

# **Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I**

## **Draft Report**

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and Assessment Product 4.7

*Lead Agency:*

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*Coordinating Agency:*

U.S. Geological Survey, U.S. Department of the Interior

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1 **Impacts of Climate Change and**  
2 **Variability on Transportation Systems**  
3 **and Infrastructure: Gulf Coast Study,**  
4 **Phase I**

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# 1 Abstract

2 Climate affects the design, construction, safety, operations, and maintenance of transporta-  
3 tion infrastructure and systems. The prospect of a changing climate raises critical questions  
4 regarding how alterations in temperature, precipitation, storm events, and other aspects of  
5 the climate could affect the Nation's roads, airports, rail, transit systems, pipelines, ports,  
6 and waterways. Phase I of this regional assessment of climate change and its potential  
7 impacts on transportation systems addresses these questions for the region of the U.S.  
8 Central Gulf Coast between Galveston, Texas, and Mobile, Alabama. This region contains  
9 multimodal transportation infrastructure that is critical to regional and National transporta-  
10 tion services.

11 Historical trends and future climate scenarios were used to establish a context for exam-  
12 ining the potential effects of climate change on all major transportation modes within the  
13 region. Climate changes anticipated during the next 50-100 years for the Central Gulf  
14 Coast include warming temperatures, changes in precipitation patterns, and increased storm  
15 intensity. The warming of the oceans and decline of polar ice sheets is expected to  
16 accelerate the rate of sea level rise globally. The effects of sea level rise in most Central  
17 Gulf Coast counties will be exacerbated by the sinking of the land surface, which is  
18 accounted for in this assessment.

19 The significance of these climate factors for transportation systems was assessed. Warming  
20 temperatures are likely to increase the costs of transportation construction, maintenance,  
21 and operations. More frequent extreme precipitation events may disrupt transportation  
22 networks with flooding and visibility problems. Relative sea level rise will make much of  
23 the existing infrastructure more prone to frequent or permanent inundation – 25 percent of  
24 the major roads, 9 percent of the rail lines, and 72 percent of the ports are built on land at or  
25 below 122 centimeters (4 feet) in elevation. Increased storm intensity may lead to increased  
26 service disruption and infrastructure damage: More than half of the area's major highways  
27 (64 percent of Interstates; 57 percent of arterials), almost half of the rail miles, 29 airports,  
28 and virtually all of the ports are below 7 meters (23 feet) in elevation and subject to  
29 flooding and possible damage due to hurricane storm surge. Consideration of these factors  
30 in today's transportation decisions and planning processes should lead to a more robust,  
31 resilient and cost-effective transportation network in the coming decades.



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# Executive Summary

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The changing climate raises critical questions for the transportation sector in the United States. As global temperatures increase, sea levels rise, and weather patterns change, the stewards of our Nation's infrastructure are challenged to consider how these changes may affect the country's roads, airports, rail, transit systems, and ports. The U.S. transportation network – built and maintained through substantial public and private investment – is vital to the nation's economy and the quality of our communities. Yet little research has been conducted to identify what risks this system faces from climate change, or what steps managers and policy-makers can take today to ensure the safety and resilience of our vital transportation system.

This study: *The Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* has investigated these questions through a case study of a segment of the U.S. central Gulf Coast. The research, sponsored by the U.S. Department of Transportation (DOT) in partnership with the U.S. Geological Survey (USGS), has been conducted under the auspices of the U.S. Climate Change Science Program (CCSP). The study is one of 21 “synthesis and assessment” products planned and sponsored by CCSP. The interdisciplinary research team included experts in climate and meteorology; hydrology and natural systems; transportation; and decision-support.

A case study approach was selected for this research as an approach that would both generate useful information for local and regional decision-makers, while helping to develop research methodologies for application in other locations. In defining the study area, the DOT sought to design a project that would increase the knowledge base regarding the risks and sensitivities of all modes of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that can be considered to ensure a robust and reliable transportation network. The availability of reliable data, interest of local agencies and stakeholders, and transferability of findings were also important criteria in selecting the study area. While the methods presented in this report can be applied to any region, the modeled climate projections and the specific implications of these scenarios for transportation facilities are specific to the Gulf Coast study area.

This report presents the findings of the first phase of a three phase research effort. The ultimate goal of this research is to provide knowledge and tools that will enable transportation planners and managers to better understand the risks, adaptation strategies, and tradeoffs involved in planning, investment, design, and operational decisions. The objective of Phase I was to conduct a preliminary assessment of the risks and vulnerabilities of transportation in the region, after collecting and integrating the range of

1 data needed to characterize the region – its physiography and hydrology, land use and land  
2 cover, past and projected climate, current population and trends, and transportation  
3 infrastructure. Subsequent phases will conduct more detailed analyses. Phase II will  
4 conduct an in-depth assessment of risks to transportation in a selected location, reporting  
5 on implications for long-range plans and impacts on safety, operations, and maintenance.  
6 This phase will also develop a risk assessment methodology and identify techniques to  
7 incorporate environmental and climate data in transportation decisions. Phase III will  
8 identify and analyze adaptation and response strategies and develop tools to assess these  
9 strategies, while enumerating future research needs.

## 10 ■ **The Gulf Coast Study Area**

11 The Gulf Coast study area includes 48 contiguous coastal counties in four states, running  
12 from Houston/Galveston, Texas to Mobile, Alabama. This region is home to almost 10  
13 million people living in a range of urban and rural settings, and contains critical  
14 transportation infrastructure that provides vital service to its constituent states and the  
15 Nation as a whole. It is also highly vulnerable to sea-level rise and storm impacts. A  
16 variety of physical datasets were compiled for review and use by the project research team.  
17 Most of the spatial data is organized in GIS formats or “layers” that can be integrated to  
18 assess the vulnerability and risks of the transportation infrastructure in the study area and  
19 inform the development of adaptation strategies.

## 20 **Physical and Natural Environment**

21 The coastal geography of the region is highly dynamic due to a unique combination of  
22 geomorphic, tectonic, marine, and atmospheric forcings that shape both the shoreline and  
23 interior land forms. Due largely to its sedimentary history, the region is low-lying; the  
24 great majority of the study area lies below 30 meters in elevation. Due to its low relief,  
25 much of the central Gulf Coast region is prone to flooding during heavy rainfall events,  
26 hurricanes, and lesser tropical storms. Land subsidence is a major factor in the region, as  
27 sediments naturally compact over time. Specific rates of subsidence vary across the region,  
28 influenced by both the geomorphology of specific locations as well as by human activities.  
29 Most of the coastline also is highly vulnerable to erosion and wetland loss, particularly in  
30 association with tropical storms and frontal passages. It is estimated that 56,000 hectares  
31 (217 square miles) of land were lost in Louisiana alone during Hurricane Katrina. Further,  
32 many Gulf Coast barrier islands are retreating and diminishing in size. The Chandeleur  
33 Islands, which serve as a first line of defense for the New Orleans region, lost roughly 85  
34 percent of their surface area during Hurricane Katrina. As barrier islands and mainland  
35 shorelines erode and submerge, onshore facilities in low-lying coastal areas become more  
36 susceptible to inundation and destruction.

## **The Gulf Coast Transportation Network**

The central Gulf Coast study area's transportation infrastructure is a robust network of multiple modes – critical both to the movement of passengers and goods within the region and to national and international transport as well:

- The region has 17,000 miles (27,000 km) of major highways – about 2 percent of the nation's major highways – that carry 83.5 billion vehicle miles of travel annually. The area is served by 13 major transit agencies; over 136 providers offer a range of public transit services to Gulf Coast communities.
- Roughly two-thirds of all U.S. oil imports are transported through this region, and pipelines traversing the region transport over 90 percent of domestic Outer Continental Shelf oil and gas. Approximately one-half of all the natural gas used in the United States passes through or by the Henry Hub gas distribution point in Louisiana.
- The study area is home to the largest concentration of public and private freight handling ports in the United States, measured on a tonnage basis. These facilities handle a huge share – around 40 percent – of the nation's waterborne tonnage. Four of the top five tonnage ports in the United States are located in the region: South Louisiana, Houston, Beaumont, and New Orleans. The study area also has four major container ports.
- Overall, more than half of the tonnage (54 percent) moving through study area ports is petroleum and petroleum products. Additionally, New Orleans provides the ocean gateway for much of the U.S. interior's agricultural production.
- The region sits at the center of transcontinental trucking and rail routes, and contains one of only four major points in the United States where railcars are exchanged between the dominant eastern and western railroads.
- The study area also hosts the nation's leading and third-leading inland waterway systems (the Mississippi River and the Gulf Intracoastal) based on tonnage. The inland waterways traversing this region provide 20 states with access to the Gulf of Mexico.
- The region hosts 61 publicly owned, public-use airports, including 11 commercial service facilities. Over 3.4 million aircraft takeoffs and landings take place at these airports annually, led by the major facilities at George Bush Intercontinental (IAH), William P. Hobby, and Louis Armstrong New Orleans International. IAH also is the leading airport in the study area for cargo, ranking 17<sup>th</sup> in the nation for cargo tonnage.

Given the scale and strategic importance of the region's transportation infrastructure, it is critical to consider the potential vulnerabilities to the network that may be presented by climate change. A better understanding of these risks will help inform transportation managers as they plan future investments.

## 1 ■ The Gulf Coast Climate Is Changing

2 The research team’s assessment of historical and potential future changes in the Gulf Coast  
3 study region draws on publications, analyses of instrumental records, and models that  
4 simulate how climate may change in the future. The scenarios of future climate referenced  
5 in this report were generated by the National Center for Atmospheric Research (NCAR)  
6 using an ensemble of 21 different atmosphere-ocean coupled General Circulation Models  
7 (GCM) for the Gulf Coast region. Model results, climatic trends during the past century,  
8 and climate theory all suggest that extrapolation of the 20<sup>th</sup> century temperature record  
9 would likely underestimate the range of change that could occur in the next few decades.  
10 While there is still considerable uncertainty about the *rates* of change that can be expected,  
11 there is a fairly strong consensus regarding the direction of change for most of the climate  
12 variables that affect transportation in the Gulf Coast region. Key findings for the study  
13 region include:

- 14 • **Rising relative sea levels** – Relative sea-level in the study area is likely to increase at  
15 least 0.3 meter (1 foot) across the region and possibly as much as 2 meters (6 to 7 feet)  
16 in some parts of the study area. Relative sea-level rise (RSLR) is the combined effect  
17 of the projected increase in the volume of the world’s oceans (eustatic sea-level  
18 change), which results from increases in temperature and melting of ice, and the  
19 projected changes in land surface elevation at a given location due to subsidence of the  
20 land surface. The highest rate of relative sea-level rise will very likely be in the central  
21 and western parts of the study area (Louisiana and East Texas), where subsidence rates  
22 are highest. The analysis of a “middle range” of potential sea-level rise of 0.6 to  
23 1.2 meters (2 to 4 feet) indicates that a vast portion of the Gulf Coast from Houston to  
24 Mobile may be inundated over the next 50 to 100 years. The projected rate of relative  
25 sea-level rise for the region is consistent with historical trends, other published region-  
26 specific analyses, and the IPCC 4<sup>th</sup> Assessment Report findings, which assumes no  
27 major changes in ice sheet dynamics.
- 28 • **Storm activity** – Hurricanes are more likely to form and increase in their destructive  
29 potential as the sea surface temperature of the Atlantic and Gulf of Mexico increase.  
30 The literature indicates that the intensity of major storms could possibly increase by 10  
31 percent or more. This indicates that Category 3 storms and higher may return more  
32 frequently to the central Gulf Coast, and thus cause more disruptions. Rising relative  
33 sea-level will exacerbate exposure to storm surge and flooding. Depending on the  
34 trajectory and scale of individual storms, facilities at or below 9 meters (30 feet) could  
35 be subject to direct storm surge impacts.
- 36 • **Warming temperatures** – All GCMs available from the Intergovernmental Panel on  
37 Climate Change (IPCC) for use in this study indicate an increase in average annual  
38 Gulf Coast temperature through the end of this century. Based on GCM runs under  
39 three different emission scenarios developed by the IPCC Special Report on Emissions  
40 Scenarios (SRES) (the low-emissions B1, the high-emissions A2 and the mid-range  
41 A1B scenarios), the average temperature in the Gulf Coast region appears likely to



1 increase by at least  $1.5^{\circ}\text{C} \pm 1^{\circ}\text{C}$  ( $2.7^{\circ}\text{F} \pm 1.8^{\circ}\text{F}$ ) during the next 50 years. Extreme high  
2 temperatures are also expected to increase – with the number of days above  $32.2^{\circ}\text{C}$   
3 ( $90^{\circ}\text{F}$ ) very likely to increase significantly across the study area. Within 50 years the  
4 probability of experiencing 21 days a year with temperatures of  $37.8^{\circ}\text{C}$  ( $100^{\circ}\text{F}$ ) or  
5 above is greater than 50 percent.

- 6 • **Changes in precipitation patterns** – Some analyses, including the GCM results from  
7 this study, indicate that average precipitation will increase in this region while others  
8 indicate a decline of average precipitation during the next 50 to 100 years. In either  
9 case, it is expected that average runoff could decline, due to increasing temperature and  
10 resulting higher evapotranspiration rates. While *average* annual rainfall may increase  
11 or decrease slightly, the *intensity* of individual rainfall events is likely to increase  
12 during the 21<sup>st</sup> century.

13 In the near term, the direction and scale of these modeled outcomes are consistent  
14 regardless of the assumptions used for level of greenhouse gas emissions: Model outputs  
15 are relatively similar across a range of IPCC SRES emission scenarios for the next four  
16 decades. However, long-range projections (modeled to 100 years) do vary across  
17 scenarios, with the magnitude of impacts indicated being more severe under higher-  
18 emission assumptions.

## 19 ■ **Climate Change Has Implications for Gulf Coast Transportation**

20 The four key climate drivers in the region: rising temperatures, changing precipitation  
21 patterns, rising relative sea levels, and increasing storm intensity, present clear risks to  
22 transportation infrastructure in the study area. These factors can be incorporated into  
23 today's transportation decisions to help prepare for and adapt to changing environmental  
24 conditions.

- 25 • **Warming temperatures may require changes in materials, maintenance, and**  
26 **operations.** The combined effects of an increase in mean and extreme high  
27 temperatures across the study region are likely to affect the construction, maintenance,  
28 and operations of transportation infrastructure and vehicles. Higher temperatures may  
29 also suggest areas for materials and technology innovation to develop new, more heat  
30 tolerant materials. Some types of infrastructure deteriorate more quickly at  
31 temperatures above  $32.2^{\circ}\text{C}$  ( $90^{\circ}\text{F}$ ). As the number of very hot days increases, different  
32 materials may be required. Further, restrictions on work crews may lengthen  
33 construction times. Rail lines may be affected by more frequent rail buckling due to an  
34 increase in daily high temperatures. Ports, maintenance facilities, and terminals are  
35 expected to require increased refrigeration and cooling. Finally, higher temperatures  
36 affect aircraft performance and the runway lengths that are required. However,  
37 advances in aircraft technology are expected to offset the potential effects of the  
38 temperature increases analyzed in this report, so that current runway lengths are likely  
39 to be sufficient. The effects of increases in average temperatures and in the number of

1 very hot days will have to be addressed in designing and planning for vehicles,  
2 facilities, and operations.

- 3 • **Changes in precipitation patterns may increase short-term flooding.** The analysis  
4 of future annual precipitation change based on results of climate model runs is  
5 inconclusive: some models indicate an increase in average precipitation and some  
6 indicate a decrease. In either case, the hotter climate may reduce soil moisture and  
7 average run-off, possibly necessitating changes in right-of-way land management. The  
8 potential of changes in heavy rainfall may have more significant consequences for  
9 transportation; more frequent extreme precipitation events may result in more frequent  
10 flooding, stressing the capacity of existing drainage systems. The potential of extreme  
11 rainfall events and more frequent and prolonged flooding may disrupt traffic  
12 management, increase highway incidents, and impact airline schedules – putting  
13 additional strain on a heavily used and increasingly congested system. Further,  
14 prolonged flooding – inundation in excess of one week – can damage pavement  
15 substructure.
- 16 • **Relative sea-level rise may inundate existing infrastructure.** To assess the impact of  
17 relative sea-level rise (RSLR), the implications of rises equal to 61 cm and 122 cm (two  
18 and four feet) were examined. As discussed above, actual RSLR may be higher or  
19 somewhat lower than these levels. Under these scenarios, substantial portions of the  
20 transportation infrastructure in the region are at risk: 27 percent of the major roads,  
21 9 percent of the rail lines, and 72 percent of the ports are at or below 122 centimeters  
22 (4 feet) in elevation, although portions of the infrastructure are guarded by protective  
23 structures such as levees and dikes. While protective structures will continue to be an  
24 important strategy in the area, rising sea levels significantly increase the challenge to  
25 transportation managers in ensuring reliable transportation services. Inundation of even  
26 small segments of the intermodal system can render much larger portions impassable,  
27 disrupting connectivity and access to the wider transportation network.
- 28 • **Increased storm intensity may lead to greater service disruption and  
29 infrastructure damage.** This study examined the potential for flooding and damage  
30 associated with storm surge levels of 5.5 meters and 7.0 meters (18 feet and 23 feet).  
31 These modeled outputs are comparable to potential surge levels during severe storms in  
32 the region: Simulated storm surge from model runs across the central Gulf Coast  
33 demonstrated a 6.7 to 7.3 meter (22- to 24-foot) potential surge for major hurricanes.  
34 These levels may be conservative; surge levels during Hurricane Katrina (rated a  
35 Category 3 at landfall) exceeded these heights in some locations. The specific location  
36 and strength of storm surges are of course determined by the scale and trajectory of  
37 individual tropical storms, which are difficult to predict. However, substantial portions  
38 of the region’s infrastructure are located at elevations below the thresholds examined,  
39 and recent storms have demonstrated that major hurricanes can produce flooding miles  
40 inland from the location of initial landfall. At 7 meters (23 feet), more than half of the  
41 area’s major highways (64 percent of Interstates; 57 percent of arterials), almost half of  
42 the rail miles, 29 airports, and virtually all of the ports are subject to flooding due to  
43 storm surge.

1 Other damage due to severe storms is likely, as evidenced by the damage caused by  
2 Hurricanes Katrina and Rita in 2005. Damage from the force of storm surge, high  
3 winds, debris, and other effects of hurricanes can be catastrophic, depending on where a  
4 specific hurricane strikes. This study did not examine in detail these effects; the  
5 cumulative direct and indirect impacts of major storms need to be further analyzed.  
6 However, given the expectation of increasing intensity of hurricanes in the region,  
7 consideration should be given to designing new or replacement infrastructure to  
8 withstand more energy-intensive, high category storms.

## 9 ■ **Climate Change Considerations Need to Be Incorporated in** 10 **Transportation Decisions**

11 This preliminary assessment raises clear cause for concern regarding the vulnerability of  
12 transportation infrastructure and services in the central Gulf Coast due to climate and  
13 coastal changes. The effects of potential climate changes, particularly when combined with  
14 other factors such as subsidence, are likely to be significant. These changes threaten to  
15 cause both major and minor disruptions to the smooth provision of transport service  
16 through the study area. As transportation agencies work to meet the challenges of  
17 congestion, safety, and environmental stewardship – as well as maintaining transportation  
18 infrastructure in good repair – addressing the risks posed by a changing climate can help  
19 ensure that the substantial investments in the region’s infrastructure are protected in the  
20 coming decades by appropriate adaptation strategies.

21 While several of the impacts of climate change identified above are significant,  
22 transportation planners and managers can incorporate effective adaptation strategies into  
23 transportation decisions today. Some level of adaptation will be required in the near-term  
24 to address the effects of climate change processes that are underway. Concentrations of  
25 greenhouse gases already in the atmosphere will further force climate changes for the next  
26 three to four decades. The scale of adaptation required over the longer term – through this  
27 century – will be shaped in part by future emissions levels, as projections of lower-  
28 emission scenarios demonstrate lesser impacts.

## 29 **Transportation Planning Processes**

30 Transportation decisions are made by a number of different entities, both public and  
31 private, and transportation infrastructure is financed through a range of government and  
32 private investments. Within the study area, four state departments of transportation  
33 (DOTs) – for Texas, Louisiana, Mississippi, and Alabama – and 10 Metropolitan Planning  
34 Organizations (MPOs) lead surface transportation planning, in close coordination with  
35 local governments. To use Federal funding, these agencies must adhere to Federal  
36 requirements for surface transportation planning and investment. These laws are contained  
37 in Titles 23 and 49 of the United States Code (USC), and most recently amended in August

1 2005 by the *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for*  
2 *Users* (SAFETEA-LU), the latest six-year authorization of Federal funding for surface  
3 transportation.

4 In surface transportation separate but coordinated long-range transportation plans are  
5 cooperatively developed on a statewide basis by each state DOT and for each urbanized  
6 area by an MPO. The long-range transportation plan is developed with a minimum of a  
7 20-year forecast period, with many areas using a 30-year timeframe. These plans provide a  
8 long-range vision of the future of the transportation system, considering all passenger and  
9 freight modes and the intermodal system as a whole. The planning and investment process  
10 is highly collaborative; transportation agencies need to work in partnership with natural  
11 resource agencies, communities, businesses, and others as they chart a course for the  
12 transportation network that will meet multiple goals, supporting mobility, economic  
13 development, community, safety, security, and environmental objectives.

14 While climate and environmental projections inherently have a degree of uncertainty, this  
15 is not unusual to transportation. Transportation decision-makers are well accustomed to  
16 planning and designing systems under conditions of uncertainty on a range of factors –  
17 such as future travel demand, vehicle emissions, revenue forecasts, and seismic risks. In  
18 each case, decision-makers exercise best judgment using the best information available at  
19 the time. In an ongoing iterative process, plans may be revised or refined as additional  
20 information becomes available. Incorporating climate information and projections is an  
21 extension of this well developed process.

22 Similarly, environmental considerations have long played a role in the planning and  
23 development of transportation projects. As awareness of the complex interactions among  
24 environmental factors and transportation systems has grown, the transportation community  
25 has assumed increasing responsibilities for environmental stewardship. Integration of  
26 climate factors into transportation decisions continues this trend. However, interviews with  
27 a number of transportation managers in the region confirmed that most agencies do not  
28 consider climate change projections per se in their long-range plans, infrastructure design,  
29 or siting decisions. This appears to be changing, spurred in part by the devastating effects  
30 of Hurricanes Katrina and Rita. The damage caused by these storms highlighted the need  
31 to incorporate more information and model data related to climate change and other long-  
32 term shifts in environmental conditions as transportation plans are developed and  
33 implemented.

## 34 **New Approaches to Incorporate Climate Information**

35 The incorporation of climate factors into transportation decisions may require new  
36 approaches.

- 37 • **Planning timeframes** – The timeframes generally used for the Federal transportation  
38 planning process – 20 to 30 years – are short compared to the multidecadal period over  
39 which climate changes and other environmental processes occur. The longevity of  
40 transportation infrastructure – which can last beyond a century – argues for a long

1 timeframe to examine potential impacts from climate change and other elements of the  
2 natural environment. While the current timeframe is realistic for investment planning,  
3 agencies need to consider incorporating longer-term climate change effects into their  
4 visioning and scenario planning processes that inform their long-range plans.

- 5 • **Risk assessment approach** – Given the complexities of climate modeling and the  
6 inherent uncertainties regarding the magnitude and timing of impacts of climate factors,  
7 the deterministic methods currently used to support decisions cannot fully address the  
8 range of potential environmental conditions transportation managers need to consider.  
9 Adopting an iterative risk management approach would provide transportation  
10 decision-makers, public officials, and the public a more robust picture of the risks to –  
11 and level of resilience of – various components of the transportation network.

12 A conceptual framework and taxonomy for consideration of climate factors was  
13 developed. This approach incorporates four key factors that are critical to  
14 understanding how climate change may impact transportation:

- 15 – *Exposure:* What is the magnitude of stress associated with a climate factor (sea-  
16 level rise, temperature change, severe storms, precipitation) and the probability that  
17 this stress will affect a transportation segment or facility?
- 18 – *Vulnerability:* Based on the structural strength and integrity of the infrastructure,  
19 what is the potential for damage and disruption in transportation services from this  
20 exposure?
- 21 – *Resilience:* What is the current capacity of a system to absorb disturbances and  
22 retain transportation performance?
- 23 – *Adaptation:* What response(s) can be taken to increase resilience at both the facility  
24 (e.g., a specific bridge) and system levels?

## 25 **Adaptation Strategies**

26 Ultimately, the purpose of a risk assessment approach is to enhance the resilience of the  
27 transportation network. Analysis of these factors can help transportation decision-makers  
28 identify those facilities most at risk and adopt adaptation strategies to improve the  
29 resilience of facilities or systems. Structures can be hardened, raised, or even relocated as  
30 need be and – where critical to safety and mobility – expanded redundant systems may be  
31 considered as well.

32 What adaptation strategies are employed, and for which components of the system, will be  
33 determined considering the significance of specific parts of the network to the mobility and  
34 safety of those served, the effects on overall system performance, the cost of  
35 implementation, and public perceptions and priorities. Generally speaking, as the  
36 importance of maintaining uninterrupted performance increases, the appropriate level of  
37 investment in adaptation for high-risk facilities should increase as well. This study does  
38 not make recommendations about specific facilities or adaptation strategies, but rather

1 seeks to contribute to the information available so that states and local communities can  
2 make more informed decisions.

### 3 ■ **Future Research Would Benefit Decision-Makers**

4 The analysis of how a changing climate might affect transportation is in its infancy. While  
5 there is sufficient information today to begin to assess risks and implement adaptation  
6 strategies, further development of data and analysis would help planners, engineers,  
7 operators, and maintenance personnel as they create an even more robust and resilient  
8 transportation system, ultimately at lower cost. Key research opportunities include:

- 9 • **Integrated climate data and projections** – It would be useful to the transportation  
10 community if climatologists could continue to develop more specific data on future  
11 impacts. Higher resolution of climate models for regional and subregional studies  
12 would support the integration of region-specific data with transportation infrastructure  
13 information. More information about the likelihood and extent of extreme events,  
14 including temperature extremes, storms with associated surges and winds, and  
15 precipitation events could be utilized by transportation planners.
- 16 • **Risk analysis tools** – In addition to more specific climate data, transportation planners  
17 also need new methodological tools to address the uncertainties that are inherent in  
18 projections of climate phenomena. Such methods are likely to be based on probability  
19 and statistics as much as on engineering and materials science. The approaches taken  
20 to address risk in earthquake-prone areas may provide a model for developing such  
21 tools.
- 22 • **Region-based analysis** – The impacts that a changing climate might have on an area  
23 depends on where the region is and its natural environment. Replication of this study in  
24 other areas of the country could help determine the possible impacts of climate change  
25 on transportation infrastructure and services in those locations. Transportation in  
26 northern climates will face much different challenges than those in the south. Coastal  
27 areas will similarly face different challenges than interior portions of the country.  
28 Further, additional analysis on demographic responses to climate change, land use  
29 interactions, and secondary and national economic impacts would help elucidate what  
30 impacts climate will have on the people and the nation as a whole should critical  
31 transportation services in the region be lost.
- 32 • **Interdisciplinary research** – This study has demonstrated the value of cross-  
33 disciplinary research that engages both the transportation and climate research  
34 communities. Continued collaboration will benefit both disciplines in building  
35 methodologies and conducting analysis to inform the nation’s efforts to address the  
36 implications of climate change.

# 1.0 Why Study Climate Change Impacts on Transportation?

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Transportation is such an integral part of daily life in the United States that few pause to consider its importance. Yet the nation's strong intermodal network of highways, public transit, rail, marine, and aviation is central to our ability to work, go to school, enjoy leisure time, maintain our homes, and stay in touch with friends and family. U.S. businesses depend on reliable transportation services to receive materials and transport products to their customers; a robust transportation network is essential to the economy. In short, a sound transportation system is vital to the nation's social and economic future. Transportation professionals – including planners, designers, engineers, financial specialists, ecologists, safety experts, and others – work hard to ensure that U.S. communities have access to safe and dependable transportation services.

Given the ongoing importance of the nation's transportation system, it is appropriate to consider what effect climate change may have on this essential network. Through a regional case study of the central Gulf Coast, this report begins to examine the potential implications of climate change on transportation infrastructure, operations, and services. Investments in transportation are substantial, and result in infrastructure that lasts for decades. Transportation plans and designs should, therefore, be carefully considered and well informed by a range of factors, including consideration of climate variability and change. Climate also affects the safety, operations, and maintenance of transportation infrastructure and systems. This research investigates the potential impacts of climate variability and change on transportation, and assesses how planners and managers may incorporate this information into their decisions to ensure a reliable and robust future transportation network. This report does not make specific recommendations about specific facilities or adaptation strategies, but rather seeks to contribute to the information available so that states and local communities can make more informed decisions when planning for the future.

Four key questions guide this investigation:

1. How important are the anticipated changes in climate?
2. Can we anticipate them with confidence?
3. What information is useful to transportation decisions?
4. How can decision-makers address uncertainty?

1 The answers to these questions require first developing an understanding of how the  
2 climate is changing and the range of potential climate effects, and then considering the  
3 relevance of these changes to transportation.

4 To set the context for this regional case study, this chapter first provides in Section 1.1 an  
5 overview of how climate change is occurring globally, based on current scientific research.  
6 Section 1.2 introduces the questions these changes raise for the transportation sector, and  
7 the research required to support effective responses to climate change. Section 1.3  
8 provides a synthesis of the state of existing research regarding the impacts of climate  
9 change on transportation, discussing the focus of current investigations – both in terms of  
10 specific climate factors and individual transportation modes, major findings, and what  
11 entities are sponsoring and conducting this research. Section 1.4 draws conclusions from  
12 this literature review to identify what is known – and what research questions remain – on  
13 this multifaceted topic. Section 1.5 then discusses how the U.S. DOT selected the Gulf  
14 Coast region for its first case study of the potential impacts of climate change on  
15 transportation, and describes the objectives and organization of the research effort.

## 16 ■ 1.1 The Climate is Changing

17 The natural “greenhouse” effect is an essential component of the planet’s climate process.  
18 Naturally occurring greenhouse gases – carbon dioxide, methane, and nitrous oxide –  
19 effectively prevent part of the heat radiated by the earth’s surface from otherwise escaping  
20 to space. In the absence of these greenhouse gases, the earth’s temperature would be too  
21 cold to support life as we know it today.

22 However, atmospheric concentrations of greenhouse gases have increased markedly since  
23 the industrial age began. The concentration of carbon dioxide (CO<sub>2</sub>) in the atmosphere has  
24 been increasing due to the combustion of fossil fuels and, to a lesser extent, land use  
25 changes. Direct atmospheric measurements made over the past 50 years have documented  
26 the steady growth in carbon dioxide concentrations. In addition, analysis of ice bubbles  
27 trapped in ice cores show that atmospheric carbon dioxide has increased by roughly one-  
28 third since 1750. Atmospheric concentration of CO<sub>2</sub> was 379 parts per million (ppm) in  
29 2005, compared to a preindustrial level of 280 ppm (IPCC, 2007). Other heat-trapping  
30 gases – methane and nitrous oxide – also are increasing as a result of human activities.  
31 Finally, once in the atmosphere these greenhouse gases have a relatively long life time, on  
32 the order of decades to centuries, which means that the atmospheric warming taking place  
33 today will continue.

34 **Temperature has increased and is projected to continue to do so.** Temperatures have  
35 been rising over the last century, with more rapid increases since 1970 than earlier.  
36 According to the International Panel on Climate Change (IPCC) Working Group I Fourth  
37 Assessment Report (AR4), average global temperatures increased 0.74°C (1.33°F) during  
38 the past 100 years, with most of that increase – 0.65°C (1.17°F) experienced in the last 50  
39 years. Recent years have set record highs; 11 of the past 12 years were the warmest years



1 on record since 1850. While some of this change may be due to natural variability, human  
2 activities have contributed to the earth's warming. The IPCC report finds with very high  
3 confidence that the globally averaged net effect of human activities since 1750 has been  
4 one of warming. The last major challenge to whether the planet was warming or not was  
5 resolved in April 2006 with publication of "Temperature Trends in the Lower Atmosphere"  
6 (U.S. Climate Change Science Program, Synthesis, and Assessment Product 1.1, 2006).  
7 This study reconciled the remaining analytical issues regarding differences between surface  
8 and satellite temperature readings.

9 The climate models used to estimate temperature changes agree that it will be warmer in  
10 the future. According to the IPCC report, global average warming is expected to be about  
11 0.4°C (0.72°F) during the next 20 years. Even if the concentrations of all greenhouse gases  
12 and aerosols had been stabilized at 2000 levels, warming of 0.2°C (0.36°F) would be  
13 expected during this period (IPCC, 2007). Over the longer term, the IPCC models project  
14 average global temperature increases ranging from 1.1°C (1.98°F) to 6.4°C (11.5°F) by the  
15 end of the 21<sup>st</sup> century, although climate responses in specific regions will vary. These  
16 projections are the result of reviewing a robust set of global climate models under a variety  
17 of future scenarios – using a range of assumptions for future economic activity and energy  
18 use – for the earth as a whole.

19 The average increase in temperature may not be as important to the transportation  
20 community as the changes in extreme temperature, which also are expected to increase.  
21 Over the last 50 years, the frequency of cold days and nights has declined, while hot days,  
22 hot nights, and heat waves have become more frequent. The number of days with  
23 temperature above 32°C (90°F) and 38°C (100°F) has been increasing since 1970, as has  
24 the intensity and length of periods of drought. The IPCC report finds that it is virtually  
25 certain that the next century will witness warmer and more frequent hot days and nights  
26 over most land areas (IPCC, 2007).

27 **Precipitation patterns are changing, and more frequent intense precipitation events**  
28 **are expected.** Over the past century precipitation amounts have increased in several  
29 regions – including the eastern parts of North and South America – while drying has been  
30 observed in other regions in Africa and Asia. During the 21<sup>st</sup> century, the IPCC (2007)  
31 anticipates that increases in the amount of precipitation are *very likely* in high latitudes,  
32 while decreases are likely in most subtropical land regions, continuing observed patterns in  
33 recent trends. While total average levels of precipitation will vary by region, the incidence  
34 of extreme precipitation events is expected to increase.

35 According to NOAA analyses, the magnitude of the highest precipitation events has been  
36 increasing since 1970. A Simple Daily Intensity Index which examines the total  
37 precipitation for the United States divided by the number of days with precipitation clearly  
38 demonstrates an increase in average intensity from 1970 to 2005. These observed increases  
39 in extreme precipitation are not only in keeping with observational analyzes, but with  
40 model projections for the future. The IPCC AR4 (2007) concludes that heavy precipitation  
41 events will continue to become more frequent during the coming decades.

1       **Sea level is rising and the rate of change is likely to accelerate.** As the earth warms, two  
2 changes are occurring causing sea levels to increase: glacial melting and thermal  
3 expansion of the oceans. Sea level rise is perhaps the best documented and most accepted  
4 impact of climate change. The IPCC reports that – on a global level – the total 20<sup>th</sup> century  
5 rise is estimated to be 0.17 meter (0.56 feet), and that global sea level rose at an average  
6 rate of 1.8 mm (0.07 inches) per year between 1961 and 2003. Excluding rapid changes in  
7 ice flow, the IPCC model-based projections for global sea level rise over the next century  
8 across multiple scenarios range from 0.18 to 0.59 meters (0.59 to 1.94 feet). Should the  
9 melting of the land-based polar ice caps accelerate, sea level could rise much higher.

10       **The intensity of severe storms is expected to increase.** It is likely that future tropical  
11 cyclones (typhoons and hurricanes) will become more intense, with larger peak wind  
12 speeds and heavier precipitation (IPCC, 2007). (There is insufficient evidence to identify  
13 changing trends for other storm phenomenon, such as tornadoes, hail, and lightning (IPCC,  
14 2007); these types of storm activity are not addressed by this report.) There are several  
15 aspects of tropical storms that are relevant to transportation: precipitation, winds, and  
16 wind-induced storm surge. All three tend to get much worse during strong storms. Strong  
17 storms tend to have longer periods of intense precipitation and wind damage increases  
18 exponentially with wind speed. The primary concern with hurricanes is for strong storms  
19 of Categories 3, 4, and 5. These storms have considerably more destructive energy. For  
20 example, a Category 5 storm may have winds twice as fast as a Category 1 storm, but its  
21 kinetic energy is over four times that of a Category 1 storm.

22       Chapter 3.0 of this report provides a detailed discussion of how the climate is changing in  
23 the central Gulf Coast study area.

## 24   ■   **1.2 How Will Changes in Climate Affect Transportation?**

25       That the climate is changing leads to a number of intriguing and critically important  
26 questions for transportation. For the transportation community – the planners, engineers,  
27 builders, operators, and stewards of our nation’s roads, airports, rail, transit systems, and  
28 ports – the primary question is how such changes will affect infrastructure and associated  
29 services, and the trillions of dollars of investment these facilities represent. Transportation  
30 services are vital to our economy and quality of life. Individuals use transportation not  
31 only to get to and from work but for a wide variety of personal travel. Further,  
32 transportation systems increasingly are being used as our nation’s mobile warehouses as  
33 “just-in-time” delivery reduces producer warehousing costs and places new stresses on  
34 service providers to make sure that economic goods are delivered on time. As the number  
35 of vehicles – and miles traveled – continues to grow, congestion on our roadways is an  
36 increasing concern.

37       Nationally, we invest about \$110 billion annually in highways and transit alone. Federal  
38 investment in passenger rail approaches \$2 billion a year. Add to this the considerable  
39 investment made by the private sector in freight rail, airports, and ports, and it is clear that

1 the value that we place on these systems is enormous. Any disruption to the goods and  
2 services provided through the U.S. transportation network can have immediate impacts  
3 ranging from the annoying, such as flight delays due to severe weather, to the catastrophic,  
4 such as the chaos wrought by Hurricanes Katrina and Rita.

5 The question of how a changing climate might affect transportation infrastructure and  
6 services led the U.S. Department of Transportation (DOT), under the auspices of its Center  
7 for Climate Change and Environmental Forecasting, to hold a first-ever workshop on  
8 October 1-2, 2002. Cosponsored by the Environmental Protection Agency, the Department  
9 of Energy, and the U.S. Climate Change Science Program, the workshop brought together  
10 noted climate scientists, top transportation executives and practitioners, and experts in  
11 assessment research, environment, planning, and energy. This interdisciplinary group was  
12 charged to explore the potential impacts of climate change for transportation and to  
13 delineate the research necessary to better understand these implications. In preparation, the  
14 Center commissioned a series of white papers on overviews of climate change, regional  
15 case studies, potential system impacts, and environment and planning. The workshop  
16 participants identified significant gaps in the knowledge and processes necessary to fully  
17 incorporate climate science information into transportation decisions – and developed a  
18 framework to pursue future research in this multifaceted area of investigation. The two-  
19 day session deepened practitioners’ understanding of the significance of climate change for  
20 transportation, and led to a firm commitment by the DOT to pursue needed research. The  
21 Gulf Coast Study was designed to begin to address the research needs identified at this  
22 important forum.

### 23 **1.2.1 What are the Challenges to Research?**

24 Several research challenges must be met to successfully incorporate climate information  
25 into transportation decisions. Framing this new area of research is a complex undertaking  
26 that requires a new style of interdisciplinary work among scientists, planners, engineers,  
27 and policy-makers.

- 28 • **Articulating Data and Information Needs** – First, transportation practitioners need to  
29 be able to articulate the types of climate data and model projections that will be  
30 relevant to transportation decisions: *What information could lead a public or private*  
31 *transportation agency to change a transportation investment plan, road location, or*  
32 *facility design?* Determining what climate information is useful includes identifying  
33 the appropriate regional scale and timeframe for climate scenarios, as well as the types  
34 of climate factors that could result in a revised decision. Generating this practical  
35 information may require scientists to analyze and portray existing data in different ways  
36 in order to be useful to transportation decisions.
- 37 • **Identifying Most Relevant Climate Information** – At the same time, climate  
38 scientists need to be able to explain to transportation and planning professionals what  
39 information is available today that may be relevant to transportation decisions. The  
40 pace of climate science is advancing rapidly, and new and increasingly reliable climate

1 findings are being released regularly. The sheer volume of significant climate  
2 information poses a major challenge to the scientific community: How can scientists  
3 effectively translate the findings of basic research into information that can be  
4 understood by other professions – and the general public – and be applied to the  
5 choices transportation managers need to make?

- 6 • **Integrating Multiple Environmental Factors** – Further, climate factors need to be  
7 considered, not in isolation, but as part of a broader set of social and ecological factors  
8 that provide the context for thoughtful and informed transportation decisions. This will  
9 require that natural scientists and geospatial specialists work with transportation  
10 planners to integrate climate information into maps and data addressing other  
11 environmental factors. Incorporating new types of information – including longer-  
12 range climate scenario projections – may require the transportation community to adopt  
13 new approaches to planning and visioning exercises that engage a broader range of  
14 stakeholders and subject matter experts.
- 15 • **Incorporating Uncertainty** – An additional challenge is learning how to incorporate  
16 uncertainty in transportation decisions – how to assess risk and vulnerability of the  
17 transportation system and individual facilities given a range of potential future climate  
18 conditions. While transportation practitioners historically have planned and designed  
19 to meet established standards – for weight loads, flood levels, temperature extremes,  
20 etc. – today’s transportation planner needs to consider the most effective strategies to  
21 ensure a robust transportation system across a broader range of possible futures,  
22 potentially encompassing longer timeframes and a wider variety of impacts. This  
23 challenge may require new approaches to design and investment that use probabilistic,  
24 rather than deterministic, analysis.

25 To begin to explore these complex research questions, the team conducted a review of  
26 existing literature regarding climate change impacts on transportation to determine the state  
27 of science.

### 28 ■ **1.3 State of Science Regarding Climate Change Impacts** 29 **on Transportation**

30 What is the state of knowledge about climate change impacts on transportation? The  
31 research team undertook a review of the literature to assess the depth and breadth of  
32 existing research that specifically examines changes in climate and the resulting  
33 implications for transportation infrastructure and services.

34 Although there is a large body of research concerning climate change and how  
35 transportation contributes to greenhouse gas emissions, less work has been done  
36 concerning the impacts of climate change on transportation. A review of existing literature  
37 indicates that the impacts of climate change on transportation is an emerging area of  
38 research, and one that is growing steadily more sophisticated. As a new field, the level of

1 analysis given to the variety of subtopics within this broad area of research has been  
2 uneven; some aspects of climate change impacts on transportation have received much  
3 greater scrutiny than others depending on the particular concerns of individual authors and  
4 research sponsors.

### 5 **1.3.1 Overview of State of Practice**

6 Although there are relevant studies going back at least two decades, the pace of  
7 investigation has accelerated in more recent years. Several studies were conducted in this  
8 field in the late 1980s and early 1990s as international agreements on climate change were  
9 first under serious discussion (Marine Board, 1987; Hyman, 1989; Black, 1990; Irwin and  
10 Johnson, 1990). However, citations from this period are relatively infrequent, and as  
11 recently as 1998, FHWA (1998) found relatively little literature on this topic. Since then,  
12 the citations found show growing recognition of climate impacts on transportation as an  
13 issue; this topic was highlighted in the United States' Third National Communication as a  
14 topic under study (U.S. Department of State, 2002). In fact, the majority of references  
15 cited are from the new millennium (Table 1.1).

16 In addition to the growing number of research efforts, the analytic rigor of studies –  
17 particularly in the use of climate information – has progressed as well. While early  
18 discussions tend to be exploratory in nature, recent work has incorporated more  
19 sophisticated climate information and model outputs, addressed issues of uncertainty, and  
20 begun to examine the implications of climate factors on specific regions and infrastructure.  
21 This trend is likely to continue as awareness of the issues grows within the transportation  
22 community and decision-makers seek improved information and tools to assess risks and  
23 adaptation strategies.

24 The literature encompasses a wide variety of studies conducted for different time periods,  
25 sponsored by a range of organizations, and undertaken for different purposes. General  
26 characteristics of the literature reviewed are described below:

- 27 • **Key Climate Factors Examined** – The major climate factors most often discussed in  
28 the literature in terms of transportation impacts are temperature, precipitation, and sea  
29 level rise. Some articles explicitly dealt with storm activity or storm surge. (These  
30 climate factors are also analyzed as significant drivers in the Gulf Coast Study.) Many  
31 northern studies also examined permafrost thawing and navigation issues relating to ice  
32 cover on seaways and inland waterways.
- 33 • **Modal Focus** – Information on modes is uneven. The majority of articles dealt with  
34 highways and marine transport; other modes such as rail, aviation, and transit were not  
35 as well represented. Relatively few articles addressed pipelines or emergency  
36 management issues in the context of climate change.
- 37 • **Geographic Focus** – Much of the work done in this field has a national or regional  
38 focus; only the IPCC (1996 and 2001) has considered the topic at a truly global level.  
39 The Arctic Climate Impacts Assessment (Instanes et al., 2005) is a rare example of

1 transnational regional study, in that it focused on impacts throughout the Arctic nations.  
2 In addition, some studies focused on specific urban areas (Kirsten et al., 2004; Suarez,  
3 2005; Greater London Authority, 2005).

- 4 • **Climate Zones Examined** – The literature does not examine all climate zones equally  
5 or in proportion to the amount of transportation infrastructure present. In particular,  
6 transportation in Arctic climates received substantial study, as warming impacts already  
7 are being observed in those regions. Many other studies looked at temperate climates,  
8 as in the United States or Europe. Australian studies were among the few that  
9 examined desert climates or hot climates. In addition, most of the literature focused on  
10 the industrialized world.
- 11 • **Timeframe Examined** – Most studies examined time horizons of 50- to 100-years into  
12 the future, consistent with the timescale of projections and scenarios often used in the  
13 climate literature. Though this is well beyond the 20- to 30-year planning horizons  
14 typically used in transportation planning, it was noted in the literature that some  
15 infrastructure (such as bridges) is designed with life expectancies of 100 years or more  
16 (Eddowess et al., 2003; Wooler, 2004; Norwell, 2004). Other researchers eschewed  
17 timescales and instead chose specific thresholds to consider. For instance, Marine  
18 Board (1987) chose to examine the impacts of 0.5, 1.0, and 1.5 meter rises in sea levels,  
19 without specifying a projected year for when these might take place. Finally, several  
20 Arctic studies focused on changes *presently* occurring, as in Grondin’s (2005) study of  
21 the effect of thawing permafrost on airfields and roads in Nunavik due to increasingly  
22 warmer winters.

### 23 **1.3.2 Major Sponsors Conducting Related Research**

24 Studies on the impacts of climate change on transportation have been conducted by a  
25 variety of researchers and organizations, including governmental agencies, academic  
26 researchers, and the private sector, reflecting the range of stakeholders with an interest in  
27 the topic. These studies incorporate a variety of approaches, and can be found as stand-  
28 alone assessments of transportation impacts or as one aspect of a broader examination of  
29 climate impacts.

30 Two very significant impact assessment efforts have dealt with this issue in a limited  
31 fashion. The IPCC’s multivolume assessment reports (IPCC, 1996; IPCC, 2001) discussed  
32 the topic in general terms, particularly noting the vulnerability of transportation  
33 infrastructure in coastal zones and permafrost regions to climate impacts, with the 2001  
34 report broadly discussing some transportation operations impacts and more detail on  
35 Europe-specific concerns, such as impacts to aviation operations and river navigation.

36 Similarly, the U.S. National Assessment, which represents one of the broadest  
37 examinations of climate impacts to date in the U.S., did not include transportation as a  
38 sector of interest (National Assessment Synthesis Team, 2000). However, some of the  
39 regional studies conducted under the umbrella of the national assessment process did  
40 examine transportation impacts, most notably the Metro East Coast and Alaska studies

1 (Zimmerman, 2002a; Weller et al., 1999). The 2002 DOT report, *The Potential Impacts of*  
2 *Climate Change on Transportation: Summary and Discussion Papers*, contains 15  
3 discussion papers addressing potential climate impacts on various modes of transportation  
4 across the nation, and a summary of priority research needs identified.

5 The United Kingdom (U.K.) Climate Impacts Programme, an initiative similar to the U.S.  
6 National Assessment, specifically included impacts on the transportation sector in the  
7 overall assessment and in each of the regional reports prepared under its umbrella. The  
8 Canadian and Australian governments also have commissioned studies to examine impacts  
9 of special interest to them – Canada with permafrost concerns and interest in the opening of  
10 the Northwest Passage; Australia with dry land salinity impacts due to its unusual soil and  
11 climatic conditions (Andrey and Mills, 2003; Norwell, 2004). References to research on  
12 this topic also were seen for New Zealand, Finland, and the Netherlands (Kinsella and  
13 McGuire, 2005; Ministry of Housing, Spatial Planning, and the Environment, 2001). A  
14 small number of city agencies also have commissioned studies examining impacts to their  
15 own transportation networks, such as in Seattle and London (Soo Hoo, 2005; Greater  
16 London Authority, 2005).

17 Many studies also were identified in engineering and transportation journals, ranging from  
18 transportation-specific publications such as the National Academy of Science  
19 Transportation Research Board's (TRB) *Transportation Research Review* to more general  
20 sources such as *Civil Engineering – ASCE* or the *Journal of Cold Regions Engineering*, and  
21 even some transportation trade journals (Barrett, 2004). A small number of private sector  
22 reports, all from the U.K., were identified, including one study from a ports company and  
23 two from the insurance industry (ABP Marine Environmental Research, Ltd., 2004;  
24 Dlugolecki, 2004; Climate Risk Management and Metroeconomica, 2005).

25 Finally, though many nongovernmental organizations (NGO) are engaged in research and  
26 policy advocacy related to climate change, we found few NGOs producing literature on  
27 climate impacts on transportation. For instance, the Union of Concerned Scientists (UCS)  
28 and the Pew Center on Global Climate Change have both published multiple reports on  
29 impacts and adaptation (see the UCS regional impact studies<sup>1</sup> and Easterling, 2004), yet  
30 transportation implications have received little direct attention in these reports.

### 31 **1.3.3 State of Technical Analysis**

32 The level of technical analysis in current research regarding their use of climate data and  
33 modeling varies, depending both on when the study was done and the magnitude of the  
34 study. Early studies, for instance, focused on CO<sub>2</sub>-doubling scenarios (i.e., examining an  
35 equilibrium state at an unspecified point in the future), because standardized emissions and  
36 climate change scenarios had not yet been developed for researchers to use (Hyman, 1989;  
37 Black, 1990; Irwin and Johnson, 1990). Later studies took advantage of the climate

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<sup>1</sup> [http://www.ucsusa.org/global\\_warming/science](http://www.ucsusa.org/global_warming/science).

1 projections developed by the IPCC process or by other large modeling efforts, such as the  
2 U.S. and U.K. national assessments. Several studies demonstrated advanced approaches to  
3 climate modeling, making use of multiple climate models and regional models to generate  
4 projections of climate variables (Instanes et al., 2005; Kinsella and McGuire, 2005;  
5 National Assessment Synthesis Team, 2000; Entek UK Limited, 2004). Other studies took  
6 more simplified approaches, using global temperature or sea level rise projections as the  
7 basis for examining potential impacts. A few studies did not use climate modeling at all,  
8 instead relying on historic trend data (Sato and Robeson, 2006; ABP Marine  
9 Environmental Research Ltd., 2004).

10 In many cases, climate variables produced by global or regional climate models were used  
11 as inputs into secondary effects models relevant for specific transportation questions. For  
12 example, Cheng (2005) used permafrost models to assess the impact of rising temperatures  
13 on road and rail structures in Tibet. Lonergan et al. (1993) integrated climate projections  
14 into snowfall and ice cover models for northern Canada to understand climate impacts on  
15 freight shipments via ice roads and waterways.

16 On the whole, relatively few studies attempted to quantify the estimated costs, benefits, or  
17 effects on performance resulting from climate change; more commonly, they identified  
18 potential impacts without a quantitative assessment. Some examples of the kinds of  
19 quantitative analyses performed include:

- 20 • Hyman et al. (1989) estimated that it would cost more than \$200 million (in 1989  
21 dollars) to elevate affected Miami streets to compensate for rising groundwater levels  
22 due to sea level rise, and that increases in winter temperatures and decreases in  
23 snowfall would reduce Cleveland's snow and ice control budget by 95 percent (about  
24 \$4.4 million, or nearly 2 percent of the city's operating budget).
- 25 • Kirshen et al. (2004) estimated an 80 percent increase in traveler delays due to  
26 increased incidence of flooding in the Boston area. They also tested overall monetary  
27 and environmental costs for three adaptive strategies, finding that aggressive adaptation  
28 strategies proved less costly in the long run than doing nothing.
- 29 • Kinsella and McGuire (2005) estimated the approximate cost of retrofitting or  
30 redesigning New Zealand's road bridges to accommodate increased precipitation (and  
31 higher stream flows). They found that although designing for climate change increased  
32 initial costs by about 10 percent, over the life of the structure the incremental cost was  
33 small (less than 1 percent) due to the decreased probability of climate-related damage.
- 34 • Olsen (2005) conducted a Monte Carlo simulation of total annual losses to shippers on  
35 the Mississippi from having to switch to more expensive modes of transport when  
36 barge travel is restricted due to low or high water flows. He found that future losses  
37 could range from \$1.5 million to \$41 million per year, compared to an historical  
38 average of \$12 million per year.
- 39 • Associated British Insurers used insurance catastrophe models to examine the financial  
40 implications of climate change through its effects on severe storms (Climate Risk



1 Management and Metroeconomica, 2005), estimating that climate change could  
2 increase the annual costs of flooding in the United Kingdom almost 15-fold by the  
3 2080s under high-emissions scenarios.

4 Studies also have been done on the cost of severe storms on transportation networks, which  
5 will provide useful data for future studies relating them to climate change. For instance,  
6 Grenzeback and Lukmann (2006) summarize some costs to the transportation network  
7 resulting from Hurricane Katrina. Although they do not attempt a full accounting of these  
8 costs, they note that infrastructure restoration costs will run into the billions of dollars –  
9 replacement of the I-10 Twin Span Bridge between New Orleans and Slidell, Louisiana  
10 alone will cost \$1 billion and of the CSX rail line another \$250 million.

### 11 **1.3.4 Impacts, Assessment, and Adaptation**

12 A review of the literature indicates that the potential impacts of climate changes on  
13 transportation are geographically widespread, modally diverse, and may affect both  
14 transportation infrastructure and operations. Indeed, numerous transportation impacts were  
15 discussed in the literature. However, the degree to which a study discussed an impact  
16 varied; some studies addressed impacts at length, while others gave an impact only a  
17 passing mention. A complete list of impacts and adaptations addressed in the literature,  
18 along with references, can be found in Table 1.1.

19 Four major categories of climate change factors are addressed most frequently in the  
20 literature. These closely parallel the major factors addressed later in this report's study of  
21 the Gulf Coast region. These climate factors and their major impacts are:

- 22 1. **Increasing temperatures**, which can damage infrastructure, reduce water levels on  
23 inland waterways, reduce ice cover in the Arctic, and melt permafrost foundations;
- 24 2. **Increasing precipitation**, which can degrade infrastructure and soil conditions;
- 25 3. **Rising sea levels**, which can inundate coastal infrastructure; and
- 26 4. **Changes in storm activity**, which can damage infrastructure and operations due to  
27 increased storm intensity, though winter snowstorms may decrease in frequency.

28 A summary of the literature findings regarding these impacts, and their corresponding  
29 adaptation measures, is presented below. This is followed by a brief discussion of the  
30 indirect or secondary impacts, on the economy, environment, population, and security of a  
31 region.

32 [INSERT TABLE 1.1 Impacts of Climate Change Identified in the Literature 1987-2006]

### 1.3.5 Direct Climate Impacts on Transportation Addressed in Existing Literature

#### *Increasing Temperatures*

Increasing temperatures have the potential to affect multiple modes of transportation, primarily impacting surface transportation. The transportation impacts mentioned most often in the literature included pavement damage; rail buckling; less lift and fuel efficiency for aircraft; and the implications of lower inland water levels, thawing permafrost, reduced ice cover on seaways, and an increase in vegetation. These are discussed in greater detail below:

- **Pavement Damage** – The quality of highway pavement was identified as a potential issue for temperate climates, where more extreme summer temperatures and/or more frequent freeze/thaw cycles may be experienced. Extremely hot days, over an extended period of time, could lead to the rutting of highway pavement and the more rapid breakdown of asphalt seal binders, resulting in cracking, potholing, and bleeding. This, in turn, could damage the structural integrity of the road and/or cause the pavement to become more slippery when wet. Adaptation measures mentioned included more frequent maintenance, milling out ruts, and the laying of more heat resistant asphalt.
- **Rail Buckling** – Railroads could encounter rail buckling more frequently in temperate climates that experience extremely hot temperatures. If unnoticed, rail buckling can result in derailment of trains. Peterson (2006) noted, “Lower speeds and shorter trains, to shorten braking distance, and lighter loads to reduce track stress are operational impacts.” Adaptation measures included better monitoring of rail temperatures and ultimately more maintenance of the track, replacing it when needed.
- **Vegetation Growth** – The growing season for deciduous trees that shed their leaves may be extended, causing more slipperiness on railroads and roads and visual obstructions. Possible adaptation measure included better management of the leaf foliage and planting more low-maintenance vegetation along transportation corridors to act as buffers (Wooler, 2004).
- **Reductions in Aircraft Lift and Efficiency** – Higher temperatures would reduce air density, decreasing both lift and the engine efficiency of aircraft. As a result, longer runways and/or more powerful airplanes would be required. However, one analyst projected that technical advances would minimize the need for runway redesign as aircraft become more powerful and efficient (Wooler, 2004).
- **Reduced Water Levels** – Changes in water levels were discussed in relation to marine transport. Inland waterways such as the Great Lakes and Mississippi could experience lower water levels due to increased temperatures and evaporation; these lower water levels would mean that ships and barges would not be able to carry as much weight. Adaptation measures included reducing cargo loads, designing vessels to require less draft, or dredging the water body to make it deeper.

- 1       • **Reduced Ice Cover** – Reduced ice cover was generally considered a positive impact of  
2 increasing temperatures in the literature. For example, a study conducted by John D.  
3 Lindeberg and George M. Albercook, which was included in the *Report of the Great*  
4 *Lakes Regional Assessment Group for the U.S. Global Change Research Program*,  
5 stated, “the costs of additional dredging [due to lower water levels] could be partially  
6 mitigated by the benefits of additional shipping days on the [Great] Lakes caused by  
7 less persistent ice cover” (Sousounis, 2000). Additionally, arctic sea passages could  
8 open; for example, the *Arctic Climate Impact Assessment* noted, “projected reductions  
9 in sea-ice extent are likely to improve access along the Northern Sea Route and the  
10 Northwest Passage” (Instanes et al., 2005). However, negative environmental and  
11 security impacts also may result from reduced ice cover as well from as the increased  
12 level of shipping. These are discussed below in the subsection on indirect impacts  
13 (Section 1.3.6.).
- 14       • **Melting Permafrost** – The implications of melting permafrost for Arctic infrastructure  
15 receive considerable attention in the literature. Permafrost is the foundation upon  
16 which much of the Arctic’s infrastructure is built. The literature consistently noted that  
17 as the permafrost thaws the infrastructure will become unstable – an effect being  
18 experienced today. Roads, railways, and airstrips are all vulnerable to the thawing of  
19 permafrost. Adaptation measures vary depending on the amount of permafrost that  
20 underlies any given piece of infrastructure. The literature suggested that some assets  
21 will only need rehabilitation, other assets will need to be relocated, and different  
22 construction methods will need to be used, including the possibility of installing  
23 cooling mechanisms. According to the Arctic Research Commission, “roads, railways,  
24 and airstrips placed on ice-rich continuous permafrost will generally require relocation  
25 to well-drained natural foundations or replacement with substantially different  
26 construction methods” (U.S. Arctic Research Commission Permafrost Task Force,  
27 2003).
- 28       • **Other** – Other impacts of increasing temperatures included a reduction in ice loads on  
29 structures (such as bridges and piers) that could eventually allow them to be designed  
30 for less stress, and a lengthening of construction seasons due to fewer colder days in  
31 traditionally cold climates.

### 32 ***Increasing Precipitation***

33 Increases in precipitation will likely affect infrastructure in both cold and warm climates,  
34 although in different ways. Increases in the frequency and intensity of the precipitation  
35 could impact roads, airstrips, bikeways/walkways, and rail beds. The literature suggested  
36 most of the impact would be felt in the more rapid deterioration of infrastructure.  
37 According to a report released by Natural Resources Canada in 2004, “accelerated  
38 deterioration of these structures may occur where precipitation events and freeze-thaw  
39 cycles become more frequent, particularly in areas that experience acid rain.” Other  
40 impacts of increased flooding include subsidence and heave of embankments (ultimately  
41 resulting in landslides), and deterioration in water quality due to run-off and sedimentation.  
42 Adaptation measures included monitoring infrastructure conditions, preparing for service

1 delays or cancellations, and replacing surfaces when necessary (Warren, 2004). Although  
2 mentioned less frequently, some attention was given in the literature to bridge scour from  
3 increased stream flow. Bridge scour could cause abutments to move and damage bridges.

#### 4 ***Rising Sea Levels***

5 Sea level rise could impact coastal areas. While incremental sea level rise impacts may not  
6 be as immediate or severe as the storm activity, the impacts could nevertheless affect all  
7 modes of transportation. Low-level roads and airports are at risk of inundation, and ports  
8 may see higher tides. Titus concluded “the most important impact of sea level rise on  
9 transportation concerns roads. In many low-lying communities, roads are lower than the  
10 surrounding lands, so that land can drain into the streets. As a result, the streets are the first  
11 to flood.” Adaptation measures include more frequent maintenance, relocation, and the  
12 construction of flood defense mechanisms (such as dikes) (Titus, 2002). Although  
13 mentioned less often in the literature, deeper water caused by sea level rise could permit  
14 greater ship drafts in ports and harbors.

#### 15 ***Changes in Storm Activity***

16 Storm activity was discussed as an issue for all climates, impacting both inland areas and  
17 coastal areas. Impacts most frequently mentioned in the literature include storm surges that  
18 could potentially cause damage to coastal areas, and a decrease in winter snowstorms (with  
19 more winter precipitation falling as rain). These are discussed in greater detail below:

- 20 • **Increased Storm Activity or Intensity** – In coastal areas, increased storm activity or  
21 intensity could lead to an increase in storm surge flooding and severe damage to  
22 infrastructure, including roads, rails, and airports. These effects could be exacerbated  
23 by a rise in sea level. In addition, coastal urban areas, like New York City, could  
24 potentially see storm surges that flood the subway system. As Zimmerman noted,  
25 “transportation systems are traditionally sited in low-lying areas already prone to  
26 flooding.” She went on to state that, “New York City alone has over 500 miles of  
27 coastline, much of which is transgressed [sic] by transportation infrastructure –  
28 roadways, rail lines, and ventilations shafts, entrances and exits for tunnels and transit  
29 systems, many are at elevations at risk of being flooded even by traditional natural  
30 hazards.” Adaptation measures included construction of barriers to protect against  
31 storm surges, relocating infrastructure, and preparing for alternative traffic routes  
32 (Zimmerman, 2002a).

33 Other impacts related to storm activity included an increase in wind speed and an  
34 increase in lightning. Increased wind speeds could damage signage and overhead  
35 cables. Increased lightning strikes could cause electrical disturbances disrupting  
36 electronic transportation infrastructure, like signaling.

- 37 • **Reduced Snowfall** – A decrease in winter snowstorms could potentially relieve areas  
38 that typically see large amounts of snow from some of the cost of maintaining winter  
39 roads. Natural Resources Canada concluded, “empirical relationships between weather

1 variables and winter maintenance activities indicated that less snowfall is associated  
2 with reduced winter maintenance requirements. Thus, if populated areas were to  
3 receive less snowfall and/or experience fewer days with snow; this could result in  
4 substantial savings for road authorities” (Warren et al., 2004).

### 5 **1.3.6 Indirect Climate Impacts on Transportation Addressed in** 6 **Existing Literature**

7 Four secondary, or indirect, impacts were addressed to some degree in the literature:  
8 economic, environmental, demographic, and security impacts.

#### 9 ***Economic***

10 The economic impact of climate change received considerable attention. Some studies  
11 made an attempt to approximate the cost of replacing infrastructure, or place a monetary  
12 figure on loss of specific aspects of system performance, such as traffic disruptions. For  
13 example, Suarez et al., when discussing the effects flooding could have on the Boston  
14 Metro area, stated, “over the period 2000 to 2100, the results indicate that delays and trips  
15 lost (i.e., canceled trips) increased by 80 percent and 82 percent under the climate change  
16 scenario. While this is a significant increment in percentage terms, the magnitude of the  
17 increase is not enough to justify a great deal of infrastructure improvements.”

18 The economic implications of impacts on freight were particularly studied. Three climate  
19 factors were analyzed in most depth: changing inland water levels, specifically on the  
20 Great Lakes; thawing permafrost and warmer temperatures in traditionally colder climates;  
21 and the potential opening of the Northwest Sea Passage through the Canadian Arctic as a  
22 result of sea ice melt. These are discussed in greater detail below:

- 23 • **Changing Inland Waterway Levels** – Quinn analyzed the economic impacts of lower  
24 water levels in the Great Lakes, which would require ships to lighten their loads  
25 because of lower water levels. According to Quinn (2002), “a 1,000-foot bulk carrier  
26 loses 270 tons of capacity per inch of lost draft.” If lower water levels occur on a  
27 regular basis, Great Lakes shippers are likely to see less profit, and will run the risk of  
28 the freight being transported by competing modes (e.g., rail or truck). A few analyses  
29 considered the impacts of rising inland water levels (Olsen, 2005).
- 30 • **Increasing Temperatures in Northern Regions** – Other analysts assessed the  
31 economic impacts of warming temperatures on trucking in northern regions. Typically,  
32 trucks are allowed to carry more weight when the underlying roadbeds are frozen, and  
33 some Arctic regions are served by ice roads over the tundra in winter. If temperatures  
34 increase and northern roads thaw before their usual season, truckloads may have to be  
35 reduced during the traditionally higher weight-limit trucking season. This impact  
36 already is occurring in some regions of the United States and Canada. As a result, a  
37 few highway authorities are adjusting their weight restrictions based on conditions,  
38 rather than linking them to a given date (Clayton et al., 2005).

- 1       • **Opening of the Northwest Passage** – The literature indicated that the reduction of  
2       waterway ice cover and the eventual opening of an Arctic Northwest Passage have by  
3       far the largest economic consequences of all the impacts. The passage could provide an  
4       alternative to the Panama Canal and stimulate economic development in the Arctic  
5       region (Johnston, 2002).

## 6       *Environmental*

7       A small number of environmental impacts have been addressed in the literature to date,  
8       focusing on the effects of specific adaptation responses to changing climate and weather  
9       conditions. These included the potential of increased dredging of inland waterways,  
10      reduced use of winter road maintenance substances, and the environmental impact  
11      increased shipping could have on the Arctic.

- 12      • **Dredging** – Dredging of waterways – in response to falling water levels – could have  
13      unintended, harmful environmental impacts. According to the Great Lakes Regional  
14      Assessment, “in a number of areas the dredged material is highly contaminated, so  
15      dredging would stir up once buried toxins and create a problem with spoil disposal”  
16      (Sousounis, 2000).
- 17      • **Increased Shipping in the Arctic** – The transportation benefits of the Northwest  
18      Passage could be offset by the negative environmental impacts associated with its use,  
19      particularly oil spills (Struck, 2006). Johnston (2002) noted that there is “serious  
20      concern on the part of many Inuit and other residents that regular commercial shipping  
21      will, sooner or later, cause serious harm to the Arctic ecology.”
- 22      • **Reduced Winter Maintenance** – Some positive environmental impacts also were  
23      mentioned, particularly in relation to milder winter weather in northern regions. For  
24      example, “less salt corrosion of vehicles and reduced salt loadings in waterways, due to  
25      reduced salt use” during winter months could positively impact the environment.  
26      According to Natural Resources Canada, “experts are optimistic that a warmer climate  
27      is likely to reduce the amount of chemicals used, thus reducing costs for the airline  
28      industry, as well as environmental damage caused by the chemicals” (Warren et al.,  
29      2004).

## 30      *Demographic*

31      Demographic shifts were rarely addressed in the literature. A few reports raised the  
32      potential for shifts in travel destinations and mode choices. For instance, in a U.K. Climate  
33      Impacts Programme Report on the West Midlands it was noted: “1) higher temperatures  
34      and reduced summer cloud cover could increase the number of leisure journeys by road;  
35      and 2) there could be a possible substitution from foreign holidays if the climate of the  
36      West Midlands becomes more attractive relative to other destinations, reducing demand at  
37      Birmingham International Airport.” In addition, the Arctic regions, located near the  
38      Northwest Passage, could see an influx of population (Entek UK Limited, 2004).

## 1 **Security**

2 Security was identified as an issue in relation to the Northwest Passage. Given the  
3 enormous changes the development of the Northwest Passage would precipitate, it is no  
4 surprise that global diplomacy, safety, and security is of concern. Johnston stated, “even if  
5 the remoteness of the Northwest Passage seems to make it an unlikely target for terrorists,  
6 security concerns will centrally have to be factored in to any major undertaking in the  
7 Arctic or elsewhere that would be perceived by enemies as an important component of the  
8 North American economy.” If the Northwest Passage does become practical for shipping,  
9 security, ownership, maintenance, and safety of the waterway will become an issue.  
10 Indeed, the U.S. Navy already had begun thinking about the implications of an ice-free  
11 Arctic during a symposium held in April 2001 (Office of Naval Research, 2001).  
12 Sovereignty issues also will need to be resolved to clarify whether the passage will be  
13 considered international or Canadian waters (Johnston, 2002).

### 14 **1.3.7 Decision-Making Processes and Tools**

15 Until recently, studies typically concluded with recommendations for additional analysis of  
16 uncertainty, thresholds, and prioritization of actions. Recent work has begun to respond to  
17 this need, but the field still has a long way to go. Some reports have begun to make  
18 suggestions for institutional changes necessary to integrate climate impacts into the  
19 transportation planning and investment decision-making process. Studies have suggested  
20 some approaches to more adequately dealing with uncertainty. Finally, several studies  
21 have attempted to develop methodologies that can integrate potential climate impacts into  
22 risk prioritization processes, decision trees, and other decision support tools.

23 The following sections discuss institutional changes that were identified in the literature,  
24 evaluate the manner in which uncertainty and probability was addressed, and present four  
25 case studies highlighting different methodologies used in risk analysis and impact  
26 assessment.

### 27 ***Institutional Changes***

28 On the whole, analysis and recommendations concerning needed changes in standard  
29 design practice or institutional changes are beginning to emerge, but are at a nascent stage.  
30 A few recent studies illustrate this point:

- 31 • **Urban-Scale Planning** – Two recent studies developed recommendations for London  
32 and Seattle. The Greater London Authority (2005) urged transportation decision-  
33 makers to incorporate climate into routine risk management procedures, build  
34 adaptation measures into new infrastructure when appropriate, and make certain that  
35 whatever measures are taken are flexible and easily adaptable to future climatic  
36 changes. However, the report gave little direction on how they should go about this;  
37 suggestions about how and when officials should incorporate these adjustments were  
38 not well-defined. Likewise, a 2005 Seattle study, authored by the city auditor,

1 recommended that the Seattle Department of Transportation “identify, prioritize, and  
2 quantify the potential effects of climate change impacts; and plan appropriate responses  
3 to changes in the region’s climate.” A specific institutional recommendation made was  
4 the synchronization of sea level rise assumptions among Seattle’s various city agencies  
5 (for instance, in the assumptions made for construction of seawalls) (Soo Hoo et al.,  
6 2005).

- 7 • **Arctic Maritime Regulatory Regime** – For the Arctic, several studies identified the  
8 need for a new regulatory system to govern ships in Arctic waters. Johnston (2002)  
9 recommended a new “transit management regime” be developed for the Northwest  
10 Passage to clarify Canadian and international responsibilities and jurisdiction over  
11 maritime passage, and the Arctic Marine Transport Workshop (Brigham, 2004)  
12 suggested the development of harmonized safety and environmental measures for the  
13 larger Arctic region.
- 14 • **General Planning Considerations** – Several other reports recommended that as a first  
15 step a process be developed for including climate impacts in planning. For instance,  
16 the Northern Ireland assessment recommended that a formalized policy on climate  
17 impacts be developed within three years (Smyth et al., 2002), and Associated British  
18 Ports indicated that it planned to periodically re-examine potential impacts to ports in  
19 order to see if their assessment changes with new information (ABP Marine  
20 Environmental Research Ltd., 2004). Interestingly, Norwell (2004) noted that planning  
21 for sea level rise already has been incorporated into planning documents in several  
22 Australian states.

23 In general, the mismatch between typical planning horizons and the longer-term  
24 timeframe over which climate impacts occur appears to be a barrier to incorporating  
25 climate change factors in decision-making. For example, Kinsella and McGuire (2005)  
26 concluded that for infrastructure with replacement horizons of less than 25 years, there  
27 was no need to consider longer-term climate effects in the present day, as the  
28 infrastructure would turn over before it became a problem.

### 29 ***Uncertainty and Probability***

30 The literature indicates that only recently have analysts begun to address the issue of  
31 transportation risk assessment and decision-making under uncertainty. Even now, the  
32 analytical sophistication of studies that attempt to address these concerns is in its infancy.  
33 The studies consistently showed awareness of the uncertainty of climate projections,  
34 quoting ranges for potential climate changes. However, probabilistic approaches were not  
35 implemented in the literature reviewed, and rarely discussed. Nor was there a focus on the  
36 development of “robust” strategies that can bear up under multiple possible futures, or  
37 other strategies designed specifically to deal with decision-making under uncertainty.  
38 Dewar and Wachs (forthcoming) note that this is a gap in transportation planning more  
39 generally, and not simply in the matter of climate change. They call for a paradigmatic  
40 shift in transportation planning approaches.



1 Several studies did discuss possible approaches to the issue of uncertainty and decision-  
2 making, without applying them to specific cases. For example, Meyer (forthcoming) noted  
3 that, “in recent years, many engineering design analyses have been incorporating more  
4 probabilistic approaches into their design procedures that account for uncertainty in both  
5 service life and in environmental factors.” He continued, “In considering wind speeds, for  
6 example, probabilities of different wind speeds occurring based on an underlying  
7 distribution of historical occurrences are used to define a design wind speed. Other  
8 analysis approaches are incorporating risk management techniques into the tradeoff  
9 between design criteria that will make a structure more reliable and the economic costs to  
10 society if the structure fails.” Furthermore, Dewar and Wachs (forthcoming) discuss a  
11 wide variety of conceptual decision-making tools which could be considered when  
12 designing frameworks to understand how to incorporate climate uncertainty into  
13 transportation infrastructure decisions.

#### 14 ***Approaches to Risk Analysis and Impact Assessment***

15 Among those studies that attempted to implement a risk analysis or impact assessment  
16 framework for a particular transportation system, a number of different approaches were  
17 taken. For instance, Associated British Ports demonstrates an approach to risk evaluation  
18 that relies on expert elicitation to make a judgment on risk levels for U.K. ports (ABP  
19 Marine Environmental Research Ltd., 2004). Risk was broken into four themes:  
20 1) flooding; 2) insurance; 3) physical damage; and 4) disruption. Port managers were  
21 asked to evaluate the risk level of each impact by indicating whether they thought it was a:  
22 1) Very Low Risk; 2) Low Risk; 3) Moderate Risk; 4) High Risk; or 5) Very High Risk.  
23 Using this methodology, the study concluded that storm surge events represent the biggest  
24 threat to U.K. ports.

25 For the U.K. rail network, Eddowess et al. (2003) developed a framework for prioritizing  
26 risks that integrates the probability that a particular climate effect would impact the rail  
27 industry (“risk likelihood”) with the scale of the impact, if it did occur (“risk impact”). The  
28 “risk likelihood” essentially combined an assessment of the present-day vulnerability to  
29 specific climate factors with projections of how they might change under global climate  
30 change scenarios, while the “risk impact” took into account the severity of a given impact,  
31 the amount of infrastructure affected, and the ability to adapt to the change.

32 Their study did not explicitly specify thresholds for when a given level of adaptation was  
33 worth implementing. Transit New Zealand developed a methodology for determining  
34 thresholds for taking action, using a two-stage process (Kinsella and McGuire, 2005). The  
35 first stage constituted a decision tree that examined the necessity of taking action in the  
36 near term. No action was deemed necessary if it was determined that a given impact was  
37 unlikely to occur before 2030, or that the impact would not occur within the design life of  
38 the facility (for facilities with lifetimes of less than 25 years), or that current standards  
39 would adequately address the climate impact. If present-day action deemed necessary, the  
40 second stage analysis determined the feasibility of taking action by comparing the costs of  
41 doing nothing, retrofitting the infrastructure, or designing all new infrastructure with future  
42 climate changes in mind.

1 Finally, the CLIMB report develops tools for scenario analysis tools and decision support  
2 for Boston decision-makers to use in understanding climate impacts. Specifically, the  
3 researchers developed a dynamic analytical modeling tool to help policy and decision-  
4 makers assess changes in climate, socioeconomic, and technological developments and  
5 understand their associated interrelated impacts on Boston's infrastructure system as a  
6 whole. The model allows users to input climate drivers in order to assess performance  
7 impacts and potential adaptation strategies for infrastructure systems, including  
8 transportation. (Kirshen et al., 2004)

## 9 ■ 1.4 Conclusions Drawn from Current Literature on the 10 State of Research

11 Assessing the literature on the impacts of climate change on transportation as a whole, it  
12 becomes apparent that there are a number of areas in which more research is needed on  
13 potential impacts of climate change on transportation. Many authors noted that research on  
14 the potential impacts of climate change on transportation systems is limited. Warren et al.  
15 (2004) note that though much work has been done on adaptation to climate change in  
16 general, relatively little concerns climate impacts on transportation systems – to date,  
17 transportation research has been focused on emission-reduction strategies. Other authors  
18 noted the need for more research on specific impacts or modes. For instance, in their study  
19 of seasonal weight limits on prairie highways, Clayton et al. (2005) noted that there was  
20 essentially no transportation and climate impacts literature on their topic to draw upon.

21 Work in this field has so far been focused on the initial stages of risk assessment and  
22 adaptation: i.e., building a basic understanding of the issues involved. In general, the  
23 literature review shows that some work has been done on collecting data, assessing  
24 impacts, and evaluating the significance of these risks. Less work has been done to  
25 develop methodologies for assessment or to systematically evaluate adaptation strategies.  
26 Work to develop decision support tools to facilitate these processes has received little  
27 formal attention. The state of research in each analytic area is summarized below.

28 **Collecting Data Needed to Assess Transportation Vulnerability to Climate Impacts.**  
29 Some credible work on data collection and analysis has been done for selected modes and  
30 facilities in specific regions. Researchers have been able to make use of the good data on  
31 transportation networks and transportation engineering practice that exists for most of the  
32 developed world.

33 Most studies used climate projections consistent with long-term IPCC global projections as  
34 the basis for their analyses. However, few studies considered a broader range of plausible  
35 climate futures that could occur, such as scenarios, including additional feedbacks or abrupt  
36 climate change. In addition, few studies addressed the implications of changes in  
37 temperature or precipitation extremes.

1 In addition, there are significant gaps in data collection and analysis for several modes and  
2 for transportation infrastructure in hot or tropical climates, such as are found in the  
3 southwestern and southeastern portions of the United States. Most of the available  
4 literature addresses temperate or Arctic climates.

5 **Developing Knowledge about Potential Impacts.** Researchers considered a wide variety  
6 of potential impacts on transportation, and significant work has been done for selected  
7 modes and facilities. However, a number of important gaps were found in the current  
8 literature, most notably the lack of quantitative assessment and dearth of literature on  
9 operations, network, performance, and secondary impacts:

- 10 • **Quantitative Assessment** – Most studies to date have been qualitative. More  
11 quantitative assessments of impacts, along with the development of quantitative  
12 analytical methodologies, will provide needed information for decision-makers.
- 13 • **Operations Impacts** – The implications of climate change impacts on operations (both  
14 normal and emergency) are not as well explored as they are for physical infrastructure.  
15 Most of the existing literature on operations is focused on a select few issues such as  
16 waterborne freight and winter maintenance.
- 17 • **Network and Performance Impacts** – Relatively few studies (Kirshen et al., 2004;  
18 Suarez et al., 2005) focused on the network-level impacts of climate change. Most  
19 focused on the facility level (impacts to a type of facility, for instance, rather than  
20 system-level impacts on the whole network), and few measured performance impacts.
- 21 • **Secondary Impacts** – Several secondary impacts mentioned in the literature but not  
22 discussed in-depth could provide useful avenues for further study. These include shifts  
23 in transportation demand due to climate-induced changes in economic activity and  
24 demographics; the impact of a warming climate on air quality (which influences  
25 transportation investment decisions); and other environmental impacts related to  
26 climate change that may intersect with transportation decision-making in relation to  
27 ecosystem and habitat preservation, water quality and stormwater management,  
28 mitigation strategies, safety, and system and corridor planning.

29 **Assessing the Significance of these Risks.** Work in this area is largely qualitative.  
30 Though many researchers were able to communicate an assessment of which risks were  
31 significant enough to require further study, few produced quantitative assessments of cost  
32 or performance impacts. In particular, more work is needed regarding the economic  
33 implications of climate impacts on transportation facilities and systems. Relatively few  
34 studies addressed this quantitatively from an overall life-cycle benefits/costs framework.

35 **Developing a Methodological Approach for Assessment.** Most studies used a similar  
36 basic approach (identify climate effects of concern, assess potential risks for specific  
37 modes/facility types, and identify potential adaptations). However, very few attempted to  
38 develop a generalized approach or consider the ramifications of translating their approach  
39 to other modes/regions.

1       **Identifying Strategies for Adaptation and Planning.** Most studies dealt with adaptation  
2       from a facility engineering approach, rather than a strategic or systems performance level.  
3       Thus, it is largely specific design adaptations appropriate for particular types of facilities  
4       that were identified in the literature (for instance, insulating railbeds to prevent permafrost  
5       melt, or raising roads to protect it against sea level rise).

6       Nonetheless, beginning elements of larger adaptation strategies were recognized in the  
7       literature. There is a general understanding of the differences between likely short- and  
8       long-term effects, and acknowledgment that different approaches might be needed at  
9       different points in time (Meyer, forthcoming). In addition, some studies recognized that  
10      institutional change is necessary and recommended institutional processes for examining  
11      impacts and deciding on adaptations.

12      Significantly, almost no research has been done on how climate change can be incorporated  
13      into the long-range transportation planning process. Issues to address in future research  
14      include the mismatch between the timeframe of 20- and 30-year long-range plans and the  
15      50- and 100-year projections of climate impacts; how to address the potential for nonlinear  
16      or abrupt changes in climate systems in a planning process; and how to make planning  
17      decisions that account for uncertainty in climate projections.

18      **Developing Decision-Support Tools.** Very little work has been done to develop decision-  
19      support tools for transportation managers and planners. The field is sufficiently new that  
20      there has likely been little demand from transportation decision-makers for such tools;  
21      rather they are only now beginning to learn about the potential impacts they might face in  
22      the future.

23      One of the most important gaps in this area is the lack of probabilistic approaches to  
24      address uncertainty. More sophisticated methodologies to incorporate uncertainty will  
25      need to be developed for transportation decision-makers in order to incorporate climate  
26      change into transportation planning. Currently, uncertainty is rarely incorporated in a  
27      probabilistic sense in the literature on climate impacts on transportation (though the  
28      existence of uncertainty is acknowledged and expressed through the use of ranges in the  
29      climate factors, and sometimes the use of scenarios). In addition, little attention is given to  
30      decision-making practices under uncertainty, such as the development of adaptation  
31      strategies that are robust across multiple potential futures.

32      In summary, research on the potential impacts of climate change on transportation is an  
33      emerging field, and one that has shown a remarkable upturn in interest and activity over the  
34      past few years. This has coincided with greater interest in the subject of adaptation in  
35      general, as recognition has grown that some degree of climate change is inevitable in the  
36      coming decades, even as steps are taken to reduce future emissions. Considerable work  
37      remains to be done in bringing this field to a greater level of maturity, including  
38      investigations of impacts not yet thoroughly examined and developing strategies,  
39      methodologies, and tools that decision-makers at all levels can use to both assess the  
40      importance of climate impacts and identify ways to respond.

## ■ 1.5 Gulf Coast Study Selection, Objectives, and Organization

### 1.5.1 Study Selection

To advance research on the implications of climate change for transportation, the DOT Center for Climate Change solicited and reviewed a range of project concepts. A case study approach was selected as an initial research strategy that would both generate concrete, useful information for local and regional decision-makers, while helping to develop a prototype for analysis in other regions and contribute to research methodologies for broader application.

In selecting the study, DOT considered the extent to which the research would:

- Increase the knowledge base regarding the risks and sensitivities of transportation infrastructure to climate variability and change, the significance of these risks, and the range of adaptation strategies that may be considered to ensure a robust and reliable transportation network;
- Provide relevant information and assistance to transportation planners, designers, and decision-makers;
- Build research approaches and tools that would be transferable to other regions or sectoral analyses;
- Produce near-term, useful results;
- Address multiple aspects of the research themes recommended by the 2002 workshop;
- Build on existing research activities and available data; and
- Strengthen DOT partnerships with other Federal agencies, state and local transportation and planning organizations, research institutions, and stakeholders.

Based on these criteria, the DOT selected a study of the Gulf Coast as the first of a series of research activities that the DOT Center for Transportation and Climate Change will pursue to address these research priorities.

There are several intended uses for the products of this study. First, the findings of the study will help inform local and regional transportation decision-makers in the central U.S. Gulf Coast region. While focused on one region of the United States, it is expected that this study will provide a prototype for analysis in other regions. The study findings will contribute to research methodologies in this new area of investigation. For example, Phase I has identified priority databases and methodologies for the integration of data for analysis in a GIS format, developed formats for mapping products, and developed criteria for assessing and ranking infrastructure sensitivities to the potential impacts of climate variability and change. Each of these outputs will offer useful information and example

1 methodologies to research activities in other locations, as well as to transportation and  
2 planning decision-making processes in other areas. This research also is intended to help  
3 scientists and science agencies better understand the transportation sector's information  
4 needs, leading to improved data and better decision support.

## 5 **1.5.2 Gulf Coast Study Objectives and Three Phases**

6 The Gulf Coast Study has been organized into three phases, as depicted in Figure 1.1. This  
7 report presents the findings of Phase I. The objectives of the overall study are to:

- 8 • Develop knowledge about potential transportation infrastructure sensitivities to climate  
9 changes and variability through an in-depth synthesis and analysis of existing data and  
10 trends;
- 11 • Assess the potential significance of these sensitivities to transportation decision-makers  
12 in the central U.S. Gulf Coast region;
- 13 • Identify potential strategies for adaptation that will reduce risks and enhance the  
14 resilience of transportation infrastructure and services; and
- 15 • Identify or develop decision support tools or procedures that enable transportation  
16 decision-makers to integrate information about climate variability and change into  
17 existing transportation planning and design processes.

18 The two primary objectives of Phase I of the central Gulf Coast transportation impact  
19 assessment were to: 1) collect data needed to characterize the region – its physiography  
20 and hydrology, land use and land cover, past and projected climate, current population and  
21 trends, and transportation infrastructure; and 2) demonstrate an approach for assessing risks  
22 and vulnerability of transportation at regional and local scales. The results of this analysis  
23 are presented in this report. The methodologies developed during Phase I of the study can  
24 be applied to assess transportation risk and vulnerability at a community, county, or  
25 regional level.

26 Phase II of the study will entail an in-depth assessment of impacts and risks to selected  
27 areas and facilities (as identified in Phase I) and will contribute to the development of risk  
28 assessment tools and techniques that can be used by transportation decision-makers to  
29 analyze the vulnerability of other areas.

30 The objectives of Phase III are to identify the range of potential adaptation strategies  
31 available to Federal, regional, and local transportation managers to respond to the risks  
32 identified in Phases I and II; to identify the potential strengths and weaknesses of these  
33 responses; and to develop an assessment tool that may assist transportation managers in  
34 selecting adaptation strategies appropriate to their agency, community, or facility, and to  
35 the identified sensitivity to climate change.

36 [INSERT FIGURE 1.1 Gulf Coast Study Design]

### 1.5.3 Study Organization and Oversight

The Gulf Coast Study is 1 of 21 “synthesis and assessment” products planned and sponsored by the U.S. Climate Change Science Program (CCSP). The primary objective of the CCSP is to provide scientific information needed to inform public discussions and government and private sector decision-making on key climate-related issues. This project is one of seven projects organized under CCSP Goal 4, which is “to understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes” (CCSP, 2003).

Led by the U.S. Department of Transportation (DOT) in collaboration with the U.S. Geological Survey (USGS), this study was conducted through a groundbreaking interdisciplinary approach that integrated natural science disciplines with expertise in risk assessment, transportation, and planning. DOT and USGS convened a research team with expertise in multiple fields based on each agency’s mission and core capabilities. USGS coordinated the provision of scientific research support, coordinating expertise in climate change science and impacts assessment; meteorology; hydrology; storm surge analysis and modeling; risk analysis; and economics. Cooperators from Louisiana State University, the University of New Orleans, and Texas A&M University assisted in the data collection aspects of Phase I and in developing a framework for assessing risk and vulnerability. (DOT assembled expertise in transportation planning, engineering, design, and operation.) Cambridge Systematics, Inc., (CS) a transportation consulting firm, supported the coordination and design of the study, assisted in organizing the data, and provided transportation experts with expertise in ports, rail, highways and transit, pipelines, aviation, emergency management, and transportation planning and investment. The CS Transportation Analysis Team included consultant support from Wilbur Smith Associates and the Texas Transportation Institute. DOT’s Bureau of Transportation Statistics (BTS) supported geospatial and other data collection and analysis related to transportation, working in coordination with USGS geospatial experts. Collectively, this group of scientists and transportation experts has served as the research team conducting Phase 1 of the study.

The Secretary of Transportation, following the guidelines of the Federal Advisory Committee Act (5 U.S.C. App. 2) or “FACA,” established a U.S. Department of Transportation’s (DOT) Advisory Committee on Synthesis and Assessment Product 4.7: Impacts of Climate Variability and Change on Transportation Systems and Infrastructure – Gulf Coast Study, Phase I. The committee provides technical advice and recommendations in the development of this product for the CCSP. The committee provides balanced, consensual advice on the study design, research methodology, data sources and quality, and study findings. The committee functions as an advisory body to the two Federal agencies leading the research project.

This product adheres to Federal Information Quality Act (IQA) guidelines and Office of Management and Budget (OMB) peer review requirements. Background sources of information, included as illustrative material and to provide context, are clearly identified as such at the end of the list of sources in each chapter.

## 1.5.4 Characterizing Uncertainty

Some degree of uncertainty is inherent in any consideration of future climate change; further, the degree of certainty in climate projections varies for different aspects of future climate. Throughout this report, the research team has adopted a consistent lexicon first developed by the IPCC to indicate the degree of certainty that can be ascribed to a particular potential climate outcome. As presented in Figure 1.2, the “Degree of Likelihood” ranges from “Impossible” to “Certain,” with different terminology used to describe different ranges of statistical certainty as supported by available scientific modeling and analysis. The analytic approach required to characterize uncertainty for each climate factor (e.g., temperature, precipitation, sea level rise, storm surge) is discussed in detail in the relevant section of this report.

[INSERT FIGURE 1.2 Uncertainty Lexicon]

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**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006.**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Temperature Increase</i>				
Increased Summer Temperatures	Highway asphalt rutting		Proper design/construction, milling out ruts, more maintenance, overlay with more rut resistant asphalt	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Andrey and Mills. 2003.</li> <li>3) Hass, et al. 2006.</li> <li>4) Black, William. 1990.</li> <li>5) Meyers, Michael. 2006.</li> <li>6) Barrett, et al. 2004.</li> <li>7) Marbek Resource Consultants Ltd. 2003.</li> <li>8) Kerr, Andrew, et al. 1999.</li> <li>9) Warren, et al. 2004.</li> <li>10) Entek U.K. Limited. 2000.</li> <li>11) Entek U.K. Limited. 2004.</li> <li>12) Lockwood, Steve. 2006.</li> <li>13) Kinsella, Y. and McGuire, E. 2005.</li> <li>14) Mills and Andrey. 2002.</li> </ol>
	Rail buckling	Speed restrictions could increase travel time	Speed restrictions, reducing frequency of some services, better air conditioning for signals	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Eddowes, M.J., et al. 2003.</li> <li>3) Kerr, Andrew, et al. 1999.</li> <li>4) Warren, et al. 2004.</li> <li>5) Entek U.K. Limited. 2000.</li> <li>6) Land Use Consultants, et al. 2002.</li> <li>7) Smyth, et al. 2002.</li> <li>8) Kerr, Andy. 2001.</li> <li>9) Entek U.K. Limited. 2004.</li> <li>10) Rossetti. 2002.</li> </ol>
	More airport runway length and fuel needed because of less dense air		New planes designed to takeoff more efficiently	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Andrey and Mills. 2003.</li> <li>3) Irwin and Johnson. 1990.</li> <li>4) Warren, et al. 2004.</li> <li>5) Entek U.K. Limited. 2000.</li> <li>6) Smyth, et al. 2002.</li> <li>7) Entek U.K. Limited. 2004.</li> </ol>
	Heat/Lack of ventilation on London Underground	Overcrowding, failed, or delayed service will only compound the problem. Could cause passengers to avoid taking public transportation (mode shift)	Install better ventilation systems	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Greater London Authority. 2005.</li> </ol>

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Temperature Increase (continued)</i>				
	Low water levels on inland waterways	Increased shipping costs; shift to other modes (rail, truck)	Changes to navigation, dredging of channels, flow augmentation	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Andrey and Mills. 2003.</li> <li>3) Olsen, et al. 2005.</li> <li>4) Black, William. 1990.</li> <li>5) Irwin and Johnson. 1990.</li> <li>6) U.S. Federal Highway Administration Office of Environment and Planning. 1998.</li> <li>7) U.S. Department of State. 2002.</li> <li>8) Institute for Water Resources, U.S. Army Corps of Engineers. 2004.</li> <li>9) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000.</li> <li>10) National Assessment Synthesis Team. 2000.</li> <li>11) Marbek Resource Consultants Ltd. 2003.</li> <li>12) D'Arcy, Pierre. 2004.</li> <li>13) Warren, et al. 2004.</li> <li>14) Entek U.K. Limited. 2000.</li> <li>15) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001.</li> <li>16) Ruth, Matthais. 2006.</li> <li>17) Quinn. 2002.</li> </ol>
	Thermal expansion of bridges	Frequent detours, traffic disruptions	Increased ongoing maintenance	<ol style="list-style-type: none"> <li>1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005.</li> </ol>
	Overheating of diesel engines		Adaptation of cooling systems	<ol style="list-style-type: none"> <li>1) Entek U.K. Limited. 2000.</li> </ol>
	Increased vegetation – leaf fall	Ineffective braking of rail cars, visual obstruction	Vegetation management, plant low-maintenance vegetation as buffer	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Eddowes, M.J., et al. 2003.</li> <li>3) Land Use Consultants, et al. 2002.</li> <li>4) Smyth, et al. 2002.</li> <li>5) Kerr, Andy. 2001.</li> <li>6) Entek U.K. Limited. 2004.</li> <li>7) Kinsella, Y. and McGuire, E. 2005.</li> </ol>
	Changes to landscape/biodiversity	Highway agency owns many medians. Increased pest management. Impact on wetlands commitments	Different types of vegetation may have to be considered	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Kinsella, Y. and McGuire, E. 2005.</li> <li>3) Mortenson and Bank. 2002.</li> </ol>

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Temperature Increase (continued)</i>				
<b>Increased Summer Temperature and Decreased Precipitation</b>	Less rain to dilute surface salt may cause steel reinforcing in concrete structures to corrode (Australia)		Better protect reinforcing in saline environments	1) Norwell, Gary. 2004.
<b>Increased Winter Temperatures</b>	Reduction in cold weather rail maintenance Longer construction season	Fewer broken rails, excessive wheel wear, and frozen switches Drier and warmer days		1) Andrey and Mills. 2002. 1) Andrey and Mills. 2003. 2) Kinsella, Y. and McGuire, E. 2005.
<b>Thawing Permafrost (U.S., Canada, China)</b>	Road, rail, airport, pipeline embankments will fail and shallow pile foundations could settle	Potential for fewer construction problems in long run	Crushed rock cooling system, insulation/ground refrigeration systems, rehabilitation, relocation, mechanically stabilize embankments against ground movement, remove permafrost before construction	1) Instanes et al., 2005. 2) Brown, Jeff. 2005. 3) Cheng, Guadong. 2005. 4) Hass, et al. 2006. 5) Black, William. 1990. 6) Irwin and Johnson. 1990. 7) U.S. Arctic Research Commission Permafrost Task Force. 2003. 8) Weller, Gunter, et al. 1999. 9) Grondin et al. 2005. 10) Wright, Fred. 2001. 11) Warren, et al. 2004. 12) Ruth, Matthais. 2006. 13) Smith and Levasseur. 2002. 14) Caldwell et al. 2002.
<b>Reduction of Freezing Season for Ice Roads (Arctic)</b>	Roads unusable during certain seasons	Shorter shipping season, higher maintenance costs, higher life-cycle costs, seasonal mode shift	Reconstruction of severely damaged infrastructure with less frost-susceptible foundation (geosynthetic barrier), retrofitting road side drains	1) Instanes et al., 2005. 2) Lonergan, et al. 1993. 3) Andrey and Mills. 2003. 4) Hass, et al. 2006. 5) Weller, Gunter, et al. 1999. 6) Marbek Resource Consultants Ltd. 2003. 7) Clayton et al. (and Montufar). 2005. 8) Warren, et al. 2004. 9) Lockwood, Steve. 2006.

