may occur, thereby encompassing a representative range of possible future conditions.

Selection of Storm Surge Scenarios

The first step of the scenario-based analysis was to select scenarios to represent a wide range of storms that could plausibly strike Mobile. For this analysis, records from historic storms were selected to use as the basis in developing these storm scenarios. There were two main questions that the scenario-based analysis attempted to address:

1. *What are the implications of a moderate hurricane striking the region under a scenario of increased sea level?* According to the Gulf Coast Phase 1 report, planners in the Gulf Coast region can expect a Category 1 or 2 hurricane approximately once every five years.¹⁹³ A set of scenarios was developed to examine the extent of flooding from such storms when exacerbated by sea level rise.
2. *What are the implications of a strike by a larger hurricane than the region has experienced in recent history?* Although the odds of an intense hurricane strike are difficult to determine, those odds are likely increasing.¹⁹⁴ A set of scenarios was developed to examine the implications of hurricanes that are larger in magnitude than recently experienced in the study area, but that will become more likely in the future. This was done by selecting a storm that occurred relatively recently, and intensifying it using different methods (described below) and including the effects of sea level rise.

In selecting the storms, historical storms were chosen that met the following criteria:

- Local tide gage data are available throughout most of the course of the storm.
- Post-storm high water mark data are available in the Mobile area.
- The storm approached the coast relatively perpendicularly.
- The strengths of the storms and their storm surges were appropriate to the two questions being addressed.

After reviewing records of all land-falling hurricanes in the Mobile area over the past few decades, the 1998 Hurricane Georges was selected to address Question #1, and the 2005 Hurricane Katrina was selected to address Question #2.

Using Hurricanes Georges and Katrina as base storms, 11 storm scenarios (see Table 23) were developed by adjusting certain characteristics of the storm parameters to simulate what could happen under alternate conditions. For the Georges simulations, all four sea level rise scenarios (0 meters (0 feet), 0.3 meters (1.0 foot), 0.75 meters (2.5 feet), and 2.0 meters (6.6 feet)) were examined. For the Katrina simulations, the modeling considered different adjustments, including shifting the path of Katrina so that it hit Mobile directly, intensifying the storm, and adding in 0.75 meters (2.5 feet) of sea level rise. Subsidence was not included in the storm surge analysis scenarios. Two of the 11 scenarios were hindcasts of Georges and Katrina. They were used to validate the model and to serve as a basis from which to build the other 9 scenarios.

¹⁹³ USCCSP, 2008a

¹⁹⁴ Karl et al., 2008

Table 23: Storm Scenarios

Name	Sea level rise	Track Shift	Amplification	Question Addressed ¹⁹⁵
Georges-Natural	None	No	None	Baseline
Katrina-Natural	None	No	None	Baseline
Georges-Natural-0.3m	0.3 m	No	None	(1)
Georges-Natural-0.75m	0.75 m	No	None	(1)
Georges-Natural-2.0m	2.0 m	No	None	(1)
Katrina-Natural-0.75m	0.75 m	No	None	(1), (2)
Katrina-Shift¹⁹⁶	None	Yes	None	(2)
Katrina-Shift-0.75m	0.75 m	Yes	None	(2)
Katrina-Shift-ReducedPress-0.75m	0.75 m	Yes	Central pressure reduced according to Knutson and Tuleya (2004) ¹⁹⁷	(2)
Katrina-Shift-MaxWind	None	Yes	Max. wind speed sustained through landfall ¹⁹⁸	(2)
Katrina-Shift-MaxWind-0.75m	0.75 m	Yes	Max. wind speed sustained through landfall	(2)

¹⁹⁵ The two questions being addressed are: (1) What are the implications of a moderate hurricane striking the region with a higher sea level? (2) What are the implications of a strike by a larger hurricane than the region has experienced in recent history?

¹⁹⁶ The term “shift” indicates an eastward shift of the storm track. This is used to explore the potential for a direct hit of a major hurricane on the Mobile area. See Appendix D.8.1 for more details.

¹⁹⁷ The term “ReducedPress indicates that the central pressure of the storm along its entire track was reduced by 14% according to the findings of Knutson and Tuleya (2004), which assessed the potential intensification of hurricanes due to an increase in atmospheric greenhouse gas concentrations. The central pressure of the storm is a measure of the storm’s intensity: the lower the pressure, the more intense the storm. See Appendix D.8.1 for more details.

¹⁹⁸ The term “MaxWind” indicates that the wind speeds were held constant at the values they had when the storm’s maximum sustained wind speed of approximately 150 knots was recorded in the central Gulf of Mexico on August 28, 2005. See Appendix D.8.1 for more details.

Figure 62: Original Track of Hurricane Katrina

The image shows the observed track of Katrina used in the “Natural” scenarios. Each dot represents the approximate location of NOAA’s National Hurricane Center 6-hour advisory bulletin used in the model simulations. kph = knots per hour. Times are UTC.

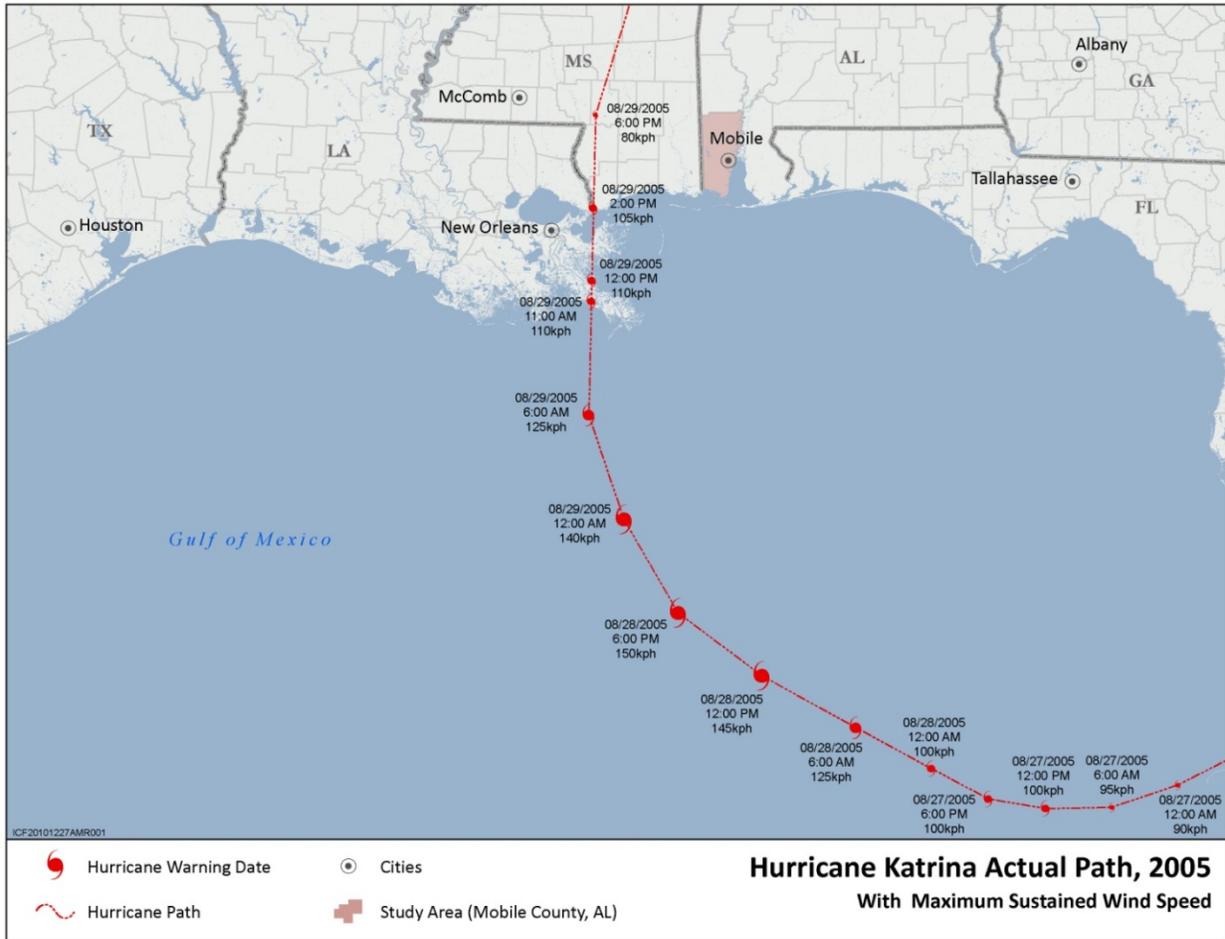


Figure 63: Shifted Track of Hurricane Katrina

This image shows the shifted track of Katrina that corresponds to the five “shift” scenarios explored in this study.



Advanced Circulation Modeling

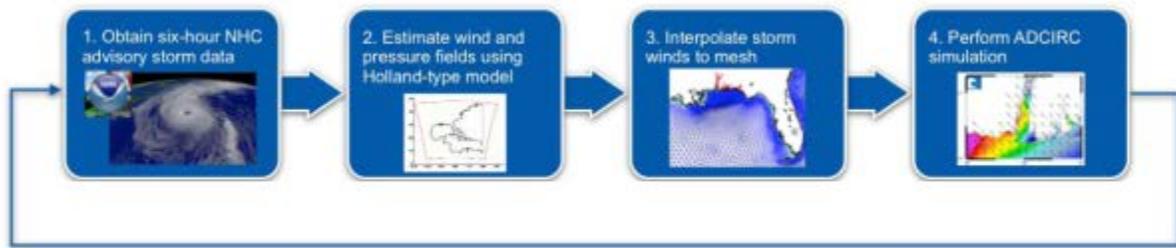
Simulations of storm-induced water levels (i.e. storm surge) were performed using the ADvanced CIRCulation model, ADCIRC.¹⁹⁹ This finite-element hydrodynamic code is robust, well-developed, extensively-tested, and highly adaptable to a number of coastal-ocean processes. The storm simulations were performed using the two-dimensional, depth integrated (2DDI) form of ADCIRC assuming barotropic forcing only (i.e. no density-driven flows). While the ADCIRC model is capable of applying a variety of internal and external forcings, including tidal forces and harmonics, inflow boundary conditions, density stratification, and wave radiation stresses, only the meteorological forcing input is used here to drive the storm-induced flows and water levels.

The ADCIRC storm simulations are driven by meteorological forcing data extracted from six-hour advisory forecast and observation reports issued by the NOAA National Hurricane Center (NHC). Meteorological data must be assembled in a modified Automated Tropical Cyclone

¹⁹⁹ Luettich et al., 1992; Luettich and Westerink, 2004; Westerink et al., 1994

Forecast (ATCF) best track format. An asymmetric hurricane vortex formulation²⁰⁰ based on a Holland-type gradient wind model²⁰¹ is used to estimate the wind and pressure field of the storm. The Garratt (1977) formula is used to convert wind speed to an applied wind stress. These data are spatially interpolated onto the ADCIRC mesh (see Appendix D.8 for more information), and a linear interpolation is used to map six-hour advisory data to each intermediate time that the model performs its calculations²⁰² falling between advisory information. A general schematic of this process is provided in Figure 64.

Figure 64: A Representative Model Schematic for Meteorological Coupling in ADCIRC Storm Simulations²⁰³



Advanced Circulation Model Testing

Hindcast simulations of storm-induced water levels using the ADCIRC hydrodynamic model were completed for Hurricanes Georges and Katrina to evaluate the model's ability to accurately reproduce the spatial distribution and peak storm-induced water levels of historical events. Results for ADCIRC are reported relative to Mean Sea Level. See Appendix D.8.3 for a description of testing.

Differences between the hindcast simulations and observations may be attributed to a number of simplifications, or assumptions, applied to the model scenarios or to deficiencies in the hydrodynamic model itself. These possible causes are listed below and described in detail in Appendix D.8.3:

- The hindcast simulations do not include the effects of the tide.
- The hindcast simulations do not include the effects of waves and wave breaking²⁰⁴.
- The hindcast simulations do not consider watershed contributions to the simulated storm surge hydrograph.
- The meteorological forcing used to drive the hindcast scenarios is a gross simplification of historical weather conditions and is limited further by the estimations of storm characteristics provided by the NHC advisory bulletins.

²⁰⁰ Mattocks and Forbes, 2008; Mattocks et al., 2006

²⁰¹ Holland, 1980

²⁰² The model computes all parameters.

²⁰³ After Blain et al., 2007

²⁰⁴ When a wave breaks against the shore it runs a distance horizontally up the beach slope.

Wave Modeling

The wave characteristics accompanying each of the storm surge scenarios were simulated using a state-of-the-art model, STeady State spectral WAVE (STWAVE). It is a flexible, robust model for nearshore wind-wave growth and propagation. It is one of the most widely used models to compute waves in coastal environments, based on wind and bottom topography.

For each scenario, the STWAVE model was run following the ADCIRC model. The coupling between the models was asynchronous. In other words, the models were run separately and the wave fields did not influence surge estimates.

The wind fields used to drive STWAVE were derived from the Holland-type model that was used to drive the ADCIRC model. Waves were simulated over both open water and the land simulated to be inundated.

Dauphin Island currently helps to protect the mainland by attenuating waves generated out in the open Gulf. Some of that attenuation may be diminished if the topography of the island is reduced through erosion from prior storm wave action or through human actions. Following the 2010 Gulf oil spill, sediment was dug out from parts of the north side of Dauphin Island to build a berm on the south side, which was intended to keep oil from washing ashore. This had the effect of reducing the width of the island in places, which may have left it more vulnerable to breaching in future storms.²⁰⁵ These and potential future changes in morphology of the island are not taken into account in the simulations performed in this study.

Exposure Mapping

Finally, a Geographic Information System was used to overlay inundation under each of the storm surge scenarios on top of the critical assets defined in Task 1 of the Gulf Coast Study. This analysis accounts for the projected surge level and the elevations of each asset. This analysis considered the bare earth elevation of assets—that is, the elevation of the land on which the assets sit. It did not consider the height of the assets themselves.

²⁰⁵ Raines, 2012

Key Findings

Key Findings for Storm Surge Modeling

- Projected exposure of critical transportation assets to storm surge is much greater than exposure to long-term sea level rise.
- Future storm surge has the potential to greatly exceed any historical surges.
- The magnitude of the highest sea level rise scenario examined in this study is lower than the range of flooding that may occur due to future hurricanes. However, sea level rise will invariably increase the area of flooding from coastal storms.
- Critical port facilities are most exposed to storm surge, with the highest fractional extent of exposure.
- Pipelines are least exposed, with the lowest fractional extent of exposure.

This section presents the key findings from the scenario-based analysis of hurricane storm surge and waves. Results are presented in a series of figures and a table at the end of this section.

Figure 65 through Figure 75 present maps of the storm surge results produced by the ADCIRC model under each of the scenarios indicated Table 23. The storm surge maps indicate the depth of inundation relative to current dry ground. They also show the infrastructure deemed to be critical in Task 1 of this project.²⁰⁶

Table 24 shows the maximum water elevation at the ADCIRC node closest to the NOAA tidal station at the Mobile Docks.