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<b>Precipitation Increase</b>				
<b>Increased Winter Precipitation – Rain/Snow</b>	Flooding of roads/airport runways/bikeways and walkways (frequency and magnitude will increase)	Infrastructure deterioration (quicker with acid rain), impacts on water quality	Seek alternative routes, improve flood protection, risk assessment for new roads, emergency contingency planning, ensure bridge openings/culverts sufficient to deal with flooding, improve drainage, improved asphalt/concrete mixtures, perform adequate maintenance, and minimize repair backlogs	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Andrey and Mills. 2003.</li> <li>3) Irwin and Johnson. 1990.</li> <li>4) U.S. Department of State. 2002.</li> <li>5) Kirshen, Paul H. and Matthais, Ruth. 2004.</li> <li>6) Intergovernmental Panel on Climate Change. 2001.</li> <li>7) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000.</li> <li>8) Wilkenson, Robert. 2002.</li> <li>9) Meyers, Michael. 2006.</li> <li>10) Barrett, et al. 2004.</li> <li>11) Kerr, Andrew, et al. 1999.</li> <li>12) Warren, et al. 2004.</li> <li>13) Entek U.K. Limited. 2000.</li> <li>14) Land Use Consultants, et al. 2002.</li> <li>15) Smyth, et al. 2002.</li> <li>16) Kerr, Andy. 2001.</li> <li>17) Entek U.K. Limited. 2004.</li> <li>18) Norwell, Gary. 2004.</li> <li>19) Kinsella, Y. and McGuire, E. 2005.</li> <li>20) Rossiter, Lisa. 2004.</li> <li>21) Smith, Orson. 2006.</li> </ol>
	Flooding of rails	Service disruption	Engineering solutions	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Irwin and Johnson. 1990.</li> <li>3) Eddowes, M.J., et al. 2003.</li> <li>4) Entek U.K. Limited. 2000.</li> <li>5) Smyth, et al. 2002.</li> </ol>
	Bridge scour		Speed restrictions, closure to traffic, new materials, better maintenance	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Hass, et al. 2006.</li> <li>3) Kirshen, Paul H. and Matthais, Ruth. 2004.</li> <li>4) Meyers, Michael. 2006.</li> <li>5) Eddowes, M.J., et al. 2003.</li> <li>6) Smith, Orson. 2006.</li> </ol>
	Flooding of underground transit systems	Drowned passengers	Pumping systems	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Zimmerman, 2002a and 2002b.</li> </ol>
	River flooding	Interruptions of river navigation		<ol style="list-style-type: none"> <li>1) Intergovernmental Panel on Climate Change. 2001.</li> <li>2) Ning, Zhu H., et al. 2003.</li> </ol>

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Precipitation Increase(continued)</i>				
<b>Increased Precipitation and Increased Summer Temperatures</b>	Highway, rail, and pipeline embankments at risk of subsidence/ heave	Landslides	Fill cracks and carry out more maintenance	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Instanes et al.. 2005.</li> <li>3) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005.</li> <li>4) Wilkenson, Robert. 2002.</li> <li>5) Weller, Gunter, et al. 1999.</li> <li>6) Eddowes, M.J., et al. 2003.</li> <li>7) Konuk, Ibrahim. 2005.</li> <li>8) Marbek Resource Consultants Ltd. 2003.</li> <li>9) Kerr, Andrew, et al. 1999.</li> <li>10) Warren, et al. 2004.</li> <li>11) Entek U.K. Limited. 2000.</li> <li>12) Land Use Consultants, et al. 2002.</li> <li>13) Smyth, et al. 2002.</li> <li>14) Entek U.K. Limited. 2004.</li> <li>15) Kinsella, Y. and McGuire, E. 2005.</li> <li>16) Rossiter, Lisa. 2004.</li> <li>17) du Vair et al. 2002.</li> </ol>
	Concrete deterioration			<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) U.S. Department of State. 2002.</li> </ol>
	More frequent and larger slush-flow avalanches (Arctic)		Incorporate potential risk into planning process for new settlements, detection systems, temporary closures	<ol style="list-style-type: none"> <li>1) Instanes et al.. 2005.</li> <li>2) Marbek Resource Consultants Ltd. 2003.</li> <li>3) Warren, et al. 2004.</li> <li>4) Stethem, Chris, et al. 2003.</li> </ol>
	Altered runoff patterns (Arctic)	Disruption of the ice-water balance		<ol style="list-style-type: none"> <li>1) Instanes et al.. 2005.</li> </ol>
<i>Glacial Melting/Thermal Expansion of Oceans</i>				
<b>Sea Level Rise</b>	Erosion of coastal highways		Construction of sea walls	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Black, William. 1990.</li> <li>3) U.S. Federal Highway Administration Office of Environment and Planning. 1998.</li> <li>4) Marbek Resource Consultants Ltd. 2003.</li> <li>5) Norwell, Gary. 2004.</li> <li>6) Kinsella, Y. and McGuire, E. 2005.</li> <li>7) Ruth, Matthais. 2006.</li> <li>8) Hyman, William, et al. 1989.</li> <li>9) Titus, 2002.</li> </ol>

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<b>Glacial Melting/Thermal Expansion of Oceans (continued)</b>				
	Higher tides at ports/harbor facilities			1) Wooler, Sarah. 2004. 2) Black, William. 1990. 3) U.S. Department of State. 2002. 4) Kirshen, Paul H. and Matthais, Ruth. 2004. 5) Smyth, et al. 2002. 6) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001. 7) Caldwell et al. 2002.
	Deeper water	Permit greater ship drafts		1) Andrey and Mills. 2003. 2) Kerr, Andrew, et al. 1999. 3) Titus. 2002.
	Low-level aviation infrastructure at risk		Relocation or protection of facilities	1) Andrey and Mills. 2003. 2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 3) Warren, et al. 2004. 4) Ruth, Matthais. 2006. 5) Hymen, William, et al. 1989.
	Less bridge clearance			1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005. 2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987. 3) Norwell, Gary. 2004. 4) Hymen, William, et al. 1989.
		More search and rescue operations	Obtain more vessels with emergency towing capabilities, better weather forecasting, change seasonal classifications of waters around coast, change ship/boat design	1) Wooler, Sarah. 2004. 2) Marbek Resource Consultants Ltd. 2003.

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Storm Activity</i>				
<b>Storm Surges</b>	Coastal road flooding	Increased VMT and VHT; increased number of road accidents	Seawalls, build more redundancy into system, support land use policies that discourage development on shoreline, design and material changes, pumping of underpasses, raise roads	<ol style="list-style-type: none"> <li>1) Choo, Kristin. 2005.</li> <li>2) U.S. Federal Highway Administration Office of Environment and Planning. 1998.</li> <li>3) Intergovernmental Panel on Climate Change. 2001.</li> <li>4) Suarez, Pablo et Al. 2005.</li> <li>5) Rosenzweig, Cynthia and Soleki, William. 2001.</li> <li>6) Wilkenson, Robert. 2002.</li> <li>7) National Assessment Synthesis Team. 2000.</li> <li>8) Meyers, Michael. 2006.</li> <li>9) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.</li> <li>10) Greater London Authority. 2005.</li> </ol>
	Railway flooding		Seawalls, raising rails	<ol style="list-style-type: none"> <li>1) Black, William. 1990.</li> <li>2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.</li> <li>3) Kerr, Andrew, et al. 1999.</li> <li>4) Greater London Authority. 2005.</li> </ol>
	Subway flooding		Flood barriers	<ol style="list-style-type: none"> <li>1) Choo, Kristin. 2005.</li> <li>2) Black, William. 1990.</li> <li>3) Greater London Authority. 2005.</li> <li>4) Ruth, Matthais. 2006.</li> <li>5) Zimmerman, 2002.</li> </ol>
	Port flooding/damage		Reduce "cope" level at ports to reduce likelihood of water flowing across docks; construct flood defense mechanisms	<ol style="list-style-type: none"> <li>1) ABP Marine Environmental Research Ltd 2004.</li> <li>2) Committee on Engineering Implications of Change in Relative Mean Sea Level. 1987.</li> <li>3) Entek U.K.Limited. 2000.</li> <li>4) Land Use Consultants, et al. 2002.</li> </ol>
<b>Increased Frequency/Magnitude of Storms</b>		Closures of roads, railways, airports; emergency evacuations		<ol style="list-style-type: none"> <li>1) Instanes et al., 2005.</li> <li>2) Smyth, et al. 2002.</li> <li>3) Ruth, Matthais. 2006.</li> </ol>
	Damage to seaports/airports	Travel delays		<ol style="list-style-type: none"> <li>1) Intergovernmental Panel on Climate Change. 2001.</li> </ol>
<b>Increased Wind Speeds</b>	Bridges, signs, overhead cables, tall structures at risk		Design structures for more turbulent wind conditions, build with better material, use "smart" technologies to detect abnormal events	<ol style="list-style-type: none"> <li>1) Wooller, Sarah. 2004.</li> <li>2) Meyers, Michael. 2006.</li> <li>3) Eddowes, M.J., et al. 2003.</li> <li>4) Kerr, Andrew, et al. 1999.</li> <li>5) Kerr, Andy. 2001.</li> <li>6) Kinsella, Y. and McGuire, E. 2005.</li> </ol>

**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Storm Activity (continued)</i>				
<b>Lightning/Electrical Disturbance</b>	Disruption to transportation electronic infrastructure, signaling, etc.	Unknown	Unknown	<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Eddowes, M.J., et al. 2003.</li> </ol>
<b>Fewer Winter Storms</b>	Less snow/ice for all modes	Improved mobility/safety, reduced maintenance costs, less pollution from salt, decrease in vehicle corrosion		<ol style="list-style-type: none"> <li>1) Andrey and Mills. 2003.</li> <li>2) Black, William. 1990.</li> <li>3) Irwin and Johnson. 1990.</li> <li>4) Intergovernmental Panel on Climate Change. 2001.</li> <li>5) Barrett, et al. 2004.</li> <li>6) Marbek Resource Consultants Ltd. 2003.</li> <li>7) Kerr, Andrew, et al. 1999.</li> <li>8) Warren, et al. 2004.</li> <li>9) Entek U.K. Limited. 2000.</li> <li>10) Land Use Consultants, et al. 2002.</li> <li>11) Entek U.K. Limited. 2004.</li> <li>12) Wooler, Sarah. 2004.</li> <li>13) Kinsella, Y. and McGuire, E. 2005.</li> <li>14) Hyman, William, et al. 1989.</li> <li>15) Pisano et al. 2002.</li> </ol>
<i>Ice Melting</i>				
<b>Reduced Ice Cover (Canada, Alaska, Great Lakes)</b>	Reduced ice loading on structures, such as bridges or piers			<ol style="list-style-type: none"> <li>1) Instanes et al.. 2005.</li> </ol>
	New northern shipping routes	Shorten shipping distance and delivery time, security concerns, environmental risks, law-diplomacy issues, Inuit unease	Develop a "transit management regime" for area	<ol style="list-style-type: none"> <li>1) Instanes et al.. 2005.</li> <li>2) Johnston, Douglas. 2002.</li> <li>3) Brigham, Lawson and Ben Ellis, Eds. 2004.</li> <li>4) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001.</li> <li>5) National Assessment Synthesis Team. 2000.</li> <li>6) Marbek Resource Consultants Ltd. 2003.</li> <li>7) Warren, et al. 2004.</li> <li>8) Smith and Levasseur. 2002.</li> <li>9) Caldwell et al. 2002.</li> </ol>
		Lengthened season for float planes		<ol style="list-style-type: none"> <li>1) Black, William. 1990.</li> <li>2) Irwin and Johnson. 1990.</li> </ol>

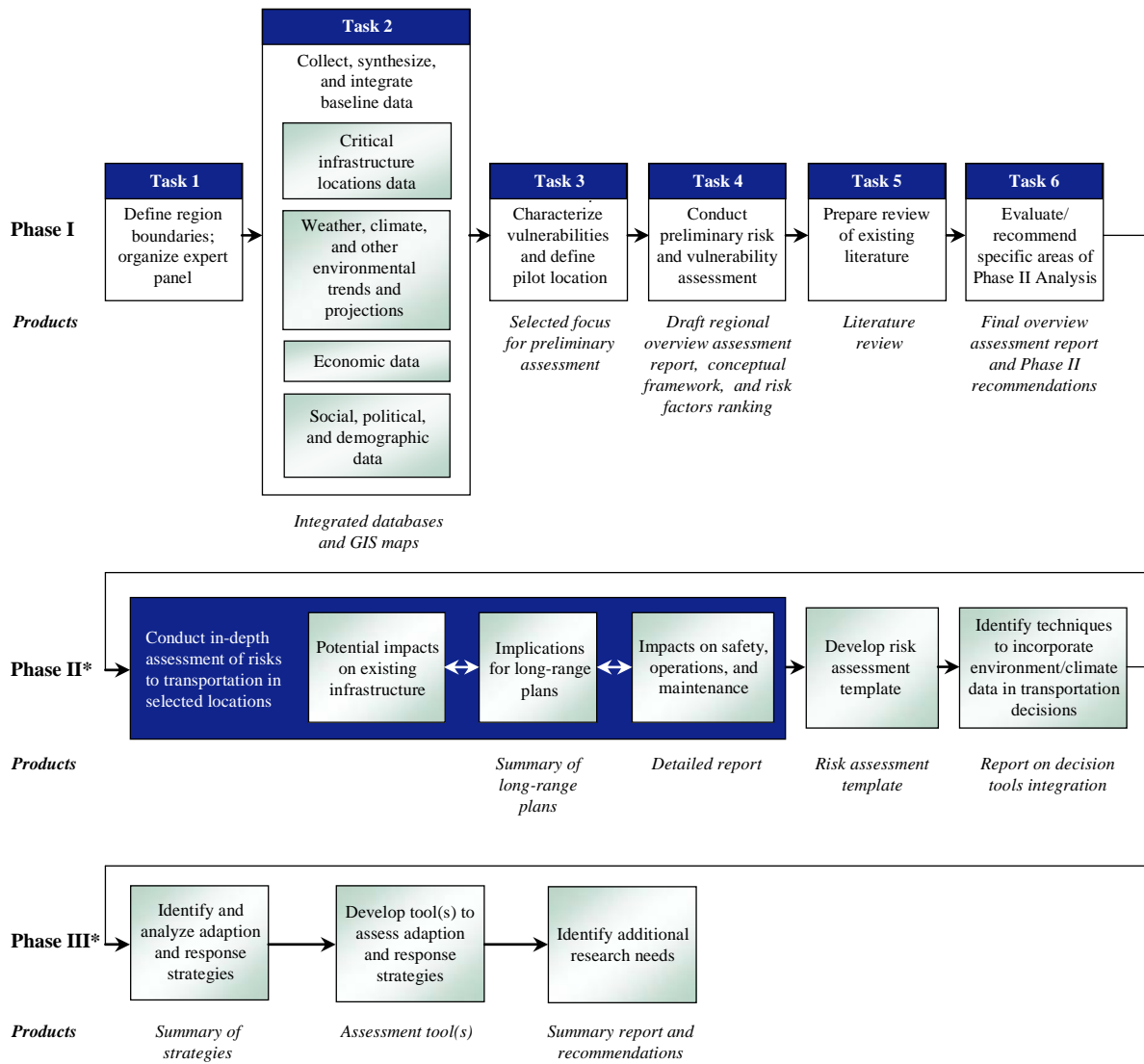


**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<b>Ice Melting (continued)</b>				
		Longer shipping season		1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Black, William. 1990. 4) Irwin and Johnson. 1990. 5) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 6) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000. 7) National Assessment Synthesis Team. 2000. 8) Warren, et al. 2004. 9) Ruth, Matthais. 2006. 10) Caldwell et al. 2002.
	Multi-year ice, in low concentrations, will be hazard to ships and naval submarines		New ship/submarine design or modifications	1) Brigham, Lawson and Ben Ellis, Eds. 2004. 2) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001.
<b>Earlier River Ice Breakup (U.S., Canada)</b>	Ice-jam flooding risk			1) Instanes et al.. 2005. 2) Hass, et al. 2006. 3) Smith and Levasseur. 2002.

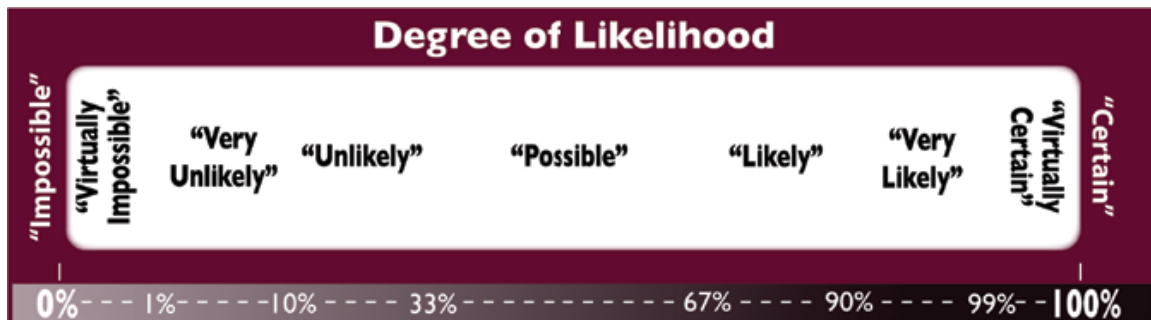


**Figure 1.1 Gulf coast study design.**



\*Study design of Phases II and III will be refined based on findings of Phase I.

**Figure 1.2** Lexicon of terms used to describe the likelihood of climate outcomes.



Source: Karl *et al.* 2006.

## 2.0 Why Study the Gulf Coast?

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### 2.1 Overview of the Study Region

#### 2.1.1 Regional and National Significance

The Phase 1 Study area includes 48 contiguous coastal counties in four states, running from the Galveston Bay region in Texas to Mobile Bay region in Alabama. This region is home to almost 10 million people living in a range of urban and rural settings, contains some of the nation's most critical transportation infrastructure, and is highly vulnerable to sea level rise and storm impacts.

This area has little topographic relief but is heavily populated. Given its low elevation and the regional climate, the area is particularly vulnerable to flooding and storm surges that accompany hurricanes and tropical storms – almost half of the nation's repetitive flood damage claims are paid to homeowners and businesses in this region. These effects may be exacerbated by global sea level rise and local land subsidence.

In addition, the central Gulf Coast's transportation modes are both unique and economically significant. The study area contains transportation infrastructure that is vital to the movement of passengers and a variety of goods domestically and internationally. Ports and pipeline infrastructure represent perhaps the most conspicuous transport modes in the region. Some of the nation's most important ports, such as the ports of Houston-Galveston, South Louisiana, and New Orleans are found in the study area. The Port of South Louisiana, for example, is a critical agricultural export center. The agricultural producers in the Midwest depend on the continued operation of this port to ship their products for international sale. Likewise, disruptions in the functioning of pipelines and fuel production and shipping facilities in the study region have broad domestic and international impacts. Roughly two-thirds of all U.S. oil imports are transported through this region, and pipelines traversing the region transport over 90 percent of domestic Outer Continental Shelf oil and gas.

1 The importance of these marine facilities and waterways to the study area, and to the nation  
2 as a whole, is difficult to overstate. These are vital national resources, providing essential  
3 transportation and economic services. While some of these functions could be considered  
4 “replaceable” by facilities and waterways elsewhere, many of them – by virtue of  
5 geography, connections to particular industries and markets, historic investments, or other  
6 factors – represent unique and largely irreplaceable assets.

7 In addition to ports and pipelines, the study region contains critical air, rail, highway, and  
8 transit infrastructure. Passenger and freight mobility depend both on the functioning of  
9 each mode and the connectivity of the modes in an integrated transport network. The  
10 efficacy of evacuation during storms is an important determinant of the safety and well-  
11 being of the region’s population. The region sits at the center of transcontinental trucking  
12 and rail routes, and contains one of only four major points in the United States where  
13 railcars are exchanged between the dominant eastern and western railroads.

14 The region is experiencing a population shift from rural to urban and suburban areas.  
15 Much of the population inhabiting the study area, as well as the transportation  
16 infrastructure supporting them, reside in low-lying areas vulnerable to inundation and  
17 flooding. In addition, parts of the population face challenges that may make it more  
18 difficult for them to adapt to the conditions imposed by a changing climate, such as  
19 poverty, lack of mobility, and isolation. Some of Louisiana’s rural counties and the urban  
20 centers of New Orleans and Mobile County have particularly high proportions of  
21 vulnerable citizens.

## 22 **2.1.2 Study Area Boundaries**

23 This initial study focuses on the central portion of the low-lying Gulf of Mexico coastal  
24 zone. The study region extends from Mobile, Alabama to Galveston, Texas as shown in  
25 Figure 2.1. The study area encompasses all coastal counties and parishes along that stretch  
26 of the Gulf of Mexico as well as their adjacent inland counties (Figure 2.2). In addition,  
27 the boundaries of the study area were extended so that all portions of MPOs within this  
28 two-county swath of coastline would be included (Figure 2.3). Table 2.1 provides the  
29 resulting list of counties and parishes included in the study area.

30 [INSERT FIGURE 2.1: Map of study area]

31 [INSERT FIGURE 2.2: Study area counties and Federal Information Processing Standard  
32 (FIPS) codes]

33 [INSERT FIGURE 2.3: Metropolitan planning organizations in the study area]

34 [INSERT TABLE 2.1: Study area counties and Federal Information Processing Standard (FIPS)  
35 codes]

### 2.1.3 Structure of This Chapter

The following sections provide a more detailed overview of the central Gulf Coast Study region, as follows:

- Section 2.2 describes the transportation system in the study area;
- Section 2.3 describes the physical setting and natural environment of the study area, including factors that make it more susceptible to climate change impacts; and
- Section 2.4 discusses the social and economic setting, including factors that make portions of the population more vulnerable to climate impacts.

## 2.2 The Transportation System in the Gulf Coast Region

The transportation network of the Gulf Coast Study area comprises a complex system of multiple modes that enables both people and goods to move throughout the region and supports national and international transport. While roadways are the backbone of the region's transportation system, the viability of the network as a whole depends on reliable service connections across all modes. Section 2.2.1 provides an introduction to passenger travel, freight transport, intermodal facilities, and emergency management in the Gulf Coast Study area, while Section 2.2.2 provides an in-depth look at each of the transportation modes present in the region. Climate impacts to this transportation system are then discussed in Section 4.0. The transportation facility location information cited and shown in maps throughout the report is from the National Transportation Atlas Database (BTS, 2004).

### 2.2.1 Overview of the Intermodal Transportation System in the Gulf Coast Region

#### *Passenger Travel*

Passenger travel in the Gulf Coast Study area is accommodated by a variety of modes, including highway, transit, rail, and aviation. Roads are the most geographically extensive system in the study area, and autos traveling on the highways serve as the principal mode for passenger travel. Some of those highways, particularly I-10/I-12, serve substantial national travel that is passing through the study area. The 27,000 kilometers (17,000 miles) of major highways within the study area comprise about 2 percent of the nation's major highways. These highways carry 134 billion vehicle kilometers of travel (83.5 billion vehicle miles of travel) annually.

Public transit provides an important function – particularly in urban areas – by carrying passengers more efficiently (in densely populated areas) than they could be carried in autos

1 and thus relieving congestion. Further, transit provides essential accessibility to those  
2 passengers who do not own or cannot rely on autos for transportation. Lower-income  
3 workers rely heavily on city and intercity bus services for basic needs: getting to and from  
4 work, transporting children to school or childcare services, and shopping. The majority of  
5 transit ridership in the study area is carried by scheduled bus services. Other transit  
6 services available include light rail, ferries, and unscheduled paratransit vans and  
7 minibuses.

8 Intercity passenger rail services are provided by the National Railroad Passenger  
9 Corporation (Amtrak), which operates three long-distance routes connecting the study area  
10 to other parts of the nation. Passenger rail services are not extensive, but they do supply an  
11 alternative mode of transportation and are important to certain segments of the population.

12 Airports are critical in connecting local, regional, and national economies, as well as the  
13 global economy. Several major airports serve the larger cities of the study area; in  
14 addition, numerous airports outside of the major metropolitan markets serve smaller  
15 municipal markets and many provide general aviation services. Smaller regional airports  
16 are critical infrastructure elements as they are often used for the movement of emergency  
17 medical supplies and patients.

### 18 ***Freight Transport***

19 The Gulf Coast Study area is a critical crossroads for the nation's freight network, with  
20 marine, rail, pipeline, trucking, and air cargo all represented. A large portion of the  
21 nation's oil and gas supply originates in the study area, either as domestic production or  
22 imports. New Orleans provides the ocean gateway for much of the U.S. interior's  
23 agricultural production, and is a major interchange point for freight railroads. Products are  
24 shipped from the study area to points throughout the United States. Figure 2.4 depicts  
25 FHWA Freight Analysis Framework data describing combined domestic truck flows  
26 originating in Louisiana (FHWA, 2004).

27 [INSERT FIGURE 2.4: Combined truck flows shipped domestically from Louisiana]

28 The pipeline network along the Gulf of Mexico coast is vital to the supply and distribution  
29 of energy for national use everywhere east of the Rocky Mountains. Approximately one-  
30 half of all the natural gas used in the United States passes through or by the Henry Hub gas  
31 distribution point in Louisiana. The pipelines originating in this region provide a low-cost,  
32 efficient way to move oil and gas long distances throughout the United States.

33 The study area also is home to the largest concentration of public and private freight  
34 handling ports in the United States, measured on a tonnage basis. These facilities handle a  
35 huge share – around 40 percent – of the nation's waterborne tonnage. The study area also  
36 hosts the nation's leading and third leading inland waterway systems (the Mississippi River  
37 and the Gulf Intracoastal) based on tonnage. The inland waterways traversing this region  
38 provide 20 states with access to the Gulf of Mexico, as shown in Figure 2.5.

39 [INSERT Figure 2.5 Navigable inland waterways impacting the study area, shown as named  
40 waterways]



1 The rail links in the study area provide crucial connectivity to the national rail network for  
2 ports in the region and, via intermodal facilities, the major highway freight corridors.  
3 Figure 2.6 shows the network of major freight railroads nationwide, illustrating an obvious  
4 divide between the eastern railroads and the western railroads along the Mississippi River.  
5 New Orleans is one of four major gateways nationwide where the dominant eastern and  
6 western railroads interchange transcontinental shipments (Chicago, St. Louis, and Memphis  
7 are the others). At New Orleans, for example, CSX interchanges over 1,000 cars per day  
8 with the western railroads. A disruption to any of the four major gateways has implications  
9 for the entire U.S. rail network.

10 [INSERT Figure 2.6 National network of Class I railroads]

### 11 ***Intermodal Facilities***

12 Intermodal facilities are critical infrastructure facilities that enable the transfer of goods and  
13 passengers between different transport modes. These facilities are critical to transportation  
14 logistics processes and provide a key link in industrial and public sector supply chains.

15 There are more than 100 intermodal facilities in the study area. Figure 2.7 shows the  
16 locations of these facilities in the study area, with coded symbols for the various mode  
17 combinations handled at each. Unsurprisingly, many of these facilities are clustered in the  
18 port and rail hubs of New Orleans and Houston.

19 [INSERT Figure 2.7: Intermodal facilities in the study area]

### 20 ***Emergency Management***

21 Interstates and arterial roadways provide the majority of the transportation infrastructure  
22 for emergency management and evacuation along the Gulf Coast. While public  
23 transportation facilities exist, they typically rely on the highway system; there are no large  
24 scale transit systems operating on separate right-of-ways. This substantial reliance on a  
25 single mode of transportation represents a risk if the highway infrastructure is damaged or  
26 made inaccessible during an emergency.

27 Existing infrastructure may be able to handle local evacuations and diversions such as in  
28 the case of spilled hazardous material from a tanker truck or risk from a point source  
29 event – like a ruptured pipeline. However, network-wide roadway capacity is not designed  
30 nor built to handle large scale evacuations or emergencies. Further, evacuation protocols  
31 require time-sensitive actions which existing roadway infrastructure cannot accommodate.

32 The limitations of the existing infrastructure to accommodate a major evacuation during a  
33 broad-scale emergency were dramatically illustrated during the 2005 hurricane season. As  
34 Hurricane Rita demonstrated, evacuating a substantial portion of the population from a  
35 major metropolitan area is problematic and, in many ways, difficult to accomplish in a  
36 timely and orderly fashion. The “normal” condition of the already capacity-constrained  
37 transportation infrastructure does not allow for a major ramp-up of evacuation capabilities  
38 during daylight hours in major urban areas.

1 Managing the transportation infrastructure and leveraging its available capacity is highly  
2 dependent upon: 1) means for gathering real-time traffic information; and 2) robust and  
3 integrated communication systems that are consistent across regional jurisdictional  
4 boundaries. In this regard, the state of practice within the region varies considerably.  
5 Advanced transportation management systems such as the TranStar Traffic Management  
6 Center in Houston and a similar array of intelligent transportation system (ITS)  
7 technologies and a traffic control center in New Orleans represent relatively new and  
8 effective advancements in obtaining accurate real-time data upon which to base  
9 transportation system management decisions. On the other hand, the interagency and  
10 interjurisdictional communication systems in the Gulf Coast region are sometimes  
11 independent from one another, with multiple radio systems in use by emergency responders  
12 in each state.

## 13 **2.2.2 Modal Characteristics**

### 14 **Highways**

#### 15 **Highway Network and Usage**

16 Highways provide the overwhelming majority of the public transportation infrastructure in  
17 the Gulf Coast Study area. There are 28,154 center line kilometers (17,494 center line  
18 miles) of highway in the study region (Table 2.2, Figure 2.8) (FHWA, 2005). Highway  
19 facilities in the Gulf Coast Study area are primarily owned and operated by the state  
20 departments of transportation (DOT). Roads are classified as:

- 21 • **Interstates** – Highways that are designated as part of the Dwight D. Eisenhower  
22 National System of Interstate and Defense Highways;
- 23 • **Arterials** – Highways which provide longer through travel between major trip  
24 generators (larger cities, recreational areas, etc.);
- 25 • **Collectors** – Roads that collect traffic from the local roads and also connect smaller  
26 cities and towns with each other and to the arterials; and
- 27 • **Local** – Roads that provide access to private property or low-volume public facilities.

28 Local roads serve mainly a land access function carry little of the demand for transportation  
29 compared to the Interstates and the arterial roadways, and they are not included as part of  
30 the highways studied in this report.<sup>1</sup> State DOTs administer 100 percent of the centerline

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<sup>1</sup> According to FHWA's Highway Statistics, while local roads represent 75 percent of the miles of the nation's highways (Table HM-18), they carry less than 0.2 percent of the nation's Vehicle Miles of Travel (VMT) (Table HM-44) (FHWA, 2005).

1 miles on Interstate highways, 60 percent of the centerline miles on Arterial highways, and  
2 50 percent of the centerline miles on Collector highways.

3 [INSERT Table 2.2: Gulf Coast study area centerline miles of highway, by classification and  
4 ownership]

5 [INSERT Figure 2.8: Highways in the study area]

6 The volumes on the interstate, arterial, and collector classified roads are primarily on the  
7 state-owned highways, to an even greater extent than that of centerline miles. Of the 83.5  
8 billion Annual Vehicle Miles of Travel (VMT) in the study area, 63.7 billion (76.3 percent)  
9 of that travel is on state-owned nonlocal roads (FHWA, 2005).

10 State-owned nonlocal roads carry an even larger share of truck volumes. As shown in  
11 Figure 2.9, 92 percent of the truck VMT is on state roads. Additionally, while truck VMT  
12 is 7.5 percent of the total VMT, which compares closely to national truck percentages of  
13 volumes, trucks represent 9.1 percent (5.7 billion of 63.7 billion) of traffic on all state-  
14 owned roads and 10 percent of the VMT (2.4 billion of 24.4 billion) of all traffic on state-  
15 owned interstate highways (FHWA, 2005).

16 [INSERT Figure 2.9: Total and truck annual vehicle miles traveled (VMT) on nonlocal roads,  
17 2003]

## 18 **Intermodal Connectors**

19 Access to intermodal facilities is most often provided by highways. Because this access  
20 function is critical to the viability of other modes, states have been given the authority to  
21 designate major intermodal passenger and freight terminals and the road connectors  
22 between these terminals and the National Highway System (NHS) as NHS Intermodal  
23 Connectors. The NHS Intermodal Connectors for the Gulf Coast Study area were  
24 identified from an FHWA database (FHWA, 2006). The official listing of the NHS  
25 Intermodal Terminals and Connectors includes the following:

- 26 • Ferries/Ports:
  - 27 – Five Ferry terminals served by 25 Intermodal Connector segments totaling 478.2
  - 28 kilometers (297.1 miles); and
  - 29 – Twenty-three Ports served by 54 Intermodal Connector segments totaling 380.9
  - 30 kilometers (236.7 miles).

- 1       • **Bus/Transit:**
    - 2           – One Intercity bus terminal served by 12 Intermodal Connector segments totaling
3           26.7 kilometers (16.6 miles);
  - 4           – Two multipurpose passenger terminals served by nine Intermodal Connector
5           segments totaling 13.0 kilometers (8.1 miles); and  - 6           – Eight Public Transit Stations served by 14 Intermodal Connector segments totaling
7           17.7 kilometers (11.0 miles).
- 8       • **Railroads:**
  - 9           – Two Amtrak stations (Houston and New Orleans) served by four Intermodal
10          Connector segments totaling 3.9 kilometers (2.4 miles); and
- 11          – Thirteen rail freight terminals served by 23 Intermodal Connector segments totaling
- 12          49.4 kilometers (30.7 miles).
- 13      • **Pipelines:**
  - 14           – Four pipeline terminals served by seven Intermodal Connector segments totaling
15           30.7 kilometers (19.1 miles).
- 16      • **Airports:**
  - 17           – Six airports served by 24 Intermodal Connector segments totaling 44.7 kilometers
18           (27.8 miles).

## 19       **Bridges**

20       Highway bridges are structures that carry the highway over a depression or an obstruction,  
21       such as water, a highway, or railway. As shown in Figure 2.10 there are almost 8,200  
22       bridges that serve nonlocal roads in the study area. The overwhelming majority, 80  
23       percent, of those bridges are owned by the states. Of those state bridges, almost 80 percent  
24       serve interstate or arterial highways. Seventy-five percent of the bridges in the study area  
25       pass over water, making them susceptible to scour of their piers by water runoff (FHWA,  
26       2001).

27       [INSERT Figure 2.10: Nonlocal bridges in the study area (NBI latitude and longitude location)]

28       Eighty-one percent of the bridge structures are concrete compared to 15 percent of the  
29       bridges which are steel, and 80 percent of the road surface on bridge decks are concrete  
30       compared to 16 percent which are asphalt (FHWA, 2001).

## 31       **Other Facilities**

32       While roads and bridges are the primary facilities that comprise the highway system in the  
33       Gulf Coast Study area, highway agencies own and operate many ancillary facilities  
34       necessary to operate and maintain the highway system. These facilities include  
35       maintenance buildings and facilities, truck weight and inspection stations, rest areas, toll

1 booths, traffic controls/signs, luminaries, fences, guardrails, traffic monitoring equipment,  
2 etc.

### 3 ***Transit***

4 The American Public Transportation Association (APTA) lists over 136 public transit  
5 providers that serve the Gulf Coast Study area (APTA, 2005). Most of those providers  
6 offer transportation as a social service to elderly, disabled, or low-income passengers.  
7 These transit providers include 13 major transit agencies that receive funding from the  
8 Federal Transit Administration and are included in the National Transit Database (NTD)  
9 (FTA, 2005). Statistical information on transit services in the study region have been  
10 drawn from this database.

11 By far the largest transit networks in the study area are found in Houston and New Orleans.  
12 As an illustration, in 2003 the NTD showed Houston with almost \$88 million in citywide  
13 transit revenues and New Orleans with almost \$35 million – while no other city in the  
14 study area topped \$4 million.

### 15 **Fixed Guideway (Light Rail)**

16 There are three transit agencies that operate fixed guideway rail service in the Gulf Study  
17 Area. Fixed guideway rail service carries passengers in vehicles moving on fixed light  
18 rails. The service operated by the RTA in New Orleans and Metro in Houston consists of  
19 street cars operated by overhead power lines, over 47 kilometers (29 miles) and 27  
20 kilometers (17 miles) of routes, respectively. The service operated by Island Transit in  
21 Galveston consists of heritage streetcars powered by diesel and operated on rails, on 29  
22 kilometers (18 miles) of route. These light rail services account for a relatively small  
23 portion of total transit passengers in the study area: the New Orleans light rail service  
24 carried 8.9 million passengers in 2004, Houston's carried 5.4 million, and Galveston's  
25 carried 40,000. By comparison, fixed-route bus services in the study area carried 10 times  
26 as many passengers in 2004 (FTA, 2005).

### 27 **Fixed-Route Buses**

28 Not including the ridership for HART/Hub City Transit (Hattiesburg), LCTS (Lake Charles  
29 Transit System), and SBURT (Saint Bernard Urban Rapid Transit) which was not reported,  
30 fixed-route bus service in the Gulf Coast Study area in 2004 carried 139 million passengers  
31 traveling 650 million passenger miles for an average trip length of 7.6 kilometers (4.7  
32 miles).

33 Table 2.3 shows data on equipment, service levels, and ridership for fixed-route bus service  
34 of the 13 major transit agencies in the Gulf Coast Study area. Houston's Metro, New  
35 Orleans' RTA, and Jefferson Transit provide a small portion of this service as Bus Rapid

1 Transit (BRT).<sup>2</sup> A total of 586 route kilometers (364 route miles) of BRT are provided in  
2 the study area, of which 558 kilometers (347 miles) are in the Houston area (FTA, 2005).

3 [INSERT Table 2.3: Equipment, annual service, and passengers for fixed-route bus operations  
4 in the study area, 2004]

## 5 **Paratransit**

6 Transit agencies also provide special services to elderly, disabled, and other disadvantaged  
7 passengers. This paratransit service is offered in addition to accessible service on the fixed  
8 routes. The service is typically offered in smaller buses or vans with door-to-door service  
9 for passengers on a demand responsive flexible schedule. Twelve agencies in the study  
10 area offer paratransit service annually carrying 2.3 million passengers over 24 million  
11 passenger miles for an average trip of 17.1 kilometers (10.6 miles) per trip. By far the  
12 largest paratransit provider in the study area is Houston's Metro, which accounts for 80  
13 percent of the paratransit vehicles in the region, 64 percent of the passengers, and 69  
14 percent of the passenger miles.

## 15 **Other Facilities**

16 In addition to transit vehicles and guideways, transit agencies may own other facilities to  
17 serve vehicles or riders. According to the 2004 National Transit Database (NTD), within  
18 the Gulf Coast Study area 10 transit agencies own 86 terminals and transfer stations. Those  
19 terminals are most numerous in the light rail systems operated by the New Orleans RTA  
20 and the Houston Metro. Also included are the terminals associated with passenger ferries  
21 within the study area.

22 Other facilities include vehicle maintenance facilities, of which the NTD lists six major  
23 facilities owned by six transit agencies. In addition, transit agencies also own numerous  
24 small passenger shelters and signs and other controls that are neither inventoried nor  
25 located in the NTD.

## 26 **Rail**

27 The Gulf Coast region has an extensive rail network, with east-west lines linking the  
28 southern U.S., north-south lines paralleling the Mississippi River, and diagonal lines  
29 connecting the region to the northeastern and northwestern U.S. Six of the seven Class I  
30 railroads in the United States serve the study region, along with several short lines.<sup>3,4</sup>

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<sup>2</sup> i.e., scheduled bus service on fixed guideways or HOV lanes.

<sup>3</sup> Railroad classification is determined by the Surface Transportation Board. In 2004, a Class I railroad was defined as having \$289.4 million or more in operating revenues. A Class II railroad, often referred to as a regional railroad, was defined as a non-Class I line-haul railroad operating 563 kilometers (350 miles) or more with operating revenues of at least \$40 million. Class III railroads, or short lines, are the remaining non-Class I or II line-haul railroads. A switching or terminal railroad is a railroad engaged primarily in switching and/or terminal services for other railroads.

1 These railroads support important regional industries, such as chemicals, paper, lumber,  
2 and international trade. The Gulf Coast region also serves as a critical junction for national  
3 freight movements, with New Orleans serving as a major gateway between the eastern and  
4 western railroads (most rail freight using New Orleans infrastructure is interchanging rather  
5 than originating or terminating in New Orleans).

6 Intercity passenger rail services are provided by the National Railroad Passenger  
7 Corporation (Amtrak). Amtrak operates nationwide routes through the region over track  
8 owned by the Class I railroads. Passenger rail services are not extensive, but they do  
9 supply an alternative mode of transportation and are important to certain segments of the  
10 population.

### 11 **Freight Rail**

12 Six Class I railroads operate in the study region: Burlington Northern Santa Fe (BNSF);  
13 Canadian National Railway (CN); CSX; Kansas City Southern Railroad (KCS); Norfolk  
14 Southern (NS); and Union Pacific (UP).

15 Figure 2.11 shows the annual density of traffic on the rail lines in the Gulf Coast Study  
16 region (BTS, 2004). The most densely used lines (60 million to 99.9 million gross ton-  
17 miles per mile per year (mgmt/mile)) are short segments in Houston and New Orleans. In  
18 the 40 to 59.9 mgmt/mile category is part of the UP line between Houston and New  
19 Orleans, some segments around Houston, and the CSX line east of Mobile. The 20 to  
20 39.9 mgmt/mile range includes the remainder of the UP line into New Orleans, the CSX  
21 line between Mobile and New Orleans, the NS line into New Orleans, and several lines  
22 around Houston.

23 [INSERT Figure 2.11: Freight railroad traffic density (annual millions of gross ton-miles per  
24 mile) in the study area]

25 In addition to track infrastructure, there are 94 major freight rail-owned and served  
26 facilities in the study region, including rail yards, intermodal terminals, and transloading  
27 facilities.<sup>5</sup> These facilities originate and terminate rail traffic, reclassify inbound railcars to  
28 outbound trains for through traffic, and interchange railcars between railroads. They  
29 include facilities owned by the railroads and nonrail-owned facilities that depend on rail  
30 service, such as the ports. Although these facilities can be found throughout the region,  
31 there are clearly two major hubs: New Orleans and Houston.

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<sup>4</sup> Canadian Pacific Railway is the only North American Class I railroad not serving the study region.

<sup>5</sup> A transloading facility handles “nonflowing” commodities transferred between railcars and trucks for customers without direct rail service. Examples include steel, lumber, and paper. A transflow facility handles “flowing” commodities transferred between railcars and trucks, such as corn syrup, petroleum products, and plastic pellets.

1 Table 2.4 provides a more complete description of the railroads operating in the Gulf Coast  
2 Study area, showing the geographical service area and primary commodities hauled for  
3 each. A complete list of freight rail facilities in the study area is provided in Appendix C.

4 [INSERT Table 2.4: Freight railroads in the Gulf Coast study area]

## 5 **Passenger Rail**

6 The National Railroad Passenger Corporation (Amtrak) offers three intercity passenger rail  
7 services in the Gulf Coast Study Region: City of New Orleans, Crescent, and Sunset  
8 Limited. The City of New Orleans provides north-south passenger service between New  
9 Orleans and Jackson (Mississippi), Memphis, and Chicago over track owned by CN. The  
10 Crescent provides service between New Orleans, Atlanta, Washington D.C., Philadelphia,  
11 and New York. Both the City of New Orleans and the Crescent services travel north from  
12 New Orleans and have relatively little track mileage in the study area.

13 The Sunset Limited, however, traverses a distance of 4,448 kilometers (2,764 miles)  
14 between Orlando, Florida and Los Angeles, California, and makes stops throughout the  
15 Gulf Coast Study region, as shown in Figure 2.12. East of New Orleans the service runs  
16 along the coast, and has been indefinitely suspended since Hurricane Katrina occurred in  
17 2005. However, even before Katrina, the Sunset Limited was one of the lowest ridership  
18 long-distance trains operated by Amtrak, with fewer than 100,000 passengers per year  
19 according to Amtrak ridership reports. A complete list of Amtrak stations in the study area  
20 is provided in Appendix C.

21 [INSERT Figure 2.12: Sunset Limited route map, Houston, Texas – Mobile, Alabama segment]

## 22 ***Marine Facilities and Waterways***

### 23 **Freight Handling Ports and Waterways**

24 Ports can be comprised of a single facility or terminal, but most are actually made up of a  
25 mix of public and private marine terminals within a given geographic region along a  
26 common body of water. The U.S. Army Corps of Engineers identifies almost 1,000 public  
27 and private freight handling facilities throughout the study area, including different  
28 terminals within various defined port areas. These are mapped in Figure 2.13. Major port  
29 complexes include, from west to east:

- 30 • Port of Freeport, Texas;
- 31 • Ports of Houston, Texas City, and Galveston, Texas;
- 32 • Ports of Port Arthur and Beaumont, Texas;
- 33 • Port of Lake Charles, Louisiana;
- 34 • Mississippi River ports of Baton Rouge, South Louisiana, New Orleans, St. Bernard



1 (included in the New Orleans district by the U.S. Army Corps of Engineers), and  
2 Plaquemines, Louisiana;

- 3 • Ports of Bienville, Gulfport, Biloxi, and Pascagoula, Mississippi; and
- 4 • Port of Mobile, Alabama.

5 [INSERT Figure 2.13 Freight handling ports and waterways in the study area]

## 6 **Waterborne Freight Types and Volumes**

7 Table 2.5 shows that 4 of the top 5 ports in the United States, as measured by annual  
8 tonnage of goods handled by the port, are located in the study area. South Louisiana – at  
9 almost 199 million tons – is the nation’s leading tonnage port, while Houston – at over 190  
10 million tons – ranks second. Collectively, study area ports handle almost 40 percent of all  
11 tonnage moved through all U.S. ports.

12 The study area also includes 4 of the nation’s top 30 container ports<sup>6</sup>, including Houston  
13 (number 11), New Orleans (number 19), Gulfport (number 21), and Freeport (number 30)  
14 (AAPA, 2004).

15 Along with these fixed marine facilities, the study area hosts critically important navigable  
16 marine transportation networks. Among the most significant are the Gulf Intracoastal  
17 Waterway, a protected coastal route running from the Texas-Mexico border to Appalachee  
18 Bay in Florida; the Mississippi River and its tributaries; and the Tombigbee, Tennessee,  
19 and Black Warrior rivers, feeding the Mobile River in Alabama. These inland waterways  
20 and their associated lock structures (numbering in the hundreds) provide 20 states with  
21 access to the Gulf of Mexico, mostly through the Mississippi River and the Tennessee-  
22 Tombigbee River systems. Tonnage data (Table 2.6) shows that largest volumes are on the  
23 Mississippi River (almost 213 million tons between Baton Rouge and New Orleans, and  
24 116 million tons between New Orleans and the Gulf of Mexico) and the Gulf Intracoastal  
25 Waterway (almost 118 million tons) (Institute for Water Resources, 2003). In fact, these  
26 two systems comprise the nation’s leading and third leading inland waterway systems by  
27 tonnage. Agriculture and other industries depend on efficient, reliable inland water  
28 transportation to move goods downriver to ports in Louisiana and Alabama, where goods  
29 are transloaded from domestic barges to international vessels. Petroleum, chemicals, and  
30 bulk products utilize the Gulf Intracoastal Waterway as an alternative to congested  
31 highway and rail corridors within the region.

32 [INSERT Table 2.5: Domestic and international waterborne tonnage of study area ports, 2003]

33 [INSERT Table 2.6: Tonnage on study area inland and coastal waterways, 2003]

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<sup>6</sup> Ports with the ability to load and unload container ships, and transfer the shipping containers to or from other modes of travel, usually rail or truck.

1 [INSERT Figure 2.14: Barge tow on the Mississippi River]

## 2 **Key Commodities and Industries**

3 Overall, more than half of the tonnage (54 percent) moving through study area ports is  
4 petroleum and petroleum products – gasoline, fuel oil, natural gas, etc. This is not  
5 surprising, as the Gulf is a major petroleum producing and processing region, and an  
6 estimated 60 percent of U.S. petroleum imports passes through Gulf gateways. Of the rest,  
7 the majority – around 18 percent – is comprised of food and farm products such as grains  
8 and oilseeds. Around 12 percent is chemicals, and the remaining commodities – around  
9 4 percent to 6 percent each – are crude materials, manufactured goods, and coal (Institute  
10 for Water Resources, 2003).

11 There are important differences between ports in different parts of the study area. The  
12 Alabama and Mississippi ports specialize in coal, petroleum, manufactured (containerized)  
13 goods, and crude materials. In contrast, around 38 percent of tonnage through the  
14 Mississippi River ports consists of food and farm products, much of it related to the  
15 transloading of barge traffic from the nation’s interior, with petroleum accounting for  
16 another 30 percent of tonnage. The western Louisiana and Texas ports are dominated by  
17 petroleum, which represents 75 percent of their tonnage.

## 18 **Nonfreight Marine Facilities**

19 The study area also hosts a large array of nonfreight maritime uses. The U.S. Army Corps  
20 of Engineers database lists around 800 nonfreight facilities (including unused berths) in the  
21 study area. These serve a variety of functions, including commercial fishing; vessel  
22 fueling, construction, repair, and outfitting (including shipyards); marine construction  
23 services (channel dredging and maintenance, construction of berths and other facilities);  
24 government and research facility docks; recreational and commercial vessel berthing;  
25 passenger ferry and cruise docks; and support for offshore oil facilities.

## 26 **Aviation**

27 The system of airports analyzed in the Gulf Coast Study includes 61 publicly owned,  
28 public-use airports. Private facilities are excluded from the sample as are the 387 heliports  
29 located in the study area.<sup>7</sup> Twenty-eight of these airports (more than 45 percent) are in  
30 Louisiana, 16 are in Texas, 9 are in Mississippi, and 8 are in Alabama.

31 There are over 3,800-based aircraft at publicly owned, public use airports in the study area.  
32 Over 3.4 million aircraft takeoffs and landings take place at these airports annually, with  
33 the majority of operations taking place at Commercial Service airports.

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<sup>7</sup> Heliports primarily serve hospitals, office buildings, and oil and gas industry facilities.

1 Of these 61 airports, 44 are general aviation airports, 11 are commercial service, 4 are  
2 industrial, and 2 are military, as described below:

- 3 • **Commercial Service Airport (CS)** – Commercial Service airports primarily  
4 accommodate scheduled passenger airline service. Two Houston airports led the region  
5 in passenger enplanements in 2005 (George Bush Intercontinental Airport and  
6 William P. Hobby), followed by Louis Armstrong New Orleans International.
- 7 • **Military Airfield (MIL)** – Military Airfields accommodate strictly military aircraft and  
8 are off limits to civilian aircraft. The two active military airfields in the study area are  
9 Keesler AFB and the New Orleans Naval Air Station/Joint Reserve Base. Keesler AFB  
10 is notable for being the home of the 53<sup>rd</sup> Weather Reconnaissance Squadron, the  
11 “Hurricane Hunters,” who fly aircraft into tropical storms and hurricanes to gather  
12 weather data.
- 13 • **Industrial Airport (IND)** – Industrial Airports are airports which can accommodate  
14 both commercial and privately owned aircraft. Typically, an industrial airport is used  
15 by aircraft service centers, manufactures, and cargo companies, as well as general  
16 aviation aircraft. The four industrial airports in the study area are former military  
17 airfields, designed to accommodate the largest aircraft. None of them have scheduled  
18 passenger service.
- 19 • **General Aviation Airport (GA)** – General Aviation airports accommodate aircraft  
20 owned by private individuals and businesses.

21 In addition to leading the region in passenger enplanements, George Bush Intercontinental  
22 Airport (IAH) in Houston also is the leading airport in the study area for cargo tonnage,  
23 processing 75 percent of all cargo enplaned in the study area. It ranks 17<sup>th</sup> nationally for  
24 cargo, with 387,790 annual tons (ACI, 2005). Louis Armstrong New Orleans International  
25 ranked second for cargo, followed by Mobile Downtown, an industrial airport.

26 Table 2.7 details the passenger enplanements and cargo tonnage for the major study area  
27 airports. Figure 2.15 identifies the location of airports in the study area.

28 [INSERT Table 2.7: Passenger enplanements and cargo tonnage for select commercial service  
29 and industrial airports in the study area, 2005]

30 [INSERT Figure 2.15: Study area airports]

### 31 ***Pipelines***

32 The pipeline system in and around the Gulf Coast is a major transporter of gas, petroleum,  
33 and chemical commodities. It links many segments of the country with energy sources  
34 located on the Gulf Coast. Unlike other transportation systems, pipelines are singularly a  
35 transportation system for bulk commodities that have little or no time sensitivity for  
36 product delivery. The entire pipeline network is privately funded and held. The onshore  
37 portion is principally regulated by the Office of Pipeline Safety (OPS), within the U.S.

1 Department of Transportation, Pipeline and Hazardous Materials Safety Administration  
2 (PHMSA). Regulation focuses on safe operations to protect people, the environment, and  
3 the national energy supply. Off-shore pipelines are regulated by the U.S. Department of  
4 the Interior, Minerals Management Service.

5 There is a total of 42,520 kilometers (26,427 miles) of onshore liquid (oil and petroleum  
6 product) transmission and natural gas transmission pipelines in the Gulf Coast area of  
7 study, with some extended sections beyond the boundaries of the study. This includes  
8 22,913 kilometers (14,241 miles) of onshore natural gas transmission pipelines and 19,607  
9 kilometers (12,186 miles) of onshore hazardous liquid pipelines (PHMSA, 2007). The  
10 liquid pipelines are concentrated in Texas while the natural gas pipelines are concentrated  
11 in Louisiana.

12 Approximately 49 percent of U.S. wellhead natural gas production either occurs near the  
13 Henry Hub, which is the centralized point for natural gas futures trading in the United  
14 States, or passes close to the Henry Hub as it moves to downstream consumption markets.  
15 The Henry Hub is located near the town of Erath in Vermilion Parish, Louisiana. The  
16 Henry Hub interconnects nine interstate and four intrastate pipelines, including: Acadian,  
17 Columbia Gulf, Dow, Equitable (Jefferson Island), Koch Gateway, LRC, Natural Gas Pipe  
18 Line, Sea Robin, Southern Natural, Texas Gas, Transco, Trunkline, and Sabine's mainline.

## 19 ■ 2.3 Gulf Coast Physical Setting and Natural Environment

20 The unique natural environment and geology of the Gulf Coast Study region brings its own  
21 set of considerations and challenges in designing the built environment. Some of these  
22 physical characteristics, such as low topography, high rates of subsidence, and predilection  
23 for coastal erosion, significantly increase the vulnerability of the area to climate change  
24 impacts. A robust transportation system must accommodate the natural features of this  
25 landscape.

26 A variety of physical datasets were compiled for Phase I of the Gulf Coast study and posted  
27 on a web site for review and use by the project research team (Appendix A). Most of the  
28 spatial data is organized in GIS-type formats or "layers" that can be integrated for the  
29 purposes of assessing the vulnerability and risks of the transportation infrastructure in the  
30 study area and informing the development of adaptation strategies in Phases II and III of  
31 the study, respectively. Examples of the spatial data products developed for the study are  
32 presented in the following sections.

### 33 2.3.1 Geomorphology

34 The Gulf Coast region of the United States is in the physiographic province called the  
35 southeastern Coastal Plain, which is a broad band of territory paralleling the Gulf and  
36 South Atlantic seacoast from North Carolina to Texas, with a deep extension up the

1 Mississippi River valley. The Coastal Plain is relatively flat, with broad, slow-moving  
2 streams and sandy or alluvial soils (Figure 2.16).

3 Much of the land area in the Coastal Plain is overlain with sediments deposited during the  
4 Holocene or Recent Age epoch, i.e., during the past 10,000 years. The remainder of the  
5 Coastal Plain surface consists primarily of late Cretaceous deposits (65 to 100 million years  
6 old). These sedimentary rocks, deposited mostly in a marine environment, were later  
7 uplifted and now tilt seaward; part of them form the broad, submerged Continental Shelf.  
8 Coastal Plain deposits overlap the older, more distorted, Paleozoic and Precambrian rocks  
9 immediately to the north and west (more than 250 million years old) (USGS, 2000a).

10 The center of the study area is dominated by the Mississippi Embayment, a geologic  
11 structural trough in which the underlying crust of the earth forms a deep valley that extends  
12 from the Gulf Coast inland to the confluence of the Ohio and Upper Mississippi Rivers.  
13 The Lower Mississippi Valley occupies the center of the inland part of the embayment and  
14 ranges from 30 to 180 kilometers (20 to 110 miles) wide. Large rivers, such as the  
15 Mississippi, Arkansas, and Ohio Rivers, have flowed through this region, carved the  
16 surface, and deposited clay, silt, sand, and gravel, collectively called alluvium.

17 Nearly annually, the Mississippi River and its tributaries flood vast areas of the lower  
18 alluvial valley. Traditionally, these floods have lasted for several months and a few for  
19 even longer periods. For example, the great flood of 1927 occurred from April to June  
20 when the lower Mississippi River system stored the equivalent of 60 days of discharge in  
21 its 22 million-acre alluvial valley. The river flows through the Lower Mississippi Valley in  
22 a 15- to 30-kilometers (10- to 20-mile) wide meander belt, and historical and prehistoric  
23 records indicate the river is continually creating new channels and abandoning old ones.  
24 The alluvium provides the rich soils for massive agricultural development.

25 Where the Mississippi river empties into the Gulf of Mexico, old deltas are abandoned and  
26 new ones formed. This Mississippi River Deltaic Plain lies at the center of the Gulf Coast  
27 Study area. During the formation of the deltaic plain, millions upon millions of tons of  
28 sediment were deposited in a series of overlapping delta lobes that are presently in various  
29 phases of abandonment and deterioration. The barrier island chains off the coast of  
30 Louisiana are remnant features of old deltas that are naturally eroding and retreating  
31 landward as sea level rises. Erosional forces dominate this part of the Central Gulf Coast  
32 landscape.

33 [INSERT FIGURE 2.16: Surface geology of the southeastern United States.]

34 Due largely to its sedimentary history, land along the central Gulf Coast tends to be low  
35 and flat and is dissected by numerous slow moving streams or bayous that drain runoff  
36 from the coastal plain and the adjacent uplands. The central Gulf coastal zone includes  
37 many barrier islands and peninsulas, such as Galveston Island, Texas, Grand Isle,  
38 Louisiana, and the land between Gulfport and Biloxi, Mississippi. These landforms protect  
39 numerous bays and inlets. The low-lying areas of the central Gulf Coast region are (or  
40 were) primarily marshland and wetland forests.

1 Erosion, sediment transport and deposition, and changes in elevation relative to mean sea  
2 level (i.e., subsidence, discussed in greater detail below) are the main land surface  
3 processes that interact with climate change and variability in a manner that could adversely  
4 affect transportation in the study area. Erosion is exacerbated by increased water depth,  
5 increased frequency or duration of storms, and increased wave energy – and all of these  
6 changes could potentially accompany an increase in the temperature of the atmosphere.

### 7 **2.3.2 Current Elevation and Subsidence**

8 The great majority of the study area lies below 30 meters in elevation (Figure 2.17) (USGS,  
9 2004). Due to its low relief, much of the central Gulf Coast region is prone to flooding  
10 during heavy rainfall events, hurricanes, and lesser tropical storms. The propensity for  
11 flooding is higher in areas that are experiencing subsidence (i.e., the gradual lowering of  
12 the land surface relative to a fixed elevation). Near the coastline, the net result of land  
13 subsidence is an apparent increase in sea level.

14 Land subsidence is a major factor in the study region. The rate of subsidence varies across  
15 the region, and is influenced by both the geomorphology of specific areas as well as by  
16 human activities. Parts of Alabama, Texas, and Louisiana are experiencing subsidence  
17 rates that are much higher than the 20<sup>th</sup> century rate of global sea level rise of 1-2 mm/year  
18 (IPCC, 2001). For example, in the New Orleans area the average rate of subsidence  
19 between 1950 and 1995 was about 5 mm/year (Burkett et al., 2003), with some man-made  
20 levees, roads, and artificial fill areas sinking at rates that exceed 25 mm/year (Dixon et al.,  
21 2006). As a result of subsidence, which was accelerated by the forced drainage of highly  
22 organic soils and other human development activity, most of the city of New Orleans is  
23 below sea level.

24 [INSERT FIGURE 2.17: Relative elevation of study area counties (delineated in blue)]

25 Subsidence in the Houston-Galveston-Baytown region is associated primarily with  
26 groundwater withdrawals, which peaked in the 1960s. By the mid 1970s, industrial  
27 groundwater withdrawals had caused roughly two meters of subsidence in the vicinity of  
28 the Houston Ship Channel and almost 8,300 square kilometers (3,200 square miles) of land  
29 in this region had subsided more than one foot. The growing awareness of subsidence-  
30 related flooding in the southeast Texas prompted the 1975 Texas Legislature to create the  
31 Harris-Galveston Coastal Subsidence District, which was authorized to regulate ground  
32 water withdrawals and promote water conservation programs (Coplin and Galloway, 1999).  
33 Shallow oil and gas withdrawals also have contributed to subsidence in southeast Texas  
34 (Coplin and Galloway, 1999) and coastal Louisiana (Morton et al., 2005). Recent  
35 geological and geophysical investigations suggest that subsidence across the Central Gulf  
36 Coast is occurring more rapidly than previously thought (Shinkle and Dokka, 2005; Dixon  
37 et al., 2006).

38 Recognizing the increasing trend in flooding in the region, the Federal Emergency  
39 Management Agency (FEMA) currently is updating its Base Flood Elevations Maps of the

1 region. However, even new elevation maps can be outdated within just a few years due to  
2 the high rates of subsidence in some parts of the study area (AGU, 2006).

3 While the Gulf Coast is considered at very low risk for earthquakes, it does have hundreds  
4 of subsurface faults that can be expressed at the surface by differences in elevation, by the  
5 zonation of plant communities, or by patterns of wetland loss (Morton et al., 2005).  
6 Generally, these faults run parallel to the shoreline and are displaced “down to the coast”  
7 due to the slow sliding of thick sediments towards the Gulf of Mexico. Subsidence and  
8 subsurface fluid withdrawals can activate shallow faults and cause ground failure along  
9 highways and beneath buildings. Since the late 1930s, 86 active faults in the Houston-  
10 Galveston area have offset the land surface by slow seismic creep at rates of up to 2.5 cm  
11 per year (Holzer and Gabrysch, 1987; Coplin and Galloway, 1999).

### 12 **2.3.3 Sediment Erosion, Accretion, and Transport**

13 The northern Gulf of Mexico coastal zone is highly dynamic due to a unique combination  
14 of geomorphic, tectonic, marine, and atmospheric forcings that shape both the shoreline  
15 and interior land forms. Most of coastline of the study area is classified as “highly  
16 vulnerable” to erosion (Theiler and Hammar-Close, 1999). The retreat of shoreline of the  
17 reticulated marshes which dominate much of the coastal zone is often translated to  
18 “wetland loss” which occurs via submergence of land or erosion of the land/water  
19 interface. Highest erosion and wetland loss rates are associated with tropical storms and  
20 frontal passages. It is estimated that 56,000 hectares (217 square miles) of land were lost in  
21 Louisiana alone during Hurricane Katrina (Barras, 2006).

22 The barrier islands of the central Gulf Coast region are shaped continually by wind and  
23 wave action and changes in sea level, including the short-term increase in sea level  
24 associated with storm surge. The Chandeleur Islands, which serve as a first line of defense  
25 for the New Orleans region, are extremely vulnerable to intense tropical storms, having lost  
26 85 percent of their surface area during Hurricane Katrina (USGS, 2007). As barrier islands  
27 and mainland shorelines erode and submerge, onshore facilities in low-lying coastal areas  
28 become more susceptible to inundation and destruction. Many Gulf Coast barrier islands  
29 are retreating and diminishing in size, with the most significant breaching and retreat  
30 occurring during storms and frontal passages. The combined effects of beach erosion and  
31 storms can lead to the erosion or inundation of other natural coastal systems. For example,  
32 an increase in wave heights in coastal bays is a secondary effect of sandy barrier island  
33 erosion in Louisiana where increased wave heights have enhanced erosion rates of bay  
34 shorelines, tidal creeks, and adjacent wetlands (Stone and McBride, 1998; Stone et al.,  
35 2003).

36 Theiler and Hammar-Close (1999) assessed the relative importance of six variables that  
37 influence coastal erosion rates and developed a coastal vulnerability index (CVI) for the  
38 Gulf Coast region. Their analyses indicated that geomorphology and tide range are the  
39 most important variables in determining the CVI for the Gulf of Mexico coast, since both  
40 variables reflect very high vulnerabilities along nearly the entire shoreline. Wave height,  
41 relative sea level rise, and coastal slope explain the large-scale (50-200 kilometers

1 alongshore) variability of erosion rates. They concluded that erosion and accretion rates  
2 contribute the greatest variability to the CVI at short spatial scales. Rates of shoreline  
3 change, however, are the most complex and poorly documented variable in this data set  
4 developed by the USGS. To best understand where physical changes may occur, large-  
5 scale variables must be clearly and accurately mapped and small-scale variables must be  
6 understood on a scale that takes into account their geologic and environmental influences.  
7 Marshes that receive sufficient inputs of mineral or organic sediments, for example, can  
8 offset the potential for submergence due to subsidence and sea level rise (Rybczyk and  
9 Cahoon, 2002).

10 Sediments eroded by winds, tides, and waves are transported generally towards shore and  
11 continually reworked into a mosaic of wetlands, shallow bays, and barrier islands. Some  
12 sediments, however, are lost to the Gulf or deposited along the shoreline to the east or west  
13 of the study area. Nearshore currents east of the mouth of the Mississippi River carry  
14 sediments eastward. To the west of the Mississippi River delta, the predominant direction  
15 of this nearshore drift is westward.

16 At the geographic center of the study area, the Mississippi alluvial or deltaic plain has been  
17 built on the continental shelf during the past 6,000 years, during a period of relatively slow  
18 sea level rise when most of the world's present deltas were formed (Woodruffe, 2003). In  
19 recent times, sediments that would be delivered to the Mississippi delta marshes via  
20 seasonal overbank flooding have been cut off by levees and deep channel dredging of the  
21 Mississippi River for navigation (Reed, 2002). Thousands of miles of smaller navigation  
22 channels, oil and gas field access canals, and other development activities have contributed  
23 to the vulnerability of the Mississippi Deltaic Plain to sediment deprivation and land loss  
24 (MMS, 1994).

#### 25 **2.3.4 Land Use and Land Cover**

26 Land use of the Gulf Coast Study area was defined using the National Land Cover Dataset  
27 (NLCD). The NLCD consists of 21 classifications, of which 19 were found in this study  
28 area. The data were collected from the Landsat Thematic Mapper satellite in the early to  
29 middle 1990s and are of 30 meter resolution. Table 2.8 summarizes this data for the study  
30 area.

31 The central Gulf Coast Study area covers an area of approximately 1 million hectares (23.4  
32 million acres or 36,485 square miles). Land cover is dominated by wetlands (32.4 percent),  
33 agriculture (19.1 percent), and upland forests (17.7 percent). The study area can be broadly  
34 divided into six Ecological Units based on Bailey's classification of U.S. ecoregions  
35 (Bailey, 1976) (Figure 2.18). Land cover within the study area has strong similarities from  
36 east to west across the study area and appears to be influenced more by soils, topography,  
37 and human activity than by climatic differences. Natural plant community distributions are  
38 generally oriented along north/south gradients, reflecting salinity, water level, and  
39 disturbance regimes.



1 Nonurbanized land use in the region is devoted mainly to Federal/state protected lands,  
2 large-scale commercial agriculture, and relatively undeveloped wetlands associated with  
3 the Mobile River in Alabama; the Pearl River in Mississippi and Louisiana; the  
4 Mississippi, Atchafalaya, and Calcasieu Rivers in Louisiana; and the Neches, Sabine, and  
5 Trinity Rivers in Texas. In addition to contributing to the formation of wetlands running  
6 inland from the coast, each of these rivers intersects or connects with the Gulf Intracoastal  
7 Waterway and each forms the basis for an urbanized port area, of varying sizes, adjacent to  
8 the coast.

9 [INSERT Table 2.8: Land use of the central Gulf Coast study area as defined by the 1992  
10 National Land Cover Dataset]

11 [INSERT Figure 2.18: Map of terrestrial ecoregions within and adjacent to the study area]

## 12 ■ 2.4 Social and Economic Setting

13 Transportation networks exist to facilitate the movement of people and goods, and are an  
14 integral part of a region's social and economic fabric. The need for these networks, or  
15 transportation demand, therefore, is defined by demographic and economic  
16 considerations – connecting population centers, providing access to economic resources,  
17 etc. It is important, therefore, to understand the people and the economy that exist in the  
18 Gulf Coast study region in order to assess the significance of climate impacts on its  
19 transportation systems.

20 The Gulf Coast study region, like many parts of the country, has been growing in  
21 population and economic activity, and has become increasingly urbanized in recent  
22 decades. These trends were seriously disrupted by the 2005 hurricanes, which caused  
23 massive property damage and wide-scale relocation of residents in affected areas. It is too  
24 early to know what long-term impacts Hurricanes Katrina and Rita will have on the  
25 region's population distribution.

26 According to the U.S. Census Bureau estimates for 2004, the 48 counties of the designated  
27 study area are home to about 9.7 million people. Within the region are 419 cities, towns,  
28 and villages (defined as "Places" by the U.S. Census Bureau), ranging in population from  
29 less than 50 residents to nearly 2 million. A quick perusal of the interstate and highway  
30 map illustrates, to some degree, the interconnectedness of the region. The majority of these  
31 places are served by a vast land- and water-based transportation grid designed to move  
32 people and goods east and west along the coast, as well as into and out of the United States  
33 via Gulf of Mexico port facilities.

34 Figure 2.19 illustrates the degree to which urbanized zones have spread throughout the  
35 study area. Population growth and industrialization in the region are continuing to urbanize  
36 the central coast of the Gulf of Mexico. Nonetheless, major contrasts remain among urban,  
37 suburban, and rural settings within the region.

1 Mean Household Income for the study area population was lower than for the nation  
2 (\$53,600 per household compared to \$56,500 in the nation). The study region also  
3 experiences higher poverty rates (15.6 percent of all persons compared to 12.4 percent in  
4 the nation), and higher rates of children below 5 years living in poverty (17.4 percent  
5 compared to 12.5 percent nationally). The demographic distribution showed a slightly  
6 younger population when compared to the nation (52.8 percent of the population was less  
7 than 35 years, compared to 49.3 percent nationwide).

8 [INSERT FIGURE 2.19: U.S. Census Bureau Metropolitan Statistical Areas in study area]

## 9 **2.4.1 Population and Development Trends**

10 Before the impacts of the hurricanes in 2005 were fully realized, the region had  
11 experienced an average population growth rate from 1990 to 2000 of 16 percent, with an  
12 additional 5 percent growth estimated for the period 2000 to 2004 (Figures 2.21 and 2.22).  
13 Measured in terms of building permits issued, the region has experienced an overall  
14 housing growth rate of 12 percent during the period 1997 to 2002. However, a wide  
15 variation in growth rates exists among counties in the study area, including 17 counties  
16 (primarily rural) that have experienced declines in building permit issuance over this  
17 period.

18 [INSERT FIGURE 2.20: Population density in study area, 2004]

19 [INSERT FIGURE 2.21: Estimated population change in study area, 2000 to 2005]

20 Population and housing growth patterns for the region are dominated by urban-rural  
21 migration and the increasing suburbanization of the larger urban areas of  
22 Houston/Galveston, Baton Rouge/New Orleans, Hattiesburg, and Mobile. Rural counties  
23 along the western and central portions of the Louisiana coast, which tend to be dominated  
24 by wetland landscapes of the Atchafalaya and Mississippi Rivers, have experienced low  
25 and/or declining population growth over this period. These counties primarily host  
26 agricultural economies, and, like many similar rural counties in the United States, they  
27 have been experiencing slowly declining population growth rates for many decades.

28 Urban growth has been primarily characterized by spatial expansion around existing  
29 urbanized areas. In the case of Houston/Galveston, growth has been focused on those  
30 counties surrounding the core county of Harris, especially due to the residential and  
31 commercial expansion along I-10 to the west and I-45 to the south and east. The Baton  
32 Rouge/New Orleans area is experiencing a similar suburbanization process focused on the  
33 “Northshore” of Lake Pontchartrain. This growth in “bedroom” communities on the  
34 Northshore is supported by commuter pathways along I-12 and I-10 and the Lake  
35 Pontchartrain Causeway. Baton Rouge continues to grow to the east toward these  
36 Northshore counties and the New Orleans metro area has been undergoing the same cross-

1 lake residential migration for many years. One of the numerous impacts of Hurricane  
2 Katrina appears to be an acceleration of this trend among residents of Orleans and  
3 St. Bernard Counties,<sup>8</sup> as many residents are finding the Northshore communities more  
4 affordable or attractive despite the greater commute into New Orleans. Mobile, Alabama  
5 appears to be experiencing a similar pattern of suburbanization as the greatest growth is  
6 taking place in the less densely populated county of Baldwin east of Mobile Bay.  
7 Figure 2.22, “Mean Travel Time to Work,” illustrates this trend toward suburbanization in  
8 the region.

9 [INSERT FIGURE 2.22: Mean travel time to work in study area]

10 It is still too early to know what the long-term impacts of Hurricane Katrina will be on  
11 regional demographics. Some locations, particularly New Orleans, experienced major  
12 shifts. According to the 2005 American Community Survey Special Product for the Gulf  
13 Coast Area (U.S. Census Bureau, 2005), in the months following the storm, the New  
14 Orleans MSA showed a 30 percent drop in population, accompanied by a nearly four-year  
15 increase in median age (from 37.7 years to 41.6 years). The civilian labor force dropped  
16 from nearly 600,000 to about 340,000. The survey measured higher median incomes for  
17 those remaining, indicating that more higher-income workers in relatively stable  
18 professions have tended to stay in place, while lower-income, low-skilled workers have  
19 been more likely to relocate. Many people moved to other locations within the study area,  
20 such as the Houston-Galveston and Baton Rouge areas, while others left the study area  
21 entirely.

## 22 **2.4.2 Employment, Businesses, and Economic Drivers**

23 Energy production, chemical manufacturing, and commercial fishing dominate the  
24 economy of the study region. While the economy in the overall area has grown, certain  
25 parts of the region have not shared in this development. Table 2.9 shows the top 10  
26 industries in the study area by employment, according to the 2000 Census (U.S. Census  
27 Bureau, 2007). On the whole, these mirror national-level census results. Differences  
28 include a smaller share of workers employed in manufacturing (11.6 percent in the study  
29 region, compared to 14 percent in the nation) and a larger share in construction (8.6 percent  
30 in the Gulf Coast area compared to 6.8 percent in the nation). In addition, a much larger  
31 share of study area workers are employed in extraction industries (2.2 percent in the study  
32 area, versus 0.3 percent nationally).

33 [INSERT TABLE 2.9: Top 10 industries in the study area by employment percentage, 2000]

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<sup>8</sup> The U.S. Census Bureau term “County” is used here for consistency in Louisiana, rather than the more common term “Parish.” Both indicate the same political unit.

1 The study region is host to nationally significant concentrations of several industries:

- 2 • **Oil and Natural Gas Production and Refining** – Much of the U.S. domestic oil  
3 production is supported by facilities in the Gulf of Mexico region – fixed oil platforms  
4 and mobile rigs, transportation systems, refineries, storage facilities, and distribution  
5 systems. An estimated 60 percent of all U.S. energy imports come through port  
6 facilities in the Gulf of Mexico region.
- 7 • **Chemical and Petrochemical Manufacturing** – Due to the presence of petroleum and  
8 natural gas supplies and infrastructure, the Gulf is a leading center for the U.S.  
9 chemical industry, which generally relies on expensive investments in fixed  
10 infrastructure.
- 11 • **Commercial Fishing** – This is a multibillion dollar industry that is critical to the  
12 economies of many Gulf States.

13 As of 2003, the study area hosted approximately 214,768 private business establishments  
14 employing approximately 3,691,883 employees. The region experienced a 4 percent  
15 growth both in the number of establishments during the period 1998 to 2003, and in the  
16 total number of employees. Despite this overall growth, certain counties have experienced  
17 decline and/or stagnation in businesses development. The growth verses decline patterns  
18 very closely match the same patterns as the population and housing discussed earlier, with  
19 suburbanizing counties on the periphery of the larger urban areas realizing most of the  
20 growth. Most notable again are the counties currently expanding west and south around  
21 Houston/Galveston, west of Baton Rouge, the counties of Louisiana’s Northshore area, and  
22 Baldwin County west of Mobile Bay. Orleans and Jefferson Counties (constituting the  
23 bulk of metro New Orleans) again stand out as having a relatively high rate of business  
24 decline in recent years, while the counties to the east and north have flourished.

25 Most rural counties have experienced decline or stagnation in terms of total businesses and  
26 total employees. These patterns again reflect the overall development and growth that is  
27 characterized by suburbanization in the region. In some areas, this trend may be more  
28 related to technological change in agriculture or petroleum extraction methods than a true  
29 decline in the general economy.

30 Counties with port facilities or Mississippi River access dominate the manufacturing  
31 shipments measured in dollar amounts (Figure 2.23). Retail sales patterns, on the other  
32 hand, exhibit a less rational spatial pattern and seem to be tied to idiosyncratic changes in a  
33 small sample of counties. For instance the county of Waller, Texas in the farthest  
34 northwest corner of the Houston area registers a top value in terms of retail sales, but a low  
35 value in terms of manufacturer’s shipments. Much of this can be explained by the  
36 establishment of the Katy Mills Mall, which has caused the county to develop from one  
37 dominated by agriculture and industry to one based on a growing retail economy in recent  
38 years. Small-scale changes in the economic structure or productivity of specific sectors  
39 may be behind other local trends.

40 [INSERT FIGURE 2.23: Manufacturers shipments in thousands of dollars, 1997]

### 2.4.3 Societal Vulnerability

Social vulnerability measures are important both as general background to the regional demographics but also to understand implications for future infrastructure needs and for emergency management. In this case, vulnerability refers to the inability of a social group to respond to, adapt to, or avoid negative impacts resulting from extreme or significant long-term deviations from average environmental conditions.

Generally, vulnerability assessments are conducted in respect to a single risk or hazard (flooding, radioactive release, drought, hurricane evacuation, etc.). For this study, the “hazards” are the anticipated impacts of climate change and variability, specifically as it relates to transportation interests. Since this encompasses multiple changes over a protracted time period, it is difficult, at this spatial and temporal scale, to comprehensively measure those features of the current social landscape that will be most vulnerable to future changes as they occur. Therefore, numerous social measures were included in this analysis in an effort to describe the most general patterns of vulnerability. The attributes included in this social vulnerability index are:

1. Percent persons reporting disabilities for civilian noninstitutionalized population five years and over;
2. Percent total population: Age 14 and below;
3. Percent total population: 65 years and over;
4. Percent households: Two-or-more-person household; family households; maritally single; with own children under 18 years;
5. Percent households: All languages; linguistically isolated;
6. Percent population 25 years and over: No high school graduate (includes equivalency);
7. Percent below study area median household income in 1999;
8. Percent households: With public assistance income;
9. Percent population for whom poverty status is determined: Income in 1999 below poverty level;
10. Percent housing units: Mobile home;
11. Percent housing units: Built 1969 or earlier;
12. Percent occupied housing units: No vehicle available;
13. Percent occupied housing units: Renter occupied;
14. Specified owner-occupied housing units: Percent below study area median value; and

1       15. Specified owner-occupied housing units: Percent housing units with a mortgage;  
2       contract to purchase; or similar debt; with either a second mortgage or home equity  
3       loan; but not both.

4       To illustrate how these multiple attributes can be agglomerated, these 15 measures were  
5       subjected to an indexing process to create a continuum of vulnerability at both the county-  
6       and block-group scale (most vulnerable, more vulnerable, less vulnerable, and least  
7       vulnerable). In future phases of this research, particularly for in-depth analysis of one site,  
8       the attributes included in this index can be changed or statistically weighted in response to  
9       particular transportation management or other concerns at that site. Figure 2.24 maps this  
10      vulnerability index for the study region. Maps depicting conditions within the region for  
11      each of the 15 societal attributes are contained in Appendix B.

12      A number of patterns emerge from these measures of vulnerability. The first is the obvious  
13      pattern of counties with high degrees of social vulnerability expressed in the central portion  
14      of the Louisiana section of the study area. These counties correspond with the physical  
15      feature of the Atchafalaya River valley, the western portions of the Mississippi River  
16      valley, and the wetland landscapes produced by both. One can interpret from this analysis  
17      that these populations, if faced with extreme changes in their physical environments, will  
18      find coping with those changes extremely difficult. Many of these counties are  
19      traditionally rural, impoverished areas (Figure 2.25). Also included is the urban-core  
20      county of Orleans, which ranks extremely high on many of the vulnerability measures  
21      included here.

22      However, poverty alone does not explain the higher rankings. These counties also tend to  
23      rank high in presence of disabled populations, persons over 65 (Figure 2.26), absence of a  
24      vehicle per household, presence of single parents, linguistic isolation, and a number of  
25      other attributes. It can be argued that these are all dimensions of impoverishment.  
26      However, it is not the simple fact that a person is poor that makes them vulnerable, rather it  
27      is the context that widespread poverty can create in terms of public services, durability of  
28      infrastructure, access to egress, etc. acting together that make a community vulnerable to  
29      extreme environmental change.

30      To a lesser degree, this pattern of vulnerability extends southeast into the delta region of  
31      central Louisiana. Other counties with similar characteristics outside central Louisiana  
32      tend to be rural and tertiary to urban-suburban growth. Exceptions to this statement are the  
33      heavily industrialized counties around Beaumont, Port Arthur, Lake Charles, and  
34      St. Bernard County. The rapidly urbanizing county of Mobile also falls into this category  
35      of vulnerability.

36      Counties that tend to have fewer vulnerability characteristics are those on the periphery of  
37      large urban areas that were described earlier as undergoing the fastest rates of  
38      suburbanization. Again, this is tied heavily to overall income patterns, but is not fully  
39      explained by that single attribute. For instance, these counties also tend to have higher  
40      rates of children per capita and more manufactured housing. It can be assumed that, at  
41      least for the time being, the populations of these counties will be better prepared to cope  
42      with the negative impacts of extreme environmental change.

1 From a transportation perspective, it also might be assumed that these areas will have  
2 special needs for transportation infrastructure in coming years. Vulnerable areas may need  
3 more services and infrastructure in the future to help them reduce their vulnerability – and  
4 cope with destructive natural events – such as severe storms – as they occur.

5 [Insert Figure 2.24: Social vulnerability index for study area]

6 [Insert Figure 2.25: Persons in poverty in study area]

7 [Insert Figure 2.26: Persons aged 65 and older in study area]

## 8 ■ 2.5 Conclusions

9 The central Gulf Coast study area contains transportation infrastructure that is vital not just  
10 to the movement of passengers and goods within the study area, but is also critical to the  
11 national transportation network and economy. However, the geomorphology of the region  
12 makes it particularly sensitive to certain climate impacts. Due largely to its sedimentary  
13 history, the region is low-lying – much of it below five meters – with little topographical  
14 relief. Much of the region experiences high rates of subsidence as these sediments  
15 naturally compact over time, while high rates of erosion mean sections of coastline are  
16 literally washed away after tropical storms and hurricanes. As a result, the region is  
17 particularly vulnerable to the effects of sea level rise and storm activity.

18 In keeping with national trends, the region is experiencing a shift in population from rural  
19 to urban areas, and seeing increasing suburbanization of the larger urban areas. Much of  
20 the infrastructure supporting this population is located in vulnerable, low-lying areas. Parts  
21 of the population face vulnerabilities that may make it more difficult for them to adapt to  
22 the conditions imposed by a changing climate. This pattern of vulnerability is most  
23 focused in the rural counties of central coastal Louisiana, the urban core of New Orleans,  
24 and to a lesser extent southeast into the delta region of Louisiana and also rapidly  
25 urbanizing Mobile County. On average, the population of the study area shows lower-  
26 income levels and higher poverty rates than the rest of the nation.

27 The following section will present the climate changes projected for the study area, while  
28 Section 4.0 will discuss the resulting impacts to transportation systems in the central Gulf  
29 Coast region.

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**Table 2.1 Study area counties and Federal Information Processing Standard (FIPS) codes.**

<b>Name</b>	<b>State</b>	<b>FIPS</b>	<b>Name</b>	<b>State</b>	<b>FIPS</b>
Baldwin	Alabama	003	St. Tammany	Louisiana	103
Mobile	Alabama	097	Tangipahoa	Louisiana	105
Acadia	Louisiana	001	Terrebonne	Louisiana	109
Ascension	Louisiana	005	Vermilion	Louisiana	113
Assumption	Louisiana	007	West Baton Rouge	Louisiana	121
Calcasieu	Louisiana	019	Forrest	Mississippi	035
Cameron	Louisiana	023	George	Mississippi	039
East Baton Rouge	Louisiana	033	Hancock	Mississippi	045
Iberia	Louisiana	045	Harrison	Mississippi	047
Iberville	Louisiana	047	Jackson	Mississippi	059
Jefferson	Louisiana	051	Lamar	Mississippi	073
Jefferson Davis	Louisiana	053	Pearl River	Mississippi	109
Lafayette	Louisiana	055	Stone	Mississippi	131
Lafourche	Louisiana	057	Brazoria	Texas	039
Livinston	Louisiana	063	Chambers	Texas	071
Orleans	Louisiana	071	Fort Bend	Texas	157
Plaquemines	Louisiana	075	Galveston	Texas	167
St. Bernard	Louisiana	087	Hardin	Texas	199
St. Charles	Louisiana	089	Harris	Texas	201
St. James	Louisiana	093	Jefferson	Texas	245
St. John the Baptist	Louisiana	095	Liberty	Texas	291
St. Landry	Louisiana	097	Montgomery	Texas	339
St. Martin	Louisiana	099	Orange	Texas	361
St. Mary	Louisiana	101	Waller	Texas	473

Note: The FIPS county code is a number that uniquely identifies each county in the United States.

**Table 2.2 Gulf Coast study area centerline miles of highway, by classification and ownership. (Cambridge Systematics from 2004 Highway Performance Monitoring System database for Gulf Coast Study supplied by the Bureau of Transportation Statistics)**

	<b>State</b>	<b>County</b>	<b>Municipal</b>	<b>Other</b>	<b>Total</b>
Interstate	1,096	0	0	0	1,096
Arterials	4,484	794	2,268	105	7,651
Collector	4,390	1,776	2,016	35	8,747
<b>Total</b>	<b>9,970</b>	<b>2,570</b>	<b>4,284</b>	<b>140</b>	<b>17,494</b>

**Table 2.3 Equipment, annual service, and passengers for fixed-route bus operations in the study area, 2004. (Cambridge Systematics from 2004 National Transit Database)**

Agency	Urban Area	Vehicles	Type of Vehicle	Passengers		Revenue	
				(000)	Miles (000)	Miles (000)	Hours (000)
Metropolitan Transit Authority of Harris County, MTAHC (Metro)	Houston, Texas	1,434	210 articulated diesel buses, 1224 diesel buses	87,940	504,902	44,097	3,051
New Orleans Regional Transit Authority (RTA)	New Orleans, Louisiana	367	367 diesel buses	38,202	92,252	10,655	748
Capital Area Transit System (CATS)	Baton Rouge, Louisiana	74	5 CNG buses, 51 diesel buses, 18 diesel vans	4,805	15,749	3,172	159
Jefferson Transit (JeT)	New Orleans, Louisiana	63	59 diesel buses, 4 diesel vans	4,192	19,581	2,276	149
Lafayette Transit System (LTS)	Lafayette, Louisiana	22	22 diesel buses	1,156	4,856	536	41
Island Transit (IS)	Galveston, Texas	20	11 diesel buses, 9 diesel vans	940	1,454	555	45
The Wave Transit (The Wave)	Mobile, Alabama	31	26 diesel buses, 5 diesel vans	860	5,233	1,371	97
Beaumont Municipal Transit System	Beaumont, Texas	19	1 CNG bus, 18 diesel buses	662	2,858	729	52
Coast Transit Authority	Gulfport-Biloxi, Pascagoula, Mississippi	18	16 diesel buses, 2 LPG buses	534	2,672	770	61
Port Arthur Transit (PAT)	Port Arthur, Texas	11	10 diesel buses, 1 diesel van	125	935	235	14
Hattiesburg Area Redit Transit, Hub City Transit (HART)	Hattiesburg, Mississippi	5	3 gasoline buses, 2 diesel vans	N/A	N/A	N/A	N/A
Lake Charles Transit System (LCTS)	Lake Charles, Louisiana	8	8 diesel buses	N/A	N/A	N/A	N/A
Saint Bernard Urban Rapid Transit (SBURT)	New Orleans, Louisiana	9	8 diesel buses, 1 diesel van	N/A	N/A	N/A	N/A
<b>Total</b>		<b>2,081</b>		<b>139,416</b>	<b>650,492</b>	<b>64,396</b>	<b>4,417</b>

**Table 2.4 Freight railroads in the Gulf Coast study area. (Bureau of Transportation Statistics, 2004)**

<b>Railroad</b>	<b>Class</b>	<b>Service Area</b>	<b>Primary Commodities</b>
Acadiana Railway	III	Crowley, Louisiana through Eunice and Opelousas to Bunkie, Louisiana.	Agricultural products, edible oils, and general freight.
Alabama and Gulf Coast Railway	III	Pensacola, Florida to Columbus, Alabama. Extensions to Mobile, Alabama via NS trackage.	Paper industry: logs, woodchips, chlorine, sodium chlorate, hydrogen peroxide, rolled and boxed paper, and kaolin clay.
Burlington Northern Santa Fe Railway	I	Over 32,000 route miles in western U.S. Operate between Houston and New Orleans.	Coal, grains, intermodal, lumber, and chemicals.
Canadian National Railway (formerly Illinois Central Gulf)	I	Over 19,000 route miles in U.S. and Canada. Serves Mobile and New Orleans via north-south route.	Petroleum, chemicals, grain, fertilizers, coal, metals, minerals, forest products, intermodal, and automotive.
CSX Transportation	I	Over 22,000 route miles in eastern U.S. Operate between Florida and New Orleans along I-10 corridor.	Coal, chemicals, autos, minerals, agricultural products, food, consumer goods, metals, forest and paper products, and phosphates and fertilizer.
Kansas City Southern	I	Operates approximately 3,100 route miles in central and southeastern U.S. Serves New Orleans, Lake Charles, Port Arthur, Galveston, and Mexico.	Agriculture, minerals, general merchandise, intermodal, autos, and coal.
Lake Charles Port and Harbor District	Switching	Owned by the Port. Switches traffic for Union Pacific.	Port traffic.
Louisiana and Delta Railroad	III	Multiple branches connected by trackage rights on UP between Lake Charles and Raceland, Louisiana.	Carbon black, sugar, molasses, pipe, rice, and paper products.
Mississippi Export Railroad		Escatawpa River at Evanston, Mississippi to port at Pascagoula, Mississippi.	Transloading services for intercoastal and river barges or vessels.
New Orleans and Gulf Coast Railway	III	Westwego, Louisiana to Myrtle Grove, Louisiana.	Food products, oils, grains petroleum products, chemicals, and steel products.
New Orleans Public Belt Railroad	Switching	Serves Port of New Orleans along the Mississippi River and Industrial Canal.	Exports: lumber, wood products, and paper. Imports: metal products, rubber, plastics, and copper. Domestic: clay, cement, and steel plate.
Norfolk Southern Corporation	I	Over 21,000 route miles in eastern U.S. Operate from Birmingham to Mobile and New Orleans.	Agriculture, autos, chemicals, coal, machinery, intermodal, metals, construction material, paper, clay, forest products.
Pearl River Valley Railroad	III	Goodyear, Mississippi to Nicholson, Mississippi.	Lumber and forest products.
Port Bienville Railroad	Switching	Port Bienville Industrial Park, Hancock County, Mississippi.	Plastic resins and other goods for industrial park tenants.
Sabine River and Northern Railroad	III	Between Buna and Orange, Texas.	Wood chips, chemicals, and other raw materials for the paper industry. Finished paper and lumber products.
Terminal Railway Alabama State Docks	Switching	Operates over 75 miles in the Mobile area, serving the port and local industries.	Port cargo.
Timber Rock Railroad Company	III	De Ridder, Louisiana west through Merryville to Kirbyville, Texas.	Forest products and rock.
Union Pacific Railroad	I	Over 32,000 route miles in western U.S. Operate between Houston and New Orleans.	Chemicals, coal, food, forest products, grains, intermodal, metals, minerals, and autos.

**Table 2.5 Domestic and international waterborne tonnage of study area ports, 2003. (U.S. Army Corps of Engineers, Navigation Data Center)**

National Rank	Port	2003 Short Tons
1	South Louisiana, Louisiana	198,825,125
2	Houston, Texas	190,923,145
4	Beaumont, Texas	87,540,979
5	New Orleans, Louisiana	83,846,626
9	Texas City, Texas	61,337,525
10	Baton Rouge, Louisiana	61,264,412
11	Plaquemines, Louisiana	55,916,880
12	Lake Charles, Louisiana	53,363,966
14	Mobile, Alabama	50,214,435
23	Pascagoula, Mississippi	31,291,735
24	Freeport, Texas	30,536,657
27	Port Arthur, Texas	27,169,763
	<b>Gulf Coast Study Area Total</b>	<b>932,231,248</b>
	<b>National Total</b>	<b>2,394,251,814</b>

**Table 2.6 Tonnage on study area inland and coastal waterways, 2003. (U.S. Army Corps of Engineers, Waterborne Commerce of the United States, 2003)**

<b>Waterways Segments Within Study Area</b>	<b>2003 Short Tons (Millions)</b>
Mississippi River, Baton Rouge to New Orleans, Louisiana	212.9
Mississippi River, Mouth of Ohio to Baton Rouge, Louisiana	185.5
Gulf Intracoastal Waterway, Texas-Florida	117.8
Mississippi River, New Orleans to Gulf	115.8
Gulf Intracoastal Waterway, Port Allen Route, Louisiana	24.3
Black Warrior and Tombigbee Rivers, Alabama	21.0
Atchafalaya River, Louisiana	9.8
Tennessee-Tombigbee Waterway, Alabama and Mississippi	5.2
Red River, Louisiana	4.2
Chocolate Bayou, Texas	3.3
Petit Anse, Tigre, Carlin bayous, Louisiana	2.5
Ouachita and Black Rivers, AR and Louisiana	2.2
Bayou Teche, Louisiana	1.4
<b>Subtotal for Waterway Segments Within Study Area</b>	<b>705.9</b>
<b>Subtotal for Full Gulf Coast and Mississippi River Systems, including Waterway Segments Within or Connecting to Study Area</b>	<b>1650.5</b>
<b>National Total of All Major Inland and Coastal Waterway Segments</b>	<b>1717.0</b>



**Table 2.7 Passenger enplanements and cargo tonnage for select commercial service and industrial airports in the study area, 2005.**

Associated City	FAA Code	State	County	Airport Name	Airport Type	2005	
						Passenger Enplanements	Cargo Tonnage
Mobile	MOB	Alabama	Mobile	Mobile Regional	CS	638,953	582
Mobile	BFM	Alabama	Mobile	Mobile Downtown	IND	0	44,000 <sup>a</sup>
Lake Charles	LCH	Louisiana	Calcasieu	Lake Charles Regional	CS	43,250 <sup>a</sup>	2 <sup>a</sup>
Lake Charles	CWF	Louisiana	Calcasieu	Chennault International	IND	0	75
Baton Rouge	BTR	Louisiana	East Baton Rouge	Baton Rouge Metropolitan, Ryan Field	CS	973,625	5,663
New Orleans	MSY	Louisiana	Jefferson	Louis Armstrong New Orleans International	CS	7,775,147	66,123
Lafayette	LFT	Louisiana	Lafayette	Lafayette Regional	CS	343,301	6,774
Hattiesburg	HBG	Mississippi	Forrest	Bobby L Chain Muni	CS	8,000 <sup>a</sup>	
Gulfport	GPT	Mississippi	Harrison	Gulfport-Biloxi International	CS	769,669	
Houston	EFD	Texas	Harris	Ellington Field	CS	53,947	15
Houston	HOU	Texas	Harris	William P. Hobby	CS	8,252,532	7,000
Houston	IAH	Texas	Harris	George Bush Intercontinental/Houston	CS	39,684,640	387,790
Beaumont/ Port Arthur	BPT	Texas	Jefferson	Southeast Texas Regional	CS	43,038 <sup>a</sup>	
<b>Study Area Total</b>						<b>58,586,102</b>	<b>517,418</b>
<b>National Total</b>						<b>738,629,000</b>	<b>30,125,644</b>

Source: Alabama airports from <http://www.brookleycomplex.com/cargo/statistics.asp>. Louisiana airports from the Airports Council International and U.S. DOT BTS T100 data. Texas airports from <http://www.city-data.com/us-cities/The-South/Houston-Economy.html>. Wilbur Smith Associates. National totals from Bureau of Transportation Statistics ([http://www.bts.gov/programs/airline\\_information/air\\_carrier\\_traffic\\_statistics/airtraffic/annual/1981-2001.html](http://www.bts.gov/programs/airline_information/air_carrier_traffic_statistics/airtraffic/annual/1981-2001.html)) and Airports Council International.

<sup>a</sup> Estimated.

**Table 2.8 Land use of the central Gulf Coast study area as defined by the 1992 National Land Cover Dataset. (National Land Cover Dataset, USGS)**

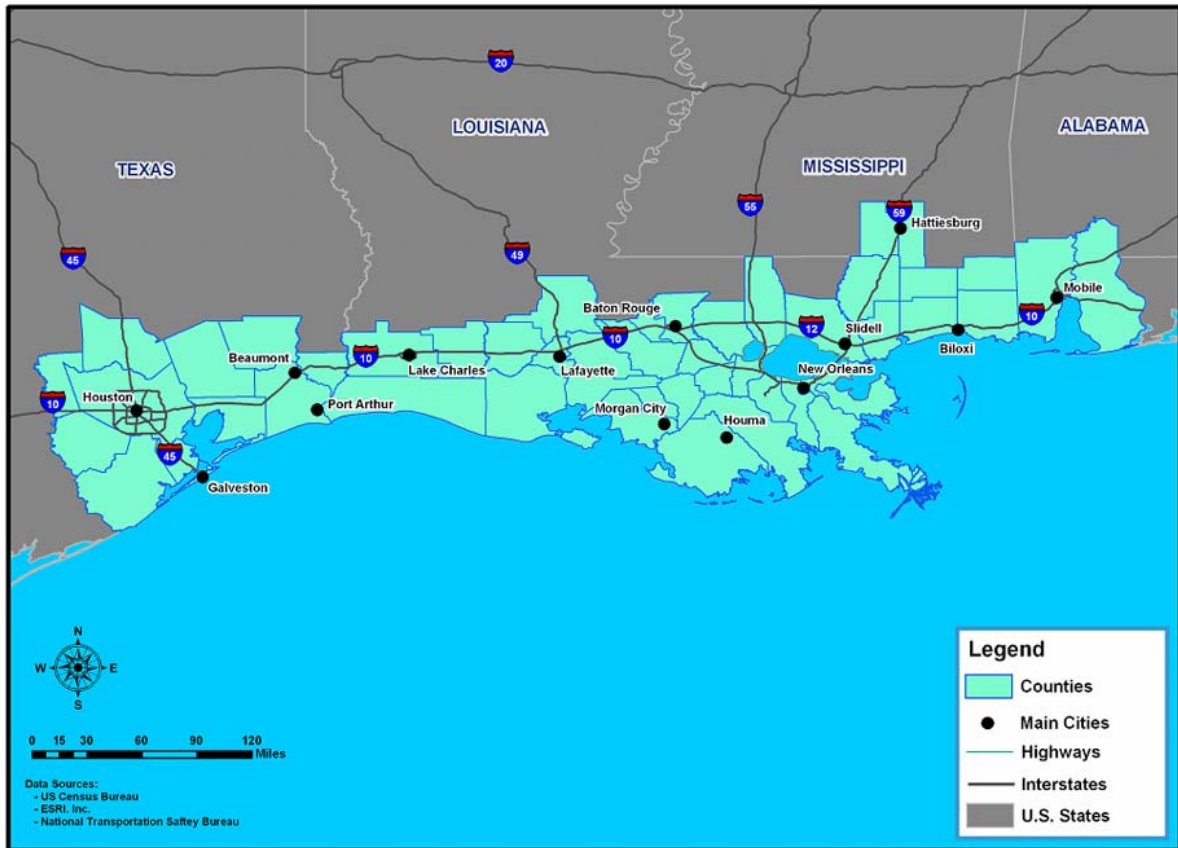
<b>Land Use Category</b>	<b>Area (Hectares)</b>	<b>Percent of Total</b>
Water	508,735	5.38%
Low-Intensity Residential	250,032	3.00%
High-Intensity Residential	106,637	1.13%
Commercial, Industrial, Transportation	152,744	1.62%
Bare Rock, Sand, Clay	14,126	0.15%
Quarries, Strip Mines, Gravel Pits	3,921	0.04%
Transitional from Barren	92,835	0.98%
Deciduous Forest	492,245	5.21%
Evergreen Forest	1,175,278	12.44%
Mixed Forest	861,726	9.12%
Shrubland	23,096	0.24%
Orchard, Vineyard	5	Negligible
Grasslands, Herbaceous	123,576	1.31%
Pasture, Hay	1,213,343	12.84%
Row Crops	591,105	6.26%
Small Grains	694,855	7.35%
Urban, Recreation Grasses	83,476	0.88%
Woody Wetlands	1,087,093	11.50%
Emergent Herbaceous Wetlands	1,974,788	20.90%
<b>Total</b>	<b>9,449,615</b>	

**Table 2.9 Top 10 industries in the study area by employment percentage, 2000. (United States Census 2000, U.S. Census Bureau, 2007)**

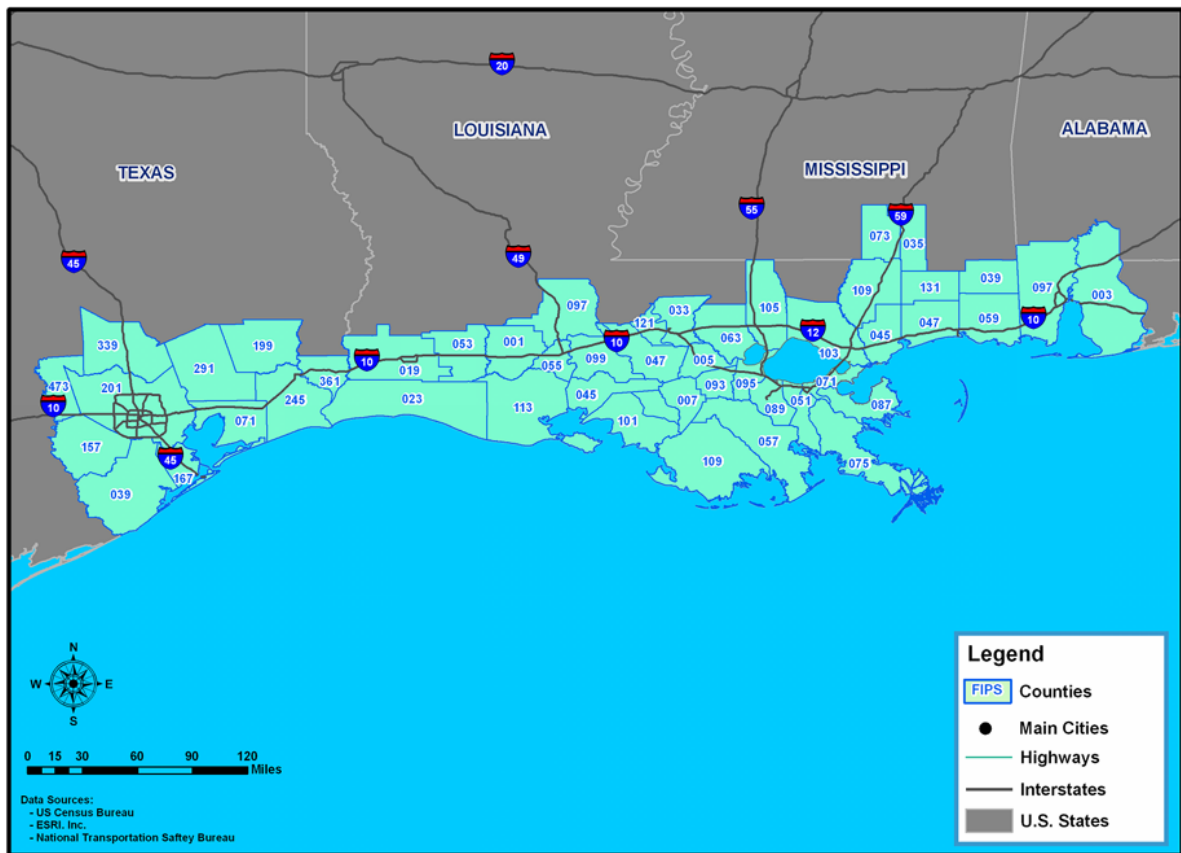
<b>Industry</b>	<b>Percent of Study Area Employment</b>
Retail Trade	11.6
Manufacturing	11.6
Health Care and Social Assistance	10.2
Educational Services	8.9
Construction	8.6
Accommodation and Food Services	6.4
Professional, Scientific, and Technical Services	6.2
Other Services (except Public Administration)	5.2
Transportation and Warehousing	4.8
Public Administration	4.3



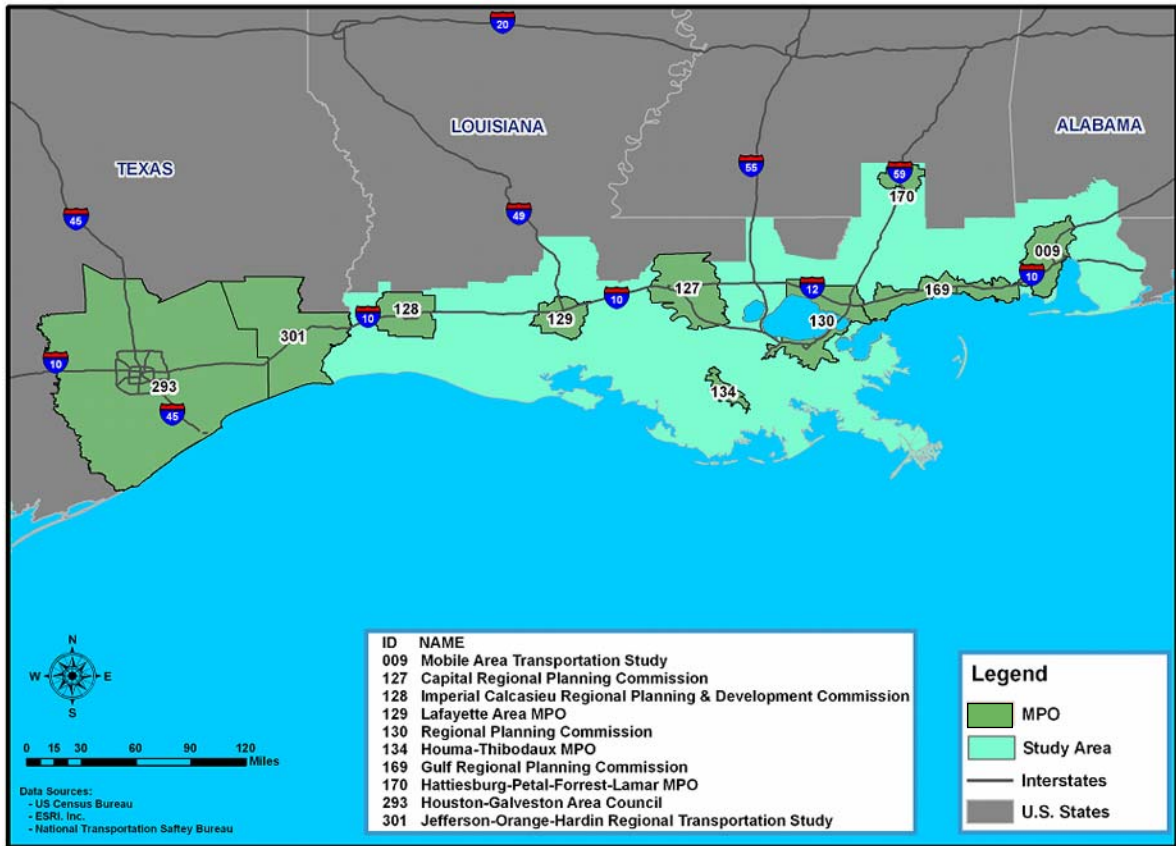
**Figure 2.1** Map of study area. Study area extends from Mobile, Alabama to Houston/Galveston, Texas. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)



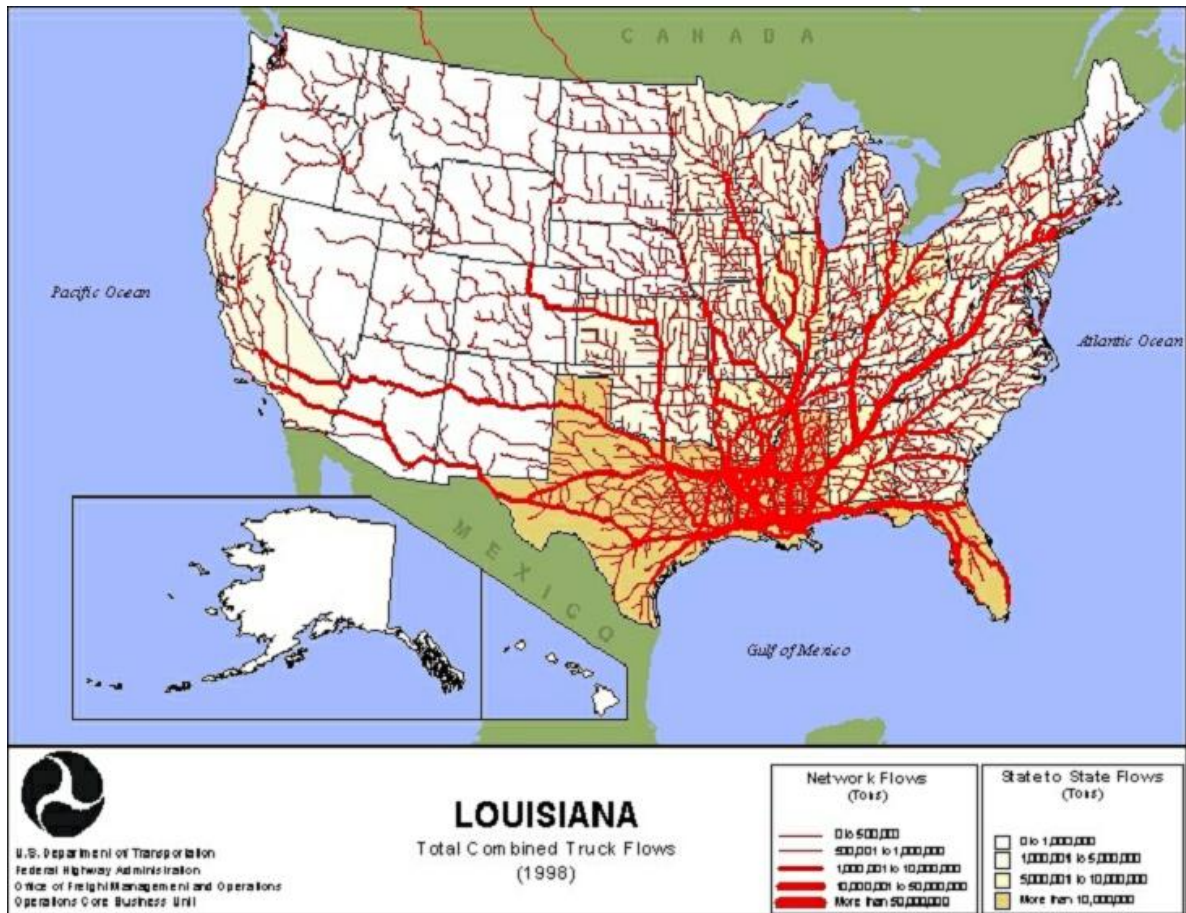
**Figure 2.2 Study area counties and Federal Information Processing Standard (FIPS) codes. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)**



**Figure 2.3 Metropolitan planning organizations in the study area. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)**



**Figure 2.4 Combined truck flows shipped domestically from Louisiana, 1998.**  
(Source: U.S. Department of Transportation Federal Highway Administration, Freight Management and Operations, Office of Operations)

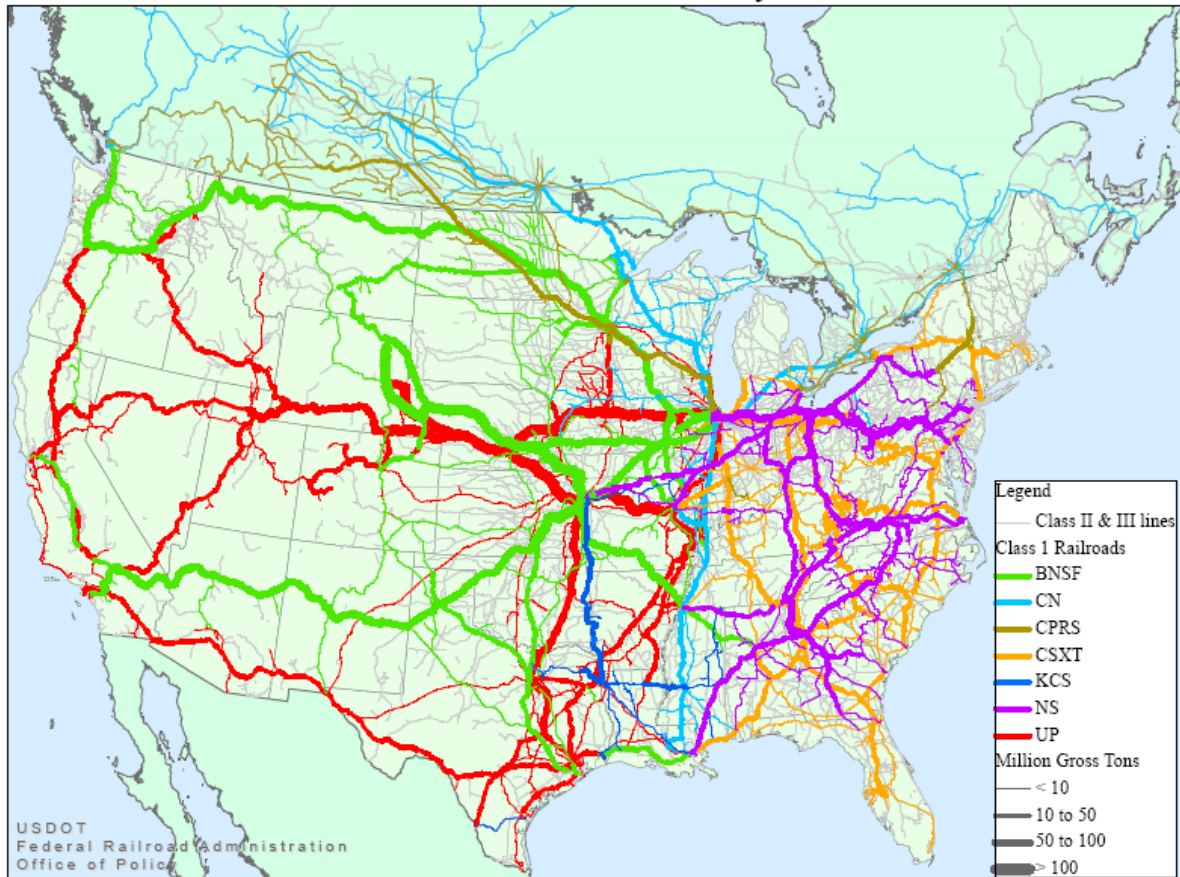




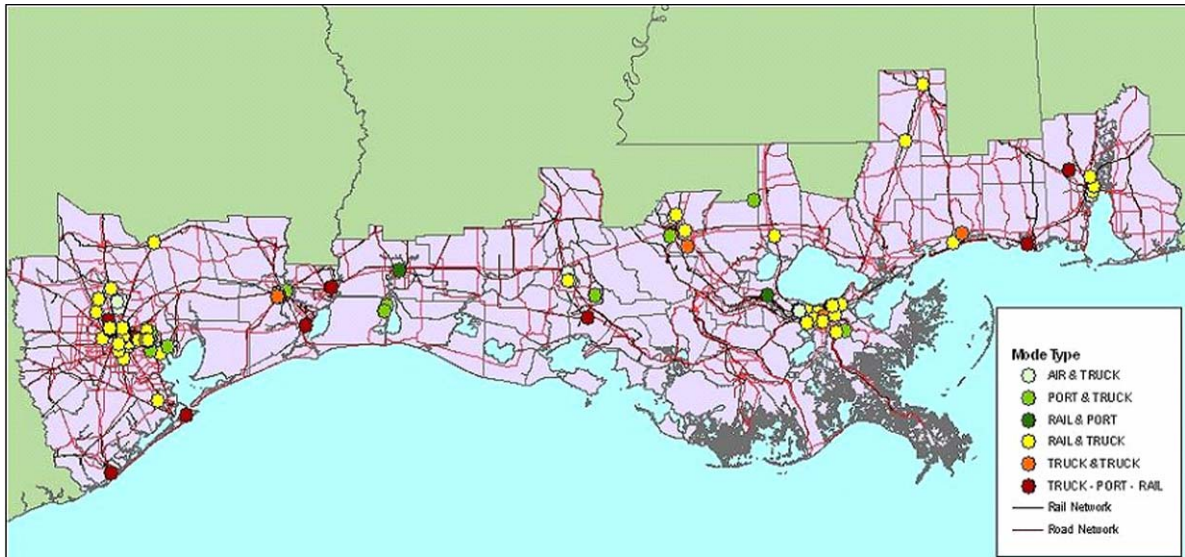
**Figure 2.5** Navigable inland waterways impacting the study area, shown as named waterways. (Source: U.S. Department of Transportation)



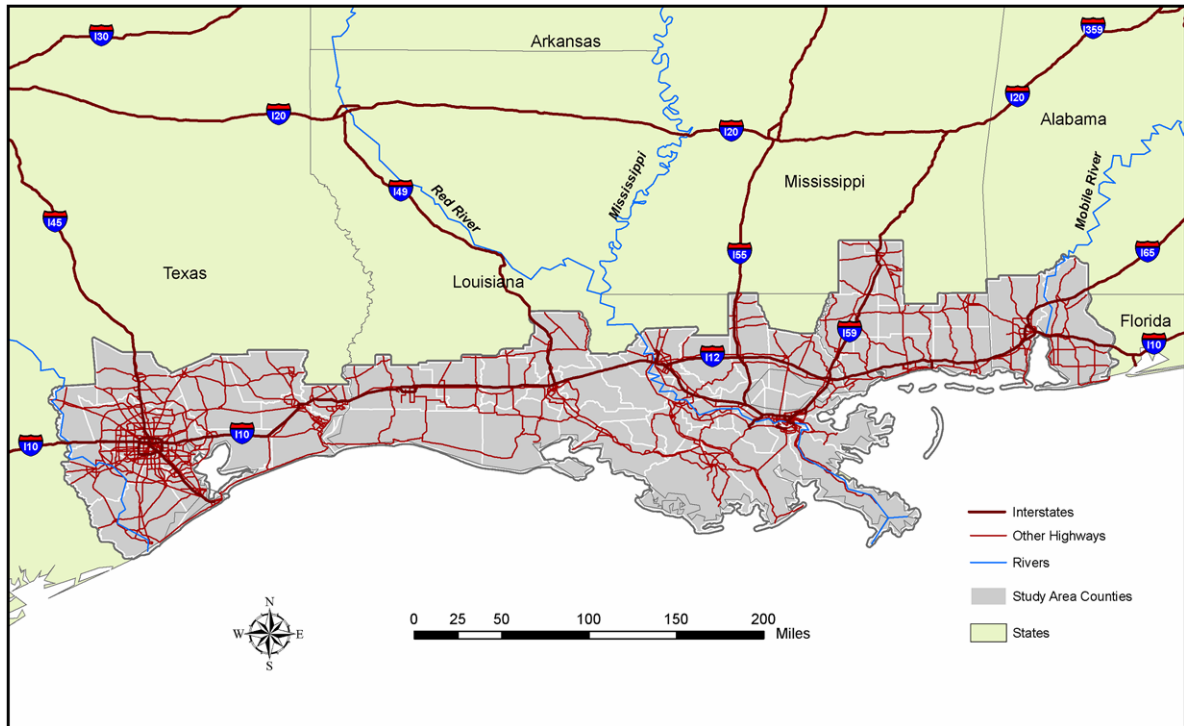
**Figure 2.6 National network of Class I railroads.**  
(Source: Federal Railroad Administration Office of Policy,  
U.S. Department of Transportation)



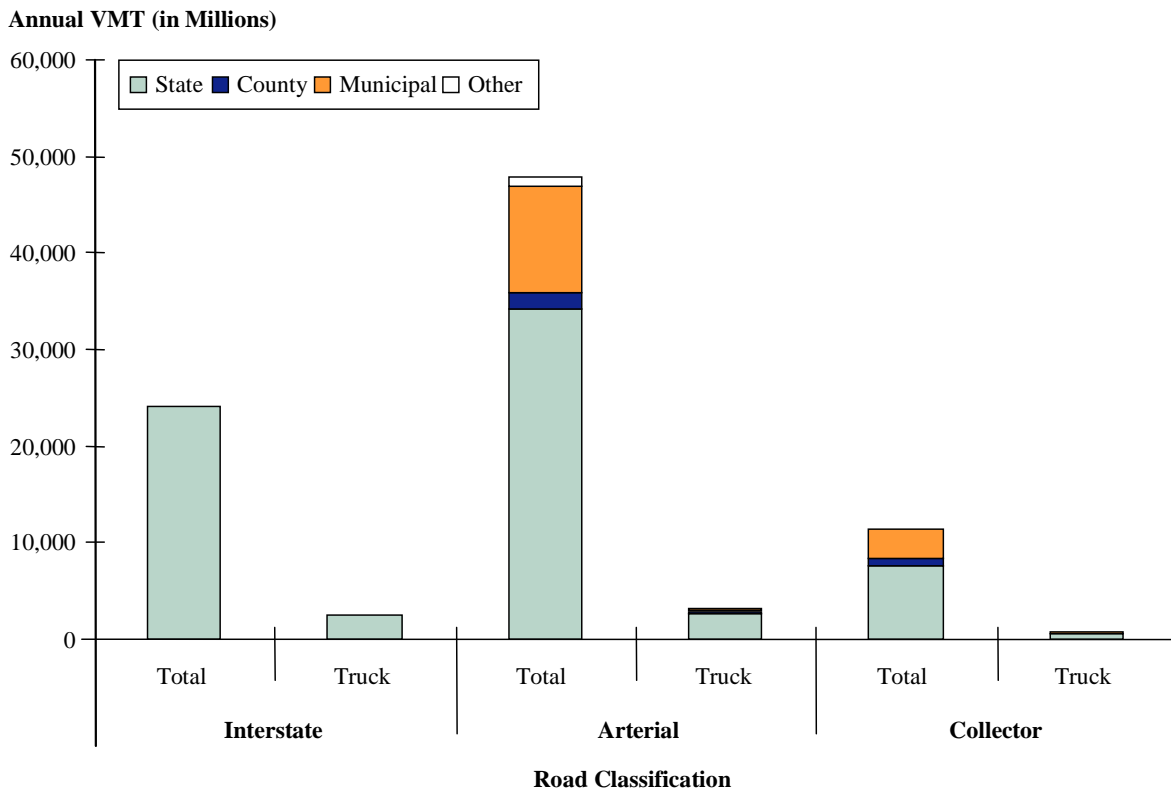
**Figure 2.7 Intermodal facilities in the study area. (Source: Bureau of Transportation Statistics, U.S. Department of Transportation)**



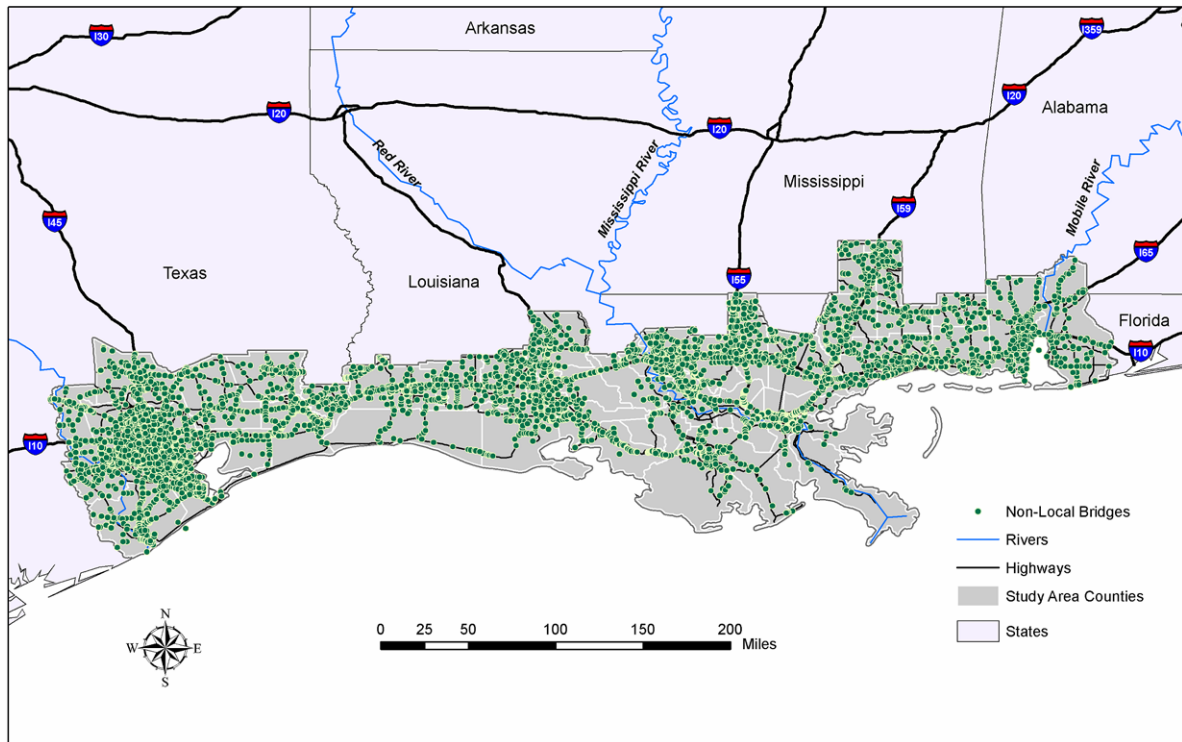
**Figure 2.8 Highways in the study area. (Source: Cambridge Systematics analysis of U.S. Department of Transportation data)**



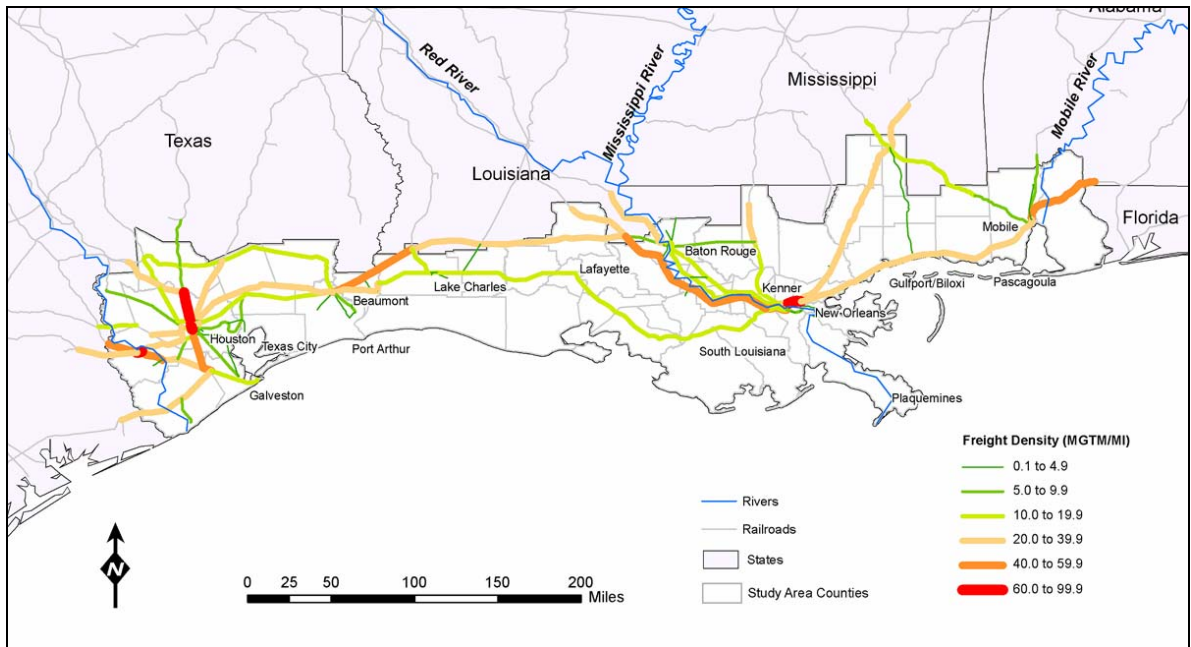
**Figure 2.9 Total and truck annual vehicle miles traveled (VMT) on nonlocal roads, 2003. (Source: Cambridge Systematics, from 2004 Highway Performance Monitoring System database for Gulf Coast Study supplied by the Bureau of Transportation Statistics, U.S. Department of Transportation)**



**Figure 2.10 Nonlocal bridges in the study area (NBI latitude and longitude location). (Source: Cambridge Systematics analysis of U.S. Department of Transportation data)**



**Figure 2.11 Freight railroad traffic density (annual millions of gross ton-miles per mile) in the study area. (Source: Bureau of Transportation Statistics, U.S. Department of Transportation)**

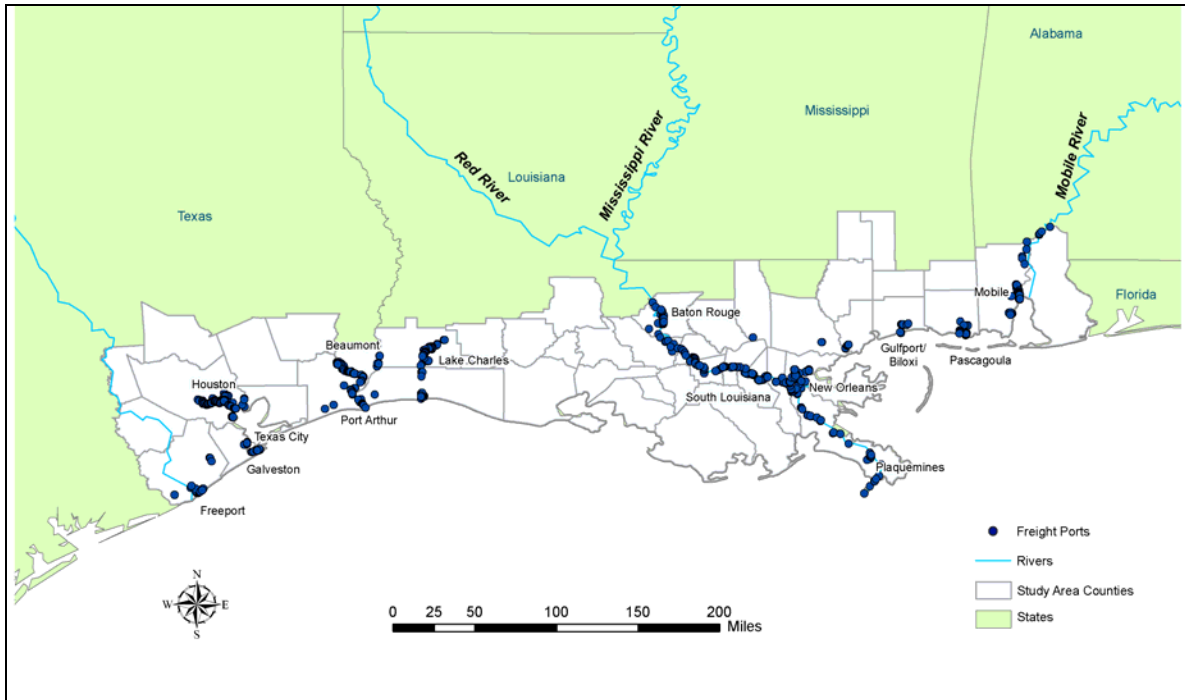


**Figure 2.12 Sunset Limited route map, Houston, Texas – Mobile, Alabama segment. (Source: Amtrak)**





**Figure 2.13 Freight handling ports and waterways in the study area.**  
(Source: Cambridge Systematics analysis of U.S. Army Corps of Engineers data)

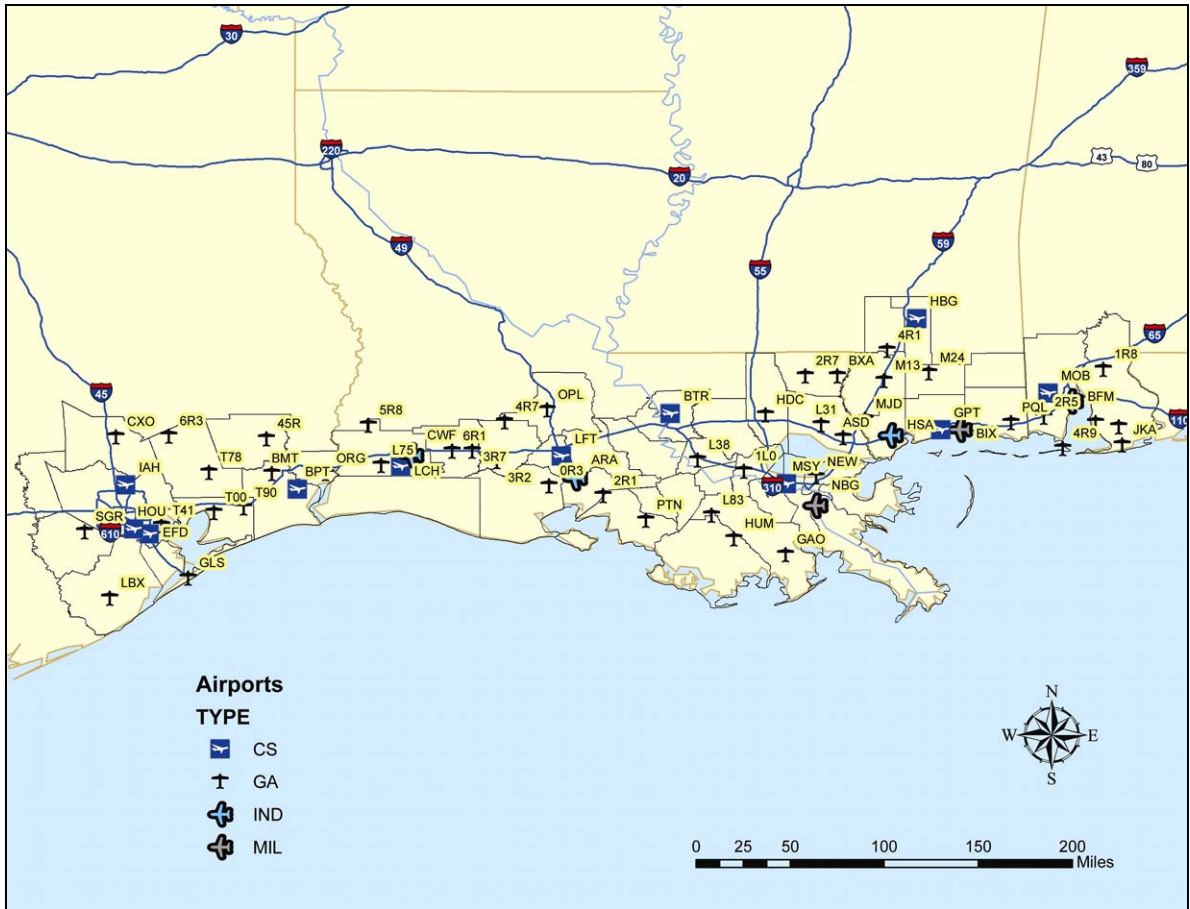


**Figure 2.14 Barge tow on the Mississippi River.**  
(Source: U.S. Army Corps of Engineers)



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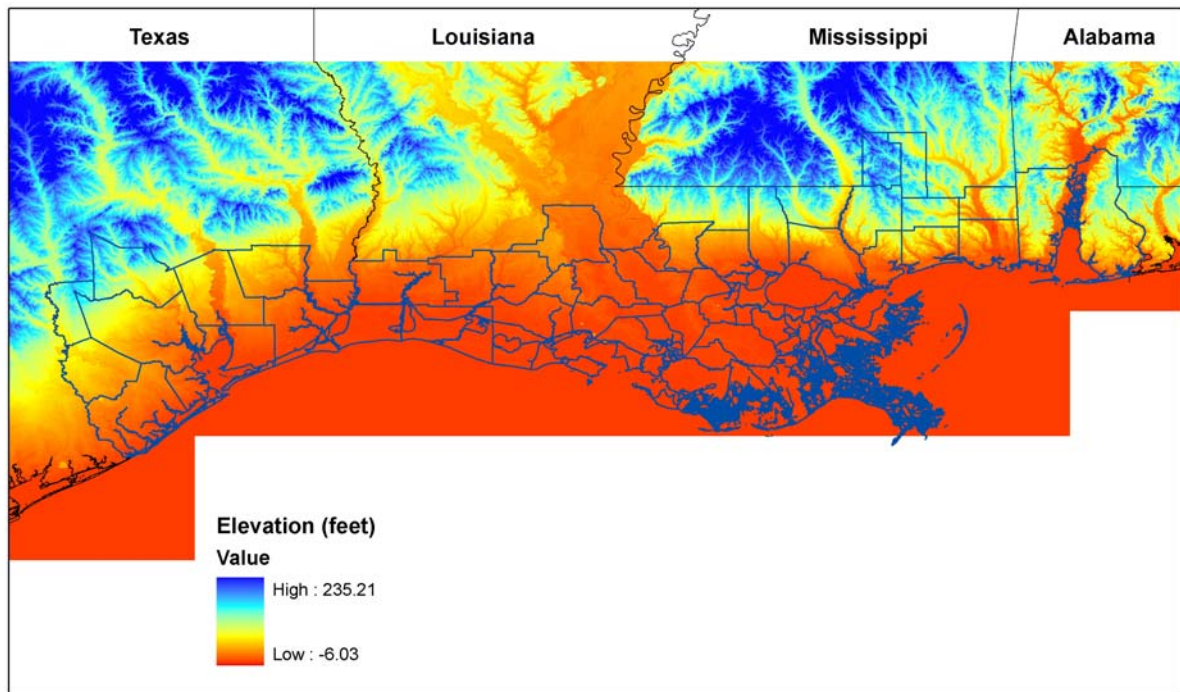
**Figure 2.15 Study area airports. (Source: Bureau of Transportation Statistics, U.S. Department of Transportation)**



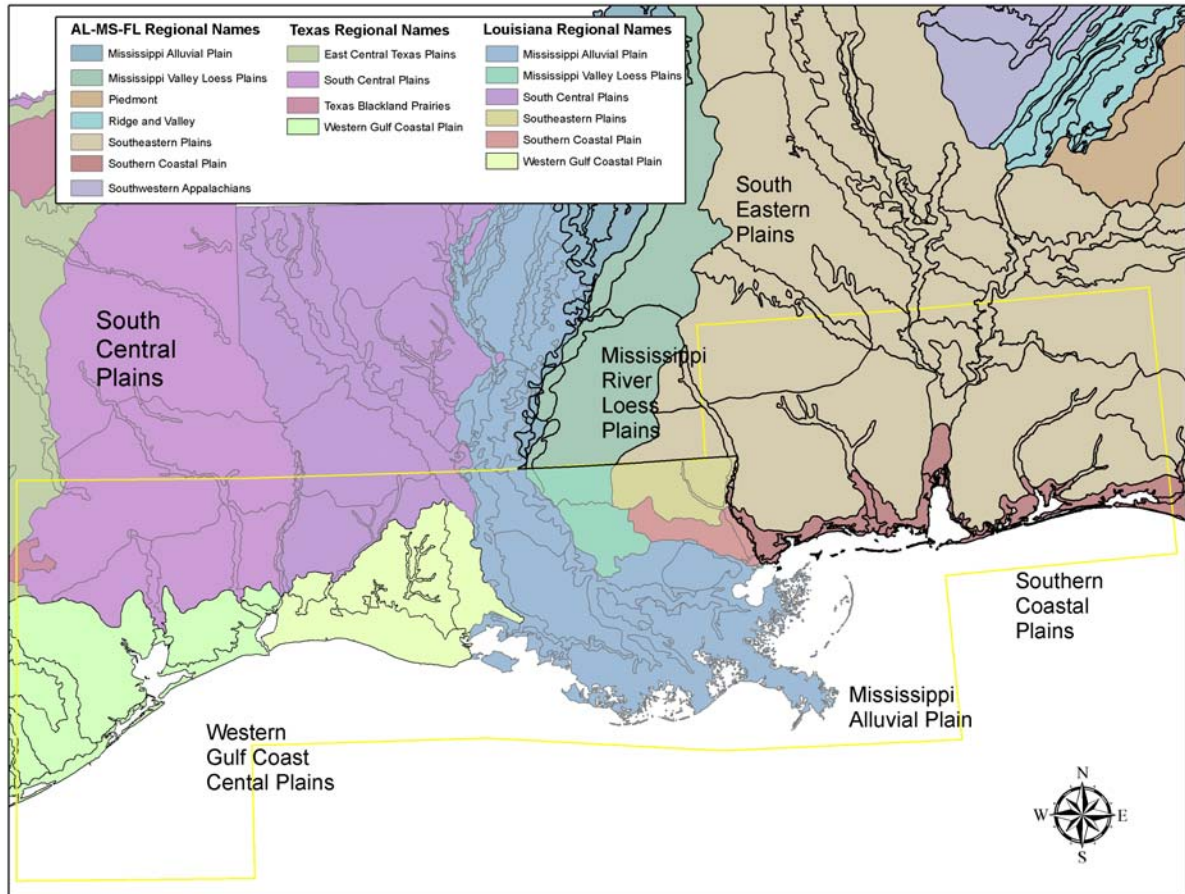
**Figure 2.16** Surface geology of the southeastern United States. White line denotes inland extent of the coastal plain and grey area is Holocene alluvium. (Source: USGS, 2000a)



**Figure 2.17** Relative elevation of study area counties (delineated in blue).  
All areas shown in bright orange are below 30 m elevation.  
(Source: USGS)



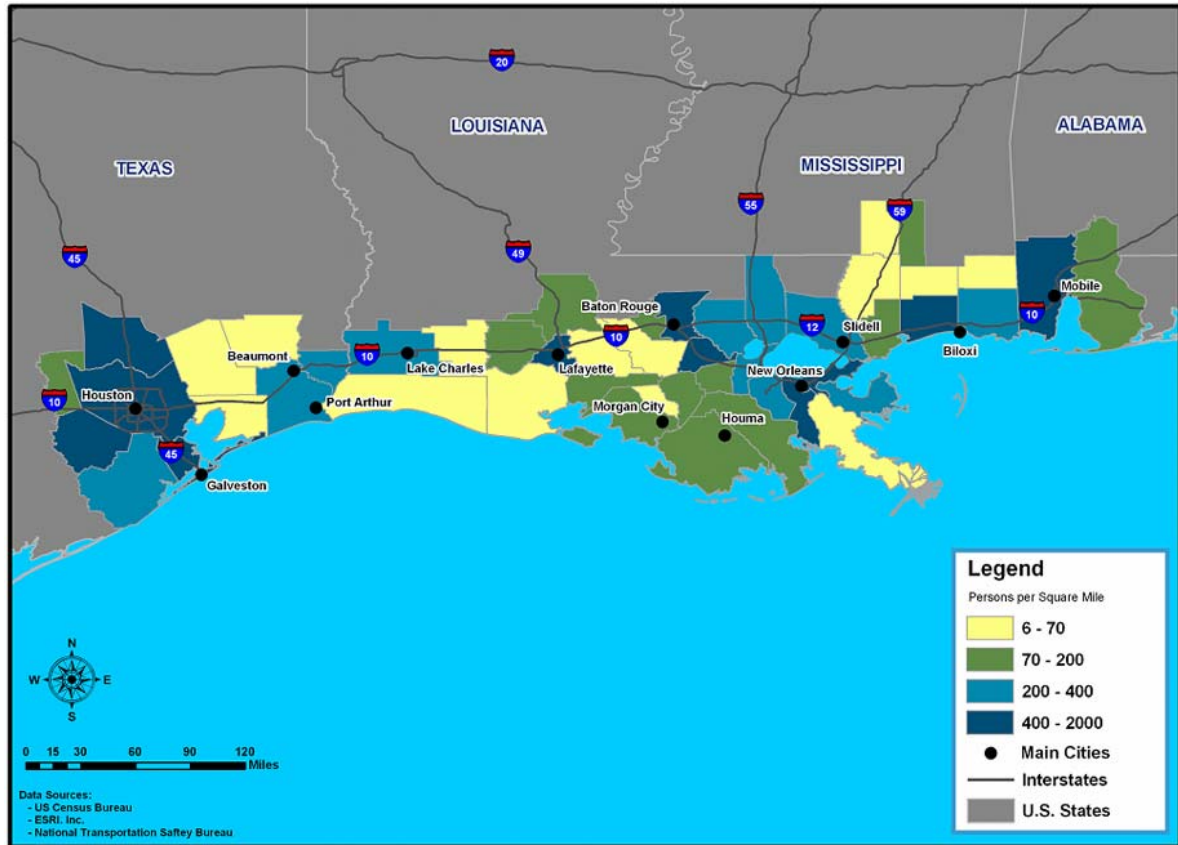
**Figure 2.18** Map of terrestrial ecoregions within and adjacent to the study area. (modified from Bailey, 1975)



**Figure 2.19 U.S. Census Bureau Metropolitan Statistical Areas in study area.**  
(Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)

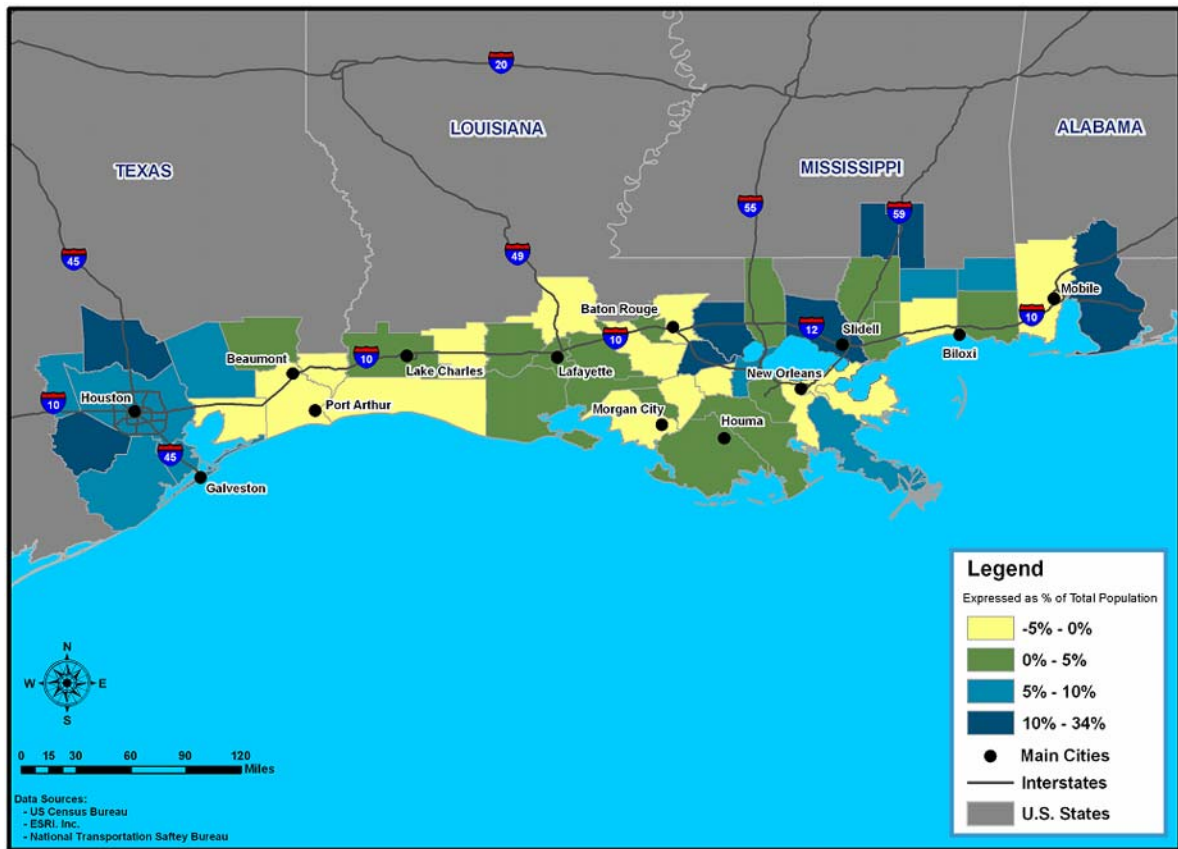


**Figure 2.20 Population density in study area, 2004. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)**

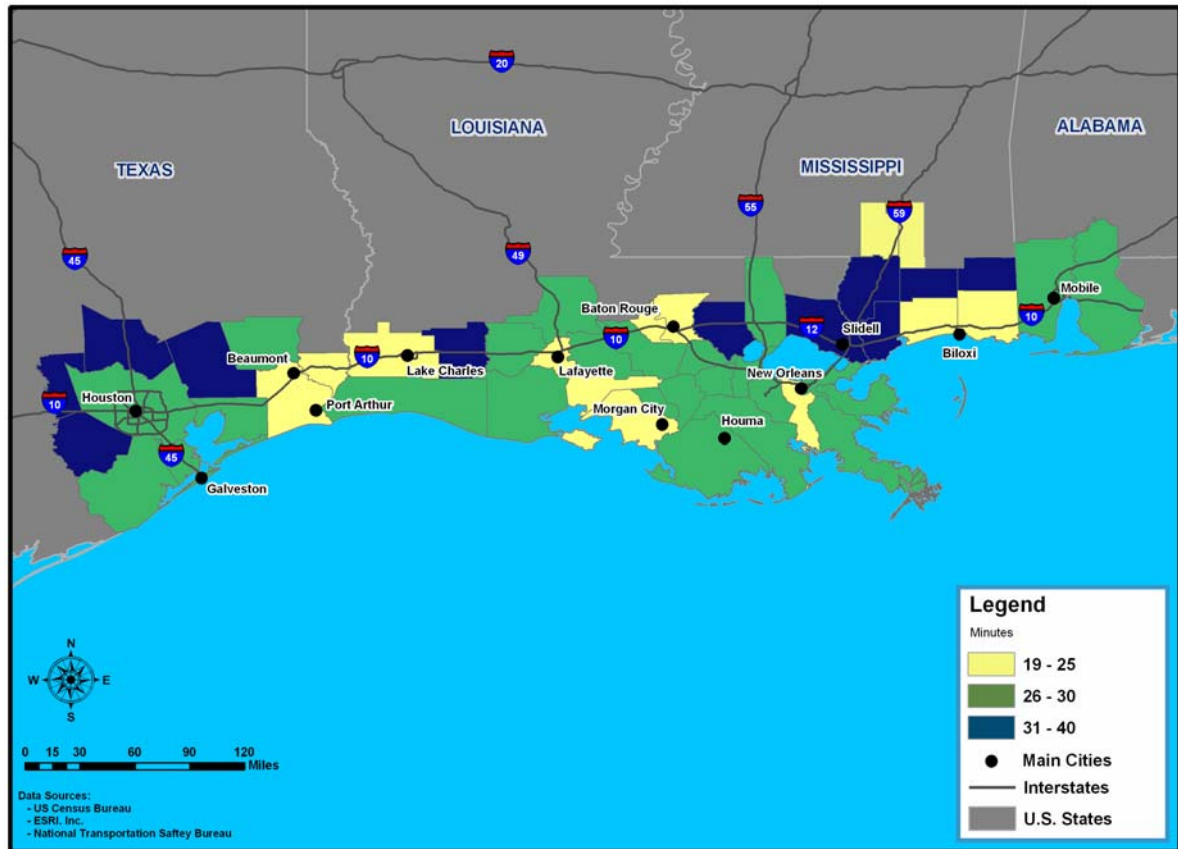




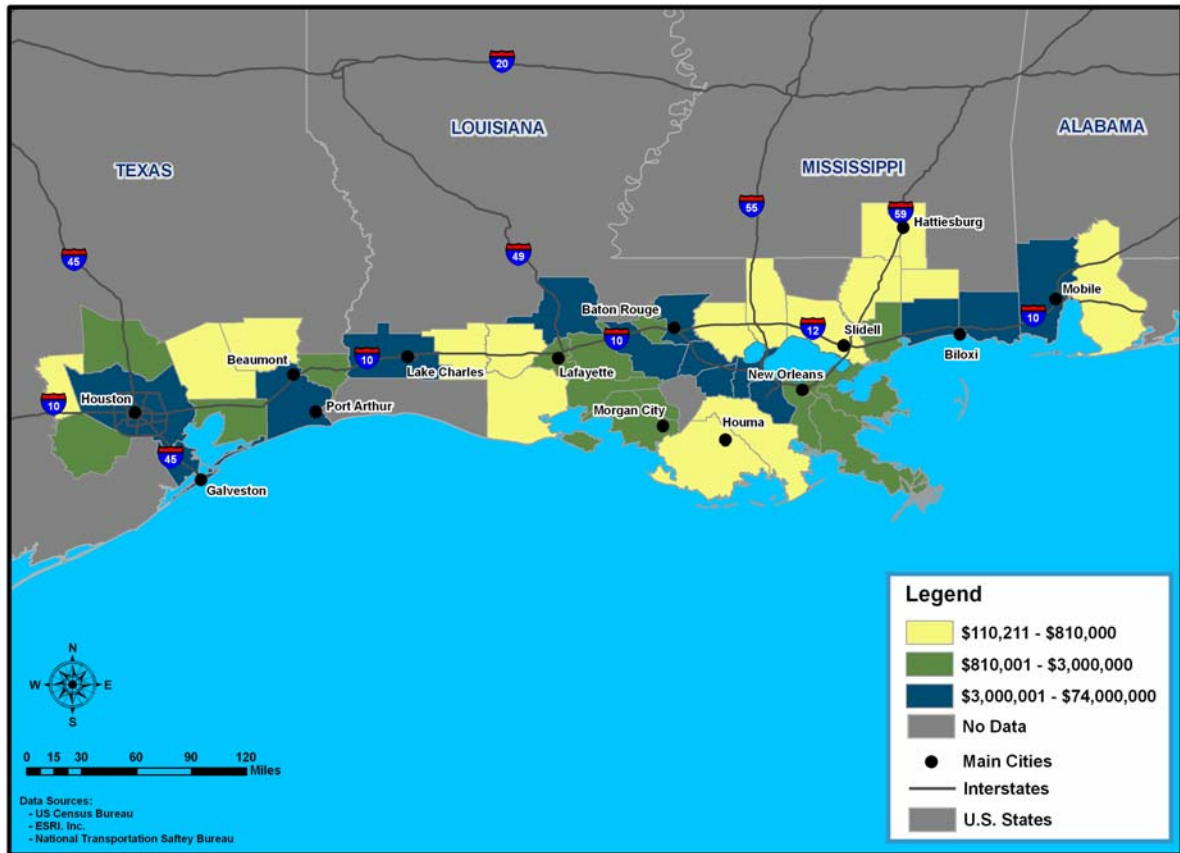
**Figure 2.21** Estimated population change in study area, 2000 to 2005.  
(Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)



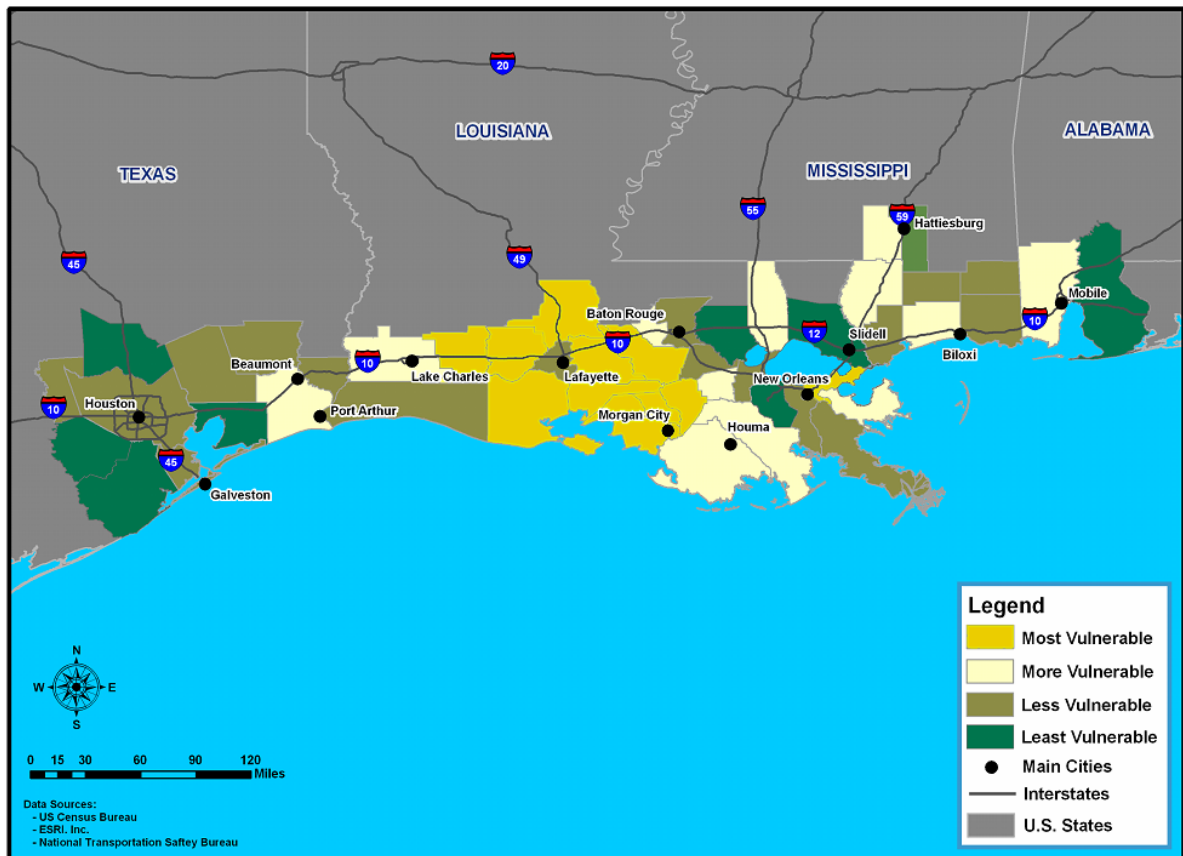
**Figure 2.22 Mean travel time to work in study area. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)**



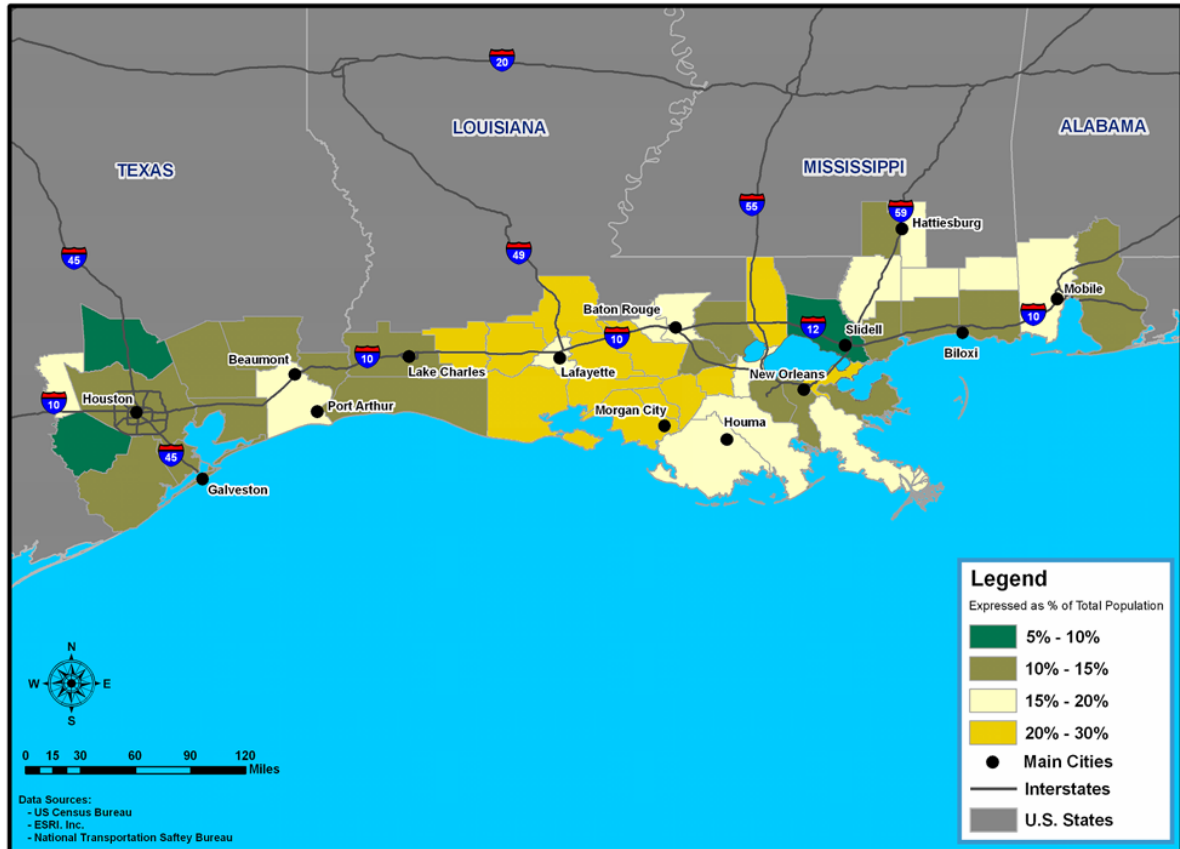
**Figure 2.23** Manufacturers shipments in thousands of dollars, 1997.  
(Source: U.S. Census Bureau, ESRI, Inc.,  
National Transportation Safety Bureau)



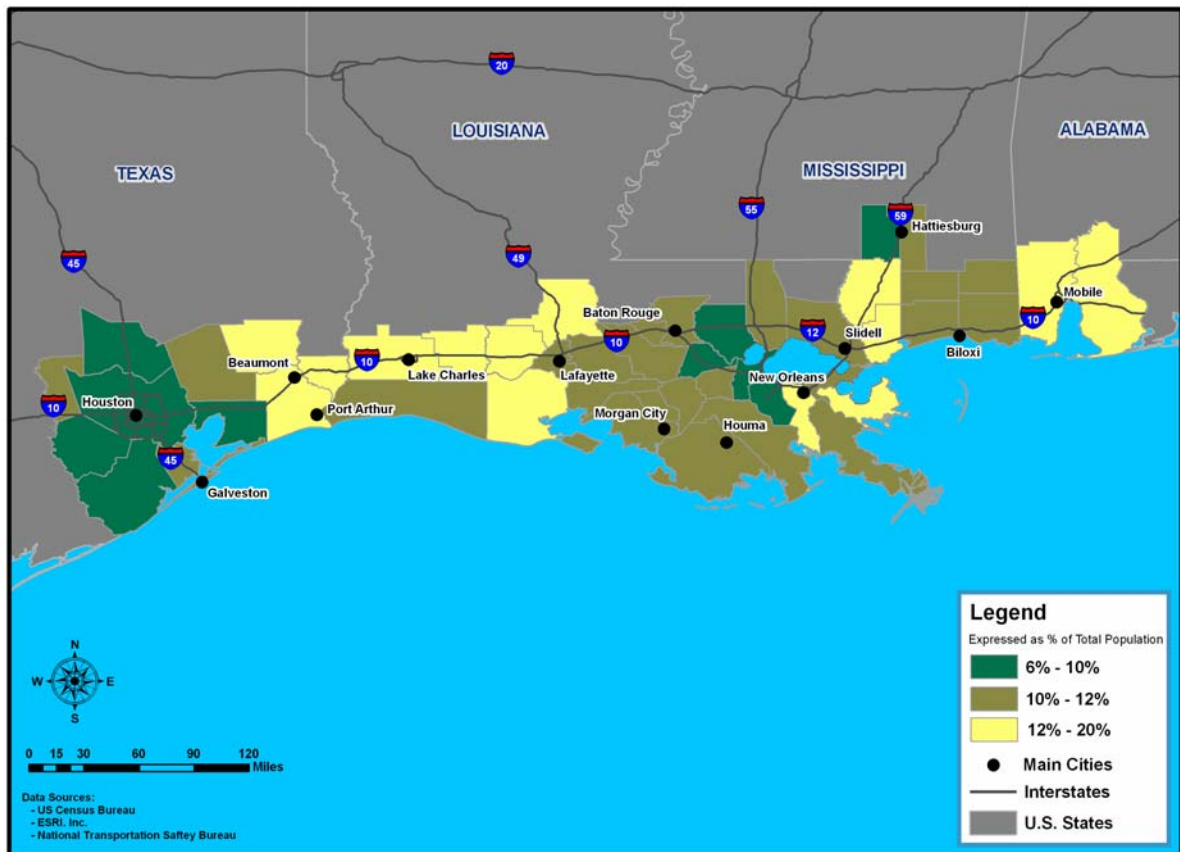
**Figure 2.24 Social vulnerability index for study area. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)**



**Figure 2.25 Persons in poverty in study area. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)**



**Figure 2.26** Persons aged 65 and older in study area. (Source: U.S. Census Bureau, ESRI, Inc., National Transportation Safety Bureau)



## 3.0 How is the Gulf Coast Climate Changing?

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The central Gulf Coast is one of warmest, wettest regions in the United States, where annual rainfall averages over 150 cm (60 inches) per year (Christopherson, 2000). Since there is very little topographic relief, changes in precipitation and runoff could have a dramatic impact on fragile Gulf Coast ecosystems and coastal communities by changing the hydroclimatology of the region. Changes in runoff are important to virtually all transportation modes in the Gulf Coast region. Interstate highways in Houston and New Orleans, for example, are occasionally flooded by locally intense rainfall, and several state and local highways are closed due to high rainfall at least once every five years. Even ports can be affected by high rainfall and runoff to shallow coastal waterways. Changes in temperature and moisture regime also are relevant to many aspects of transportation planning, construction and maintenance. Airport runway length requirements, for example, are determined by mean maximum temperature for the hottest month of the year. As the climate and sea surface warm, we can anticipate an increase in the intensity of hurricanes making landfall along the Gulf of Mexico coastline. As the ocean warms and ice sheets decline, sea level rise is likely to accelerate, which has serious implications for the Gulf Coast region where much of the land is sinking (subsiding) due to local geological processes and human development activity.

This chapter summarizes the direct and indirect effects of climate change that are most likely to affect transportation in the Gulf Coast region. The key climate “drivers” examined in the study region are:

- Temperature;
- Precipitation;
- Sea level rise; and
- Hurricanes and less intense tropical storms.

The interactive effects of these drivers, coupled with ongoing environmental processes in the region, are discussed in the following sections. This chapter presents scenarios of future climate change in addition to analysis of historical trends. While the environmental trend information for the study area is compiled from region-specific data sources, a

1 regional model of future climate was not available for the Gulf Coast study area. One  
2 approach that is widely used to identify plausible changes in climate at a regional scale is to  
3 extract output from general circulation models run at a global scale. This approach was  
4 used in this study and is described in the following sections of the report. Specific  
5 implications of the scenarios of future climate for each mode of transportation are  
6 discussed in the subsequent chapter of this report.

## 7 **Intended Use of Climate and Emission Scenarios in the Context of This Report**

8 A “scenario” is a plausible description of possible future conditions and is generally  
9 developed to inform decision-making under uncertainty. Building and using scenarios can  
10 help people explore what the future might look like and the likely challenges of living in it  
11 (Shell International, 2003). Scenarios are distinct from assessments, models, and similar  
12 decision-support activities, although they can provide important inputs to these activities.  
13 Scenarios also can be distinguished from precise statements about future conditions, which  
14 may be referred to as “forecasts” or “predictions.” Compared to these, scenarios tend to  
15 presume lower predictive confidence, because they pertain to processes for which weaker  
16 causal understanding or longer time horizons increase uncertainties (Parson et al., 2007).

17 Climate scenarios describe potential future climate conditions and are used to inform  
18 decision-making relative to adaptation and mitigation. Scenarios can be constructed for  
19 higher order aspects of climate change and its impacts, such as future changes in sea level,  
20 drought and storm intensity, or vegetation distribution. Scenarios of relative sea level rise,  
21 for example, in a subsequent section of this report were constructed by combining climate-  
22 change scenarios with information about coastal subsidence and other specific regional  
23 characteristics. The climate and sea level rise scenarios discussed in this report identify  
24 plausible potential future conditions for the Gulf Coast region. They are intended to frame  
25 the analysis of potential risks and vulnerability within the transportation sector.

26 The earth’s climate is determined, in part, by the concentration of atmospheric greenhouse  
27 gases and particulates that absorb infrared radiation (heat) reflected from the earth’s  
28 surface. Human activity is increasing greenhouse gas and particulate emissions, which has  
29 resulted in an increase in the earth’s temperature (IPCC, 2001, 2007). In order to assess  
30 how the climate may change in the future, future emissions must be specified. The  
31 Intergovernmental Panel on Climate Change (IPCC) has conducted three exercises to  
32 generate scenarios of 21<sup>st</sup> century greenhouse-gas emissions, the most recent being the  
33 IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart, 2000). To  
34 explore the potential effects on transportation, we selected a range of emissions futures  
35 from the SRES report, including the low-emissions B1 scenario, the mid-range A1B  
36 scenario, and the high-emissions A2 scenario. The AIFI scenario, which assumes the  
37 highest reliance on fossil fuels during this century, also was added to the SRES scenarios  
38 used to assess the effects of sea level rise.

39 The SRES A1B scenario assumes a balance across all energy sources, meaning it does not  
40 rely too heavily on any one particular source, including fossil fuels. It is, therefore, based  
41 on the assumption that improvement rates apply to all energy sources and end-use



1 technologies. The A2 scenario assumes that economic development is primarily regionally  
2 oriented and per capita economic growth and technological change more fragmented and  
3 slower than for the other emission scenarios. The B1 scenario assumes a high level of  
4 social and environmental awareness with an eye toward sustainability. It includes an  
5 increase in resource efficiency and diffusion of cleaner technologies (IPCC, 2001). These  
6 three emission scenarios are among the six “marker/illustrative scenarios” selected for  
7 climate model simulations the IPCC’s Third and Fourth Assessment Reports (IPCC, 2001,  
8 2007) (Figure 3.1). The B1 scenario lies at the lower extreme end of the potential changes  
9 in atmospheric CO<sub>2</sub> concentrations during this century, while the A1B emission scenario is  
10 considered a middle-of-the-range scenario in terms of the hypothesized rate of greenhouse  
11 gas emissions. The A2 scenario is among the higher end of the SRES scenarios in terms of  
12 both CO<sub>2</sub> and SO<sub>2</sub> emissions. The influence of SRES emission scenario on global  
13 temperature simulations is presented in Table 3.1.

### 14 ■ 3.1 Temperature, Precipitation, and Runoff

15 The climate of the study area is influenced by remote global factors, including the El Niño  
16 Southern Oscillation, and regional factors such as solar insolation. Due to the influence of  
17 the nearby Gulf of Mexico, the region is warmer and moister than most other continental  
18 regions at this latitude. Rainfall across the study area has little seasonality, with slightly  
19 higher rainfall values in spring and summer relative to fall and winter. The region enjoys  
20 mild winters, which are occasionally interrupted by cold air masses extending far south  
21 from the northern pacific or the Arctic, which brings low temperatures and freezing  
22 conditions. Rainfall in the region is dependent upon a variety of processes, including  
23 frontal passages in the winter and spring (Twilley et al., 2001). Short-lived, unorganized  
24 thunderstorms fueled by afternoon heating and moisture are common in the study area and  
25 associated, in part, with a prominent sea/land breeze (Ahijevych et al., 2003).

26 The Gulf Coast, like much of the world, has experienced significant changes in climate  
27 over the past century. With continued increases in atmospheric greenhouse gases and their  
28 radiative forcing, the earth’s climate is expected to change even more rapidly during the  
29 21<sup>st</sup> century (IPCC, 2007). Computer-based climate simulation models are used to study  
30 the present climate and its responses to past perturbations like variation in the sun’s output  
31 or major volcanic eruptions. They also are used to assess how the future climate would  
32 change under any specified scenario of greenhouse-gas emissions or other human activity  
33 (Parson et al., 2007).

#### 34 3.1.1 Historical Data Sources

35 Changes in the historical climatology of the study area were investigated from an empirical  
36 perspective relying on instrumental records. The assessment of the present climate and 20<sup>th</sup>  
37 century trends was built around climatic data from the United States Climate Division  
38 Datasets (CDD) (Guttman and Quayle, 1996) and the United States Historical Climate  
39 Network (USHCN) (Karl et al., 1990; Easterling et al., 1996). Since CDD were used in a  
40 portion of this analysis, caution needs to be taken with data from 1905 to 1930 which are

1 synthesized from statewide data as described by Guttman and Quayle (1996) and therefore  
2 are not true averages of data from within a climate division.

3 Empirical trends and variability were analyzed for temperature and precipitation at the  
4 CDD level for the climate divisions along the Gulf Coast from Galveston to Mobile,  
5 including Texas Climate Division 8, Louisiana Divisions 6-9, Mississippi Division 10, and  
6 Alabama Division 8 (Figure 3.2).

7 Keim and others (2003) showed that CDD can have spurious temperature trends. Our  
8 analysis synthesized CDD consisting of averages of stations within each division from the  
9 USHCN (Table 3.2). FILNET data have undergone numerous quality assurances and  
10 adjustments to best characterize the actual variability in climate. These adjustments take  
11 into consideration the validity of extreme outliers, time of observation bias (Karl et al.,  
12 1986), changes in instrumentation (Quayle et al., 1991), random relocations of stations  
13 (Karl and Williams, 1987), and urban warming biases (Karl et al., 1988). Furthermore,  
14 missing data were estimated from surrounding stations to produce a nearly continuous data  
15 set for each station.

16 Monthly averages from the USHCN stations from 1905 to 2003 within each climate  
17 division were then averaged annually, thereby constructing an alternative “divisional data”  
18 annual time series. The year 1905 was selected as a starting point because it represents a  
19 common period of record for all but one of the USHCN stations utilized in the study – the  
20 exception is Fairhope, Alabama, beginning in 1919. Fairhope was maintained because it is  
21 the only USHCN station available in Alabama Climate Division 8. Only USHCN FILNET  
22 stations with a continuous monthly record of temperature from January 1905 through  
23 December 2003 were included in the analysis, with the exception of Fairhope. USHCN  
24 precipitation data were not as serially complete as temperature and there were fewer  
25 stations available. As a result, this study incorporated the original CDD for precipitation,  
26 which seems reasonable given results of Keim and others (2005).

### 27 **3.1.2 GCM Applications for the Study Area**

28 The scenarios of future climate referenced in this report were extracted from an ensemble  
29 of up to 21 different atmosphere-ocean General Circulation Model (GCM) efforts which  
30 contributed the results of their simulations in support of the IPCC’s Fourth Assessment  
31 Report, and are labeled Coupled Model Intercomparison Project 3 (CMIP3). Gridded  
32 output limited to the study area was extracted from each GCM. Figure 3.3 shows the study  
33 region and the boundaries used to subset the global grid of a typical GCM output. Results  
34 are presented as spatial averages across the entire area. The GCMs were run under three  
35 forcings, the low-emissions B1, the high-emissions A2 and the mid-range A1B scenarios  
36 from the IPCC’s Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart,  
37 2000).

38 Scenarios of future temperature and precipitation change for the middle of the 21<sup>st</sup> century  
39 were derived from the regional GCM runs. Scatter diagrams were produced to convey the  
40 range of output of the models with respect to present conditions following the procedures

1 of Ruosteenoja et al. (2003) (Figure 3.4). Probability Density (or Distribution) Functions  
2 (PDF) were developed by applying the method of Tebaldi and others (2004, 2005). Data  
3 forming the basis of the PDF estimation is an ensemble of historical and future climate  
4 simulations (from which temperature and precipitation are extracted). Output of  
5 temperature and precipitation from up to 21 different GCMs under the three different  
6 scenarios, area- and seasonally averaged, was considered for two 20-year periods, one  
7 representative of recent climatology (1980-1999), and one representative of the future mid-  
8 century time slice (2040-2059). Thus scenarios of “climate change” are to be interpreted  
9 with respect to these two time periods and conditional on the SRES A1B, A2, and B1  
10 scenarios (Nakicenovic and Swart, 2000). While the results from the GCM runs are indeed  
11 plausible, they should be interpreted as mid-, high-, and low-range results, respectively,  
12 among the SRES scenarios of the potential changes in temperature and precipitation.

13 The statistical procedure synthesizes the multimodel ensemble of projections into a  
14 continuous PDF by applying a Bayesian method of estimation. At the core of the method  
15 is the idea that both observed and modeled temperature and precipitation contribute  
16 information to the estimate, so that different models will be differently “weighted” in the  
17 final probabilistic projections on the basis of their differential skill in reproducing observed  
18 climate. The method used also considered the convergence of different models when  
19 producing future trajectories, rewarding models that agree with one another and  
20 downweighting outliers. In the version of the statistical procedure applied here, the latter  
21 criterion is discounted, ensuring that even model projections that disagree with the  
22 consensus inform the shape of the final PDFs. This choice is made as a result of two  
23 considerations: the ensemble of GCMs at our disposal is not made of independent models  
24 (there are components and algorithms in common, for example) so rewarding agreement is  
25 somewhat questionable when one can argue that the agreement is not independently  
26 created. The second consideration has to do with the width of the PDFs produced, since  
27 enforcing the convergence criterion has the effect of narrowing the width of the PDFs to a  
28 range even smaller than the original ensemble range. It is well understood that the range of  
29 uncertainty addressed by this particular ensemble of models is limited when compared to  
30 the whole range of sources of uncertainty that can be listed, when examining climate  
31 change projections. Thus we preferred to produce conservative estimates of the uncertainty  
32 (i.e., larger rather than smaller). The result of applying the statistical analysis to the GCM  
33 output are PDFs of temperature and precipitation change (the latter as absolute values or  
34 percent change with respect to historical precipitation averages) from which any percentile  
35 can be derived.

### 36 **3.1.3 Water-Balance Model**

37 The primary tool used to investigate the hydroclimatology of the study area was a modified  
38 Thornthwaite Water Balance Model as described by Dingman (2002). The Thornthwaite  
39 model is simply an accounting of hydroclimatological inputs and outputs. Monthly values  
40 of temperature, precipitation, and potential evapotranspiration – called reference  
41 evapotranspiration – were entered into the budget and parameters such as rain/snow ratios,  
42 soil moisture, soil moisture deficits, and runoff were calculated. The water balance was

1 modified slightly by using an alternative reference evapotranspiration (ET<sub>o</sub>) term than that  
2 originally used by Thornthwaite to provide a better estimate of ET<sub>o</sub> in the central Gulf  
3 Coast region. As with any monthly water balance, atmospheric and terrestrial variables  
4 (such as ET<sub>o</sub>, soil moisture, runoff, etc.) were parameterized using bulk terms. A  
5 description of the procedures used to estimate evapotranspiration, soil moisture, and other  
6 components of the water balance model are presented in Appendix D.

### 7 **3.1.4 Temperature and Runoff Trends**

8 Results from our analysis of temperature variability during 1905 to 2003 indicate that the  
9 1920s or 1930s was generally the warmest decade for the various Gulf Coast climate  
10 divisions (Figure 3.5). After a step down in the temperature in the late 1950s, the coolest  
11 period occurs in the 1960s, while a warming trend is evident for all seven climate divisions  
12 beginning in the 1970s and extending through 2003. Of the seven climate divisions, LA6,  
13 LA8, and MS10 have slight but significant cooling trends at an  $\alpha \leq .05$  over the 98-year  
14 period of record. Precipitation variability shows that the 1940s and 1990s were the wettest  
15 decades, while the 1950s was generally the driest (Figure 3.6). Although all of the climate  
16 divisions at least suggest long-term patterns of increasing rainfall, only MS10 and AL8  
17 have trends that are significant at an  $\alpha \leq .05$ .

18 Data for each of the seven climate divisions were amalgamated into a regional dataset, by  
19 month, and the continuous monthly water balance model was run. In a typical year, ET<sub>o</sub> is  
20 low in winter and early spring, and most rainfall is converted to runoff because soil  
21 moisture storage remains at, or near, capacity. As temperatures rise in late spring and early  
22 summer and the number of hours of daylight increases, ET<sub>o</sub> also increases.  
23 Evapotranspiration will often exceed rainfall in July, August, and September, which leads  
24 to soil moisture utilization, on the average. Then in late fall, precipitation often exceeds  
25 ET<sub>o</sub> leading to recharge of soil moisture. Regional trends in model-derived runoff shows  
26 large inter-annual variability with the high values in the 1940s and from 1975 to 2003  
27 (Figure 3.7). Despite the variability, a long-term trend was detected in the data at an  
28  $\alpha \leq .05$ , and the trend line indicates a 36 percent increase in runoff over the time period.  
29 Moisture deficits show high values from the mid-1940s through the mid-1960s, with 1998  
30 to 2000 also high (Figure 3.7) but without any long-term trends.

31 Historical monthly extremes of precipitation, runoff, and deficit in the Gulf Coast Region  
32 were analyzed to provide a focus for this portion of the analysis. In the empirical record,  
33 there is some evidence of an increase in precipitation extremes in the United States and in  
34 the Gulf South. Karl et al. (1995) shows that one-day extreme rainfall events have  
35 increased in portions of the United States, and Keim (1997) shows heavy rainfall events  
36 have increased in the south-central U.S. These heavy rainfall events have very likely  
37 contributed the increases in runoff found in this study.

38 The period 1971 to 2000 serves as the baseline climatology for this analysis. Using water  
39 balance output for this 30-year period, partial duration series (PDS) are generated for the  
40 three variables. A PDS includes the number of events (monthly extremes) equal to the  
41 number of years under examination, which is 30 in this case. As such, the 30 largest

1 monthly totals of precipitation, runoff, and deficit were extracted and then fit to the beta-p  
2 distribution, as recommended by Wilks (1993), and the 2-, 5-, 10-, 25-, 50-, and 100-year  
3 quantile estimates are determined for each. These data serve as a baseline for assessing  
4 potential future changes in extremes of precipitation, runoff, and deficit.

### 5 **3.1.5 GCM Results and Future Climate Scenarios**

6 To explore how the regional climate may change over the next 50 years, output from an  
7 ensemble of GCM runs used by IPCC for the Fourth Assessment Report (2007) was  
8 analyzed. Scatterplots and probability density functions of average temperature and  
9 precipitation change were derived from the GCM ensemble output for the IPCC SRES  
10 greenhouse gas emission scenarios labeled A1B, A2, and B1. The results presented in the  
11 following discussion are based on GCMs (Table 3.3) contributing runs to the IPCC archive  
12 used in the IPCC's Fourth Assessment Report and are consistent with the temperature and  
13 precipitation projections reflected in IPCC Fourth Assessment Report (2007).

14 The GCM results run with the A1B, A2, and B1 emissions scenarios suggest a warmer  
15 Gulf Coast Region, with the greatest increase in temperature occurring in summer and  
16 lowest increases in winter (Tables 3.4, 3.6, and 3.8). This is consistent with another  
17 analysis of historical data that shows a significant increase in summer minimum  
18 temperature across the Gulf Coast study area between 1950 and 2002 (Groisman et al.,  
19 2004).

20 Although the climate model output for the A1B, A2, and B1 emissions scenarios  
21 demonstrate a large degree of similarity, the A1B scenario was retained for more detailed  
22 analysis since it is considered "mid-range" of the IPCC emissions scenarios. Also, we note  
23 that the major differences in CO<sub>2</sub> concentrations under the IPCC SRES scenarios occur  
24 after 2040 (Figure 3.1), which helps explain why temperature and precipitation do not vary  
25 widely among the GCM experiments with the high-, low-, and mid-range emission  
26 scenarios (Tables 3.4 to 3.9). Stated another way, the climate scenarios presented in these  
27 tables are not likely to change significantly during the next three to four decades by  
28 mitigation measures that would reduce emissions, although mitigation measures could  
29 substantially affect the climate in the latter half of this century. Probability density  
30 functions (PDF) for seasonal temperature and precipitation change through 2050 are  
31 presented in Figures 3.8 and 3.9, respectively.

32 Hourly or daily precipitation extremes cannot be reliably simulated by current GCM  
33 experiments. The percentiles (i.e., the 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentiles) from the A1B PDFs  
34 were used as a proxy for assessing potential changes to hydrological extremes across the  
35 region. These percentiles stretch the range of output from all 21 GCMs, while also  
36 providing the middle of the PDF, or region under the curve where there is most agreement  
37 between the models (i.e., 50<sup>th</sup> percentile). The 1971-2000 temperature and precipitation  
38 data therefore were modified seasonally according to the predicted changes presented in  
39 Tables 3.5, 3.7, and 3.9 for each of the three quartiles. The water balance model was then  
40 rerun using the three quartile datasets to simulate the hydrology under these altered climate

1 conditions. These datasets provided the means necessary to produce new PDS of  
2 precipitation, runoff, and deficit for additional extreme value statistical testing.

3 The 2-, 5-, 10-, 25-, 50-, and 100-year return periods for mean monthly precipitation show  
4 only modest differences between the current climate and the projected climate in 2050 at  
5 the three PDF percentiles (Figure 3.10). As expected, there is a decrease in monthly  
6 precipitation extremes at the 5<sup>th</sup> percentile for the less rare return periods (2- to 25-year),  
7 relative to the current climate, which would be expected given the reduction in  
8 precipitation by up to 36 percent in summer. However, given the shape of the beta-p  
9 distribution, the 100-year precipitation event is slightly larger than the baseline. Results for  
10 the 50<sup>th</sup> percentile indicate that the less rare return periods are on par with current climate,  
11 but that the rare return periods may have modestly larger storms. At the 95<sup>th</sup> percentile,  
12 storms are generally larger across the board.

13 Monthly runoff extremes show a very different relationship to the current climate. At both  
14 the 5<sup>th</sup> and 50<sup>th</sup> percentiles, there is a dramatic reduction in projected runoff (Figure 3.11).  
15 The mid-range of the GCMs suggests a decline in runoff relative to the 1971-2000 baseline  
16 period. Runoff rates are lower because precipitation is somewhat reduced, but perhaps  
17 more importantly, the projected increases in temperature also lead to increases in potential  
18 and actual evapotranspiration, and evapotranspiration rates are highest in the Gulf and  
19 southeastern United States compared to other U.S. regions (Hanson, 1991). An increase in  
20 actual evapotranspiration, without any increase in precipitation, translates into a reduction  
21 in runoff rates. However, at the 95<sup>th</sup> percentile, precipitation increases anywhere from 9 to  
22 26 percent, depending on season.

23 Extremes in monthly deficit show a more complex pattern between the quartiles and over  
24 the various return periods (Figure 3.12). The 5<sup>th</sup> percentile shows much larger deficits  
25 occurring relative to the 1971-2000 baseline. This is especially relevant at the two-year  
26 return period, which is nearly 30 percent larger in magnitude/intensity than in the current  
27 climate. This makes physical sense as temperatures become somewhat warmer, thereby  
28 increasing potential evapotranspiration, there also are substantial reductions in  
29 precipitation. The net effect of this combination would be an increase in deficits (and  
30 drought intensity). Smaller reductions in precipitation at the 50<sup>th</sup> percentile dampen the  
31 increases in deficits. At the 95<sup>th</sup> percentile, increases in temperature are more than offset by  
32 the dramatic increases in precipitation, with deficits substantially reduced in their intensity.

### 33 **3.1.6 Changes in Daily Temperature**

34 To examine trends in extreme temperature for the study area, daily maximum temperature,  
35 and minimum temperature were analyzed from 1950 through 2005. The historical analysis  
36 presented uses a data set and tools developed for an analysis of North American extremes  
37 based on the Daily data set from the USHCN (NOAA, 2006).<sup>1</sup> Temperature indices of

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<sup>1</sup> We acknowledge the modeling groups for providing their data for analysis, the Program for Climate Model  
(Footnote continued on next page...)

1 transportation sensitive parameters were created on a station basis and then averaged  
2 together. For localized analyses, anomalies of the indices for all stations within 500 km of  
3 the target location were averaged together. For the U.S. time series, anomalies of station  
4 level indices were first averaged into 2.5° latitude by 2.5° longitude grid boxes. Where a  
5 grid box did not have any stations, the values of the indices from neighboring grid boxes  
6 were interpolated into that grid box in order to make the averaging area more spatially  
7 representative. The grid box values were then averaged on an area-weighted basis to create  
8 U.S. time series. The time series figures show the annual values and a smoothed line  
9 derived from a locally weighted regression (Lowess filter; Cleveland et al., 1988). An  
10 advantage of a Lowess filter is that it is not impacted very much by one extreme annual  
11 value that might occur in an El Niño year, and therefore depicts the underlying long-term  
12 changes quite well.

13 The number of very hot days has been increasing on average across the United States.  
14 Figure 3.13 shows the average change since 1950 in the warmest 10 percent of July  
15 maximum and minimum temperatures at each station. The positive trend in minimum  
16 temperatures implies significantly warmer nights. The maximum temperature decreased  
17 after a period of south-central U.S. droughts in the 1950s and has been increasing ever  
18 since.

19 Temperature trends across the Gulf Region are not as pronounced as they are nationally  
20 due to the moderating effect of the proximate Gulf of Mexico waters. Figure 3.14 shows  
21 the anomaly in the number of days above 100°F averaged over stations within 500 km of  
22 Dallas, Texas. Although centered outside the Gulf States regions considered in this report,  
23 many of the stations are well within this region of interest and this figure is certainly  
24 representative of the behavior of Gulf State extreme temperatures in the recent past. Note  
25 the cooling following the 1950s droughts. Also, note that the magnitude of interannual  
26 variations is considerably larger than any trend.

27 Notwithstanding this absence of a detectible trend in the number of days exceeding a high  
28 threshold temperature, it is very likely that in the future the number of very hot days will  
29 substantially increase. Figure 3.15 shows a prediction of the average number of days  
30 exceeding 37.8°C (100°F) in the June-July-August (JJA) season 25 years, 50 years and 90  
31 years into the future under the SRES A2 scenario for Houston, Texas, the closest station to  
32 Galveston, Texas with available data. The algorithm used for this prediction exploits  
33 current observations as well as predictions of the JJA average temperature from 17 of the  
34 climate models contained in the WGNE-CMIP3 database prepared for the IPCC Fourth  
35 Assessment Report. Twenty-five years from now, the probability of a week (although not  
36 necessarily continuous) of 37.8°C temperatures in this region is greater than 50 percent.  
37 Fifty years from now, the overall heating is such that the probability of three weeks of  
38 37.8°C temperatures is greater than 50 percent. Note that results obtained under either the

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Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model output, and the  
JSC/CLIVAR Working Group on Coupled Modeling (WGCM) for organizing the model data analysis  
activity. The multimodel data archive is supported by the Office of Science, U.S. Department of Energy.

1 B1 or A1B forcing scenarios would be statistically indistinguishable from these results  
2 until well after the mid-century mark.

3 Climate models predict that the extreme temperature events could change more than the  
4 average climate over the course of the next century (IPCC, 2007). One way of quantifying  
5 this is consider 20-year return values of the annual maximum of the daily average  
6 temperature. The 20-year return value is that value that is exceeded by a random variable  
7 once every 20 years on average over a long period of time. Such an event is truly rare,  
8 occurring only three or four times over the course of a typical human lifetime. Generalized  
9 extreme value theory provides a robust statistical framework to perform these calculations  
10 (Zwiers and Kharin, 1998; Wehner, 2005). Figure 3.16 shows the predicted change in this  
11 quantity at the end of 21<sup>st</sup> century under the SRES A1B scenario from a mean model  
12 constructed from 10 models from the WGNE-CMIP3 database. Over the Gulf States  
13 region, this extreme value change is about 1°C greater than the change in the average  
14 temperature. Another way to put this in perspective is to consider how frequent currently  
15 considered rare events will be encountered in the future. Figure 3.17 shows the number of  
16 times in a 20-year period that the 1990-1999 return value would be reached near the end of  
17 the century. The purple shaded regions exceed 10 times, hence currently considered rare  
18 events are likely to happen every other year or more frequently.

### 19 **3.1.7 Changes in Specific Temperature Maxima Affecting Transportation**

20 Transportation analysts have identified several specific attributes of temperature change of  
21 concern in transportation planning. Changes in annual days above 32.2°C (90°F) and  
22 maximum high temperature, for example, will impact the ability to construct and maintain  
23 transportation facilities. Concrete loses strength if it is set at air temperatures greater than  
24 32.2°C and the ability of construction workers and maintenance staff to perform their  
25 duties is severely curtailed at temperatures above 32.2°C degrees. In order to properly  
26 design for the thermal expansion of concrete and steel elements of transportation facilities,  
27 knowledge of the maximum expected temperatures is required.

28 Since global climate models are integrated at spatial scales around 200 km, a linear  
29 regression analysis was used to downscale relationships between the three variables of  
30 greatest concern at the localized scale of a weather station to the transportation sector.  
31 Historical data from the USHCN for eight observation stations in the Gulf Coast study area  
32 were analyzed to determine highest temperature of record, mean number of days at  
33 minimum temperature 32.2°C or higher, and mean daily temperature. Table 3.10 shows  
34 the reported observations for the eight weather stations for days above 32.2°C and the  
35 associated annual and July mean daily temperatures.

36 Based on the relationship established in the regression analysis of the historical data,  
37 changes in mean and extreme temperatures were calculated for the study area relevant to  
38 the temperatures in 2050 and 2100, as predicted by the global climate models used in this  
39 study. The analysis focused on the relationship between mean daily temperature, output  
40 from the climate models at 200 km scales, and the desired values downscaled to local  
41 spatial scales: number of days above 32.2°C and the highest temperature of record.



1 Comparisons were made to each of the annual mean daily temperatures and mean daily  
2 temperatures for the month of July to determine which relationship better provided the  
3 desired forecast variables.

4 A linear regression of days above 32.2°C (90°F) as an independent variable for the stations  
5 shown was undertaken for each of the annual mean daily and the July mean daily  
6 temperatures as the dependent variables. The regression of observed days above 32.2°C  
7 versus annual mean daily temperature showed that for each 0.6°C (1°F) degree rise in  
8 annual mean daily temperature there is an associated 3.9-day increase in the annual days  
9 above 32.2°C. However, the data for New Orleans falls outside the trend line for this  
10 relationship.<sup>2</sup> The regression of days above 32.2°C versus July mean daily temperature  
11 showed that for each 0.6°C (1°F) degree rise in July mean daily temperature there is an  
12 associated 10-day increase in the annual days above 32.2°C.<sup>3</sup>

13 The regression of observed high temperature versus annual mean daily temperature  
14 suggested that for each 0.6°C (1°F) rise in annual mean daily temperature there is an  
15 associated 0.6°F rise in high temperature. However, this relationship only has an  
16 R-squared of 0.10 largely because the data for New Orleans falls outside the trend line.  
17 The regression of high temperature versus July mean daily temperature showed that for  
18 each 0.6°C (1°F) rise in July mean daily temperature there is an associated 1.2°C (2°F) rise  
19 in the high temperature.<sup>4</sup>

20 The mean daily temperature for the study area is 27.6°C (81.7°F) degrees. Based on the  
21 relationships established above, this implies that the existing high temperature should be  
22 approximately 40.6°C (105°F) degrees. For each additional 1°F degree increase in July  
23 mean daily temperature that is forecast by the GCMs, this high temperature can be  
24 expected to increase by 1.2°C (2°F) degrees. Using the relationship developed, this implies  
25 that the baseline/historical number of days above 32.2°C (90°F) is approximately 77 days.  
26 For each additional 0.6°C (1°F) degree increase in July mean daily temperature that is  
27 forecasted by the GCMs, the number of days above 32.2°C (90°F) can be expected to  
28 increase by approximately 10 days or 17 days for each increase by 1°C (2°F).

29 Airport runway length in the United States is generally calculated based on the mean  
30 maximum temperature (that is, the average of the daily high temperatures) during the  
31 hottest month of the year during the prior 30-year record. August is the month with the  
32 highest monthly mean max temperature in the Gulf Coast study area. Mean maximum  
33 temperature is reported by National Oceanic and Atmospheric Administration (NOAA) for  
34 283 NOAA stations across the United States, six of which are located in the study area.  
35 The average mean maximum temperature for the hottest month of the year from these six

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<sup>2</sup> As a result, this relationship only has an R-squared of 0.27.