Figure 76 through Figure 86 show the wave modeling results that correspond to the storm surge simulations. The waves simulated here exacerbate the surge: they represent the significant wave heights above the still-water level of the corresponding surge. In other words, the wave heights may be added to the surge heights shown in Figures 65 through 75. We show the two separately, in part, to illustrate the difference in the wave heights and surge. The effect of the waves will be quantitatively assessed in a subsequent task that will account for the effect of their kinetic energy on transportation structures as well as their contribution to scour.

Descriptions of key findings for each class of storm surge simulations (“natural,” “sea level rise,” and “intense”) follow.

The “Natural” Surge Simulations

As noted earlier in the Advanced Circulation Model Testing section of this report, the “natural” simulations of Georges and Katrina indicate relatively similar surge depths and extents. The maximum flooding depth at the Mobile Docks gage was simulated to be 11.32 feet (3.43

²⁰⁶ The maps also indicate parts of CR188, CR59, and the Cochrane Bridge as critical, in response to comments received from local stakeholders.

meters)²⁰⁷ above mean higher high water (MHHW²⁰⁸) in Georges and 12.41 feet (3.76 meters) above MHHW in Katrina (see Table 24).

This degree of flooding generated by these “natural,” unadjusted hurricanes is somewhat greater than the inundation from even the most extreme long-term sea level rise scenario (2.0 meters) considered in this report (see Figure 55). The flooded areas include all of the coastal wetlands in Mobile County, as well as Gaillard Island, Terrapin Island, and nearly all of Dauphin Island.²⁰⁹ Some of the low-lying areas along the waterfront and ports would also be inundated.

Wave heights are estimated at a few meters along the open bay shoreline and the open ocean, as well as in the wetlands to the north of I-10. Similar conditions are estimated for other wetlands with a direct fetch and close proximity to the ocean or bay. Wave heights in more inland inundated areas are estimated to be a meter or less. In general, wave heights will tend to scale in proportion to the depth of the water over the inundated land (lower depth implies lower wave heights).

A few interesting features are evident in all of the wave simulations. First, both Dauphin Island and Fort Morgan play a major role in reducing the wave energy entering Mobile Bay and striking the mainland. The reduction in wave heights from the south to the north sides of Dauphin Island and Fort Morgan is readily apparent. Second, the triangularly shaped low-wave feature to the southeast of Mobile Downtown Airport is created by the protective properties of Gaillard Island as well as the deeper water of the Bay’s shipping channels that produces less wave shoaling. The main shipping channel can be seen bisecting the east part of the Bay’s wave field from the west side.

The “Sea level Rise” Surge Simulations

The 0-meter (0 foot), 0.3-meter (1.0 foot), 0.75-meter (2.5 feet), and 2.0-meter (6.6 feet) GSLR scenarios for Georges were designed to address the question, *what are the implications of a moderate hurricane striking the region under a scenario of increased sea level?*

The analysis indicates that there are not large-scale difference between the “natural”, 0.3-meter (1.0 foot), and 0.75-meter (2.5 feet) Georges simulations. There are, however, distinctions that are likely noteworthy for transportation. For example, sea level rise could expand the flooded area downtown.

²⁰⁷ Three significant digits are reported here for the sake of completeness in documentation. However, the variability across the scenarios and the uncertainty associated with the model is so great that for transportation planning purposes only a small amount of credence should be placed in the second digit. The third digit is generally only useful in illustrating differences between scenarios.

²⁰⁸ MHHW at the Mobile Docks gage is 1.2 feet above the NAVD88 vertical datum. Therefore, one must subtract about 1.2 ft from these elevations to obtain the corresponding elevations above NAVD88.

²⁰⁹ The western two-thirds of Dauphin Island is so thin that the ADCIRC mesh does not permit inundation of it in order to avoid numerical instabilities that might otherwise arise. Thus, although the maps of storm surge shown here do not explicitly indicate any flooding on the western two-thirds of the island, the reader should assume that it is flooded in all of the scenarios. For the same reason as western Dauphin Island, small islands along the coast have not been included.

In the 2.0-meter (6.6 feet) Georges simulation, nearly all of the central downtown area is under water. The number of evacuation routes that would be under water also increase significantly. Table 24 indicates that the inundation levels at Mobile Docks correspond quite closely to the amount of assumed GSLR. This finding indicates that rather than performing additional ADCIRC model runs with multiple sea level rise inputs, higher water levels could have simply been added on to the original Georges storm simulation to generate relatively similar maps. This study did not rigorously assess the geographic applicability of this conclusion. However, for the purposes of a first-order analysis, it is likely a robust conclusion.

The “Intense” Surge Simulations

All of the Katrina shifted path scenarios were designed to address the question, *what are the implications of a hurricane striking the region that is larger than any in Mobile’s historical record?*

The maximum surge elevation at Mobile Docks from the “shifted” Katrina is 7.03 feet (2.13 meters) greater than the natural Katrina simulation. The magnitude of this surge corresponds very roughly to the magnitude of surge estimated from the Georges 2.0-meter (6.6 feet) scenario: 19.44 feet (5.89 meters) vs. 17.99 feet (5.45 meters). In addition, it is approximately what would be expected from the Katrina “natural” storm were it to occur on top of 2 meters of LSLR. In the shifted Katrina scenario, roughly a third of the area to the east of I-65, north of the downtown airport, and south of Chickasaw is inundated, as well as most of the area in Mobile County to the southeast of Bayou La Batre.

If the shifted Katrina scenario were to occur with sea level 0.75 meters (2.5 feet) higher, the surge at Mobile Docks is estimated to be 22.74 feet (6.89 meters). In addition to the flooding described above, nearly the entire stretch of Route 193 north of Mon Louis would be inundated. In addition, bands of flooding would reach west of downtown nearly to I-65.

If the shifted Katrina storm were to be more intense at landfall than the original storm, as per the “MaxWind” scenario (in which the maximum sustained wind speed at landfall is 150 knots), the surge at the Mobile Docks is estimated at 27.65 feet (8.38 meters). In this case, nearly all of the land to the east of I-65 would become flooded. Moreover, the water depths would be so great in many coastal areas that are currently dry ground that the waves could reach a few meters in height. Thus, structures more than 33 feet (10 meters) above sea level could be affected, including the downtown airport runways and hangars.

If the baseline local sea level under the “MaxWind” scenario was 0.75 meters (6.6 feet) higher, the surge at Mobile Docks is estimated at 31.02 feet (9.40 meters) and the inundation impacts would be correspondingly greater. Under the more conservative “ReducedPress” scenario (in

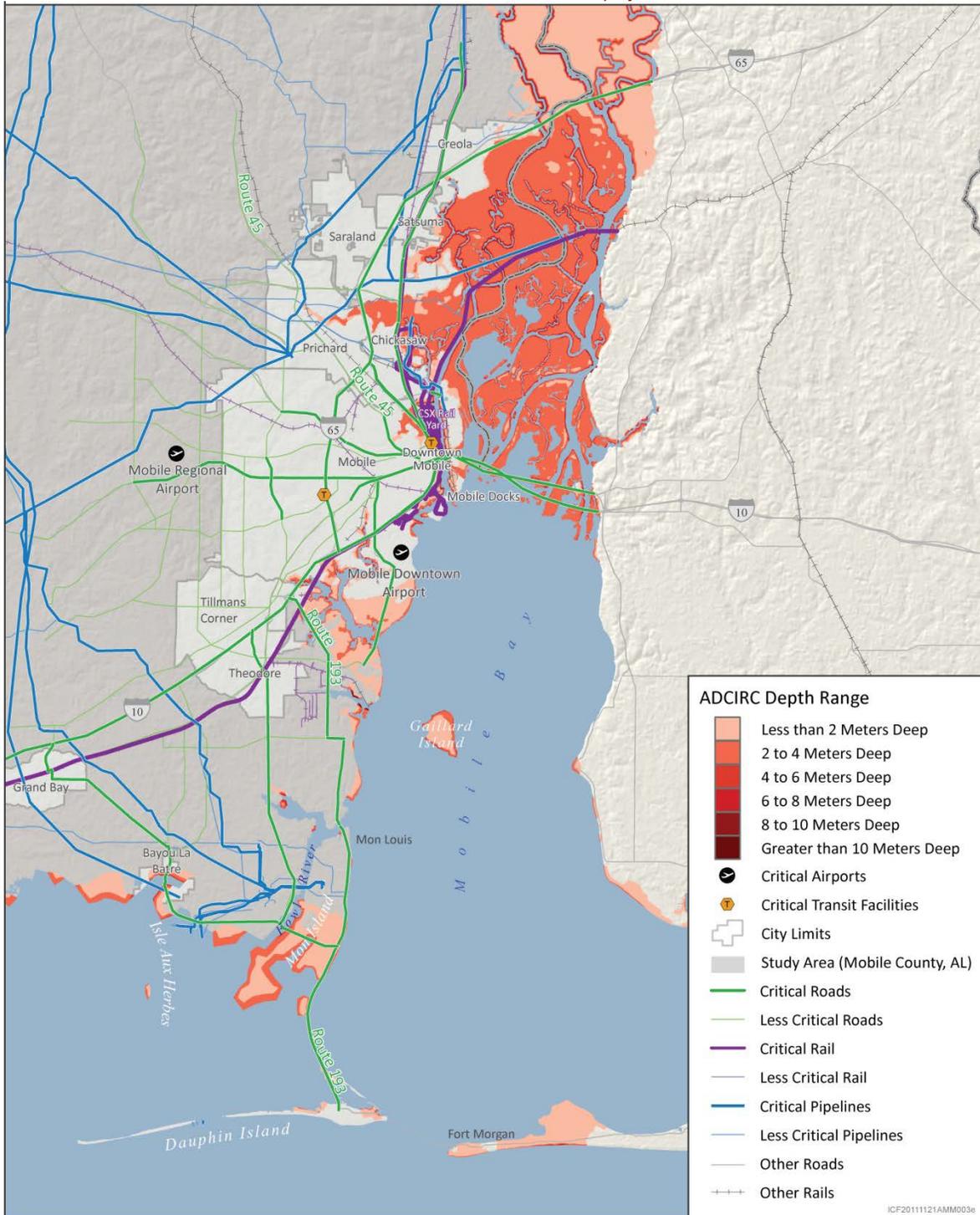
which the central pressure²¹⁰ of the shifted Katrina storm is reduced according to Knutson and Tuleya, 2004), the surge at Mobile Docks is estimated to be 24.85 feet (7.53 meters).

Note that increases in global sea level will not necessarily cause a corresponding one-to-one increase in peak storm surge elevations at all locations due to such factors as: non-linear variations in the forces increasing storm surge (such as wind setup) and forces resisting storm surge (such as bottom friction).

²¹⁰ The intensity of a hurricane is defined in part by its central pressure. The lower the central pressure, the more intense it generally is.

Figure 65: Storm Surge Depth for the Hurricane Georges Natural Path Scenario

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.^{211, 212}



²¹¹ This figure and the following maps show the entire extent of the modeling domain, but do not show the entirety of Mobile County.

²¹² Critical port structures are not shown in this figure and the following maps since doing so at the scale of the modeling domain would make it difficult to read the map in the area of the ports. As discussed below, a large majority of the critical ports are inundated in all of the scenarios.

Figure 66: Storm Surge Depth for the Hurricane Katrina Natural Path Scenario

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

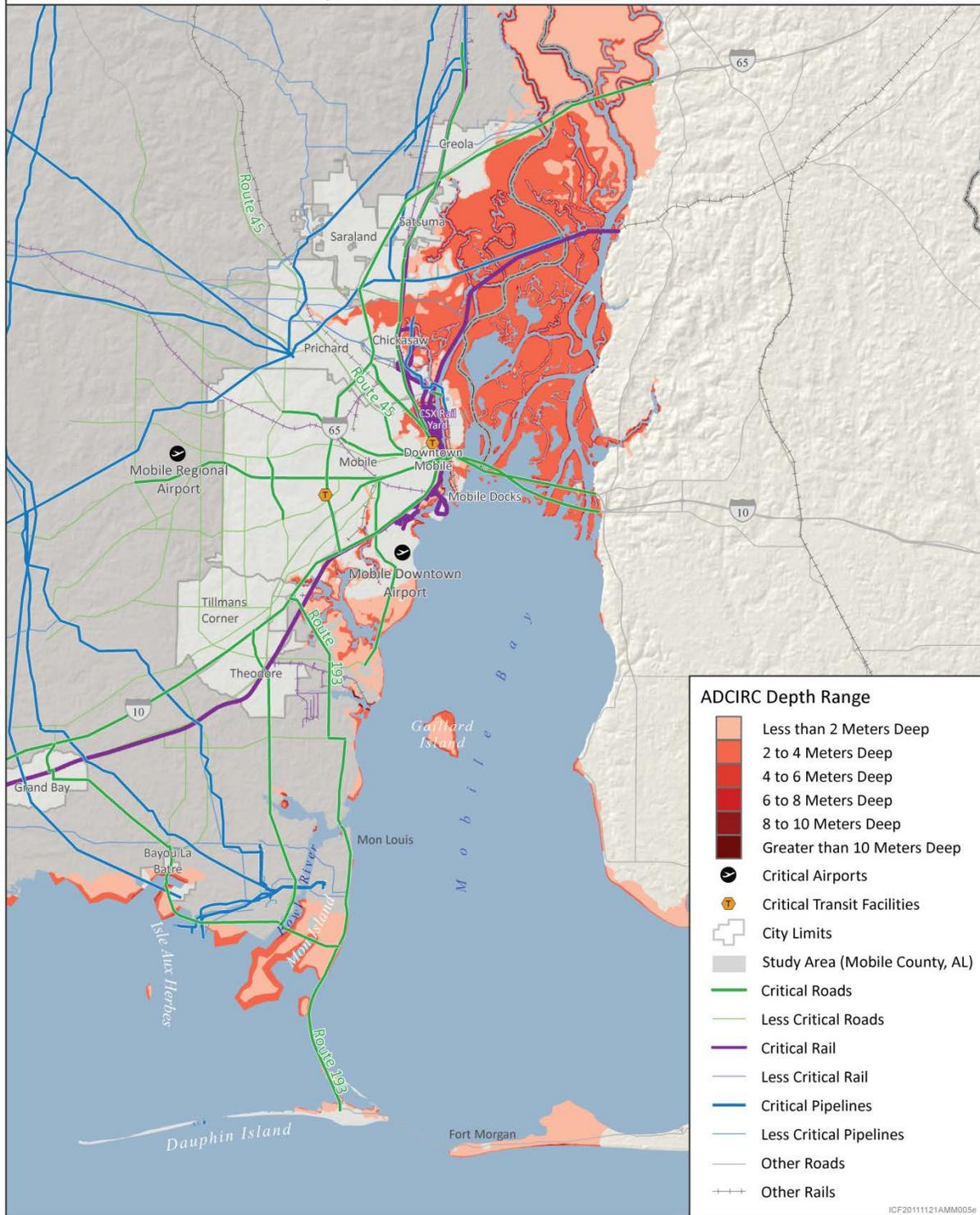


Figure 67: Storm Surge Depth for the Hurricane Georges Natural Path Scenario with 0.3 meter Sea level Rise