<sup>3</sup> With an R-squared of 0.61 if New Orleans is included and 0.77 if New Orleans is excluded from the analysis.

<sup>4</sup> The R-squared associated with this data is 0.42 if New Orleans is included, and 0.89 if New Orleans is excluded from the analysis.

1 stations is 33.1°C (91.6°F). To verify this, we determined the 30-year mean maximum  
2 temperature data (1972 to 2002) from the Carbon Dioxide Information Analysis Center  
3 (CDIAC) which encompasses 12 reporting stations located in the study area. CDIAC data  
4 provides station elevation data as well as latitude and longitude data. The average mean  
5 maximum temperature from the 12 CDIAC stations is 33.0°C (91.4°F) (Table 3.11). The  
6 airport section in the subsequent chapter deals more specifically with this dataset in an  
7 analysis of how runway length may be impacted by changes in temperature during the next  
8 50 to 100 years.

### 9 **3.1.8 Increasing Daily Precipitation Extremes**

10 As mentioned above, current generation climate models are limited in their ability to  
11 simulate individual storms by a lack of horizontal resolution. From a simple theoretical  
12 argument (Allen and Ingram, 2003), it is expected that extreme precipitation events should  
13 become more intense as the climate warms. The IPCC (2007) concluded that the frequency  
14 of heavy precipitation events had increased over most areas during the past century and that  
15 a continued increase in heavy precipitation events is very likely during the 21<sup>st</sup> century.  
16 The largest rainfall rates occur when a column of air is completely saturated and  
17 precipitates out nearly completely. The Clausius-Claperyon relationship dictates that as the  
18 air temperature increases, the atmosphere has the ability to hold more water vapor. Hence,  
19 under a warmer climate, it is very likely that specific humidity will increase both on  
20 average and in extreme saturation conditions. Extreme value analysis of model output  
21 daily precipitation in the Gulf States region, similar to the analysis discussed above with  
22 daily surface air temperatures, reveals a predicted increase of around 10 percent in the 20-  
23 year return value of the annual maximum daily averaged precipitation as shown in  
24 Figure 3.18. The coarse horizontal resolution of the climate models used in this analysis  
25 results in an underestimation of extreme precipitation events (Wehner, 2005).  
26 Furthermore, these models lack the resolution to simulate tropical cyclones, a further  
27 source of extreme precipitation events. However, these deficiencies likely cause the  
28 predictions errors to be conservative and it is likely that currently rare daily mean  
29 precipitation levels will become more commonplace in the future.

## 30 ■ **3.2 Hurricanes and Less Intense Tropical Storms**

31 Tropical cyclones (called hurricanes in the Atlantic and Gulf Coast regions) pose a severe  
32 risk to natural systems, personal property, and public infrastructure in the Gulf Coast  
33 region and this risk will likely be exacerbated as the temperature of atmosphere and sea  
34 surface increase. Whereas loss of life from hurricanes has decreased in recent decades,  
35 property losses due to rapid population growth and economic development of coastal areas  
36 has increased (Herbert et al., 1997; Pielke and Pielke, 1997; Pielke and Landsea, 1998).  
37 Hurricanes have their greatest impact at the coastal margin where they make landfall and  
38 sustain their greatest strength. Severe beach erosion, surge overwash, inland flooding, and  
39 windfall casualties are exacted on both cultural and natural resources. Transportation

1 facilities – roads, rails, pipelines, airports, ports – in coastal counties will likely be  
2 subjected to increasing hurricane intensity in the coming decades. Changes in Atlantic  
3 Basin hurricane formation and the behavior of hurricanes that make landfall in the Gulf  
4 Coast region have important implications for transportation planning, design, and  
5 maintenance in the short and long term.

### 6 **3.2.1 Assessing Trends in Historical Hurricane Frequency and Intensity**

7 Understanding hurricane frequency and landfall patterns is an important process in  
8 calculating insurance liabilities and rates for coastal communities as well as forecasting  
9 future risk under changing climate. Several studies have shown that landfalling hurricanes  
10 are more or less frequent for given coastal reaches of the United States (see Figure 3.19)  
11 and within given decades over the recorded history of North Atlantic storms (Simpson and  
12 Lawrence, 1971; Ho et al., 1987; Neumann, 1991; Jarrell et al., 1992; Gray et al., 1997;  
13 Pielke and Pielke, 1997; Neumann et al., 1999; Vickery et al., 2000). While different  
14 methods have been employed to calculate landfall probabilities at the state and county  
15 levels, there is general agreement that south Florida, the Carolinas, and the western Gulf  
16 Coast are most frequently impacted by major hurricanes (Figure 3.19).

17 Studies of multidecadal hurricane variability and cycles have been complicated by the  
18 relatively short period of available and reliable data. Landfall counts of tropical storms and  
19 hurricanes at Grand Isle, Louisiana produced with the HURASIM model (Doyle and Girod,  
20 1997) for five-year periods from 1951 through 2005 show periods of greater and lesser  
21 hurricane history with short- and long-term variability (Figure 3.20). If there is any  
22 pattern, historical records exhibit episodic hurricane activity, rather than trends toward  
23 more frequent or stronger hurricanes despite the most recent period of intense hurricane  
24 activity. While the long-term frequency trend of named storms within the Atlantic basin  
25 has remained fairly constant, interannual variability is prominent particularly among major  
26 hurricanes (Gray, 1990; Landsea et al., 1992; Gray et al., 1997; Goldenberg et al., 2001;  
27 Bell and Chelliah, 2006). Hurricane spawning patterns have been linked to regional  
28 oscillation cycles, Atlantic thermohaline circulation, and African West Sahel rainfall  
29 patterns that have improved our understanding and forecasting of hurricane activity in the  
30 North Atlantic Basin (Gray et al., 1997; Landsea et al., 1999).

31 Increased tropical storm activity is likely to accompany global warming as a function of  
32 higher sea surface temperatures, which have been observed globally (Figure 3.21). The  
33 kinetic energy of tropical storms and hurricanes is fueled from the heat exchange in warm  
34 tropical waters. An increase in sea surface temperature (SST) from global climate change  
35 is likely to increase the probability of higher sustained winds per tropical storm circulation  
36 (Emanuel, 1987; Holland, 1997; Knutson et al., 1998). Sea surface temperature has  
37 increased significantly in the main hurricane development region of the North Atlantic  
38 during the past century (Bell et al., 2007) (Figure 3.22) as well as in the Gulf of Mexico  
39 (Smith and Reynolds, 2004) (Figure 3.23).

40 Many scientists have evaluated the relationships between 20<sup>th</sup> century warming and  
41 hurricane intensity, with some suggesting that the incidence of intense hurricanes over the

1 past decade for the Atlantic basin could signal the beginning of an ENSO-related cycle of  
2 increased hurricane activity (Gray, 1984; O'Brien et al., 1996; Saunders et al., 2000).  
3 Henderson-Sellers et al. (1998) found no discernible trends in global hurricane trends with  
4 respect to number, intensity, or location during the past century. More contemporary  
5 analysis of the upswing in intense hurricane activity since the 1990s demonstrates that the  
6 proportion of intense, more destructive hurricanes has increased in some ocean basins,  
7 including the North Atlantic, concomitant with rising sea surface temperature (Emanuel,  
8 2005; Hoyos et al., 2006; Mann and Emanuel, 2006; Trenberth and Shea, 2006; Webster et  
9 al., 2005). Some studies conclude that the increase in recent decades is due to the  
10 combination of natural cyclical events (such as the North Atlantic Oscillation) and human-  
11 induced increases in sea surface temperature (Elsner, 2006).

12 Ocean currents that regulate heat content also appear to play an important role in the  
13 intensity of hurricanes when atmospheric conditions are favorable (Shay, 2006). In the  
14 Gulf of Mexico, the Loop Current is a heat conveyor that can build a heat reservoir  
15 spanning 200-300 kilometers in diameter and 80-150 meters in depth that is generally  
16 oriented towards the central Gulf Coast (Figure 3.24) (Jaimes et al., 2006). Satellite-based  
17 and *in situ* measurements by support the hypothesis that the warm water brought into the  
18 Gulf of Mexico by the Loop Current played an important role on the rapid intensification  
19 of Hurricanes Katrina, Rita, and Wilma (Jaimes et al., 2006).

20 Santer et al. (2006) used 22 climate models to study the possible causes of increased SST  
21 changes in the Atlantic and Pacific tropical cyclogenesis region, where SST increased from  
22 0.32°C to 0.67°C over the 20<sup>th</sup> century. Their analysis suggests that century-timescale SST  
23 changes of this magnitude cannot be explained solely by unforced variability of the climate  
24 system. In experiments in which forcing factors are varied individually rather than jointly,  
25 human-caused changes in greenhouse gases are the main driver of the 20<sup>th</sup> century SST  
26 increases in both tropical cyclogenesis regions. Ouuchi et al. (2006) used an atmospheric  
27 general circulation model at 20 km horizontal resolution to directly simulate the  
28 relationship between the tropical storm cycle and SST. This hurricane resolving model  
29 produced seasonal tropical storm statistics under present day conditions and was capable of  
30 hurricane force winds. When driven with the SST anomalies taken from A1B scenario  
31 experiments, the model produced fewer tropical storms everywhere except the North  
32 Atlantic basin where an increase was predicted. Tropical storms were more intense on  
33 average in all basins in these modeling experiments.

34 These results and those from similar studies suggest that as radiative forcing and SST  
35 continue to increase, hurricanes will be more likely to form in the Atlantic and Pacific  
36 basins and more likely to intensify in their destructive capacity. In its Fourth Assessment  
37 Report, the IPCC (2007) concludes that:

- 38 • There is observational evidence for an increase of intense tropical cyclone activity in  
39 the North Atlantic since about 1970, correlated with increases of tropical sea surface  
40 temperatures;

- Multi-decadal variability and the quality of the tropical cyclone records prior to the beginning of routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity; and
- There is no clear trend in the annual numbers of tropical cyclones.

### **3.2.2 Gulf Coast Hurricane History**

Gulf coast ecosystems are exposed to varying degrees of hurricane disturbance as influenced by storm frequency, periodicity, and duration. Figure 3.25 shows that tropical storm landfall across the Gulf basin increases geometrically from west to east. Because most storms spawn in tropical waters in the eastern Atlantic there is a greater probability for eastern landmasses on the same latitude to incur tropical storms (Elsner, 1999). Temporal patterns of the past century reveal periods of relatively frequent hurricanes as well as inactive periods for most of the Gulf Coast region. The relatively calm period of record for hurricanes from the 1950s through the 1970s, has some hurricane specialists purporting an increase in North Atlantic storms over the past decade related to ENSO oscillations and general warming trends (Elsner and Kara, 1999). Palynological and geological studies offer another means to reconstruct the regional history of hurricane activity over several centuries coincident with species changes and sedimentary overwash indicative of surge heights and storm intensity. One study of lake sediments in coastal Alabama suggests that major hurricanes of a Category 4 or 5 struck the Alabama coast with a frequency of about 600 years during the past three millennia (Liu and Fearn, 1993).

### **3.2.3 HURASIM: Model Application**

HURASIM is a spatial simulation model of hurricane structure and circulation for reconstructing estimated windforce and vectors of past hurricanes. The model uses historic tracking and meteorological data of dated North Atlantic tropical storms from 1851 to present. A description of the HURASIM model is presented in Appendix E.

The HURASIM model was applied in a hindcast mode to reconstruct hurricane windfields across the Gulf Coast region from Galveston, Texas to Pensacola, Florida on a 10 km grid basis for the period of record 1851 to 2003. The model calculated windspeed and direction for every 15 minutes of storm movement retaining only wind events of 30 mph or greater for all proximal storms and grid cells within the study region. Storm tracking for calendar years 2004 and 2005 have not been added to the HURDAT data set as yet and, therefore, have been omitted from this analysis despite record storm activity that may be associated with multi-decadal cycles and/or current global warming trends.

### 3.2.4 Historical Storm Frequency across the Northern Gulf Coast Study Region

HURASIM model results were categorized by storm class based on the commonly used Saffir-Simpson scale over a 153-year period from 1851 to 2003 to gain an historical perspective of recurrence potential and spatial distribution of storm events along the northern Gulf Coast between Galveston, Texas and Pensacola, Florida. Table 3.12 outlines the Saffir-Simpson scale for categorizing storms by intensity associated with range of windspeed. Storms on the Saffir-Simpson scale also have been ascribed typical storm surge levels based on observations during the 20<sup>th</sup> century. For example, NOAA states that storm surge during landfall of a Category 1 Hurricane is “generally 4 to 5 feet above normal” and a Category 3 Hurricane storm surge is “generally 9 to 12 feet above normal” (NOAA, 2007). In the Gulf Coast region, however, storm surge is highly variable for given class of storm on the Saffir Simpson scale in the Gulf Coast region. For example, Hurricane Camille, a Category 5 Hurricane at landfall, had a peak storm surge in coastal Mississippi of 7.6 meters (25 feet) while the storm surge associated with Hurricane Katrina (a Category 3 Hurricane at landfall) had peak storm surge of 8.5 meters (28 feet) (Graumann et al., 2005).

Figure 3.26 shows the frequency patterns of storm events with Category 1, 2, and 3 winds or higher across the study region. Results show that storm frequency by storm class is highest for southeast coastal Louisiana than elsewhere and lowest in inland locations decreasing with increasing latitude. Secondary locations with high hurricane incidence include Galveston, Texas and the Mississippi coast. Coastal reaches west of Galveston, Texas, the Chenier Plain of southwest Louisiana, and northwest Florida have experienced low to moderate hurricane frequency respectively. The highest frequency of Category 3 storm winds or greater for the entire region are seven storms over the 153-year period, equivalent to four to five storms per century. Based on the historical perspective alone, transportation planners should expect at least one major hurricane of Category 3 or greater to strike the northern Gulf Coast every 20 years. Over the same 20 years, planners can expect another Category 2 hurricane and two Category 1 hurricanes for a combined incidence rate of at least one hurricane every five years. While this rate is indicative of the worst-case grid location coastwide and over the entire historical record, the chance for storm track convergence elsewhere within the region is expected to be similar. However, storm frequency may be influenced by multi-decadal variability such that some sites may experience higher incidence depending on the timeframe and whether it spans periods of on and off cycles.

### 3.2.5 Temporal and Spatial Analysis of Hurricane Landfall

The northern Gulf Coast exhibits spatially disjunct patterns of storm strikes related to the landfall tracks and storm categories (Figure 3.27). Of storms exceeding Category 3 level winds between 1851 and 2003, the HURASIM model counted a maximum of seven storms equal to a recurrence interval of one major hurricane every 22 years for southeast Louisiana. Hurricane tracking records are available from 1851 to present but data accuracy

1 was greatly improved at the turn of the century with expanded and instrumented weather  
2 stations and since 1944 when aircraft reconnaissance of tropical storms was instituted.  
3 HURASIM model output was analyzed by segmented time periods to determine short-term  
4 return frequencies of tropical storms to account for cyclical behavior and data accuracy for  
5 successive intervals of 15, 30, and 50 years of the longer 153-year record from 1851 to  
6 2003. Data analysis focuses on the maximum potential return interval of storms by  
7 category according to the Saffir-Simpson scale. Given the prospect of questionable data  
8 accuracy of storm history and multidecadal storm cycling, it was deemed prudent to report  
9 storm frequencies for different time intervals to establish upward bounds of storm  
10 recurrence probabilities for catastrophe planning and assessment akin to worst-case  
11 scenarios. Shorter time windows are likely to exhibit a wide range of storm recurrence  
12 probabilities both high and low relative to longer periods.

13 The shorter the period of observation, the greater the probability of inflating the calculated  
14 return interval. Figure 3.28 shows the storm frequency for 15-, 30-, and 50-year intervals  
15 for Category 1 storms or greater for the most active grid location across the study area.  
16 The most active time period historically for all time intervals was the latter 19<sup>th</sup> century  
17 despite concerns of data accuracy for this period. These data show a potential maximum of  
18 storm incidence of three to five hurricanes every 10 years nearly twice the strike frequency  
19 for the entire 153-year record. The lowest incidence of hurricane activity within the Gulf  
20 Coast study region for all time intervals spans the 1970s and 1980s with two to three  
21 hurricanes for every 10 years. These historic hurricane return intervals provide an expected  
22 range of .2 and .5 probability that a hurricane may strike a given coastal county within the  
23 study region that can be used to guide coastal planning and preparation. Recent hurricane  
24 studies spurred by the upswing in hurricane activity of the 1990s and early 21<sup>st</sup> century  
25 reveal the highly variable and cyclical nature of hurricane activity in the Northern Gulf of  
26 Mexico, as well as the need for reliable datasets that can be used to quantify long-term  
27 trends and relationships with sea surface temperature (Goldenberg et al., 2001).

### 28 **3.2.6 Hurricane Wind Direction Patterns**

29 The HURASIM model outputs wind direction during storm landfall which often relates to  
30 storm impact based on exposure to direct wind force. Road signs, for example, may be  
31 more prone to damage or destruction depending on their orientation to circulating storm  
32 winds. Because most storms approach the coast from the Gulf of Mexico on a northerly  
33 track, approaching storm winds are easterly and northeasterly on account of the  
34 counterclockwise rotation of North Atlantic tropical storms. Figure 3.29 displays  
35 simulated wind rows and direction of wind force derived for one of the most active grid  
36 cell locations in the study region at Grand Isle, Louisiana for tropical storm and hurricane  
37 conditions over the 153-year period of record. The concentration of wind rows is westerly  
38 and southerly for tropical storm events in accordance with prevailing storm approach from  
39 the south. Hurricane force winds and direction at Grand Isle demonstrate a distinct shift to  
40 southwesterly and southeasterly directions as a result of major hurricanes passing to the  
41 east. As hurricanes pass inland of a given site, yet sustain their strength, backside winds in  
42 the opposite direction can occur. The length of each wind row is a function of the total

1 number of 15-minute intervals of storm track interpolation and passage extracted from the  
2 HURASIM model. Longer wind rows are indicative of more frequent occurrences. Wind  
3 row data and polargrams have been generated for each grid cell within the Gulf Coast study  
4 region so that local and regional characterization of wind direction can be determined.

### 5 **3.2.7 Modeling Climate Change Effects on Tropical Cyclones into the** 6 **21<sup>st</sup> Century**

7 Early theoretical work on hurricanes suggested an increase of about 10 percent in wind  
8 speed for a 2°C (4°F) increase in tropical sea surface temperature (Emanuel, 1987). A  
9 2004 study from the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey,  
10 that utilized a mesoscale model downscaled from coupled global climate model runs  
11 indicated the possibility of a 5 percent increase in the wind speeds of hurricanes by 2080  
12 (cf. IPCC, 2001). To explore how climate change could affect 21<sup>st</sup> century hurricane  
13 intensity, windspeeds of hurricanes during 1904 to 2000 were modeled and then projected  
14 to increase from 5 to 20 percent over the equivalent forecast period of 2004 to 2100. Storm  
15 tracking for calendar years 2004 and 2005 have not been added to the HURDAT  
16 (NOAA/NCDC) data set as yet and, therefore, have been omitted from this analysis despite  
17 record storm activity in 2005 that may be associated with multidecadal cycles and/or  
18 current global warming trends. Future storm intensities were calculated by multiplying the  
19 historic wind reconstructions with the proportional increase based on the forecast year  
20 relative to a ramping increase to 5, 10, 15, and 20 percent by the year 2100. The theoretical  
21 and empirical limits of maximum hurricane intensity appear to be highly correlated with  
22 sea surface temperatures (SST) (Miller, 1958; Emanuel, 1986, 1988; Holland, 1997).  
23 While climatologists debate the weight of contributing factors, including SST, modeling  
24 and recent empirical evidence suggest that a 10 percent or more increase in potential  
25 intensity gain in storm intensity is plausible under warming conditions predicted for the  
26 21<sup>st</sup> century (Emanuel, 1987; Camp and Montgomery, 2001; Knutson and Tuleya, 2004).

27 Due to the differences in multidecadal hurricane activity over the 20<sup>th</sup> century, it was  
28 appropriate to evaluate the potential increase in storm frequency relative to the period of  
29 record. Figure 3.30 shows the potential increase in storm frequency by year 2050 and 2100  
30 under climate change supposing increased ramping of hurricane intensity concomitant with  
31 warming sea surface temperatures projected at 5, 10, 15, and 20 percent over the 21<sup>st</sup>  
32 century. Results show that an increase of one to two hurricanes can be expected by year  
33 2050 and up to four added hurricanes by year 2100 above the historic frequency. The  
34 potential gain of four hurricanes over the next century from a 20 percent increase in storm  
35 intensities nearly doubles the strike probability of the historical record. Not only will  
36 hurricane incidence increase under these assumptions, individual storms will be stronger  
37 such that more catastrophic storms are likely to develop regardless of landfall location.  
38 These models and simulated data provide transportation planners with discrete and  
39 generalized probabilities of potential hurricane impact based on past and future climate.



### ■ 3.3 Sea Level Rise and Subsidence

Changes in climate during ice ages and warming periods have affected sea levels and coastal extent as evidenced from geologic records. Currently, global sea level is on the rise and is likely to accelerate with continued fossil fuel consumption from modernization and population growth (IPCC, 2001, 2007). As sea level rises, coastal shorelines will retreat and low-lying areas will tend to be inundated more frequently, if not permanently, by the advancing sea. Subsidence (or sinking) of the land surface already is contributing to the flooding of transportation infrastructure in many Gulf Coast counties. In order to assess the vulnerability of transportation systems to inundation due to sea level rise, an integrated assessment of all important influences on coastal flooding must be considered. Relative sea level rise (RSLR) is the combined effect of an increase in ocean volume resulting from thermal expansion and the melting of land ice (“eustatic” sea level rise) and the projected changes in land surface elevation at a given location.

In this section, global sea level trends are first reviewed, including a comparison of IPCC findings in the Third and Fourth Assessments. This is followed by an examination of sea level rise and subsidence in the study region. The application of two different models to project RSLR in the region is then discussed, and a summary of the modeled range of projected RSLR to 2100 is presented.

#### 3.3.1 Historic and Projected Global Sea Level Trends

Sea level has risen more than 120 meters since the peak of the last ice age (about 20,000 B.P.) and over the 20<sup>th</sup> century by 1-2 mm/year (Douglas, 1991, 1997; Gornitz, 1995; IPCC, 2001). The rate of global sea level rise since 1963 is estimated at 1.8 mm/year (IPCC, 2007). More recent analysis of satellite altimetry data for the period 1993 to 2003 shows a global average rate of sea level rise of about 3.1 (2.4-3.8) mm per year. Whether the faster rate since 1993 reflects decadal variability or a long-term acceleration over the 20<sup>th</sup> century rate is unclear. There is high confidence, however, that the rate of observed sea level rise was greater in the 20<sup>th</sup> century compared to the 19<sup>th</sup> century (IPCC, 2007).

The rate of sea level rise in the world ocean basins varied significantly during 20<sup>th</sup> century. Sea level rise during the 21<sup>st</sup> century is projected to have substantial geographical variability as well. The historical rate of sea level rise calculated from tide gauge records and satellite altimetry is much higher in the Gulf of Mexico than many other ocean basins (see IPCC, 2007, Working Group I, page 412).

The IPCC Third Assessment Report (TAR) (2001) projected an increase of 0.09-0.88 meter in average global sea level by year 2100 with a mid-range estimate of 0.45 meter. The range of projected sea level rise through 2100 is slightly lower and narrower in the IPCC Fourth Assessment Report (AR4) (see Table 3.1). The midpoint of the projections in sea level rise differs by roughly 10 percent and the ranges in the two assessment reports would have been similar if they had treated uncertainties in the same way (IPCC, 2007). As noted in earlier, the IPCC 2007 sea level rise projections do not include rapid dynamical changes

1 in ice flow from Greenland or Antarctica. If realized, some of the model-based projections  
2 could more than double the rate of sea level rise over the past century.

### 3 **3.3.2 Tide Records, Sea Level Trends, and Subsidence Rates along the Central** 4 **Gulf Coast**

5 Changes in mean water level at a given coastal location are affected by a combination of  
6 changes in sea level in an ocean basin and by local factors such as land subsidence. Gulf  
7 Coastal Plain environments, particularly in the central and western parts of the Gulf Coast  
8 study area, are prone to high rates of land surface subsidence attributed to soil  
9 decomposition and compaction, deep fluid extraction (Morton et al., 2001, 2002; White and  
10 Morton, 1997), and the lack of sediment deposition. For example, the Mississippi River  
11 delta region demonstrates relative sea level rates of 10 mm/year, tenfold greater than  
12 current eustatic sea level rise (Penland and Ramsay, 1990; Gornitz, 1995). Cahoon et al.  
13 (1998) measured subsidence rates for several Gulf Coast sites ranging from a low of 0.27  
14 cm/year in the Big Bend region of northwest Florida up to 2.39 cm/year for coastal  
15 Louisiana. Some of the forces driving shallow subsidence apparently included seasonal  
16 changes in water levels and aperiodic occurrences of major storms.

17 The National Ocean Service (NOS), a division of NOAA, validates and reposit historical  
18 water level records at primary tide stations along the coast and Great Lakes of the United  
19 States. Historic data from tide stations located within the Gulf Coast study region have  
20 been downloaded from the NOS web site at <[www.co-ops.nos.noaa.gov](http://www.co-ops.nos.noaa.gov)> in graphical and  
21 digital formats to be used in model simulations for projecting future sea level rise. Three  
22 tide stations at Pensacola, Florida; Grand Isle, Louisiana; and Galveston, Texas comprise  
23 the most reliable long-term tide records corresponding with the eastern, central, and  
24 western coverage of the study area (Figure 3.31). The mean sea level trend for these  
25 gauges shows Grand Isle, Louisiana with the highest rate at 9.85 mm/year followed by  
26 Galveston, Texas at 6.5 mm/year and Pensacola, Florida at the lowest rate of 2.14  
27 mm/year. These trend values are indicative of the high rates of local subsidence in  
28 Louisiana and Texas relative to the more stable geology underlying the Florida Panhandle.  
29 Multiple studies have extracted subsidence rates from these and other tide gauges within  
30 the Gulf Coast sector with some variability in rate estimates and methodology that mostly  
31 reaffirm regional patterns of generally high or low subsidence trends (Swanson and  
32 Thurlow, 1973; Penland and Ramsay, 1990; Zervas, 2001; Shinkle and Dokka, 2004).

33 Long-term tide gauge records are among the most reliable measures of local and regional  
34 subsidence. However, tide records also include the long-term trend of eustatic sea level  
35 change which over the last century has been estimated at 1.7-1.8 mm/year on a global basis  
36 (Douglas, 1991, 1997, 2001; IPCC, 2001, 2007; Holgate and Woodworth, 2004).  
37 Accounting for historic eustatic change in accord with the global average equates to  
38 regional subsidence rates of 8.05 mm/year for Grand Isle, Louisiana and the Mississippi  
39 River Deltaic Plain; 4.7 mm/year for Galveston, Texas and the Chenier Plain; and 0.34  
40 mm/year for Pensacola, Florida and Mississippi/Alabama Sound of the central Gulf Coast.  
41 The high subsidence rate of the Mississippi Delta region at Grand Isle, Louisiana is more

1 than four times greater than the historic eustatic trend of the last century and will account  
2 for a relative rise in sea level approaching 0.81 meter by the year 2100 apart from future  
3 eustatic changes. Some areas within the coastal zone of Louisiana have subsidence rates  
4 exceeding 20 mm/year demonstrating the potential range and variability within a subregion  
5 (Shinkle and Dokka, 2004).

6 Subsidence rates across a broad region like the Gulf Coast are highly variable on a local  
7 scale even within a representative coastal landform such as the Mississippi River Deltaic  
8 Plain or Chenier Plain. Many factors contribute to the rate and process of subsidence at a  
9 given locale by natural compaction, dewatering, and subsurface mineral extractions.  
10 Releveling surveys of benchmark monuments and well heads provide additional evidence  
11 and rates of rapid subsidence (Morton et al., 2001, 2002; Shinkle and Dokka, 2004). An  
12 extensive releveling project of the Lower Mississippi Coastal Plain of first-order  
13 benchmarks along major highway corridors provides an expansive network of measured  
14 subsidence rates (Shinkle and Dokka, 2004). Oil and gas extractions in coastal Louisiana  
15 and southeast Texas have accelerated local subsidence and wetland loss concomitant with  
16 production (Morton et al., 2001, 2002). Releveling projects in large cities such as New  
17 Orleans and Houston-Galveston have demonstrated high subsidence rates related to  
18 sediment dewatering and groundwater pumping increasing the vulnerability to local  
19 flooding (Gabrysch, 1984; Zilkowski and Reese, 1986; Gabrysch and Coplin, 1990;  
20 Holzschuh, 1991; Paine, 1993; Galloway et al., 1999; Burkett et al., 2002).

### 21 **3.3.3 Sea Level Rise Scenarios for the Central Gulf Coast Region**

22 Two different sea level rise models were used to assess the range of sea level change that  
23 could be expected in the study area during the next 50 to 100 years. The Sea Level Rise  
24 Rectification Program (SLRRP) is a model developed by the U.S. Geological Survey to  
25 explore the combined effects of future sea level change and local subsidence on coastal  
26 flooding patterns. CoastClim is a commercially available model that allows users to select  
27 GCM and emission scenario to predict sea level change within GCM grid cells over  
28 oceans. Table 3.13 outlines the selection list of GCM models that were available for use  
29 with SLRRP and the CoastClim models at the time of this study.

30 SLRRP projects future sea level rise for select tide gauge locations by rectifying the  
31 historic tide record of monthly means for the period of record and adding the predicted  
32 global mean eustatic sea level change obtained from IPCC (2001).<sup>5</sup> The tidal data input for

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<sup>5</sup> The sea level rise estimates from the IPCC Fourth Assessment Report were not available when the sea level rise simulations were run for this study. The projected range of sea level change in the IPCC Fourth Assessment Report (2007) has an upper limit that is slightly lower and a lower limit that is slightly greater than the projections contained in the IPCC Third Assessment Report (2001). The IPCC Fourth Assessment Report also indicates, however, that the rate of historical sea level rise was greater in the Gulf of Mexico than most other ocean basins, so the global average rate may tend to underestimate the rate of change in the study area.

1 the SLRRP model is composed of mean monthly water levels which captures both short-  
2 term seasonal deviations and long-term trends of sea level change. Monthly values are  
3 derived from averaged hourly recordings for each month. A mean sea level trend is  
4 calculated for each tide gauge station, which includes both the local subsidence rate of  
5 vertical land movement and eustatic rate of global sea level change for the period of record.  
6 Data records are given in stage heights for different tidal datums such as mean low water,  
7 mean tide level, and mean high water, which were rectified to North America Vertical  
8 Datum of 1988 (NAVD88) to readily compare with land-based elevations of roads and  
9 other transportation infrastructure. Monthly extremes data also were used in this study to  
10 show that daily highs within a month can exceed the monthly average by as much 0.284  
11 meter and 0.196 meter for Galveston, Texas and Pensacola, Florida, respectively. (SLRRP  
12 model procedures and inputs are explained in further detail in Appendix F.)

13 The SLRRP model indicates that surface elevations between 47.8 cm and 119.6 cm  
14 (NAVD88) will be inundated by sea level rise through 2050, dependent on geographic  
15 location, emission scenario, and GCM forecast. The SLRRP model suggests that surface  
16 elevations between 70.1 cm and 199.6 cm (NAVD88) will be inundated by sea level rise  
17 through 2100, again dependent on geographic location, emission scenario and GCM  
18 forecast. Table 3.14 provides SLRRP model results showing the mean land surface  
19 elevations (cm, NAVD88) subject to coastal flooding for Galveston, Texas, Grand Isle,  
20 Louisiana, and Pensacola, Florida by 2050 and 2100 based on averaged output for all seven  
21 GCM models for the A1F1, B1, A1B, and A2 emission scenarios.

22 The CoastClim V.1. model is another database tool for extracting predicted sea level for a  
23 given location, GCM, and emission scenario much like the SLRRP model. CoastClim has  
24 a global database to predict regional patterns of sea level change associated with grid cell  
25 output of inclusive GCM models. CoastClim's user-friendly interface allows the user to  
26 select the region of interest from a global map. With a mouse click on the shoreline map,  
27 CoastClim picks the closest GCM grid cell and extracts a normalized index of regional sea  
28 level change relative to the global-mean sea level. The normalized index is derived as a  
29 ratio or scaling factor for the average pattern of sea level change for the region or grid cell  
30 resolution divided by the global mean sea level change for the forecast period of 2071 to  
31 2100. Table 3.15 shows the equivalent normalized index for each of seven GCM model  
32 selections for Galveston, Texas, Grande Isle, Louisiana, and Pensacola, Florida. The  
33 different models display a variable range of grid cell resolution and projected sea level  
34 response above and below the global mean from 0.88 to 1.04 for the northern Gulf Coast  
35 region. The user also can select from six SRES emission scenarios (A1B, A1F1, A1T, A2,  
36 B1, and B2) to run for a given GCM application. CoastClim displays the predicted  
37 outcome in relative sea level rise above zero in tabular and graphical format from 1990 to  
38 2100.

39 CoastClim was used to generate predicted outcomes for seven different GCM models, six  
40 SRES scenarios, and three greenhouse gas forcing conditions of low, mid, and high for a  
41 total of 126 individual sea level rise curves for the 21<sup>st</sup> century. Results indicate that sea  
42 level rise will vary with both the selected model and emission scenario. The high  
43 emissions A1F1 outcome for all GCM models predicts the highest rates of sea level change  
44 among SRES options with a minimum eustatic sea level rise of 0.67 meter by 2100,

1 maximum potential rise of 1.55 meter, and a mid-range around 1 meter depending on  
2 model selection. The CoastClim model shows that relative sea level will rise between  
3 12.68 cm and 75.42 cm by 2050, dependent on-site location, emission scenario, and GCM  
4 forecast. By 2100, CoastClim predicts a potential sea level rise between 23.64 cm and  
5 172.06 cm depending on-site location, emission scenario, and GCM forecast. Table 3.16  
6 displays the CoastClim model results of the mean predicted sea level rise (cm) for the Gulf  
7 Coast region by 2050 and 2100 under a high, mid-, and low IPCC (2001) scenarios based  
8 on combined output for all seven GCM models for the A1F1, B1, A1B, and A2 emission  
9 scenarios. However, these same eustatic rates are captured in the SLRRP model but  
10 rectified to a geodetic datum and local tidal conditions that more accurately reflect the  
11 potential for coastal flooding.

## 12 ■ 3.4 Storm Surge

13 Storm surge is a wave of water that is pushed onshore by the force of the winds in the right  
14 quadrant of hurricane approach that can often inundate shoreline and inland areas up to  
15 many miles, length, and width. The added wave energy from advancing storms combines  
16 with normal tides to create the hurricane storm tide, which increases mean water levels to  
17 record heights usually inundating roadways and flooding homes and businesses. The level  
18 of surge in a particular area is determined by the slope of the offshore continental shelf and  
19 hurricane intensity. The stronger the hurricane and the shallower the offshore water, the  
20 higher the surge will be. This advancing surge combines with the normal tides to create the  
21 hurricane storm tide, which can increase the mean water level 15 feet or more. In addition,  
22 wind driven waves are superimposed on the storm tide. This rise in water level can cause  
23 severe flooding in coastal areas, particularly when the storm tide coincides with the normal  
24 high tides.

### 25 3.4.1 Predicting Storm Surge with the SLOSH Model

26 NOAA's National Weather Service forecasters model storm surge using the SLOSH (Sea,  
27 Lake, and Overland Surges from Hurricanes) model. NOAA and FEMA use SLOSH to  
28 predict potential height of storm surge so as to evaluate which coastal areas are most  
29 threatened and must evacuate during an advancing storm. The SLOSH model is a  
30 computerized model run by the National Hurricane Center (NHC) to estimate storm surge  
31 heights and winds resulting from historical, hypothetical, or predicted hurricanes by taking  
32 into account storm barometric pressure, size, forward speed, track, and wind force. The  
33 model accounts for astronomical tides by specifying an initial tide level, but does not  
34 include rainfall amounts, riverflow, or wind-driven waves. SLOSH also considers the  
35 approach or angle of hurricane landfall which can effectively enhance surge height of  
36 westerly and northwesterly approaching storms along the northern Gulf Coast. Graphical  
37 output from the model displays color coded storm surge heights for a particular area in feet  
38 above the model's reference level, the National Geodetic Vertical Datum (NGVD), which

1 is the elevation reference for most maps. Emergency managers use output data and maps  
2 from SLOSH to determine which areas must be evacuated for storm surge.

3 Modeling, theory, and recent empirical evidence suggest that hurricane intensity is likely to  
4 increase in the Gulf Coast region (see prior section on hurricanes). Even if hurricanes do  
5 not become more intense, however, sea level rise alone will increase the propensity for  
6 flooding that will occur when hurricanes make landfall in the Gulf Coast region. To assess  
7 the combined potential effects of hurricanes and sea level rise on the Gulf Coast  
8 transportation sector, a database of storm surge heights for Category 3 and 5 hurricanes  
9 was developed utilizing NOAA's SLOSH model for all coastal counties (extending inland  
10 from coastal counties along the Gulf of Mexico to those counties incorporating I-10) for the  
11 study area. Resulting surge elevations were overlaid on ArcView representations of each  
12 study area, enabling views of the study area in its entirety and minimum graphic  
13 representations at the county/parish level.

14 NOAA's National Hurricane Center (NHC) developed the SLOSH (Sea, Lake, and  
15 Overland Surges from Hurricanes) model to predict storm surge potential from tropical  
16 cyclones for comprehensive hurricane evacuation planning. The SLOSH models requires  
17 grid-based configurations of near-shore bathymetry and topography on a basin level. NHC  
18 has defined 38 basins in the Atlantic and Pacific Oceans of which there are 14 subbasins  
19 that define the offshore and onshore geomorphology of the Gulf Coast shoreline from the  
20 Florida Keys to the Laguna Madre of Texas. SLOSH model simulations were performed  
21 for a merged suite of SLOSH basins (n=7) that covers the central Gulf Coast between  
22 Galveston, Texas and Mobile, Alabama (Table 3.17). SLOSH output were compiled for 28  
23 simulation trials to extract surge levels for varying storm intensities (Categories 2-5) and  
24 landfall approaches. A sample simulation of surge height predictions are shown based on  
25 combined output for storms of Category 2, 3, 4, and 5 approaching the eastern half of the  
26 study area (Louisiana, Mississippi, and Alabama) on different azimuths (Figure 3.32).  
27 Storm intensity, speed, and direction produces different storm surge predictions. Model  
28 simulation trials conducted for the SLOSH basin that covers New Orleans involved  
29 calibration and validation checks with historic storms and flood data.

30 Study area SLOSH applications involved the collection, synthesis, and integration of  
31 various geospatial information and baseline data for the central Gulf Coast region relevant  
32 to storm surge model implementation and predictions with the following objectives:

- 33 • To derive a database of storm surge heights for Category 3 and 5 hurricanes utilizing  
34 NOAA's SLOSH model for all coastal counties (extending inland from coastal counties  
35 along the Gulf of Mexico to those counties incorporating I-10), for the study area  
36 spanning Galveston, Texas to Mobile, Alabama;
- 37 • To overlay the resulting surge elevations on ArcView representations of each study  
38 area, enabling views of the study area in its entirety and minimum graphic  
39 representations at the county level;

- To add topographic contours at 1 meter intervals to the study area data sets; and
- To color code storm surge heights based on surge elevation in meters.

The integration of SLOSH output with local geospatial data will be particularly useful in Phase 2 of the study, which will involve an assessment of transportation impacts for a particular county or MPO within the study area.

### **3.4.2 Future Sea Level Rise and Storm Surge Height**

Sea level rise can be incorporated into surge height predictions from SLOSH simulations for future years by elevating surge levels in proportion to the amount of rise for any given scenario (Figure 3.33). Sea level change will be particularly important in influencing this coastal area, since the land already is subject to flooding with supranormal tides and surge and rainfall events of even smaller, less powerful, tropical storms. Improved spatial detail and vertical accuracy of coastal elevations will greatly enhance predictions of the spatial extent of flooding from projected sea level rise and storm surges. LIDAR imagery used in this project for coastal Louisiana offers distinct advantages for modeling purposes and graphical representation over other available DEM data sources such as the National Elevation Dataset (Figure 3.34). Also, it is expected that storm surges superimposed on higher mean sea levels will tend to exacerbate coastal erosion and land loss. During Hurricanes Rita and Katrina, for example, 562 km<sup>2</sup> (217 mi<sup>2</sup>) of land in coastal Louisiana was converted to open water (Barras, 2006) and the Chandeleur Island chain was reduced in size by roughly 85 percent (USGS, 2007). The implications of the loss of these natural storm buffers on transportation infrastructure have not been quantified.

Surge analyses were conducted for the Gulf Coast study area by reviewing historical tide records and simulated hurricane scenarios based on the NOAA SLOSH model. Highest tide records for over 70 coastal tide stations were obtained from historical records within the study area with the highest recorded surge of 6.2 meters (20.42 feet) (NAVD88) at Bay St. Louis, Mississippi in the wake of a northerly approaching Category 5 storm, Hurricane Camille (1969). Post-Katrina (2005) high watermark surveys in New Orleans proper and east along the Mississippi Coast revealed storm surge heights approaching 8.5 meters (28 feet) msl. Simulated storm surge from NOAA SLOSH model runs across the central Gulf Coast region demonstrate a 6.7-7.3 meters (22-24 feet) potential surge with major hurricanes of Category 3 or greater without considering a future sea level rise effect. Storm approach from the east on a northwesterly track can elevate storm surge 0.3-1.0 meter (1-3 feet) in comparison to a storm of equal strength approaching on a northeasterly track. The combined conditions of a slow churning Category 5 hurricane making landfall on a westerly track along the Central Gulf Coast under climate change and elevated sea levels indicate that transportation assets and facilities at or below 9 meters (30 feet) mean sea level are subject to direct impacts of projected storm surge.

## 3.5 Other Aspects of Climate Change with Implications for Gulf Coast Transportation

Temperature, precipitation, runoff, sea level rise, and tropical storms are not the only components of Gulf Coast climate that have the potential to change as the temperature of the atmosphere and the sea surface increase. Changes in wind and wave regime, cloudiness, and convective activity could possibly be affected by climate change and would have implications for some modes of transportation in the Gulf Coast region.

### 3.5.1 Wind and Wave Regime

There have been very few long-term assessments of near surface winds in the United States. Groisman and Barker (2002) found a decline in near surface winds of about -5 percent (50) years during the second half of the 20<sup>th</sup> century for the United States, but they suggest that a stepwise increase in the number of wind reporting stations noticeably reduced the variance of the regionally averaged time series. They note that most reporting stations are located near airports and other developed areas. They did not attribute the decrease to climate change or land use change. Warming trends can be expected to generate more frequent calm weather conditions typical of summer months that are generally characterized by lower winds than in cold-season months (Groisman et al., 2004).

Few studies have been made of potential changes in prevailing ocean wave heights and directions as a consequence of climate change, even though such changes can be expected (Schubert et al., 1998, McLean et al., 2001). In the North Atlantic, a multidecadal trend of increased wave height has been observed, but the cause is poorly understood (Gulev and Hasse, 1999, Mclean et al., 2001). Wolf (2003) attributes the increasing North Atlantic wave height in recent decades to the positive phase of the North Atlantic Oscillation, which appears to have intensified commensurate with the slow warming of the tropical ocean (Hoerling et al., 2001; Wang et al., 2004). Changes in wave regime will not likely be uniform among ocean basins, however, and no published assessments have focused specifically on how climate change may affect wind and wave regime in the Gulf of Mexico. One three-year study of wave and wind climatologies for the Gulf of Mexico (Teague et al., 1997) indicates that that wave heights and wind speeds increase from east to west across the Gulf. This particular study, which is based on TOPEX/POSEIDEN satellite altimetry and moored surface buoy data, also indicates seasonality with the highest wind speeds and wave heights in the fall and winter.

Scenarios of future changes in seasonal wave heights constructed using climate model projections for the northeast Atlantic projected increases in both winter and fall seasonal means in the 21<sup>st</sup> century under three forcing scenarios (Wang et al., 2004). The IPCC (2007) concludes that an increase in peak winds associated with hurricanes will accompany an increase in tropical storm intensity. Increasing average summer wave heights along the U.S. Atlantic coastline are attributed to a progressive increase in hurricane activity between 1975 and 2005 (Komar and Allan, 2007). Wave heights greater than 3 meters increased by



1 0.7 to 1.8 meter during the study period, with hourly averaged wave heights during major  
2 hurricanes increased significantly from about 7 meters to more than 10 meters since 1995  
3 (Komar and Allan, 2007). A more recent study of wave heights in the central Gulf of  
4 Mexico between 1978 and 2005 suggests an increasing trend (Komar and Allan, 2008)  
5 (Figure 3.35).

6 If tropical storm windspeed increases as anticipated (see Section 3.2.8), this will tend to  
7 have a positive effect on mean wave height during the coming decades. Wave heights in  
8 coastal bays also will tend to increase due to the combined erosional effects of sea level  
9 rise and storms on coastal barrier islands and wetlands (Stone and McBride, 1998; Stone et  
10 al., 2003).

### 11 **3.5.2 Humidity and Cloudiness**

12 As the climate warms, the amount of moisture in the atmosphere is expected to rise much  
13 faster than the total precipitation amount (Trenberth et al., 2003). The IPCC (2007) has  
14 concluded that tropospheric water vapor increased over the global oceans by  $1.2 \pm 0.3$   
15 percent per decade from 1988 to 2004, consistent in pattern and amount with changes in  
16 sea surface temperature (SST) and a fairly constant relative humidity. Several studies have  
17 reported an increase in the near surface specific humidity (the mass of water vapor per unit  
18 mass of moist air) over the United States during the second half of the past century (Sun et  
19 al., 2000, Ross and Elliot, 1996). Sun and others found that during 1948 to 1993, the mean  
20 annual specific humidity under clear skies steadily increased at a mean rate of 7.4 percent  
21 per 100 years.

22 Gaffen and Ross (1999) analyzed annual and seasonal dewpoint temperature, specific  
23 humidity, and relative humidity at 188 first-order weather stations in the United States for  
24 the period 1961 to 1995. (Relative humidity is a measure of comfort based on temperature  
25 and specific humidity.) Coastal stations in the Southeastern United States were moister  
26 than inland stations at comparable latitude, and stations in the eastern half of the country  
27 had specific humidity values about twice those at interior western stations. This dataset  
28 also shows increases in specific humidity of several percent per decade, and increases in  
29 dewpoint of several tenths of a degree per decade over most of the country in winter,  
30 spring, and summer, with nighttime humidity trends larger than daytime trends (Gaffen  
31 and Ross, 1999). In the southeastern United States, specific humidity increased 2 to 3  
32 percent per decade between 1973 and 1993 (Ross and Elliot, 1996) and this trend is  
33 expected to continue.

### 34 **3.5.3 Convective Activity**

35 Sun and others (2001) documented a significant increase in total, low, cumulonimbus, and  
36 stratocumulus cloudiness across the United States during 1948 to 1993. The largest  
37 changes in the frequency of cumulonimbus cloudiness occurred in the intermediate  
38 seasons, especially in the spring. The increase in the frequency of cumulonimbus cloud

1 development is consistent with the nationwide increase in the intensity of heavy and very  
2 heavy precipitation observed by Karl and Knight (1998) and Groisman and others (2004).  
3 Cumulonimbus clouds are commonly associated with afternoon thunderstorms in the Gulf  
4 Coast region. The historical and projected increase in summer minimum temperatures for  
5 the study area suggest an increase in the probability of severe convective weather (Dessens,  
6 1995, Groisman et al., 2004).

## 7 ■ 3.6 Conclusions

8 The empirical climate record of the past century, in addition to climate change scenarios,  
9 was examined to assess the past and future temperature and hydrology of the central Gulf  
10 Coast region. The empirical record of the region shows an annual temperature pattern with  
11 high values in the 1920s-1940s, with a drop in annual temperatures in late 1950s, which  
12 persisted through the 1970s. Annual temperatures then began to climb over the past three  
13 decades, but still have not reached the highs of previous decades. The timing of the  
14 increase in Gulf Coast temperatures is consistent with the global “climate shift” since the  
15 late 1970s (Karl et al., 2000 and Lanzante, 2006) when the rate of temperature change  
16 increased in most land areas.

17 Annual precipitation in the study area shows a suggestion toward increasing values, with  
18 some climate divisions, especially those in Mississippi and Alabama, with significant long-  
19 term trends. There also is a long-term trend of increasing modeled annual runoff  
20 regionwide. Over the entire record since 1919, there was an increase in rainfall, and that  
21 combined with relatively cool temperatures, led to an estimated 36 percent increase in  
22 runoff. Modeled future water balance, however, suggests that runoff is expected to either  
23 decline slightly or remain relatively unchanged, depending upon the balance of  
24 precipitation and evaporation. Moisture deficits and drought appear likely to increase  
25 across the study area, though model results are mixed. These findings are consistent with  
26 the IPCC (2007), which concludes that it is very likely that heat waves, heat extremes and  
27 heavy precipitation events over land will increase during this century and that the number  
28 of dry days (or spacing between rainfall events) will increase. Even in mid-latitude regions  
29 where mean precipitation is expected to decrease, precipitation intensity is expected to  
30 increase (IPCC, 2007).

31 Changes in rainfall beyond the study area can play an important role in the hydrology of  
32 the coastal zone. Weather patterns over the Mississippi River basin, which drains 41  
33 percent of the United States, and other major drainages, contribute to the total runoff in the  
34 Gulf Coast region. Several recent modeling efforts suggest an increase in average annual  
35 runoff in the eastern half of the Mississippi River watershed while drainage west of the  
36 Mississippi and along the southern tier of states is generally predicted to decrease (Milly et  
37 al., 2005; IPCC, 2007). In the case of the Mississippi River, drainage to the coast is not  
38 presently a major factor in terms of flooding of infrastructure, because the river is leveed  
39 and only a small portion of its flow reaches the marshes and shallow waters of the  
40 Louisiana coastal zone. Drainage of the Mississippi and other rivers to the coast, however,

1 is important in maintaining coastal soil moisture and water quality. The decline of  
2 approximately 150,000 acres of coastal marsh in south Louisiana in 2000 was attributed to  
3 extreme drought, high salinities, heat and evaporation, and low river discharge (State of  
4 Louisiana, 2000).

5 As stated earlier, climate models currently lack the spatial and temporal detail needed to  
6 make confident projections or forecasts for a number of variables, especially on small  
7 spatial scales, so plausible “scenarios” are often used to provide input to decision-making.  
8 Output from an ensemble of 21 global climate models (General Circulation Models or  
9 GCMs) run with the three emission scenarios indicate a wide range of possible changes in  
10 temperature and precipitation out to the year 2050. The models agree to a warmer Gulf  
11 Coast region of about  $1.5^{\circ}\text{C} \pm 1^{\circ}\text{C}$ , with the greatest increase in temperature occurring in  
12 the summer. Based on historical trends and model projections, we conclude that it is very  
13 likely that in the future the number of very hot days will substantially increase across the  
14 study area. Due to the non-normality of temperature distributions over the five Gulf States,  
15 extreme high temperatures could be about  $1^{\circ}\text{C}$  greater than the change in the average  
16 temperature simulated by the GCMs.

17 Scenarios of future precipitation are more convoluted with indications of increases or  
18 decreases by the various models, but the models lean slightly toward a decrease in annual  
19 rainfall across the Gulf Coast. However, by compounding changing seasonal precipitation  
20 with increasing temperatures, average runoff is likely to remain the same or decrease, while  
21 deficits (or droughts) are more likely to become more severe.

22 Each of the climate model and emission scenarios analyzed in this report represent  
23 plausible future world conditions. As stated earlier, GCMs currently lack the spatial and  
24 temporal detail needed to make projections or forecasts, so plausible “scenarios” are often  
25 used to provide input to decision-making. Nor do these models have the capacity for  
26 simulating small-scale phenomena such as thunderstorms, tornadoes, hail, and lightning.  
27 However, climate models do an excellent job of simulating temperature means and  
28 extremes. Hourly and daily precipitation and runoff extremes are much more difficult to  
29 simulate due to horizontal resolution constraints. However, based on observational and  
30 modeling studies the IPCC (2007) and numerous independent climate researchers have  
31 concluded that more intense precipitation events are very likely during this century over  
32 continental land masses in the Northern Hemisphere.

33 Recent empirical evidence suggests a trend towards more intense hurricanes formed in the  
34 North Atlantic basin and this trend is likely to intensify during the next century (IPCC,  
35 2007). In the Gulf region, there is presently no compelling evidence to suggest that the  
36 number or paths of tropical storms have changed or are likely to change in the future.  
37 Convective activity, heavy precipitation events, and cloudiness all appear likely to increase  
38 in the Gulf Coast region as the climate warms.

39 Change in the rate of sea level rise is dependent on a host of interacting factors that are best  
40 evaluated on decadal to centennial time scales. Two complimentary modeling approaches  
41 were applied in this study to assess the potential rise in sea level and coastal submergence  
42 over the next century. Both models were used to estimate relative sea level rise (RSLR) by

1 2050 and 2100 under a range of greenhouse gas emissions scenarios. Both models account  
2 for eustatic sea level change as estimated by the global climate models, and also  
3 incorporate values for land subsidence in the region based on the historical record. One  
4 model, CoastClim, produces results that are closer to a simple measure of future sea level  
5 change under the scenarios of future climate. A similar model, SLRRP, also incorporates  
6 values for high and low tidal variation attributed to astronomical and meteorological  
7 causes, which are pulled from the historical record. The SLRRP model is rectified to the  
8 North American Vertical Datum (NAVD88) that is commonly used by surveyors to  
9 calculate the elevations of roads, bridges, levees, and other infrastructure. The tide data  
10 used in the SLRRP model is based on a monthly average of the mean high tide (called  
11 Mean High Higher Water) for each day of the month. The SLRRP results capture seasonal  
12 variability and inter-annual trends in relative sea level change, while the CoastClim results  
13 do not.

14 The three long-term tide gauge locations analyzed in this study represent three subregions  
15 of the study area: Galveston, Texas (the Chenier Plain); Grand Isle, Louisiana (the  
16 Mississippi River Deltaic Plain); and Pensacola, Florida (Mississippi/Alabama Sound). For  
17 each of these gauges, we examined potential range of relative sea level rise through 2050  
18 and 2100 using the SRES B1, A1B, A2, and A1F1 emissions scenarios based on the  
19 combined output of 7 GCMs (Table 3.14). Results for 2100 generated with CoastClim  
20 range from 24 cm (0.8 feet) in Pensacola to 167 cm (5.5 feet) in Grand Isle. Results for  
21 2100 from SLRRP, which as noted above accounts for historical tidal variation, are  
22 somewhat higher: predicted relative sea level ranges from 70 cm (2.3 feet, NAVD88) in  
23 Pensacola to 199 cm (6.5 feet, NAVD88) in Grand Isle.

24 Storm surge simulations accomplished basin specific surge height predictions for a  
25 combination of storm categories, track speeds, and angled approach on landfall that can be  
26 summarized by worst-case conditions to exceed 6 to 9 meters (20-30 feet) along the Central  
27 Gulf Coast. Storm attributes and meteorological conditions at the time of actual landfall of  
28 any storm or hurricane will dictate actual surge heights. Transportation officials and  
29 planners within the defined study area can expect that transportation facilities and  
30 infrastructure at or below 9 meters of elevation along the coast are subject to direct and  
31 indirect surge impacts. Sea level rise of 1 to 2 meters (3-6 feet) along this coast could  
32 effectively raise the cautionary height of these surge predictions to 10 meters (33 feet) or  
33 more by the end of the next century.

34 Changes in climate can have widespread effects on physical and biological systems of low-  
35 lying, sedimentary coasts. However, the large and growing pressures of development are  
36 responsible for most of the current stresses on Gulf Coast natural resources, which include:  
37 water quality and sediment pollution, increased flooding, loss of barrier islands and  
38 wetlands, and other factors that are altering the resilience of coastal ecosystems (U.S. EPA,  
39 1999). Human alterations to freshwater inflows through upstream dams and  
40 impoundments, dredging of natural rivers and man-made waterways, and flood control  
41 levees also have affected the amount of sediment delivered to the Gulf coastal zone.  
42 Roughly 80 percent of U.S. coastal wetland losses have occurred in the Gulf Coast region  
43 since 1940, and predictions of future population growth portend increasing pressure on  
44 Gulf coast communities and their environment. Sea level rise will generally increase

1 marine transgression on coastal shorelines (Pethick, 2001) and the frequency of barrier  
2 island overwash during storms, with effects most severe in coastal systems that already are  
3 stressed and deteriorating. An increase in tropical storm intensity or a decrease in fresh  
4 water and sediment delivery to the coast would tend to amplify the effects of sea level rise  
5 on Gulf Coast landforms.

6 Our assessment of historical and potential future changes in Gulf Coast climate section  
7 draws on publications, analyses of instrumental records and models that simulate how  
8 climate may change in the future. Model results, climatic trends during the past century,  
9 and climate theory all suggest that extrapolation of the 20<sup>th</sup> century temperature record  
10 would likely underestimate the range of change that could occur in the next few decades.  
11 The global near-surface air temperature increase of the past 100 years is approaching levels  
12 not observed in the past several hundred years (IPCC, 2001); nor do current climate  
13 models span the range of responses consistent with recent warming trends (Allen and  
14 Ingram, 2002). Regional “surprises” are increasingly possible in the complex, nonlinear  
15 earth climate system (Groisman et al., 2004), which is characterized by thresholds in  
16 physical processes that are not completely understood or incorporated into climate model  
17 simulations, e.g., interactive chemistry, interactive land and ocean carbon emissions, etc.  
18 While there is still considerable uncertainty about the *rates* of change that can be expected  
19 (Karl and Trenberth, 2003), there is a fairly strong consensus regarding the direction of  
20 change for most of the climate variables that affect transportation in the Gulf Coast region.  
21 Key findings from this analysis and other published studies for the study region include:

22 **Warming Temperatures** – An ensemble of GCMs indicate that the average annual  
23 temperature is likely to increase by 1-2°C (2-4°F) in the region by 2050. Extreme high  
24 temperatures also are expected to increase and within 50 years the probability of  
25 experiencing 21 days a year with temperatures of 37.8°C (100°F) is greater than 50  
26 percent.

27 **Changes in Precipitation Patterns** – While average annual rainfall may increase or  
28 decrease slightly, the intensity of individual rainfall events is likely to increase during the  
29 21<sup>st</sup> century. It is possible that average soil moisture and runoff could decline, however,  
30 due to increasing temperature, evapotranspiration rates and spacing between rainfall events.

31 **Rising Sea Levels** – Relative sea level is likely to rise between 1 and 6 feet by the end of  
32 the 21<sup>st</sup> century, depending upon model assumption and geographic location. The highest  
33 rate of relative sea level rise will very likely be in the central and western parts of the study  
34 area (Louisiana and East Texas) where subsidence rates are highest.

35 **Storm Activity** – Hurricanes are more likely to form and increase in their destructive  
36 potential as the sea surface temperature of the Atlantic and Gulf of Mexico continue to  
37 increase. Rising relative sea level will exacerbate exposure to storm surge and flooding.  
38 Depending on the trajectory and scale of individual storms, facilities at or below 9 meters  
39 (30 feet) could be subject to direct storm surge impacts.

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**Table 3.1 Projected global average surface warming and sea level rise at the end of the 21<sup>st</sup> century (IPCC, 2007). These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity (EMIC), and a large number of Atmosphere-Ocean Global Circulation Models (AOGCM). Sea level projections do not include uncertainties in carbon-cycle feedbacks, because a basis in published literature is lacking (IPCC, 2007).**

Case	Temperature Change (°C at 2090 -2099 Relative to 1980-1999)		Sea Level Rise (M at 2090-2099 Relative to 1980-1999)
	Best Estimate	Likely Range	Model-Based Range, Excluding Future Rapid Dynamical Changes in Ice Flow
Constant Year 2000 Concentrations	0.6	0.3-0.9	NA
B1 Scenario	1.8	1.1-2.9	0.18-0.38
A1T Scenario	2.4	1.4-3.8	0.20-0.45
B2 Scenario	2.4	1.4-3.8	0.20-0.43
A1B Scenario	2.8	1.7-4.4	0.21-0.48
A2 Scenario	3.4	2.0-5.4	0.23-0.51
A1F1 Scenario	4.0	2.4-6.4	0.26-0.59

**Table 3.2 United States Historical Climatology Network (USHCN) stations within the seven Climate Divisions of the central Gulf Coast region.**

<b>Climate Division</b>	<b>USHCN Stations</b>
Texas CD 8	Danevang, Liberty
Louisiana CD 7	Jennings <sup>a</sup>
Louisiana CD 8	Franklin, Lafayette
Louisiana CD 9	Donaldsonville, Houma, New Orleans, Thibodaux
Louisiana CD 6	Amite, Baton Rouge, Covington
Mississippi 10	Pascagoula, Poplarville, Waveland
Alabama CD 8	Fairhope

<sup>a</sup> The Jennings climate record only dates back to the late 1960s. As a result, LA-CD 7 is made up of an average of Liberty, Texas to the west and Lafayette, Louisiana to the east.



**Table 3.3 List of GCMs run with the three SRES emission scenarios (A1B, A2, and B1) for this study. Not all model runs were available from the IPCC Data Centre for each SRES scenario.**

A1B		A2		B1	
Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
CCCMA	CCCMA.T63	BCCR	BCCR	BCCR	BCCR
CCCMA.T63	CNRM	CCCMA	CNRM	CCCMA	CCCMA.T63
CNRM	CSIRO	CNRM	CSIRO	CCCMA.T63	CNRM
CSIRO	GFDL0	CSIRO	GFDL0	CNRM	CSIRO
GFDL0	GFDL1	GFDL0	GFDL1	CSIRO	GFDL0
GFDL1	GISS.AOM	GFDL1	GISS.ER	GFDL0	GFDL1
GISS.AOM	GISS.EH	GISS.ER	INMCM3	GFDL1	GISS.AOM
GISS.EH	GISS.ER	INMCM3	IPSL	GISS.AOM	GISS.ER
GISS.ER	IAP	IPSL	MIROC.MEDRES	GISS.ER	IAP
IAP	INMCM3	MIROC.MEDRES	ECHAM	IAP	INMCM3
INMCM3	IPSL	ECHO	MRI	INMCM3	IPSL
IPSL	MIROC.HIRES	ECHAM	CCSM3	IPSL	MIROC.HIRES
MIROC.HIRES	MIROC.MEDRES	MRI	PCM	MIROC.HIRES	MIROC.MEDRES
MIROC.MEDRES	ECHAM	CCSM	HADCM3	MIROC.MEDRES	ECHAM
ECHO	MRI	PCM	HADGEM1	ECHO	MRI
ECHAM	CCSM3	HADCM3		ECHAM	CCSM3
MRI	PCM	HADGEM1		MRI	PCM
CCSM	HADCM3			CCSM	HADCM3
PCM				PCM	
HADCM3				HADCM3	
HADGEM1					

**Table 3.4 Scenarios of temperature change from an ensemble of GCMs for the 5<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles for the A1B scenario for 2050 relative to 1971-2000 means, in degrees Celsius.**

	5 <sup>th</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Winter	0.18	0.95	1.42	1.89	2.56
Spring	1.22	1.55	1.80	2.04	2.38
Summer	1.24	1.66	1.94	2.23	2.70
Autumn	1.31	1.69	1.93	2.22	2.62

**Table 3.5 Scenarios of precipitation change from an ensemble of GCMs for the 5<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles for the A1B scenario for 2050 relative to 1971-2000 means, in percent.**

	5 <sup>th</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Winter	-13.30	-5.95	-1.79	2.49	9.01
Spring	-21.07	-11.04	-5.04	1.80	10.17
Summer	-36.10	-17.77	-6.39	6.25	26.24
Autumn	-8.20	0.46	5.97	12.05	21.50

**Table 3.6 Scenarios of temperature change from an ensemble of GCMs for the 5<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles for the A2 scenario for 2050 relative to 1971-2000 means, in degrees Celsius.**

	5 <sup>th</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Winter	0.2	1.0	1.5	2.0	2.9
Spring	0.8	1.3	1.7	2.0	2.6
Summer	1.1	1.5	1.8	2.1	2.5
Autumn	1.0	1.5	1.8	2.1	2.6

**Table 3.7 Scenarios of precipitation change from an ensemble of GCMs for the 5<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles for the A2 scenario for 2050 relative to 1971-2000 means, in percent.**

	5 <sup>th</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Winter	-12.7	-5.7	0.4	5.6	13.6
Spring	-22.9	-12.8	-6.0	0.5	10.3
Summer	-31.2	-15.0	-5.2	5.9	21.3
Autumn	-7.3	1.3	7.0	12.7	22.1

**Table 3.8 Scenarios of temperature change from an ensemble of GCMs for the 5<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles for the B1 scenario for 2050 relative to 1971-2000 means, in degrees Celsius.**

	5 <sup>th</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Winter	-0.31	0.44	1.02	1.53	2.32
Spring	0.67	1.05	1.32	1.62	2.03
Summer	0.64	1.09	1.35	1.63	2.03
Autumn	0.62	1.04	1.33	1.62	2.07

**Table 3.9 Scenarios of precipitation change from an ensemble of GCMs for the 5<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> percentiles for the B1 scenario for 2050 relative to 1971-2000 means, in percent.**

	5 <sup>th</sup>	25 <sup>th</sup>	50 <sup>th</sup>	75 <sup>th</sup>	95 <sup>th</sup>
Winter	-9.77	-4.37	-0.52	3.36	9.51
Spring	-16.94	-7.96	-2.94	2.41	11.38
Summer	-27.06	-14.16	-3.36	7.43	24.19
Autumn	-7.83	-0.06	5.63	11.13	19.40

**Table 3.10 Days above 32.2°C (90°F) and mean daily temperature in the study area for datasets running through 2004. The start date varies by location (note the number of years of observed data).**

<b>Station</b>	<b>Years of Observed Data</b>	<b>Annual Days Above 90°F</b>	<b>Normal Mean Daily (°F)</b>	
			<b>Annual</b>	<b>July</b>
Mobile, Alabama	42	74	66.8	81.5
Baton Rouge, Louisiana	45	84	67.0	81.7
Lake Charles, Louisiana	40	76	67.9	82.6
New Orleans, Louisiana	58	72	68.8	82.7
Meridian, Mississippi	40	80	64.7	81.7
Houston, Texas	35	99	68.8	83.6
Port Arthur, Texas	44	83	68.6	82.7
Victoria, Texas	43	106	70.0	84.2

**Table 3.11 Potential temperature increase scenarios for August.  
 Modeled outputs shown in Celsius and Fahrenheit.**

Mid-Term Potential (2050 Scenarios)				Long-Term Potential (2100 Scenarios)			
Temperature Increase by Scenario Percentile: °C (°F)				Temperature Increase by Scenario Percentile: °C (°F)			
Scenario	5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>	Scenario	5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>
<b>A1B</b>	1.6 (2.9)	2.5 (4.5)	<b>3.4 (6.1)</b>	<b>A1B</b>	3.0 (5.4)	3.9 (7.0)	5.0 (9.0)
<b>B1</b>	<b>0.9 (1.6)</b>	1.8 (3.2)	2.6 (4.7)	<b>B1</b>	<b>1.8 (3.2)</b>	2.7 (4.9)	3.6 (6.5)
<b>A2</b>	1.1 (2.0)	2.3 (4.1)	<b>3.4 (6.1)</b>	<b>A2</b>	3.3 (5.9)	4.7 (8.5)	<b>6.0 (10.8)</b>

Note: Lowest/highest changes in bold.

**Table 3.12 Saffir-Simpson Scale for categorizing hurricane intensity and damage potential. Note that maximum sustained wind speed is the only characteristic used for categorizing hurricanes.**

Saffir-Simpson Scale and Storm Category	Central Pressure (MB)	Maximum Sustained Wind Speed (MPH)	Damage Potential
1	980	74-95	Minimal
2	965-979	96-110	Moderate
3	945-964	111-130	Extensive
4	920-944	131-155	Extreme
5	< 920	>155	Catastrophic

**Table 3.13 GCM model selection options based on data availability for the USGS SLRRP model and CoastClim model for generating future sea level rise projections. There are 3 GCM model data sets shared between SLRRP and CoastClim and a total of 11 GCM models and data sets altogether.**

SLRRP GCM Listing	CoastClim GCM Listing
CSIRO_Mk2	CGCM1
CSM 1.3	CGCM2
ECHAM4/OPYC3	CSIRO_Mk2
GFDL_R15_a	GFDL_R15_b
HadCM2	GFDL_R30_c
HadCM3	HadCM2
PCM	HadCM3

Notes: Canadian Global Coupled Model – CGMC1, CGCM2.

CSIRO: Commonwealth Scientific and Industrial Research Organisation [Australia] – CSIRO\_Mk2.

Geophysical Fluid Dynamics Laboratory – GFDL\_R15a, R15b, R30c.

Hadley Centre Coupled Model – HADCM2, HADCM3.

Parallel Climate Model – DOE/NCAR, PCM.

**Table 3.14 USGS SLRRP model results showing the mean land surface elevations subject to coastal flooding for the Gulf Coast region by 2050 and 2100 under a high, mid, and low scenario based on combined output for all 7 GCM models for the A1F1, B1, A1B, and A2 emission scenarios, in centimeters (NAVD88).**

Year 2050	Low				Year 2100	Low			
	A1F1	B1	A1B	A2		A1F1	B1	A1B	A2
Galveston, Texas	83.0	80.9	83.4	83.4	Galveston, Texas	130.7	117.0	124.9	127.0
Grand Isle, Louisiana	107.5	106.0	108.8	106.3	Grand Isle, Louisiana	171.2	159.7	168.7	167.6
Pensacola, Florida	48.0	47.8	48.4	53.7	Pensacola, Florida	83.9	70.1	78.2	75.2

Year 2050	Mid				Year 2100	Mid			
	A1F1	B1	A1B	A2		A1F1	B1	A1B	A2
Galveston, Texas	88.9	86.7	88.7	88.8	Galveston, Texas	146.0	129.5	137.1	140.8
Grand Isle, Louisiana	113.6	111.8	114.2	111.8	Grand Isle, Louisiana	185.3	171.4	180.2	181.3
Pensacola, Florida	53.9	53.6	53.7	60.0	Pensacola, Florida	99.2	82.6	90.3	89.3

Year 2050	High				Year 2100	High			
	A1F1	B1	A1B	A2		A1F1	B1	A1B	A2
Galveston, Texas	94.8	92.5	93.9	94.3	Galveston, Texas	161.3	142.0	149.3	154.5
Grand Isle, Louisiana	119.6	117.6	119.6	117.3	Grand Isle, Louisiana	199.6	183.1	191.7	195.1
Pensacola, Florida	59.8	59.4	58.9	66.3	Pensacola, Florida	114.5	95.0	102.5	103.5

**Table 3.15 Regional grid cell counts and normalized indices of sea level rise relative to global mean sea level projections for northern Gulf Coast tide gage locations by different GCM models used in CoastClim simulations.**

CoastClim Models	Gulf Coast Grid Cell Count	Normalized SLR Index		
		Galveston, Texas	Grand Isle, Louisiana	Pensacola, Florida
CGCM1	5	0.89	0.89	0.89
CGCM2	5	1.04	1.04	0.95
CSIRO_Mk2	3	0.90	0.94	0.94
GFDL_R15_b	2	0.94	0.88	0.89
GFDL_R30_c	6	0.98	1.01	1.01
HadCM2	2	1.02	1.02	1.02
HadCM3	7	1.03	1.00	0.96



**Table 3.16 CoastClim model results showing the mean sea level rise for the Gulf Coast region by 2050 and 2100 under a high, mid, and low scenario based on combined output for all 7 GCM models for the A1F1, B1, A1B, and A2 emission scenarios, in centimeters.**

Year 2050	Low				Year 2100	Low			
	A1F1	B1	A1B	A2		A1F1	B1	A1B	A2
Galveston, Texas	40.5	39.2	40.2	39.6	Galveston, Texas	81.8	72.4	76.3	78.6
Grand Isle, Louisiana	60.6	59.3	60.3	59.8	Grand Isle, Louisiana	118.8	109.3	113.3	115.6
Pensacola, Florida	14.2	13.0	14.0	14.2	Pensacola, Florida	33.6	24.3	28.2	32.0

Year 2050	Mid				Year 2100	Mid			
	A1F1	B1	A1B	A2		A1F1	B1	A1B	A2
Galveston, Texas	46.2	44.3	45.8	44.8	Galveston, Texas	101.8	84.9	92.2	95.4
Grand Isle, Louisiana	66.4	64.4	66.0	64.9	Grand Isle, Louisiana	138.9	121.8	129.3	132.4
Pensacola, Florida	20.0	18.1	19.6	19.8	Pensacola, Florida	53.5	36.8	44.1	49.3

Year 2050	High				Year 2100	High			
	A1F1	B1	A1B	A2		A1F1	B1	A1B	A2
Galveston, Texas	54.3	51.6	53.8	52.1	Galveston, Texas	130	103.7	115.5	119.3
Grand Isle, Louisiana	74.5	71.7	73.9	72.3	Grand Isle, Louisiana	167.3	140.7	152.5	156.4
Pensacola, Florida	28.1	25.3	27.5	27.5	Pensacola, Florida	81.6	55.6	67.2	73.9

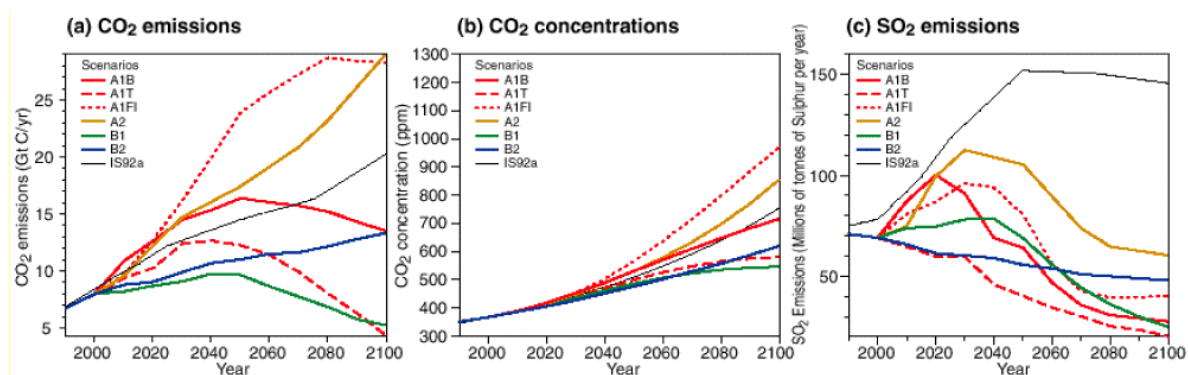
**Table 3.17 Seven SLOSH basin codes, name descriptions, and storm categories included in the central Gulf Coast study region and simulation trials from Mobile, Alabama to Galveston, Texas.**

Basin Code	Basin Name	Storm Category
EMOB	Elliptical Mobile Bay	Cat2, Cat3, Cat4, Cat5
NBIX	MS – Gulf Coast	Cat2, Cat3, Cat4, Cat5
MS2	New Orleans	Cat2, Cat3, Cat4, Cat5
LFT	Vermillion Bay	Cat2, Cat3, Cat4, Cat5
EBPT	Elliptical Sabine Lake	Cat2, Cat3, Cat4, Cat5
EGL2	Elliptical Galveston Bay (2002)	Cat2, Cat3, Cat4, Cat5
PSX	Matagorda Bay Texas	Cat2, Cat3, Cat4, Cat5

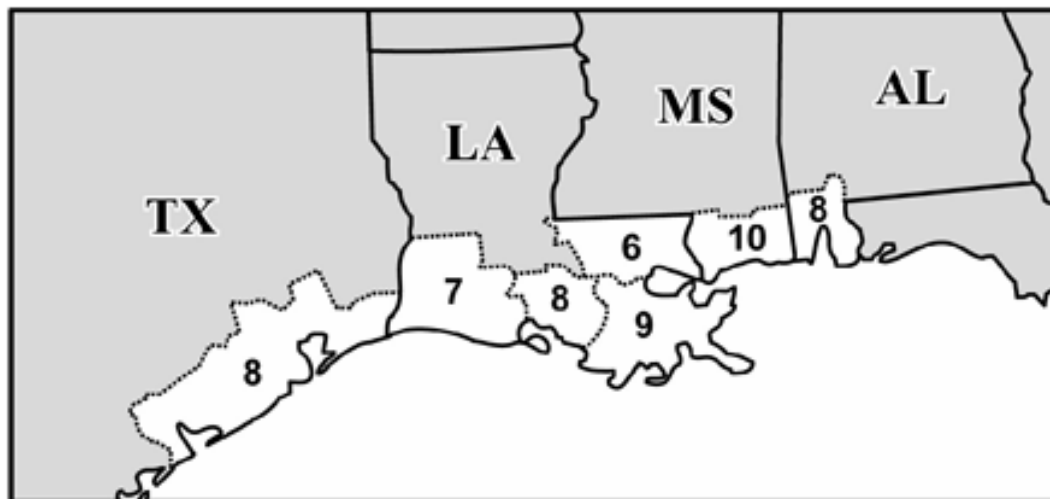
**Table 3.18 SLRRP model parameters and results showing the mean sea level rise projections for the Gulf Coast region by 2050 and 2100 under a high, mid, and low scenario based on combined output for all 7 GCM models for the A1F1 emission scenario.**

Model Parameters	Scenarios	Louisiana-Texas Chenier Plain	Louisiana Deltaic Plain	Mississippi- Alabama Sound
Tide Gage		Galveston, Texas	Grand Isle, Louisiana	Pensacola, Florida
Sea Level Trend (mm/yr)		6.5	9.85	2.14
Subsidence (mm/yr)		4.7	8.05	0.34
Sea Level Rise by 2050 (cm, NAVD88)	High	94.8	119.6	59.8
	Mid	88.9	113.6	53.9
	Low	83.0	107.5	48.0
Sea Level Rise by 2100 (cm, NAVD88)	High	161.3	199.6	114.5
	Mid	146.0	185.3	99.2
	Low	130.7	171.2	83.9

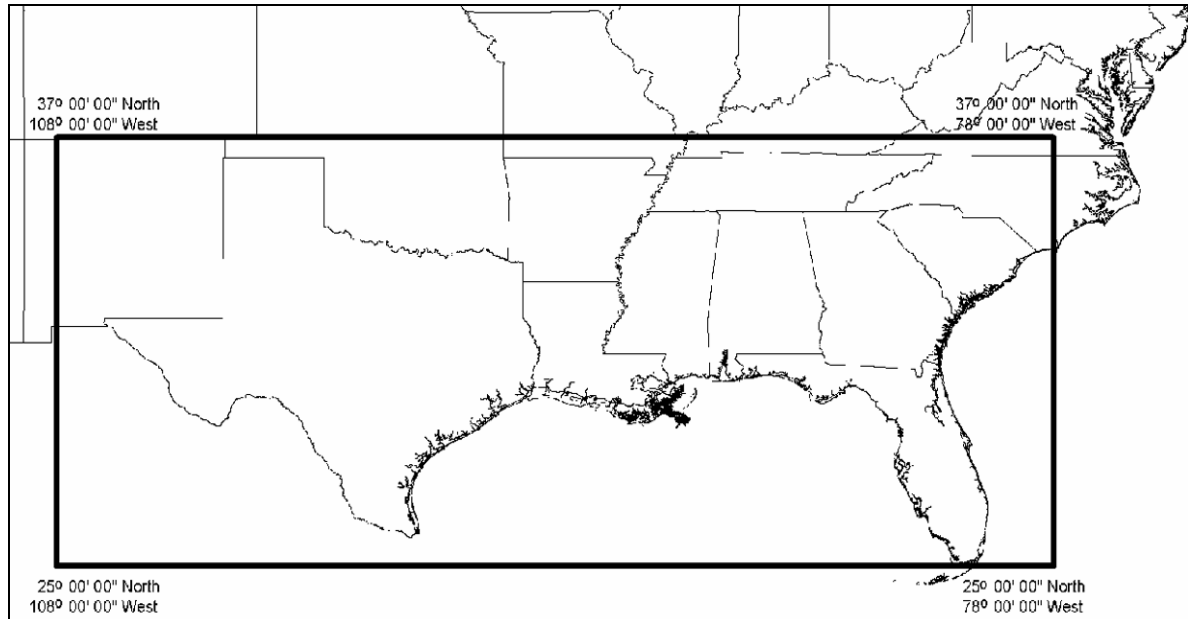
**Figure 3.1** CO<sub>2</sub> emissions, SO<sub>2</sub> emissions, and atmospheric CO<sub>2</sub> concentration through 2100 for the six “Marker/Illustrative” SRES scenarios and the IS92a scenario (a “business as usual” scenario, IPCC (1992)). (Source: IPCC 2001)



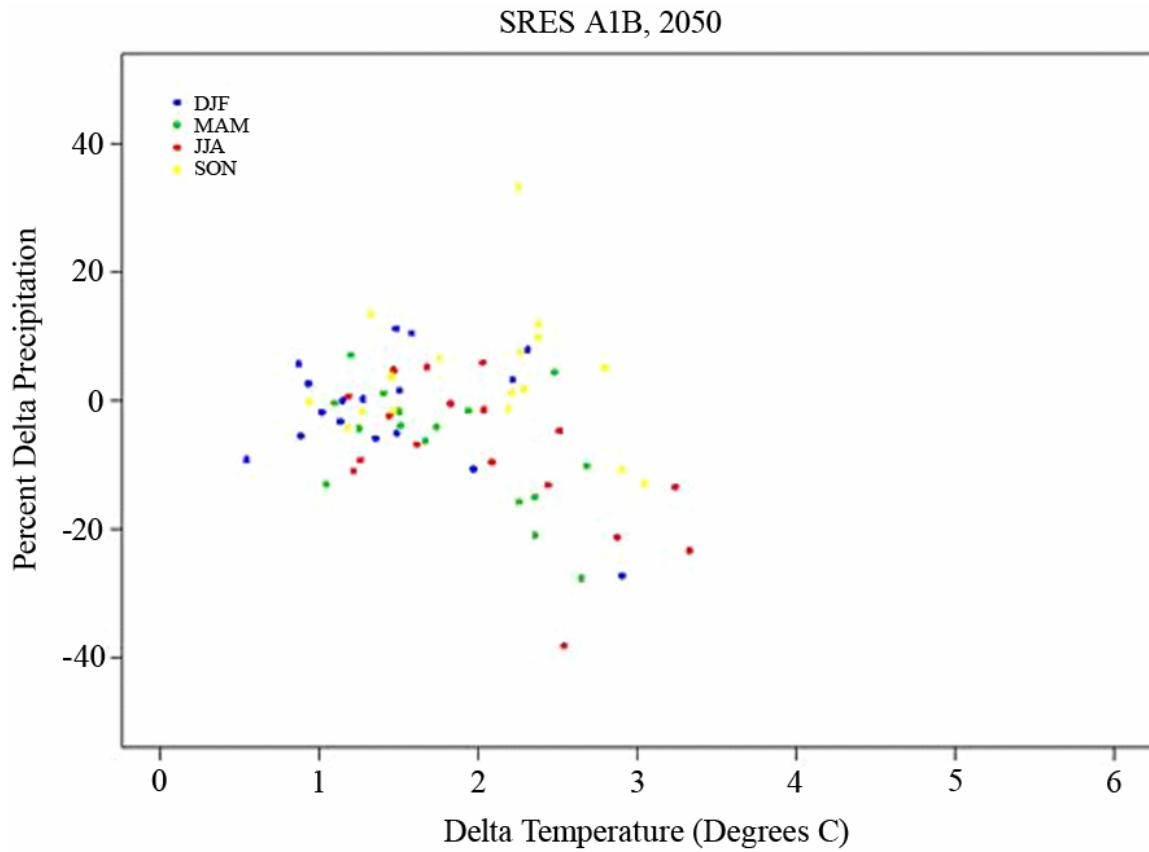
**Figure 3.2** United States Climate Divisions of the central Gulf Coast study area. Empirical trends and variability were analyzed for temperature and precipitation at the Climate Division Dataset (CDD) level for the climate divisions along the Gulf Coast from Galveston to Mobile, including Texas Climate Division 8, Louisiana Divisions 6-9, Mississippi Division 10, and Alabama Division 8. These climatic divisions cover the entire central Gulf Coast study area.



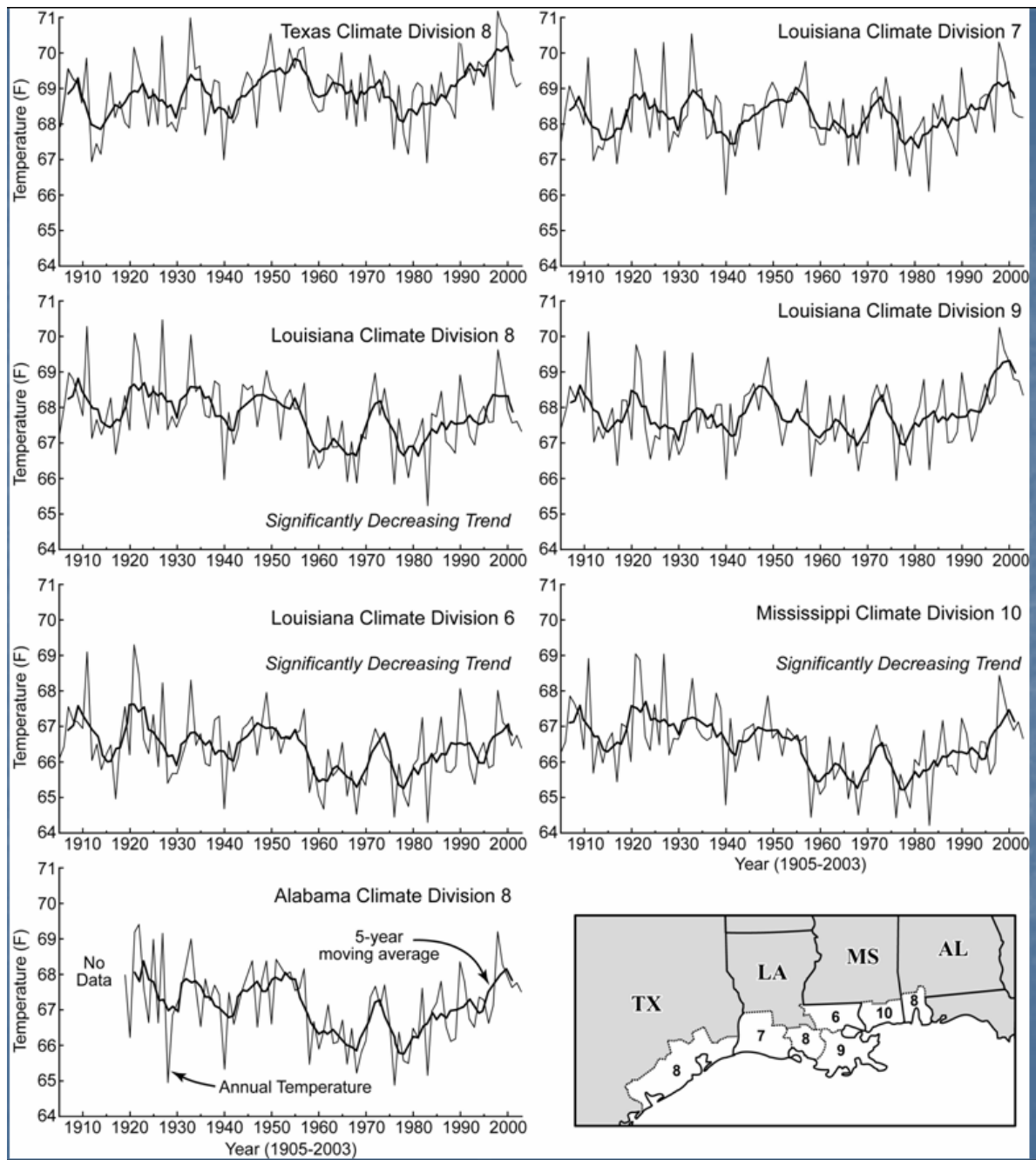
**Figure 3.3** Grid area for the GCM temperature and precipitation results presented in Section 3.15 of this report, which is a subset of the global grid of a typical GCM output.



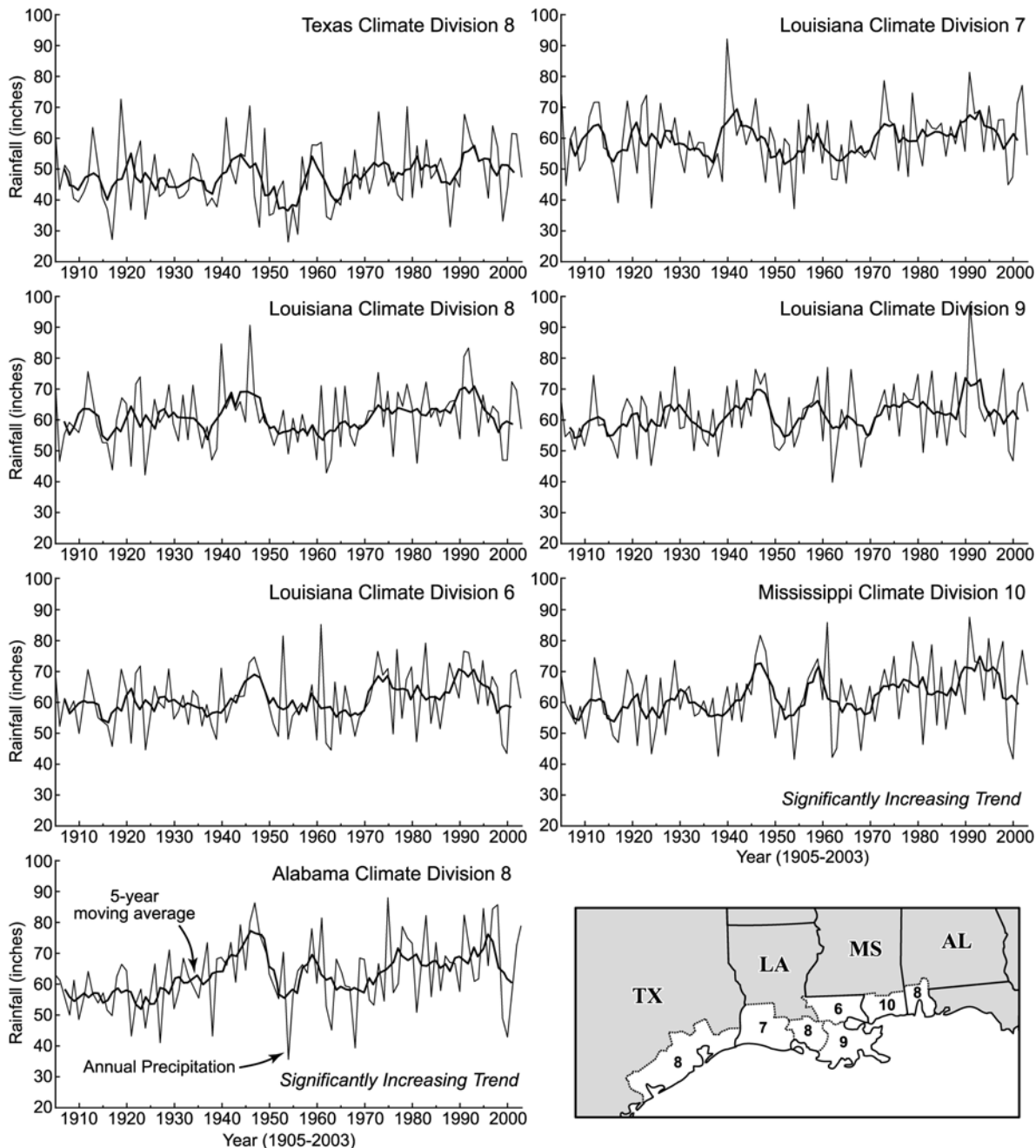
**Figure 3.4** Scatterplot of seasonal temperature and precipitation predictions by an ensemble of GCMs for the Gulf Coast region in 2050 using the SRES A1B emissions scenario.



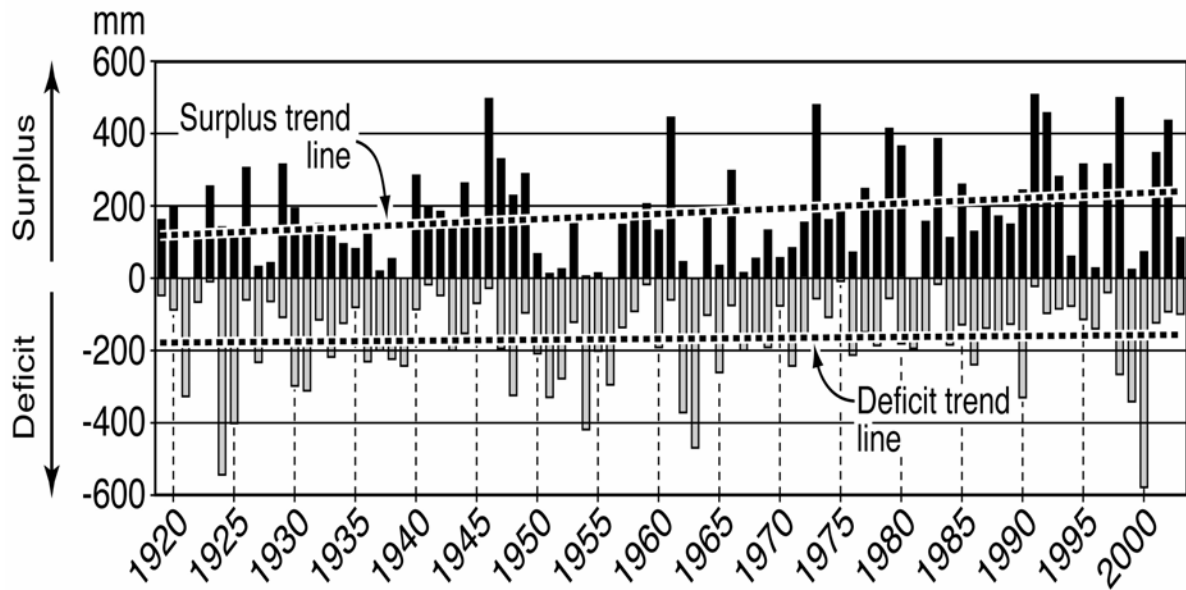
**Figure 3.5** Temperature variability from 1905-2003 for the 7 Climate Divisions making up the Gulf Coast study area.



**Figure 3.6** Precipitation variability from 1905 to 2003 for the seven Climate Divisions making up the Gulf Coast study area.

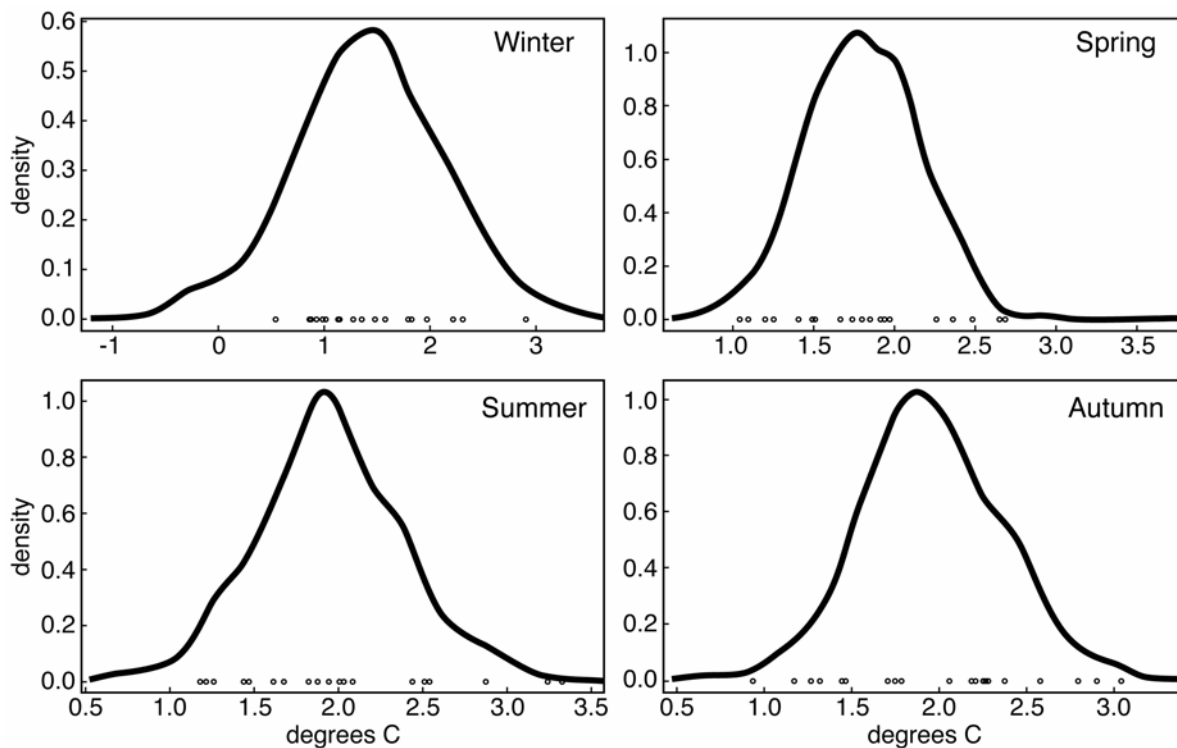


**Figure 3.7** Variability and trends in model-derived surplus (runoff) and deficit from 1919 to 2003 for the Gulf Coast study area.

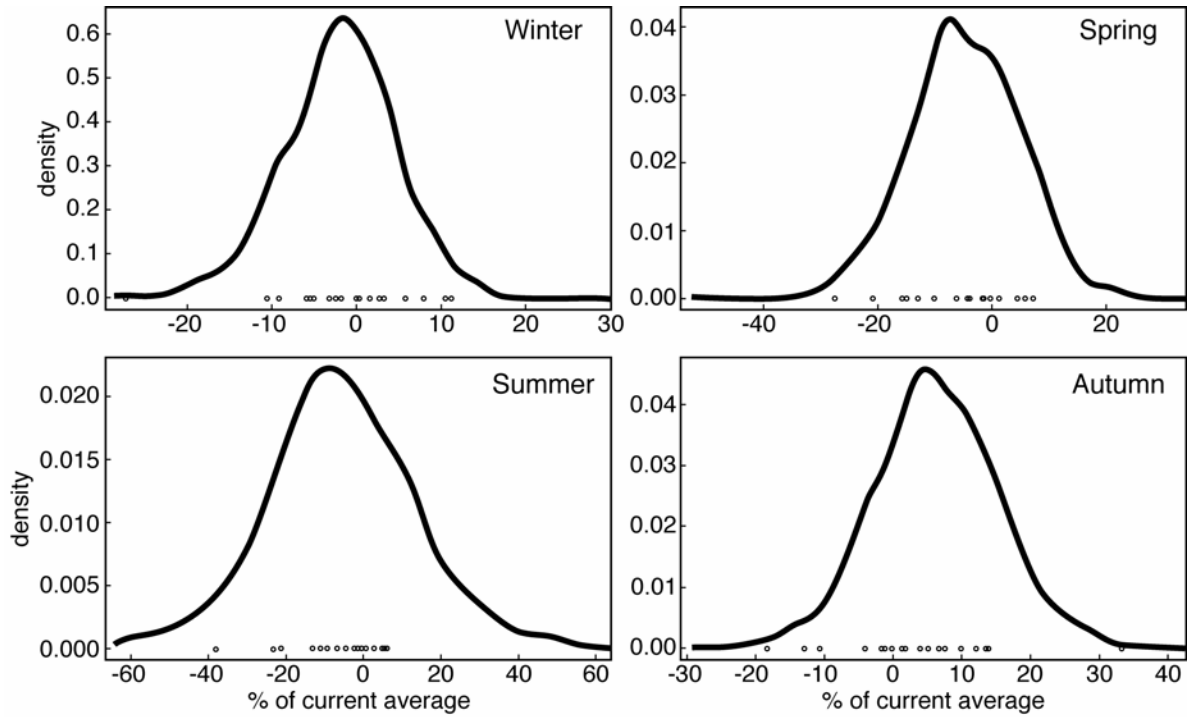




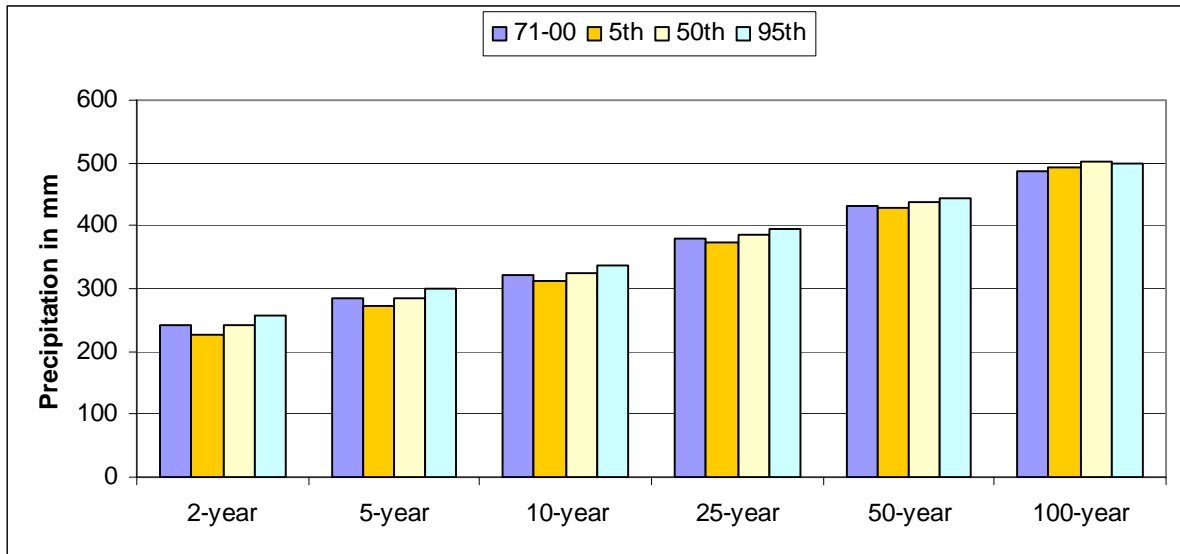
**Figure 3.8** Probability density functions for seasonal temperature change (in °C) in the Gulf Coast study area for 2050 using the A1B emissions scenario.



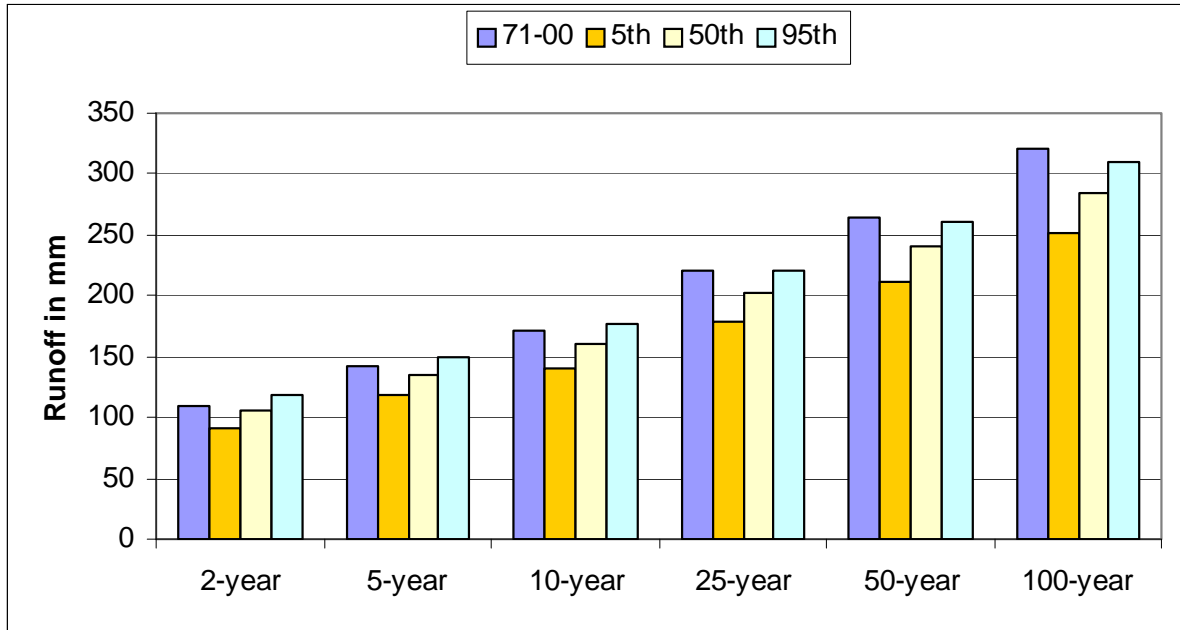
**Figure 3.9** Probability density functions for seasonal precipitation change (in percent) in the U.S. Gulf Coast study area for 2050 using the A1B emissions scenario.



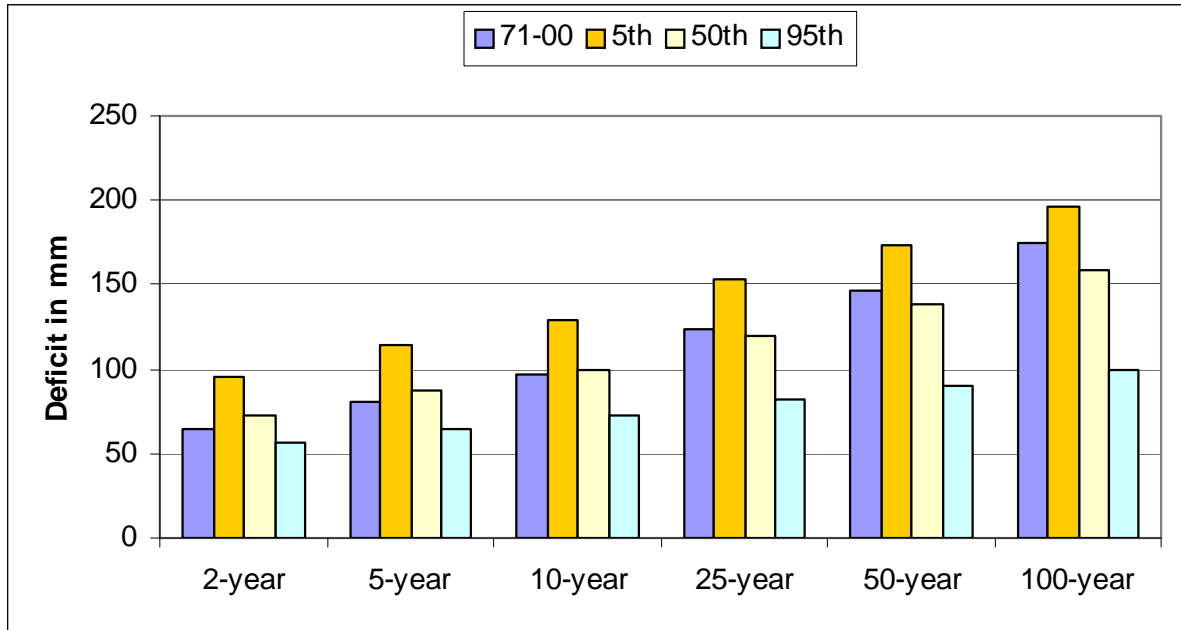
**Figure 3.10** Quantile estimates of monthly precipitation for the 2- to 100-year return period using the 1971 to 2000 baseline period relative to GCM output for the A1B emissions scenario at the 5%, 50%, and 95% quartiles.



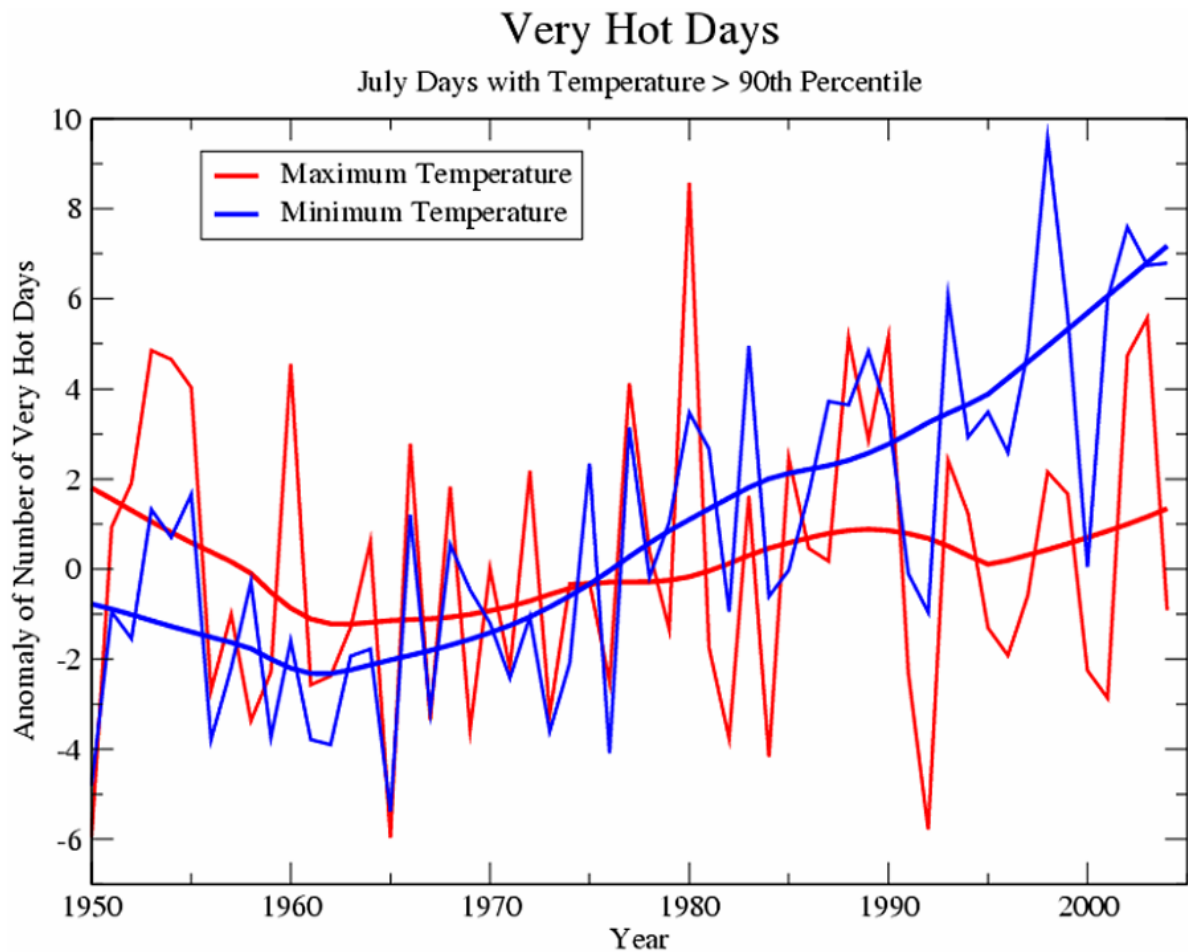
**Figure 3.11** Quantile estimates of monthly average runoff for the 2- to 100-year return period using the 1971 to 2000 baseline period relative to GCM output for the A1B emissions scenario at the 5%, 50%, and 95% quartiles.



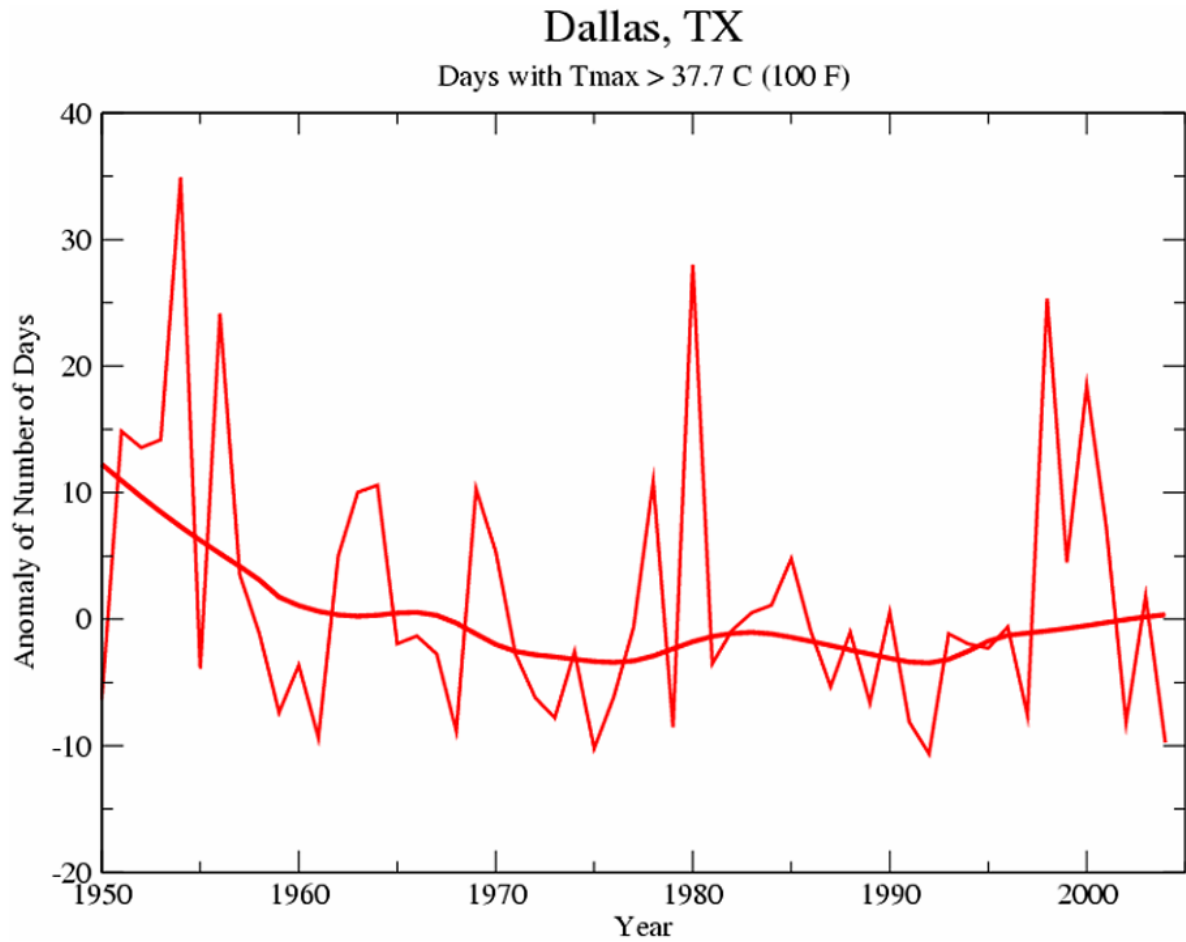
**Figure 3.12** Quantile estimates of monthly average deficit for the 2- to 100-year return period using the 1971 to 2000 baseline period relative to GCM output for the A1B emissions scenario at the 5%, 50%, and 95% quartiles.



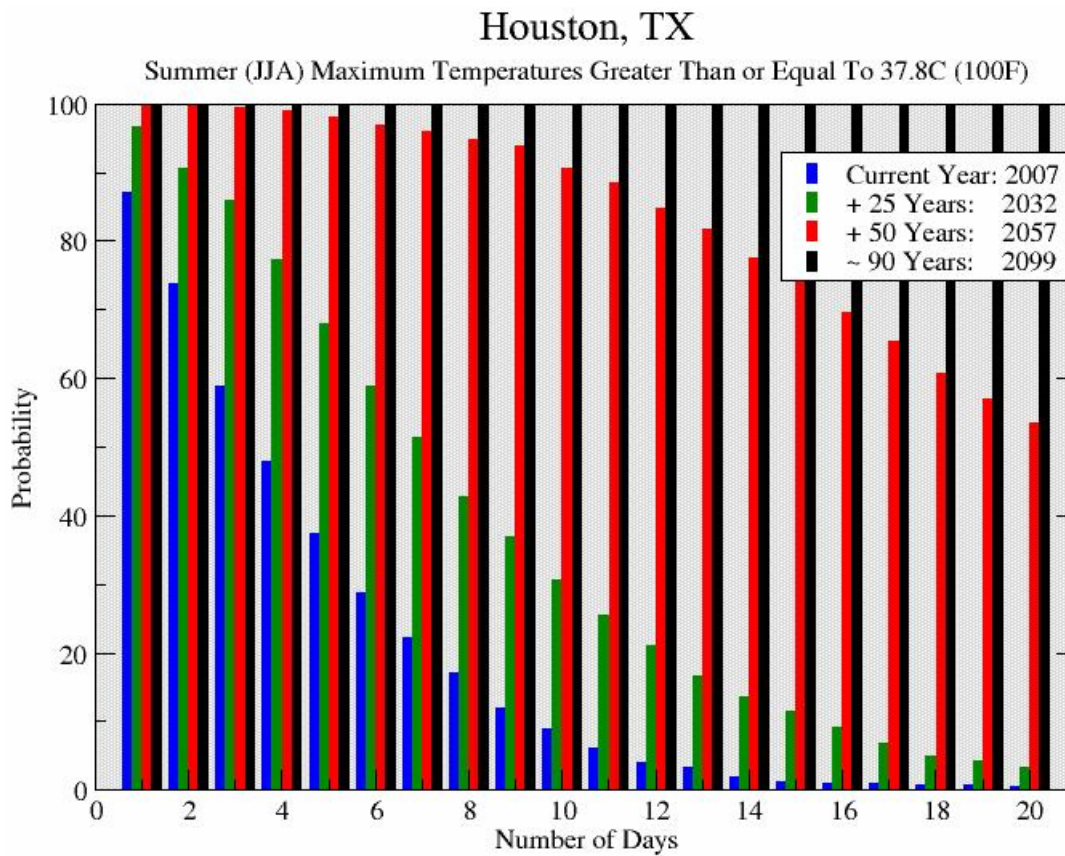
**Figure 3.13** The change in the warmest 10% of July maximum and minimum temperatures at each station across the entire United States, for 1950-2004. Note the number of days above the 90<sup>th</sup> percentile in minimum temperature is rising faster than maximum temperature.



**Figure 3.14** Historical time series from stations within 500 km of the Dallas, Texas showing anomalies of the number of days above 37.7°C (100°F), for 1950-2004.

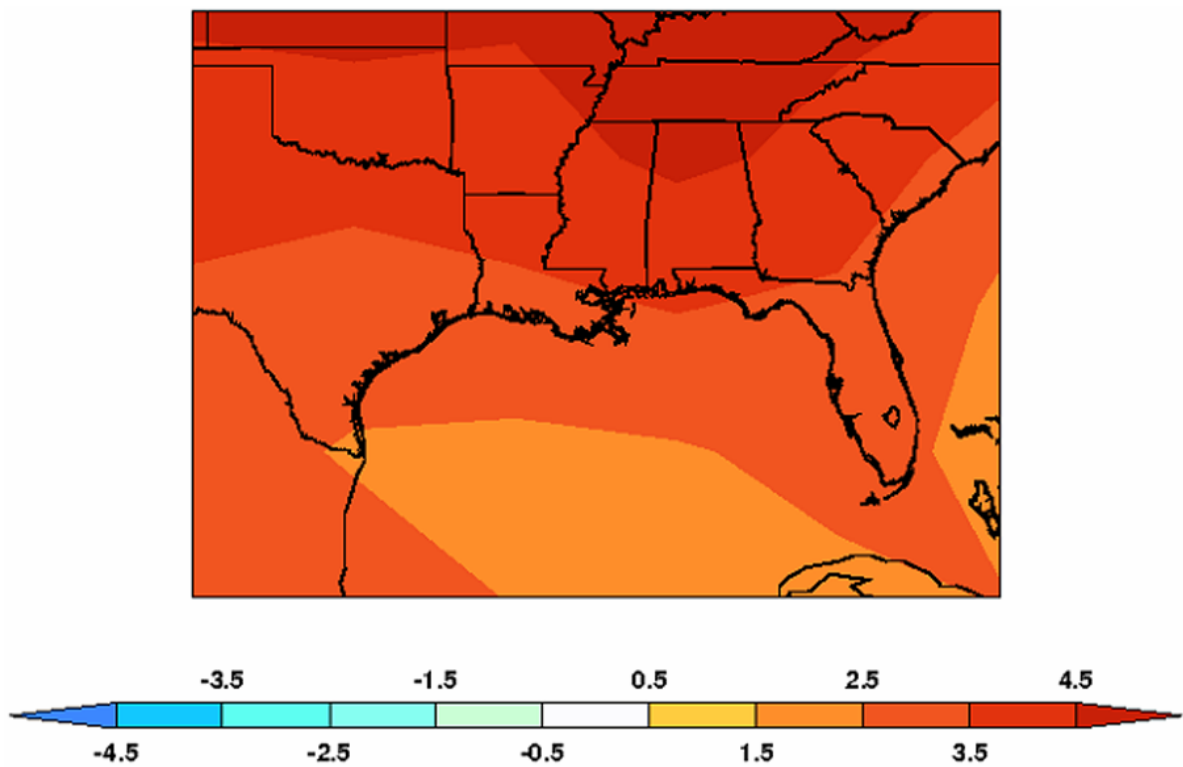


**Figure 3.15** The current and future probabilities of having one to twenty days during the summer at or above 37.8°C (100°F) in or near Houston, Texas under the A2 emissions scenario.

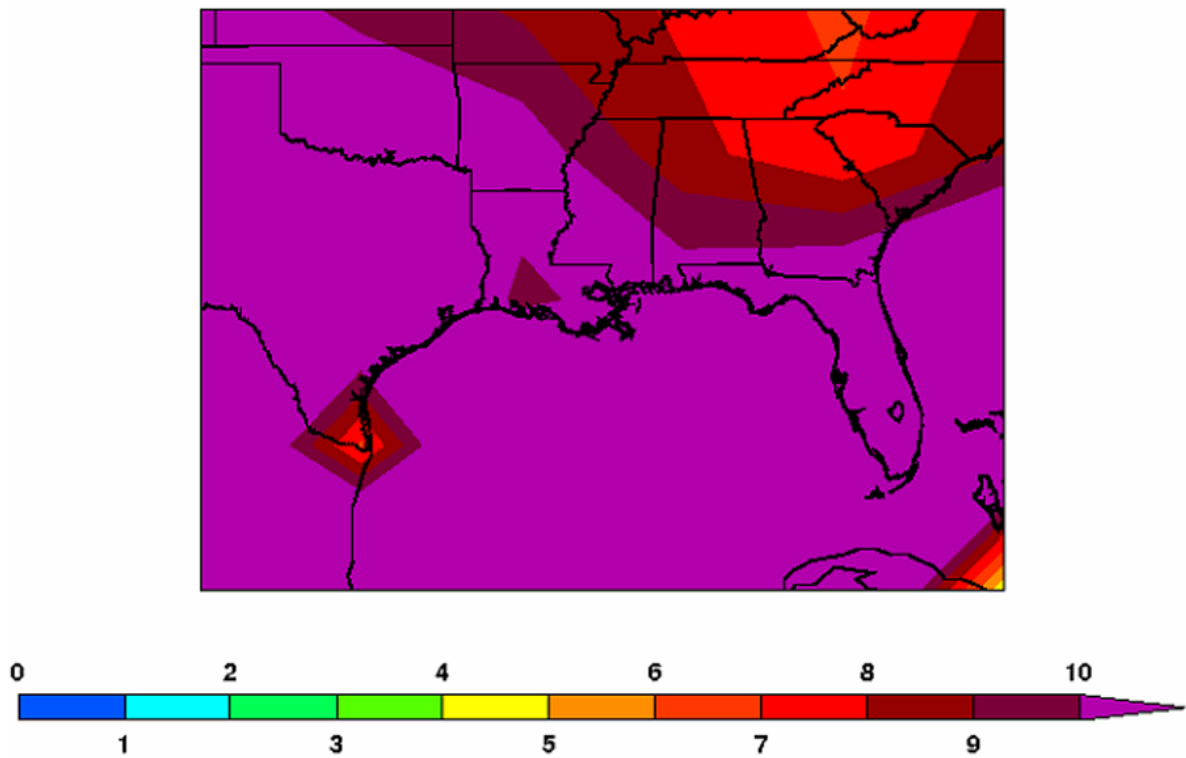




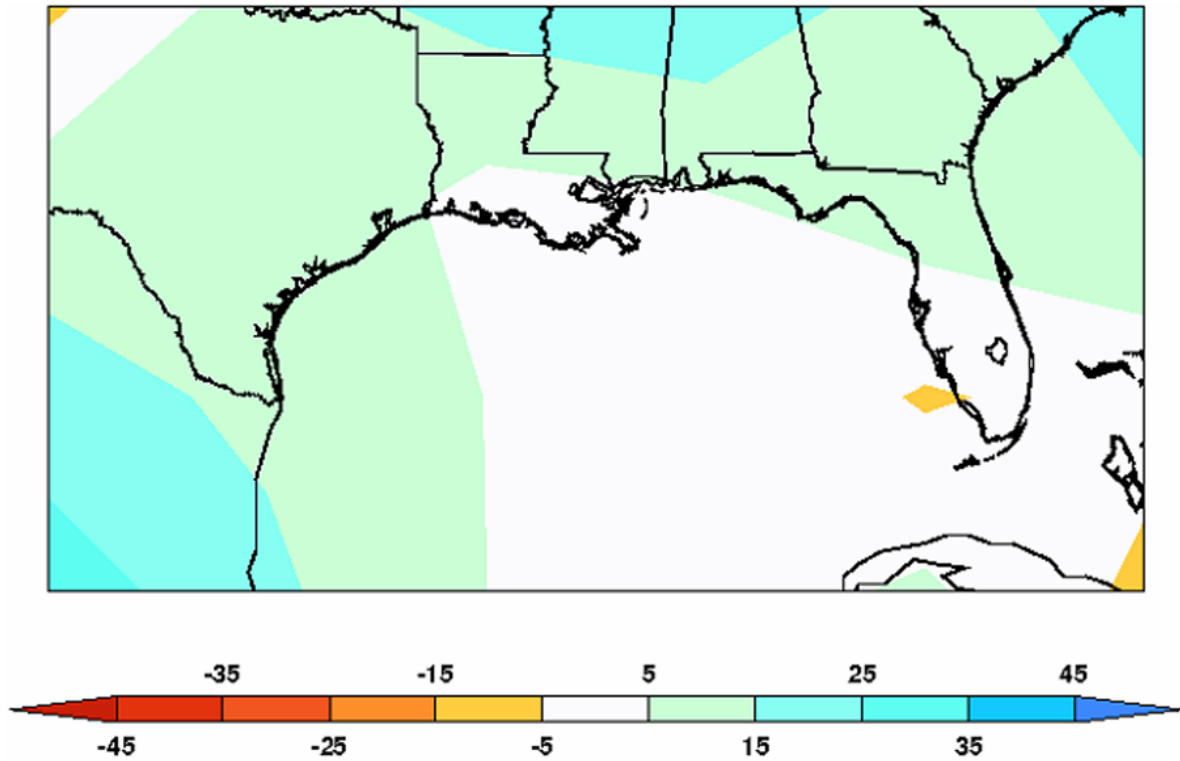
**Figure 3.16** Mean model predicted change (Celsius) of the 20-year return value of the annual maximum daily averaged surface air temperature under the A1B emissions scenario in the Gulf States region. This analysis compares the 1990-1999 period to the 2090-2099 period.



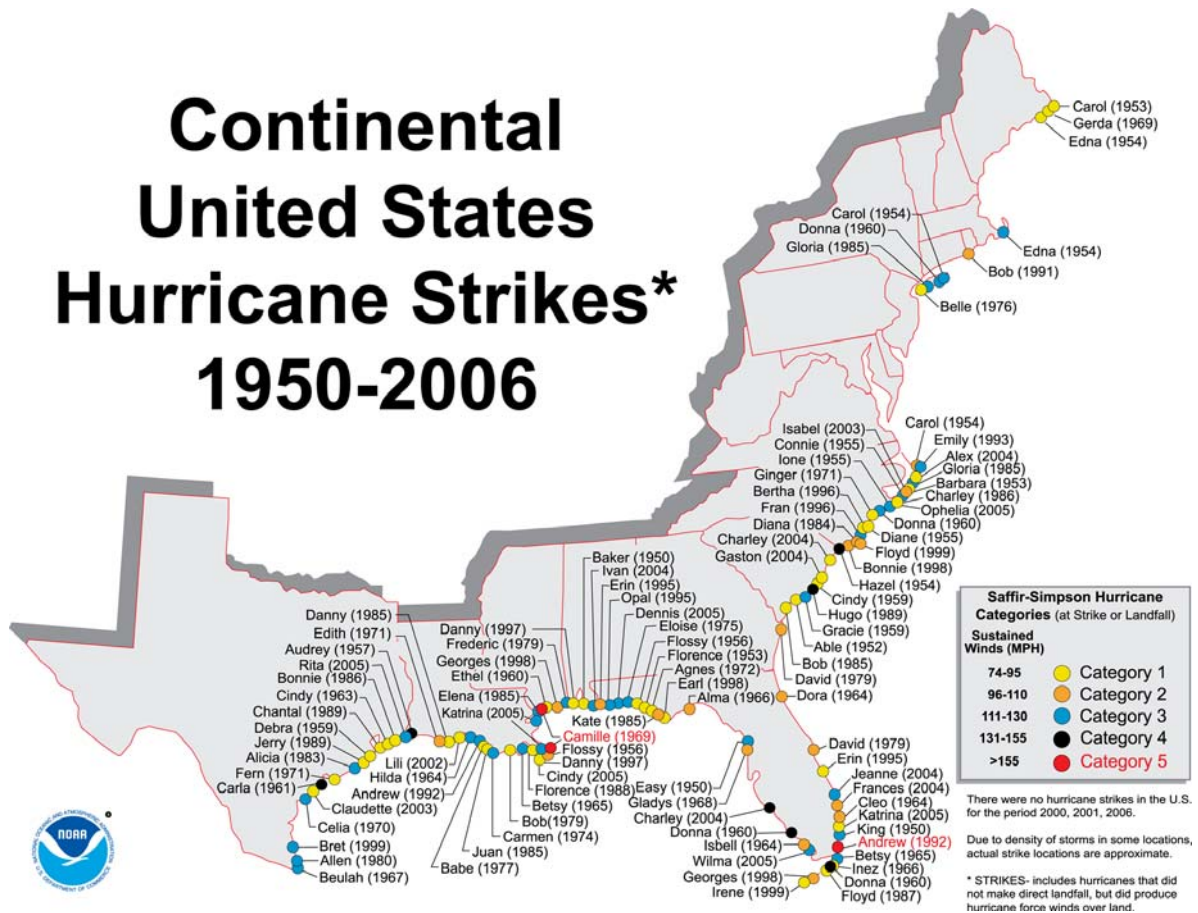
**Figure 3.17** Number of times on average over a 20-year period that the 1990-1999 annual maximum daily averaged surface air temperature 20-year return value levels would be reached under the SRES A1B 2090-2099 forcing conditions over 20 years. Under 1990-1999 forcing conditions, this value is defined to be one.



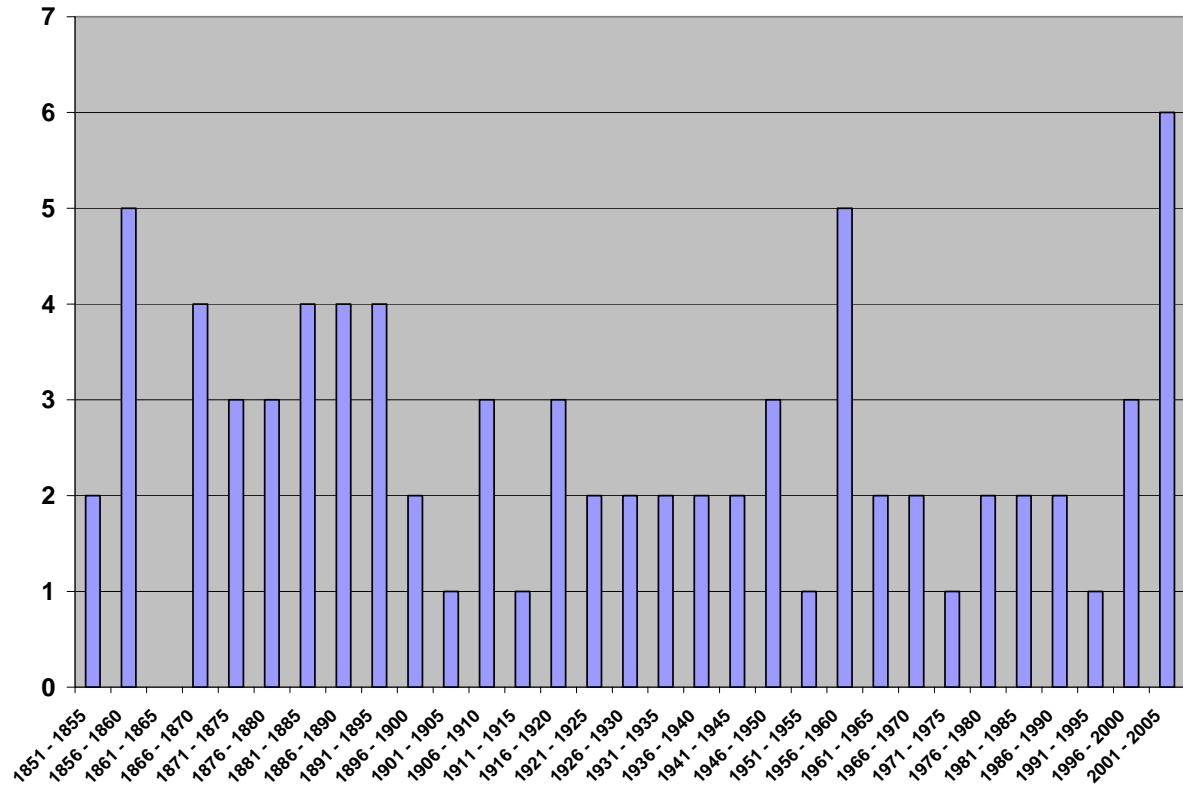
**Figure 3.18** Mean model predicted fractional change of the 20-year return value of the annual maximum daily averaged precipitation under the SRES A1B in the Gulf States region. This analysis compares the 1990-1999 period to the 2090-2099 period.



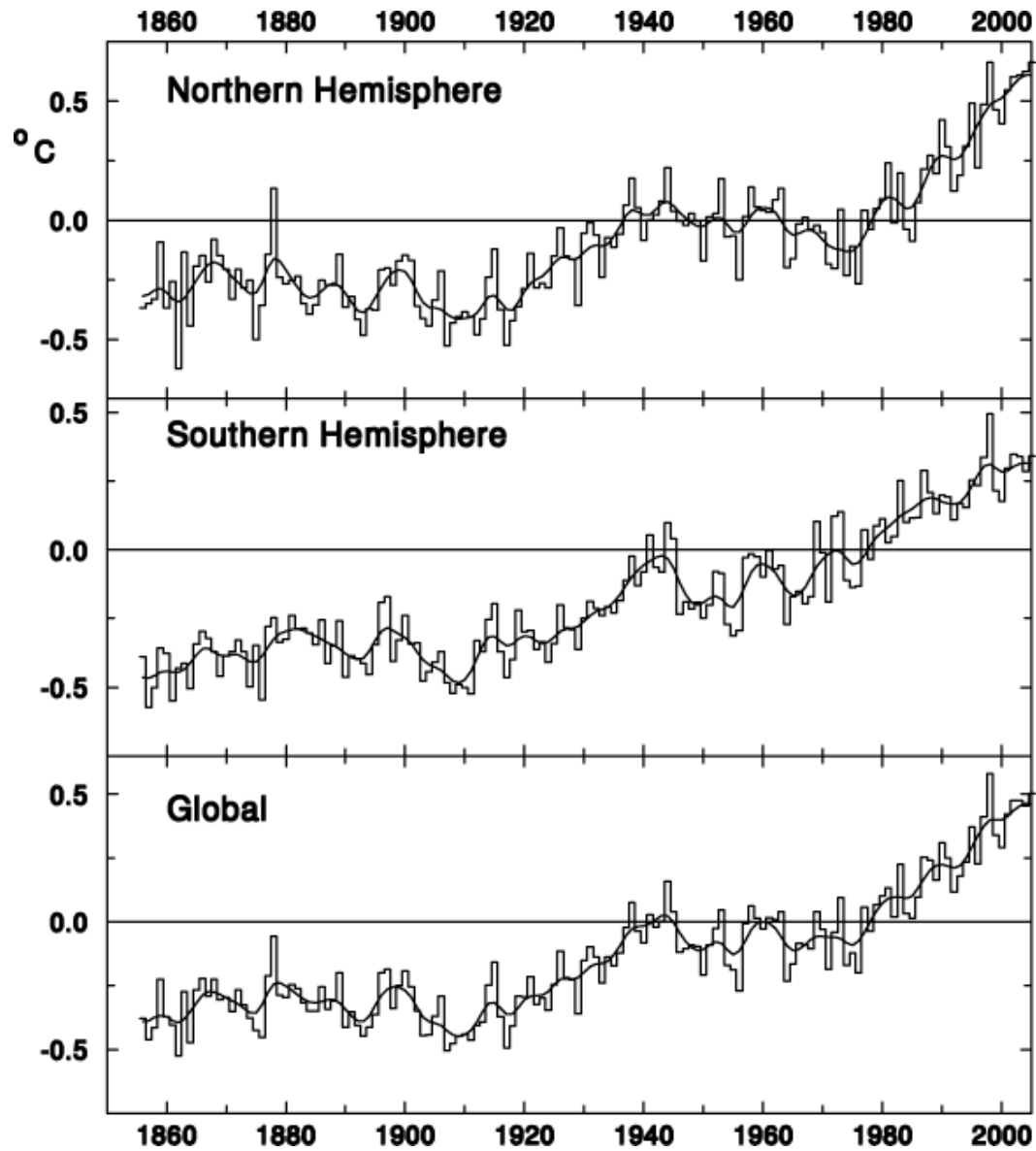
**Figure 3.19 Geographic distribution of hurricane landfalls along the Atlantic and Gulf Coast region of the U.S., from 1950 to 2006. (Source: NOAA, National Climate Data Center, Asheville, N.C.)**



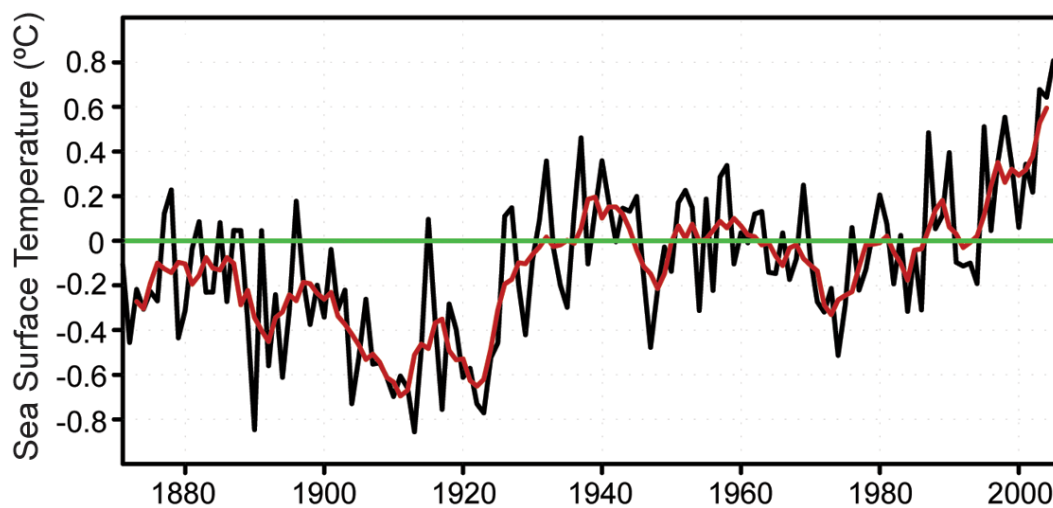
**Figure 3.20** Frequency histogram of landfalling storms of tropical storm strength or greater in Grand Isle, Louisiana summarized on a 5 year basis, for the period 1851-2005. (Source: NOAA National Hurricane Research Division)



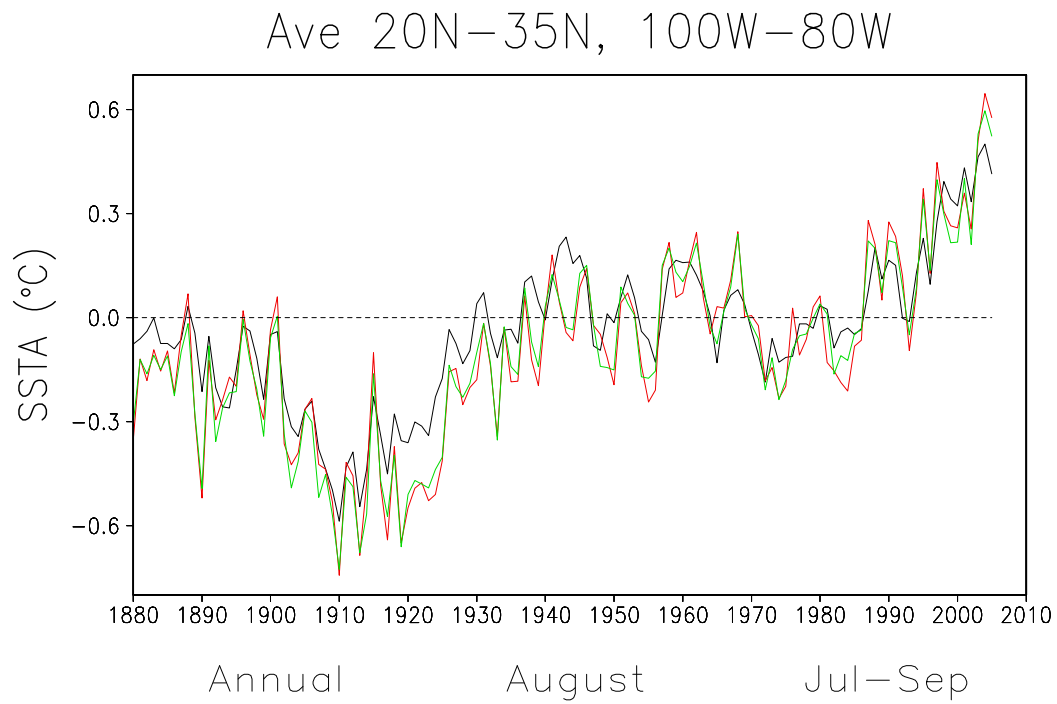
**Figure 3.21 Hemispherical and global mean sea-surface temperatures for the period of record 1855 to 2000. (Source: NOAA, National Climate Data Center, Asheville, N.C.)**



**Figure 3.22** Sea surface temperature trend in the main hurricane development region of the North Atlantic during the past century. Red line shows the corresponding 5-yr running mean. Anomalies are departures from the 1971–2000 period monthly means. (Source: Bell *et al.* 2007)

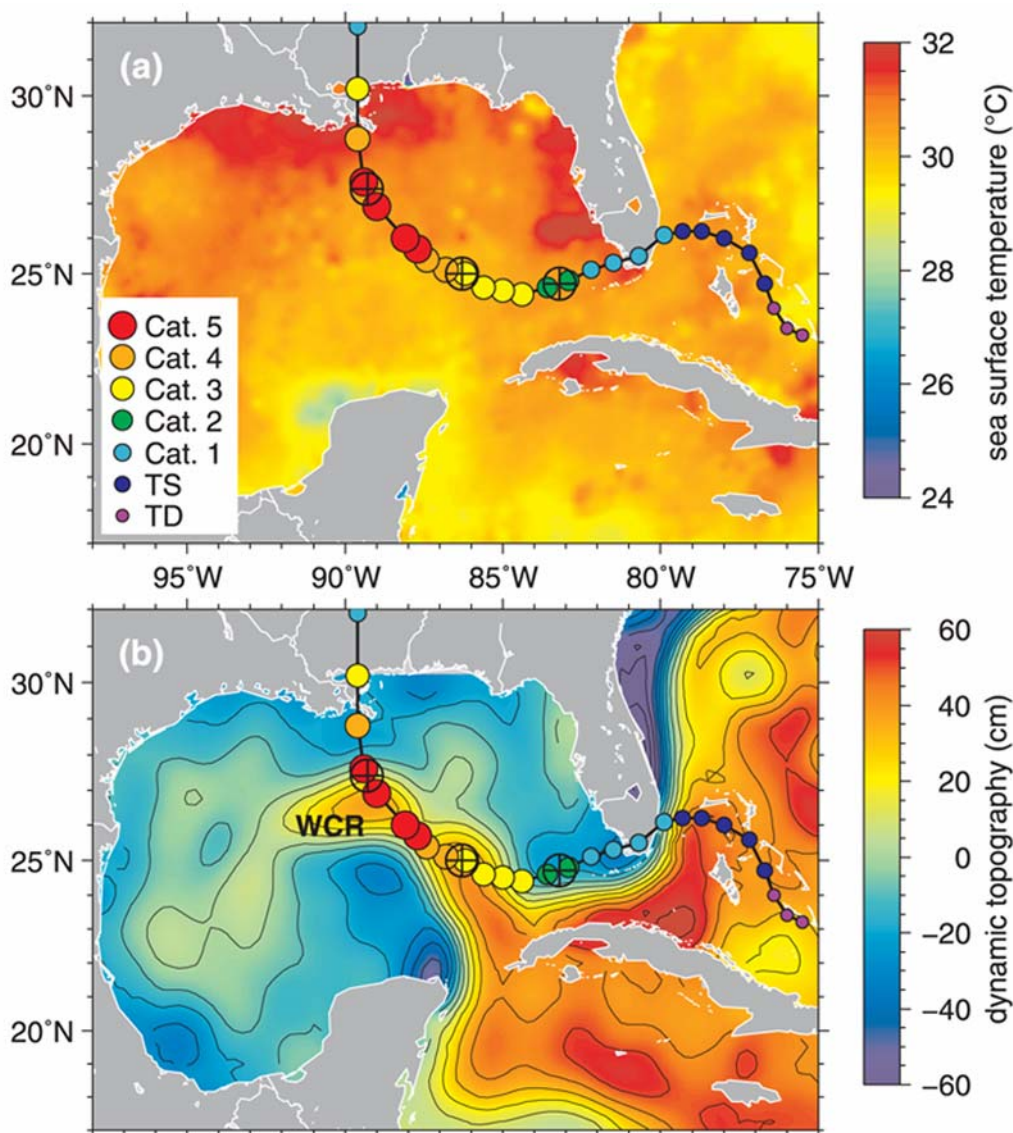


**Figure 3.23** Sea surface temperature trend in the Gulf of Mexico region produced using the ERSST v.2 database. The plot includes the SST anomalies averaged annually, as well as the anomalies determined from the averages for August only and the July-September peak of the hurricane season. (Source: Smith and Reynolds, 2004)

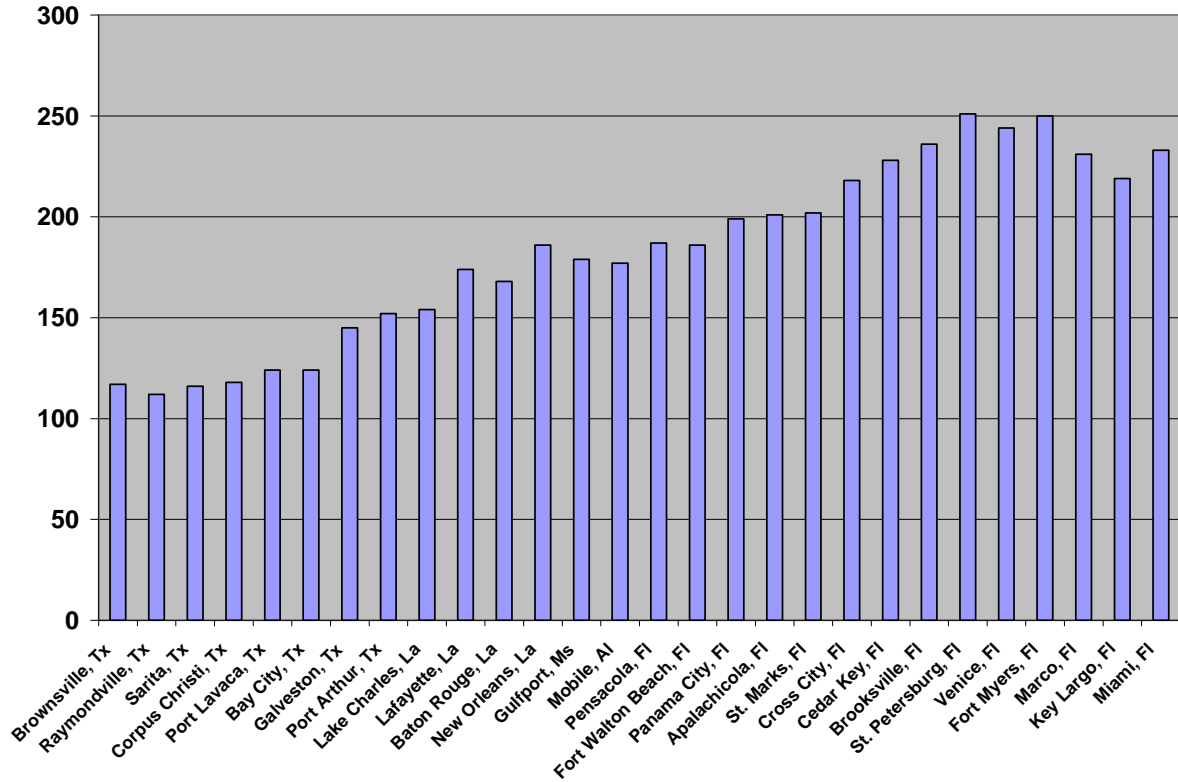




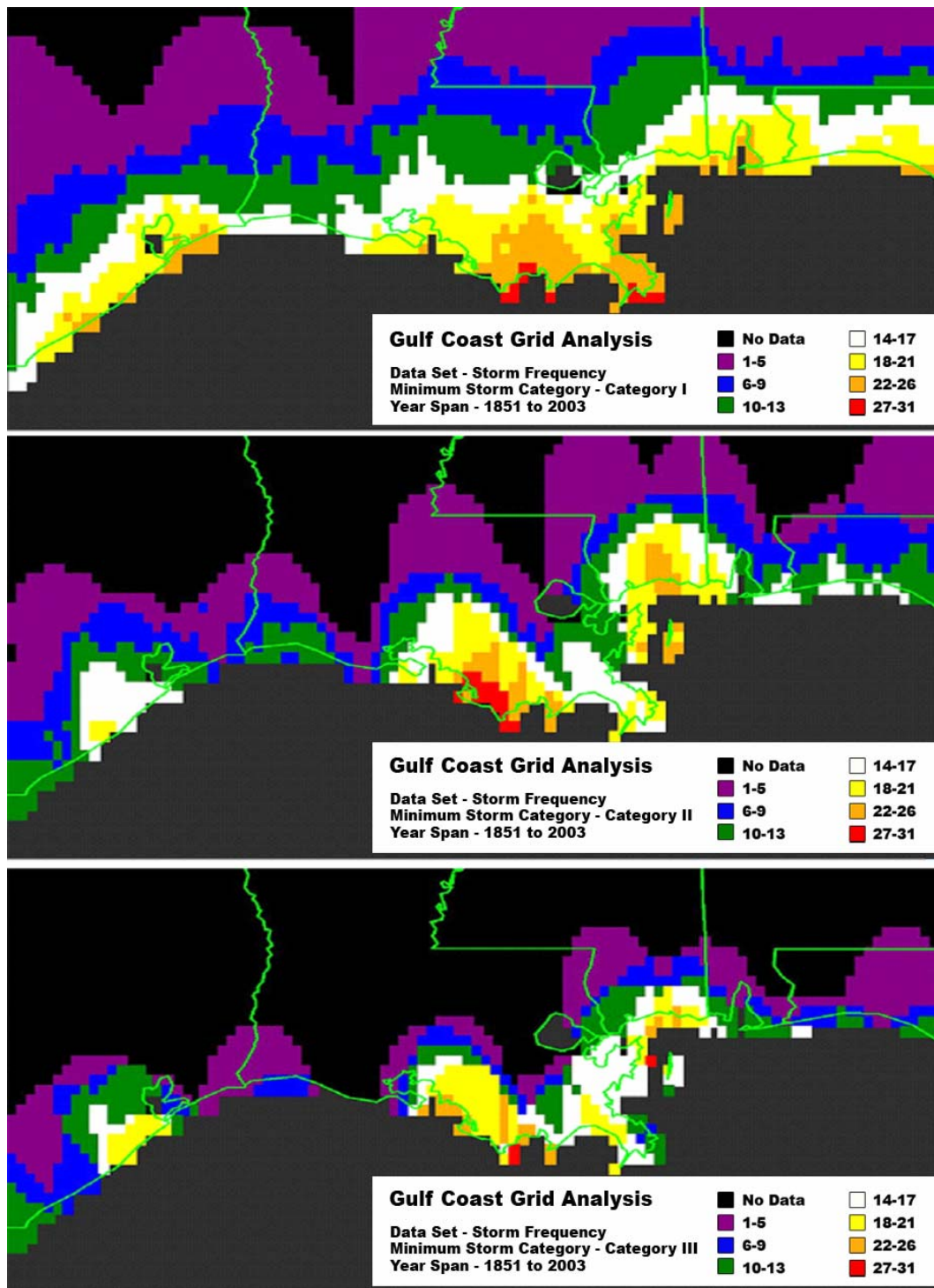
**Figure 3.24** The location and intensity of Katrina at intervals of six hours show two intensification events. Circles indicate data from National Hurricane Center advisories showing storm intensity (TS and TD stand for tropical storm and tropical depression, respectively). (a) Intensification is not correlated with sea surface temperature (from POES high-resolution infrared data). (b) In contrast, the intensifications correlate well with highs in the ocean dynamic topography (from Jason 1, TOPEX, Envisat, and GFO sea surface height data). The Loop Current can be seen entering the Gulf south of Cuba and exiting south of Florida; the warm-core ring (WCR) is the prominent high shedding from the Loop Current in the center of the Gulf. (Source: Scharroo et al., 2005)



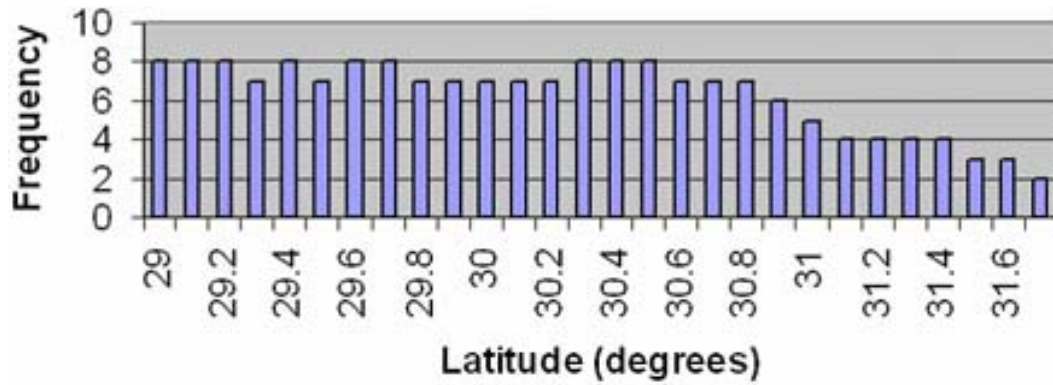
**Figure 3.25** Frequency histogram of tropical storm events for coastal cities across the Gulf of Mexico region of the United States over the period of record from 1851 to 2006.



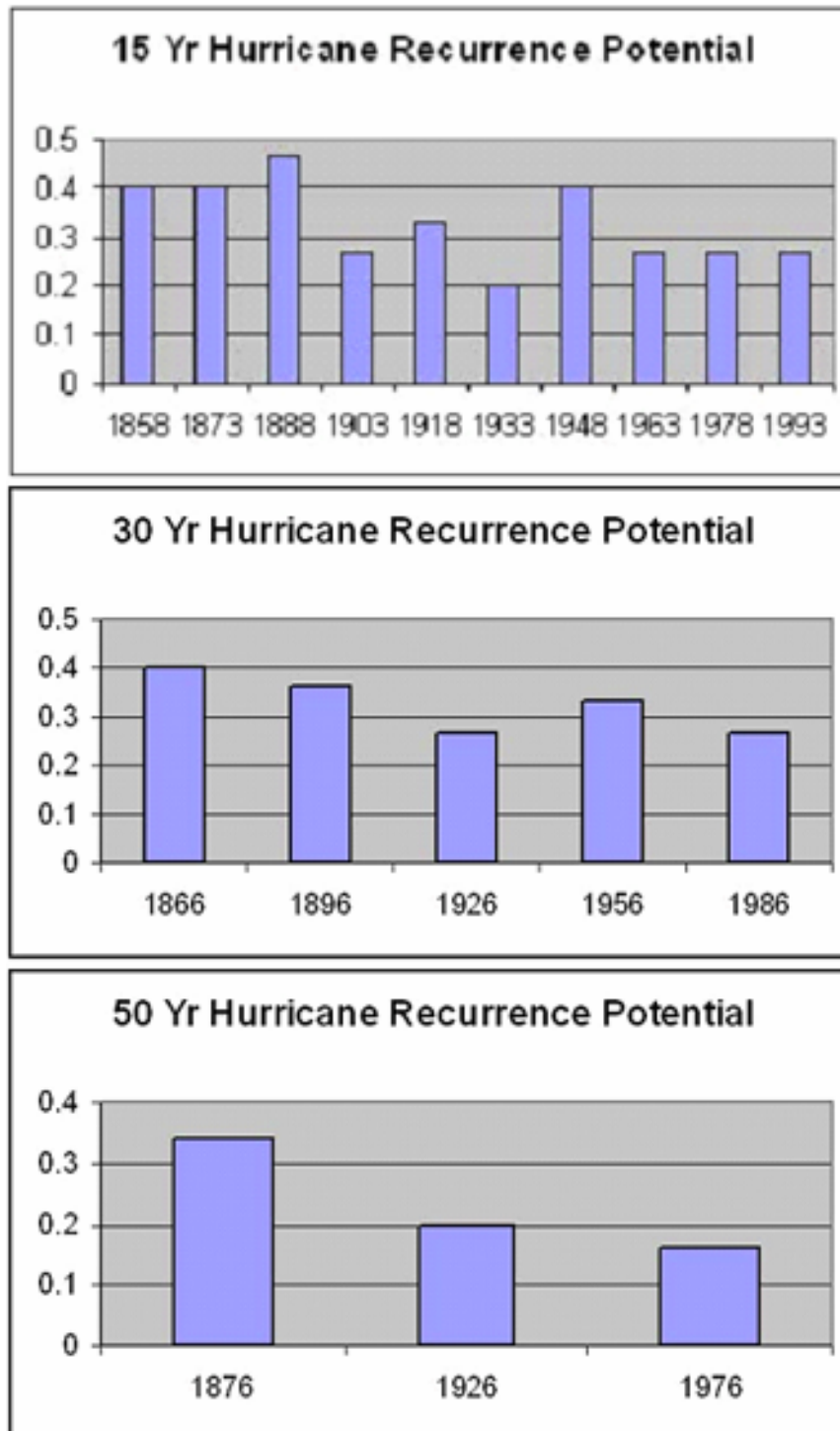
**Figure 3.26** Frequency analysis of storm events exhibiting Category 1, 2, and 3 winds or higher across the Gulf Coast study area.



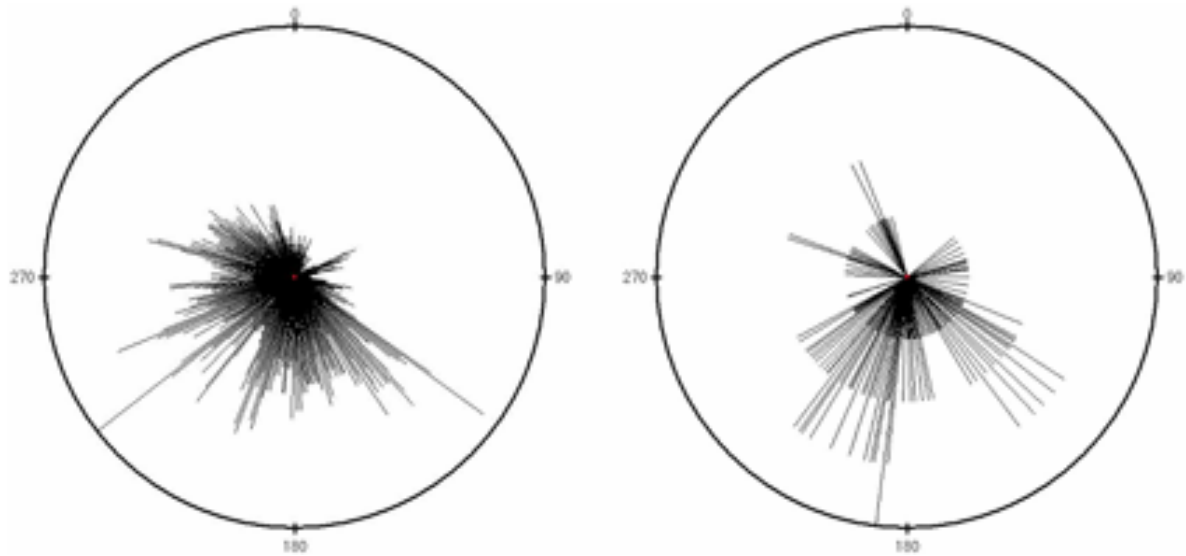
**Figure 3.27** Latitudinal gradient of declining storm frequency of Category 1 hurricanes or greater from Grand Isle, LA inland illustrating the reduction of storm strength overland away from the coast, for the period 1951-2000.



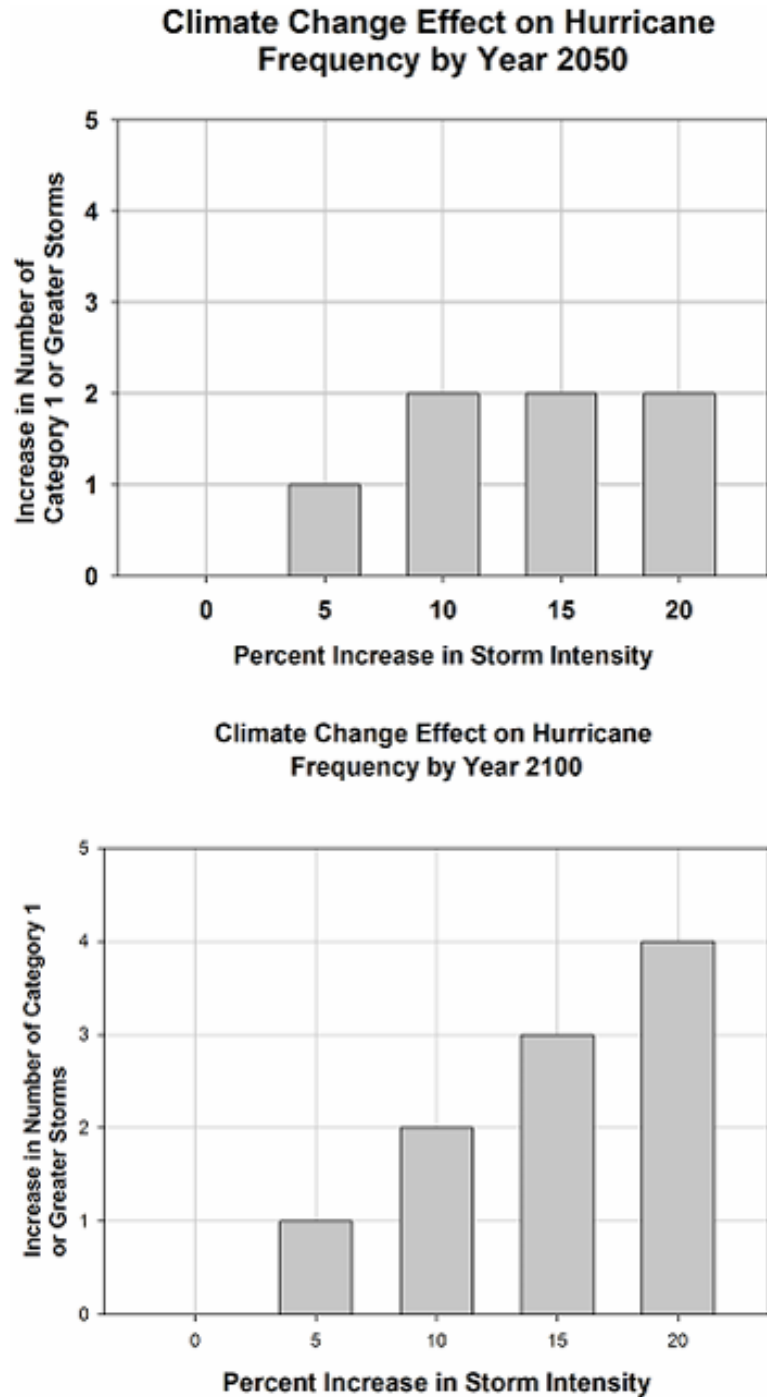
**Figure 3.28 15-, 30-, and 50-year hurricane recurrence potential. Storm frequency variation for 15, 30, and 50 year intervals for Category 1 storms or greater for the most active grid location across the Gulf Coast study region.**



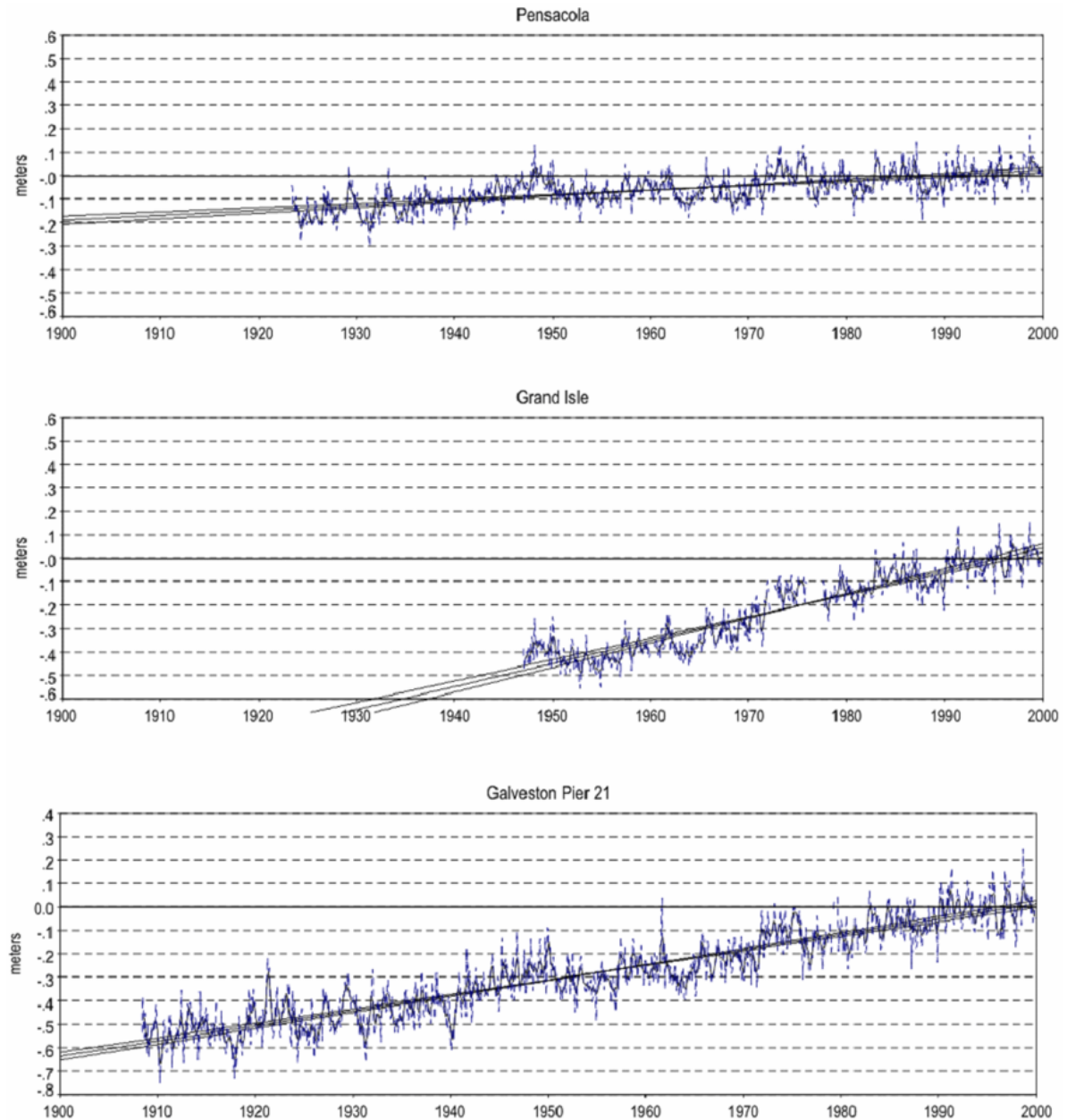
**Figure 3.29** Simulated wind rows and direction of wind force derived from the HURASIM Model for one of the most active grid cell locations in the study area at Grand Isle, LA for tropical storm and hurricane conditions over the 153-year period of record.



**Figure 3.30 Potential increase in the number of hurricanes by the year 2050 and 2100 assuming an increase in hurricane intensity concomitant with warming sea surface temperatures projected at 5%, 10%, 15%, and 20%.**

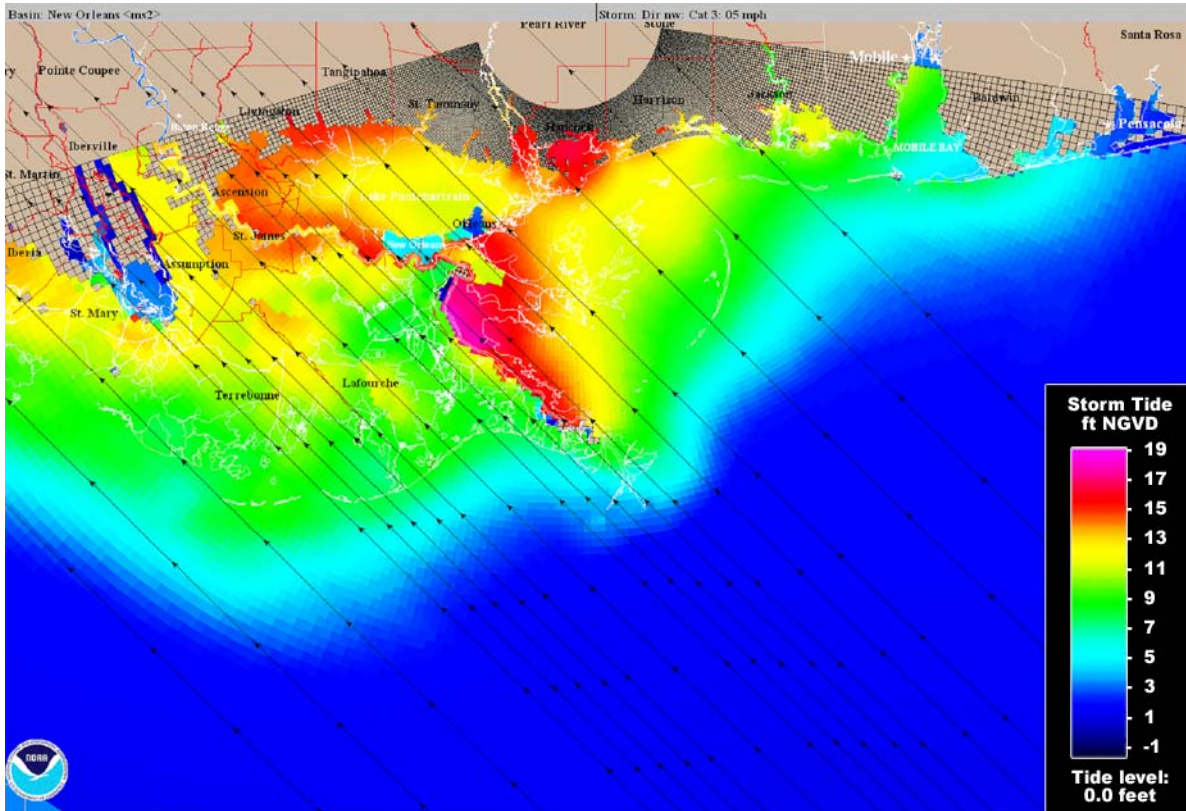


**Figure 3.31** Tide gauge records and mean sea level trend line for three northern Gulf Coast tide stations at Pensacola, FL, Grand Isle, LA, and Galveston, TX corresponding with the eastern, central, and western coverage of the study area (1900-2000).

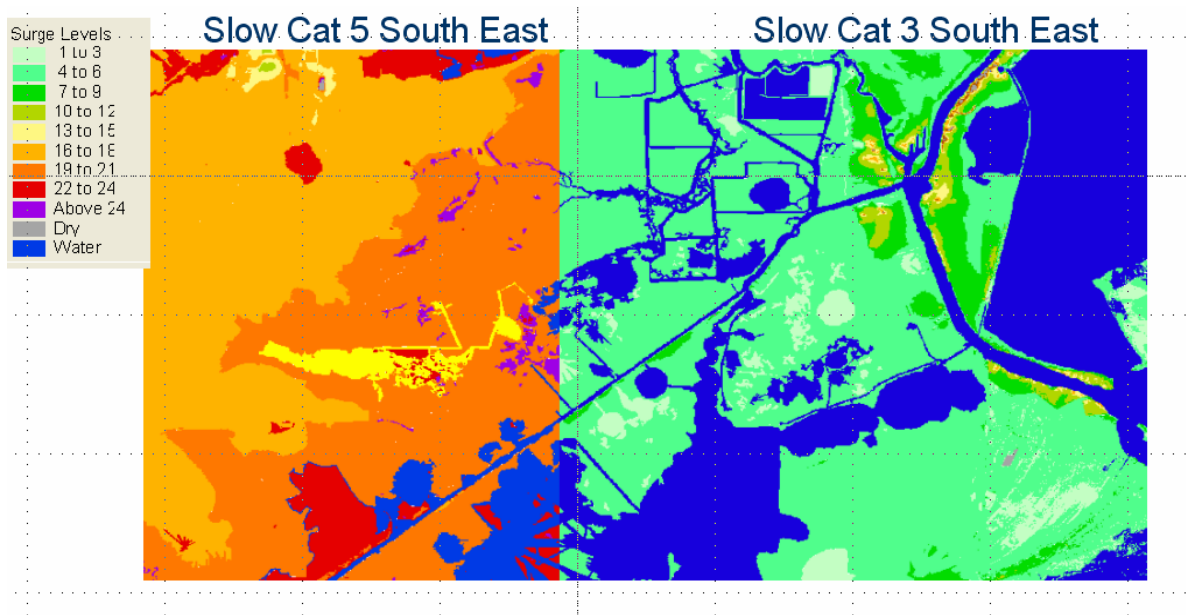




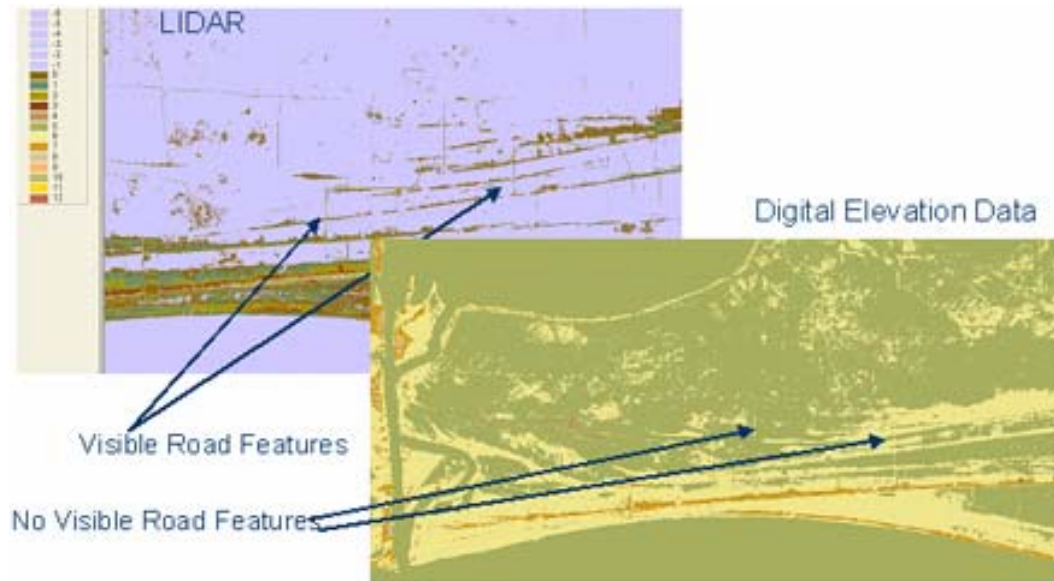
**Figure 3.32** Merged results of Category 2 through 5 hurricane surge simulations of slow moving storm approaching from the southeast (toward northwest in database), using SLOSH model simulations.



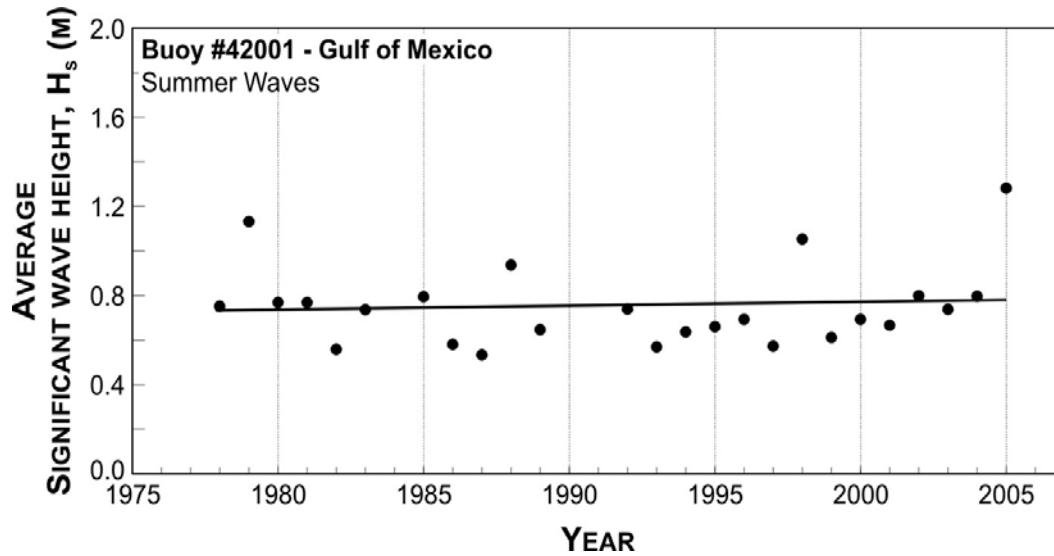
**Figure 3.33** Color schemes illustrate the difference in surge inundation between a Category 3 and Category 5 storm approaching the southeastern Louisiana coast from the southeast.



**Figure 3.34 Comparison of Lidar and National Digital Elevation Data (DEM) for eastern Cameron Parish, Louisiana. The advantages of using a LiDAR-derived topography are many, particularly as the effects of climate change are likely to be subtle in the short-term but significant for this low-lying coast where 1 foot of added flooding will impact a large land area.**



**Figure 3.35** Trend in summer wave height (1978-2005) in the mid-Gulf of Mexico. (Figure source: Komar and Allan, 2008; data source: National Buoy Data Center, NOAA, Stennis, Mississippi)



# 4.0 What are the Implications of Climate Change and Variability for Gulf Coast Transportation?

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The major climate drivers discussed in Chapter 3.0 have significant implications for the transportation system in the Gulf Coast region. This chapter provides an overview, in Section 4.1, of the impacts of climate change on the region's transportation infrastructure. It starts with a summary organized around the primary climate effects addressed in Chapter 3.0 (temperature, precipitation, sea level rise, and storm activity) and continues with a discussion of freight and private sector concerns. In Section 4.2, it shifts to a more detailed discussion organized by transportation mode; this subsection ends by summarizing and discussing freight and private sector concerns involving multiple modes. Finally, we use a series of case studies in Section 4.3 to illustrate some of the effects of the 2005 hurricanes on transportation.

Based on the analysis of the climate scenarios relayed in Chapter 3.0, climate change is likely to have the largest impact on highways, ports, and rail, particularly through sea level rise and storm surge. Temperature increases, particularly temperature extremes, are likely to increase energy consumption for refrigerated storage as well as rail and highway maintenance. Bridges, included in multiple modes, also could be affected by changes in precipitation, particularly through changes in peak stream flow. Changes in severe weather patterns (thunderstorms) or cloud cover could affect flight operations. See Tables 4.3 through 4.6 for summary statistics.

## ■ 4.1 Climate Drivers and their Impacts on the Transportation System

This section focuses on the main impacts on transportation facilities and features (e.g., bridges) resulting from the primary climate drivers: temperature, precipitation, sea level rise, and storm activity, and summarizes some of the issues that affect multiple modes.<sup>1</sup> While each climate factor has implications for the transportation network, relative sea level rise (RSLR) and storm activity have the potential to cause the most serious damage to transportation infrastructure in this study region. The relative significance of different climate factors will vary from region to region. The section closes with a look at key cross-modal issues, particularly private sector involvement and the potential for climate impacts in the Gulf Coast region to disrupt freight movements outside the study region.

As noted in Chapter 3.0, the climate impacts on transportation infrastructure assessed in this study rely on the combination of an understanding of historical climate trends and future projections from General Circulation Models (GCM). While model results imply that change will be gradual and linear, it should be noted that regional “surprises” are increasingly possible in the complex, nonlinear earth climate system (Groisman et al., 2004), which is characterized by thresholds in physical processes that are not completely understood or incorporated into climate model simulations, e.g., interactive chemistry, interactive land and ocean carbon emissions, etc. While there is still considerable uncertainty about the rates of change that can be expected (Karl and Trenberth, 2003), there is a fairly strong consensus concerning the direction of change for most of the climate variables that affect transportation in the Gulf Coast region.

### 4.1.1 Effects of Warming Temperatures

Based on the results presented in Chapter 3.0 for the Gulf Coast subset of the GCM runs performed for the IPCC Fourth Assessment Report (2007), the average temperature in the Gulf Coast region appears likely to increase by at least  $1.5^{\circ}\text{C} \pm 1^{\circ}\text{C}$  ( $2.7^{\circ}\text{F} \pm 1.8^{\circ}\text{F}$ ) during the next 50 years. While changes in average temperatures have some implications for transportation infrastructure and services, the more significant consideration is the potential change in temperature extremes. As the number of days that the temperature is above  $32^{\circ}\text{C}$  ( $90^{\circ}\text{F}$ ) increases – rising in the next century to as much as 115 days (plus or minus 16 days) per year from the current level of 77 days – stress will increase on both the infrastructure itself and on the people who use and provide transportation services. Temperature extremes are most likely to cause the greatest maintenance problems. The greater frequency of very hot days will lead to greater need for maintenance of roads and

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<sup>1</sup> Aside from introductory and summary sections, the climate drivers are not addressed in order of relative importance but rather according to a specific order for purposes of analysis: temperature, precipitation, sea level rise, and storm activity.

1 asphalt pavement (although some paving materials may handle temperature extremes better  
2 than others), rail tracks and freight facilities, some vehicles, and facility buildings and  
3 structures due to degradation in materials. Further, construction and maintenance  
4 schedules may be affected, as work crews may be unable to work during extreme heat  
5 events as higher temperatures make it difficult for workers to work outside. For aviation,  
6 longer runways may be required, although this will probably be offset by advancements in  
7 engine technology and airframe materials.

8 Increases in temperatures also are likely to increase energy consumption for cooling. This  
9 applies particularly to freight operations, including ports where energy is required to  
10 provide for refrigeration, as well as to trains and truck operations. Air conditioning  
11 requirements for passengers also can be expected to increase, which may lead to a need for  
12 additional infrastructure at terminal facilities. This has both environmental and economic  
13 costs, and may pose a public health concern to vulnerable populations during emergency  
14 situations.

#### 15 **4.1.2 Effects of Precipitation Levels and Patterns**

##### 16 ***Precipitation and Runoff***

17 In this study, annual and monthly (January and July) precipitation totals are examined.  
18 Changes in mean precipitation levels appear to have a less significant effect on  
19 transportation than do sea level rise, storm surge, and temperature extremes. However, the  
20 potential exists for increased intensity in individual precipitation events, which would  
21 likely affect transportation network operations, safety, and storm water management  
22 infrastructure. Runoff resulting from such events could lead to increased peak streamflow,  
23 which could affect the sizing requirement for bridges and culverts.

24 As reported in Chapter 3.0, the climate models show relatively wide variance in average  
25 precipitation projections, with plausible scenarios showing annual rainfall potentially  
26 increasing or decreasing by as much as 13 percent by 2050, and by plus or minus 15  
27 percent by 2100. However, regardless of whether average precipitation rises or falls,  
28 higher temperatures are expected to result in more rapid evaporation. This would result in  
29 declining soil moisture and decreased runoff to rivers and streams. The size and extent of  
30 natural habitats adjacent to highways may be altered, resulting in changes in some plant  
31 and animal communities. These ecological changes may have implications for  
32 environmental mitigation strategies and commitments.

33 While changes in annual average precipitation may have some effects, change in the  
34 intensity of individual rainfall events is likely to be the more significant implication for the  
35 transportation system. An increase in the intensity or frequency of heavy downpours may  
36 require redesign of storm water management facilities for highway, bridges and culverts,  
37 ports, aviation, and rail. Severe weather events are correlated to higher incidence of  
38 crashes and delays, affecting both safety and mobility. Further, aviation services can be  
39 disrupted by intense rainfall events as well as an increase in the probability of severe

1 convective weather. No attempt is made in this study to quantify potential changes in  
2 intensity under the climate scenarios presented in Chapter 3.0.

### 3 **4.1.3 Relative Sea Level Rise**

#### 4 ***Background***

5 Based on the range of projected relative sea level rise discussed in Chapter 3.0 of 24-199  
6 cm (about 1-7 feet, depending on location, GCM, and SRES emission scenario), scenarios  
7 of 61 cm and 122 cm (2 and 4 feet) of relative sea level rise were selected as inputs to our  
8 analysis of potential transportation impacts in the study area. Even the lowest end of the  
9 range of increase in relative sea level has the potential to threaten a considerable proportion  
10 of the transportation infrastructure in the region. Future planning, construction, and  
11 maintenance activities should be informed by an understanding of the potential  
12 vulnerabilities. This subsection begins with a summary of the relative sea level rise  
13 analysis conducted for this study (see Chapter 3.0 for the full discussion), and continues by  
14 summarizing the potential effects of relative sea level rise on the transportation modes.

15 As noted in Chapter 3.0, relative sea level rise (RSLR) is the combined effect of the  
16 projected increase in the volume of the world's oceans (eustatic sea level change), which  
17 results from increases in temperature and melting of ice, and the projected changes in land  
18 surface elevation at a given location. In the Gulf Coast region, land surface elevation  
19 change is dominated by subsidence, or sinking, of the land surface. While sea level may  
20 continue to rise incrementally, the potential for abrupt increases in relative levels cannot be  
21 dismissed. Gradual and relatively consistent rates of sea level increases will be more easily  
22 addressed by transportation planners and designers than would more abrupt or  
23 discontinuous changes in water levels. No analysis is conducted regarding the implications  
24 of a catastrophic degree of sea level change that would result from major changes in the  
25 rate of land ice decline (e.g., a rapid collapse of the Greenland Ice Sheet).

26 Two different sea level rise models were used to estimate potential RSLR in the study area.  
27 Both models were used to estimate relative sea level rise by 2050 and 2100 under the  
28 greenhouse gas emissions scenarios considered in this study (see Chapter 3.0 for more on  
29 the scenarios). Both models account for eustatic sea level change and land subsidence in  
30 the region based on the historical record. One model, CoastClim, produces results that  
31 approximate future change in RSLR under the climate scenarios. A similar model, SLRRP,  
32 also incorporates values for high and low tidal variation attributed to astronomical and  
33 meteorological causes, which are pulled from the historical record. The tide data used is  
34 based on a monthly average of the mean high tide (Mean Higher High Water) for each day  
35 of the month. The SLRRP results presented in the study are the highest predicted monthly  
36 sea level elevations by 2050 and 2100. Thus, the SLRRP results capture seasonal  
37 variability and inter-annual trends in sea level change, while the CoastClim results do not.

38 Results for the low- and high-range RSLR cases are summarized in Tables 4.1 and 4.2.  
39 (See Tables 3.14 and 3.16 for the full range of results.) Analysis was conducted for three  
40 long-term tide gage locations, as subsidence rates vary substantially across the region:



1 regional subsidence rates are 4.7 mm/year (0.19 in/year) for Galveston, Texas and the  
2 Chenier Plain; 8.05 mm/year (0.32 in/year) for Grand Isle, Louisiana and the Mississippi  
3 River Deltaic Plain; and 0.34 mm/year (0.013 in/year) for Pensacola, Florida and the  
4 Mississippi/Alabama Sound of the central Gulf Coast. Results generated using CoastClim  
5 range from 24 cm (0.8 foot) in Pensacola to 167 cm (5.5 feet) in Grand Isle. Results from  
6 SLRRP, which as noted above accounts for historical tidal variation, are somewhat higher  
7 with predicted sea level ranging from 70 cm (2.3 feet, NAVD88) in Pensacola to 199 cm  
8 (6.5 feet, NAVD88) in Grand Isle.

9 [INSERT Table 4.1: Relative sea level rise (RSLR) modeled using SLRRP]

10 [INSERT Table 4.2: Relative sea level rise (RSLR) modeled using CoastClim]

11 This Phase 1 analysis broadly examines the potential effects of sea level rise on the region  
12 as a whole; the results related in this study should not be used to predict specific impacts on  
13 any single location at a specific point in time. Impacts were analyzed assuming two  
14 different levels of relative sea level rise; 61 cm (2 feet) and 122 cm (4 feet). From a  
15 regional perspective, the selection of this range for analysis is clearly supported by the  
16 model results. In fact, given that the results range from 24 cm to 199 cm (0.8 to 6.5 feet),  
17 analyzing for 61 cm and 122 cm (2- and 4-foot) increases in RSLR may be overly  
18 conservative from a regional perspective. For both Galveston and especially Grand Isle,  
19 analyzing at the 122 cm level (4 feet) is conservative, given that the high-range scenario  
20 results modeled to 2100 range from 130 cm (4.3 feet) to 199 cm (6.5 feet) for these two  
21 areas. In the case of Pensacola, given that 3 of the 4 values that define the range of the  
22 results are above 61 cm (2 feet), 61 cm level should be considered conservative. The 122  
23 cm (4-foot) level, however, is representative of the high-range scenario results (114 cm or  
24 3.8 feet) for Pensacola.

25 The effect of existing flood control works has not been addressed in this study. Many  
26 existing facilities at lower elevations are protected by levees and other physical structures,  
27 which are intended to provide resistance to storm surge. The present land-based elevation  
28 data allows us to identify general geographic zones of potential risk, and identify areas that  
29 merit further study. More detailed future assessments of specific sites and facilities should  
30 consider the presence and viability of protective structures as part of an analysis of risk and  
31 vulnerability at those locations.

32 As discussed in Chapter 3.0, RSLR will not be uniform across the region. This study's  
33 results are meant to give a broad indication of where relative sea levels could be by 2100  
34 and what infrastructure could be affected as a result of the analysis under the 61 and  
35 122 cm (2- and 4-foot) RSLR scenarios. This analysis provides a first approximation of  
36 potential vulnerabilities and provide insights for transportation planners; more detailed  
37 analyses can then be conducted to further assess specific locations and facilities that may  
38 be at risk. Phase 2 of this study will examine specific sublocations within the region, and  
39 incorporate location-specific projections of future RSLR.

## ***Impact on Transportation***

Relative sea level rise poses the greatest danger to the dense network of ports, highways, and rail lines across the region. An increase in relative sea level of 61 cm (2 feet) has the potential to affect 64 percent of the region's port facilities, while a 122 cm (4-foot) rise in relative sea level would affect nearly three-quarters of port facilities. This is not surprising given that port facilities are adjacent to a navigable water body. For highways and rail, while the percentages are lower, the effect also is quite large. About a quarter of arterials and interstates, nearly half of the region's intermodal connector miles and 10 percent of rail miles would be affected by a 122 cm (4-foot) rise. Because goods are transferred to and from ports by both trucks and rail, service interruptions on selected segments of infrastructure are likely to affect much more than these percentages imply due to the disruption to network connectivity. For example, an increase in relative sea level of 61 cm (2 feet) would affect 220 km (137 miles) of I-10 east of New Orleans, which could affect on-road transport of both people and goods into and out of New Orleans and, to a lesser extent, Houston. Similarly, while less than 10 percent of rail miles would be affected, most of the rail lines linking New Orleans to the rail system could be affected. This could hinder freight movements in the region, especially since New Orleans is the main east-west link for rail located in the region, one of four in the United States. While airports in the region are less directly vulnerable to sea level rise, the vulnerability of roads and rail lines serving them affects the passenger and freight services these facilities provide as well. See Table 4.3 for a summary of this information.

[INSERT TABLE 4.3 – Relative sea level rise impacts on Gulf Coast transportation modes: percentage of facilities vulnerable.]

Relative sea level rise is likely to have an impact on the other modes as well. While bus routes can be adjusted over time should facilities no longer be of use, light rail facilities are not so easily moved; some of the light rail routes in Galveston and New Orleans would be affected by a 61 cm (2-foot) rise. Airports would not escape the direct and indirect effects of relative sea level rise; New Orleans International airport, at 122 cm (4 feet), and two other smaller airports could be affected directly by higher sea levels. Others could be affected indirectly if the roads and connectors leading to them are flooded.

The data and analysis for both relative sea level rise and storm surge are based on land area elevations, rather than facility elevations. Facility elevations generally were not readily available for this phase of the study in a consolidated and geospatial format. The elevation of land areas was determined from the National Elevation Dataset (NED) maintained by the United States Geological Survey (USGS) (USGS, 2004). Mapping data for transportation infrastructure was obtained from the DOT's Bureau of Transportation Statistics (BTS, 2004).

The NED has a horizontal resolution of 30 meters (98 feet). Since the positional accuracy of the transportation facilities is plus or minus 80 meters (262 feet), the elevation data is sufficient only to make general conclusions about transportation facilities that are vulnerable to flooding. While some sections of the transportation network – particularly roads and rail lines – may be elevated, it is important to note that inundation of even short

1 segments of the system can shut down significant portions of the broader network due to  
2 the essential connectivity provided by these segments. Furthermore, such inundation can  
3 undermine infrastructure's foundations and substructures.

#### 4 **4.1.4 Storm Activity**

5 As discussed in Chapter 3.0, the intensity of hurricanes making landfall in the Gulf Coast  
6 study area is likely to increase. In addition, the climate analysis indicates that the number  
7 of hurricanes may increase as the temperature of the sea surface continues to warm.  
8 Simulated storm surge from model runs across the central Gulf Coast at today's elevations  
9 and sea levels demonstrated a 6.7-7.3 meter (22- to 24-foot) potential surge for major  
10 hurricanes of Category 3 or greater. Based on recent experience even these levels may be  
11 conservative; surge levels during Hurricane Katrina (rated a Category 3 at landfall)  
12 exceeded these heights in some locations.

13 Many of the region's major roads, railroads, and airports have been constructed on land  
14 surfaces at elevations below 5 meters. Storm surge poses significant risk to transportation  
15 facilities<sup>2</sup> due to the immediate flooding of infrastructure, the damage caused by the force  
16 of the water, and secondary damage caused by collisions with debris. While surges at  
17 varying heights may disrupt operations and damage infrastructure, the effects of storm  
18 surges of 5.5 and 7 meters (18 and 23 feet) were assessed for the purposes of this analysis.