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

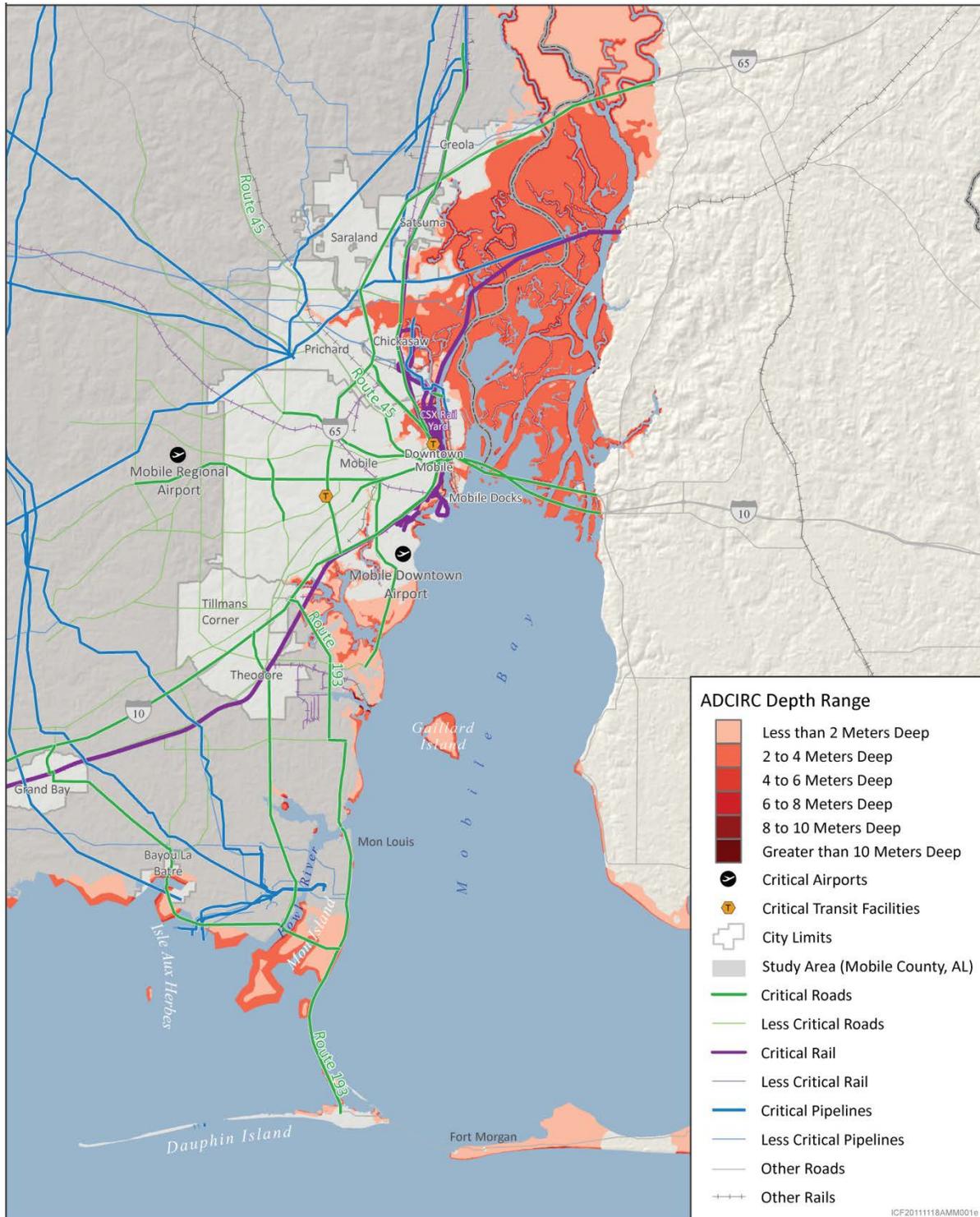


Figure 68: Storm Surge Depth for the Hurricane Georges Natural Path Scenario with 0.75 meter Sea level Rise
 The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

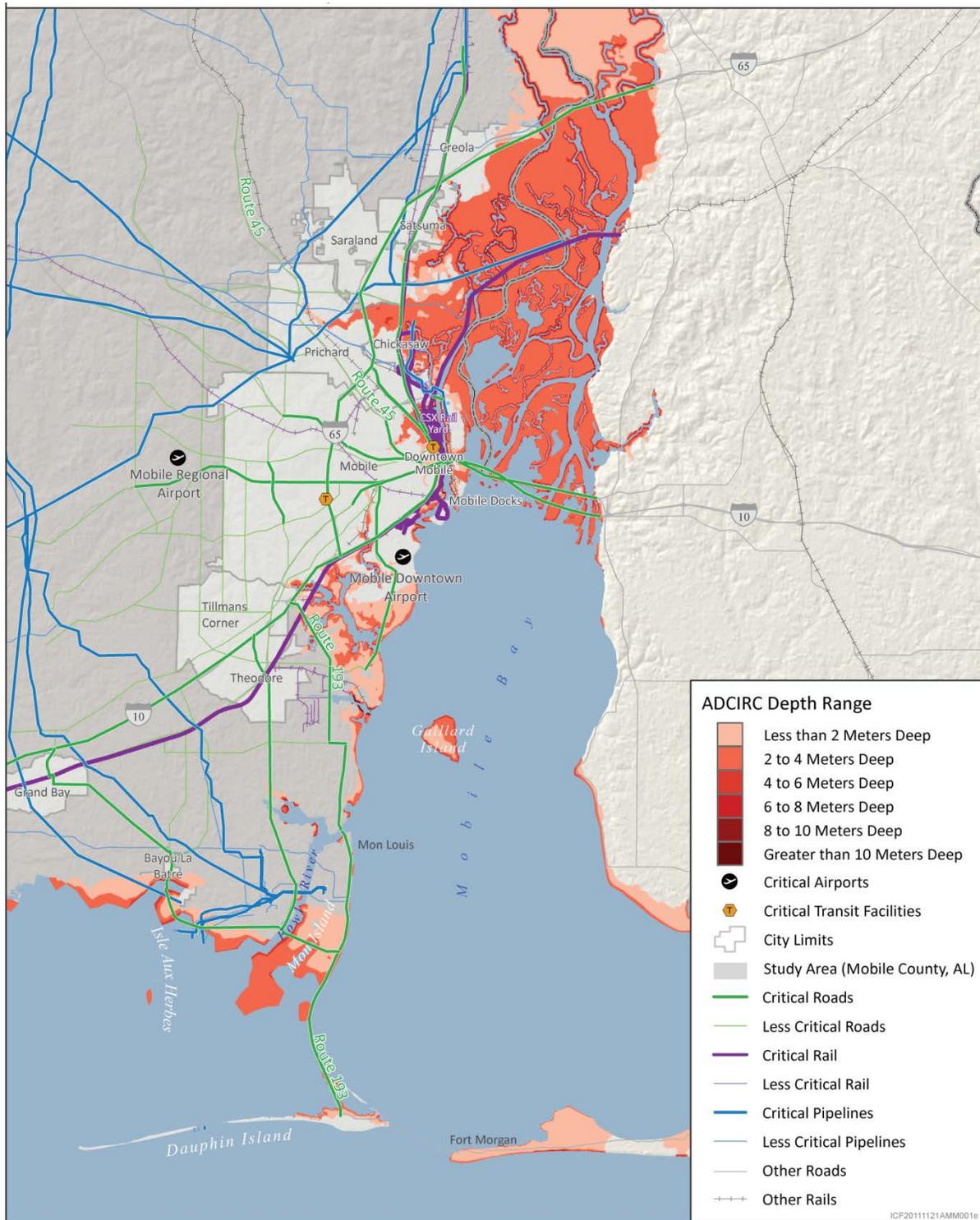


Figure 69: Storm Surge Depth for the Hurricane Georges Natural Path Scenario with 2.0 meter Sea level Rise
 The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

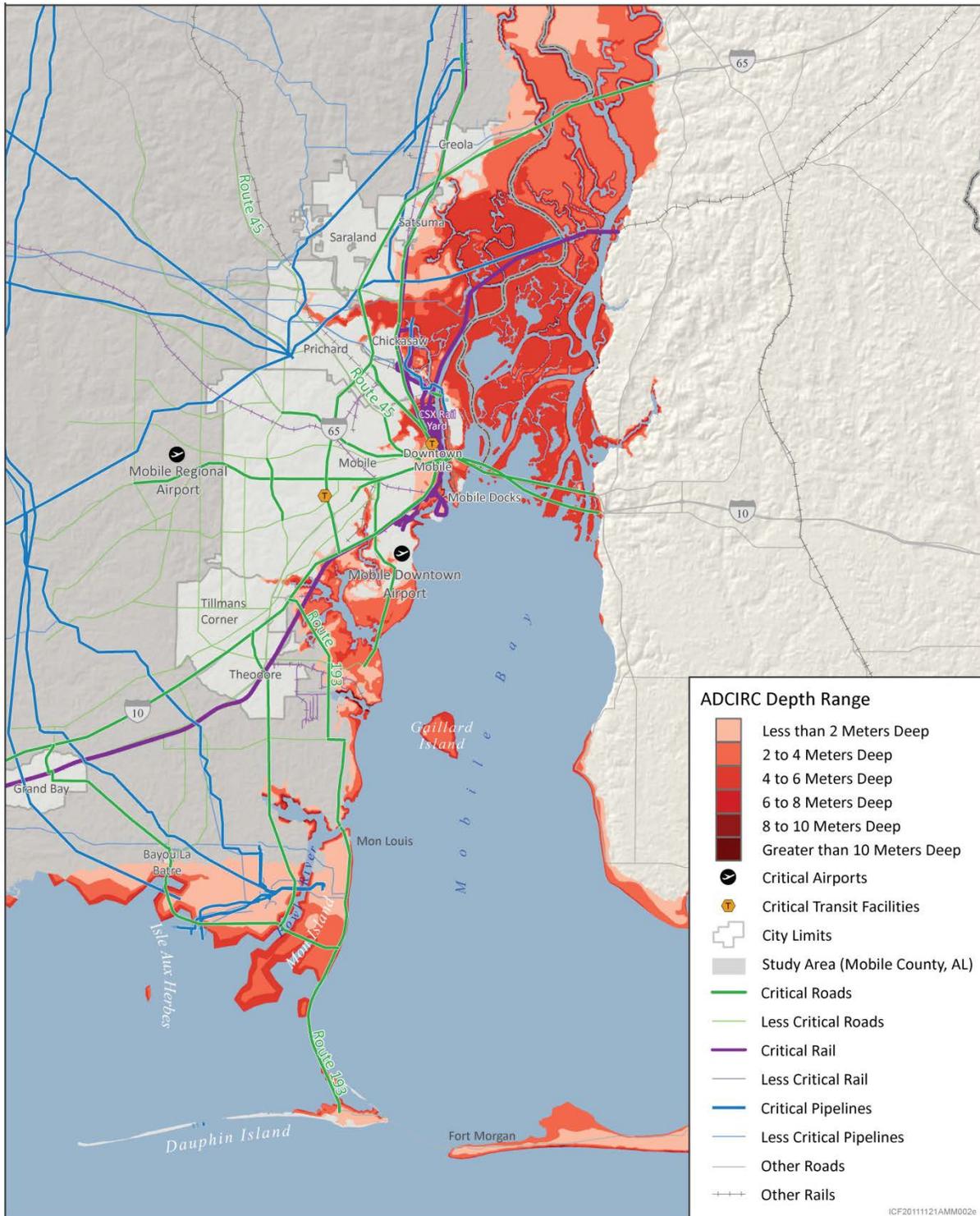


Figure 70: Storm Surge Depth for the Hurricane Katrina Natural Path Scenario with 0.75 meter Sea level Rise
 The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