19 This assessment does not take into account the possible dampening of surge effects due to  
20 distance inland from coastal areas, and the buffering qualities of both ecological systems  
21 (barrier islands, wetlands, marshes) and the built environment. The analysis identifies  
22 portions of the transportation network that are at land elevations below 5.5 and 7 meters  
23 (18 and 23 feet) as an initial indication of areas and facilities that may be at risk and  
24 warrant more detailed analysis. Areas significantly inland from the coast or protected by  
25 buffering systems may be less vulnerable, depending on site-specific coastal  
26 geomorphology and the characteristics of individual storm events.

27 As shown clearly by Hurricanes Katrina and Rita, storm surge has the potential to cause  
28 serious damage and loss of life in low-lying areas. As considered in this study, much of the  
29 region's infrastructure is vulnerable to storm surges on the order of 5.5 to 7 meters (18 to  
30 23 feet), though the specific infrastructure that would be flooded depends on the  
31 characteristics of a given storm, including its landfall location, wind speed, direction, and  
32 tidal conditions.

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<sup>2</sup> Bridges may be of particular interest in this regard. Phase II of this study, which will include an in-depth analysis of a single location within the study region, is expected to include a systematic analysis of the potential impacts of climate change on bridges, as they play a key role across multiple modes, and their failures can produce bottlenecks.

1 As in the case of relative sea level rise, ports, highway, and rail are the transportation  
2 facilities that would be most directly affected by storm surge. Ports have the most  
3 exposure, as 98 percent of port facilities are vulnerable to a storm surge of 5.5 meters (18  
4 feet). Fifty-one percent of arterials and 56 percent of interstates are located in areas that  
5 are vulnerable to a surge of 5.5 meters (18 feet), and the proportions rise to 57 and 64  
6 percent, respectively, for a surge of 7 meters (23 feet). Some 73 percent of intermodal  
7 connector miles are vulnerable to surges of 5.5 or 7 meters (18 feet or 23 feet). One-third  
8 of rail lines are vulnerable to a storm surge of 5.5 meters (18 feet); this proportion climbs to  
9 41 percent vulnerable at 7 meters (23 feet). Twenty-nine airports are vulnerable to a surge  
10 of 7 meters (23 feet), and one major commercial service facility – New Orleans  
11 International – also is vulnerable to a 5.5 meter (18-foot) surge. Vulnerability of the  
12 region’s infrastructure to storm surge is summarized in Table 4.4.

13 [INSERT TABLE 4.4. Storm surge impacts on Gulf Coast transportation modes: percentage of  
14 facilities vulnerable]

15 The effects of storms on the transportation network go beyond the impacts of storm surge.  
16 Severe winds and rainfall events throughout the study region can cause damage and  
17 flooding, disrupting system performance. Wind damage risk contours were not mapped as  
18 part of this project. Experience shows that the highest hurricane velocities are experienced  
19 along the coasts, diminishing as storms move inland, but that severe damaging winds can  
20 be sustained well inland. Hurricanes also spawn tornados, which can have substantially  
21 higher velocities over much smaller areas. The entire study area is within 100 miles of the  
22 Gulf of Mexico shoreline, and all of it could be considered potentially vulnerable to  
23 significant wind damage. As noted in Chapter 3.0, while historical and projected increase  
24 in summer minimum temperatures for the study area suggest an increase in the probability  
25 of severe convective weather (Dessens, 1995, Groisman et al., 2004), GCMs currently lack  
26 the capacity for simulating small-scale phenomena such as thunderstorms, tornadoes, hail,  
27 and lightning.

28 One factor that complicates the effects of both storm surge and relative sea level rise is the  
29 condition of the barrier islands. As noted in Section 3.5.1, wave heights in coastal bays  
30 will tend to increase due to the combined erosional effects of sea level rise and storms on  
31 coastal barrier islands and wetlands. As the barrier islands erode, their role in shielding  
32 Gulf Coast waterways and infrastructure from the effects of waves will diminish, which  
33 means their ability to protect coastal infrastructure from waves at current sea levels and  
34 future sea levels, as well as from storm surge, will likely diminish.

35 Any facility subject to flooding may incur structural damage or be rendered inoperable due  
36 to debris or other obstructions. Restoring facility and system performance necessitates  
37 considerable time and investment on the part of facility owners. The secondary economic  
38 costs to both businesses and communities who rely on these transportation networks could  
39 be considerable as well, depending on the time required to restore system performance.

40 This report does not attempt to estimate the total costs of protecting, maintaining, and  
41 replacing Gulf Coast transportation infrastructure due to damage caused by climate change.

1 It does, however, include a case study on Hurricane Katrina in Section 4.3.1 that provides  
2 examples of the efforts associated with addressing the impacts of the hurricane.

### 3 **4.1.5 Climate Impacts on Freight Transport**

4 The private sector has made massive investments in transportation infrastructure in the  
5 Gulf Coast study area, a large portion of which revolves around moving freight. Almost all  
6 of the roads and major airports are publicly owned, but the vehicles that operate over them,  
7 and the commercial and freight services that they accommodate, are private. Many of the  
8 ports are private and the vessels and commercial services using them are private. Almost  
9 all of the nation's rail infrastructure is privately owned and operated.

10 Disruption of privately owned infrastructure can have huge costs for the owners and users  
11 of these facilities. Repair costs for the more than 65 km (40-mile) CSX railroad segment  
12 damaged in Hurricane Katrina, \$250 million, could be dwarfed by the costs of moving the  
13 line if the company chose to relocate the line further inland; Congressional proposals have  
14 considered authorizing \$700 million in Federal funding to help relocate the damaged  
15 portion of the CSX segment. This is just a small share of the 1,915 km (1,190 miles) of rail  
16 line in the study area that are vulnerable to sea level rise and storm surge. Critical  
17 transportation-dependent industries – petroleum, chemical, agricultural production and  
18 transportation, etc. – are heavily concentrated in the study area. The private sector,  
19 therefore, has a significant interest in the impacts of climate change on transportation  
20 infrastructure, as it potentially affects hundreds of billions of dollars annually in  
21 commercial activity over study area roads, railroads, airports, seaports, and pipelines.

22 One of the key issues that draws the private sector into the discussion of climate impacts on  
23 transportation is the movement of freight. The private sector has proven adept at using  
24 intermodal freight systems – involving ports, highways, rail, and aviation – to transport  
25 goods as inexpensively as possible. However, this lean and efficient system is vulnerable:  
26 a disruption that seemingly affects a limited area or a single mode can have a ripple effect  
27 throughout the supply chain.

28 The loss of direct freight transportation service or connectivity in the Gulf Coast would  
29 likely have a substantial impact beyond the transportation provider and the local economy.  
30 The interruption of freight transportation service in the Gulf Coast could impact the  
31 distribution of goods nationally and, therefore, impact the national economy. Costs of raw  
32 materials or products that have to be rerouted or transported by an alternate mode would  
33 likely increase to absorb higher transportation costs. Further, most businesses and  
34 industries that once held large inventories of products have shifted to low inventory, just-  
35 in-time delivery business models, managing much of their inventories in transit. Therefore,  
36 they have lower tolerance for delays in shipment and receipt of goods, and now demand  
37 greater reliability and visibility from their freight carriers. This system is very cost  
38 effective, but it leaves shippers with little cushion when the freight transportation system  
39 fails. A large failure such as that caused by a hurricane can quickly disrupt thousands of  
40 supply chains, undermining the operations and profitability of many shippers, carriers, and  
41 customers. For example, after Hurricane Katrina, CSX rerouted trains and experienced an

1 increase in operating costs of the railroad through increased fuel usage, crew costs,  
2 equipment delays, and a loss of overall system capacity. Other freight transportation  
3 impacts included the disruption in the distribution of petroleum by pipelines and the failure  
4 of ships being able to make port in the Gulf Coast. An increase in transportation costs such  
5 as these is likely to increase the price of the final product, and could jeopardize the national  
6 and global competitiveness of affected businesses.

## 7 ■ 4.2 Climate Impacts on Transportation Modes

8 This section begins with an in depth examination of the impacts of climate change on each  
9 individual mode. It continues by looking at how these impacts could affect emergency  
10 management and evacuation, and closes with a look at key cross-modal issues.

### 11 4.2.1 Highways

12 As in most parts of the nation, roads are the backbone of the transportation network in the  
13 Gulf Coast. Highways<sup>3</sup> are the chief mode for transporting people across the region. And,  
14 together with rail, highways are essential for moving freight throughout the region and to  
15 other parts of the United States. Thus, impacts to the highway network could serve as  
16 choke points to both passenger and freight traffic that emanates in or flows through the  
17 region. While temperature and precipitation changes have some implications for highway  
18 design and maintenance, the key impacts to the highway network result from relative sea  
19 level rise and storm surge.

#### 20 *Temperature*

21 Impacts related to projected changes in average temperatures appear to have moderate  
22 implications for highways, while increases in extreme heat may be significant.  
23 Maintenance and construction costs for roads and bridges are likely to increase as  
24 temperatures increase. Further, higher temperatures cause some pavement materials to  
25 degrade faster, requiring earlier replacement. Such costs will likely grow as the number of  
26 days above 32°C (90°F) – projected to grow from the current average of 77 days to a range  
27 of 99 to 131 days over the next century – increases, as well as the projected maximum  
28 record temperatures anticipated in the region.

29 While maintenance and construction costs are expected to rise as the number of very hot  
30 days increase, the incremental costs have not been calculated as part of this analysis. These  
31 additional excessive temperature-related costs are incorporated into the total maintenance

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<sup>3</sup> As noted in Chapter 2.0, this report focuses on interstates, arterials and collectors, and not local roads.

1 and construction costs for all pavements and bridges. Changes in materials used may help  
2 reduce future temperature-induced maintenance costs. For example, Louisiana DOT has  
3 begun to use asphalts with a higher polymer content, which helps pavement better handle  
4 higher temperatures, though at a higher initial cost than standard asphalt.

5 There are measures that could be taken to mitigate the loss in productivity associated with  
6 maintenance and construction, such as evening work hours, but these measures also would  
7 increase costs. In subsequent phases of this study, the implications on construction,  
8 maintenance, and operation budgets in specific sublocations should be examined.

9 The designs of steel and concrete bridges and of pavements in the study area typically are  
10 based on a maximum design temperature of 46°C (115°F) to 53°C (125°F). The increase  
11 in maximum record temperatures implied by the climate model projections are less than  
12 these values, although under the climate scenarios they would approach those values over  
13 the next century. It may be prudent for future designers of highway facilities to ensure that  
14 joints in steel and concrete bridge superstructures and concrete road surfaces can  
15 adequately accommodate thermal expansion resulting from these temperatures. The state  
16 DOT design manuals generally establish the maximum design temperature at a value near  
17 53°C (125°F), well above the current maximum recorded temperatures in the study area,  
18 but as temperatures increase there may well be more failures of aging infrastructure.  
19 Consideration should be given to designing for higher maximum temperatures in  
20 replacement or new construction.

### 21 ***Precipitation***

22 As previously noted, the analysis generally indicates little change in mean annual  
23 precipitation (152 cm or 60 inches per year) through either 2050 or 2100, but the range of  
24 possible futures includes both reductions and increases in seasonal precipitation. In either  
25 case, the analysis points to potential reductions in soil moisture and runoff as temperatures  
26 and the number of days between rainfall events increase. The research team analyzed  
27 average annual precipitation separately from potential changes in intensity of rain events.

28 Under a scenario of insignificant change or a reduction in average precipitation, coupled  
29 with drier soils and less runoff, there would be decreases in soil moisture, which may result  
30 in a decline of slides in slopes adjacent to highways. It also would mean less settling under  
31 pavements, with a decrease in cracking and undermining of pavement base courses. While  
32 uniform decreases in runoff could reduce scouring of bridge piers in rivers and streams,  
33 greater frequency of high-intensity events could result in more scour. Stresses on animal  
34 and plant populations brought about by higher temperatures and changes in rainfall patterns  
35 could make it more difficult and expensive to mitigate the impacts of highway  
36 development on the natural environment.

37 Pavement settling, bridge scour, and ecosystem impacts may not be significantly impacted  
38 by modest increases in average annual rainfall because of the effects of increasing  
39 temperature on evaporation rates. However, while potential changes in average annual  
40 precipitation are likely to have minor impacts, an increase in the intensity of individual  
41 rainfall events may have significant implications for highways. An increase in the

1 frequency of extreme precipitation events – as discussed in Chapter 3.0 – would increase  
2 accident rates, result in more frequent short-term flooding and bridge scour, as well as  
3 more culvert washouts, and exceed the capacity of stormwater management infrastructure.  
4 More instances of intense rainfall also may contribute to more frequent slides, requiring  
5 increased maintenance. However, some states, such as Louisiana, already address  
6 precipitation through pavement grooving and sloping, and thus may have adequate capacity  
7 to handle some increase in precipitation.

### 8 ***Relative Sea Level Rise***

9 As discussed above, the effects of 61 and 122 cm (2 and 4 feet) were analyzed to assess the  
10 implications of relative sea level rise on highways. The presence or absence of protective  
11 structures was not considered in this baseline analysis, but would be an important factor in  
12 subsequent sublocation assessments.

13 As shown in Figure 4.1, the majority of the highways at risk from a 61 cm (2-foot) increase  
14 in relative sea level are located in the Mississippi River delta near New Orleans. The most  
15 notable highways at risk are I-10 and U.S. 90, with 220 km (137 miles) and 235 km (146  
16 miles), respectively, passing through areas that will be below sea level if sea levels rise by  
17 61 cm (2 feet). Overall 20 percent of the arterial miles and 19 percent of the interstate  
18 miles in the study area are at elevations below 61 cm (2 feet) and thus at risk from sea level  
19 rise unless elevated or protected by levees (Table 4.5).

20 The majority of the highways at risk from a 122 cm (4-foot) increase in relative sea level  
21 are similarly located in the Mississippi River delta near New Orleans (Figure 4.2). The  
22 most notable highways at risk remain I-10 and U.S. 90, with the number of miles  
23 increasing to 684 km (425 miles) and 628 km (390 miles) passing through areas below sea  
24 level, respectively. Overall 28 percent of the arterial miles and 24 percent of the interstate  
25 miles are at elevations below 122 cm (4 feet). Currently, about 130 miles or about 1  
26 percent of major highways (interstates and arterials) in the study region are located on land  
27 that is at or below sea level.

28 As shown in Figure 4.3, many of the NHS Intermodal Connectors pass through low-lying  
29 areas concentrated in the Mississippi River Delta, where sea level rise is expected to have  
30 the most pervasive impact. Intermodal connectors are primarily necessary to provide  
31 highway access for various transportation facilities, such as rail, ports, and airports, some  
32 of which will be below sea level with a relative sea level rise of 61 to 122 cm (2 to 4 feet).  
33 Of the 1,041 km (647 miles) of IM Connectors, 238 km (148 miles), or 23 percent, are at  
34 risk to a 61 cm (2-foot) increase in relative sea levels; and a total of 444 km (276 miles), or  
35 43 percent, are at risk to a 122 cm (4-foot) increase. In addition to the terminals at risk  
36 under the 61 cm (2 feet) increase scenario (the New Orleans International Airport, Port  
37 Fourchon, most rail terminals in New Orleans, ferry terminals in New Orleans, and ferry  
38 terminals outside of the Mississippi River Delta in Galveston and Houston), additional  
39 terminals at risk under the 122 cm (4 feet) relative sea level rise scenario include port  
40 facilities in Lake Charles, Galveston, Pascagoula, and Gulfport.



1 The cost of various adaptation options – including relocating, elevating, or protecting  
2 highways and intermodal connectors – is not addressed by this study. Additionally, the  
3 costs of right-of-way and environmental mitigation for relocating or elevating such  
4 facilities are unknown at this time. The adaptation and investment plans for specific  
5 facilities will be determined by local and regional decision-makers.

6 As discussed in Section 4.2.1, the available elevation data for the study area is sufficient to  
7 make first order conclusions about roads that are at risk of flooding; it does not indicate the  
8 elevation of specific highways. However, it is worth noting that the loss of use of a small  
9 individual segment of a given highway may make significant portions of that road network  
10 impassable. Further, even if a particular interstate or arterial is passable, if the feeder roads  
11 are flooded, then the larger road becomes less usable.

12 [INSERT FIGURE 4.1: Highways at risk from a relative sea level rise of 61 cm (2 feet)]

13 [INSERT [FIGURE 4.2.: Highways at risk from a relative sea level rise of 122 cm (4 feet)]

14 [INSERT FIGURE 4.3: NHS Intermodal Connectors at risk from a relative sea level rise of 122  
15 cm (4 feet)]

16 [INSERT TABLE 4.5: Relative sea level rise impacts on highways: percentage of facilities  
17 vulnerable]

### 18 ***Storm Activity***

19 As discussed in Chapter 3.0, the intensity of hurricanes making landfall or striking in the  
20 Gulf Coast study area can be expected to increase. About half of the region’s arterial miles  
21 and about three-quarters of the intermodal connectors are vulnerable to a storm surge of 5.5  
22 meters (18 feet), and these proportions are even higher for a 7 meter (23-foot) storm surge.

### 23 **Surge Wave Crests and Effects on Bridges**

24 The wave energy during storm surge events is greatest at the crest of the wave. The  
25 facilities most at risk are bridge decks and supports that are constructed at the wave heights  
26 reached during a storm. The impact of the 2005 hurricanes vividly illustrated some of the  
27 factors involved in infrastructure vulnerability (see Section 4.3.1.) While only a small  
28 percentage of the study area’s bridges are located at the shore and have bridge decks or  
29 structures at these heights, when storm waves meet those bridges the effect is devastating;  
30 spans weighing 300 tons were dislodged during Hurricane Katrina. Although these bridges  
31 are few in number compared to the over 8,000 bridges on the functionally classified  
32 system, over two dozen bridges were hit by wave surges resulting from Hurricane Katrina  
33 and experienced serious damage.

34 An example is shown in Figure 4.4. In perhaps the most spectacular example, the Bay  
35 St. Louis Bridge on U.S. 90, which links Bay St. Louis and Henderson Point, Mississippi,  
36 was destroyed by Hurricane Katrina’s storm surge. The 3.2 km (2-mile) long bridge was  
37 recently replaced at a cost of \$267 million, and has two lanes in each direction and a shared

1 use path. At its highest point, the new bridge reaches 26 meters (85 feet) above the bay, 17  
2 meters (55 feet) higher than its predecessor (Nossiter, 2007; Sloan, 2007).

3 Design features such as lack of venting along the length of the span, solid railings  
4 (preventing water from flowing through), and lack of connectors anchoring the spans to the  
5 pilings or corrosion in existing connectors, made some bridges more susceptible than  
6 others to the force of the water during Katrina. In the absence of standard AASHTO  
7 design factors for storm surge, both the Louisiana DOTD and Mississippi DOT have  
8 developed their own approaches to designing for future storms. For instance, Louisiana  
9 DOTD is developing standards calling for new bridges to be elevated beyond a 500-year  
10 event for the main span (9.1-11.6 meters, or 30-38 feet) and a 100-year event for transition  
11 spans close to shore. In addition, new bridges will be designed with open railings to reduce  
12 the impact of pounding water (Paul, 2007). Mississippi also has adopted more stringent  
13 design standards and is rebuilding the Biloxi Bay and St. Louis Bay bridges as high-rise  
14 structures, to keep the bridge decks above future storm surges.

15 As the sea level rises, the coastline will change. Bridges that were not previously at risk  
16 may be exposed in the future. Additionally, bridges with decks at an elevation below the  
17 likely crest of storm surges, based on experience from previous storms, will be below water  
18 during the storm event and not subject to wave damage. Only data regarding the height of  
19 bridges above navigable channels was available to this study – a small portion of all  
20 bridges in the region. Therefore, a full analysis of the possible impacts of wave crests on  
21 bridges was not feasible.

22 [INSERT FIGURE 4.4 Hurricane Katrina damage to Highway 90 at Bay St. Louis, MS]

### 23 **Surge Inundation**

24 Figures 4.5 and 4.6 show areas potentially vulnerable to surge inundation at the 5.5 and 7  
25 meter (18- and 23-foot) levels and identifies interstate and arterial highways that pass  
26 through these risk areas. As illustrated, a substantial portion of the highway system across  
27 the study area is vulnerable to surge inundation: 51 percent of all arterials and 56 percent  
28 of the interstates are in the 5.5 meter (18-foot) surge risk areas. At the 7 meter (23-foot)  
29 level, these percentages increase only slightly: 57 percent of all arterials and 64 percent of  
30 the interstates are in 7 meter (23-foot) surge risk areas (Table 4.6).

31 The risk from surge inundation for NHS Intermodal Connectors is even greater than that  
32 for all highways. Seventy-three percent of IM Connector miles are located in areas that  
33 would be inundated by a 5.5 meter (18-foot) surge, and the proportion of IM connectors  
34 that is vulnerable at the 7 meter (23-foot) level is only slightly higher (see Figure 4.7).

35 As noted above, the elevation data is sufficient to make only general conclusions about  
36 roads that are at risk of inundation. Local conditions for specific segments and facilities  
37 may be important, and individual roads that may be vulnerable should be studied in detail.

38 While inundation from storm surges is a temporary event, during each period of inundation  
39 the highway is not passable, and after the surge dissipates, highways must be cleared of

1 debris before they can function properly. Of particular concern is that a substantial portion  
2 of all of the major east-west highways in the study area, particularly I-10/I-12, are at risk to  
3 storm surge inundation in some areas, and during storm events and the recovery from these  
4 events, all long-distance highway travel through the study area is likely to be disrupted.

5 The expense of these post-storm cleanups can be considerable and is often not included in  
6 state DOT budgets. For instance, the Louisiana DOTD spent \$74 million on debris  
7 removal alone following Hurricanes Katrina and Rita (Paul, 2007). In the 14 months  
8 following the hurricanes, the Mississippi DOT spent \$672 million on debris removal,  
9 highway and bridge repair, and rebuilding the Biloxi and Bay St. Louis bridges  
10 (Mississippi DOT, 2007). See Section 4.3.1 for a fuller discussion of post-storm cleanup  
11 costs.

12 Moreover, data from the Louisiana DOTD suggests that prolonged inundation can lead to  
13 long-term weakening of roadways. A study of pavements submerged longer than three  
14 days during Katrina (some were submerged several weeks) found that asphalt concrete  
15 pavements and subgrades suffered a strength loss equivalent to two inches of pavement.  
16 Portland concrete cement pavements suffered little damage, while composite pavements  
17 showed weakening primarily in the subgrade (equivalent to one inch of asphalt concrete).  
18 The study estimated a \$50 million price tag for rehabilitating the 320 km (200 miles) of  
19 submerged state highway pavements, and noted that an additional 2,900 km (1,800 miles)  
20 of nonstate roads were submerged in the New Orleans area. The data was collected several  
21 months after the waters had receded; there has not been a subsequent analysis to test  
22 whether any strength was restored over time (Gaspard et al., 2007).

23 [INSERT FIGURE 4.5 Highways at risk from storm surge at elevations currently below 5.5  
24 meters (18 feet)]

25 [INSERT FIGURE 4.6 Highways currently at risk from storm surge at elevations currently  
26 below 7.0 meters (23 feet)]

27 [INSERT FIGURE 4.7 NHS Intermodal Connectors at risk from storm surge at elevations  
28 currently below 7.0 meters (23 feet)]

29 [INSERT TABLE 4.6: Storm surge impacts on highways: percentage of facilities vulnerable]

## 30 **Wind**

31 Wind from storms may impact the highway signs, traffic signals, and luminaries  
32 throughout the study area. The wind design speed for signs and supports in the study area  
33 is typically 160 to 200 km/hr (100 to 125 mph). These designs should accommodate all but  
34 the most severe storm events. More significant safety and operational impacts are likely  
35 from debris blown onto roadways and from crashes precipitated by debris or severe winds.

## 4.2.2 Transit

Transit in the region consists of bus systems as well as light rail in New Orleans, Houston, and Galveston. While bus routes could be affected by relative sea level rise, transit operators can presumably adjust their routes as needed, particularly since the location of transit users and routes also might change. Storm surge could be a more serious, if temporary, issue. For the light rail systems in New Orleans and Galveston, an increase in relative sea level of 61 or 122 cm (2 or 4 feet) would affect at least some of the routes, especially in New Orleans; storm surge of 5.5 or 7.0 meters (18 or 23 feet) would have an even greater impact. The light rail system in Houston would not likely be affected. Projected rises in temperature could lead to greater maintenance and air conditioning costs, and an increased likelihood of rail buckling for the light rail systems. If the intensity of precipitation increases, accident rates could be expected to increase. If total average annual precipitation increases, it could lead to higher accident rates.

### *Temperature*

Given the temperature projections noted in Chapter 3.0, temperature stresses on engines and air conditioning systems could possibly affect vehicle availability rates, disrupting overall scheduled service. Since these additional excessive temperature-related costs are included in the total maintenance and construction costs of transit agencies, it is possible that those amounts will at a minimum increase by an amount proportional to the increase in the number of days above 32°C (90°F).

Furthermore, temperature increases, especially increases in extremely high temperatures, will cause increases in the use of air conditioning on buses to maintain passenger comfort. This will exacerbate the issue of vehicle availability rates and raise costs due to increased fuel consumption.

Increases in (record maximum) temperatures are likely to only impact fixed guideway rail networks and have little or no impact on bus or paratransit systems, aside from the vehicle maintenance issues noted above. As discussed in greater detail in Section 4.2.3, rail networks are subject to “sun kinks” (the buckling of sections of rail) at higher temperatures; sun kinks are likely to occur more frequently as (record maximum) temperatures increase. The possibility of rail buckling can lead to speed restrictions to avoid derailments. The track used by the trolley systems in Galveston and New Orleans have expansion joints which generally are not significantly affected by sun kinks, while Houston’s METRORail uses Continuously Welded Rail (CWR) track. CWR track lacks expansion joints and thus is more prone to sun kinks.

### *Precipitation*

The climate model results point to potential increases or decreases in average annual precipitation. If precipitation increases, it very likely would lead to an increase in accidents involving buses, as well as increased costs and disruptions associated with such accidents. The same also is likely if the intensity of precipitation increases. Even an increase in

1 roadway accidents not involving buses will lead to congestion that could disrupt bus  
2 schedules.

### 3 ***Relative Sea Level Rise***

4 If relative sea level increases to an extent that transit service passes through areas that will  
5 be under water in the future, either the connectivity provided by that transit is lost or  
6 corrective actions to reroute the transit will be needed. Since the vast majority of transit  
7 service is provided by buses, schedules and routes can be modified easily, though the same  
8 is not true for terminals and maintenance facilities. Therefore, minimal impact on bus  
9 systems is expected from relative sea level rise. For light rail systems in the region,  
10 however, relative sea level rise could potentially be a much more serious issue. Moving  
11 tracks and permanent facilities is a major undertaking; tracks would need to be protected or  
12 moved to higher ground.

13 With the exception of the RTA and St. Bernard buses in New Orleans and a small portion  
14 of the routes traveled in Galveston, bus and paratransit service is not expected to be  
15 affected by either a 61 or 122 cm (2- or 4-foot) increase in relative sea levels. If bus routes  
16 are not affected, ancillary facilities such as terminals and maintenance facilities may not be  
17 affected either. Figure 4.8 shows the effect of a 122 cm (4-foot) rise in relative sea level on  
18 fixed bus routes in New Orleans. This clearly illustrates the vulnerability of the transit  
19 network in New Orleans without levees or other protection.

20 [INSERT FIGURE 4.8 Fixed bus routes at risk from a relative sea level rise of 122 cm (4 feet),  
21 New Orleans]

22 The New Orleans streetcars system operated by the RTA and some small portions of the  
23 streetcar system operated by Island Transit in Galveston are similarly at risk of inundation  
24 at either the 61 or 122 cm (2- or 4-foot) sea level rise levels. Like the city itself, portions of  
25 many of the streetcar routes in New Orleans currently are below sea level and it is only the  
26 levee system that maintains the ability of these streetcars to function. In contrast, the fixed  
27 transit system in Houston is not at risk at these levels, as show in Figure 4.9.

28 [INSERT FIGURE 4.9 Fixed transit guideways at risk from a relative sea level rise of 122 cm  
29 (4 feet), Houston and Galveston]

### 30 ***Storm Activity***

31 Transit facilities passing through areas at elevations at or below 5.5 and 7.0 meters (18 and  
32 23 feet) were identified. As shown in Figures 4.10 and 4.11, the fixed transit systems in  
33 New Orleans and Galveston are very likely to be affected by any storms that generate  
34 surges of 5.5 meters (18 feet) or more. This inundation would affect service during and  
35 immediately after a storm, though not likely result in long-term disruptions.

36 [[INSERT FIGURE 4.10: Fixed transit guideways at risk from storm surge at elevations  
37 currently below 5.5 meters (18 feet), New Orleans]

1 [INSERT FIGURE 4.11: Fixed transit guideways at risk from storm surge at elevations  
2 currently below 5.5 meters (18 feet), Houston and Galveston]

3 Fixed bus route systems also are at risk to storm surges. The bus route systems that are  
4 vulnerable to storm surges of 5.5 meters (18 feet) include all the systems except those in  
5 Baton Rouge, Beaumont, and Houston (Figure 4.12 and 4.13). At 7.0 meters (23 feet), the  
6 risk of storm surge inundation also extends to the fixed bus routes in Beaumont.

7 The risk of inundation by storm surge is that the bus routes could not operate while the  
8 roads would be flooded or obstructed. It also should be noted that in low surge events,  
9 even if the buses can operate, their utility would be influenced by whether pedestrian  
10 facilities are passable and riders can walk to bus stops. Consideration should be given to  
11 developing contingency plans for alternative routes during storms.

12 [INSERT FIGURE 4.12: Fixed bus routes at risk from storm surge at elevations currently below  
13 5.5 meters (18 feet), New Orleans]

14 [INSERT FIGURE 4.13: Fixed bus routes at risk from storm surge at elevations currently below  
15 5.5 meters (18 feet), Houston and Galveston]

## 16 **Storm Winds**

17 The transit infrastructure that is most vulnerable to impacts by the winds associated with  
18 increases in the number of intense storms are the overhead catenary lines that power street  
19 cars in New Orleans and Houston. Transit signs and control devices also are subject to  
20 wind damage.

21 However, rather than wind damage to transit facilities, the most widespread impact may be  
22 from fallen trees and property debris blocking the streets on which transit routes operate.  
23 This impact would occur during and immediately after storm events and should be  
24 addressed by highway clean up operations.

## 25 **Storm Waves**

26 With the exception of light rail and BRT systems, transit equipment can be moved away  
27 from areas subject to wave impacts and therefore, storm wave impacts during surge events  
28 are not expected to impact most transit systems. Even in the case of fixed guideways,  
29 storm waves will mostly affect areas immediately on the shoreline, which is not where  
30 fixed guideway facilities in the New Orleans and Houston systems are located. However,  
31 the trolley tracks in Galveston are at risk to these impacts.

## 32 **4.2.3 Freight and Passenger Rail**

33 Rail lines in the region play a key role in transporting freight, and a minor role in intercity  
34 passenger traffic. Much of the traffic on Class I rail lines in the region is for  
35 transshipments as opposed to freight originating or terminating in the region (Figure 2.12).

1 Rail connectivity and service also is vital to the functioning of many, if not most, of the  
2 marine freight facilities in the study area.

3 Of the four main climate drivers examined in this study, storm surge could be the most  
4 significant for rail. One-third of the rail lines in the study region are vulnerable to a storm  
5 surge of 5.5 meters (18 feet), and 41 percent are vulnerable to a storm surge of 7.0 meters  
6 (23 feet). Fifty-one freight facilities and 12 passenger facilities are vulnerable to storm  
7 surges of 7.0 meters (23 feet). Sea level rise is of less concern for rail; a 122 cm (4-foot)  
8 relative sea level rise would affect less than 10 percent of rail miles, as well as 19 freight  
9 facilities and no rail passenger facilities. Temperature increases could raise the danger of  
10 rail buckling, but would be unlikely to necessitate design changes. Projected precipitation  
11 patterns do not indicate that design changes are warranted to prevent increased erosion or  
12 moisture damage to railroad track.

### 13 ***Temperature***

14 The level of average temperature increases discussed in Chapter 3.0 is unlikely to require  
15 immediate design changes to track or other rail infrastructure, as these ranges generally fall  
16 within the current standards for existing rail track and facilities. However, the increase in  
17 temperature extremes – very hot days – could increase the incidence of buckling or “sun  
18 kinks” on all the rail tracks in the study area. This occurs when compressive forces in the  
19 rail, due to restrained expansion during hot weather, exceed the lateral stiffness of the track  
20 causing the track to become displaced laterally. The amplitude of track buckles can reach  
21 75 cm (30 inches) or more.

22 Track buckling occurs predominately on continuously welded track, though it also can  
23 occur on older jointed track when the ends of the track become frozen in place. Track  
24 buckling is most prevalent on an isolated hot day in the springtime or early summer, rather  
25 than mid to late summer when temperatures are more uniformly hot. Buckling also is more  
26 likely to occur in alternating sun/shade regions and in curves.

27 The most serious problem associated with track buckling is derailments. A derailment can  
28 occur when a buckled section of track is not observed in time for the train to safely stop.  
29 One way to overcome this is through blanket slow orders. In hot weather (more than 35°C,  
30 or 95°F), railroads issue blanket slow orders (generally to reduce all train speeds by 16 kph  
31 or 10 mph) to help prevent derailments caused by buckling. This has several negative  
32 consequences, such as longer transit times, higher operating costs, shipment delays,  
33 reduced track capacity, and increased equipment cycle time leading to larger fleet sizes and  
34 costs. Reduced train speeds similarly affect passenger rail schedules, causing delays in  
35 travel schedules.

36 Research into improved track design and installation has greatly reduced the derailments  
37 attributable to buckling. For example, concrete crossties with improved fasteners can  
38 withstand greater track stress than wooden ties with spikes. During installation, the rail is  
39 prestressed to a target neutral temperature. Since the track is more stable when the rail is in  
40 tension at temperatures below the neutral temperature, the target neutral temperature is  
41 generally 75 percent of the expected maximum temperature of the region. In the Gulf

1 Coast Region, the neutral temperature is typically 38°C (100°F), while 32°C (90°F) is used  
2 in more northern climates. Prestressing can occur either thermally (by actually heating the  
3 steel during installation) or mechanically by stretching the steel to introduce the desired  
4 stress prior to fastening it to the crossties.

5 A temperature change of 1.5°C (2.7°F) over the next 50 years may slightly raise the neutral  
6 temperature used for installation, but would have little impact on track design otherwise. A  
7 temperature increase in this range would not necessitate replacing existing track. It would  
8 most likely be replaced as part of normal maintenance, upgrades to handle increased traffic  
9 volumes, or replacement due to storm surge or other catastrophic events. The typical cost  
10 to upgrade track can vary greatly depending upon the type of upgrade, the slope and  
11 curvature, and the number of bridges and tunnels. Costs to replace track range from \$0.3  
12 million to \$1.9 million per kilometer (\$0.5 million to \$3 million per mile), excluding any  
13 additional right-of-way expenses.

14 If incidences of buckling rise it will be increasingly important to develop improved  
15 methods of detection. It is relatively easy to detect a broken rail by running a light electric  
16 current through track, but manual observation remains the best method for identifying track  
17 buckling. Research is underway to develop improved methods that measure temperature  
18 and stress of the track.<sup>4</sup>

19 The projected increases in average temperature and number of hot days, coupled with  
20 possible increases in humidity, would create serious safety concerns for workers in rail  
21 yards and other rail facilities, and would require investments to protect rail workers. This  
22 might include increases in crew size to allow for more frequent recovery breaks, or greater  
23 use of climate controlled facilities for loading and unloading the railcars. Regardless of the  
24 solution, providing the necessary relief for workers will lead to increased operating or  
25 capital expenses, which will be reflected in higher transportation costs.

## 26 ***Precipitation***

27 The primary impacts on rail infrastructure from precipitation are erosion of the track  
28 subgrade and rotting of wooden crossties. Erosion of the subgrade can wash away ballast  
29 and weaken the foundation, making the track unstable for passage of heavy locomotives  
30 and railcars. Ballast is typically granite or other hard stone used to provide a flat, stable  
31 bed for the track, and also to drain moisture from the track and ties. Without ballast,  
32 wooden crossties would rot at a faster rate, leading to more buckling and unstable track.  
33 As with buckling, subgrade erosion and rotting crossties are difficult to detect using  
34 methods other than visual inspection. This is improving, though, through remote sensing  
35 advances that detect standing water and air pockets.

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<sup>4</sup> Much of the material in this section was developed through personal communication with David Read, Principal Investigator, Transportation Technology Center, Inc., an Association of American Railroads subsidiary located in Pueblo, Colorado.



1 The precipitation projections do not indicate that design changes are warranted to prevent  
2 increased erosion or moisture damage to railroad track, even with a potential change of  
3 13 percent in precipitation levels. The runoff projections point to even fewer problems  
4 with erosion over the next century than are present today, due to possibly less precipitation  
5 and slightly higher temperatures. However, if the frequency and/or the intensity of extreme  
6 rainfall events increases, it could lead to higher rates of erosion and railroad bridge scour,  
7 as well as higher safety risks and increased maintenance requirements.

### 8 ***Relative Sea Level Rise***

9 The effects on rail lines and facilities of relative sea level of 61 and 122 cm (2 and 4 feet)  
10 over the next 50 to 100 years were analyzed. The obvious impacts for both of these sea  
11 level rise scenarios are water damage or complete submersion of existing rail track and  
12 facilities. These ground elevations affect the vulnerability of rail segments to storm surge  
13 as well.<sup>5</sup> Table 4.7 indicates the percent of rail lines and facilities vulnerable to sea level  
14 rise at 61 and 122 cm (2- and 4-foot levels). Currently, about 50 miles or about 2 percent  
15 of rail lines in the study region are located on land that is at or below sea level.

16 [INSERT Table 4.7: Relative sea level rise impacts on rail: percentage of facilities vulnerable]

17 Figure 4.14 displays the rail network, used by both freight trains and Amtrak, with the  
18 relative sea level rise elevation projections. Rail lines located in areas with a ground  
19 elevation of 0 to 61 cm (0 to 2 feet) are vulnerable to a relative sea level rise of 61 cm  
20 (2 feet) or more. Lines located in slightly higher areas, with a ground elevation of 61 to  
21 122 cm (2 to 4 feet), are vulnerable to a relative sea level rise of 122 cm (4 feet).

22 Most of the rail lines in and around New Orleans would likely be impacted by relative sea  
23 level rise. The heavily traveled CSX line between Mobile and New Orleans, which was  
24 damaged during Hurricane Katrina, also is at risk, as are several area short lines. A listing  
25 of the rail lines impacted if relative sea level rises 61 cm (2 feet) includes the following:

- 26 • Most rail lines in and around New Orleans;
- 27 • BNSF line between Lafayette and New Orleans;
- 28 • CN/IC line into New Orleans;
- 29 • CSX line between Mobile and New Orleans;
- 30 • CSX line north of Mobile;
- 31 • Louisiana and Delta Railroad west of New Orleans;

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<sup>5</sup> It should be noted that many existing facilities at low elevations are protected by levees and other physical structures, which provide some resistance to gradual changes in sea level and the impacts of storm surge. The effects of existing or planned protections were not addressed by this study. Even with this protection, the infrastructure described in this study is potentially still at risk.

- 1       • Portions of the MSE rail line in Mississippi;
- 2       • The New Orleans and Gulf Coast Railway line between New Orleans and Myrtle;
- 3       • NS line into New Orleans;
- 4       • Portions of the Port Bienville Railroad;
- 5       • Segments of the UP line west of New Orleans; and
- 6       • Various segments of track around Lake Charles and Galveston.

7 [INSERT FIGURE 4.14: Rail lines at risk due to relative sea level rise of 61 and 122 cm (2 and  
8 4 feet)]

9 Further degradation of these lines is very likely to occur should relative sea level increase  
10 by 4 feet, with additional problems on the KCS route into New Orleans, the NS line north  
11 of Mobile, and selected track segments around Beaumont and Houston.

12 Figure 4.15 shows the potential impacts of relative sea level rise on railroad-owned and  
13 served facilities in the study region. Facilities located at less than 61 cm (2 feet) of  
14 elevation are very likely to be affected by a rise in relative sea level of 61 cm (2 feet).  
15 These include the KCS, NS, and UP rail yards in the New Orleans area. Facilities between  
16 61 and 122 cm (2 and 4 feet) of elevation are very likely to be affected by a rise in relative  
17 sea level of 122 cm (4 feet). A listing of facilities with elevation 122 cm (4 feet) or less is  
18 contained in Table 4.8. A listing of all freight rail facilities in the Gulf Coast Study  
19 Region, along with their elevation grid code, is provided in Appendix C.

20 [INSERT FIGURE 4.15: Freight railroad-owned and served facilities at risk due to relative sea  
21 level rise of 61 and 122 cm (2 and 4 feet)]

22 [INSERT TABLE 4.8 Freight railroad-owned and served facilities in the Gulf Coast study  
23 region at elevation of 122 cm (4 feet) or less]

24 A related issue is how railroad customers will respond to these rising relative sea levels and  
25 storm surges, and how these decisions will affect the demand for rail services. For  
26 example, to what extent will customers choose to relocate or modify their shipping and  
27 possibly production patterns? Some industries, most notably the ports, need to remain at or  
28 near the water's edge to send and receive shipments. There will be a continued need for  
29 rail service into these locations. Other rail customers, however, may begin to relocate to  
30 higher ground or to different regions entirely. This will in turn affect the type and scale of  
31 rail network needed to meet the demand for inbound and outbound freight shipments.  
32 While it is difficult to predict the future choices of rail customers, it seems likely that  
33 climate change will negatively impact growth in goods movement at the lower elevations,  
34 and thus could lead to significantly reduced, and costlier, rail service in the region.

35 Turning to passenger rail service, none of the Amtrak passenger rail stations are at a high  
36 risk of impact due to a 122 cm (4-foot) increase in relative sea level. However, the rail  
37 lines used by Amtrak are at risk. These include the Sunset Limited routes between Mobile

1 and New Orleans on the CSX-owned track and between New Orleans and Houston on the  
2 UP-owned track.

3 Table 4.9 summarizes the impacts of relative sea level rise and storm surge on the freight  
4 and passenger rail lines and facilities in the region. These calculations are based on  
5 ground-level elevations of the rail facilities. All facilities and lines at low elevations are  
6 included, even though some are surrounded by higher land that may block rising sea levels.  
7 The actual inland flow of water due to higher relative sea levels was not available for this  
8 study.

9 [INSERT TABLE 4.9: Vulnerability from sea level rise and storm surge by rail distance and  
10 number of facilities]

11 One final factor, not directly addressed by the maps and tables discussed in this section, is  
12 the extent to which rising relative sea levels create a higher water table that leads to  
13 additional flooding during periods of normal precipitation. As the water table rises, the  
14 ground is less able to absorb normal rainfall. This could cause frequent flooding of rail  
15 track and facilities beyond the levels identified in the maps and tables.

### 16 ***Storm Activity***

17 Hurricane Katrina provided a vivid example of the devastating impacts of severe storm  
18 events to the rail system in the Gulf Coast Study Area. Making landfall on August 29,  
19 2005, Katrina caused damage to all of the major railroads in the region. BNSF, CN, KCS,  
20 and UP all suffered damage, mostly to yards in and around New Orleans. CSX track and  
21 bridges also were damaged. NS had nearly 8 km (5 miles) of track washed away from the  
22 9.3 km- (5.8-mile-) long Lake Pontchartrain Bridge. By September 13, 2005 most of these  
23 railroads had resumed operations into New Orleans, at least on a partial basis. There were  
24 still yards that had not fully opened, though this was due to a mixture of storm damage to  
25 the yard and customers not being fully operational. By October 8, 2005 most rail service  
26 on these carriers had been restored, except CSX (Association of American Railroads,  
27 2005). (See Section 4.3.1 for more on the impacts of the 2005 hurricanes.)

28 Figure 4.16 illustrates the rail lines most at risk from storm surge at the 5.5 and 7.0 meter  
29 (18- and 23-foot) marks. One-third of the rail lines in the study region are vulnerable to a  
30 storm surge of 5.5 meters (18 feet), and 41 percent are vulnerable to a storm surge of 7.0  
31 meters (23 feet) (Table 4.10). This includes the heavily traveled CSX line from New  
32 Orleans to Mobile, and the UP and BNSF lines from New Orleans to Houston. Cities at  
33 risk include Mobile, Gulfport, Biloxi, New Orleans, Baton Rouge, Lafayette, Lake Charles,  
34 Beaumont, Port Arthur, and Galveston.

35 Similarly, Figure 4.17 shows the potential impacts of storm surge on railroad-owned and  
36 served facilities in the study region. Facilities at less than 5.5 meters (18 feet) of elevation  
37 have the highest risk of 5.5 meter (18-foot) storm surge impacts. These include 43 percent  
38 of the rail facilities in the study region. An additional 11 facilities are between 5.5 and 7.0  
39 meters (18 and 23 feet) of elevation and are very likely to be affected by a 7.0 meter

1 (23-foot) storm surge. A listing of all freight rail facilities in the Gulf Coast Study Region,  
2 along with their elevation grid code, is provided in Appendix C.

3 Figure 4.18 shows the risks for Amtrak passenger rail stations due to storm surge at 5.5 and  
4 7.0 meters (18 and 23 feet). The data indicates that there is low risk overall to Amtrak  
5 stations from storm surge, but the nine stations listed in Table 4.11 are very likely to be  
6 affected by a storm surge of 5.5 meters (18 feet). Two of the stations, Galveston and La  
7 Marque, Texas, do not have direct passenger rail service, but are connected to the Amtrak  
8 services by bus. At the 7.0 meter (23-foot) storm surge level, an additional three stations  
9 are likely to be affected: New Iberia, Louisiana, and Bay St. Louis and Biloxi, Mississippi.  
10 A listing of all Amtrak stations in the Gulf Coast Study Region, along with their elevation  
11 grid code, is provided in Appendix C.

12 [INSERT FIGURE 4.16 Rail lines at risk due to storm surge of 5.5 and 7.0 meters (18 and 23  
13 feet)]

14 [INSERT Figure 4.17 Freight railroad-owned and served facilities at risk due to storm surge of  
15 5.5 and 7.0 meters (18 and 23 feet)]

16 [INSERT TABLE 4.10: Storm surge impacts on rail: percentage of facilities vulnerable]

17 [INSERT FIGURE 4.18 Amtrak facilities at risk due to storm surge of 5.5 and 7.0 meters (18  
18 and 23 feet)]

19 [INSERT TABLE 4.11: Amtrak stations projected to be impacted by storm surge of 5.5 and 7.0  
20 meters (18 and 23 feet) ]

### 21 ***Railroad Response to Hurricane Damage***

22 In the immediate aftermath of a hurricane, one of the largest problems facing railroad  
23 operators who are trying to restore service is safety issues at road-rail at-grade crossings.  
24 Without power to operate the crossing gates, the railroads either need to manually flag each  
25 crossing or not run the trains. The larger railroads purchase electric generators that can be  
26 deployed after a hurricane to operate the gates, thus allowing trains to offer emergency  
27 response services and resume economic activity. For prolonged outages, as was the case  
28 with Hurricane Katrina, the railroads need to reeducate the public on the dangers of  
29 at-grade crossing once train service resumes.

30 Other short-term responses are directed at protecting revenues and controlling costs.  
31 Business customers within a region impacted by a hurricane are likely facing the same  
32 difficulties as the railroads and may not be fully operational. Once a company is fully  
33 operational, though, a railroad needs to be ready to offer service, or risk losing business to  
34 other railroads, trucks, or barges. Delays in rail service availability can lead to a long-term  
35 loss of revenue. The other issue is continued long-haul service to businesses outside of the  
36 impacted area. After Hurricane Katrina, CSX rerouted trains that previously passed  
37 through the New Orleans gateway to junctions at St. Louis and Memphis. This extra  
38 routing increases the operating costs of the railroad through increased fuel usage, crew

1 costs, equipment delays, and a loss of overall system capacity. There is a strong financial  
2 incentive to return to normal operations as soon as possible after a catastrophic event.

3 The long-term response of the railroads to increased storm intensity currently is being  
4 evaluated. The railroads are participating with both public and private groups to identify  
5 the best ways to serve the Gulf Coast region in the future. CSX Chief Operating Officer  
6 Tony Ingram stated, “We are open to ideas that are in the best interests of CSX, its  
7 customers, and its communities.” Mr. Ingram further stated, “Our recent rebuild of the  
8 Gulf Coast line restores vital service and underscores our commitment, but does not  
9 foreclose other long-term alternatives for the rail line.” (CSX, 2006a).

10 One obvious response is to begin relocating rail track and facilities further away from  
11 coastal areas and making expanded use of intermodal shipping. For example, CSX  
12 recently announced a new 1,250-acre integrated logistics center (ILC) in Winter Haven,  
13 Florida to serve the Tampa and Orlando markets. This ILC will include truck, rail, and  
14 warehousing for the storage and transfer of consumer goods to these two urban markets  
15 (CSX, 2006b). Although this ILC location was driven by proximity to the expanding  
16 Tampa and Orlando markets and the availability of affordable land – rather than as a risk  
17 reduction strategy – it does provide an interesting model for redesigned approaches to long-  
18 haul shipping using inland locations and trucks to serve sensitive coastal markets.

19 Other proposals have included the relocation of CSX rail lines in Mississippi. As  
20 proposed, the rail relocation would occur in the Gulfport area, and would bypass the Bay  
21 St. Louis Bridge that was damaged by Hurricane Katrina. However, much of the rail line  
22 on this CSX route might remain in storm surge danger, as illustrated in Figure 4.16.

23 Another issue related to moving rail lines further away from coastal areas is that it will, in  
24 most cases, move passenger rail service further from population centers. The highest  
25 density populations tend to occur along coastal regions, making it the most desirable  
26 location for passenger rail stations. If the rail track is moved further inland to areas with  
27 lower population density, it would have a negative impact on intercity service and the  
28 potential of any future commuter passenger rail service that might be warranted by  
29 population growth along the coast. On the other hand, this effect could be obviated if rail  
30 facilities and passenger centers migrate inland in tandem, but coordinated responses cannot  
31 be assumed in part since the entities involved – private rail companies, citizens, and  
32 governments – face different decisions related to the impacts of climate change and their  
33 decision-making processes are also necessarily different.

34 The temperature and precipitation changes projected under the climate scenarios and  
35 models used in this study likely would not necessitate any rebuilding of rail facilities or any  
36 significant design changes in the Gulf Coast Study Area rail network. The larger issue is  
37 damage due to relative sea level rise, storm surge, and hurricanes. Rail lines totaling 1,915  
38 km (1,190 miles) and 40 rail facilities are at risk from storm surge as examined above.  
39 (See Figures 4.16 and 4.17.) Railroads may begin slowly relocating track and facilities  
40 further away from coastal areas, though this will be largely driven by customer location  
41 and needs. Increased use of rail-truck transloading from integrated logistics centers further  
42 from the coast might be an alternative. Any effort to move rail lines from the higher

1 density coastal areas will have a negative impact on intercity passenger rail ridership and  
2 the potential utility of the line for commuter rail service as the population along the coast  
3 increases.

#### 4 **4.2.4 Marine Facilities and Waterways**

5 Due to their location, marine facilities are most vulnerable to storm surge and relative sea  
6 level rise. Marine facilities include both freight and nonfreight facilities: ports, marinas,  
7 and industry support facilities. Virtually all of the region's port facilities, or 98 percent,  
8 have the potential to be inundated by a storm surge of 5.5 meters (18 feet), and 99 percent  
9 would be affected by a surge of 7.0 meters (23 feet). A relative sea level rise of 61 cm  
10 (2 feet) has the potential to affect 64 percent of the region's port facilities, while a 122 cm  
11 (4-foot) rise in relative sea level would affect nearly three-quarters of the port facilities.  
12 Impacts related to increased temperatures and changes in precipitation are expected to  
13 include increased costs related to maintenance as rising temperatures place greater stress on  
14 facilities, higher energy costs for refrigeration, and changes in the quantity and type of  
15 products shipped through the region as production and consumption patterns change both  
16 in and outside the region due to climate change.

17 Marine facilities and waterways are vital to the region, and to the nation as a whole. As  
18 noted in Chapter 2.0, the study area is one of the nation's leading centers of marine  
19 activity. Much of the region's economy is directly linked to waterborne commerce; and in  
20 turn, this waterborne commerce supports a substantial portion of the U.S. economy.

21 While some of these functions could be considered "replaceable" by facilities and  
22 waterways elsewhere, many of them – by virtue of geography, connections to particular  
23 industries and markets, historic investments, or other factors – represent unique and  
24 essentially irreplaceable assets. It might be possible to provide capacity equivalent to the  
25 Gulf Intracoastal Waterway or the Mississippi River on land, via highway and/or rail. It  
26 might even be possible to provide landside connections to, and sufficient capacity at,  
27 alternative international seaports. But the capital costs to provide such "replacement  
28 capacity" would undoubtedly be huge, and the costs to system users would be dramatically  
29 higher, if not prohibitively higher.

#### 30 ***Higher Temperatures***

31 Higher temperatures may affect port facilities in three key ways. First, higher temperatures  
32 will increase costs of terminal construction and maintenance, particularly of any paved  
33 surfaces which will deteriorate more quickly if the frequency of high temperatures  
34 increases. Many terminals – especially container and automobile handling terminals –  
35 have very large open paved surfaces for storing cargo that in some cases can range up to  
36 hundreds of paved acres, while most others have at least some open paved area for storage.  
37 Nearly all provide on-terminal circulation space for trucks and wheeled terminal  
38 equipment. All such areas would be vulnerable to higher temperatures. Second, higher  
39 temperatures will lead to higher energy consumption and costs for refrigerated warehouses

1 or “reefer slots” (electrical plug-ins for containers with on-board cooling units). Third,  
2 higher temperatures would likely lead to increased stress on temperature-sensitive  
3 structures. Container handling cranes, warehouses, and other marine terminal assets are  
4 made of metals. With increasing record temperatures and days over 32°C (90°F), it may be  
5 necessary to design for higher maximum temperatures in replacement or new construction.  
6 On the other hand, most dock and wharf facilities are made of concrete and lumber, which  
7 are generally less sensitive to temperature fluctuations. It is possible that lock and dam  
8 structures could be affected, although this will require further investigation. While this  
9 analysis examines existing facilities, it should be noted that development of new types of  
10 surfaces and structures that can better tolerate high temperatures; for example, would  
11 counteract some adverse impacts.

12 Temperature changes in other parts of the country may prompt some changes in  
13 consumption and production patterns in the United States that in turn would affect shipping  
14 patterns in the study region. Compared to the freight movement patterns of today,  
15 increases in temperature in the southeast or other regions could possibly lead to increases in  
16 shipments of coal or other energy supplies that pass through the region’s ports. (This  
17 assumes that the current mix of power plants and fuels remains the same; however, changes  
18 in energy consumption patterns and improvements in energy efficiency are certainly  
19 possible, which could lead to changes in demand for fossil fuels.) Additionally,  
20 temperature changes in other regions could possibly lead to changes in the quantity and  
21 location of grain production, thus changing shipping patterns involving Gulf Coast ports;  
22 such changes could have economic ramifications for the nation as a whole as well as for  
23 regional ports.

#### 24 ***Precipitation***

25 As noted previously, projections of future annual average rainfall suggest a slight increase  
26 or decrease in average annual precipitation depending on choice of GCM and emission  
27 scenario. The prospect of more intense precipitation events, as indicated in Chapter 3.0,  
28 could require the capacity of some stormwater retention and treatment facilities to be  
29 increased. The handling of stormwater can be a significant expense for container  
30 terminals, auto terminals, and other terminals with large areas of impervious surface.  
31 Increasing environmental regulatory requirements also may add to costs of adapting  
32 stormwater handling infrastructure.

#### 33 ***Relative Sea Level Rise***

34 Typically, the highest portion of the marine terminal is the wharf or pier structure, where a  
35 vessel actually berths. Structures and open storage areas behind the wharf or pier may be  
36 at the same level, or may be lower. The highway and rail connections serving the terminal  
37 will be at land level, unless they are on bridge structures. Depending on their design,  
38 different terminals will have different areas of particular vulnerability with respect to  
39 relative sea level rise.

1 It is important to note that many existing facilities at low elevations are protected by levees  
2 and other physical structures, which should provide resistance to gradual changes in sea  
3 levels. The specific effects of existing protections have not been considered in this study.  
4 For facilities that are not appropriately protected, either by elevation or by structures, rising  
5 water levels pose an increased risk of chronic flooding, leading in the worst case to  
6 permanent inundation of marine terminal facilities, either completely or in part, rendering  
7 them inoperable.

8 Of freight facilities in the study area, about 72 percent of are vulnerable to a 122 cm (4-foot  
9 rise) in relative sea level. Of the 994 freight facilities in the USACE database, 638 (64  
10 percent) are in areas with elevations between 0 and 61 cm (2 feet) above sea level, and  
11 another 80 (8 percent) are in areas with elevations between 61 and 122 cm (2 and 4 feet).  
12 More than 75 percent of facilities are potentially vulnerable in Beaumont, Chocolate  
13 Bayou, Freeport, Galveston, New Orleans, Pascagoula, Plaquemines, Port Arthur, Port  
14 Bienville, and Texas City; between 50 percent and 75 percent of facilities are potentially  
15 vulnerable in Gulfport, Houston, Lake Charles, Mobile, South Louisiana, and the Tenn-  
16 Tom. Only Baton Rouge, with 6 percent of facilities potentially at risk, appears to be well-  
17 positioned to avoid impacts of sea level rise. See Figure 4.19.

18 A similar situation faces nonfreight facilities. Seventy-three percent of study area marine  
19 nonfreight facilities are potentially vulnerable to a 122 cm (4-foot) increase in relative sea  
20 level. Of the 810 nonfreight facilities in the SACE database, 547 (68 percent) are in areas  
21 with elevations between 0 and 61 cm (2 feet) above sea level, and another 47 (6 percent)  
22 are in areas with elevations between 61 and 122 cm (2 and 4 feet). More than 75 percent of  
23 facilities are potentially vulnerable in Beaumont, Chocolate Bayou, Freeport, Galveston,  
24 New Orleans, Pascagoula, Plaquemines, Port Arthur, the Tenn-Tom, and Texas City;  
25 between 50 percent and 75 percent of facilities are potentially vulnerable in Houston, Lake  
26 Charles, Mobile, and South Louisiana. Twenty-seven percent of Gulfport facilities and no  
27 Baton Rouge facilities are potentially at risk. See Table 4.10.

28 Navigable depths are likely to increase in many harbors and navigation channels as a result  
29 of rising sea levels. This could lead to reduced dredging costs, but higher costs where  
30 rising water levels require changes to terminals. The functionality and/or protections of  
31 lock and dam structures controlling the inland waterway system also may be impacted by  
32 relative sea level rise.

33 Various indirect impacts could potentially affect operations and need for ports. As  
34 discussed in earlier sections, impacts on highways and rail connections could affect the  
35 ability to utilize and transport goods to and from affected ports. Rail connections to the  
36 Ports of New Orleans, Mobile, Pascagoula, and Gulfport/Biloxi are at greatest risk.

37 Production and consumption patterns within the study area are likely to be significantly  
38 affected by changes in sea level, which could lead to increased demand for certain types of  
39 shipments and reduced demand for others. As residential populations relocate from  
40 affected areas, demand for transported goods would decline. Similarly, as commercial  
41 activities relocate, transportation services would shift with them. Further, shifts in  
42 population could cause labor shortages for transportation and commercial facilities.



1 [INSERT TABLE 4.12: Relative sea level rise impacts on ports: percentage of facilities  
2 vulnerable]

3 [INSERT FIGURE 4.19: Freight handling ports facilities at risk from relative sea level rise of  
4 61 and 122 cm (2 and 4 feet)]

### 5 ***Storm Activity: Water and Wind Damage***

6 While the actual facilities that would be flooded depend on the particulars of a given  
7 storm – the landfall location, direction, tidal conditions, etc. – fully 99 percent of all study  
8 area facilities are vulnerable to temporary and permanent impacts resulting from a 7.0  
9 meter (23-foot) storm surge, while almost 98 percent are vulnerable to temporary and  
10 permanent impacts resulting from an 5.5 meter (18-foot) storm surge (Figure 4.20 and  
11 Table 4.13). All facilities are vulnerable to wind impacts. Similar to sea level rise, storm  
12 surge impacts on highway and rail connections could affect the ability to utilize ports for  
13 transport of goods to and from affected ports.

14 As evidenced by Katrina, fast moving water can be incredibly damaging to marine  
15 facilities. Water can physically dislodge containers and other cargo from open storage  
16 areas, knock down terminal buildings, damage, or destroy specialized terminal equipment,  
17 damage wharf and pier structures, temporarily inundate and submerge large areas, and  
18 undermine or damage pavement and foundations. Wind has its most damaging effects on  
19 un-reinforced terminal structures, such as metal warehouses which feature large surface  
20 areas and relatively light construction. Much of Katrina’s damage to the Port of New  
21 Orleans – which mostly escaped water damage – was due to wind tearing off warehouse  
22 roofs and doors.

23 Wind and water can result in navigation channels becoming inoperable due to blockages  
24 and/or loss of markers. One of the first recovery tasks following Katrina was locating and  
25 clearing the channel in the Mississippi River, allowing it to reopen to barge and vessel  
26 traffic. Wind and water also can affect the location and protection afforded by the barrier  
27 islands that help define the Gulf Intracoastal Waterway.

28 [INSERT FIGURE 4.20: Freight handling ports facilities at risk from storm surge of 5.5 and 7.0  
29 meters (18 and 23 feet)]

30 [INSERT TABLE 4.13: Storm surge impacts on ports: percentage of facilities vulnerable]

31 Further, as mentioned earlier, highway and rail connectivity is vital to the functioning of  
32 nearly all port facilities in the study area. The road and rail facilities that are potentially at  
33 risk of surge at 5.5 and 7.0 meters (18 and 23 feet) are shown in Figures 4.5, 4.6, 4.7, 4.16,  
34 and 4.17. While the actual highways that would be flooded depends on the particulars of a  
35 given storm, a substantial portion of the highway system is at risk of surge inundation,  
36 including roads in all four states in the study area. The resulting potential loss of access to  
37 ports is obviously a critical vulnerability to reliable intermodal operations.

## **Secondary Impacts**

Water levels in navigable rivers, and thus the ability to move freight, would be affected by higher or lower levels of precipitation, evapotranspiration, and runoff occurring outside the region. Such changes in the Mississippi River Basin could affect the ability to use the upper Mississippi and its tributaries to export grain and other commodities from the Midwest and Plains states through Gulf Coast ports. Dredging operations and changes in water control facilities and marine terminals at up river ports could be needed to maintain access to them. Freight transport by truck and rail outside the study region could increase if river transport is curtailed. Estimation of these effects would require the application of models and data from outside of the study area to incorporate up-river hydrology.

Demand for freight services that include use of Gulf Coast ports also could be influenced by changes in precipitation and temperature outside the study region. For example, changes in the amount and frequency of precipitation as well as temperature levels could affect demand for U.S. grain products overseas, just as changes in the same climate drivers in the United States could affect the ability of U.S. grain producers to supply export markets and domestic consumers. Such changes could have implications for Gulf Coast ports in particular as well as for national highway and rail systems.

Similarly, transport of energy supplies through Gulf Coast ports could be influenced by changes in temperature across the globe. Increases in temperature in the United States could affect the demand for energy products transported through Gulf Coast ports; demand for natural gas and coal to power electricity plants in the southeast, for example, could lead to greater production and/or importation of natural gas and LNG through the ports, and could put downward pressure on coal exports through the Gulf in favor of domestic consumption. On the other hand, coal exports through Gulf Coast ports could increase as export demand increased. Of course, climate mitigation policies could lead to significant shifts in preferred energy resources, leading to changes in energy transport demand. Such changes would have implications for pipelines (natural gas, petroleum), as well as rail (coal) and ports (coal). These secondary effects may prove to be important in the future, and such changes need to be monitored closely to track and adapt to changing demand levels.

### **4.2.5 Aviation**

It is possible that existing patterns and intensity of severe weather events could be adversely affected by climate change, and such events could have the greatest impacts on aviation. These changes in severe weather may be widespread geographically such that they could profoundly affect the operational aspects of aviation and overall air traffic and air space management. If the climate becomes wetter, more general aviation pilots would need to learn to fly by instruments or avoid flying during inclement weather. Increased precipitation also could affect commercial service operations, particularly by raising the potential for delays. However, it should be noted that predicting how severe weather patterns would change as a result of climate change is extremely difficult and uncertain.

1 Ultimately, the impact on the operational aspects of aviation could potentially supersede  
2 the overall magnitude of combined effects on aviation due to other factors discussed below

3 A total of 29 airports could be vulnerable to a storm surge of 7.0 meters (23 feet). The  
4 analysis suggests that 3 airports may be vulnerable to an increase in relative sea level rise  
5 of 1.2 meters (4 feet). Temperature increases considered by this report would indicate a  
6 small increase in baseline runway length requirements, assuming other relevant factors are  
7 held constant; however, the changes will very likely not be sufficient, especially accounting  
8 for ongoing technological change in commercial aircraft, to have any substantial impact on  
9 runway length requirements. Nevertheless, aircraft manufacturers may want to determine  
10 whether the generic hot day temperatures used in their specifications for civilian aviation  
11 aircraft are sufficiently high.

## 12 *Temperature*

### 13 **Runway Design and Utilization**

14 Required runway length is a function of many variables, including airport elevation, air  
15 temperature, wing design, aircraft takeoff weight and engine performance, runway  
16 gradient, and runway surface conditions.<sup>6</sup> Runways are designed to accommodate the  
17 most stringent conditions aircraft can experience. Climate model simulations as discussed  
18 in Chapter 3.0 have conclusively noted that future change in climate will be accompanied  
19 by increases in temperature. Generally speaking, the higher the temperature the longer the  
20 runway that is required. In fact, initial runway construction planning takes into account, as  
21 a matter of course, a range of temperatures that can very well capture the extent of the  
22 increase in mean maximum temperature derived from the model results. If increases in  
23 temperature exceed the range initially expected, then considerations for additional  
24 adjustment in runway length may be necessary, depending on other relevant considerations  
25 such as payload and elevation. However, this is considered unlikely.

26 With rising temperatures, it is possible that there could be an impact on aircraft  
27 performance that would warrant aircraft manufacturers considering field length  
28 requirements in their design specifications. However, current trends in aircraft design  
29 point to shorter takeoff distances as airframes become lighter and engines become more  
30 powerful. Thus, due to technological innovation, runway length requirements may  
31 actually decrease even if temperatures increase.

32 Forecasting aircraft manufacturer's product offerings beyond 20 to 30 years is speculative,  
33 but trends toward increased fuel efficiency, more powerful engines, and lighter weight  
34 aircraft are anticipated to continue, which could offset the need for longer runway length as  
35 temperatures rise. Analysis of passenger jet aircraft performance indicates newer aircraft

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<sup>6</sup> These variables affect the performance of departing aircraft in particular; landing aircraft use less runway as reduced landing weight (from fuel usage) as compared to take-off weight and the use of flap settings reduce runway landing lengths.

1 entering the market over the last 50 years use less runway length per pound of aircraft. A  
2 comparison of the two similar Boeing aircraft illustrates this point: the Boeing 737-200  
3 aircraft entered commercial service in 1968 with an engine thrust of 6,580 kg (14,500  
4 pounds) and a per passenger seat thrust ratio of 53 kg (117 pounds). In 2008, the  
5 company's first 787-800 "Dreamliner," made of up to 50 percent light weight composite  
6 products, will enter service. Compared to its predecessor the 737-200, the GE Aircraft  
7 Engines on the 787 will provide more than four times as much thrust and twice as much  
8 engine thrust per passenger seat. This design, paired with more fuel efficient engines,  
9 translates into increased fuel efficiency, producing fuel savings up to 20 percent versus  
10 similar sized aircraft as well as shorter takeoff distances.

11 In order to better understand how changes in temperature could affect the current  
12 generation of aircraft, we looked at both general aviation and civil aviation applications.  
13 Generally, assessments of required runway length are conducted along two tracks for  
14 general aviation and civil aviation airports, and our analysis below reflects this difference:<sup>7</sup>

- 15 • Using the procedures outlined in the FAA Advisory Circulars (for general aviation  
16 aircraft); and
- 17 • Using the manufacturer's performance curves, published by aircraft manufacturers<sup>8</sup>  
18 (primarily large commercial service aircraft).

## 19 **General Aviation**

20 While planning for runway design generally accounts for a range of temperatures, this  
21 analysis of general aviation airports looks solely at how changes in assumptions about  
22 temperature would affect the baseline analysis of runway length requirements for a  
23 hypothetical general aviation airport using the FAA's Airport Design for Microcomputers  
24 software.<sup>9</sup> The software allows for four variable inputs: airport elevation; runway slope  
25 measured in difference in elevations at each end of the runway; mean maximum  
26 temperature for the hottest day of the month; and runway conditions. Aircraft performance  
27 during takeoff varies significantly based on runway elevation, although generally speaking,  
28 there is only moderate difference in runway length needed between an airport at sea level  
29 and one at 91 meters (300 feet) above sea level. Runways located in mountainous areas,  
30 however, have significantly longer runways than those at sea level. Mean maximum  
31 temperature is used by airport planners to identify the average hottest temperature during  
32 the hottest month of the year. Generally speaking, longer runways are required at hotter

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<sup>7</sup> The approach is not completely different. The FAA AC provides design guidance for both small aircraft and large aircraft by using the charts within the AC or directing the reader to obtain manufacturer performance charts for small or large aircraft. The FAA AC also stipulates what design procedure to apply, based on whether or not Federal dollars are involved, e.g., AIP.

<sup>8</sup> Runways at military airports are designed to military aircraft specifications.

<sup>9</sup> It should be noted that the FAA Airport Design microcomputer software is solely for **planning purposes** and not for design since the software generates rough estimated lengths.

1 temperatures. Requirements for wet runways, which have less friction for braking, or  
2 slowing the aircraft, are set out in regulation.

3 Table 4.14 lists the FAA design standards for a hypothetical general aviation airport, and  
4 shows that all small airplanes (defined as having a maximum takeoff weight of less than  
5 5,670 kg or 12,500 pounds) could operate in the study area with a 1,308 meter (4,290-foot)  
6 runway on days as hot as 33°C (91.5°F). On cooler days, less runway length is required.  
7 Large aircraft with maximum takeoff weights greater than 5,670 kg (12,500 pounds)  
8 require longer runways. As noted in the table, 1,637 meters (5,370 feet) of runway is  
9 recommended to accommodate 75 percent of large airplanes up to 27,200 kg (60,000  
10 pounds) at up to a 60 percent useful load when runway surfaces are wet. Wet runway  
11 conditions require more length and these conditions are typically used when calculating  
12 runway length.

13 [INSERT Table 4.14 FAA recommended runway lengths for hypothetical general aviation  
14 airport]

15 While planning for airport construction generally accounts for a range of temperatures, this  
16 analysis looks solely at how changes in assumptions about temperature would affect the  
17 baseline results generated using the FAA's Airport Design for Microcomputers. The  
18 research team analyzed the effect of changes in mean maximum temperature for the hottest  
19 month of the year on runway length requirements as indicated by the climate scenarios  
20 reviewed in Chapter 3.0. Mean maximum temperature was the only variable changed;  
21 airport elevation, centerline elevation, and runway surface conditions (wet) were held  
22 constant.<sup>10</sup> The 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentile temperature increases demonstrated in  
23 Scenarios A1B, B1, and A2 were applied to the FAA Design standards for the hypothetical  
24 airport presented. The increases in runway length based on the increase in temperature  
25 associated with each scenario are discussed below. Mean maximum monthly temperature  
26 is derived by averaging the daily high temperature for the month with the highest average  
27 maximum temperature, which for the Gulf Coast is August. The projected temperature  
28 increases used were then added to the base year mean maximum monthly temperature. The  
29 current average mean maximum temperature is estimated to be 33°C (91.4°F), based on  
30 1972-2002 data from 12 research stations from the Carbon Dioxide Information Analysis  
31 Center (CDIAC) located in the region. For example, for Scenario A1B the 50<sup>th</sup> percentile  
32 temperature increase of 2.5°C (4.5°F) was added to the 33°C (91.4°F) base year mean  
33 maximum temperature, indicating that in 2050 the mean maximum temperature is projected  
34 to be 35.5°C (95.9°F).

35 Below is a brief discussion of the results of this analysis that indicates the range of  
36 potential changes in baseline runway length requirements under the climate scenarios,  
37 conveying the full range of results based on the models and scenarios. For 2100, we point  
38 out the lowest and highest results. These results indicate the change in baseline runway

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<sup>10</sup>One hundred percent of all large aircraft category is seldom used in runway design since very few airports experience the entire spectrum of large general aviation aircraft operations.

1 length requirements for this hypothetical airport using the FAA’s Airport Design software  
2 given a specific change in mean max temperature.

3 The analysis confirms that generally speaking, the possible increases are quite small.  
4 Given the long lead times and ongoing changes in aircraft technology, this means that  
5 possible temperature increases most probably will have little effect on runway length for  
6 commercial aircraft.

7 The potential temperature increases for the month of August are summarized in  
8 Chapter 3.0, Table 3.11. Over the longer term (to 2100), the analysis indicates an increase  
9 of between 1.8°C (3.2°F) (B1, 5<sup>th</sup> percentile) and 6°C (10.8°F) (A2, 95<sup>th</sup> percentile). An  
10 increase at the lower end would indicate a potential need to increase runway length by 9  
11 meters (30 feet) for small aircraft, and by 12 to 15 meters (40 to 50 feet) for large general  
12 aviation aircraft. At the 95<sup>th</sup> percentile, an increase of 6°C (10.8°F) could require  
13 lengthening the runway by 30 to 46 meters (100 to 150 feet) for small airplanes and by 40  
14 to 219 meters (130 to 720 feet) for large aircraft.

15 Generally speaking, the possible increases in baseline runway length requirements are very  
16 low, especially for small aircraft (see Table 4.15). The scale of these runway length  
17 requirement increases range from 8 to 16 percent for corporate jets to 2 to 3 percent for  
18 light general aviation aircraft. While these limited analyses are illustrative of the potential  
19 influence of temperature increase on runway length based on existing aircraft technology,  
20 whether more detailed analyses would need to be conducted would be decided by airport  
21 managers on a case by case basis in order to determine possible investment considerations.

22 [INSERT Table 4.15: Summary of impacts of temperature change to runway length (general  
23 aviation) under three climate scenarios (SRES Scenarios A2, B1, and A1B)]

#### 24 **Commercial Service Airports**

25 Commercial Service, Military Airfields, and Industrial Airport master plans determine the  
26 size of “critical” aircraft anticipated to operate at an airport in the future, then design the  
27 runway system to accommodate the critical aircraft. Runways at commercial airports are  
28 designed using aircraft manufacturer’s specifications. Figure 4.21 is a runway length table  
29 for airport design issued by Boeing for the 757-200 aircraft. These specifications provide  
30 length of runway required for aircraft based on payload, temperature, and elevation. In  
31 general, the higher the temperature, elevation, and payload weight, the longer the runway  
32 needs to be to accommodate the aircraft (Figure 4.21).

33 [INSERT FIGURE 4.21 B757-200 takeoff runway requirements for design purposes ]

34 Commercial airliners offer versatility in their ability to operate at a wide assortment of  
35 airports throughout the world. Large wide-body aircraft such as the Boeing 747 are  
36 designed to seat over 300 passengers and operate at international gateway airports such as  
37 Houston, whereas narrow-body aircraft – designed for medium-size markets – seat 100 to  
38 200 passengers and serve markets such as Tallahassee, Florida and Baton Rouge,

1 Louisiana. Regional jets seat 34 to 70 passengers and serve markets such as Lake Charles  
2 Regional Airport in Louisiana.

3 Airport master plans determine the size of “critical” aircraft anticipated to operate at an  
4 airport in the future, then design the runway system to accommodate these critical aircraft.  
5 Unlike general aviation airports which rely on the FAA Design software to calculate  
6 runway length requirements, runways at commercial airports are designed using aircraft  
7 manufacturer’s specifications. Once airports go into service, it is the pilot’s responsibility  
8 to calculate aircraft performance on a given day prior to takeoff based on the following:  
9 ambient temperature, aircraft gross takeoff weight (GTW), airfield elevation, wind velocity  
10 and direction, and runway surface slope and drag. Thus, on hot days the pilot can make  
11 adjustments in cargo or passenger loads in order to takeoff on a runway, given its length.  
12 On days when the temperature is higher than the aircraft specs contemplate, the airliner  
13 would need to lower its weight to accommodate the higher temperatures.

14 Table 4.16 lists the required runway lengths for three groups of aircraft, fully loaded, for a  
15 “generic” hot day (a standard day temperature of 15 °C (59°F) plus 15 °C (27°F) for a  
16 total of 30°C (86°F)), and compares the manufacturer’s specifications with the primary  
17 runway lengths of the 11 Commercial Service airports in the study area. Shortfalls in  
18 runway length for specific aircraft are presented in italics. Houston Bush Intercontinental  
19 (IAH) is the fourth largest market in the United States and is the only international gateway  
20 airport in the study area. Other airports in the study area do not require the same runway  
21 lengths since wide-body aircraft do not operate at these airports on a scheduled basis. On  
22 the opposite end of the spectrum, regional jets typically operate at Lake Charles Regional  
23 (LCH), Hattiesburg (HBG), and Beaumont/Port Arthur (BPT). These airports are designed  
24 to accommodate regional jets and turboprop aircraft and have shorter runway lengths. The  
25 other commercial airports in the study area are designed to accommodate medium-haul,  
26 narrow-body jets.

27 As shown in the discussion above, the maximum temperature contemplated by this study is  
28 39°C, or 102.2°F (33°C (91.4°F) plus 6°C (10.8°F) under Scenario A2)) in 2100, 9°C  
29 (16.2°F) higher than the “generic” hot day. Therefore, aircraft manufacturers may want to  
30 consider the extent to which the use of a standard day temperature of 15°C (59°F) plus  
31 15°C (27°F) as a measure of a typical hot day will continue to be applicable for aircraft  
32 design or whether to increase this temperature based on any projected temperature increase  
33 associated with a change in climate.

34 [INSERT TABLE 4.16: Commercial aircraft runway length takeoff requirements]

### 35 **Temperature Conclusions**

36 As is the case today, pilots will need to address how temperature increases may affect  
37 aircraft takeoff performance capabilities and payload requirements, and airports will need  
38 to address any such increases in the context of current runway utilization and future runway  
39 design. Given past trends, it is likely that future aircraft will be able to operate on shorter  
40 runways. Airports serving large commercial aircraft in the future, however, are anticipated  
41 to continue to utilize aircraft manufacturer’s specifications to determine runway lengths.

1        **Precipitation**

2        In general, airlines, airports, and aircraft operate more efficiently in dry weather conditions  
3        than wet. Weather is a critical influence on aircraft performance and the outcome of the  
4        flight operations while taking off, landing, and while aloft. Precipitation affects aircraft  
5        and airports in several ways such as decreasing visibility, slowing air traffic by requiring  
6        greater separation between aircraft, and decreasing braking effectiveness. On the ground,  
7        effects include creating turbulence, increasing the risk of icing of wings, and affecting  
8        engine thrust.

9        The climate scenarios for the years 2050 and 2100 developed as part of this research  
10       generally indicate the Gulf Coast study area could become a warmer but drier climate.  
11       However, the models do indicate the possibility that the climate could be warmer with  
12       increased annual precipitation. In either scenario, the increased intensity of individual  
13       rainfall events is likely. Nevertheless, weather always impacts aviation operations and  
14       airport design.

15       Implications of a drier climate to airport and aircraft operations may include positive and  
16       negative effects. Less precipitation would most likely reduce aircraft and air traffic delays;  
17       reduce periods of wet surfaces on runways, taxiways, and aprons; and in the winter months,  
18       reduce the risk of wing icing. It also may increase the number of days of Visual Flight  
19       Rules<sup>11</sup> (VFR) operations. A warmer climate with less precipitation may, however,  
20       increase convective weather (turbulence), as well as increase the number and severity of  
21       thunderstorms. In addition, increased water vapor in the atmosphere, particularly during  
22       the summer months, may increase haze and reduce pilot visibility, thereby reducing the  
23       number of VFR days.

24       A wetter climate would reduce the number of VFR operating time periods and would  
25       impact the general aviation sector. General aviation pilots would either learn to fly in  
26       Instrument Flight Rules (IFR) conditions by becoming “instrument rated” or not fly during  
27       periods of reduced visibility and precipitation. In order for pilots to fly in IFR conditions,  
28       aircraft flight decks must be equipped with complex navigation instruments, which is a  
29       significant investment for aircraft owners.

30       Increased extreme precipitation events also would impact commercial service aircraft  
31       operations. During severe thunderstorm activity it is not unusual for an airline to cancel  
32       flights or at a minimum experience delays in operations. Navigation in heavy precipitation  
33       is possible and currently occurs on a daily basis in the national air system. However,  
34       precipitation almost always creates delays; particularly at the most congested airports.

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<sup>11</sup> Visual flight rules (VFR) are a set of aviation regulations under which a pilot may operate an aircraft, if weather conditions are sufficient to allow the pilot to visually control the aircraft’s attitude, navigate, and maintain separation with obstacles such as terrain and other aircraft.



1 If the Gulf Coast study area climate proves to have more intense precipitation events,  
2 airport planners and engineers would need to consider the implications of periods of  
3 increased heavy rainfall in airport design and engineering. This is particularly true of  
4 airports located on floodplains in the study area since they are more susceptible to “flash  
5 flood” events. Eight of the 61 airports in the study area are located on 100-year  
6 floodplains. These airports are identified in Table 4.17.

7 [INSERT TABLE 4.17: Airports located on 100-year flood plains]

### 8 ***Relative Sea Level Rise***

9 As indicated in Chapter 3.0, relative sea level rise scenarios developed as part of this  
10 research indicate coastal zones in the Gulf Coast study area are very likely to be inundated  
11 by rising sea level combined with geologic subsidence. As a result, some airport  
12 infrastructure would most likely be susceptible to erosion and flooding.

13 GIS analysis indicates three airports in the study area would be below mean sea level  
14 (MSL) if relative sea level increases by 122 cm (4 feet). Each of these airports currently is  
15 protected by preventive infrastructure such as dikes and levees, which will need to be  
16 maintained. If feeder roads in the area are inundated, however, access to these airports may  
17 be disrupted. Table 4.18 lists these airports and their elevations. All three airports are  
18 located in Louisiana, and range from New Orleans International (122 cm or 4 feet  
19 elevation), one of the study area’s large commercial service airports, to South LaFourche  
20 (30 cm or 1 foot), a very small general aviation facility. The third is a military airport,  
21 New Orleans NAS JRB (91 cm or 3 feet).

22 [INSERT Table 4.18 Gulf Coast study area airports vulnerable to submersion by relative sea  
23 level rise of 61 to 122 cm (2-4 feet)]

### 24 ***Storm Activity***

25 Both storm surge and hurricane force winds can damage airport facilities. As indicated in  
26 Chapter 3.0, the study team analyzed the vulnerability of facilities to storm surge heights of  
27 5.5 and 7.0 meters (18 and 23 feet). At these elevations a variety of airports in the region  
28 would be vulnerable to the impacts of storm surge, though this depends on the specific  
29 characteristics of each individual storm event, including landfall location, wind speed,  
30 direction, tidal conditions, etc.

31 Figure 4.22 depicts airports within the study that are vulnerable to storm surges of 18 or 23  
32 feet. Table 4.19 lists these airports by location, type, and elevation. There are 22 airports  
33 in the 0- to 5.5 meter (18-foot) MSL category and seven airports in the 5.8 meter to 7.0  
34 meter (19- to 23-foot) MSL category. This list includes some major airports in the region,  
35 such as New Orleans International. Also, the commercial service airport in Lake Charles,  
36 Louisiana would be vulnerable. See Section 4.3.1 for a discussion of the wind impacts of  
37 the 2005 hurricanes on airport facilities.

38 [INSERT FIGURE 4.22: Gulf Coast study area airports at risk from storm surge]

1 [INSERT TABLE 4.19: Gulf Coast study area airports vulnerable to storm surge]

## 2 **4.2.6 Pipelines**

3 There is a combined total of 42,520 km (26,427 miles) of on-shore liquid (oil and  
4 petroleum product) transmission and natural gas transmission pipelines in the Gulf Coast  
5 area of study, as shown in Figure 4.23.<sup>12</sup> This includes 22,913 kilometers (14,241 miles)  
6 of onshore natural gas transmission pipelines and 19,607 kilometers or 12,186 miles of  
7 onshore hazardous liquid pipelines (PHMSA, 2007). This region is essential to the  
8 distribution of the nation's energy supply through pipeline transportation, and historically  
9 the landside pipelines have been relatively secure from disruption by increased storm  
10 activity and intensity. A number of risks and vulnerabilities to climate-related impacts  
11 have been revealed, however, particularly for submerged or very low elevation pipelines.  
12 The Pipeline and Hazardous Materials Safety Administration (PHMSA) of the U.S.  
13 Department of Transportation has jurisdiction over on-shore pipeline facilities and some  
14 offshore pipeline facilities. PHMSA has jurisdiction over offshore pipeline facilities that  
15 are exposed or hazards to navigation when the offshore pipeline facilities are between the  
16 mean watermark and the point where the subsurface is under 15 feet of water as measured  
17 from mean low water. The U.S. Department of the Interior Minerals Management Service  
18 (MMS) has jurisdiction over about 36,000 miles of offshore pipelines in the Gulf of  
19 Mexico.

20 [INSERT FIGURE 4.23 – Landside pipelines having at least one GIS link located in an area of  
21 elevation zero to 91 cm (3 feet) above sea level in the study area]

22 Some historical weather events have resulted in only minor impacts on pipelines, with the  
23 notable exceptions of Hurricanes Andrew's, Ivan's, Katrina's and Rita's fairly extensive  
24 damage to underwater pipelines and flooded distribution lines in areas where houses were  
25 destroyed. Storm surge and high winds historically have not had much impact on  
26 pipelines – either onshore transmission lines or offshore pipelines – since they are strong  
27 structures, well-stabilized and/or buried underground. Yet offshore pipelines have been  
28 damaged in relatively large numbers on occasion, as during Hurricanes Andrew and Ivan.  
29 Temperature shifts resulting from climate scenario projections are not expected to have  
30 much direct or indirect impact on pipelines. Increases or decreases in precipitation – either  
31 long-term or in the frequency or extent of droughts or inundation – could impact soil  
32 structure. Sea level rise would likely have little direct effect, but could affect water tables,  
33 soil stability, and the vulnerability of pipelines to normal wave action as well as sea surge.

34 Changes in soil structure, stability, and subsidence – whether undersea, landside, or in  
35 wetlands or transition elevations – could play an important role in pipeline-related risks.  
36 However, there is little information on this topic outside of earthquake risks. There has

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<sup>12</sup>This includes some extended pipeline sections beyond the boundaries of the study, as GIS coding of links included segments that spanned both inside and outside the study area.

1 recently been concern about how wave action could affect the seabed, either by  
2 liquefying/destabilizing the sand or silt surface above a buried pipeline or by gradually  
3 eroding away seabed that had been covering the pipeline. It is unclear at present whether a  
4 changing climate might lead to conditions that exacerbate these effects and cause additional  
5 damage.

6 The possible effects on pipelines from climate change – storm surge and extreme winds,  
7 temperature shifts, precipitation changes, and sea level rise – were considered in this  
8 analysis. Both pipeline companies and government agencies have considered pipeline  
9 risks, vulnerability, and safety, and have well-developed inspection, maintenance, and  
10 response plans. However, these plans do not appear to address a number of risks that may  
11 be arising. This study did not examine the adequacy of those plans. While some issues  
12 regarding impacts have been addressed here, there is still significant uncertainty about the  
13 overall risk to pipelines from climate change.

#### 14 ***Importance of Pipeline Operations in the Study Area***

15 Onshore natural gas transmission pipelines are primarily located in Louisiana.  
16 Approximately 49 percent of natural gas wellhead production either occurs near the Henry  
17 Hub,<sup>13</sup> which is the centralized point for natural gas futures trading in the United States, or  
18 passes close to the Henry Hub as it moves to downstream consumption markets. The  
19 Henry Hub interconnects nine interstate and four intrastate pipelines, including: Acadian,  
20 Columbia Gulf, Dow, Equitable (Jefferson Island), Koch Gateway, LRC, Natural Gas Pipe  
21 Line, Sea Robin, Southern Natural, Texas Gas, Transco, Trunkline, and Sabine’s mainline.

#### 22 ***Temperature***

23 The great majority of the transmission pipeline system is buried under at least 3 feet of soil  
24 cover, both onshore and offshore. Federal regulations require that all pipelines in  
25 navigable waters be buried. Pipelines typically carry product at significant temperature  
26 variations (natural gas under pressure in their system, while petroleum products are heated  
27 considerably above ambient temperatures. There is extensive experience with pipelines in  
28 much more extreme ambient temperature conditions (Alaska, Saudi Arabia, West Africa)  
29 than anyone expects in the Gulf Region. Sea temperatures will vary even less than land  
30 temperatures. Thus, there is not expected to be any significant effect on pipelines due to  
31 direct effects from increased (or decreased) temperatures.

#### 32 ***Precipitation Changes***

33 Sustained periods of increases or decreases in precipitation, whether over months or the  
34 cumulative effect across years, can cause substantial soil changes due to drought or  
35 saturation. Changes in water tables may occur both from local climate changes as well as

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<sup>13</sup>Located near the town of Erath in Vermilion Parish, north central Louisiana.

1 from global effects such as sea level rise. An increase in water table level or increased  
2 surface water runoff can cause erosion or slumping (collapse) of the soil surface, thereby  
3 leading to potential for pipeline exposure.

4 In the lowland and marsh areas particularly associated with the coastal regions of  
5 Louisiana, the soil is being washed away due to storm activity. With the disappearance of  
6 the soil, the pipelines in these regions are losing cover.

7 Detailed analysis of geology and pipeline-specific conditions are required to draw more  
8 precise conclusions regarding the potential for serious disruption of the transmission  
9 pipeline system from climate-related soil changes. Nonetheless, this is an area of concern  
10 as a considerable and unpredictable portion of the pipeline system could be vulnerable to  
11 these climate change and sea level induced impacts.

12 Another vulnerability is from expected short-term changes (such as torrents and floods),  
13 where significant change in water flow rate and water flow energy are a result of increased  
14 precipitation. Risk analysis of the impacts of extreme events is required to determine  
15 appropriate adaptation or mitigation actions.

#### 16 ***Storm Impact Preparation, Mitigation, and Response***

17 Wave action during storms may impact pipelines. For offshore pipelines, in instances  
18 where significant subsidence occurs and the pipeline segment is exposed, that section is  
19 exposed to wave action. High-energy waves may subject a pipeline to stress levels it was  
20 not designed to withstand, causing a fracture. An exposed offshore pipeline also could be  
21 vulnerable to lateral and vertical displacement, exposure to vessel traffic and fishing trawls,  
22 or rupture by currents, which may be very important in this context.

23 Pipeline operating companies are required to have an emergency plan in place covering all  
24 known or expected situations that may require response to repair the pipeline system due to  
25 damage, including, storms, excavation, and even sabotage or terrorist attack. Pipeline  
26 systems are segregated by sections between valves in order to allow isolation and shutdown  
27 of segments for routine maintenance, malfunctions, or response to emergency incidents.  
28 During shutdowns, pipelines are pressurized at the emergency plan design pressure and all  
29 valves are closed, preventing flow problems during the rest of the event and facilitating  
30 repair. The operating portion of the emergency plan generally presumes operations will be  
31 interrupted for a period of only up to 10 days.

32 As soon as a storm or other event dissipates in the pipeline area of concern, the pipeline  
33 response team initiates their response plan. An inspection begins as a visual flyover the  
34 pipeline in the affected region to examine it for exposure or other obvious indications of  
35 damage. Some damage also can be detected through sensors measuring pressure in  
36 different pipeline segments or through other physical indicators, although these may miss  
37 some damage (e.g., structural damage not yet causing a leak), or make it more difficult to  
38 isolate damage location more precisely. If damage is apparent, then a thorough close-up  
39 inspection will take place, including divers as necessary. After damage has been identified,  
40 a repair team initiates repairs.

1 The damages caused to pipelines by Hurricanes Andrew and Ivan were severe and fairly  
2 widespread throughout the storm front region, as documented by the Minerals Management  
3 Services (MMS) study discussed below. After Ivan, oil refineries had ample products to  
4 supply, but the pipelines could not deliver due to damages. In contrast, damage to  
5 pipelines from Katrina/Rita was relatively minor; most pipelines were ready to take  
6 product, but were hampered by the lack of available product due to refinery damage and/or  
7 power shortages.

8 One hazardous liquid pipeline representative stated that, prior to Ivan, obtaining pipeline  
9 maintenance and repair contract commitments was relatively easy, “a foregone conclusion  
10 of commitment” but, after Katrina/Rita, it has become increasingly difficult to obtain solid  
11 commitments from suppliers to respond to emergency calls. While suppliers are still  
12 offering contracts, the commitment is now only an offering to put the customer on a  
13 response list for a front end fee. There is no longer a guarantee that the supplier will  
14 respond to an emergency call within a fixed time period or otherwise provide service,  
15 because all their assets and personnel may be engaged in a prior commitment.

16 Response capabilities and reliability have thus declined, even while the acknowledged  
17 storm threat has increased due to Ivan’s illustration of a previously unknown level of  
18 damage. And while before there were emergency operating plans that matched the  
19 committed response time, not only may responses take longer, but operating plans will  
20 need to be adapted to meet these eventualities.

### 21 *Hurricane Damage Studies*

22 One of the more substantial studies of hurricane damage to pipelines in the Gulf of Mexico  
23 (GOM) was done by Det Norske Veritas (DNV) Technology Services upon a request from  
24 the Department of Interior’s Minerals Management Service (MMS) (Skinner, 2006). This  
25 was an assessment of damage to the Gulf of Mexico offshore pipelines resulting from the  
26 passage of Hurricane Ivan in September 2004. The DNV study also summarized the  
27 impacts of Hurricanes Andrew, Lili, Katrina, and Rita.

28 Hurricane Ivan reached Category 5 strength three times and was a Category 3 hurricane  
29 when it made landfall. Hurricane Ivan resulted in approximately 168 pipeline damage  
30 reports, although the vast majority of GOM offshore pipelines performed well during the  
31 passage of Hurricane Ivan. According to the MMS DNV report, the impact on the  
32 environment from pipeline spills was minimal. The majority of pipeline damage occurred  
33 at or near platform interfaces, in areas of mudflows, or as a result of an indirect hurricane  
34 impact, such as platform failure or anchor dragging. Localized failures at pipeline  
35 crossings and excessive movements in shallow water depths indicate that more hurricane  
36 resistant design considerations might be needed on a site-specific basis, but do not warrant  
37 industry-wide design or construction code revisions. The report suggests that design  
38 assumptions used for shallow water pipelines need to be evaluated in areas dominated by  
39 silty soils, particularly where self-burial is intended as the method of installation.

40 Hurricane Andrew passed through the Gulf of Mexico in August 1992 as a Category 4-  
41 level storm. It damaged more than 480 pipelines and flow lines. Prior to Hurricane

1 Andrew, minimal damage to pipelines had been experienced as a result of passing  
2 hurricanes, with combined pipeline failures from hurricanes for the period of 1971 through  
3 1988 resulting in about 100 damage reports. Most of the pipeline failures were in depths  
4 less than 30 meters (100 feet) of water.

5 Hurricane Lili was a Category 4-level storm offshore in the GOM, and was downgraded to  
6 a Category 2 hurricane at landfall in October 2002. There were 120 pipeline damage  
7 reports to the MMS following Hurricane Lili. The majority of the pipeline failures in Lili  
8 occurred in small diameter pipelines, with no apparent correlation for age, which also was  
9 true for damages reported from Andrew.

10 According to the MMS, there were 457 offshore oil and gas pipelines that were damaged as  
11 a result of Hurricanes Katrina and Rita (MMS Press Release, 2006). Most of the damage  
12 was relatively minor. Disruptions also occurred due to power outages, and pipeline  
13 operators procured portable electric power generators necessary to resume operations. The  
14 closure of major pipelines originating in the GOM region in the wake of both storms served  
15 to exacerbate the petroleum product supply situation (EIA, 2005).

#### 16 ***Storm Activity: Erosion***

17 The above information and an interview with a hazardous liquids (mostly petroleum  
18 products) pipeline company revealed that damage from erosion and soil stability due to  
19 storm wave action has focused new interest on this phenomenon. The results of Hurricane  
20 Ivan, when erosion occurred in waters up to 76 meters (250 feet) in depth, demonstrated  
21 that this effect can occur at depths previously considered impervious. The problem and  
22 solution is still being investigated in joint industry programs, along with Office of Pipeline  
23 Safety and MMS.

24 Erosion typically has been found to occur in what the industry has termed “ultra shallow  
25 waters.” This phenomenon was prevalent from Hurricane Ivan (Skinner, 2006) but almost  
26 completely lacking from Hurricanes Katrina and Rita. This indicates that risk is not only  
27 due to storm intensity, but may be based on more complex meteorological and fluid  
28 dynamics factors, making the risk less predictable than assumed.

29 In ultra shallow waters where erosion occurs, the general concurrence of industry  
30 specialists is that the seabed is “liquefying” (the sand or silt shifts from a wet solid to a  
31 suspended state) in certain wave action conditions. Pipeline design incorporates negative  
32 buoyancy (a present regulatory requirement and previously considered good design  
33 practice), but, if the sands are liquefying, the negative buoyancy may become positive and  
34 the pipeline ends up on the seabed surface. Documentation shows that the seabed level has  
35 not changed in these occurrences, but the pipeline has changed its elevation from 3 feet  
36 below the seabed surface to resting on the surface. While possible solutions are being  
37 developed, impacts from more frequent or severe storms currently can be considered a  
38 vulnerability of the pipeline system (EIA, 2005).

1       **Storm Activity: Increased Storm Severity**

2       In the Gulf Coast area of study, transmission pipelines have been designed to maintain their  
3       integrity for a (historical) 100-year storm event. Interviews with natural gas transmission  
4       pipeline company representatives indicate that the potential of pipeline damage due to  
5       increased storm activity or increased severity of storms is considered to be of marginal  
6       concern. They framed the issue as: to what extent can increased weather damage be  
7       effectively planned for, and what level of risk exposure should be assumed, beyond  
8       regulatory requirements? While there is an extensive regular inspection process that may  
9       identify weaknesses that could be expanded by a storm or by more gradual soil structure  
10      changes, it only partially prepares for and mitigates potential storm damage.

11      Discussions regarding the potential for transmission pipeline damage consistently centered  
12      on the issue that nearly all the transmission lines are buried with 0.9 meters (3 feet) of top  
13      cover, more in urban and populated areas, and they are regularly inspected for integrity.  
14      Issues regarding damage to the exposed pipeline portions (which may be the most vital, as  
15      valves, pumping stations, etc.) or damage to underground portions from previously  
16      unconsidered factors (changing water tables, soil subsidence due to sea level changes) need  
17      to be better understood.

18      Researchers interviewed MMS regulatory officials in the New Orleans, Louisiana office  
19      regarding the effects they see concerning climate change. The offshore pipelines are  
20      regulated by MMS regarding design, construction, operations, and maintenance  
21      requirements. MMS indicated they do not anticipate increased storm severity and  
22      frequency will appreciably affect the pipelines under their regulatory authority in the Gulf  
23      of Mexico. Note that MMS' authority ends at the state/Federal boundary offshore.<sup>14</sup> It is  
24      unclear whether their comments took into account the changing soil structure and shore  
25      line in the region. They based their comments on the fact that the subject pipelines are at  
26      substantial depth and the pipelines are buried 0.9 meters (3 feet) below sea floor level or  
27      anchored to piers designed to prevent pipeline movement on the sea floor. It is not certain  
28      how this accounts for the results of Hurricane Ivan and the findings of the DNV study.

29      **Secondary Impacts**

30      The level of oil and natural gas products moved via pipelines could be influenced by  
31      changes in temperature across the globe. Increases in temperature in the United States  
32      could affect the demand for energy products transported through the Gulf Coast; demand  
33      for natural gas (and coal) to power electricity plants in the southeast, for example, could  
34      lead to greater production and/or importation of natural gas through study region pipelines.  
35      Furthermore, climate mitigation policies designed to reduce carbon emissions could favor  
36      natural gas over other fossil fuels, thus promoting greater exploration and production of  
37      natural gas and importation of LNG, with clear implications for pipelines.

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<sup>14</sup>The state/Federal boundary is three miles offshore in the study area except in Texas, where it is 10 miles offshore.

1 Further study is necessary before firm conclusions can be drawn regarding the vulnerability  
2 of on- and off-shore pipelines. Relatively significant damage has occasionally occurred,  
3 yet other storms have produced only minor damage. Recent investigations have raised  
4 concerns about sea-bed conditions under which pipelines exhibit some vulnerability. It is a  
5 matter of further research whether climate change will exacerbate those conditions or  
6 whether the interface between on- and off-shore pipelines might be affected.

#### 7 **4.2.7 Implications for Transportation Emergency Management**

8 Without proactive planning, climate change could complicate evacuation efforts in the  
9 region. As noted above, some highways, the chief mode for evacuation, are very likely to  
10 be inundated permanently as relative sea level rises, and periodically when areas are  
11 flooded by storms. Further, higher temperatures could make evacuations more problematic  
12 particularly in situations where there is severe congestion; higher temperatures lead to  
13 greater air conditioning usage, making it more likely that vehicles will run out of fuel and  
14 block traffic. Large-scale emergency management is further challenged by the changing  
15 demographics of the region: an increasing percentage of residents are older and/or have  
16 special needs. Also, recent experience with evacuations suggests that congestion on key  
17 evacuation routes poses serious challenges to evacuating residents quickly. The need for  
18 interoperable communications systems across the region, currently lacking, will be  
19 heightened as the number of emergencies increases with climate change.

20 A robust emergency management system is highly dependent on the viability of the  
21 region's transportation infrastructure. Ensuring the capability to both evacuate residents,  
22 and move emergency responders and services into affected areas will require purposeful  
23 adaptation and thus focused investment in the transportation system. This section  
24 examines the implications for transportation emergency management of the potential  
25 impacts highways, transit and passenger rail presented earlier in this report. Many of these  
26 routes are expected to become increasingly vulnerable to higher sea levels and storm surge.

27 This section also highlights some of the lessons learned from recent hurricane evacuation  
28 experiences, and examines some of the issues related to the varied – and often  
29 incompatible – communications system found across the region.

30 Further analysis and institutional consensus development is necessary to more fully  
31 understand the implications of climate change on transportation emergency management.  
32 However, the preliminary vulnerability issues raised here are illustrative of the kinds of  
33 interactions that climate change and variability may cause for emergency management  
34 planning and operations. These issues are compounded by the changing demographics in  
35 the region.

36 There are two key types of emergency management/climate change scenarios. The first  
37 involves complications for emergency response activities given climate impacts. For  
38 example, unusable roads caused by higher sea levels caused by climate change could  
39 disrupt road connectivity, increasing the time needed for emergency response vehicles to  
40 reach fires, medical emergencies, etc. The second involves situations where the climate



1 impact itself causes the emergency – where hurricane induced flooding or a sudden rise in  
2 relative sea levels forces people to evacuate a particular area.

### 3 ***Temperature***

4 As discussed in Chapter 3.0, both mean and extremes temperatures are very likely to  
5 increase in the Gulf Coast region over the next 50 to 100 years. The increase in  
6 temperatures could cause more air conditioning usage during some evacuations and could  
7 further diminish mobility. Vehicles using air conditioning during storm evacuations,  
8 particularly on congested roads, would contribute to roadside blockages as fuel is depleted  
9 and vehicles are abandoned. Furthermore, an increase in temperatures, especially  
10 maximum temperatures, coupled with a growing number of special needs residents in the  
11 Gulf Coast study area, means that more lives could be vulnerable in the absence of  
12 electrical power and air conditioning in the aftermath of a storm.

### 13 ***Relative Sea Level Rise***

14 As noted above, interstates and arterials tend to serve as the major evacuation routes for  
15 emergencies in the Gulf Coast study area. This substantial reliance on a single mode of  
16 transportation may endanger many people if the highway infrastructure is damaged or  
17 made inaccessible because of relative sea level rise. If the relative sea level increases such  
18 that portions of evacuation routes are under water then the essential connectivity and  
19 evacuation provided by those highways would be lost. This will be particularly important  
20 for large-scale evacuations dependent on east-west routes. Of course, as sea levels rise  
21 over time population centers may shift to higher elevations; the segments of evacuation  
22 routes that will be most critical are likely to change with these shifts in community  
23 locations. Furthermore, if the increase in relative sea level is gradual, infrastructure  
24 development would likely follow the movement of population centers.

25 As discussed in Section 4.2.1, the majority of the highways vulnerable to a 61 and 122 cm  
26 (2- and 4-foot) rise in relative sea level are located in the Mississippi River delta near New  
27 Orleans. The most prominent vulnerable highways are I-10, with 220 km (137 miles) and  
28 U.S. 90 with 235 km (146 miles) passing through areas likely to be below sea level with a  
29 61 cm (2-foot) rise in relative sea level. Overall 19 percent of the interstate miles and 20  
30 percent of the arterial miles are at elevations below 61 cm (2 feet). With a 122 cm (4-foot)  
31 rise, the miles affected increase to 684 km (425 miles) of I-10 and 628 km (390 miles) of  
32 U.S. 90. Overall, 24 percent of the interstate miles and 28 percent of the arterial miles  
33 currently are at elevations below 122 cm (4 feet).

### 34 ***Storm Activity***

35 As noted in Chapter 3.0, studies suggest that as radiative forcing (that is, GHG  
36 concentrations) and sea surface temperatures continue to increase, hurricanes may be more  
37 likely to form in the Atlantic and Pacific and more likely to intensify in their destructive  
38 capacity. Storm surge disperses debris that blocks highways and makes many roads,  
39 including evacuation routes, impassable. In addition, storm surge may damage bridges and

1 other structures, potentially compromising mobility for extended periods. While the actual  
2 highways that would be flooded and impacted by debris depends on the specific  
3 characteristics of any given storm, a substantial portion of the highway system is  
4 vulnerable to surge inundation, including roads in all four states in the study area. The  
5 areas that are potentially vulnerable to 5.5 and 7.0 meters (18- and 23-foot) storm surge  
6 levels are shown in Section 4.2.1 above. At the 5.5 meter (18-foot) level, 51 percent of all  
7 arterial highways and 56 percent of the interstates in the study area are affected  
8 (Figure 4.24). At 7.0 meters (23-feet), these percentages rise to 57 percent of all highways  
9 and 64 percent of the interstates.

10 [INSERT FIGURE 4.24 Potential evacuation route highways vulnerable from storm surge of 5.5  
11 meters (18 feet)]

12 Although not traditionally used for evacuation and emergency management purposes,  
13 railroads also could provide a transportation choice – especially for evacuees with special  
14 needs. Figure 4.25 illustrates the impacts on Amtrak facilities due to relative sea level rise  
15 and storm surge, and identifies the Amtrak stations that are vulnerable to storm surge at the  
16 5.5 meter (18-foot) level.

17 [INSERT FIGURE 4.25 Risks to Amtrak Facilities due to relative sea level rise and storm surge]

### 18 *Other Considerations Affecting the Success of Emergency Management*

19 The issues below are important from the perspective of managing emergencies and  
20 protecting people. Highlighting these issues is important as they are relevant to preparing  
21 for potential emergencies, some of which could be related to the impacts of climate change.

### 22 **Adapting Emergency Management Plans**

23 Effective emergency evacuation plans must be living documents that incorporate current  
24 and anticipated conditions, procedures, and resources. Climate change will likely  
25 exacerbate the need to update these plans and procedures. The 2005 hurricane season  
26 highlighted the need to reassess the appropriate level of investment for emergency  
27 management planning. As discussed, the climate analysis indicates a rise in temperature  
28 and relative sea level for the Gulf Coast region. These changes – coupled with continued  
29 increases in overall population, and of particular concern, major increases in the elderly  
30 and special needs populations – translate into a difficult situation for emergency  
31 evacuations in the Gulf Coast region absent thoughtful and proactive planning.

32 The requirement to transport those with special needs is especially challenging along the  
33 Gulf Coast, where many elderly people live in rural areas. Figure 4.26 illustrates the state  
34 and county/parish boundaries and the population over 65 that were impacted by Hurricane  
35 Katrina.

36 [INSERT FIGURE 4.26 Population over age 65 impacted by Hurricane Katrina]

## **Interdependent Communications Infrastructure**

Successful emergency management depends not only on the transportation infrastructure but also on interdependent communications infrastructure that allows emergency management personnel and responders to dynamically accommodate changing needs and infrastructure availability. Lessons learned from recent events indicate that significant breakdowns in communication can occur across multiple jurisdictions and agencies during major emergencies. Although not linked to or caused by changes in climate characteristics directly, cell phones and land lines quickly become unreliable both pre- and post-event in major regional emergencies. Changes in climate may exacerbate this dynamic as greater penetration of storm surge and wind fields may disable the “day-to-day” communications infrastructure.

A recent study released by First Response Coalition, a public safety group, suggests that many wireless communications systems in hurricane-prone states are still unlikely to function well during major regional emergencies. Communication plans and infrastructure remain largely uncoordinated, even after concerted efforts to improve these dynamics following the 2005 Hurricane season (First Response Coalition, 2006).

The use of new surveillance technologies such as unmanned aerial vehicles (UAV) may help ameliorate problems with existing communications systems that would be exacerbated by future storm events. These relatively new, but increasingly efficient and more affordable devices could be effective new tools in the critical 72-hour period leading up to evacuations, as well as post-event recovery and response operations. These and other strategies may serve as a new means of acquiring and relaying real-time information when existing infrastructure is disabled during a storm.

## **Traffic Management**

Traffic management related to emergency evacuations will become increasingly critical as the population in the Gulf Coast region grows. This may lead to increased instances such as that experienced during Hurricane Rita in 2005, where a coastal community evacuation plan to a nearby regional urban area may be complicated by the inland urban area further from shore undergoing an evacuation itself. As an example, the Galveston region’s historical plans of “evacuating to” Houston changed dramatically during the 2005 hurricane season. Many Galveston (and other area coastal region) residents tried to evacuate “through Houston,” only to encounter hours of gridlock in the oversaturated transportation system that already was filled with Houston residents evacuating from the approaching storm. Also, as storm impacts and the resulting evacuations do not follow state lines, it is important that states not only plan for evacuations of their own residents but also account and allow for potential multistate evacuations that cross multiple state boundaries.

## **Critical Care Facilities and Shelters for Those with Special Needs**

The predicted changes in climate over the next century will make the care of those with special needs more complex and problematic. In the instance of “sheltering in place,” increased attention and planning will need to be given to auxiliary power and backup

1 communication systems to sustain critical health services and to maintain acceptable  
2 quality of life (air conditioning, water supply, etc.).

3 The 2005 hurricane season also produced numerous instances of evacuees with special  
4 needs arriving at their “designated shelters,” only to be turned away due to lack of capacity  
5 or the facility not even being open. Many of these shelters that denied evacuees shelter  
6 receive(d) Homeland Security funding to support the facility infrastructure and operation.  
7 With evacuee demands only expected to increase in the future, the need to ensure reliable  
8 shelter services becomes increasingly important.

### 9 **Local Development Policies**

10 As it relates to the ability to support regional evacuations during emergencies, the potential  
11 for climate impacts – particularly storm surge and wind field during major hurricanes –  
12 should be mapped (and otherwise illustrated) to determine probable zones of risk. This  
13 information can inform local development policies, and guide the location of new housing  
14 and critical care facilities to areas of lower vulnerability.

### 15 **Fiscal Impacts**

16 Revenue data collected by the State of Florida indicates that hurricane weather events  
17 reduce toll collection and increase toll system costs. As shown in Table 4.20 below, the  
18 Florida 2004 hurricane season cost the State’s tolled facilities \$62,600,000 (Ely, 2005).  
19 These financial impacts could negatively impact the fiscal viability of toll projects that are  
20 used for evacuation routes in emergencies. The toll operating agencies in Florida recognize  
21 their toll facilities as evacuation routes and are working to suspend payment of tolls in the  
22 event of a hurricane (Warren, 2005).

23 [INSERT TABLE 4.20 Hurricane impacts on toll revenue in Florida]

24 Increased frequency and severity of hurricanes might pose a challenge to the fiscal  
25 strategies of toll facilities, may discourage the trend to finance future infrastructure with  
26 tolls, and may thereby reduce infrastructure that can be used for emergency evacuation. If  
27 too much of an area is inundated for an extended period there may be a reduction in vehicle  
28 trips below the threshold needed to support repayment of bonds. For example, beaches that  
29 had served as a destination for toll bridges could be flooded by rising sea levels, and no  
30 longer support tourism. This could in turn affect toll revenues, and ultimately undermine  
31 the financial viability of key segments of evacuation routes. Bridge tolls in the Northwest  
32 Florida region (Garcon Point and Mid-Bay Bridges) offer one illustration of this potential  
33 impact.

34 Highways provide the majority of transportation infrastructure for emergency operations.  
35 There are limited public transportation capabilities that operate on separate rights-of-way.  
36 This substantial reliance on a single mode of transportation could endanger many residents  
37 if the highway infrastructure is damaged or made inaccessible.

1 The prospect of climate change may require more frequent changes to emergency  
2 management plans and procedures. After the 2005 hurricane season, many public agencies  
3 are reassessing the appropriate level of investment for this activity. Recent events, as well  
4 as the climate change projections discussed in this report, highlight the need to develop  
5 action plans for worst-case scenarios. With predictions of a warmer Gulf Coast climate,  
6 more intense storms and hurricanes, and rising relative sea levels, the future design of  
7 critical infrastructure and emergency evacuation plans will need to incorporate increased  
8 challenges to our emergency management system.

## 9 ■ 4.3 Impacts and Adaptation: Case Examples in the 10 Study Region

11 While Sections 4.1 and 4.2 analyze the potential future impacts of climate change on the  
12 region, this section focuses on the impacts associated with the recent past Hurricanes  
13 Katrina and Rita. The challenges of responding to severe weather events are all too  
14 familiar to transportation managers in the Gulf Coast. The hurricane season of 2005 was  
15 devastating for many communities in the study area. As the region rebuilds, some areas are  
16 incorporating changes to infrastructure design to help systems better withstand flooding  
17 and storm surge. The lessons learned from the costs of clean up and repair can help  
18 managers assess the implications of infrastructure damage as they consider future  
19 adaptation options. The following case examples illustrate the issues confronting managers  
20 working to ensure a safe and reliable transportation system.

### 21 4.3.1 Impacts of Hurricane Katrina on Transportation Infrastructure

22 Hurricane Katrina, which made landfall on August 29, 2005, was the most destructive and  
23 costliest natural disaster in the history of the United States, and the deadliest hurricane  
24 since the 1928 Okeechobee Hurricane. Over 1,800 people lost their lives during Hurricane  
25 Katrina and the economic losses totaled more than \$100 billion (Graumann et al., 2006).  
26 More than 233,000 km<sup>2</sup> (90,000 square miles) were declared disaster areas. While a single  
27 storm cannot be attributed to climate change, the impacts of Hurricanes Katrina and Rita in  
28 2005 illustrate the types of impacts that would occur more frequently if the Gulf Coast  
29 were to experience more Category 4 and 5 hurricanes in the future.

30 The storm had a devastating impact on much of the transportation infrastructure of coastal  
31 Mississippi, Louisiana, and Alabama, causing major damage to highways, railroads, ports,  
32 and airports. Damage was caused by flooding, pounding waves, and high winds. In  
33 addition, when the floodwaters subsided, an enormous amount of debris still had to be  
34 removed before transportation networks could function. Forty six million cubic yards of  
35 debris were removed from Mississippi alone (from all locations, not just transportation  
36 facilities). Louisiana DOTD spent \$74 million on debris removal following Hurricanes  
37 Katrina and Rita (Paul, 2007).

1 Through aggressive action by public and private transportation managers, many major  
2 transportation facilities were reopened relatively quickly considering the level of damage.  
3 Most of the study area highways, rail lines, pipelines, ports, and airports were back in  
4 service within weeks to a month. Limited access across the I-10 Twin Span Bridge was  
5 available within two months and nearly full access achieved within five months. The  
6 heavily damaged CSX Gulf Coast mainline and its bridges were reopened six months after  
7 being washed out by Hurricane Katrina. The worst damaged facilities were the river and  
8 bay bridges that carry U.S. 90 along the edge of the Gulf Coast. Though much of the  
9 roadway and three of the six badly damaged crossings were repaired within about three  
10 months, the three remaining bridges took considerably longer to repair or replace. The last  
11 of these bridges, the Biloxi-Ocean Springs Bridge, is scheduled to reopen in November  
12 2007, more than two years after Katrina. In all, the price tag of clean-up and reconstruction  
13 effort will run into the billions of dollars: the Louisiana Recovery Authority estimated  
14 costs exceeding \$15 billion for Louisiana alone (Louisiana Recovery Authority, 2006).  
15 Mississippi spent more than \$1 billion on cleanup and bridge replacement. (Mississippi  
16 DOT, 2007).

17 By most accounts, the impact of Hurricanes Katrina and Rita on national-level freight  
18 flows was modest because of redundancy in the national transportation system and timing.  
19 Truck traffic was able to divert to parallel east-west interstate routes that avoided the  
20 collapsed bridges and other barriers. Railroad operators were able to reroute intermodal  
21 and carload traffic that was not bound directly for New Orleans through Memphis and  
22 other Midwest rail hubs. Most of the Mississippi river ports and the Mississippi inland  
23 waterway were back in service in time to handle the peak export demand later in the fall of  
24 2005. Major pipelines suffered relatively little damage and were able to open within days  
25 as electrical power was restored (Grenzeback and Lukmann, 2006).

26 The following text outlines some of the key impacts by mode.

## 27 **Roads**

28 The most significant impacts to roads were to the numerous bay and river crossings  
29 throughout the region. While the effects were limited in some locations and damage was  
30 repaired within days, in some coastal sections prominent elements of the transportation  
31 network remained closed many months after the storm. The worst damage was focused in  
32 the area along and to the south of the I-10/I-12 corridor, including U.S. 90, LA-1, and I-110  
33 in Mississippi and the Lake Pontchartrain Causeway. Three major bridge crossings along  
34 the route were destroyed and two more sustained significant damage. The damage was  
35 largely caused by the immense force of wave action on the bridge spans, many of which  
36 were not sufficiently tied down to the bridge pilings to resist movement (Figure 4.4).  
37 Spans weighing 300 tons were dislodged by the hurricane.

38 Inundation also caused structural problems along many miles of roadway. More than 50  
39 km (30 miles) of coastal U.S. 90, which runs through the beachfront communities of  
40 Mississippi, were completely inundated by the storm. At a cost of \$267 million, the 3.2 km  
41 (2-mile), four-lane U.S. 90 Bay St. Louis Bridge reopened on May 17, 2007. The total

1 request for emergency repairs to Mississippi highways alone after Katrina is \$580 million  
2 (Mississippi Gulf Coast Regional Planning Commission, 2006). Much of the paved surface  
3 between Pass Christian and Biloxi buckled or dropped into sinkholes; in places it took  
4 weeks to repair washouts and to remove many feet of sand from the road surface. 3,200  
5 km (2,000 miles) of roads were submerged in Louisiana, and the Louisiana DOTD found  
6 indications that prolonged inundation can lead to long-term weakening of roadways. A  
7 study of pavements submerged longer than three days (some were submerged several  
8 weeks) found that asphalt concrete pavements and subgrades suffered a strength loss  
9 equivalent to two inches of pavement (Gaspard et al., 2007). The estimate for  
10 rehabilitating a portion of these roads, 320 km (200 miles) of submerged state highway  
11 pavements, amounted to \$50 million.

12 The expense of post-storm cleanup and repair can be considerable. The Louisiana  
13 Recovery Authority estimated that the cost of rebuilding infrastructure (defined as roads,  
14 bridges, utilities and debris removal) damaged by the hurricanes would cost \$15-18 billion.  
15 Louisiana DOTD spent \$74 million on debris removal; as of June 2007, Mississippi DOT  
16 had spent \$672 million on debris removal, highway and bridge repair, and rebuilding the  
17 Biloxi and Bay St. Louis bridges; it expects to spend an additional \$330 million in the  
18 subsequent 18 months (Mississippi DOT, 2007; Louisiana Recovery Authority, 2006).  
19 Also, debris removal is not completely benign; heavy trucks removing debris in Louisiana  
20 also damaged some roadways (Paul, 2007).

## 21 **Rail**

22 The rail infrastructure in coastal Mississippi and Louisiana suffered major damage that  
23 took weeks or months to repair. The worst storm damage was focused on a 160 km (100-  
24 mile) section of CSX's Gulf Coast Line between New Orleans and Pascagoula, Mississippi.  
25 CSX had to restore six major bridges and more than 65 km (40 miles) of track, much of  
26 which was washed out or undermined. Damage was so extensive on the line that CSX  
27 required more than five months and \$250 million to complete repairs and to reopen the  
28 line. It would take many times that if the company wanted to relocate the line further  
29 inland. In addition, New Orleans is a major rail freight interchange point for east-west rail  
30 traffic, and the railroads needed to reroute intermodal and carload traffic that was not  
31 bound directly for New Orleans through other rail hubs in Memphis and St. Louis, which  
32 increased operating expenses (Grenzeback and Lukmann, 2006).

## 33 **Ports**

34 Due to their low-lying locations, the ports were susceptible to damage from all effects of  
35 the hurricane – high winds, heavy rains, and especially the storm surge. Container cranes  
36 were knocked down, storage sheds blown apart, and navigational aids lost. In Gulfport,  
37 Mississippi, the storm surge pushed barges hundreds of feet inland and scattered 40-foot  
38 containers throughout downtown Gulfport. The storm sank nearly 175 barges near New  
39 Orleans, disrupting navigation on the river. However, almost all ports in the Central Gulf

1 Coast were able to reopen within a month of Katrina's landfall. Nonetheless, damage was  
2 costly: More than \$250 million has been allocated to repair, rebuild, and expand the Port  
3 of Gulfport in the wake of Hurricane Katrina (Grenzeback and Lukmann, 2006).

4 Fortunately, the timing of the storm prevented a catastrophic impact on U.S. agricultural  
5 exports. Gulf Coast ports typically handle 55 percent to 65 percent of U.S. raw corn,  
6 soybean, and wheat exports. Since the bulk of U.S. corn and soybean harvest moves down  
7 the Mississippi river from October to February, the ports were generally able to restore  
8 operations in preparation for this critical season, although agriculture still faced increased  
9 shipping costs due to a shortage of barges. The severe damage to Gulfport (which  
10 specializes in importing containerized bananas and winter fruits from Central and South  
11 America) did result in a regional shortage of tropical fruits, because major fruit importers  
12 such as Dole, Chiquita, and Crowley were forced to reroute shipments to Port Everglades,  
13 Florida or Freeport, Texas at extra expense (Grenzeback and Lukmann, 2006).

## 14 **Airports**

15 A number of airports in the study area received significant damage from the strong winds,  
16 flooding rains and embedded tornadoes associated with Hurricane Katrina. Airports  
17 sustained damage to passenger terminals, maintenance facilities, and navigational devices.  
18 Power outages also took air traffic control facilities off-line and darkened nighttime runway  
19 lights. As a result, some airports were closed for days and weeks while necessary repairs  
20 could be made, but relief flights were flown in before the airport facilities were fully  
21 reopened.

22 Louis Armstrong New Orleans International Airport, the third largest airport in the Central  
23 Gulf Coast, sustained damage to its roofs, hangars, and fencing, but had no significant  
24 airfield damage despite sitting only 4 feet above sea level (making it the second lowest  
25 lying international airport in the world, after Schiphol International in The Netherlands).  
26 For the first few weeks of September, the airport was open only to military aircraft and  
27 humanitarian flights, but reopened to commercial flights on September 13, 2005. On the  
28 other hand, Lakefront Airport, one of the busiest general aviation facilities in the Gulf  
29 Coast and located directly on Lake Pontchartrain to the north of the New Orleans city  
30 center, suffered extensive damage, with a number of terminals and hangars destroyed. It  
31 took seven weeks before it could even reopen for daytime operations. Gulfport-Biloxi  
32 International, the fifth busiest commercial airport in the Central Gulf Coast, was also hard  
33 hit by the storm. Located less than a mile inland, between U.S. 90 and I-10 in Gulfport, the  
34 airport's terminal building, taxiways, cargo facility, general aviation facility, and rental car  
35 facility sustained an estimated \$50 million to \$60 million in damage. The airport reopened  
36 to commercial flights on September 8 and returned to its normal volume of traffic in  
37 February 2006 (Grenzeback and Lukmann, 2006).

38 Fifty-eight airports were surveyed on how they were affected by the hurricanes – the extent  
39 of damage either hurricane caused, the ability of the airports to cope with the damage, and  
40 the use of the airports for emergency management. Twenty-nine airports, or 50 percent,  
41 responded to the survey. Forty-eight percent of respondents pointed to the following as



1 some of the main reasons for closure: electrical outage (19 percent), wind damage (16  
2 percent), and debris on runways (12 percent) were the top three reasons identified. Civil,  
3 military, and passenger airline operations were affected by the hurricanes. Figure 4.23  
4 identifies airports affected by Hurricane Katrina's winds. GIS analysis indicates 16  
5 airports experienced winds exceeding 161 km/hour (100 miles per hour) during Hurricane  
6 Katrina, including New Orleans International, Gulfport-Biloxi, and Hattiesburg  
7 commercial service airports. These airports are located in Southeast Louisiana and South-  
8 Central Mississippi. USGS data also indicates nine airports impacted by Hurricane Rita  
9 experienced winds exceeding 161 km/hour (100 miles per hour), including two commercial  
10 service airports located in Texas and Southwest Louisiana: Lake Charles Regional and  
11 Beaumont-Port Arthur. Survey responses indicated additional implications to aircraft  
12 operations as follows:

- 13 • Civil aircraft operations were closed at 12 airports. The average length of closure to  
14 civil aircraft operations was 209 hours and the maximum observed closure was 1,152  
15 hours. Lakefront Airport in New Orleans, an outlier, was closed for 48 days and skews  
16 the data. When removing this airport from the data field, the average length of time  
17 closed to civil aircraft operations is 35 hours. It is noteworthy that although many  
18 airports "opened" soon after the hurricanes passed, many were without electricity and  
19 were only open during daylight hours.
- 20 • Military aircraft operations were closed at eight airports. The average length of closure  
21 to military aircraft operations at civil airports was 33 hours and the maximum observed  
22 closure was 96 hours.
- 23 • Two commercial service airports, Lake Charles Regional and William P. Hobby,  
24 reported passenger airline operations were suspended at their airport.

25 [INSERT FIGURE 4.27 Airports affected by Hurricane Katrina winds]

26 Hangar facilities also were damaged by the two hurricanes. Thirty-eight percent of  
27 responding airports suffered damage to T-hangars, long rectangular structures with 12 to 20  
28 "bays" which store single-engine and small twin-engine aircraft. Forty-five percent of  
29 responding airports experienced damage to conventional hangars, which are designed to  
30 store large aircraft, and are 18 by 18 meters (60 by 60 feet) to 30 by 30 meters (100 by 100  
31 feet) in size. Conventional hangars are also 6 to 9 meters (20 to 30 feet) in height to  
32 accommodate large aircraft with high tails.

### 33 **Pipelines**

34 The major petroleum/petroleum product pipelines servicing the study area received  
35 relatively little physical damage from the effects of Hurricanes Katrina and Rita, but could  
36 not operate reliably due to massive power outages in the wake of the storms and by  
37 interruptions to the supply of fresh product to transport due to refinery shutdowns, causing  
38 shortages of petroleum products in parts of the nation. Even so, most of these systems  
39 were able to resume partial service within days of the storm and full service within a week.

1 At the peak of the disruption cause by Hurricane Katrina, 11 petroleum refineries were shut  
2 down, representing 2.5 million barrels per day or 15 percent of U.S. refining capacity and  
3 all major pipelines in the area were inoperable due to power outages. By September 4, five  
4 days after the storm, eight major petroleum refineries remained shut down (representing 1.5  
5 million barrels per day or nine percent of U.S. refining capacity); however, all of the major  
6 crude or petroleum product pipelines had resumed operation at either full or near-full  
7 capacity (Grenzeback and Lukmann, 2006).

### 8 **4.3.2 Evacuation during Hurricane Rita**

9 Emergency evacuation is a key strategy to cope with hurricanes in the low-lying Gulf Coast  
10 study region. The evacuation of Houston/Galveston, the largest metropolitan area in the  
11 study region, prior to Hurricane Rita presents a case study of the difficulties of evacuating  
12 large urban areas and some lessons learned for future emergency planning.

13 Unlike New Orleans, much of Houston is high enough to be out of the storm surge zone;  
14 thus generally Galveston and the low-lying eastern areas are supposed to evacuate first.  
15 However, Houstonians learned during Tropical Storm Allison (2001) that precipitation  
16 alone can cause massive flooding in the city from overflowing bayous and lack of drainage.  
17 With images of the devastation wrought by Hurricane Katrina fresh on their mind, up to 2.5  
18 million people attempted to evacuate the Houston/Galveston area in the days before Rita's  
19 projected landfall (Mack, 2005) – twice as many people as the area's evacuation planning  
20 was developed for (Durham, 2006). In fact, only about half of these people lived in  
21 evacuation zones (Feldstein and Stiles, 2005).

22 Evacuees faced massive congestion, with 160 km (100-mile) traffic jams reported  
23 (Breckinridge et al., 2006). One fifth of the evacuees spent more than 20 hours on the road  
24 to leave the area; only half completed the trip in less than 10 hours (Mack, 2005).  
25 Worsening the congestion, households traveled in multiple cars in order to get valuable  
26 property out of harm's way: the Texas Transportation Institute (TTI) estimated that on  
27 average there were 1.2 occupants per vehicle, versus the 2.1 occupants generally assumed  
28 in evacuation planning (Durham, 2006). In an effort to ease congestion, officials  
29 improvised a last-minute contraflow system on some highways, which was not part of their  
30 original evacuation plan. Fuel shortages plagued travelers as gasoline stations on the  
31 evacuation routes were overwhelmed by demand. Tragically, 23 nursing home evacuees  
32 died when their bus caught fire on the road.

33 Following the storm, the Houston-Galveston Area Evacuation and Response Task Force  
34 identified several lessons learned from the experience and recommendations for the future  
35 (Durham, 2006):

- 36 • Evacuation plans should be practiced extensively prior to the hurricane season, to  
37 reveal problems ahead of time.
- 38 • Plans should include a system for removing disabled vehicles – during Rita, an  
39 effective incident management service was available only within the Houston city

1 limits. As a result, vehicle breakdowns caused significant bottlenecks along the  
2 evacuation routes.

- 3 • Contraflow plans should be developed well in advance. However, it recognized that  
4 contraflow operations are not a panacea. Emergency planners will need to consider the  
5 numerous drawbacks of implementing contraflow strategies: They require intensive  
6 use of law enforcement and other personnel, disrupt day-to-day operations in areas not  
7 evacuating, and make it more difficult to move emergency vehicles and supplies back  
8 into the area.
- 9 • Thorough planning is necessary for special needs evacuees, including ensuring an  
10 adequate supply of vehicles, identifying destination(s) capable of supporting their  
11 needs, and providing personnel sufficient training to ensure a safe trip.

12 The Rita evacuation also demonstrated the importance of accounting for human behavior.  
13 “Too few” people evacuated New Orleans before Katrina, but “too many” evacuated the  
14 Houston-Galveston area (Breckinridge et al., 2006). Evacuation orders are meant to  
15 reinforce the fundamental strategy of “run from the water, hide from the wind”; however,  
16 in the case of Rita it seems many evacuees ran from the wind. Similarly, the tendency of  
17 households to take as many vehicles with them as possible is a logical way to protect  
18 property but counterproductive during a mass evacuation. This illustrates the need to better  
19 understand the range of potential reactions by residents during a crisis, and how best to  
20 communicate with the public to facilitate effective emergency management.

### 21 **4.3.3 Elevating Highway 1**

22 Louisiana currently is in the process of upgrading and elevating portions of Louisiana  
23 Highway 1, a road that is very important both locally and nationally. It connects Fourchon  
24 and Port Fourchon to Leeville and Golden Meadow to the north. The project is broken into  
25 multiple phases and includes a four-lane elevated highway between Golden Meadow,  
26 Leeville, and Fourchon, to be elevated above the 500-year flood level; a bridge at Leeville,  
27 with 73-foot clearance over Bayou LaFourche and Boudreaux Canal. Construction has  
28 begun on both the \$161 million bridge project, and a segment of the road south of Leeville  
29 to Port Fourchon (Wilbur Smith, 2007).

30 Hurricane Katrina’s impact on the energy infrastructure helped raise the profile of the  
31 dangers facing and importance of Highway 1. The highway floods even in low-level  
32 storms, and in addition to the effects of storm surge the existing infrastructure also faces  
33 threats from very high rates of coastal erosion and subsidence (Smith, 2006).

34 The importance of this part of the Gulf Coast, and thus Highway 1, to the nation’s energy  
35 supply and infrastructure cannot be overstated. It is the only roadway linking Port  
36 Fourchon and the Louisiana Offshore Oil Port (LOOP) to the nation. Port Fourchon  
37 supports 75 percent of deepwater oil and gas production in the Gulf of Mexico, and its role  
38 in supporting oil production in the region is increasing. The LOOP, located about 32 km  
39 (20 miles) off-shore, plays a key role in U.S. petroleum importation, production and

1 refining as it links daily imports of 1 million barrels and 300,000 barrels of oil produced in  
2 the Gulf of Mexico to 50 percent of U.S. refining capacity. Locally, the road is the key  
3 route for transporting machinery and supplies to Port Fourchon and offshore oil workers,  
4 and also for exporting seafood from the region. Perhaps most importantly, it is the  
5 evacuation route for south Lafourche and Grand Isle, as well as some 5,000 offshore oil  
6 workers (LA 1 Coalition, 2007a and b).

## 7 ■ 4.4 Conclusions

8 The results of this investigation shows a wide range of possible impacts on transportation  
9 infrastructure and services across the Gulf Coast study area. Given the uncertainties  
10 inherent in modeling and the complexities of the natural processes involved, the analysis  
11 does not attempt to pinpoint the precise timing of climate effects but rather provides a  
12 broad assessment of potential impacts during the coming decades. These findings provide  
13 a critical overview for transportation planners and managers of the potential implications of  
14 climate factors, and indicate areas of vulnerability that warrant consideration by decision-  
15 makers. Future investment decisions should be informed by the potential risks identified in  
16 this study.

17 Some of the most evident impacts are related to relative sea level rise and storm surge. A  
18 4-foot increase in RSLR could inundate a substantial portion of the transportation  
19 infrastructure in the region: 28 percent of the arterials, 43 percent of the intermodal  
20 connectors, and 20 percent of the rail miles. Nearly three quarters of ports could be  
21 affected, as well as three airports, including Louis Armstrong International in New Orleans.  
22 Impacts associated with storm activity are more acute, although confined to the specific  
23 locations of individual storm events. Some 51 percent of arterials and 56 percent of  
24 interstates along with almost all ports, a third of rail lines and 22 airports are vulnerable to  
25 a storm surge of 18 feet, should such a surge occur. As the potential of higher-intensity  
26 storms increases and sea level rises, the vulnerability of infrastructure to storm surge  
27 becomes increasingly significant.

28 The direct impacts of climate factors on specific facilities can have much broader  
29 implications than implied by the percentages and maps contained in this chapter. Damage  
30 to critical links in the intermodal network can disrupt connectivity throughout the region.  
31 These disruptions can be relatively short-term, as in the case of precipitation and some  
32 storm surge and weather events; moderate, as in the case of shut-downs to conduct  
33 maintenance required to repair pavement surfaces caused by higher temperatures or storm  
34 surges; or long-term interruptions of service caused by inundation and damage to entire  
35 segments of infrastructure due to storm surge or permanent sea level rise.

36 The safety impacts associated with climate impacts deserve further in-depth analysis  
37 beyond this effort. Storm activity and storm surge in particular have the most direct  
38 implications for safety. These include accidents caused by: debris caused by storms,  
39 washed-out roads during or after storms, or evacuations before storms. Furthermore, the

1 other key climate drivers, including changes in precipitation patterns, temperature, and  
2 relative sea level rise could have important safety impacts as well.

3 In addition to these regional impacts, the vulnerabilities of Gulf Coast transportation will  
4 have nationwide significance that merit further investigation. The resilience of Gulf Coast  
5 transportation infrastructure capabilities has implications for the country's ability to  
6 transport many key commodities into and out of the United States, including petroleum and  
7 natural gas, agricultural products, and other bulk goods.

### 8 ***Data and Research Opportunities***

9 This study identified needs for additional data and research that would further advance  
10 understanding of the implications of climate change for transportation. These include  
11 information and investigation in the following areas:

- 12 • **Integration of Site-Specific Data** – The integration of site-specific elevation and  
13 location data in a GIS-compatible format would greatly facilitate investigation of the  
14 impacts of climate change and the natural environment on transportation. This data  
15 should include information on transportation facilities as well as on protective  
16 structures such as levees and dikes
- 17 • **Additional and Refined Climate Data and Projections** – Further development of  
18 environmental trend data and climate model projections tailored to transportation  
19 decision-makers is needed to facilitate integration of climate information into  
20 transportation decisions. In addition, specific data on other climate factors not fully  
21 addressed in this study would be valuable. These factors include wind speeds, isolated  
22 hot days, and fog.
- 23 • **Effects of Climate Change on Freight Transport Demand** – Research is needed on  
24 the perspectives, investment considerations, relocation plans, and adaptation strategies  
25 of private sector shippers and freight transportation providers, and how their  
26 requirements may evolve due to climate change and shifts in market demand.
- 27 • **Demographic Response to Climate Change** – High-population density creates  
28 increased need for both passenger transport and movement of consumer goods.  
29 Population change will be driven by multiple factors, possibly including changing  
30 environmental conditions. Projections of population density along coastal regions and  
31 their impact on the demand for freight and passenger services need to be explored.
- 32 • **Design Standards and Reconstruction and Adaptation Costs** – Additional case  
33 information would be valuable regarding the costs of rebuilding transportation facilities  
34 following severe storms. Research is needed on how local agencies are adapting design  
35 standards during reconstruction (or construction of new facilities) to increase the  
36 resilience of their facilities, such as changes in bridge height or construction, use of  
37 new materials, and changes in design criteria. Analysis of the range of adaptation  
38 options available to transportation decision-makers, and the costs and benefits of

1 specific strategies, would help inform state and local transportation planners and  
2 decision-makers.

- 3 • **New Materials and Technologies** – Research is needed to develop materials that can  
4 better withstand higher temperatures and drier or wetter conditions, and technologies  
5 that can help us better adapt to the effects of climate change.
- 6 • **Pipelines** – A more complete examination of pipeline impacts from climate change and  
7 adaptation strategies is warranted.
- 8 • **Land Use and Climate Change Interactions** – Research is required to investigate  
9 how various land use development and environmental management strategies in  
10 vulnerable areas affects the magnitude of climate change impacts on communities and  
11 transportation infrastructure. A comparative analysis of current international best  
12 practices in land use and building codes, particularly in coastal regions, could provide  
13 useful information to U.S. transportation and planning agencies.
- 14 • **Emergency Management Planning/Coordination/Modeling** – Additional study on  
15 successful approaches in coordinating emergency management planning among public  
16 agencies and major private sector entities in at-risk areas could identify opportunities  
17 for improved coordination, public-private partnering, and risk reduction. Development  
18 and application of simulation modeling should be considered to illustrate the increasing  
19 challenges of evacuating major urban areas and evaluate mitigation strategies.  
20 Collection and evaluation of real-time data gathered during emergencies is needed to  
21 determine its possible use to first responders, operating agencies, the media, and the  
22 general public. Changes in communication and information technology infrastructure  
23 also should be explored.
- 24 • **Secondary and National Economic Impacts** – More in-depth research into the  
25 secondary economic impacts to the region and nation of freight disruption would  
26 benefit understanding of national trends and vulnerabilities, and inform development of  
27 appropriate policies.
- 28 • **Site Specific Impacts** – This assessment considers scenarios of change for the counties  
29 that comprise the central Gulf Coast. More detailed analysis is desirable since specific  
30 transportation facilities will ultimately be affected by climate change. This will require  
31 development of climate data and information that is specific to much smaller  
32 geographic areas, in addition to detailed analysis of specific facilities.

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31



**Table 4.1 Relative sea level rise (RSLR) modeled using SLRRP.**

	Low Range	High Range
Galveston, Texas	117 cm (3.8 feet)	161 cm (5.3 feet)
Grand Isle, Louisiana	160 cm (5.2 feet)	199 cm (6.5 feet)
Pensacola, Florida	70 cm (2.3 feet)	114 cm (3.8 feet)

**Table 4.2 Relative sea level rise (RSLR) modeled using CoastClim.**

	Projected Subsidence by 2100	RSLR, B1-Low Range	Subsidence, Percent of Low Range	RSLR, A1F1-High Range	Subsidence, Percent of High Range
Galveston, Texas	51.7 cm (1.7 feet)	72 cm (2.4 feet)	71.8%	130 cm (4.3 feet)	39.7%
Grand Isle, Louisiana	88.6 cm (2.9 feet)	109 cm (3.5 feet)	81.3%	167 cm (5.5 feet)	53.0%
Pensacola, Florida	3.7 cm (0.12 feet)	24 cm (0.8 feet)	15.4%	82 cm (2.7 feet)	4.5%

**Table 4.3 Relative sea level rise impacts on Gulf Coast transportation modes: percentage of facilities vulnerable.**

Relative Sea Level Rise	Interstate Highways	Ports (Freight)	Rail Lines	Airports
61 cm (2 Feet)	19%	64%	5%	1 airport
122 cm (4 Feet)	24%	72%	9%	3 airports

**Table 4.4 Storm surge impacts on Gulf Coast transportation modes: percentage of facilities vulnerable.**

<b>Storm Surge Height</b>	<b>Interstate Highways</b>	<b>Ports (Freight and Nonfreight)</b>	<b>Rail Lines</b>	<b>Airports</b>
5.5 m (18 Feet)	56%	98%	33%	22 airports
7.0 m (23 Feet)	64%	99%	41%	29 airports

**Table 4.5 Relative sea level rise impacts on highways: percentage of facilities vulnerable.**

<b>Relative Sea Level Rise</b>	<b>Arterials</b>	<b>Interstates</b>	<b>Intermodal Connectors</b>
61 cm (2 Feet)	20%	19%	23%
122 cm (4 Feet)	28%	24%	43%

**Table 4.6 Storm surge impacts on highways: percentage of facilities vulnerable.**

<b>Storm Surge Height</b>	<b>Arterials</b>	<b>Interstates</b>	<b>Intermodal Connectors</b>
5.5 m (18 Feet)	51%	56%	73%
7.0 m (23 Feet)	57%	64%	73%

**Table 4.7 Relative sea level rise impacts on rail: percentage of facilities vulnerable.**

<b>Relative Sea Level Rise</b>	<b>Rail Lines (track miles)</b>	<b>Rail Freight Facilities (94)</b>	<b>Rail Passenger Stations (21)</b>
61 cm (2 Feet)	5%	12%	0
122 cm (4 Feet)	9%	20%	0

**Table 4.8 Freight railroad-owned and served facilities in the Gulf Coast study region at elevation of 122 cm (4 feet) or less.**

Name	Modal Access	City	State	Elevation (Feet)
KCS	Rail and truck	Metairie	Louisiana	< 0
Larsen Intermodal, Inc.	Rail and truck	Metairie	Louisiana	< 0
New Orleans Cold Storage and Warehouse, Ltd.	Rail and truck	Metairie	Louisiana	< 0
Port of Gulfport	Truck, port, rail	Gulfport	Mississippi	< 0
Port of Galveston	Truck, port, rail	Galveston	Texas	< 0
NS – New Orleans, Louisiana	Rail and truck	New Orleans	Louisiana	0-1
UP Intermodal Facility	Rail and truck	Avondale	Louisiana	0-1
Port of Freeport	Truck, port, rail	Freeport	Texas	0-1
Dry Storage Corporation of Louisiana	Rail and truck	Kenner	Louisiana	1-2
DSC Logistics	Rail and truck	Kenner	Louisiana	1-2
Yellow Terminal	Rail and truck	New Orleans	Louisiana	1-2
BNSF – New Orleans, Louisiana	Rail and truck	Westwego	Louisiana	2-3
BNSF 539 Bridge	Rail and truck	Westwego	Louisiana	2-3
BNSF Intermodal Facility	Rail and truck	New Orleans	Louisiana	2-3
Intermodal Cartage Company	Truck, port, rail	New Orleans	Louisiana	2-3
Transflo	Rail and truck	New Orleans	Louisiana	2-3
BNSF 101 Avonda	Rail and truck	Avondale	Louisiana	3-4
Downtown Transfer, Inc.	Rail and truck	Avondale	Louisiana	3-4
Port of New Orleans	Truck, port, rail	New Orleans	Louisiana	3-4

**Table 4.9 Vulnerability from sea level rise and storm surge by rail distance and number of facilities.**

Elevation Risk Gridcode	Ground Elevation (Feet)	Cumulative		
		Mileage of Railway Segments Vulnerable	Freight Facilities Vulnerable	Passenger Facilities Vulnerable
0 and 1	<1	86	8	0
2	1-2	146	11	0
3	2-3	191	16	0
4	3-4	267	19	0
5	4-5	412	22	0
6	5-18	966	40	9
7	18-23	1,190	51	12
8	>24	2,934	94	21

**Table 4.10 Storm surge impacts on rail: percentage of facilities vulnerable.**

Storm Surge Height	Rail Lines (Track Miles)	Rail Freight Facilities (94)	Rail Passenger Stations (21)
5.5 m (18 Feet)	33%	43%	43%
7.0 m (23 Feet)	41%	54%	57%



**Table 4.11 Amtrak stations projected to be impacted by storm surge of 5.5 and 7.0 meters (18 and 23 feet).**

Station	State	Amtrak Services
<i>5.5-Meter (18-Foot) Storm Surge</i>		
Mobile	Alabama	Sunset Limited <sup>a</sup>
Pascagoula	Mississippi	Sunset Limited <sup>a</sup>
Lake Charles	Louisiana	Sunset Limited
New Orleans	Louisiana	City of New Orleans, Crescent, Sunset Limited
Schriever	Louisiana	Sunset Limited
Slidell	Louisiana	Crescent
Beaumont	Texas	Sunset Limited
Galveston	Texas	Service by bus
La Marque	Texas	Service by bus
<i>7.0-Meter (23-Foot) Storm Surge</i>		
New Iberia	Louisiana	Sunset Limited
Bay St. Louis	Mississippi	Sunset Limited <sup>a</sup>
Biloxi	Mississippi	Sunset Limited <sup>a</sup>

<sup>a</sup> Stations are currently inactive due to Hurricane Katrina.

**Table 4.12 Relative sea level rise impacts on ports: percentage of facilities vulnerable.**

Relative Sea Level Rise	Ports	
	Freight	Nonfreight
61 cm (2 Feet)	64%	68%
122 cm (4 Feet)	72%	73%

**Table 4.13 Storm surge impacts on ports: percentage of facilities vulnerable.**

Storm Surge Height	Ports (Freight and Nonfreight)
5.5 m (18 Feet)	98%
7.0 m (23 Feet)	99%

**Table 4.14 FAA recommended runway lengths for hypothetical general aviation airport. (Federal Aviation Administration, Airport Design Version 4.2D, U.S. DOT)**

<b>Airport Data</b>	
Airport Elevation	30
Maximum Difference in Runway Centerline Elevation (Feet)	1
Temperature (°F)	91.5
Runway Condition	Wet
<b>Small Airplanes</b>	
Small Airplanes with Approach Speeds of Less than 30 Knots	330
Small Airplanes with Approach Speeds of Less than 50 Knots	870
Small Airplanes with Less than 10 Passenger Seats	
75 Percent of these Small Airplanes	2,530
95 Percent of these Small Airplanes	3,100
100 Percent of these Small Airplanes	3,660
Small Airplanes with 10 or More Passenger Seats	4,290
<b>Large Airplanes</b>	
Large Airplanes of 60,000 Pounds <sup>a</sup> or Less	
75 Percent of these Large Airplanes at 60 Percent Useful Load	5,370
75 Percent of these Large Airplanes at 90 Percent Useful Load	7,000
100 Percent of these Large Airplanes at 60 Percent Useful Load	5,500
100 Percent of these Large Airplanes at 90 Percent Useful Load	8,520

<sup>a</sup> Maximum takeoff weight.

**Table 4.15 Summary of impacts of temperature change to runway length (general aviation) under three climate scenarios (SRES Scenarios A2, B1, and A1B). (Federal Aviation Administration (FAA) Airport Design Version 4.2D, U.S. DOT)**

Analysis Category	Base Year	50 <sup>th</sup> Percentile					
		2050 Climate Scenarios		2100 Climate Scenarios			
		A2	B1	A1B	A2	B1	A1B
Possible Mean Maximum Temperature of Hottest Month (°F)	91.4	95.5	94.6	95.9	99.9	96.3	98.4
<b>Runway Length Analysis by Aircraft Type</b>							
<b>Runway Length (Feet)</b>							
<b>Runway Length Percent Increase</b>							
Small Airplanes with Less than 10 Passenger Seats							
75 Percent of these Small Airplanes	2,530	1.6%	1.2%	1.6%	3.2%	1.6%	2.8%
95 Percent of these Small Airplanes	3,100	1.3%	1.0%	1.6%	2.9%	1.6%	2.6%
100 Percent of these Small Airplanes	3,660	1.6%	1.1%	1.6%	3.3%	1.6%	2.7%
Small Airplanes with 10 or More Passenger Seats	4,290	1.6%	1.2%	1.9%	3.3%	1.9%	2.8%
Large Airplanes of 60,000 Pounds or Less							
75 Percent of these Large Airplanes at 60 Percent Useful Load	5,370	0.9%	0.7%	1.1%	2.4%	1.1%	2.0%
75 Percent of these Large Airplanes at 90 Percent Useful Load	7,000	2.1%	0.9%	2.7%	7.9%	2.7%	6.0%
100 Percent of these Large Airplanes at 60 Percent Useful Load	5,500	2.5%	1.6%	3.3%	8.0%	3.3%	6.2%
100 Percent of these Large Airplanes at 90 Percent Useful Load	8,520	6.8%	4.9%	7.9%	16.3%	7.9%	13.1%

**Table 4.16 Commercial aircraft runway length takeoff requirements.**

Aircraft Group	Aircraft Type <sup>a</sup>	Required Runway Length <sup>b</sup>	Commercial Service Airport Primary Runway Lengths (Feet)												
			EFD 9,001	IAH 12,001	HOB 7,602	BPT 6,750	MSY 10,104	LFT 7,651	BTR 7,004	LCH 6,500	MOB 8,521	GPT 9,002	HBG 6,099		
Wide-Body	747-400	10,400	-1,399	1,601	-2,798	-3,650	-296	-2,749	-3,396	-3,900	-1,879	-1,398	-4,301		
	MD 11	11,800	-2,799	201	-4,198	-5,050	-1,696	-4,149	-4,796	-5,300	-3,279	-2,798	-5,701		
	777-200LR	11,500	-2,499	501	-3,898	-4,750	-1,396	-3,849	-4,496	-5,000	-2,979	-2,498	-5,401		
Medium-Haul <sup>c</sup> Narrow Body	737-900	8,700	302	3,301	-1,098	-1,950	1,404	-1,049	-1,696	-2,200	-179	302	-2,601		
	DC-9-15	8,200	801	3,801	-598	-1,450	1,904	-549	-1,196	-1,700	321	802	-2,101		
	737-800	7,300	1,701	4,701	302	-550	2,804	351	-296	-800	1,221	1,702	-1,201		
	MD-80	7,200	1,801	4,801	402	-450	2,904	451	-196	-700	1,321	1,802	-1,101		
	737-300	6,600	2,401	5,401	1,002	150	3,504	1,051	404	-100	1,921	2,402	-501		
	A300-600	6,500	2,501	5,501	1,102	250	3,604	1,151	504	0	2,021	2,502	-401		
	737-500	6,300	2,701	5,701	1,302	450	3,804	1,351	704	200	2,221	2,702	-201		
	A319	6,100	2,901	5,901	1,502	650	4,004	1,551	904	400	2,421	2,902	-1		
	757-200	6,000	3,001	6,001	1,602	750	4,104	1,651	1,004	500	2,521	3,002	99		
	737-600	5,800	3,201	6,201	1,802	950	4,304	1,851	1,204	700	2,721	3,202	299		
Regional Jets and Turboprops	ERJ 145	6,400	2,601	5,601	1,202	350	3,704	1,251	604	100	2,121	2,602	-301		
	ERJ 135	6,400	2,601	5,601	1,202	350	3,704	1,251	604	100	2,121	2,602	-301		
	CRJ	6,000	3,001	6,001	1,602	750	4,104	1,651	1,004	500	2,521	3,002	99		
	DASH8-300	5,100	3,901	6,901	2,502	1,650	5,004	2,551	1,904	1,400	3,421	3,902	999		

<sup>a</sup> MD 11 aircraft runway length based on standard day +33°F. All other aircraft based on standard day +27°F.

<sup>b</sup> Assumes all elevations at sea level.

<sup>c</sup> Medium-Haul are aircraft weights for 800 miles of fuel on-board.

EFD	Houston Ellington Field	MSY	New Orleans International	MOB	Mobile Regional
IAH	Houston Intercontinental	LFT	Lafayette Regional	GPT	Gulfport Biloxi
HOB	Houston Hobby	BTR	Baton Rouge Metropolitan	HBG	Hattiesburg Regional
BPT	Beaumont/Port Arthur Regional	LCH	Lake Charles Regional		

**Table 4.17 Airports located on 100-year flood plains. (Wilbur Smith Associates; USGS)**

<b>Associated City</b>	<b>State</b>	<b>Airport Name</b>
Gonzales	Louisiana	Louisiana Regional
Sulphur	Louisiana	Southland Field
Galliano	Louisiana	South Lafourche
New Orleans	Louisiana	Lakefront
Reserve	Louisiana	St. John The Baptist Parish
Thibodaux	Louisiana	Thibodaux Municipal
Winnie/Stowell	Texas	Chambers County-Winnie Stowell
Galveston	Texas	Scholes International at Galveston

**Table 4.18 Gulf Coast study area airports vulnerable to submersion by relative sea level rise of 61 to 122 cm (2 to 4 feet).**

<b>State</b>	<b>Associated City</b>	<b>Airport Name</b>	<b>Airport Type</b>	<b>Elevation in Feet</b>
Louisiana	Galliano	South LaFourche	GA	1
Louisiana	New Orleans	New Orleans NAS JRB	MIL	3
Louisiana	New Orleans	Louis Armstrong-New Orleans International	CS	4

**Table 4.19 Gulf Coast study area airports vulnerable to storm surge. (FAA Records, April 2006. FEMA Storm Inundation Data)**

State	Associated City	Airport Name	Airport Type	Elevation
<i>Airports 0 to 18 Feet Elevation</i>				
Alabama	Gulf Shores	Jack Edwards	General Aviation	16
Alabama	Mobile	Dauphin Island Airport	General Aviation	5
Louisiana	Abbeville	Abbeville Chris Crusta Memorial	General Aviation	15
Louisiana	Crowley	Le Gros Memorial	General Aviation	17
Louisiana	Galliano	South LaFourche	General Aviation	1
Louisiana	Gonzales	Louisiana Regional	General Aviation	15
Louisiana	Houma	Houma-Terrebonne	General Aviation	10
Louisiana	Jeanerette	Le Maire Memorial	General Aviation	14
Louisiana	Lake Charles	Lake Charles Regional	Commercial Services	15
Louisiana	Lake Charles	Chennault International	Industrial	17
Louisiana	New Orleans	New Orleans NAS JRB	Military	3
Louisiana	New Orleans	Louis Armstrong-New Orleans International	Commercial Services	4
Louisiana	New Orleans	Lakefront	General Aviation	8
Louisiana	Patterson	Harry P. Williams Memorial	General Aviation	9
Louisiana	Reserve	St. John The Baptist Parish	General Aviation	7
Louisiana	Sulphur	Southland Field	General Aviation	11
Louisiana	Thibodaux	Thibodaux Municipal	General Aviation	9
Louisiana	Welsh	Welsh	General Aviation	18
Mississippi	Pascagoula	Trent Lott International	General Aviation	17
Texas	Beaumont/Port Arthur	Southeast Texas Regional	General Aviation	15
Texas	Galveston	Scholes International at Galveston	General Aviation	6
Texas	Orange	Orange County	General Aviation	13
<i>Airports 19 to 23 Feet Elevation</i>				
Alabama	Mobile	Mobile Downtown	Industrial	19
Louisiana	Iberia	Acadiana Regional	Industrial	20
Louisiana	Jefferson Davis	Jennings	General Aviation	20
Mississippi	Hancock	Stennis International	Industrial	23
Mississippi	Harrison	Keesler AFB	Military	20
Texas	Brazoria	Brazoria County	General Aviation	22
Texas	Chambers	Chambers County-Winnie Stowell	General Aviation	21

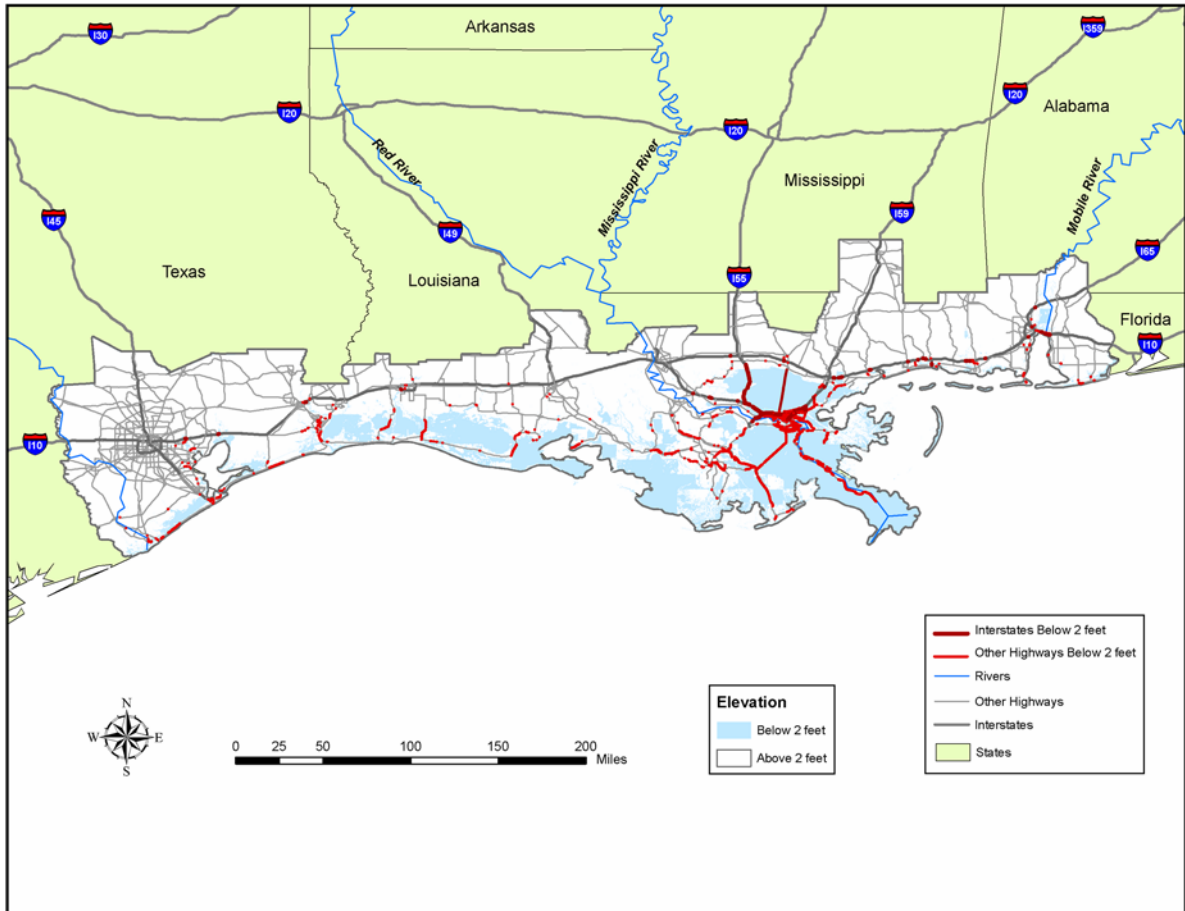
**Table 4.20 Hurricane impacts on toll revenue in Florida. (Ely 2005)**

<b>Entity</b>	<b>Hurricane Season 2004</b>		
	<b>Millions</b>		
	<b>Estimated Revenue Loss</b>	<b>Estimated Damage Costs</b>	<b>Estimated Total Loss</b>
Turnpike System	\$32.21	\$8.50	\$40.71
FDOT-Owned (5)	2.48	1.33	3.81
Garcon Point	0.27	0.22	0.49
Mid-Bay	0.52	0.25	0.77
MDX	1.03	0.00	1.03
Bob Sikes	0.30	1.76	2.06
THCEA	1.44	0.00	1.44
OOCEA	9.07	1.50	10.57
Lee County	0.70	0.87	1.57
Miami-Dade County	0.11	0.00	0.11
Monroe (Card Sound)	0.04	0.00	0.04
<b>Total</b>	<b>\$48.17</b>	<b>\$14.43</b>	<b>\$62.60</b>

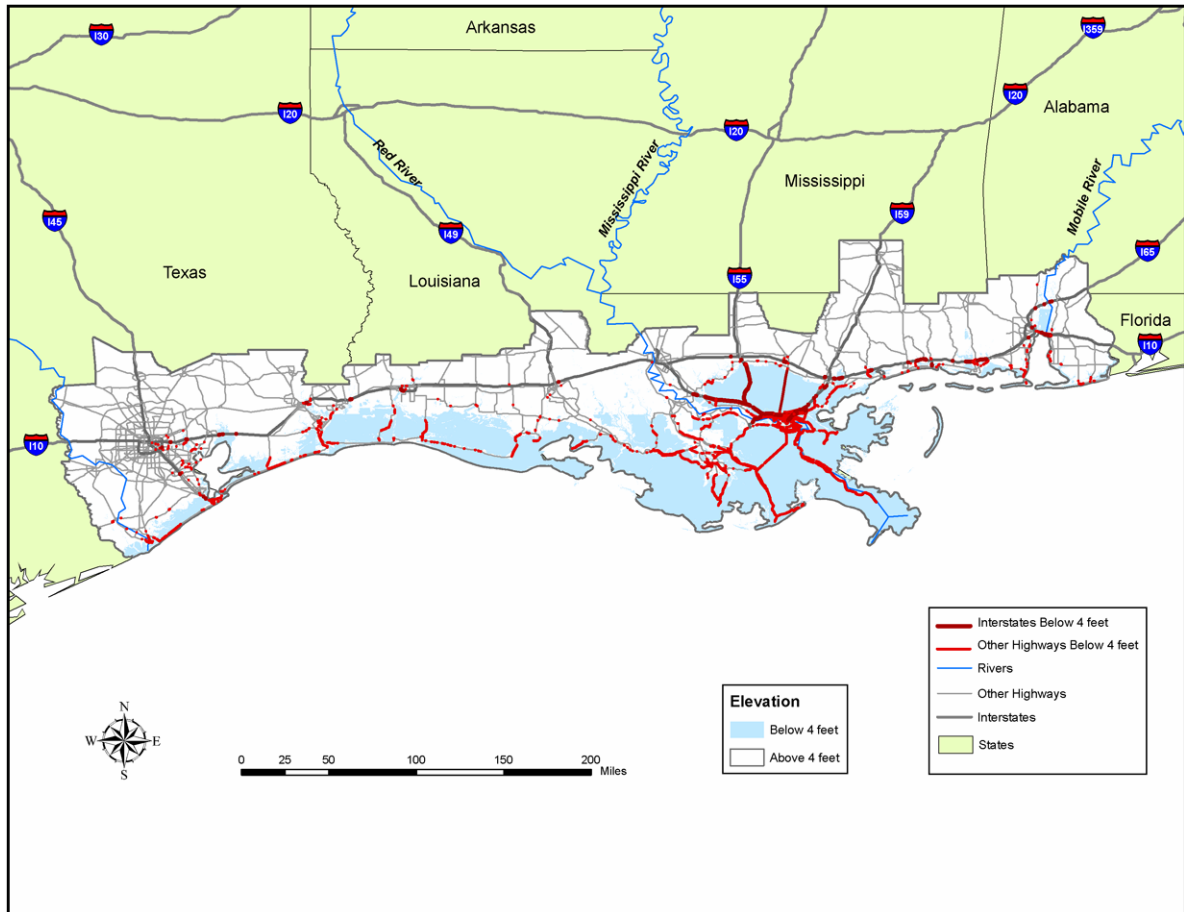




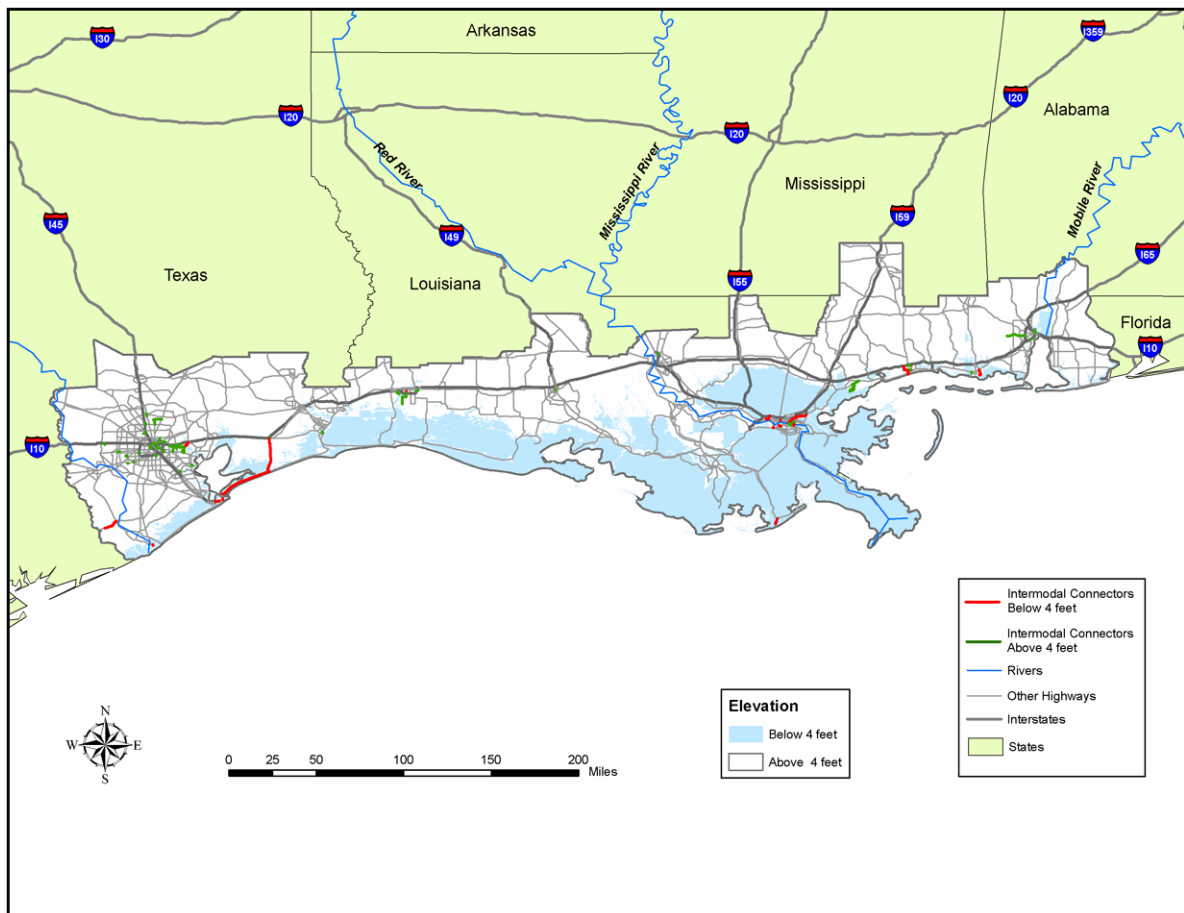
**Figure 4.1** Highways at risk from a relative sea level rise of 61 cm (two feet).  
(Source: Cambridge Systematics analysis of U.S. DOT data)



**Figure 4.2 Highways at risk from a relative sea level rise of 122 cm (four feet).  
(Source: Cambridge Systematics analysis of U.S. DOT data)**



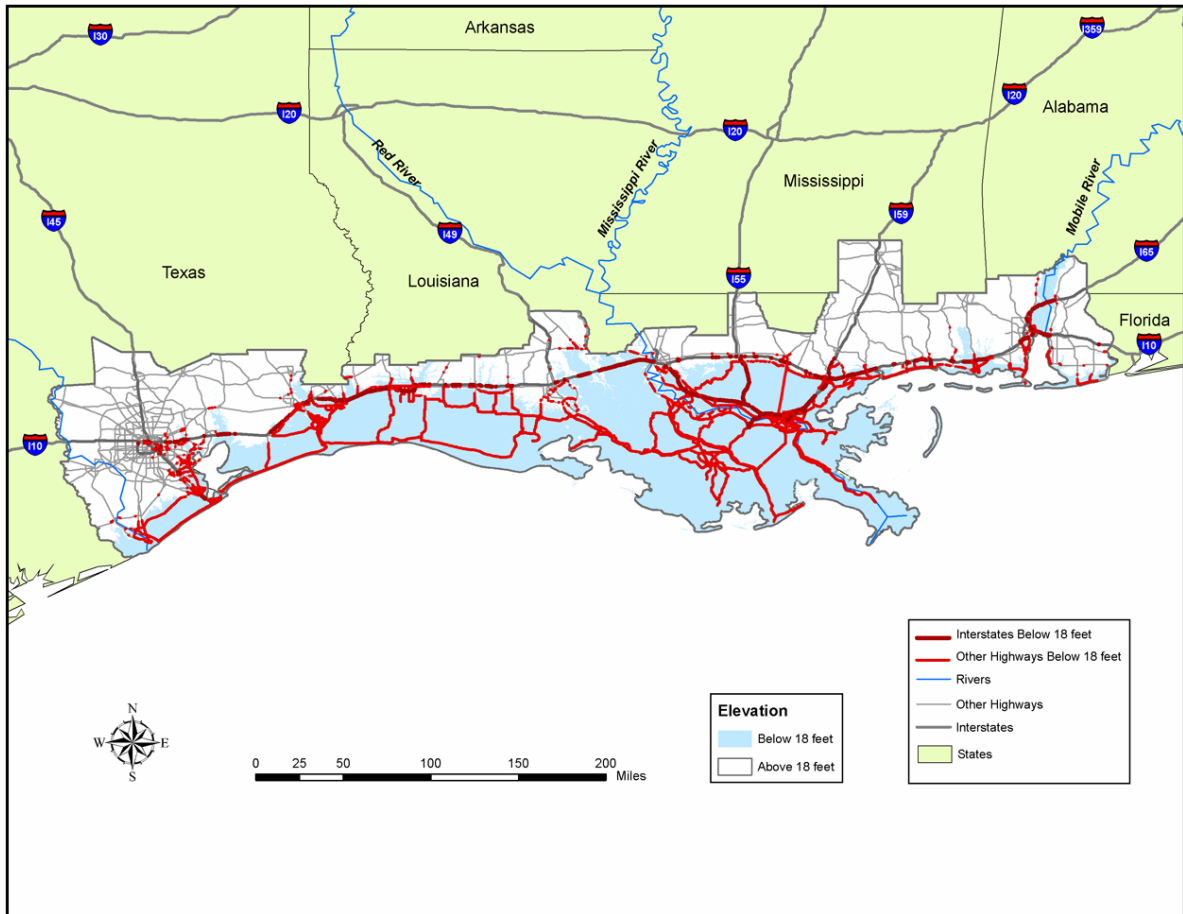
**Figure 4.3 NHS Intermodal Connectors at risk from a relative sea level rise of 122 cm (four feet). (Source: Cambridge Systematics analysis of U.S. DOT data)**



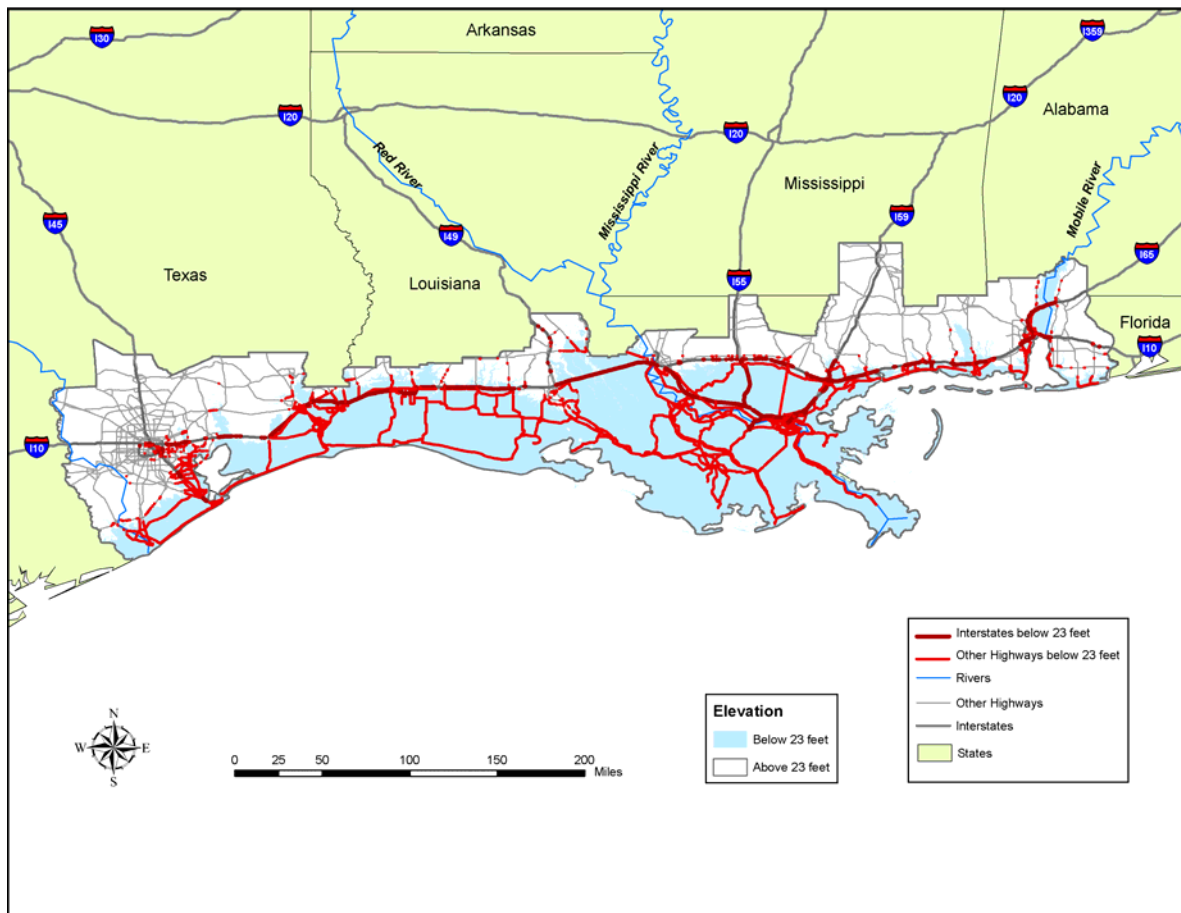
**Figure 4.4** Hurricane Katrina damage to Highway 90 at Bay St. Louis, MS.  
(Source: NASA Remote Sensing Tutorial)



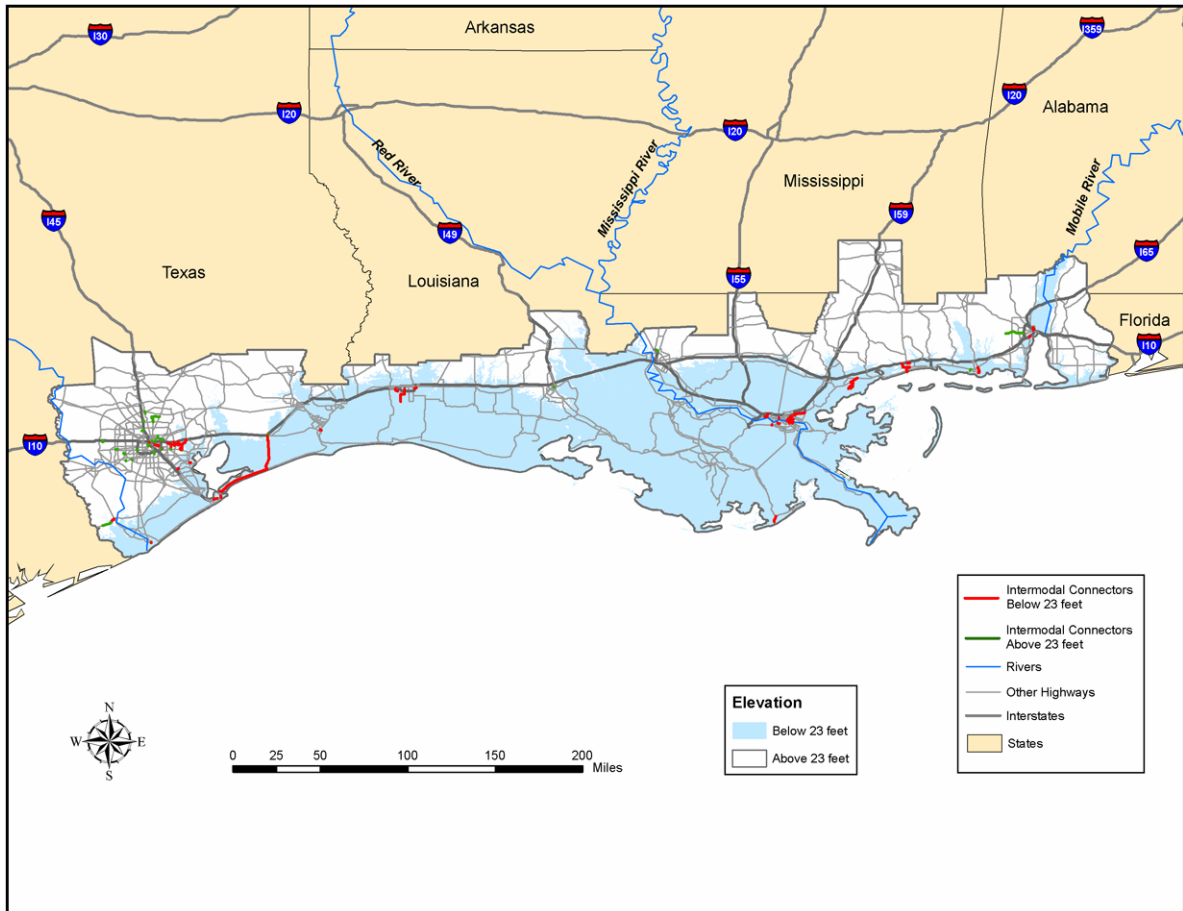
**Figure 4.5 Highways at risk from storm surge at elevations currently below 5.5 meters (18 feet). (Source: Cambridge Systematics analysis of U.S. DOT data)**



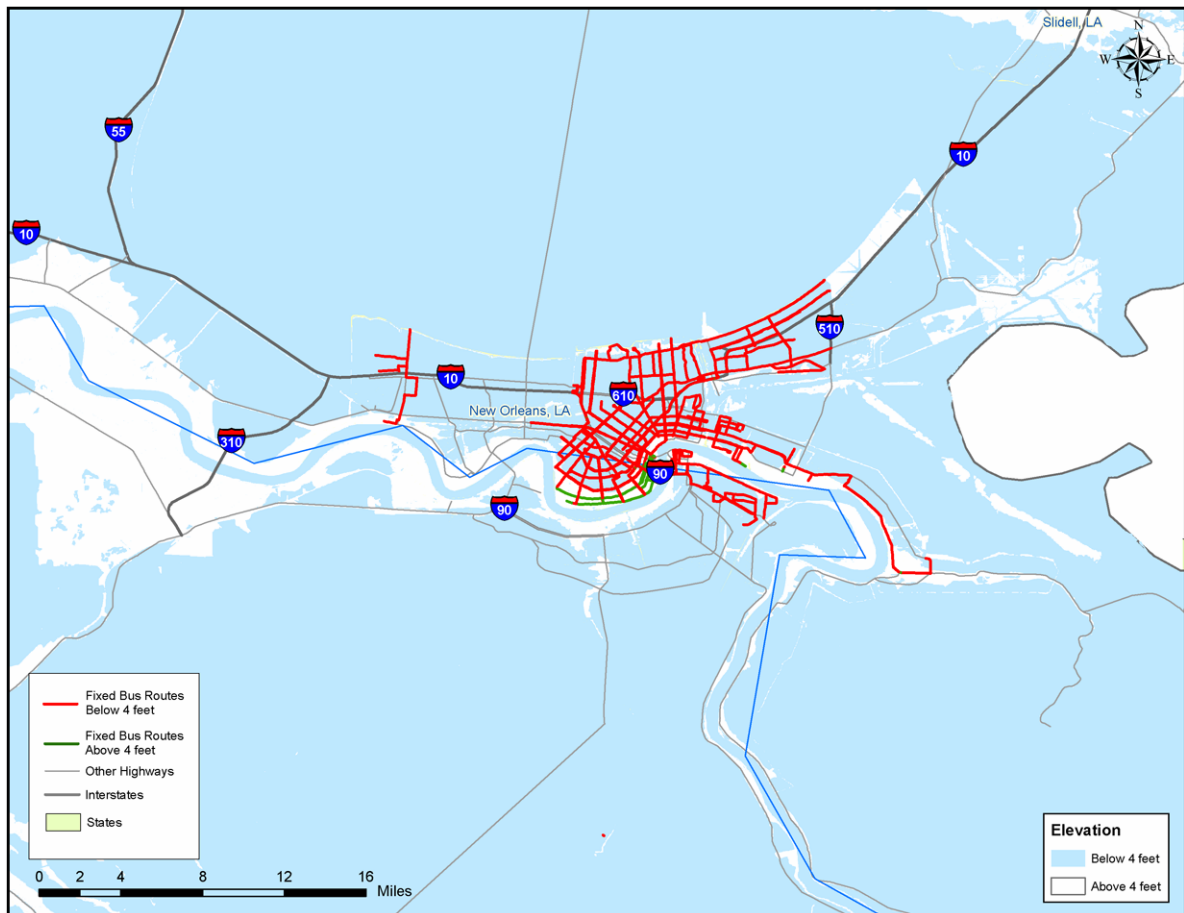
**Figure 4.6** Highways currently at risk from storm surge at elevations currently below 7.0 meters (23 feet). (Source: Cambridge Systematics analysis of U.S. DOT data)



**Figure 4.7 NHS Intermodal Connectors at risk from storm surge at elevations currently below 7.0 meters (23 feet).  
(Source: Cambridge Systematics analysis of U.S. DOT data)**

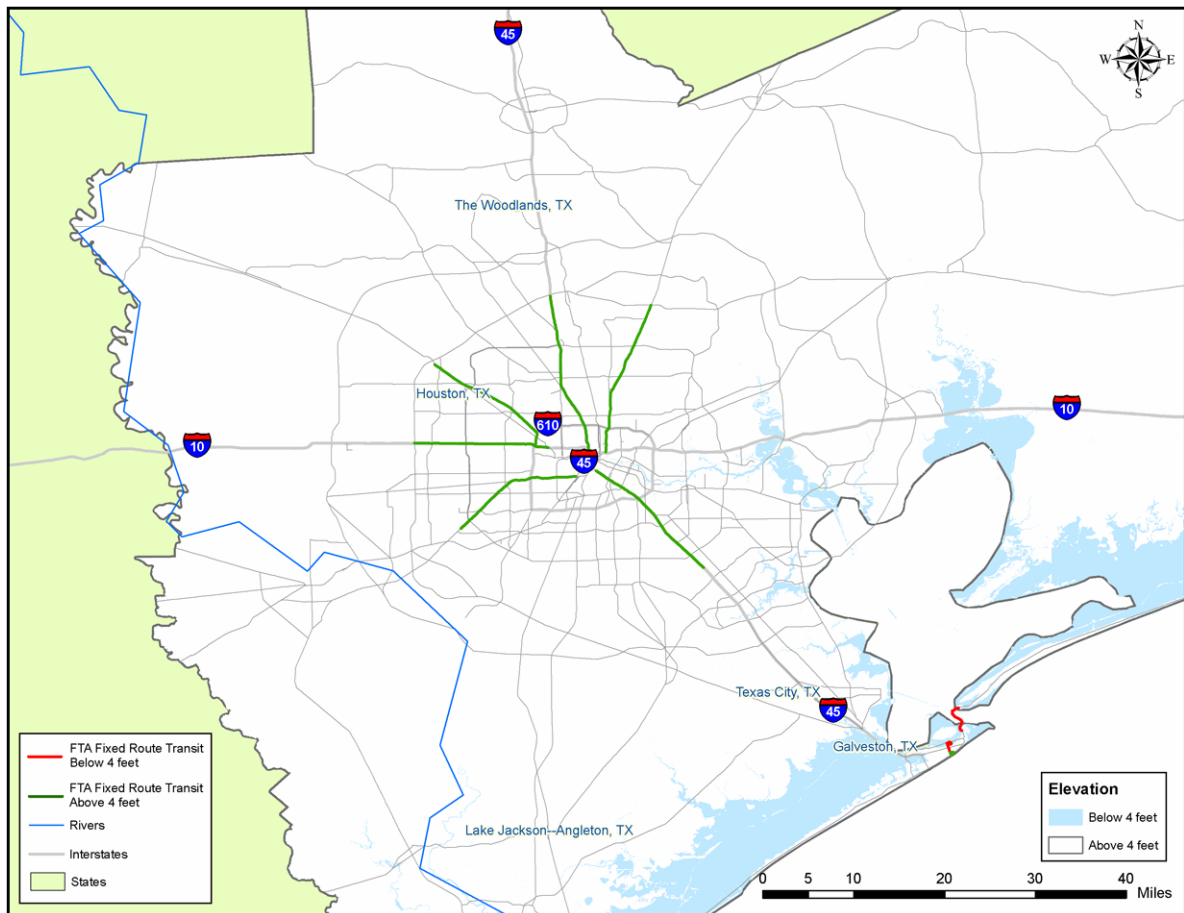


**Figure 4.8** Fixed bus routes at risk from a relative sea level rise of 122 cm (four feet), New Orleans. (Source: Cambridge Systematics analysis of U.S. DOT data)

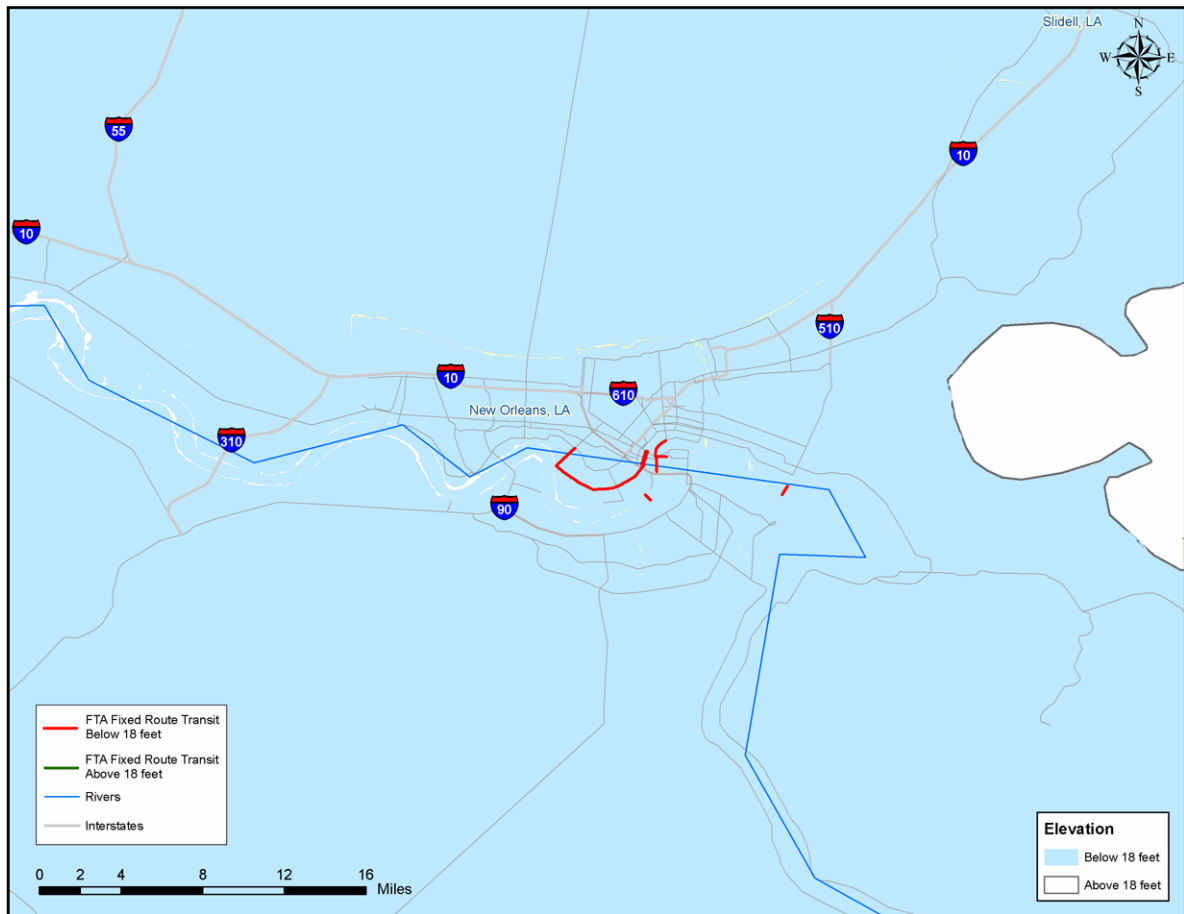




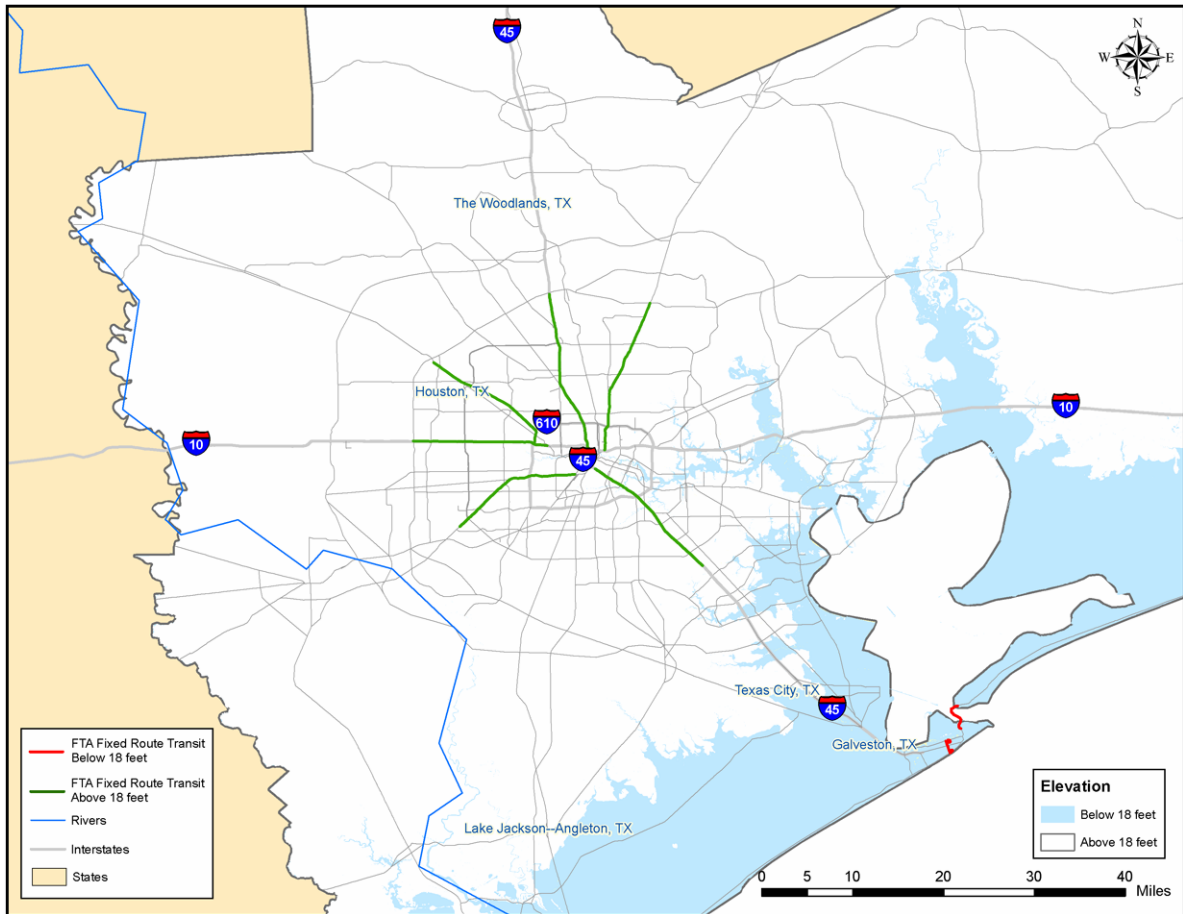
**Figure 4.9** Fixed transit guideways at risk from a relative sea level rise of 122 cm (four feet), Houston and Galveston.  
(Source: Cambridge Systematics analysis of U.S. DOT data)



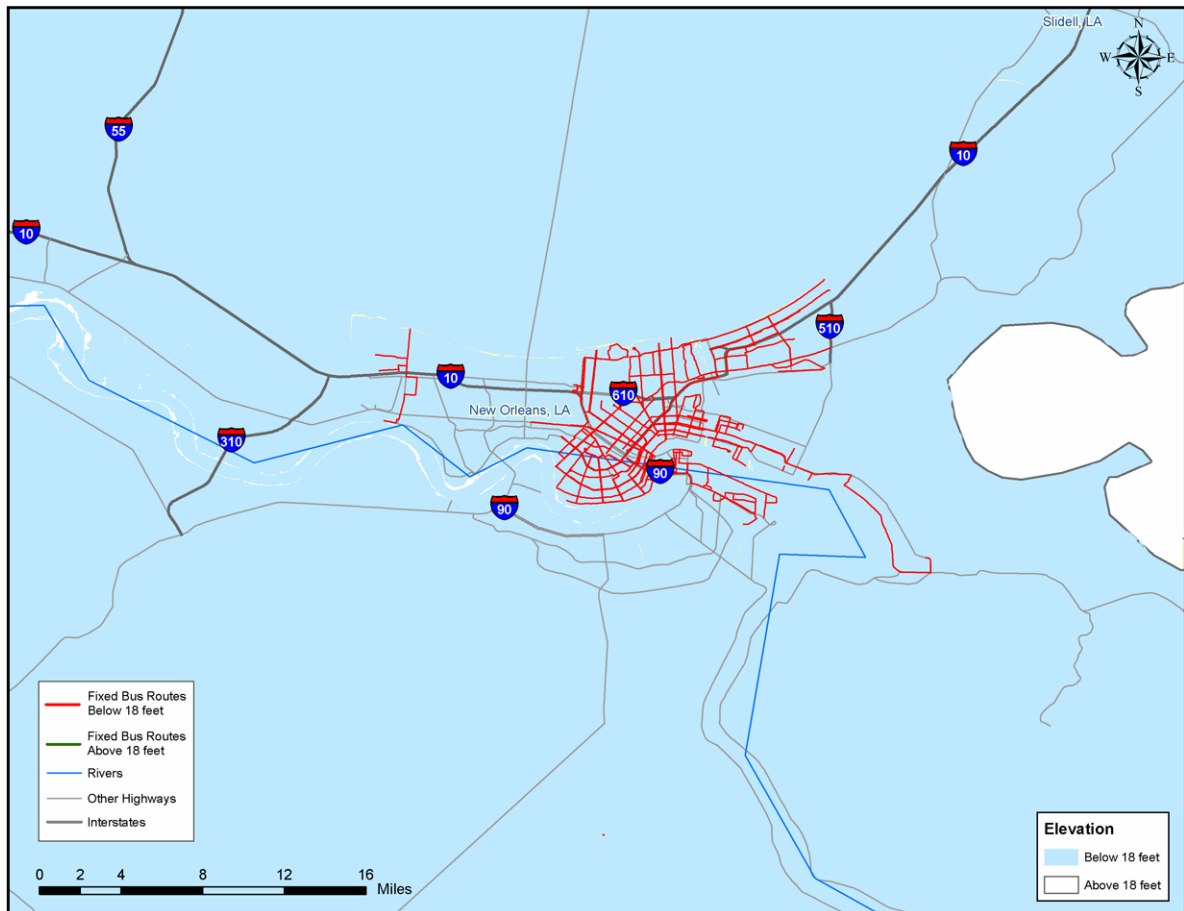
**Figure 4.10 Fixed transit guideways at risk from storm surge at elevations currently below 5.5 meters (18 feet), New Orleans. (Source: Cambridge Systematics analysis of U.S. DOT data)**