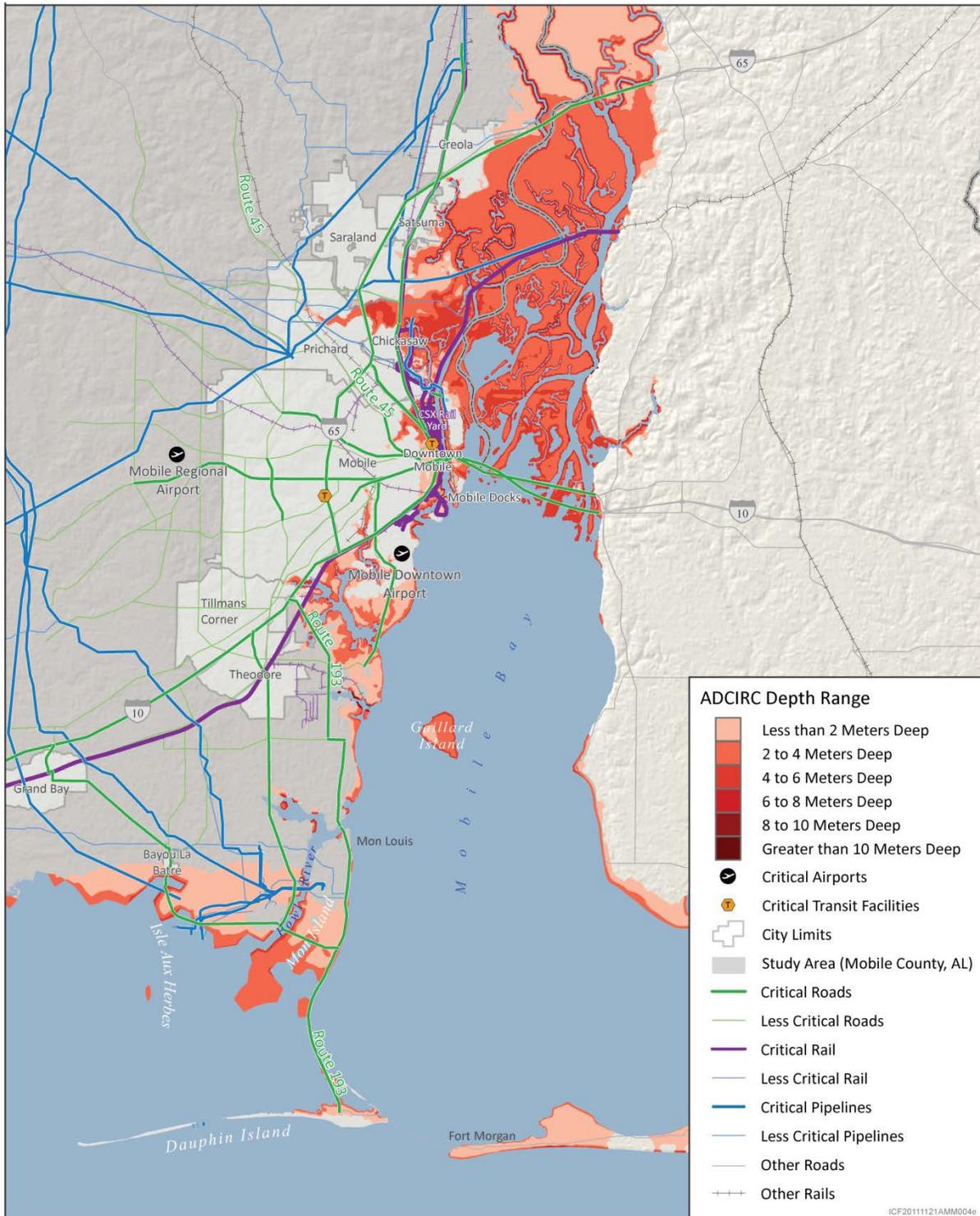


Figure 71: Storm Surge Depth for the Hurricane Katrina Shifted Path Scenario

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

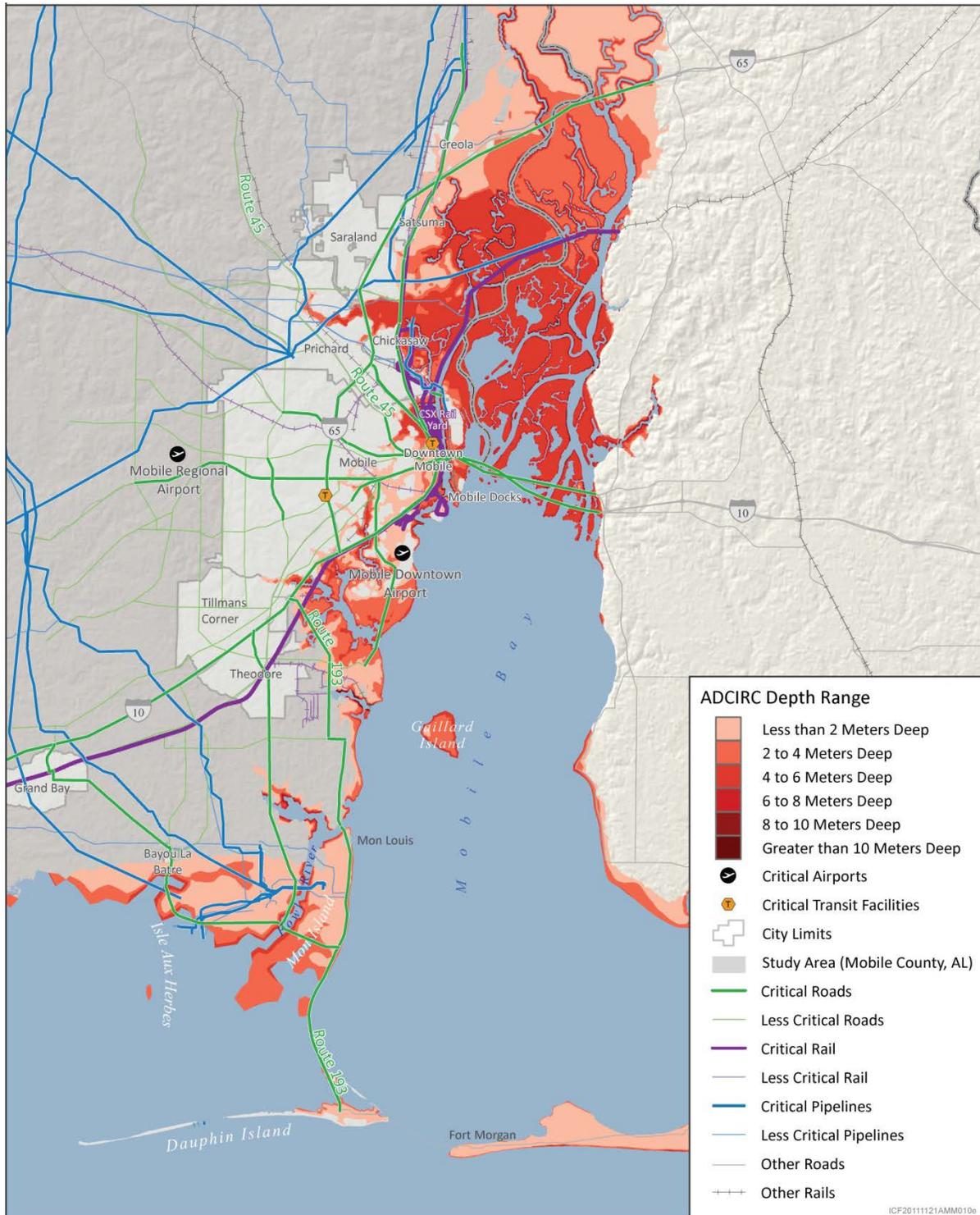


Figure 72: Storm Surge Depth for the Hurricane Katrina Shifted Path Scenario with 0.75 meter Sea level Rise

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

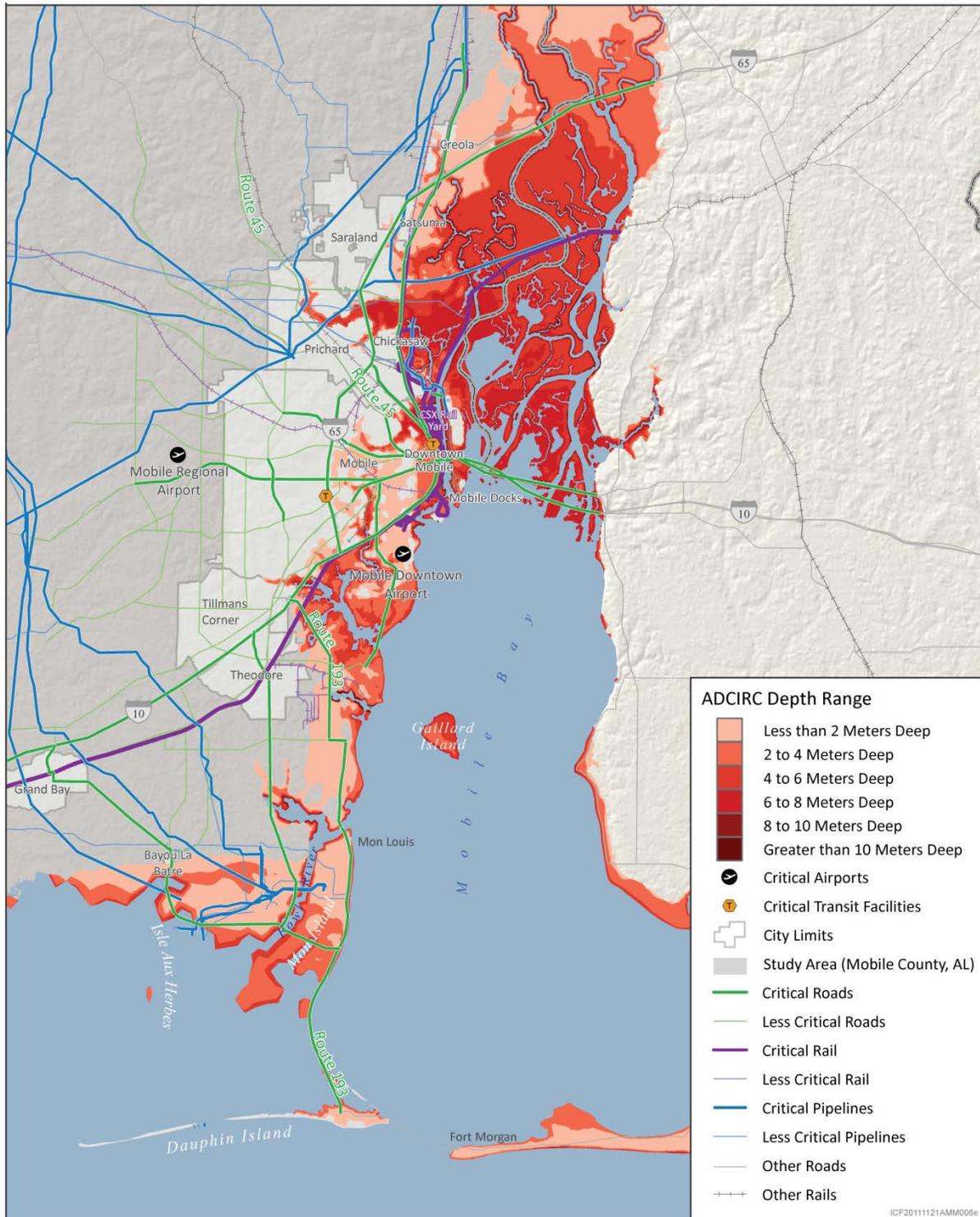


Figure 73: Storm Surge Depth for the Hurricane Katrina Shifted Path Scenario with Reduced Central Pressure and 0.75 meter Sea Level Rise

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

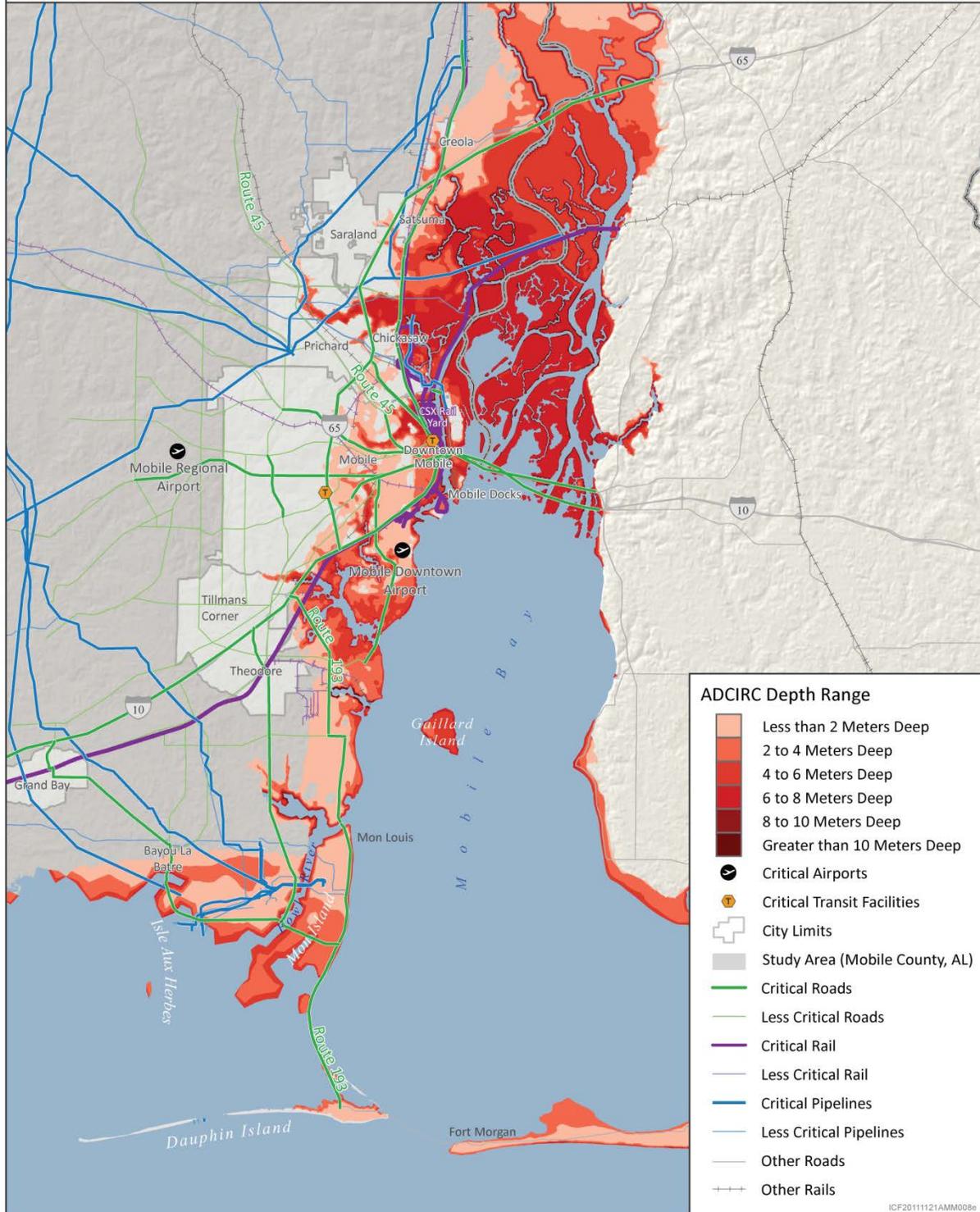


Figure 74: Storm Surge Depth for the Hurricane Katrina Shifted Path Scenario with Maximum Winds Held Constant
 The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

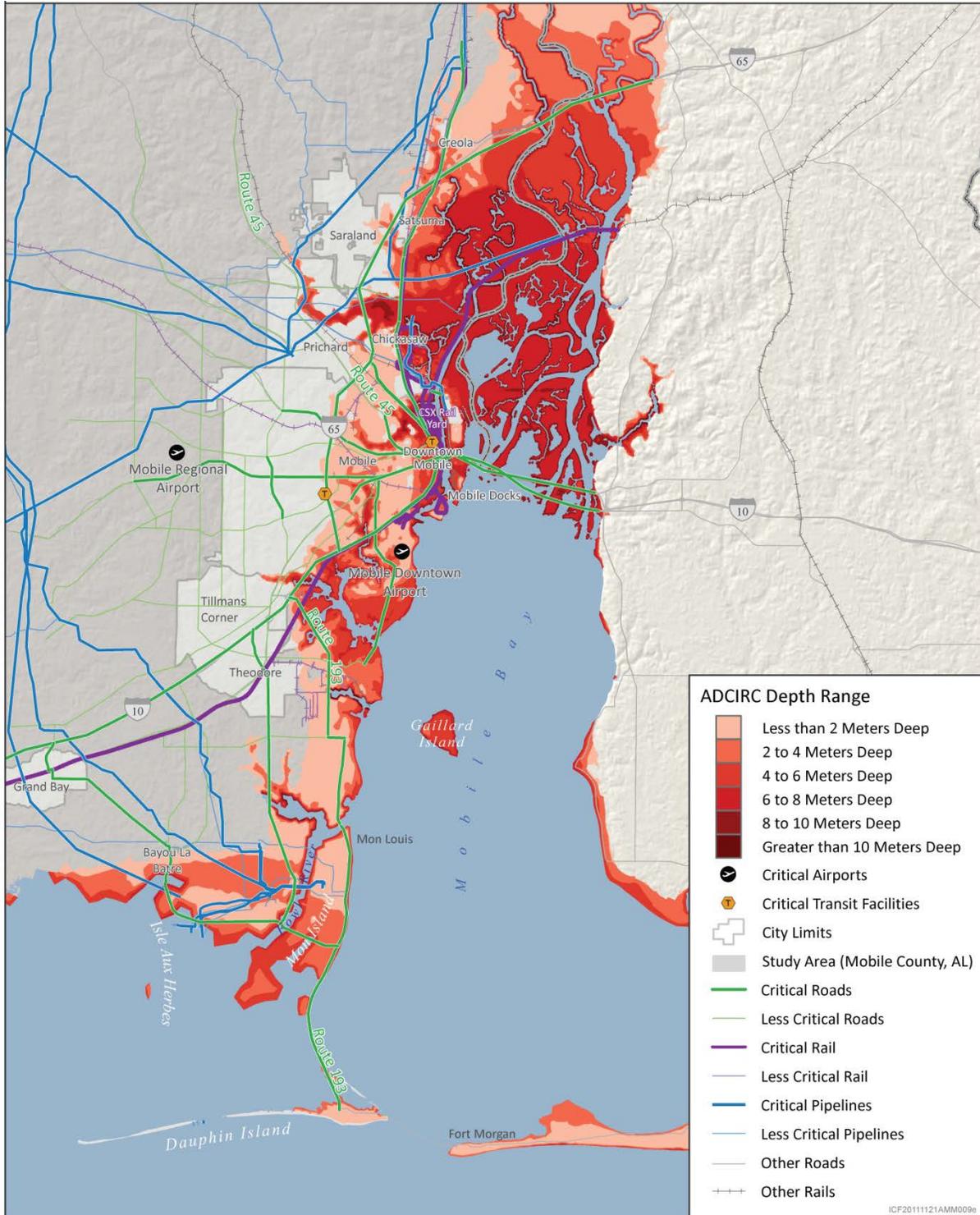


Figure 75: Storm Surge Depth for the Hurricane Katrina Shifted Path Scenario with Maximum Winds Held Constant and 0.75 meter Sea level Rise

The depth is measured relative to current dry ground. Also shown are the critical road, rail, airport, and pipeline infrastructure elements as determined in Task 1 of this project.

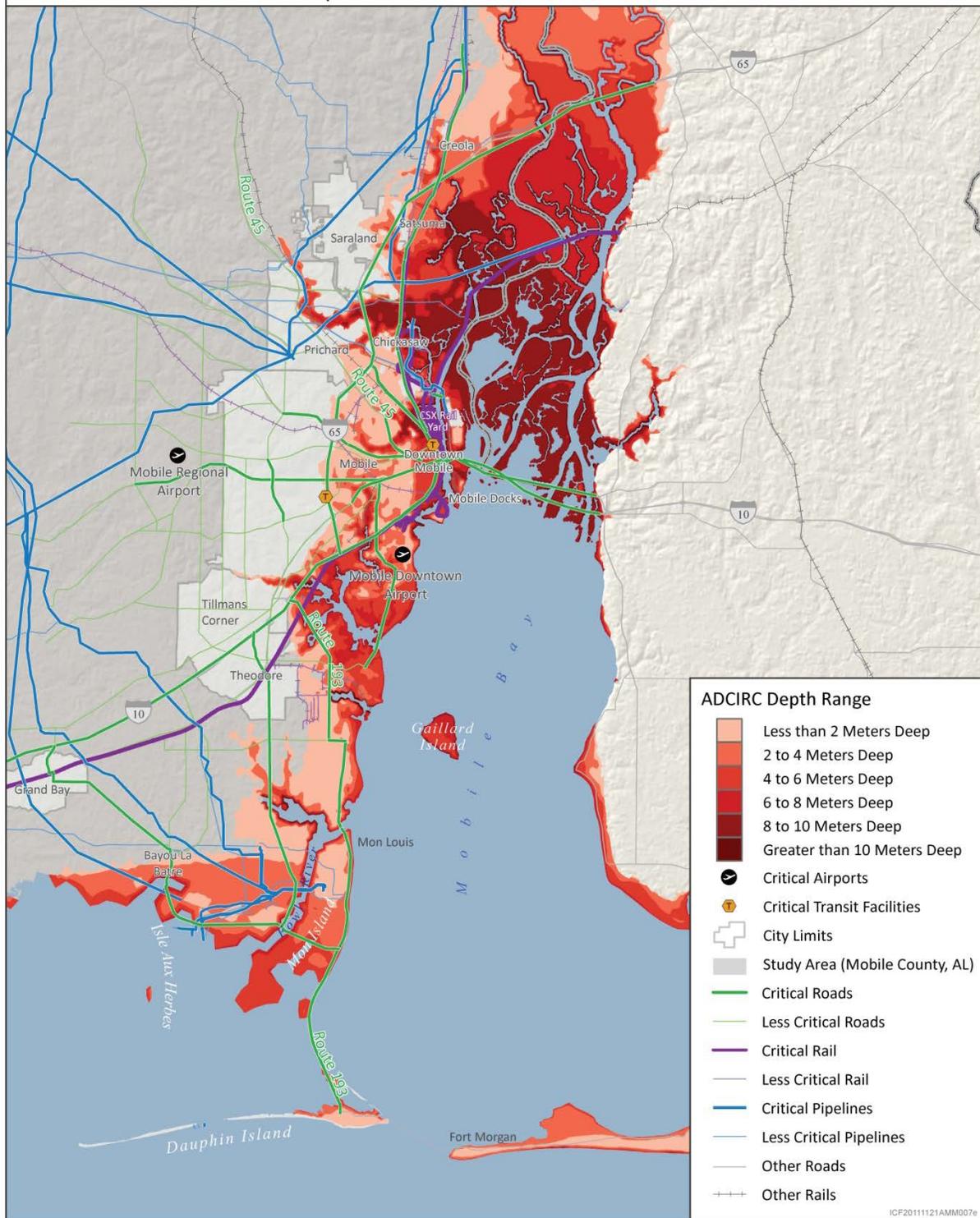


Table 24: Maximum Water Elevation at the ADCIRC Node Closest to the NOAA Tidal Station at the Mobile Docks

Name	Maximum Elevation
Georges-Natural	11.32 ft (3.45 m)
Katrina-Natural	12.31 ft (3.75 m)
Georges-Natural-0.3m	12.11 ft (3.69 m)
Georges-Natural-0.75m	13.60 ft (4.15 m)
Georges-Natural-2m	17.99 ft (5.48 m)
Katrina-Natural-0.75m	15.15 ft (4.62 m)
Katrina-Shift	19.44 ft (5.93 m)
Katrina-Shift-0.75m	22.74 ft (6.93 m)
Katrina-Shift-ReducedPress-0.75m	24.85 ft (7.57 m)
Katrina-Shift-MaxWind	27.65 ft (8.43 m)
Katrina-Shift-MaxWind-0.75m	31.02 ft (9.45 m)

Figure 76: Wave Height of Hurricane Georges Natural Path Scenario

The depths shown are the height of the waves relative to the still-water level of the surge.

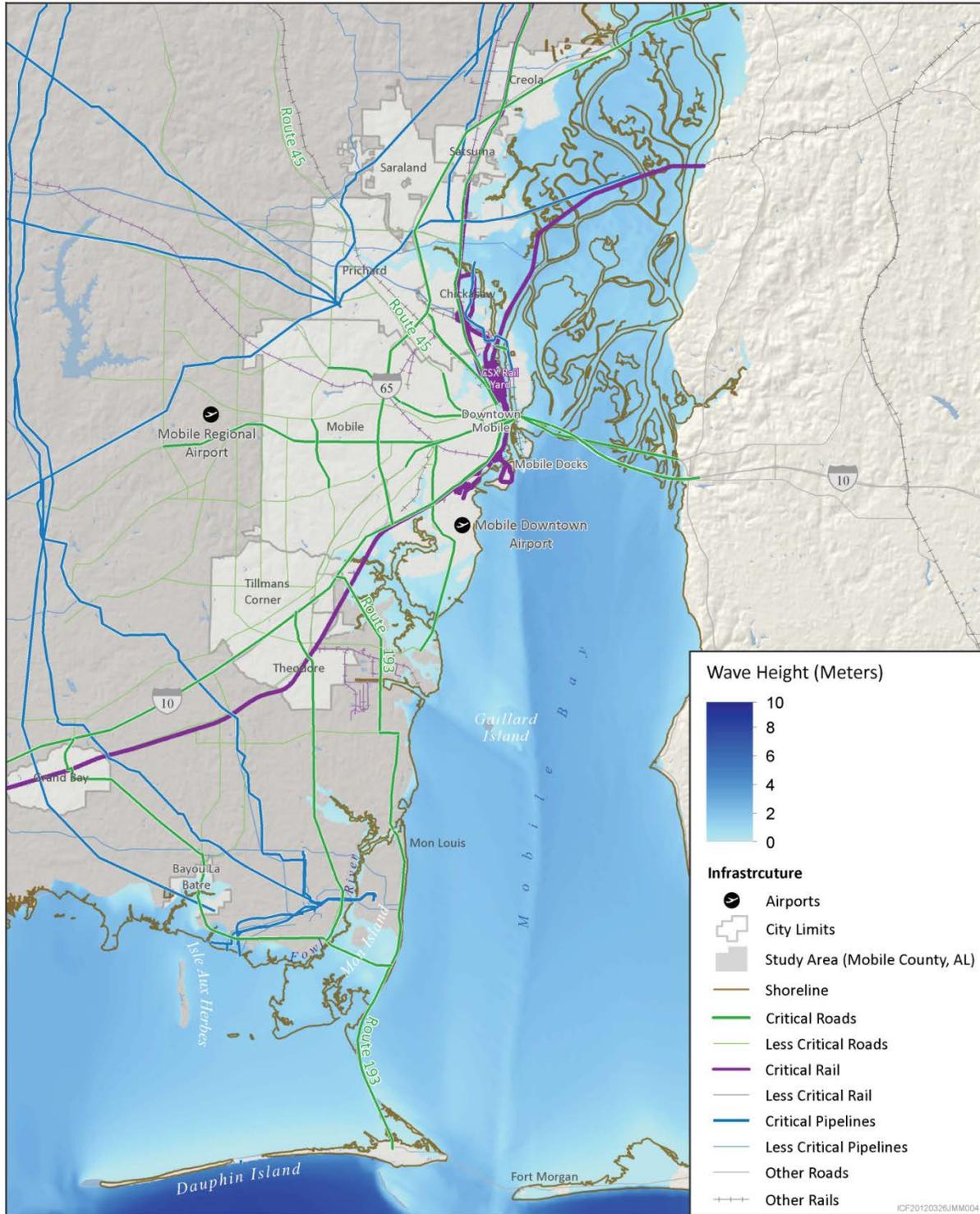


Figure 77: Wave Height of Hurricane Katrina Natural Path Scenario

The depths shown are the height of the waves relative to the still-water level of the surge.

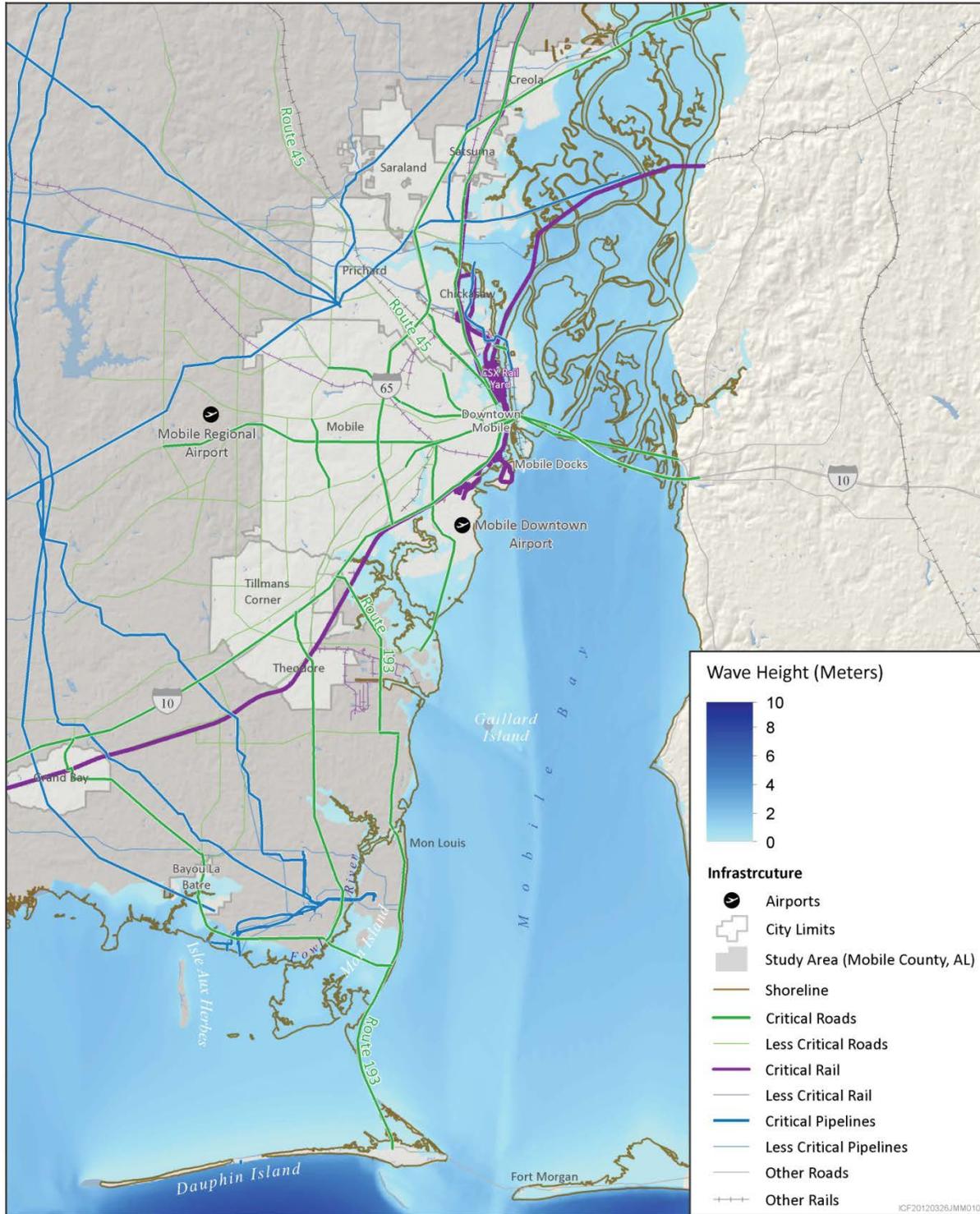


Figure 78: Wave Height of Hurricane Georges Natural Path Scenario with 0.30 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.

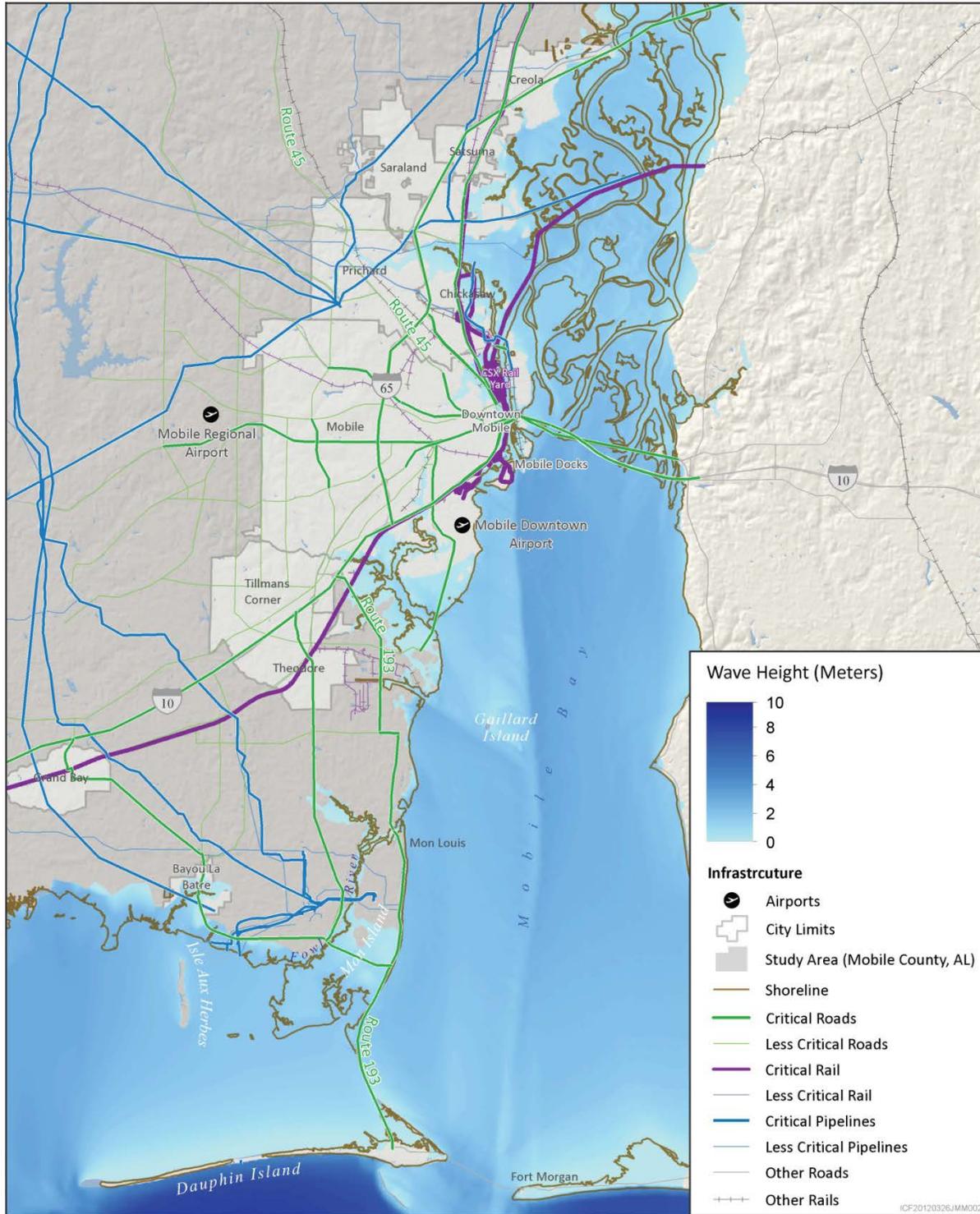


Figure 79: Wave Height of Hurricane Georges Natural Path Scenario with 0.75 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.

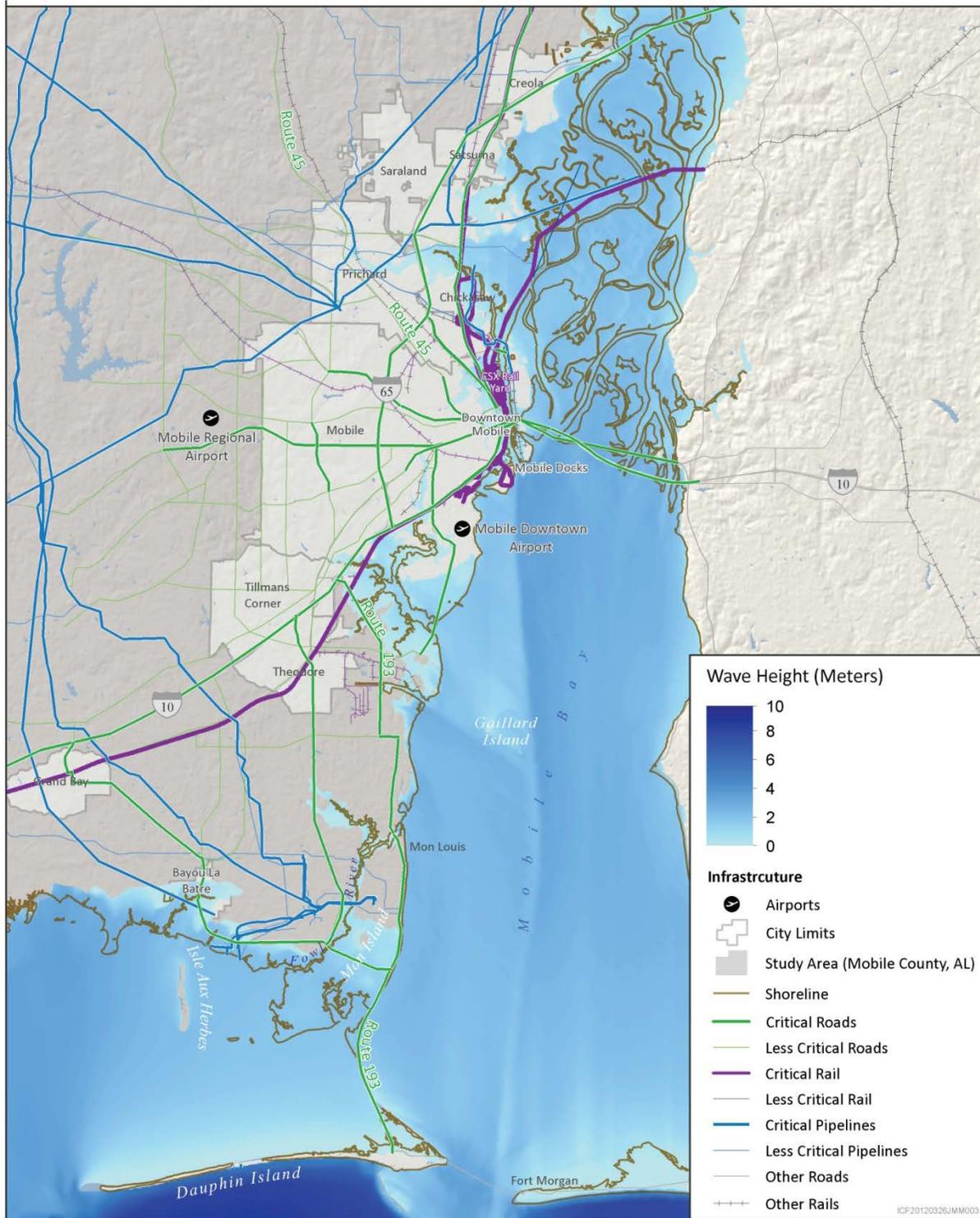


Figure 80: Wave Height of Hurricane Georges Natural Path Scenario with 2.0 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.

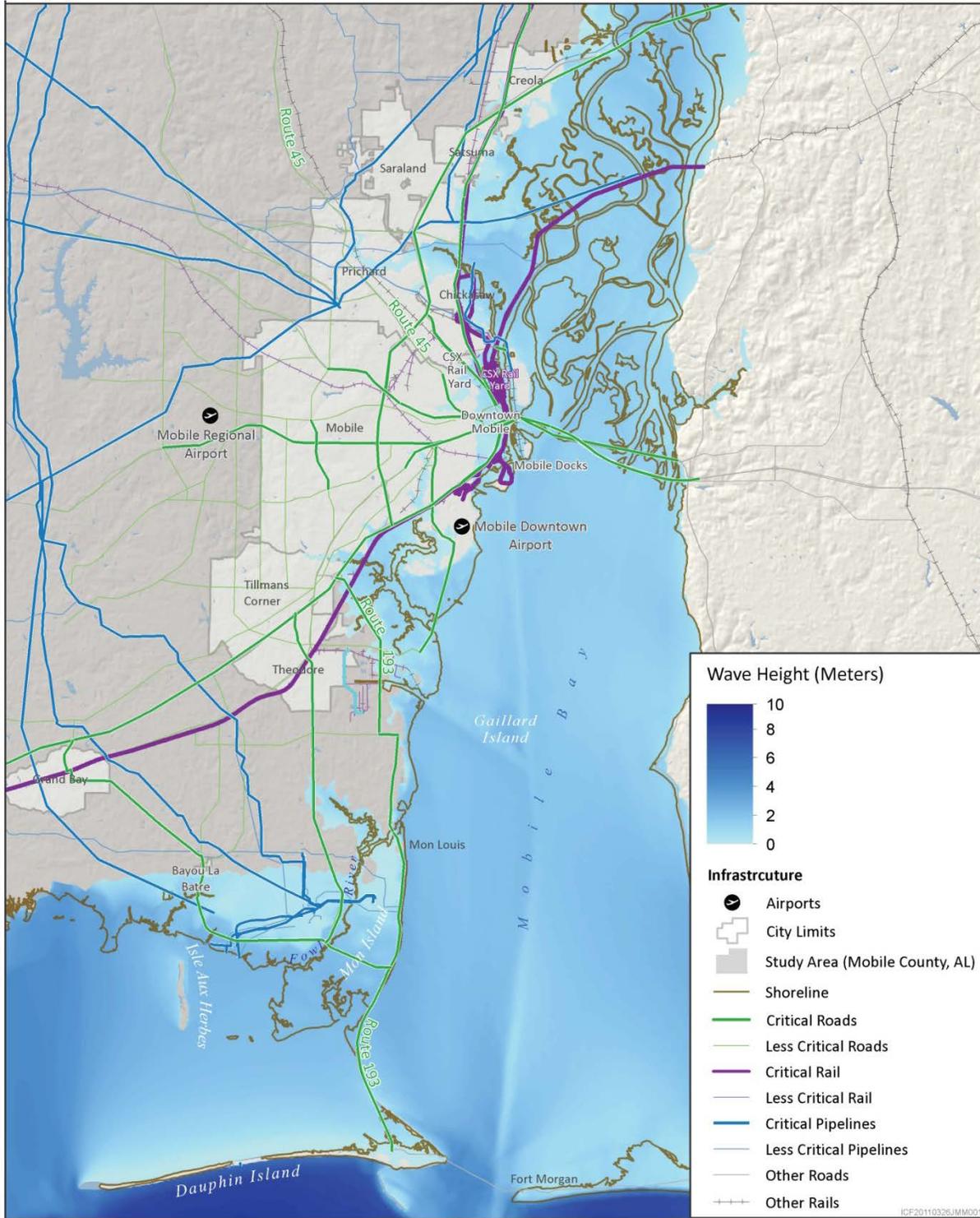


Figure 81: Wave Height of Hurricane Katrina Natural Path Scenario with 0.75 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.

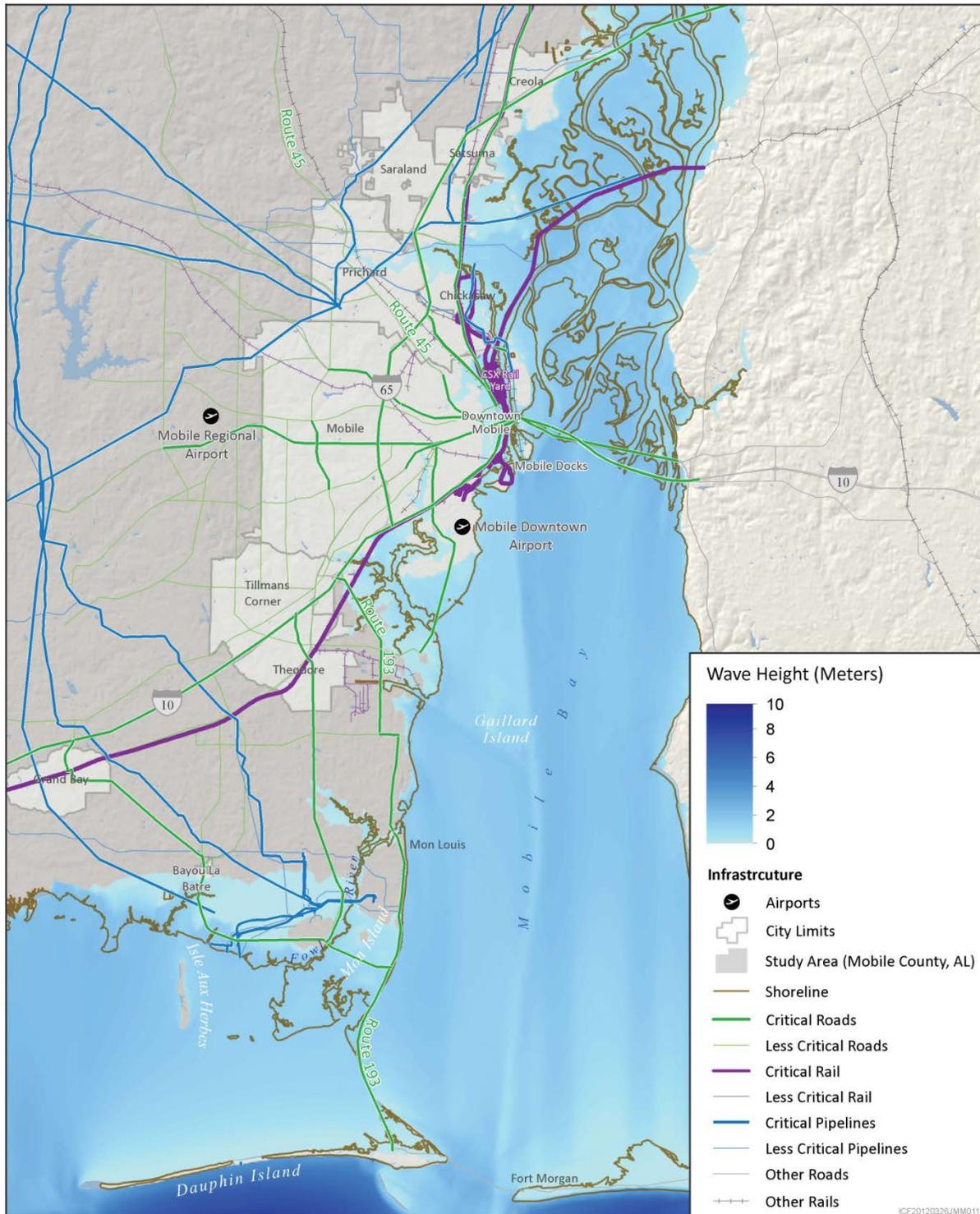


Figure 82: Wave Height of Shifted Hurricane Katrina Path Scenario

The depths shown are the height of the waves relative to the still-water level of the surge.

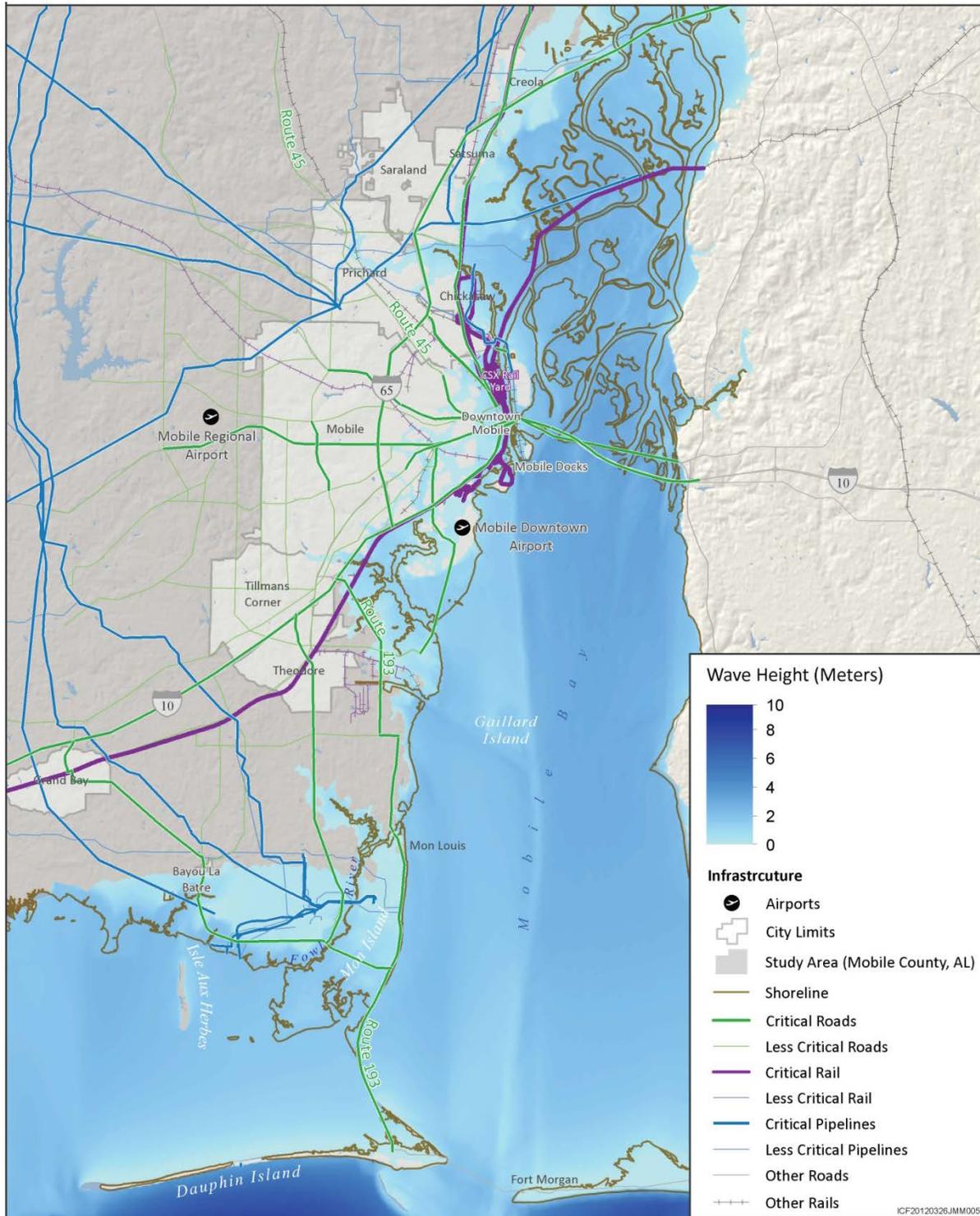


Figure 83: Wave Height of Hurricane Katrina Shifted Path Scenario with 0.75 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.

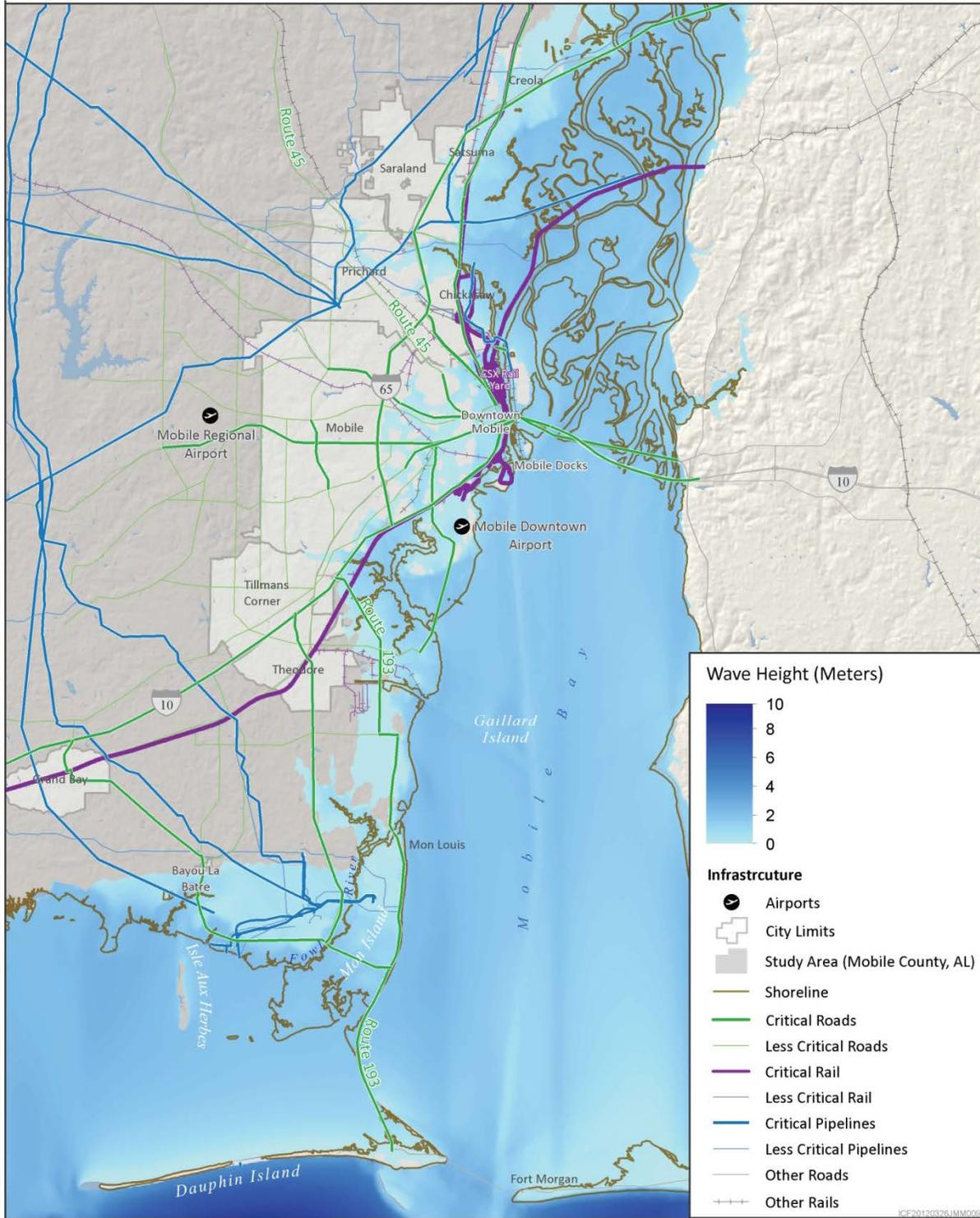


Figure 84: Wave Height of Hurricane Katrina Shifted Path Scenario with Reduced Central Pressure and 0.75 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.

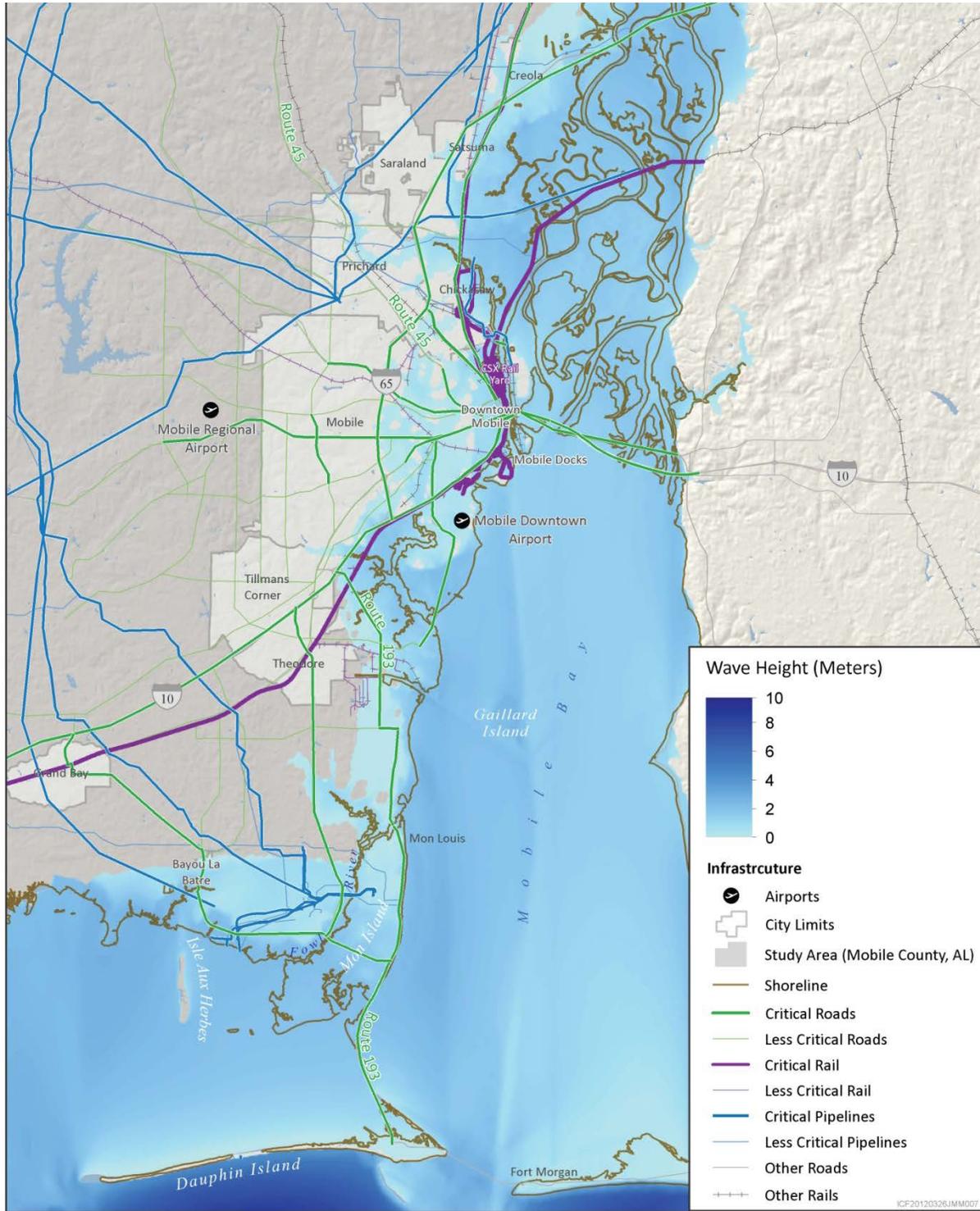


Figure 85: Wave Height of Hurricane Katrina Shifted Path Scenario with Maximum Winds Held Constant

The depths shown are the height of the waves relative to the still-water level of the surge.

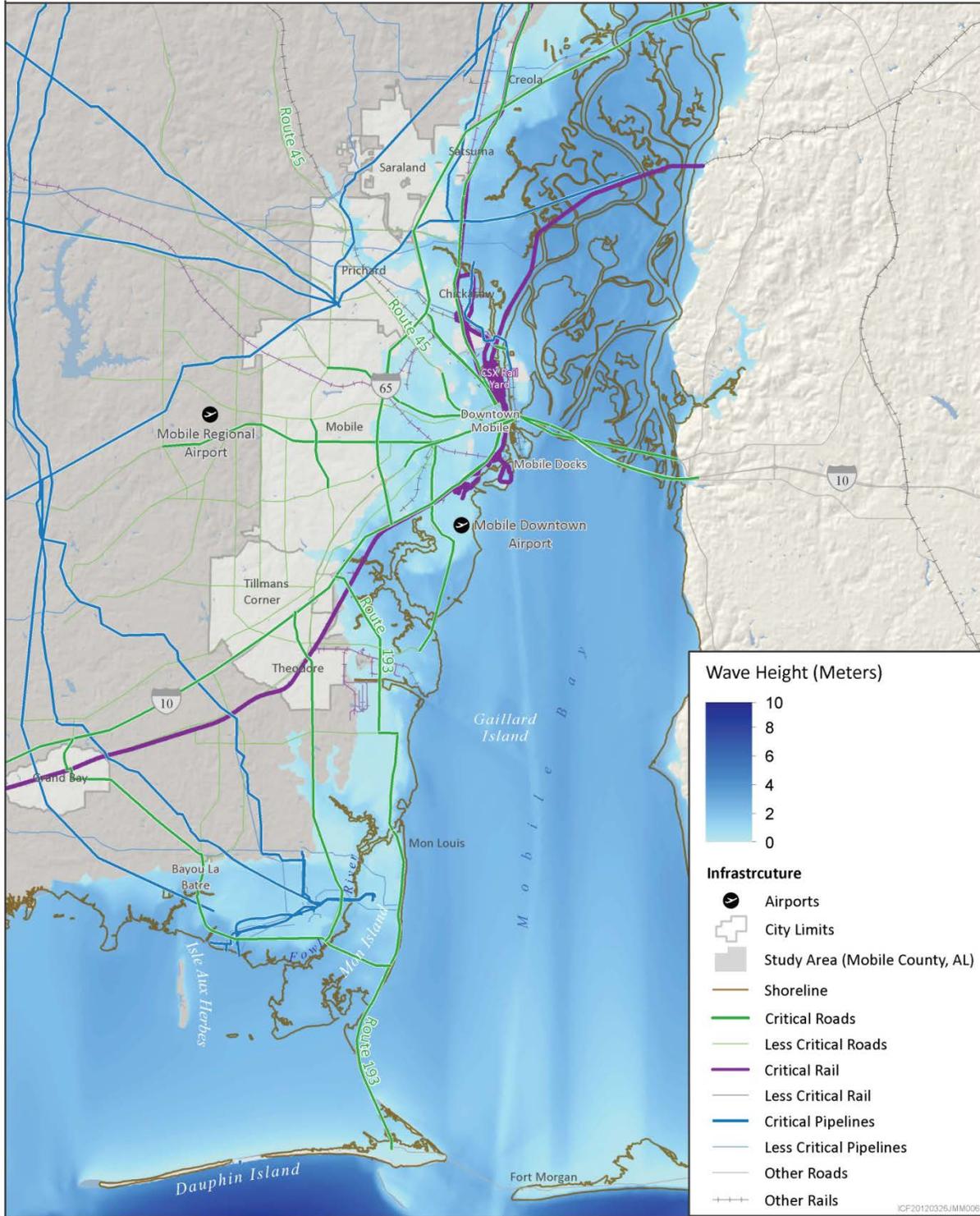
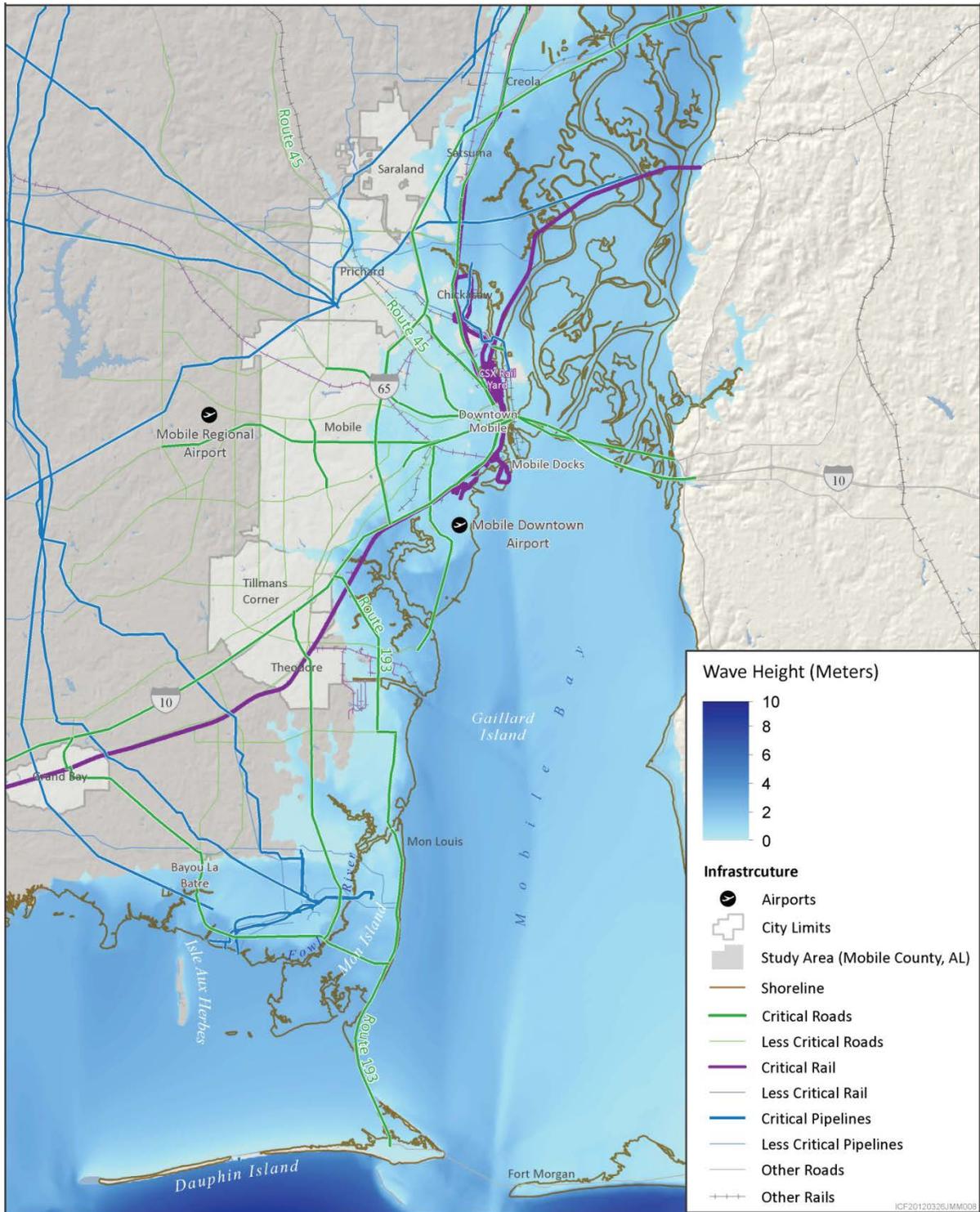


Figure 86: Wave Height of Hurricane Katrina Shifted Path Scenario with Maximum Winds Held Constant and 0.75 meter Sea level Rise

The depths shown are the height of the waves relative to the still-water level of the surge.



Caveats, Gaps, and Replicability

Not all factors affecting storm surge were taken into account in this study. For example, the study did not account for river flooding that often accompanies strong storms and tends to contribute to storm surge. Nor did it account for changes in beach profiles. For a more thorough account of the caveats, gaps, and replicability of this study, as well as lessons that may be useful in extending the results to other locales, see Appendix D.10.

7.3. Implications for Transportation

Storm surge can have very significant impacts on transportation, rendering them unusable for the duration of the surge (lasting several hours or more). Critical facilities – including roads, bridges, rail lines, airports and ports - may be unusable, or reduced in capacity, even after the waters recede due to damage to infrastructure, supporting utilities and communications, or access routes. Damage can range from debris that needs to be removed, to complete destruction of certain assets. The direct costs of clean up, repair and replacement can be high, and the secondary implications of disrupted transportation networks and supply chains can have widespread impacts on community life and on the local and regional economy.

The *extent* of inundation of critical transportation assets from storm surge is much greater than exposure to long-term sea level rise. Table 25 below was generated by using a Geographic Information System to overlay each of the storm surge scenarios over the critical assets defined in Task 1. The analysis takes into account the elevation on which each asset sits.

Based on fractional extent of exposure, critical port facilities are most exposed to storm surge. At least 92% of the 26 critical port facilities are inundated in all of the scenarios. In some of the most extreme scenarios, all of the critical port facilities are inundated.

In contrast to the port facilities, pipelines have the lowest fractional extent of exposure, ranging from 3% of pipeline-kilometers under the lowest scenario to 16% in the highest. Note that the pipeline data used in this analysis did not identify whether a particular section was above or below ground—a feature that would have a significant impact on the sensitivity of that section to inundation. Moreover, it also did not identify the exposure of pumping stations.

Most of the area’s critical rail lines are close to the water, since a vast majority of them serve the port. According to this analysis, between 57% and 80% of the critical rail-kilometers would be exposed to storm surge under these scenarios.

Under the range of scenarios, exposure varies notably for critical roadways. In the lowest surge scenario, 27% of the critical roadway length is exposed, whereas in the most extreme scenario, 75% of the critical roadway length is exposed. Importantly, even in the lowest scenario, many of the key evacuation routes are affected. The large increase in exposure under the highest scenarios is due in part to the concentration of critical roadways between I-65 and downtown Mobile.

One of the two critical transit facilities, the GM & O Transportation Center, is located near the coast and inundated under all storm scenarios.

Of the two critical airports in the study area, only Mobile Downtown Airport is inundated under any of the storm surge scenarios. Under the lowest storm surge scenario, 4% of the airport’s surface area is inundated, while the entire airport is inundated under the highest storm surge scenario. The scenarios in which the intensities of Georges and Katrina were not increased do not lead to major impacts on airport operations. However, the scenarios in which the track of Katrina is shifted would expose key aspects of the airport’s operations to inundation.

Table 25: Critical Assets Inundated Under Each Storm Scenario

Scenario	Roads (mi)	Rail (mi)	Pipe-lines (mi)	Ports (#)	Transit Facilities (#)	Mobile Downtown Airport (mi ²)*
Georges-Natural	55 of 209 (27%)	111 of 196 (57%)	14 of 426 (3%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (4%)
Katrina-Natural	58 of 209 (28%)	116 of 196 (60%)	15 of 426 (3%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (5%)
Georges-Natural-30cm	58 of 209 (28%)	114 of 196 (59%)	15 of 426 (3%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (5%)
Georges-Natural-75cm	63 of 209 (30%)	119 of 196 (61%)	24 of 426 (6%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (7%)
Georges-Natural-200cm	83 of 209 (40%)	132 of 196 (68%)	50 of 426 (12%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (15%)
Katrina-Natural-75cm	69 of 209 (33%)	127 of 196 (65%)	44 of 426 (10%)	24 of 26 (92%)	1 of 2 (50%)	0 of 3 (9%)
Katrina-Shift	95 of 209 (46%)	140 of 196 (71%)	51 of 426 (12%)	24 of 26 (92%)	1 of 2 (50%)	2 of 3 (65%)
Katrina-Shift-75cm	114 of 209 (55%)	144 of 196 (73%)	54 of 426 (13%)	25 of 26 (96%)	1 of 2 (50%)	2 of 3 (90%)
Katrina-Shift-MaxWind	140 of 209 (67%)	150 of 196 (77%)	62 of 426 (15%)	26 of 26 (100%)	1 of 2 (50%)	3 of 3 (100%)
Katrina-Shift-MaxWind-75cm	149 of 209 (75%)	154 of 196 (79%)	67 of 426 (16%)	26 of 26 (100%)	1 of 2 (50%)	3 of 3 (100%)
Katrina-Shift-ReducedPress-75cm	124 of 209 (60%)	146 of 196 (74%)	56 of 426 (13%)	25 of 26 (96%)	1 of 2 (50%)	3 of 3 (98%)

Note: The “highly critical” asset list was revised after the criticality report was completed to include parts of CR188, CR59, and the Cochrane Bridge in response to comments received from local stakeholders. Therefore, the total km presented here may differ from that reported in the Criticality Assessment report.

*The other highly critical airport, Mobile Regional Airport, is not inundated under any sea level rise scenarios.

The implications of the storm surge findings detailed in this report on transportation assets and services in Mobile will be investigated in the next task of this study (Task 3: Vulnerability Screen and Assessment).

8. Applications of Mobile Climate Information

8.1. Assessing Vulnerability in Mobile

The climate information developed in this report will inform a climate change vulnerability assessment. Vulnerability is a function of exposure, sensitivity, and adaptive capacity.

Looking at the transportation assets deemed “Highly Critical” in Task 1, **exposure** of these critical assets to future climate effects will be considered, by using the climate information developed for this report. Understanding the degree to which assets’ exposure to temperature, precipitation, streamflow, sea level rise, and storm surge will change in the future will provide insight into how existing vulnerabilities may be exacerbated, and which new vulnerabilities may arise. The vulnerability assessment will utilize information on design lifetime, temporal scale of climate effects, and magnitude of climate effects to evaluate exposure.

Sensitivity of assets to this exposure will then be evaluated, using a combination of a literature review of transportation sensitivities, interviews with local transportation managers, records of previous damage (or lack of damage) during historical weather events, and detailed asset-specific engineering assessments. An initial look at general transportation sensitivities to climate stressors was conducted under Task 2; the results of that research are presented in a separate report, *Assessing the Sensitivity of Transportation Assets to Climate Change in Mobile, Alabama*.

Adaptive capacity will also be addressed during the vulnerability assessment, but was not considered in Task 2. Adaptive capacity will be investigated through interviews with local transportation managers as well as expert understanding of how well certain assets and operations can adjust to changes in climate.

Together, this evaluation of the exposure, sensitivity, and adaptive capacity of the critical transportation assets will provide insight into the larger scale vulnerabilities of Mobile’s transportation system to climate change. The goal is to identify highly vulnerable singular assets, as well as an understanding of the vulnerabilities of the Mobile transportation system as a whole.

Understanding Vulnerability

Vulnerability = $f(\text{exposure, sensitivity, adaptive capacity})$

- **Vulnerability** is the degree to which an asset is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes
- **Exposure** is the nature and degree to which an asset is exposed to significant climatic variations;
- **Sensitivity** is the degree to which an asset is affected, either adversely or beneficially, by climate-related stimuli
- **Adaptive capacity** is the ability of a system (or asset) to adjust to climate change to moderate potential damages, to take advantage of opportunities, or to cope with the consequences

Source: IPCC, 2001

To support these goals, a detailed engineering assessment will be conducted on selected, representative assets that are believed to be highly vulnerable. These assessments will offer a more precise understanding of how specific assets could be impacted by climate change, the associated costs, and information on options to mitigate those impacts.

Finally, an important goal of Phase 2 of the Gulf Coast Study is to develop tools and resources that will assist other MPOs, counties, and state DOTs in conducting similar analyses and in reducing their respective vulnerability to climate variability and change. The processes and lessons learned throughout this report, and in other tasks, will help inform development of these resources.

8.2. Informing Similar Work Elsewhere

There are a number of other transportation climate change vulnerability assessments underway across the nation. As this work is among the earliest and most in-depth, the findings and lessons learned may help inform those efforts going forward. While there are similarities across all of the projects, each project is unique, and will bring its own lessons learned to light. Together, all of these projects will help build a strong foundation of knowledge that future vulnerability assessments can build upon.

For example, the USDOT has recently funded two sets of climate change vulnerability assessment pilots. The Federal Highway Administration (FHWA) funded the first set of five pilots. The pilot studies were designed to test and improve a draft framework for conducting vulnerability assessments of transportation assets and services, with a primary focus on highway assets. The Federal Transit Administration (FTA) is funding a second set of pilots aimed at transit assets and services. These pilot studies will build upon lessons learned through the FHWA pilots and findings in Phase 2 of this study.

There are a number of organizations and partnerships active in the Gulf Coast area that are focused on understanding the impacts of climate change to Gulf Coast communities, and promoting ways to increase the resiliency of the communities. Some examples include the Southern Climate Impacts Planning Program at Louisiana State University, the Mississippi-Alabama Sea Grant Consortium, the Mobile Bay Keeper, and the Dauphin Island Sea Lab. Although these programs are not affiliated with this project, the findings will be made available to these and other local programs, providing one more resource upon which they can draw. Moreover, later phases of this project may benefit from research findings and activities undertaken by these regional organizations.

Finally, an important goal of Phase 2 of the Gulf Coast Study is to develop tools and resources that will assist other MPOs in conducting additional analyses. The processes and lessons learned throughout this report will help inform development of these resources. Many of analyses conducted under Task 2 were resource-intensive, but there were key lessons learned, and

streamlined processes developed. The tools and resources ultimately developed under this project will reduce the barriers to conducting similar analyses at local scales across the US.

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