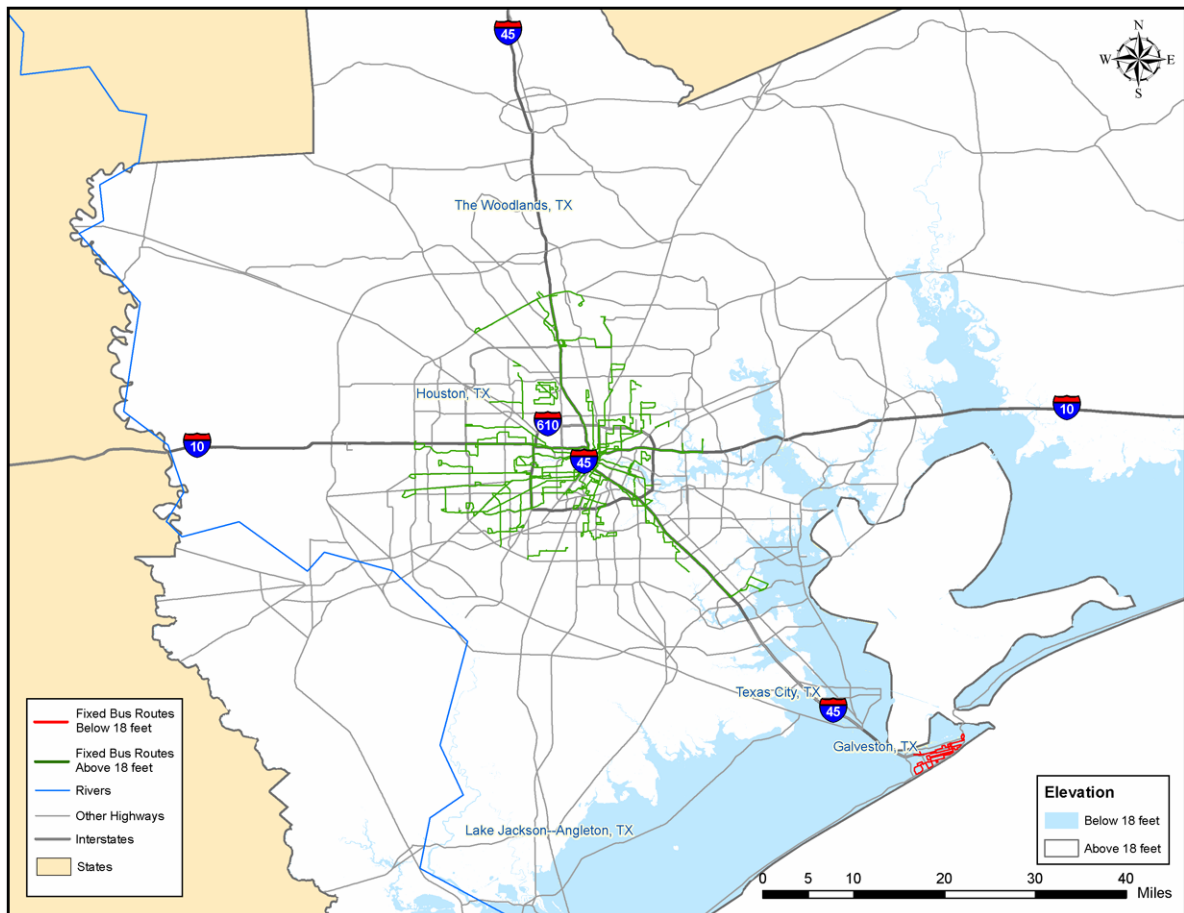
**Figure 4.11 Fixed transit guideways at risk from storm surge at elevations currently below 5.5 meters (18 feet), Houston and Galveston. (Source: Cambridge Systematics analysis of U.S. DOT data)**



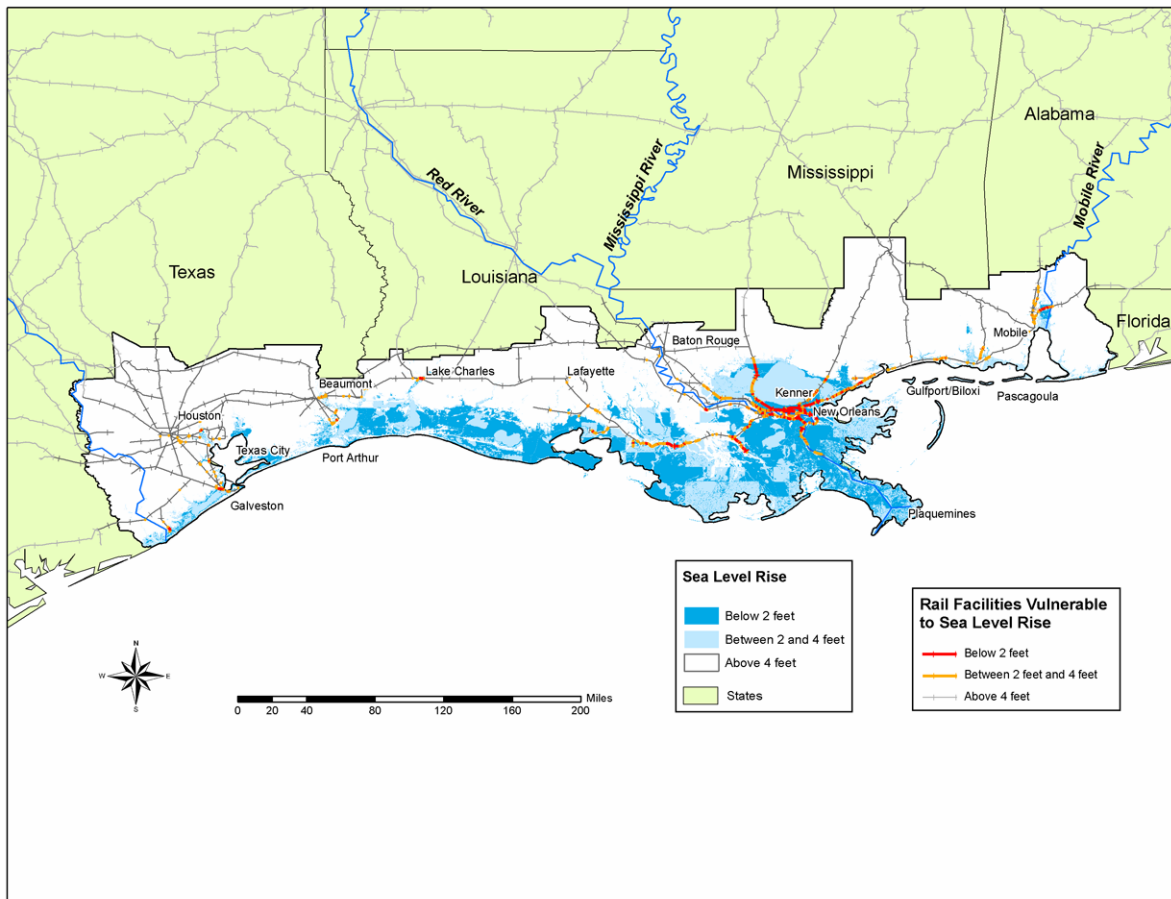
**Figure 4.12 Fixed bus routes at risk from storm surge at elevations currently below 5.5 meters (18 feet), New Orleans. (Source: Cambridge Systematics analysis of U.S. DOT data)**



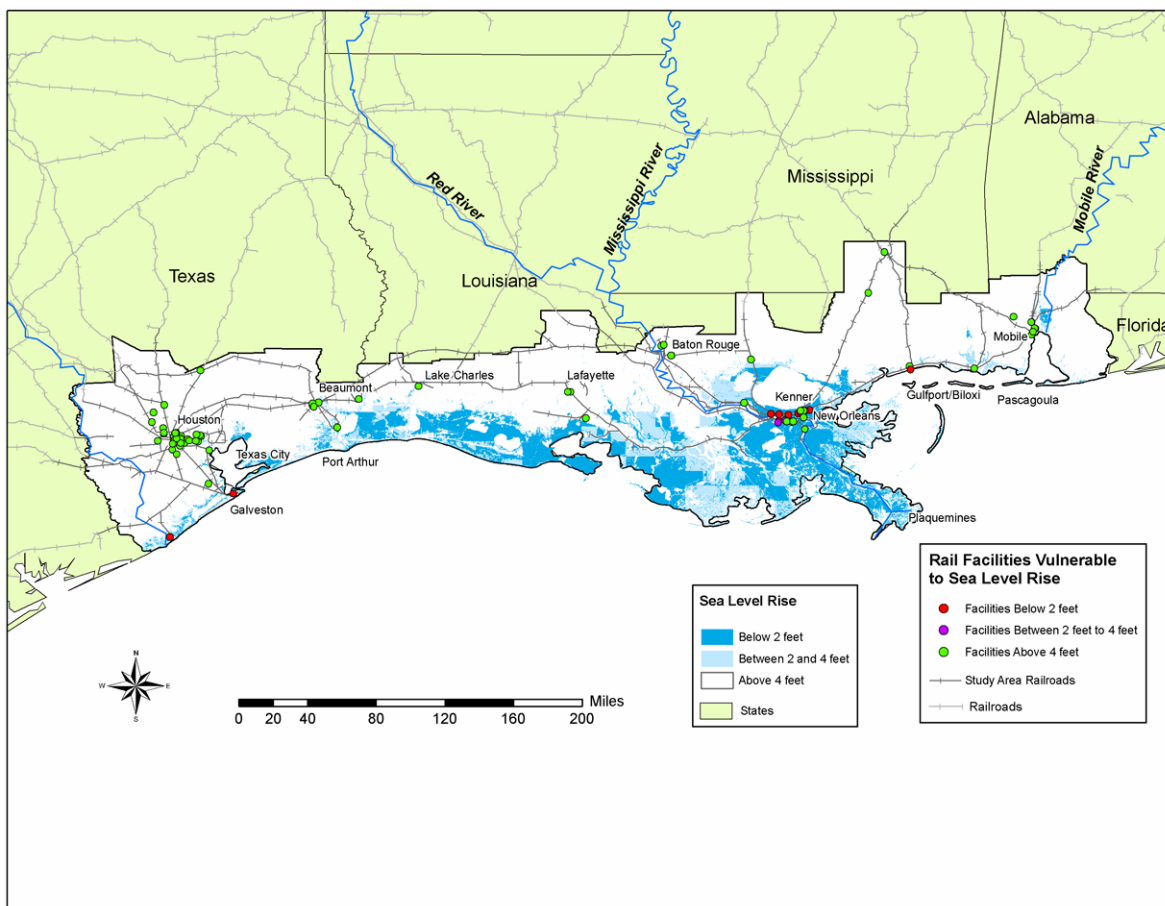
**Figure 4.13 Fixed bus routes at risk from storm surge at elevations currently below 5.5 meters (18 feet), Houston and Galveston. (Source: Cambridge Systematics analysis of U.S. DOT data)**



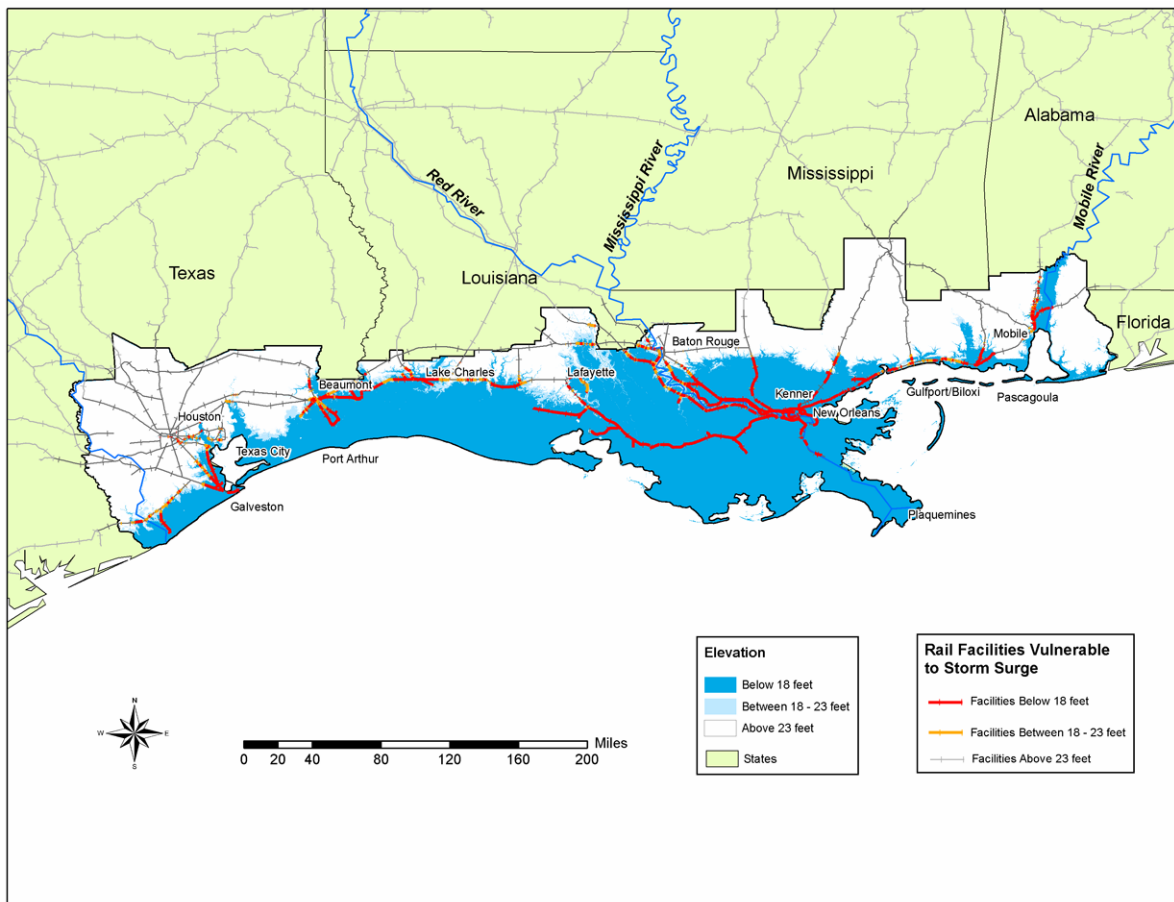
**Figure 4.14 Rail lines at risk due to relative sea level rise of 61 and 122 cm (two and four feet). Of the 2,934 miles of rail lines in the region, 146 miles, or five percent, are at risk from a relative sea level rise of two feet or less (red lines) and an additional 121 miles for a total of nine percent are at risk from an increase of two to four feet (orange lines). (Source: Cambridge Systematics analysis of U.S. DOT data)**



**Figure 4.15 Freight railroad-owned and served facilities at risk due to relative sea level rise of 61 and 122 cm (two and four feet). Of the 94 facilities in the region, 11 are at risk from two-foot increase in relative sea level (red circles) and an additional eight facilities are at risk from a four-foot increase (purple circles). (Source: Cambridge Systematics analysis of U.S. DOT data)**

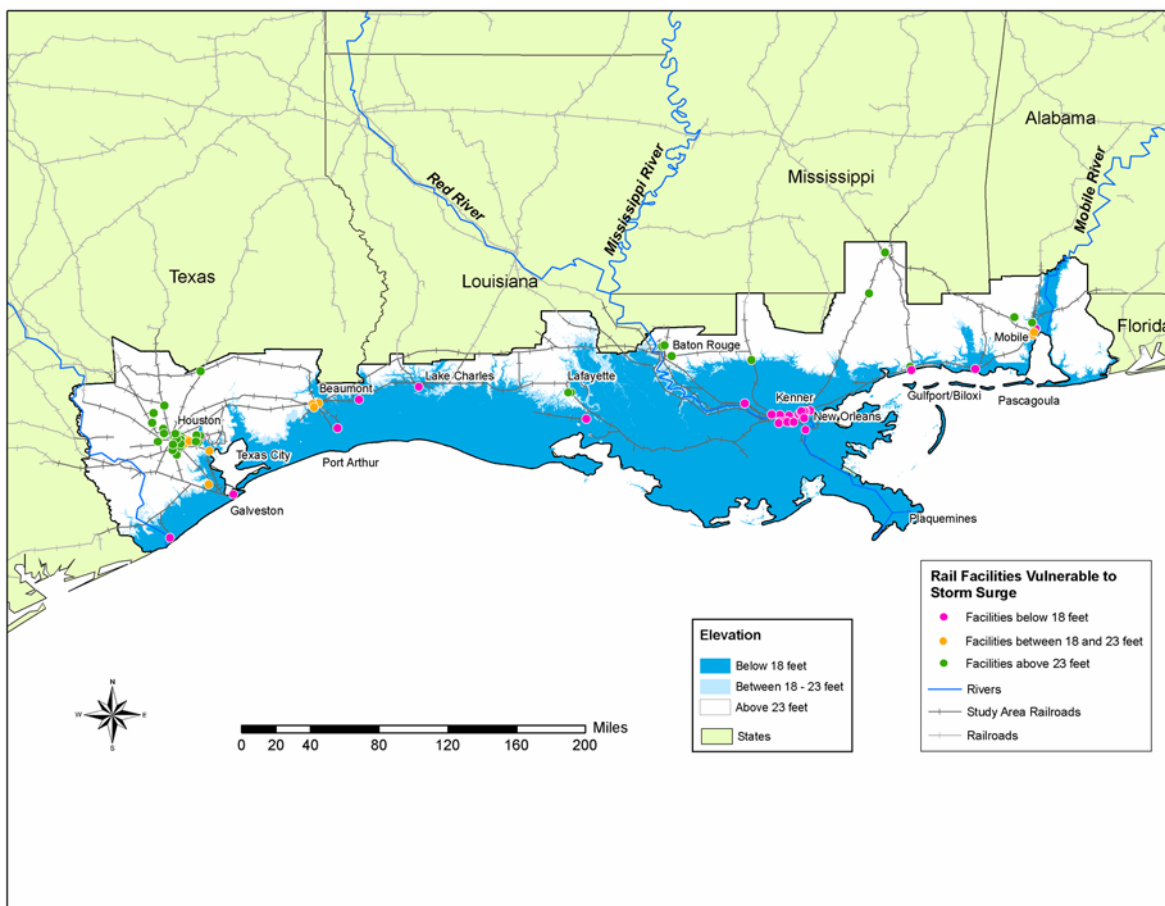


**Figure 4.16 Rail lines at risk due to storm surge of 5.5 and 7.0 meters (18 and 23 feet). Of the 2,934 miles of rail lines in the region, 966 miles are potentially at risk from a storm surge of 18 feet (red lines) and an additional 224 miles are potentially at risk from a storm surge of 23 feet (orange lines). (Source: Cambridge Systematics analysis of U.S. DOT data)**

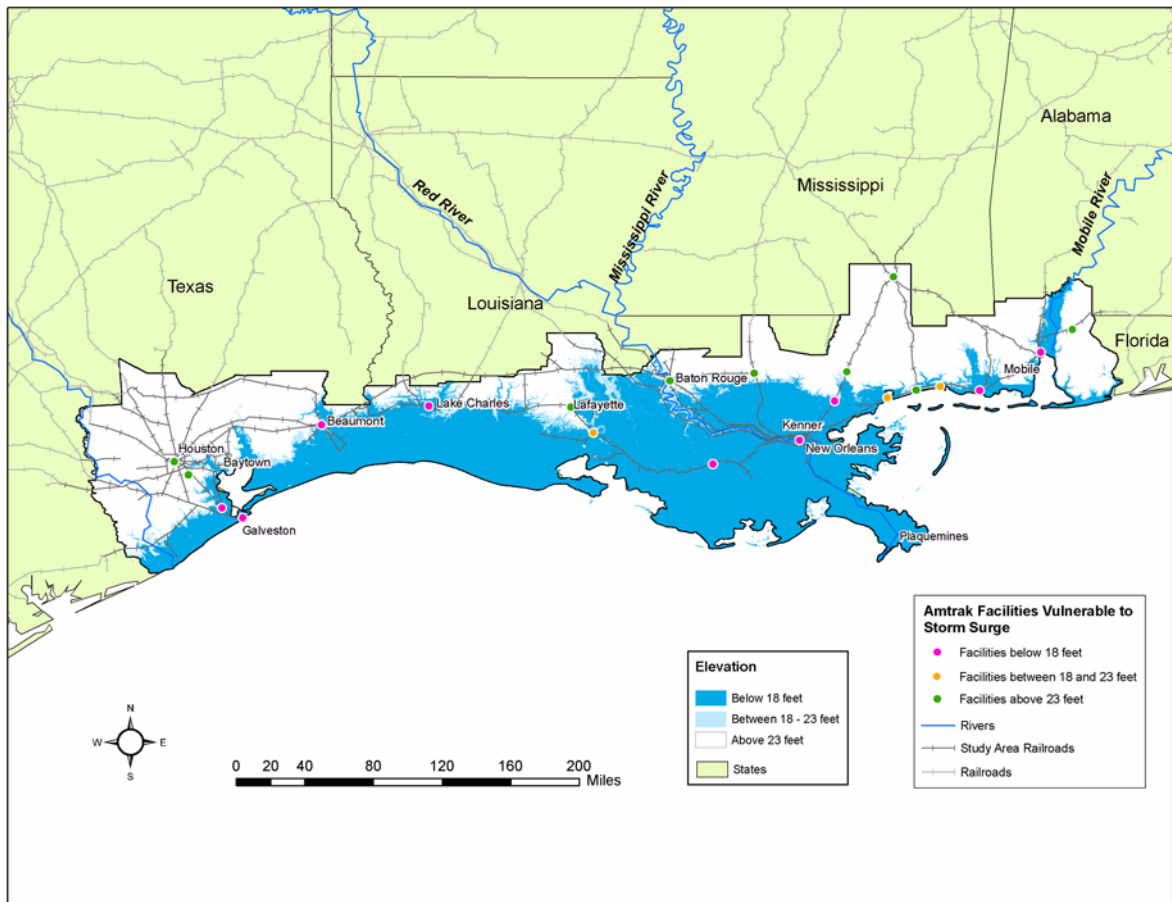




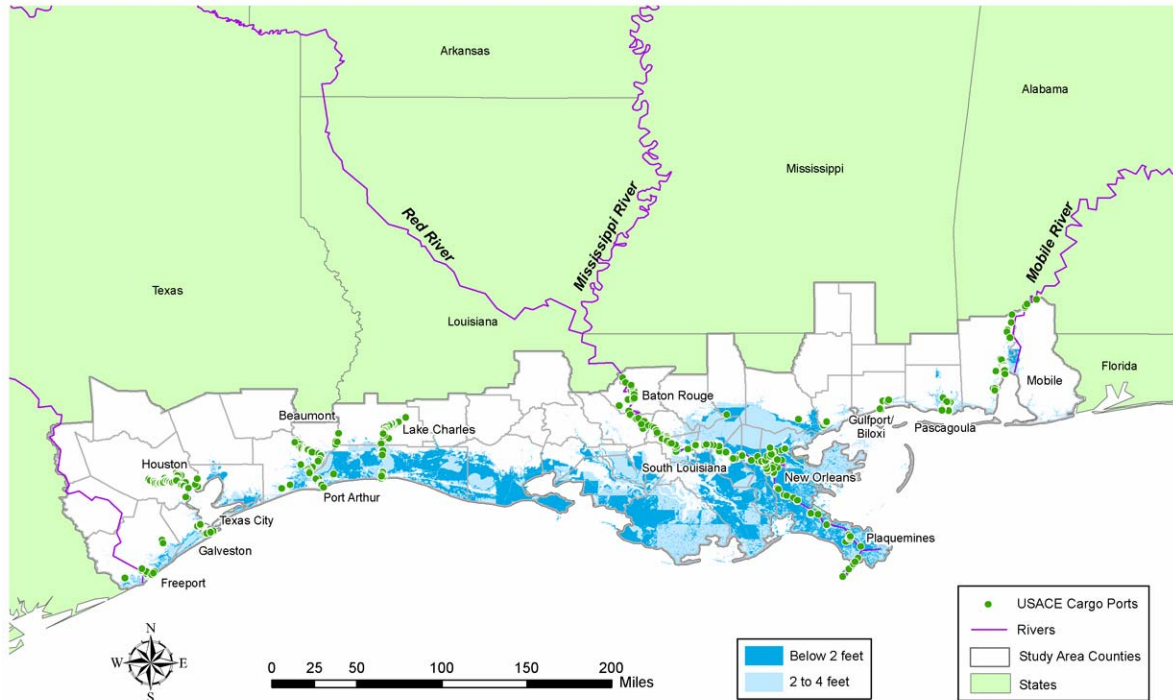
**Figure 4.17 Freight railroad-owned and served facilities at risk due to storm surge of 5.5 and 7.0 meters (18 and 23 feet). Of the 94 facilities in the region, 40 are at risk from a storm surge of 18 feet or less (purple circles) and an additional 11 facilities are at risk from storm surge of 18 to 23 feet (orange circles). (Source: Cambridge Systematics analysis of U.S. DOT data)**



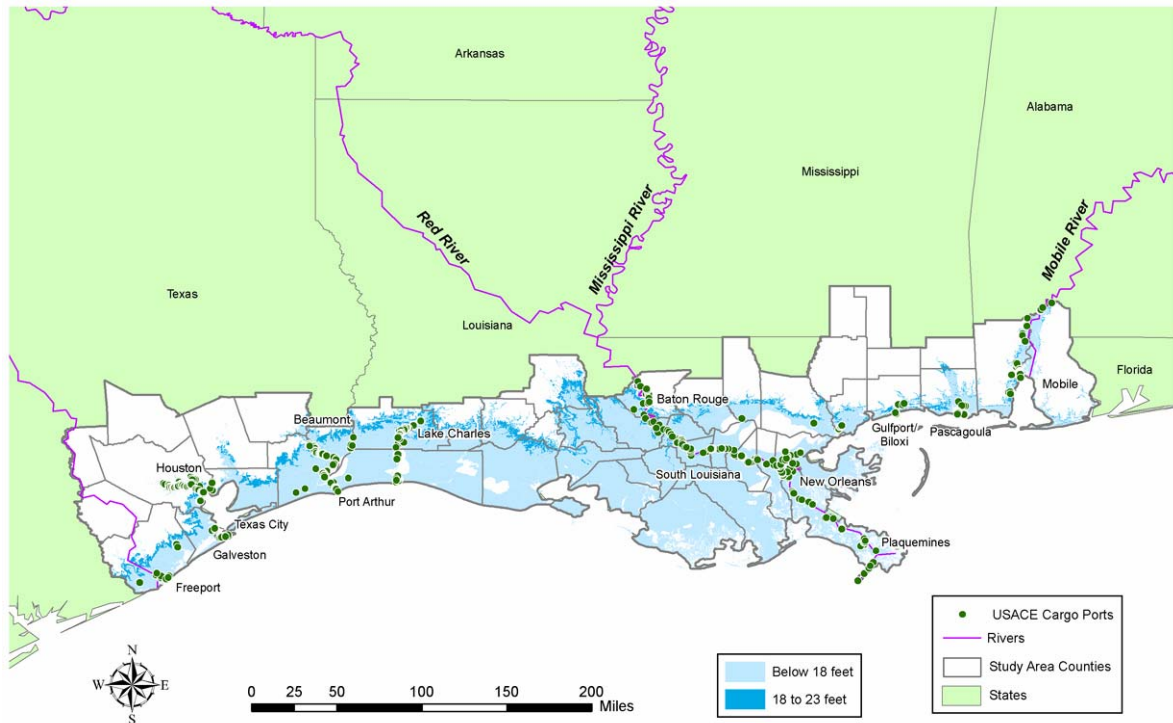
**Figure 4.18 Amtrak facilities at risk due to storm surge of 5.5 and 7.0 meters (18 and 23 feet). Of the 21 Amtrak facilities in the region, 9 are at risk from a storm surge of 18 feet or less (purple circles) and an additional 3 facilities are at risk from storm surge of 18 to 23 feet (orange circles). (Source: Cambridge Systematics analysis of U.S. DOT data)**



**Figure 4.19 Freight handling ports facilities at risk from relative sea level rise of 61 and 122 cm (two and four feet). (Source: Cambridge Systematics analysis of U.S. Army Corps of Engineers data)**



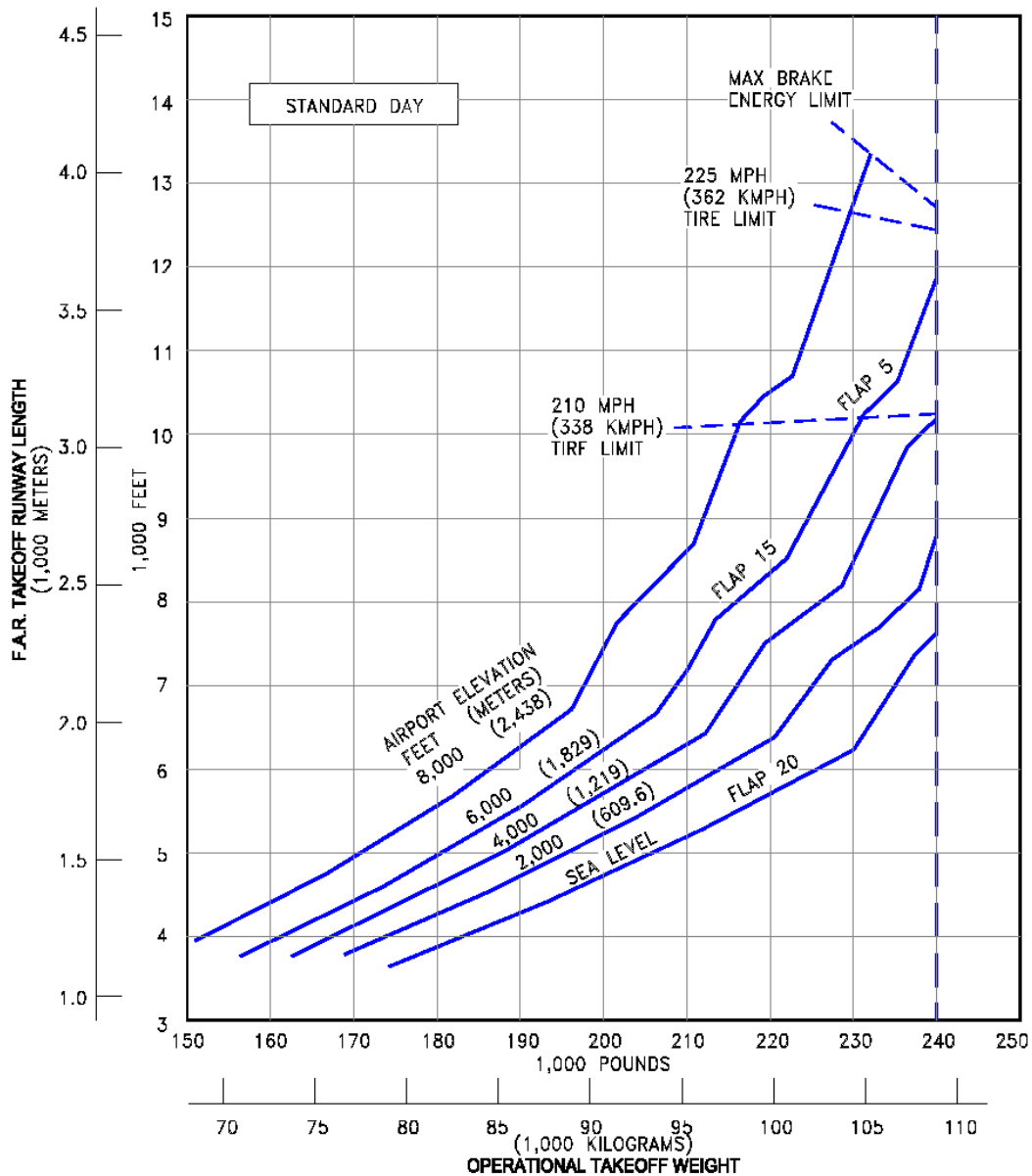
**Figure 4.20 Freight handling ports facilities at risk from storm surge of 5.5 and 7.0 meters (18 and 23 feet). (Source: Cambridge Systematics analysis of U.S. Army Corps of Engineers data)**



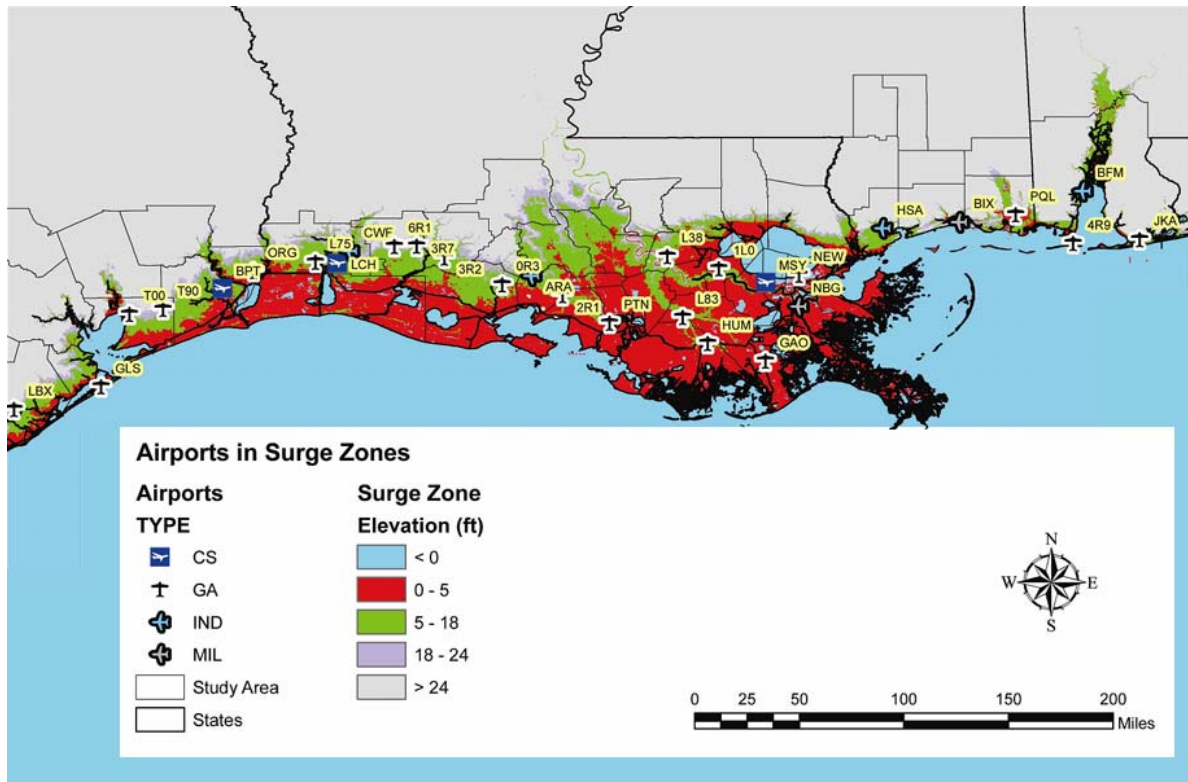
**Figure 4.21 B757-200 takeoff runway requirements for design purposes.**  
 (Source: The Boeing Company, 2002)

NOTES:

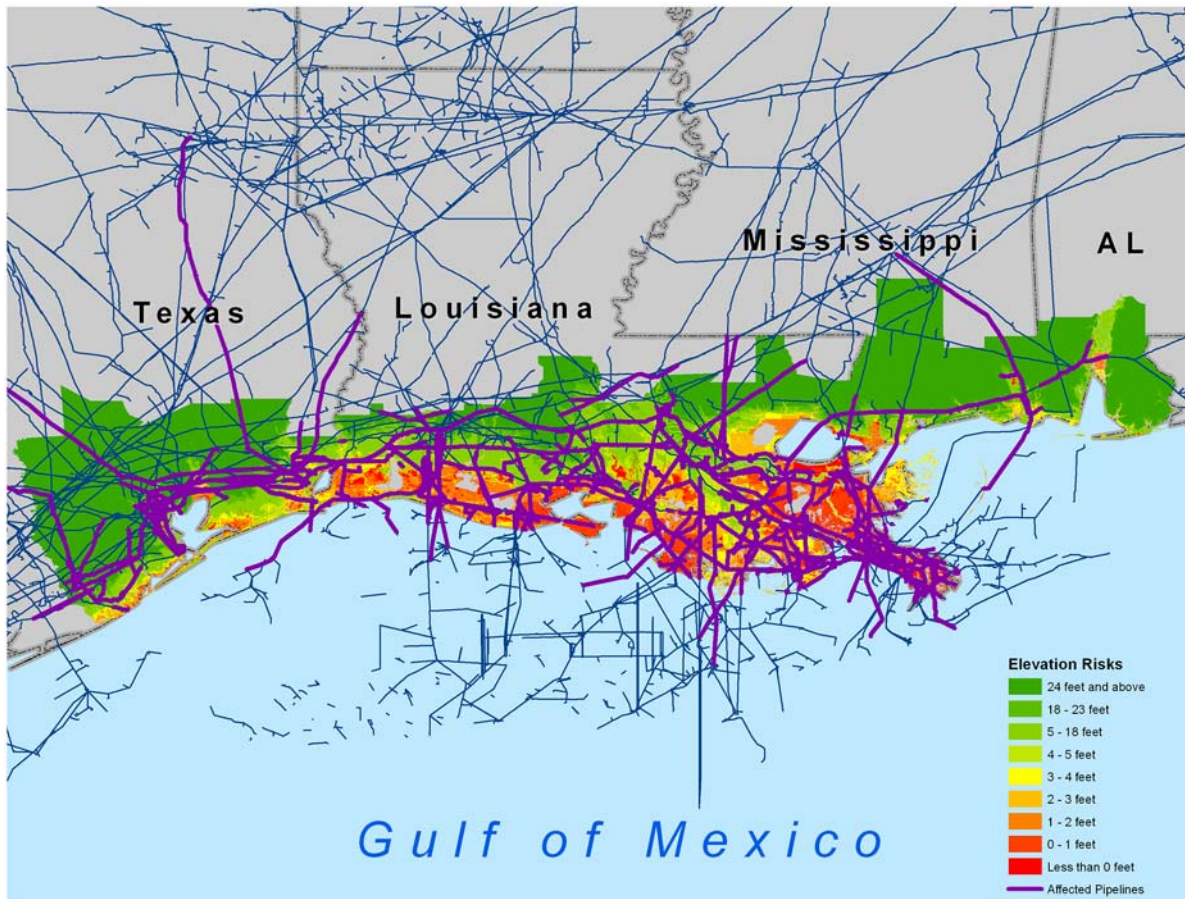
- \* RB711-535C ENGINES
- \* NO ENGINE AIRBLFDD FOR AIR CONDITIONING
- \* ZERO WIND, ZERO RUNWAY GRADIENT
- \* CONSULT USING AIRLINE FOR SPECIFIC OPERATING PROCEDURE PRIOR TO FACILITY DESIGN
- \* LINEAR INTERPOLATION BETWEEN ALTITUDES INVALID
- \* LINEAR INTERPOLATION BETWEEN TEMPERATURES INVALID
- \* NOMINAL PERFORMANCE



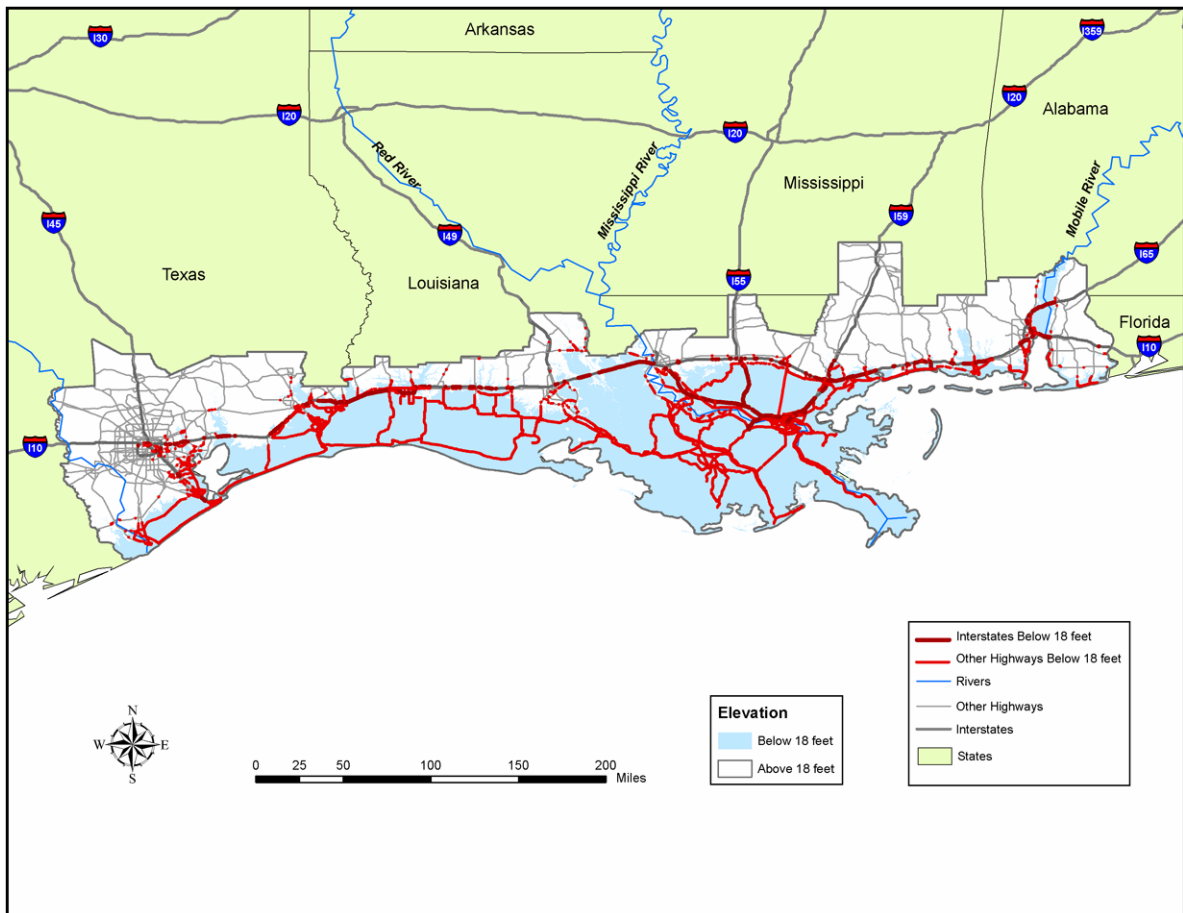
**Figure 4.22 Gulf Coast study area airports at risk from storm surge. (Source: Cambridge Systematics analysis of U.S. DOT and USGS data)**



**Figure 4.23** Landside pipelines having at least one GIS link located in an area of elevation zero to 91 cm (three feet) above sea level in the study area. (Source: Texas Transportation Institute)

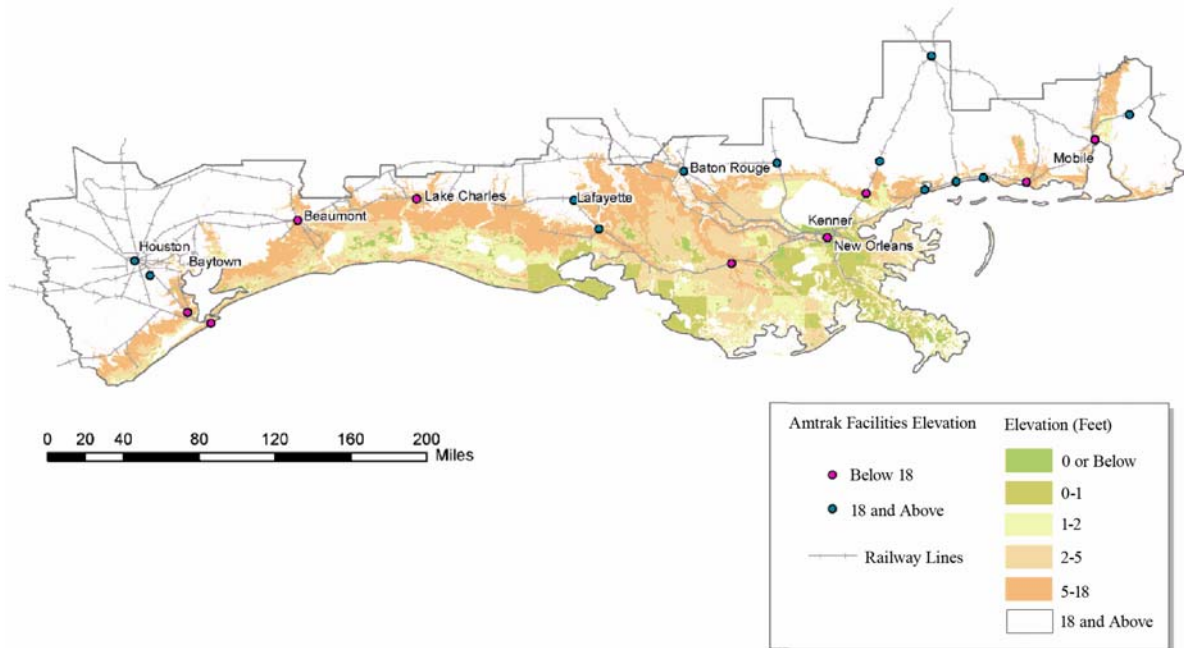


**Figure 4.24 Potential evacuation route highways vulnerable from storm surge of 5.5 meters (18 feet). (Source: Cambridge Systematics analysis of U.S. DOT data)**



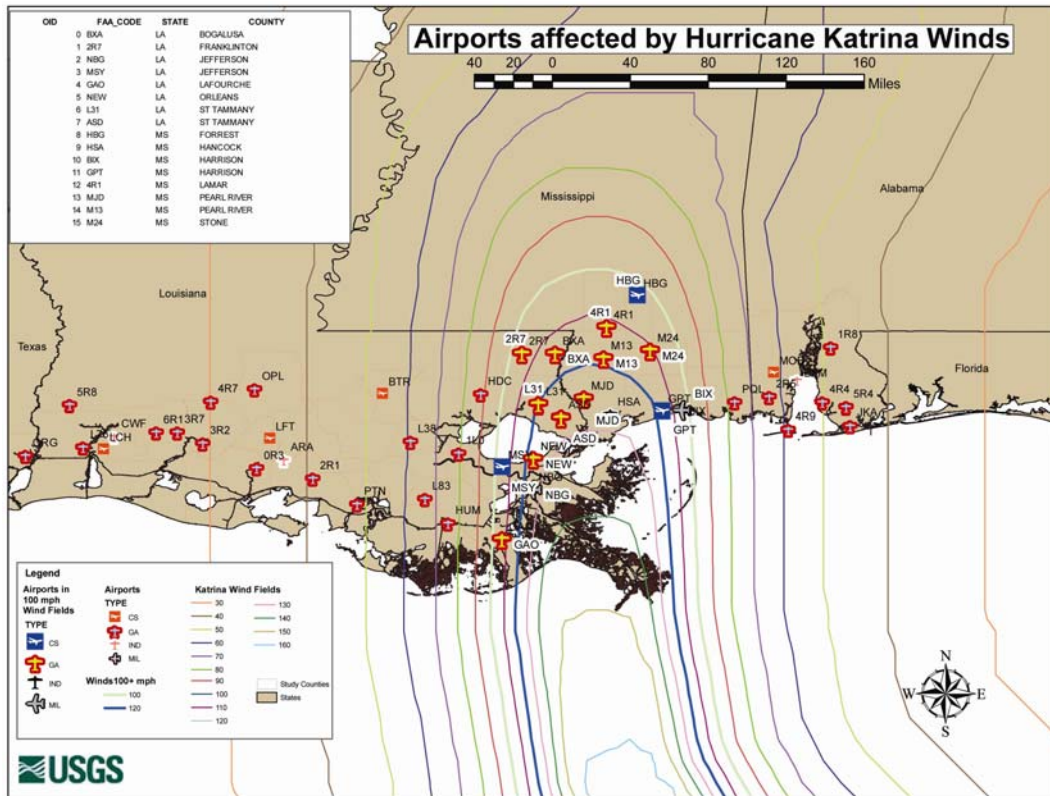


**Figure 4.25 Risks to Amtrak Facilities due to relative sea level rise and storm surge. (Source: Cambridge Systematics analysis of U.S. DOT data)**





**Figure 4.27 Airports affected by Hurricane Katrina winds. (Source: USGS)**





# 5.0 How Can Transportation Professionals Incorporate Climate Change in Transportation Decisions?

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Contributing Authors: Michael J. Savonis, Joanne R. Potter, Wesley R. Dean

As the previous chapters have demonstrated, there is benefit to including long-term climate considerations in the development of transportation systems. In fact, climate factors are likely to affect decisions in every phase of the transportation management process: from long-range planning and investment; through project design and construction; to management and operations of the infrastructure; and system evaluation (Figure 5.1). This chapter will explore how such concerns might be addressed in the continuing process of development and renewal of transportation infrastructure. To better understand this, an overview of the planning process as generally implemented today is provided, as well as specific consideration of transportation planning within the Gulf Coast States.

However, to rigorously address climate concerns, new approaches may be necessary. Since climate impacts occur into the future, and there is uncertainty as to the full magnitude and the timing of the impacts, deterministic methods as currently employed are ill suited to provide the type of information that current decision-makers need. Instead it may be more fruitful to consider these impacts through a risk management approach to more effectively give transportation executives, elected officials and the general public a more complete picture of the risks and potential solutions to climate impacts. The last section of this chapter begins the process of developing an alternate approach to planning with a conceptual framework for introducing more probabilistic approaches. Once fully operational, this type of methodology could lead to better information to address the changing climate.

[INSERT FIGURE 5.1 How will climate change affect transportation decisions?]

## ■ 5.1 Considering Climate Change in Long-Range Planning and Investment

### 5.1.1 Overview of the Surface Transportation Planning and Investment Processes

This section discusses how transportation planning and investment decisions are made in state and local governments and to some extent in private agencies. It reviews in particular the planning and decision-making processes used by state departments of transportation (DOT) and metropolitan planning organizations (MPO). Specifically, it discusses the long-range planning taking place in the Gulf Coast Study region and provides the results of a number of state DOT and MPO interviews. Finally, it discusses the challenge of how the planning process might be adapted to consider the potential impacts of climate change.

#### *The Federal Surface Transportation Planning Process*

Transportation planning processes vary with the type of agency (public or private), level of government (Federal, state, or local), mode of transportation, and other factors. This chapter will not attempt to provide an overview of all of them. But since the Federal government has specific requirements codified in law to cover the surface transportation planning process (for highways and transit investments), this chapter provides an illustrative example using the Federal process.

Surface transportation planning and investment decision-making, employed to make use of Federal transportation funding, is conducted within the framework and requirements defined by the planning provisions contained in Titles 23 and 49 of the United States Code (USC), most recently amended in August 2005 by the *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU).

State DOTs and MPOs have lead transportation planning responsibilities, working in coordination with local governments. States and local governments may implement transportation infrastructure without Federal funding. These projects may be included within the framework of the Federal transportation process, but could be implemented outside that framework.

Within the Federal process for highways and transit, state DOTs and MPOs must comply with the planning requirements to be eligible and to receive Federal transportation funds. The state DOTs within the study area are the Alabama Department of Transportation, Louisiana Department of Transportation and Development, Mississippi Department of Transportation, and Texas Department of Transportation. Ten MPOs exist within the study area, as identified in Table 5.1. Each MPO consists of one or more urbanized areas exceeding 50,000 in population with an urban area exceeding 200,000 in population also defined as a Transportation Management Area (TMA).

1 [Insert Table 5.1 Urbanized area Metropolitan Planning Organizations (MPO) in the Gulf Coast  
2 study area]

3 The MPO’s planning activities are identified in the Unified Plan Work Program which  
4 covers a two-year period for the purpose of maintaining short- and long-term transportation  
5 plans. It is within this program that MPO staff collect data on traffic and pedestrian counts,  
6 building permits, planned developments, and accident rates, etc., analyze trends, and  
7 evaluate potential projects. Two principal products are produced in the transportation  
8 planning process: a long-range transportation plan and a transportation improvement  
9 program. These two products, then, provide the basis for more detailed project  
10 development – engineering, design, and construction.

11 Separate but coordinated long-range transportation plans are cooperatively developed on a  
12 statewide basis by a state DOT and for each urbanized area by an MPO. The long-range  
13 transportation plan is developed with a minimum of a 20-year forecast period, with many  
14 areas using a 30-year time horizon. The intent of a plan is to provide a long-range vision of  
15 the future of the surface transportation system, considering all passenger and freight modes  
16 and their interrelationships. As defined by SAFETEA-LU (23 USC 134 and 135) long-  
17 range plans, “shall provide for the development and integrated management and operation  
18 of transportation systems and facilities that will function as an intermodal transportation  
19 system.” The transportation planning process for TMAs is essentially identical to that in  
20 urbanized areas having a population between 50,000 and 200,000 except that a Congestion  
21 Management Process (CMP) also is required.

22 The transportation improvement program (TIP) is a separate document for the immediate  
23 future. It must be consistent with the long-range plan and provides the list of short-term  
24 (three years) priorities for construction. A TIP must be developed for each metropolitan  
25 area and a Statewide Transportation Improvement Program (STIP) must be developed for  
26 the State that is consistent with the TIPs. The STIP must be approved by U.S. DOT.

27 Environmental considerations have long played a role in the planning and development of  
28 transportation projects. Changes over time, though, have occurred in the manner in which  
29 environmental analyses have been conducted and the underlying legal framework in which  
30 these analyses are conducted. SAFETEA-LU, in Section 6001, defines the following eight  
31 planning factors that should guide a transportation planning process and the development  
32 of projects, strategies, and services (Figure 5.2):<sup>1</sup>

- 33 1. “Support the economic vitality of the United States, the States, nonmetropolitan areas,  
34 and metropolitan areas, especially by enabling global competitiveness, productivity,  
35 and efficiency;
- 36 2. Increase the safety of the transportation system for motorized and nonmotorized users;

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<sup>1</sup> This list represents a refinement of a similar list contained in previous intermodal surface transportation legislation.

- 1       3. Increase the security of the transportation system for motorized and nonmotorized  
2       users;
- 3       4. Increase the accessibility and mobility of people and freight;
- 4       5. Protect and enhance the environment, promote energy conservation, improve the  
5       quality of life, and promote consistency between transportation improvements and state  
6       and local planned growth and economic development patterns;
- 7       6. Enhance the integration and connectivity of the transportation system across and  
8       between modes throughout the State, for people and freight;
- 9       7. Promote efficient system management and operation; and
- 10      8. Emphasize the preservation of the existing transportation system.”

11 [INSERT Figure 5.2 SAFETEA-LU Planning Factors ]

12       The SAFETEA-LU legislation requires that long-range transportation plans be developed  
13       in consultation with agencies responsible for land use management, natural resources,  
14       environmental protection, conservation, and historic preservation. Further, this  
15       consultation is to consider, where available, conservation plans or maps and inventories of  
16       natural or historic resources. This is typically a time- and labor-intensive effort requiring  
17       years to complete with extensive public involvement which was made far more difficult by  
18       the 2005 hurricanes. The Gulfport MPO reports that in addition to the several years the  
19       overall effort took prior to 2005, the agency needed another year to reconsider the land use  
20       and demographic changes taking place as well as the Plan’s regional goals to make them  
21       consistent with the Governor’s Recovery Plan.

22       An interesting question is the manner in which the impacts of climate change can be  
23       addressed in the list of eight planning factors and the associated consultative process. As  
24       will be discussed later in this section, while climate change is not now named as part of any  
25       of the eight factors, a number of them reflect considerations that are directly related to  
26       climate change. In addition to protecting, enhancing, and mitigating impacts on the  
27       environment, these include system preservation, system management and operation, safety,  
28       and economic vitality (see especially Factors 1, 2, 6, and 8).

29       Transportation plans, programs, and projects historically have been developed to meet the  
30       needs of future projected or planned land use, including population and employment  
31       patterns. In recent years, though, transportation and land use are being addressed in a much  
32       more interactive or coordinated manner. Rather than land use being viewed as driving  
33       transportation decisions, transportation investment and management decisions are  
34       increasingly being made collaboratively and in concert with growth management and  
35       economic development decisions. In this view, the manner in which transportation  
36       infrastructure is developed and managed is seen as one “tool” for helping to achieve  
37       desirable growth objectives.



1 The overall transportation planning and investment process is illustrated in Figure 5.3 with  
2 an emphasis that is helpful in identifying where in this transportation planning process  
3 considerations related to climate change impacts potentially could be introduced. Using  
4 terminology that is consistent with current planning and strategic management approaches,  
5 separate steps are identified for establishing a long-range vision and for establishing goals,  
6 objectives, and performance measures. Developing an *understanding of the problem* is  
7 seen as occurring on a continuing and iterative basis throughout the planning process,  
8 including the analysis of data and evaluating tradeoffs and establishing priorities among  
9 candidate policies and projects. The process culminates with development of a long-range  
10 transportation plan, a short-range transportation improvement program, and project  
11 development and implementation.

12 In terms of introducing climate-related changes into the long-range transportation planning  
13 and investment process, the potential exists at each step illustrated in Figure 5.3. As  
14 shown, long-range environmental quality, economic development, mobility, and other  
15 desired conditions such as safety commonly are defined as part of a vision and  
16 accompanying mission statement and then translated into goals, objectives, and  
17 performance indicators. Thus, protection from climate change impacts could be introduced  
18 at these stages as well. Given these defined goals and objectives, strategies then are  
19 developed that are specifically designed to meet the agreed upon goals and objectives, and  
20 evaluated using the appropriate performance measures. Again, strategies could be  
21 developed that address climate change and variability. Similarly, climate change  
22 protection and mitigation strategies could be evaluated with respect to their potential  
23 impact on the transportation system.

24 [INSERT Figure 5.3 Steps in the transportation planning process]

### 25 ***Coordination in Transportation Planning***

26 The Federal transportation planning and investment process is highly collaborative in  
27 which transportation agencies work in partnership with natural resource agencies,  
28 communities, businesses, and others throughout the period of planning, programming,  
29 developing, implementing, and operating transportation projects. Transportation agencies  
30 are charged with helping to accomplish multiple transportation, economic development,  
31 environmental, community, safety, and security objectives. Going beyond the Federally  
32 mandated process, the continued development and operation of the multimodal network  
33 requires extensive coordination.

34 Although planning and programming of the highway system, and its coordination with  
35 other modes of travel, are major responsibilities of the state DOT and the MPO, the actual  
36 development and operation of the transportation system is the responsibility of various  
37 levels of government and private agencies. States typically own and operate a relatively  
38 small portion of the road network but that portion (the Interstate System and Arterial  
39 Highways) usually accommodates the majority of the road travel. In some cases, states  
40 also own and operate local and state transit systems and freight rail lines. However, the  
41 majority of highway miles and transit systems are local responsibilities and most of the  
42 nation's freight system and air passenger system is owned by the private sector.

1 Meeting the requirements of the Federal planning process is necessary as a condition of  
2 receiving Federal financial assistance. However, for states and MPOs the number of  
3 different organizations who have independent roles makes it important to have a  
4 collaborative decision-making process, one that is based on valid and convincing  
5 information. At the MPO level, decisions are a collaboration of the individual local  
6 governments that comprise the MPO and serve on the policy board usually supported by  
7 the advice and analysis of a technical coordinating committee.

8 At the state level, the ultimate decisions are typically made by the Governor and the state  
9 legislature<sup>2</sup> with recommendations and advice coming from the state DOT. Decisions  
10 within the state DOT also occur at many levels and units within the organization. State  
11 DOT decisions encompass all aspects of the roadways under state jurisdiction: planning,  
12 engineering, operations, design, and construction.

13 Most of the freight and part of the aviation and passenger systems are owned by the private  
14 sector. State DOT and MPO plans that make recommendations for these systems must get  
15 the concurrence from the private sector for implementation. In the vast majority of the  
16 cases, the private sector invests in their current system or a new system if they feel it is  
17 cost-effective to do so. The state and MPO may have some influence through the planning  
18 process or through the provision of financial assistance. For instance, a railroad will not  
19 likely move a rail line unless it improves their return on investment or because the  
20 government helps finance it.

21 Since the freight network is largely owned by the private sector, the long-range  
22 transportation planning process for both states and metropolitan areas ensures that the  
23 private users and providers of transportation are represented and their comments  
24 considered. In fact, the Federal planning regulations discussed above requires that in  
25 developing or updating long-range transportation plans states and MPOs shall have a  
26 process to allow freight shippers and providers of freight transportation services a  
27 reasonable opportunity to review and comment on key decision points and the proposed  
28 transportation plan. Planning agencies normally include private shippers and transportation  
29 providers on their plan advisory committees to guarantee representation early and  
30 throughout the planning process.

31 For these systems to be effective at efficiently moving people and goods – as well as  
32 meeting the higher needs of society in terms of economic development and environmental  
33 enhancement – a high degree of coordination is crucial. In terms of meeting the particular  
34 challenges that climate change poses, each entity, whether public agency or private firm,  
35 needs to consider how climate stressors might affect their businesses. Further, these  
36 agencies need to work together to consider how climate changes affect the efficient  
37 movement of people, goods and services as a whole to take full advantage of system  
38 redundancy and resilience, explained later in this chapter.

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<sup>2</sup> Some DOTs, such as Mississippi's, do not report to the Governor.

## **5.1.2 Current State of Practice in Incorporating Climate Change Considerations**

In this Gulf Coast Study, representation of the private freight industry was sought during the development of the modal technical papers. For example, railroads were involved in the review of the rail technical paper and discussions were held with the Association of American Railroads about possible impacts to rail lines from climate change such as “sun kinks” and the importance of prestressed rail track. The CSX Railroad provided significant information on hurricane Katrina impacts and adaptation strategies through public comments and the sharing of information. The CSX reported that it cost about \$250 million to repair damage from Katrina, and the damage caused them to further consider relocating the rail line. The CSX Railroad is exploring the feasibility of new construction within the existing corridor but further inland. Also, increased use of alternative Mississippi River crossings is under study (Baton Rouge/Vicksburg). Interviews included a private toll road authority and port employees for two separate ports (Galveston and Houston) that were publicly owned but operate privately owned facilities. The toll road representative expressed concern about potential impacts of sea level rise since the toll facilities do approach the coast line particularly in the Houston metropolitan area. The port representatives also were concerned about the impacts of possible seal level rise and the impacts of increased precipitation on sedimentation of port channels and port run-off that could cause local flooding. In the next phase of the Gulf Coast Study, the private sector involvement will be intensified to determine what specific climate change impacts are possible and in detailing likely adaptation strategies and costs.

Two approaches were utilized to determine how state DOTs and MPOs currently are addressing issues of climate change and also how climate change might be addressed in the future. The approaches involved:

1. Obtaining and reviewing current long-range transportation plans, transportation improvement programs and other recent documents for the states and selected MPOs within the study area addressing infrastructure development, operation, and management; and
2. Interviewing state DOT and representative MPO officials responsible for transportation planning within the study area.

Some MPOs within the study region currently are in the process of updating their vision statements and long-range transportation plans. In some of these cases, MPOs are actively considering issues related to the potential effects of climate change and variability including the impacts of hurricanes such as Katrina and Rita. The two aspects of climate that are receiving the most attention in these more recent planning activities are: 1) evacuation planning and management; and 2) preventing infrastructure damage resulting from storm surge-related flooding.

Long-range transportation plans, statewide transportation improvement programs, and annual reports were obtained, where available, from the Internet for the states of Alabama,

1 Mississippi, Louisiana, and Texas. In addition, the corresponding documents were  
2 similarly obtained for the following urban areas:

- 3 • Mobile, Alabama (South Alabama Regional Planning Commission);
- 4 • Hattiesburg, Mississippi (Hattiesburg-Petal-Forrest-Lamar Metropolitan Planning  
5 Organization);
- 6 • Gulfport, Mississippi (Gulf Regional Planning Commission);
- 7 • Lake Charles, Louisiana (Imperial Calcasieu Regional Planning and Development  
8 Commission);
- 9 • Lafayette, Louisiana (Lafayette City-Parish Consolidated Government Metropolitan  
10 Planning Organization);
- 11 • New Orleans, Louisiana (Regional Planning Commission for Jefferson, Orleans,  
12 Plaquemine, St. Bernard and St. Tammany parishes); and
- 13 • Houston and Galveston, Texas (Houston-Galveston Area Council).

14 None of the existing state and MPO documents examined here, all of which date from 2000  
15 to 2006, directly addresses or acknowledges issues of climate change and variability. This  
16 is, in part, due to their age; most were developed two to four years ago, prior to the recent  
17 increase of interest in climate change and the associated increase in the availability of  
18 climate change-related information. Also, most of these documents were prepared prior to  
19 Hurricanes Katrina and Rita so the many actions being taken by state DOTs and MPOs in  
20 response to these two storms have only recently been included in updated and published  
21 documents.

22 The following observations result from a review of these planning documents, organized  
23 into the following three categories: plans including missions and goals, planning activities,  
24 and prioritization criteria.

### 25 ***State and MPO Plans and Planning Activities***

26 Most of the state and MPO plans in the region include a mission or goals that include  
27 statements about providing environmentally sound transportation systems or preserving the  
28 quality of the environment and enhancing the quality of life. There also are goals that  
29 include strategies to encouraging land use planning and incorporate public transportation,  
30 walking, and bicycles. Essentially, all of the plans recognize the environmental impacts  
31 (excluding climate change) and issues related to transportation growth and expansion. The  
32 Louisiana long-range transportation plan defines 57 “mega projects,” whose evaluation  
33 criteria for development and implementation include environment, demonstrating context-  
34 sensitive design and/or sound growth management principles, and emergency evacuation  
35 capabilities. Nine of the 22 Priority “A” mega projects involve I-10, including construction  
36 of a six-lane I-10 Twin Span across Lake Pontchartrain. Other Priority “A” mega projects

1 located in evacuation areas include upgrading I-49 south of Lafayette and construction of a  
2 new two-lane road between U.S. 90 and LA 3127. The Houston-Galveston long-range  
3 transportation plan identifies eight distinct ecological zones within the region and pays  
4 particular attention to the wetlands, which protect shoreline areas from erosion and serve as  
5 buffers from flooding.

6 However, as mentioned above, some of the planning activities since Hurricanes Rita and  
7 Katrina and infrastructure reconstruction are being done to address the impacts of climate  
8 change. In Mississippi, the flooding that resulted from Hurricane Katrina has resulted in  
9 new design standards for the bridges that are being rebuilt and is serving as a catalyst for  
10 considerable debate on the interrelationships between land use and transportation  
11 investment within the coastal areas of the State.

12 The Regional Planning Commission for the New Orleans urbanized area and the  
13 Mandeville/Covington and Slidell urbanized areas is refining its Metropolitan  
14 Transportation Plan (MTP) for the New Orleans region so that it can provide a framework  
15 within which the projected climate change effects can be assessed and addressed. The  
16 Houston-Galveston Area Council (H-GAC) is in the process of conducting a visioning  
17 exercise, the results of which will then guide the development of an updated regional  
18 transportation plan. Since this is occurring post-Hurricane Rita, climate change and the  
19 means of reducing the risk of flooding have been raised in the outreach sessions and  
20 working meetings.

21 In addition to including policies to provide maintain and improve the area's intermodal  
22 systems, the states and MPOs in the study area also are including consideration of future  
23 uncertainties and evacuation management. The Mississippi transportation plan and  
24 associated STIP both acknowledge uncertainty in future year conditions in areas such as  
25 growth, air quality, road maintenance, and congestion. The STIP contains a section on  
26 planning and research that states, "Planning is looking at what we have to do today to be  
27 ready for an uncertain tomorrow." While climate change and variability are not explicitly  
28 mentioned in either the current plan or the STIP and the major effects of climate change  
29 may not occur within the plan's current 30-year timeframe, the stage certainly is set to both  
30 recognize and respond to potential issues of climate change in future planning activities.

31 Following Hurricane Rita, the Governor of Texas established a task force on evacuation,  
32 transportation, and logistics. The report of this task force was completed and submitted on  
33 February 14, 2006. Twenty recommendations are made, including the development of  
34 contraflow plans for major hurricane evacuation routes, including some in the study area.  
35 Such as north out of the Houston-Galveston metropolitan area on I-45, U.S. 290, U.S. 59;  
36 west out of Houston on I-10; and north out of Beaumont on U.S. 69. Evacuation routes  
37 represent one element of the operations and system management portion of the long-range  
38 transportation plan for the Houston-Galveston metropolitan area, with extra points given to  
39 evacuation routes in the prioritization ranking of projects. Short-term recommendations to  
40 improve evacuation capabilities were developed in 2006. Longer-term evacuation  
41 priorities also are being assessed, "some of which may require significant public  
42 investment over many years." These may include new evacuation routes, reconstruction of

1 existing evacuation routes, and reduction in the number and severity of traffic bottlenecks.  
2 The location of new development in flood and storm prone areas also is arising as an issue.

### 3 ***Site Interviews with Transportation Representatives in the Gulf Coast***

4 In addition to reviewing planning documents and interviewing DOT and MPO officials as  
5 described above, another set of interviews was conducted between December 15, 2006 and  
6 January 10, 2007 to understand in more specific terms the issues facing the area selected  
7 for more intense study in Phase 2 of this effort. These interviews included a representative  
8 of each of the transportation modes represented in the site study area. The objective of the  
9 study site interviews was to consider the potential climate impacts at the level of the  
10 individual decision-maker/planner. This information was used to develop and refine the  
11 conceptual framework for assessing potential impacts on transportation presented below.  
12 There were three general lines of inquiry used to generate a localized picture of climate  
13 change impacts and transportation decision-making:

- 14 1. Interviewees' Perspectives on Climate Change – Respondents were asked about their  
15 perception of climate change, its potential impact on the respondent's specific facility  
16 or system, and whether or not the respondent currently was incorporating climate  
17 change and variability science or indicators in their decision-making and planning.
- 18 2. Decision and Planning Processes in which Respondents are Involved – Interviewees  
19 were asked to describe the types of decisions they are engaged in at the facility and/or  
20 system level in their area of responsibility. The interview guide solicited responses in  
21 regard to the factors that were the most relevant to making facility or system decisions,  
22 the role of the respondent in the local decision and planning process and interactions  
23 with the state and Federal processes, what information was used for informing these  
24 decisions, and what threshold or tipping point factors would facilitate changes in policy  
25 or planning, both from the climate perspective and in general.
- 26 3. Utility of the General Project Report Findings – Respondents were asked their opinions  
27 regarding the applicability of the climate scenarios and various report concepts that  
28 might be used in their analysis. The respondents were presented with a two-page  
29 summary of study findings – including climate scenarios for the study area, and the  
30 assessment of exposure, vulnerability, and resilience – for their review and input.

31 The interviews were designed and conducted according to standard social science research  
32 methodologies and practices. The questions were open ended in order to solicit as broad as  
33 possible a range of responses.

34 The interview subjects were contacted and interviewed using a questionnaire approved by  
35 the Texas A&M University Institutional Review Board. As such they were informed that  
36 their expressed opinions and any information they provide would be kept confidential and  
37 that they were free to refuse to answer any questions that made them uncomfortable.  
38 Because of the size and public nature of the research area, only limited references are made  
39 to the positions of these individuals within the hierarchy of their system or institution.

1 Fourteen individuals were interviewed, four of whom provided general context information  
2 on climate change and variability and the Galveston County area, and 10 of whom were  
3 formal interview subjects. These included:

- 4 • An employee of Transtar, the Houston Traffic Management Center;
- 5 • An individual responsible for evacuation in the Galveston County area,;
- 6 • A representative of a toll road authority;
- 7 • Employees of the City of Houston Aviation Department;
- 8 • A County Engineer;
- 9 • Employees of the Texas Department of Transportation (TxDOT); and
- 10 • Employees of the Ports of Galveston and Houston.

11 **Significance of Climate Considerations** – Although the respondents were comfortable  
12 with the idea that climate conditions would be changing in the Gulf Coast area, most  
13 respondents reported that climate was not an issue that they considered in development of the  
14 plans and TIPS. The perceptions of the respondents were that climate change is an issue that  
15 has been of limited concern to the state and Federal agencies that affect their decision-  
16 making. Yet responses varied. Representatives of at least one agency indicated a strong  
17 belief that climate change should be treated as an issue of importance in the transportation  
18 planning of the region. In contrast, others indicated that climate change is not an issue that  
19 has received any official treatment. Several interviewees felt that future consideration of  
20 climate change would be directed by guidelines established by the Federal government.

21 None of the interview subjects indicated they were using climate change data in their  
22 transportation decision-making. However, the entire sample of interview subjects was  
23 convinced that climate change is a matter of some concern.

24 **Value of Climate Information** – The general project synthesis report findings were of  
25 some use to the interview subjects. At least one interview subject indicated they had not  
26 concerned themselves with climate change until they saw the predictions for sea level and  
27 storm surge in the Galveston County area. The value of the specific predictions varied  
28 from one respondent to the next. Many respondents found sea level rise and storm surge  
29 information to be useful, however, they would like the projections to be for time periods  
30 more applicable to their own decision-making timeframes. At least one respondent  
31 suggested that the elevations for storm surge and sea level should be selected from a range  
32 more relevant to the Galveston County area. Much of Galveston County is at an elevation  
33 of 4.6 meters (15 feet); the 5.5 meter (18-foot) threshold used in the storm surge map was  
34 not as relevant as this decision-maker would like.

35 **Perceived Importance of Individual Climate Factors** – The degree to which respondents  
36 considered various climate stressors to affect the transportation infrastructure modes for  
37 which they were responsible is characterized in Table 5.2 with a scale of low, limited,  
38 moderate, high, and highest perceived concern.

1 [Insert Table 5.2 Level of decision-maker concern about climate stressors]

2 The high degree of concern exhibited by all respondents about *storm frequency and*  
3 *magnitude* as a stressor betrays the strong affective power of recent hurricanes on the  
4 hazard perceptions of respondents in the Galveston and Harris County area. The majority  
5 of subjects expressed their concern for storm frequency and magnitude in regards to the  
6 capacity of their infrastructure mode of responsibility to fully function during a hurricane  
7 evacuation, or in the case of the port, to be evacuated. An exception was the flood control  
8 subject who shared this fear, but was primarily concerned about the ability of the drainage  
9 system to cope with severe storms.

10 *Temperature* was of limited importance to the respondents with the exception of the  
11 Transtar subject who described his equipment as tested and hardened against temperature  
12 extremes and the airport representative who described temperature as a key variable in  
13 airport performance measures. The other airport representative was not as concerned about  
14 temperature. We account for this variation as a function of their respective roles. The  
15 second representative is involved in construction and does not directly grapple with  
16 operations logistics. Operations logistics are heavily determined by temperature as  
17 increased temperature reduces lift and results in an increase of the airport facility's average  
18 annual delay of departures.

19 *Average precipitation* was of limited importance to many of the respondents in comparison  
20 to *extreme precipitation* events. Of special interest was the flood control engineer who  
21 indicated increases or decreases in average precipitation have limited effect on flooding.  
22 His concern was principally with precipitation events that could be categorized as high in  
23 intensity, frequency, and duration. The one interview subject who was directly and  
24 seriously concerned with overall precipitation levels was the port engineer, who linked  
25 average levels of precipitation to the sedimentation of port channels. The second port  
26 engineer and manager were concerned with precipitation as well, especially with the  
27 consequences of port runoff for local flooding.

28 *Sea level* was of high importance to many of the interview subjects. The factor that  
29 governed the strength of this concern was proximity to the coast, moderated by the relative  
30 imperviousness of the infrastructure in question. For example, the toll road authority  
31 representative expressed a potential concern about sea level as the toll facility does  
32 approach the coast, however, this facility was designed to be elevated well above the surge  
33 levels predicted in the climate and vulnerability summaries, as well as the levels to which  
34 this respondent was previously familiar. Other respondents had broader purviews of  
35 responsibility such as multiple highways, the evacuation of residents, and facilities near sea  
36 level. These respondents expressed high concern about sea level rise. The port  
37 representatives characterized their concerns about sea level rise differently. One port  
38 engineer was highly concerned about sea level rise, but this respondent noted his concern  
39 was coupled with his concern about local subsidence. The second port interview subject  
40 could imagine sea level rise having an impact on the region, however, the infrastructure  
41 elements of concern – piers – were rebuilt often enough that only a catastrophic degree of  
42 sea level rise would have any impact. This respondent explicitly stated that such an event  
43 was highly unlikely.



1 The responses in regards to questions about decision-making thresholds were fairly  
2 uniform. Interview subjects suggested the impetus to make fairly radical policy shifts  
3 could only come from higher levels of government, and usually in response to a disaster.  
4 Otherwise, they simply did not have the autonomy, or the access to funding, to adopt new  
5 policies or planning approaches.

6 Since these interviews were conducted, however, there appears to have been a shift in some  
7 of the expressed opinions due to the impacts of Hurricanes Katrina and Rita as evidenced  
8 by adaptation measures being undertaken. For example, as detailed in Chapter 4.0, the  
9 rebuilding of certain facilities, like Highway 90 in Mississippi, have taken into account the  
10 likely impacts of future storms. Further the activities and opinions expressed to the study  
11 authors by state and local authorities indicate a much greater appreciation for the potential  
12 impacts of climate change than those of the interviewees.

13 The involvement of private users and providers of freight transportation in these interviews  
14 was limited. Employees at two public ports using private facilities and a private toll road  
15 authority representative were interviewed. However, the private sector's involvement in  
16 the next phase of the study will be substantially expanded to capture specific impacts and  
17 adaptation activities. Also, additional insight to private sector impacts and adaptation  
18 considerations were learned from other regions of the study area in the aftermath of  
19 Hurricane Katrina. As an example, the CSX railroad received extensive damage on the  
20 Gulf Coast particularly in Mississippi and Louisiana and had to consider alternative  
21 adaptation strategies such as rerouting, rehabilitation with strengthening or relocation  
22 further inland.

### 23 **5.1.3 Challenges and Opportunities to Integrating Climate Information**

24 Transportation agencies consider a broad range of future conditions, including  
25 demographic, environmental, economic, and other factors. It is within this broader context,  
26 that it is reasonable for some agencies to address the additional consideration of climate  
27 change over the lifetimes of their transportation facilities, to the extent possible.

28 Over time, fundamental and significant changes may be desirable in the manner in which  
29 long-range transportation plans are developed and investment decisions are made. Similar  
30 to what transportation agencies are now doing to address freight, safety, economic  
31 development, environmental mitigation, and other emerging issues, considerations of  
32 climate change can be incorporated in each step of the transportation planning process  
33 particularly during the earliest parts of the planning process – the formulation of a vision  
34 and the development of goals and objectives.

#### 35 ***Timeframes***

36 Long-range transportation plans are developed with a time horizon that typically extends  
37 20 to 30 years into the future. Most long-range transportation plans being developed today  
38 have time horizons of 2030 or 2035. However, as illustrated in Figure 5.4, individual

1 facilities being recommended in those plans will be designed with a considerably longer  
2 service life. For instance, bridges being built today should last 60 to 80 years or more.  
3 Furthermore, bridges being proposed in the long-range plans will be designed to last  
4 beyond 2100. Although the timeframe for significant climate change might appear to be  
5 longer than most plan horizons, studies have found that the effects of climate change are  
6 being experienced today. And while climate change is typically thought of as a gradual,  
7 incremental process over many years, scientists expect that climate changes are likely to  
8 include abrupt and discontinuous change as well. To begin to adequately consider the  
9 implications of climate change, transportation planners would benefit from consideration of  
10 longer time horizons. Climate changes over longer time periods could be addressed as part  
11 of a long-term visioning that helps determine where transportation investments are needed  
12 and should be located. It would thus inform the transportation planning process with  
13 supplementary information. For example, in the planning process depicted in Figure 5.3,  
14 climate change could be added to the vision step at the beginning of the process along with  
15 other factors such as economic and environmental considerations.

16 While it is difficult to know the planning horizons of private companies, given their  
17 proprietary nature, it is likely that their focus would benefit from an expanded time  
18 horizon, as well. Since the infrastructure likely affected by future climate impacts is  
19 currently under development, planners and decision-makers need to start now in  
20 considering how climate changes may affect them.

21 [Insert Figure 5.4: Relationship of transportation planning timeframe and infrastructure  
22 service life to increasing climate change impacts]

### 23 ***Land Use***

24 Responding to the potential effects of climate change, as demonstrated by the ongoing  
25 discussions in Texas, Louisiana, and Mississippi, may involve changes in the location of  
26 transportation facilities, housing, and business. Transportation planning already attempts  
27 to forecast these types of demographic and economic shifts. Potential changes in the future  
28 climate and its resulting impacts on the existing ecology may make such forecasting far  
29 more difficult.

30 A further challenge for transportation planners and climate scientists is to better understand  
31 the interplay of the built environment with the local ecology toward the betterment of both.  
32 For example, barrier islands serve to protect existing infrastructure by reducing the impacts  
33 of major storms. Preservation of these ecologically sensitive coastal wetlands areas is one  
34 way of minimizing damage from hurricanes by restoring critical buffer areas that absorb  
35 storm energy. Similarly, a variety of human activities are contributing to the current and  
36 projected rate of land subsidence, including, but not limited to the location and  
37 management of navigation channels. The impacts of climate change will likely make  
38 understanding and protecting these natural systems even more important not only for their  
39 own sake, but to prolong the viability of transportation infrastructure. The development of  
40 the full range of port, pipeline, shipping, and their supporting land transportation  
41 infrastructure can be examined for their potential to either directly or indirectly affect  
42 coastal areas. In essence, this is extending the concept of “secondary and cumulative

1 effects” to include coastal ecology and storm protection. Similarly, strategies proposed to  
2 protect coastal areas should be screened for potential implications on the transportation  
3 system.

#### 4 ***Institutional Arrangements***

5 Existing institutional arrangements may not be sufficient for transportation agencies to  
6 fully address and respond to issues of climate change. Increased collaboration may be  
7 necessary for transportation planning and investment decision-makers to effectively  
8 respond to climate change issues, including, partnering with climate change specialists.  
9 State DOTs and MPOs already are consulting with resource agencies such as natural  
10 resources, conservation, and historical preservation in the planning process. Collaborating  
11 on climate change might be a natural extension of that consultation process.

12 It also will be necessary for state DOTs to collaborate within their agencies so that  
13 planning, engineering and programming have a common understanding of the potential for  
14 climate change and the alternative responses possible. Likewise, the MPOs need to  
15 accomplish a similar effort with their members – local governments. Finally, for the vast  
16 amount of the transportation system owned by private agencies, climate change  
17 information must be made available to them so that their decisions can be coordinated with  
18 and compliment those of the public sector. In some cases, this may lead to public/private  
19 investment options.

#### 20 ***A New Approach***

21 Based on currently available climate change information, there appear to be important  
22 implications of climate change for the manner in which transportation investments are  
23 planned, developed, implemented, managed, and operated. This report shows that these  
24 implications are sufficiently significant that transportation planners should develop an  
25 improved understanding of climate change issues and reflect them in their decision-making  
26 today.

27 Yet the long timeframe for climate change, as compared to the existing 20-year view of  
28 most transportation plans, makes the specification of its impacts considerably more  
29 difficult. Instead of relatively precise estimates of potential impacts needed for many  
30 aspects of transportation planning, broad ranges are more typically what climatologists  
31 currently can provide. Given this lack of certainty, climatologists are moving toward the  
32 determination of probabilities of potential impacts.

33 Currently, the transportation planning process does not consider probabilities in  
34 determining future travel demand and ways to meet it.<sup>3</sup> Instead, transportation  
35 professionals generally rely on more deterministic methods that yield a single answer based

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<sup>3</sup> Steps have been made in this direction with the development of TRANSIMS, which employs sampling and statistical methods to generate future travel demand. However TRANSIMS is not yet in general use.

1 on the inputs, well accepted engineering, construction, and other standards, and  
2 professional judgment.

3 Such methods are ill-equipped to addressing the uncertainties associated with the timing  
4 and magnitude of many climate change impacts. What is needed are new tools that can  
5 address the uncertainties associated with climate change and yet provide more useful  
6 information to the transportation community that would be used to create a more robust and  
7 resilient system.

8 The following section provides a conceptual approach that represents the first step toward  
9 development of such a tool. It suggests a new approach to viewing both individual  
10 transportation facilities and the system as a whole, borrowing concepts and relationships  
11 from ecology, risk management, decision theory, and transportation practice. It proposes a  
12 way to help planners, designers, and engineers think through the potential harm that  
13 changing conditions in the natural environment might cause and the ability of the existing  
14 and proposed facilities to withstand such harm.

## 15 ■ **5.2 Conceptual Framework for Assessing Potential Impacts** 16 **on Transportation**

17 While climate factors are not usually considered for transportation planning purposes, as  
18 shown in the previous section, some agencies are beginning to explore how they might be  
19 incorporated. This section attempts to provide a conceptual approach to how climate  
20 concerns – with their inherent uncertainties – might be addressed in a transportation  
21 context. This is a first step toward creation of a way to consider risk and uncertainty in  
22 transportation planning as an alternative to the largely deterministic approaches currently  
23 employed. Further refinement will be necessary in Phase 2 of this study to make this  
24 approach operational in a pilot test area.

25 While the focus of this project is on a portion of the U.S. Gulf Coast, the intent is to  
26 develop a conceptual framework that lays the groundwork for an assessment linking  
27 climate change and transportation, and to focus on this nexus using a specific case as an  
28 illustration. Climate change impacts vary by region, with some areas being more  
29 vulnerable to some aspects of exposure than others. Regardless of the specific site  
30 characteristics related to this chapter, the general framework and relationships between  
31 information, decision-maker, and process will be transferable to other situations.  
32 Developing a conceptual framework at this stage in the research, rather than a static tool or  
33 model, provides the transportation sector with the basic understanding of these  
34 relationships at this early stage of recognition of the potential impacts of climate change  
35 and variability on transportation infrastructure.

36 This section focuses on: 1) a description of the basic factors that can be useful in an  
37 assessment of the potential impacts of climate change on transportation; and a

1 2) description of the development of a conceptual framework incorporating these basic  
2 components.

### 3 **5.2.1 Factors of Concern: Exposure, Vulnerability, Resilience,** 4 **and Adaptation**

5 There are four major conceptual factors to consider climate concerns in transportation:  
6 exposure to climate stressors, vulnerability, resilience, and adaptation. These concepts and  
7 their definitions are borrowed from, and consistent with, ecological and hazard assessment  
8 practices and represent transportation infrastructure's probable levels of exposure to  
9 damage from climate change factors, its capacity to resist such damage or disruption of  
10 service, and its ability to recover if damaged. For purposes of this project, we adapted the  
11 Intergovernmental Panel on Climate Change (IPCC) definitions of these concepts, in  
12 general, with reference to applied and theoretical applications for more specific or  
13 articulated examples. It was determined by the research team to closely approximate the  
14 IPCC terminology and methodology, as this also informs many other regional and sectoral  
15 assessments conducted in the United States and elsewhere.

16 With specific regard to climate change, *exposure* comprises the “nature and degree to  
17 which a system is exposed to significant climatic variations” (IPCC, 2001). Exposure also  
18 is often articulated as the probability of occurrence (the probable range of climate change  
19 stressors, such as sea level rise or increased rainfall) and the physical characterization of  
20 the local area. In this study, *exposure* is the combination of stress associated with climate-  
21 related change (sea level rise, changes in temperature, frequency of severe storms) and the  
22 probability, or *likelihood*, that this stress will affect transportation infrastructure.

23 While there are different kinds of exposure, (see Tobin and Montz, 1997, for a discussion),  
24 two types are applicable to this approach: perceived (based on the situational perspective  
25 of the particular decision-maker) and predicted (based on “objective” measures). For  
26 predicted exposures, the following environmental impacts appear to be most relevant in the  
27 Central Gulf Coast Region, depending on the specific infrastructure component and  
28 location:

- 29 • Sea level rise, historic trends, and predicted range (including rates of subsidence and/or  
30 erosion);
- 31 • Temperature range, scenarios, and probability distribution functions (with special  
32 consideration to changes in extreme temperatures);
- 33 • Precipitation range, scenarios and probability distribution functions and intensity; and
- 34 • Major storm characteristics (projected magnitude of storm surge and winds, and  
35 frequency).

36 *Vulnerability*, in general, refers to the “potential for loss” (Tobin and Montz, 1997) due to  
37 *exposure* to a particular hazard. The IPCC defines vulnerability as: “the degree to which a

1 system is susceptible to, or unable to cope with, adverse effects of climate change,  
2 including climate variability and extremes. Vulnerability is a function of the character,  
3 magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and  
4 its adaptive capacity” (IPCC, 2001). More specifically for this project, vulnerability  
5 considers the structural strength and integrity of key facilities or systems and is defined as  
6 the resulting potential for damage and disruption in transportation services from climate  
7 change stressors. The vulnerability of a facility or system then depends on the level of  
8 exposure to which it is subject.

9 The risk that a transportation facility or a system faces can be defined from these notions of  
10 exposure and vulnerability. It is the product of the probability that a facility will be  
11 exposed to a climate stressor of destructive (or disruptive, at the systems level) force times  
12 the damage that would be done because of this exposure.

13 While transportation is frequently thought of as the built infrastructure, transportation’s  
14 value to society is the service or performance this system of facilities and operations  
15 provides to move goods and people. Loss of capacity is the reduction from full  
16 performance capacity for a particular transportation system or facility. For example,  
17 Berdica (2002) defines vulnerability to the road system as a “problem of reduced  
18 accessibility.” System vulnerabilities to specific locational risks will vary based on the  
19 performance expectations of those specific system segments. The loss in performance  
20 would be the reduction of system capacity measured according to the relevant metrics. For  
21 example, highway capacity would be measured in volume of traffic flow; a loss in  
22 performance would be gauged by the reduction of traffic flow capacity.

23 It is important to note that vulnerability, like exposure, may be perceived differently among  
24 stakeholders and across modes. Key factors for the determination of transportation facility  
25 or system vulnerability may include:

- 26 • Age of infrastructure element;
- 27 • Condition/integrity;
- 28 • Proximity to other infrastructure elements/concentrations; and
- 29 • Level of service.

30 The concept of *resilience* is used to refer to the restoration capacity of the infrastructure at  
31 the facility and system level. In general, resilience is defined as the “amount of change a  
32 system can undergo without changing state” (IPCC, 2001). In the climate change context,  
33 resilience also refers to regenerative capacity, the speed of response and recovery of  
34 various system elements, and mitigation and adaptation efforts. It also is generally  
35 considered to be a “multidimensional concept, encompassing biogeophysical,  
36 socioeconomic and political factors” (Klein et al., 1998). Adger, et al., define resilience  
37 more specifically as the capacity of a system to absorb disturbances and retain essential  
38 processes (2005).

39 We can apply these concepts to the transportation context. System-level resilience is  
40 particularly important in the transportation sector because of the inherent connectivity of

1 transportation facilities. Resilience can be looked at as the ability of a transportation  
2 network to maintain adequate performance levels for mobility of goods and services  
3 through redundant infrastructure and services. The fact that one component is out of  
4 service may not be crucial in areas where alternative transportation facilities or services are  
5 available. For an individual facility such as a road or bridge, resilience can be thought of  
6 as how quickly full service can be restored either through repair or replacement.

7 Key factors influencing resilience in our conceptual framework can be categorized across  
8 three dimensions: mode or structure (highway segment or port, for example),  
9 socioeconomic (political will and resources), and system-level factors. These factors may  
10 include:

11 1. Mode/structure:

- 12 – Repair/replacement cost; and
- 13 – Replacement timeframe.

14 2. Socioeconomic:

- 15 – Public support;
- 16 – Interorganization cooperation;
- 17 – Economic resources; and
- 18 – Social resources.

19 3. System level:

- 20 – Redundancy among components;
- 21 – Essential service resumption;
- 22 – System network connectivity;
- 23 – Institutional capacity; and
- 24 – Relevance of existing plans for response to events (e.g., floods).

25 Transportation planners and decision-makers may consider these factors (either formally or  
26 informally) and generate a basic perception of resilience. For example, for any given  
27 facility the relevant decision-maker would have a general idea as to: 1) how much  
28 replacement would cost; 2) how long it would take; 3) the economic resources available for  
29 replacement; 4) public sentiment regarding replacement (or not); 5) how essential the  
30 facility is to system performance; and 6) whether or not plans exist for dealing with  
31 disruption of facility and/or system performance over the duration of the replacement time.  
32 This understanding of the resilience of the facility or system can be based on either a  
33 general feeling and experience of the decision-maker, or it can be developed systematically  
34 with quantifiable measures.

35 The IPCC defines *adaptation* as the: “adjustment to natural or human systems to a new or  
36 changing environment. Adaptation to *climate change* refers to adjustment in natural or

1 human systems in response to actual or expected climatic stimuli or their effects, which  
2 moderates harm or exploits beneficial opportunities” (IPCC, 2001). An associated concept,  
3 *adaptive capacity*, refers to “the ability of a system to adjust to climate change (including  
4 climate variability and extremes) to moderate potential damages, to take advantage of  
5 opportunities, or to cope with the consequences” (IPCC, 2001).

6 In this project, we are interested in understanding adaptation as a decision that officials can  
7 make in response to perceptions or objective measurements of vulnerability or exposure.  
8 For example, given a certain climate change scenario, a decision-maker may choose to  
9 advocate for certain adaptive policy responses beyond the status quo. This can be  
10 determined through interviews by asking such questions as: what is the planning horizon  
11 for this specific area, what factors (political and resource) constrain or encourage adaptive  
12 behavior in this area of concern, and what are the stakeholder perceptions of uncertainty in  
13 regard to the data and information provided and available for informed decision-making  
14 (see Jones, 2001, for an example).

15 Adaptive strategies can be further delineated into three possible alternatives: protect,  
16 accommodate, and retreat. These adaptive responses are derived from the IPCC framework  
17 for assessing coastal adaptation options (Bijlsma et al., 1996). Within the context of our  
18 case study which is in a coastal region, the *protection* strategy might aim to protect the land  
19 from the sea so that existing land uses can continue, by constructing hard structures (e.g.,  
20 seawalls) as well as using “soft measures” (e.g., beach nourishment, wetland restoration).  
21 *Accommodation* may call for preparing for periodic flooding by having operational plans in  
22 place to redirect traffic, for example, or cleaning up roadway obstacles to return to normal  
23 service. The *retreat* option would involve no attempt to protect the facility from the  
24 climate stressor. In an extreme case along a coastal area, for example, a facility or road  
25 segment could be abandoned under certain conditions (sea level rise, persistent storm  
26 surges that reduced the feasibility of replacement). From a system perspective, it could be  
27 determined that retreat is the best decision if the road segment could be relocated without  
28 loss of system service, if performance can be maintained through other system components,  
29 or if service is no longer required due to shifts in population and commerce.

30 A related concept, *threshold*, also will be considered in the framework. Threshold has been  
31 defined as “the point where a stimulus leads to a significant response” (Jones, 2001; Parry,  
32 Carter, and Hulme, 1996). In the case of transportation decision-making, we are interested  
33 in determining at what point within an assessment or decision process change is induced.  
34 A threshold can be quantified under certain circumstances (for example, the impact of  
35 temperature on pavement construction decisions), or it may be subjective, depending on the  
36 situation. Jones (2001) suggests two general thresholds for infrastructure: 1) economic  
37 write-off, or when replacement costs less than repair; and 2) a standard-derived threshold,  
38 when the condition of the infrastructure component falls below a certain standard. These  
39 variables can have both quantitative and qualitative characteristics. In this phase of the  
40 research, the focus is on determining qualitative characteristics and their general utility to  
41 decision-makers (see Cutter, et al, for a similar approach).



1 In summary, the following are working definitions that were applied in this section of the  
2 research. These definitions were developed in conjunction with the research team, the  
3 Federal Advisory Committee, and other experts.

4 **Exposure** – The combination of stress associated with climate-related change (sea level  
5 rise, changes in temperature, frequency of severe storms) and the probability, or *likelihood*,  
6 that this stress will affect transportation infrastructure.

7 **Vulnerability** – The structural strength and integrity of key facilities or systems and the  
8 resulting potential for damage and disruption in transportation services from climate  
9 change stressors.

10 **Resilience** – The capacity of a system to absorb disturbances and retain essential processes.

11 **Adaptation** – A decision that stakeholders can make in response to perceptions or  
12 objective measurements of vulnerability or exposure. Included in this concept is the  
13 recognition that *thresholds* exist where a stimulus leads to a significant response.

14 Each of these four factors is critical in our understanding of how climate change may  
15 impact transportation in the study region. As illustrated in Figure 5.5, an initial risk  
16 assessment for a facility or system will include analysis of the first three factors: exposure,  
17 vulnerability, and resilience. Once a risk assessment is conducted, choices for an  
18 appropriate adaptation strategy can be considered. The implementation of a particular  
19 adaptation strategy – to protect, accommodate, or retreat – will in turn affect subsequent  
20 risk assessments by changing one or more aspects of risk. The effectiveness of the  
21 adaptation strategy can be assessed by the degree of success in maintaining system or  
22 facility performance.

23 [ INSERT FIGURE 5.5: A risk assessment approach to transportation decisions ]

## 24 **5.2.2 Framework for Assessing Local Climate Change Impacts** 25 **on Transportation**

26 Having introduced the major factors for consideration in a climate change impact  
27 assessment, this section introduces the conceptual framework and outlines the input and  
28 outputs. This is followed by a description of an approach to implementing such a  
29 framework.

30 In general, the objective is to illustrate how climate change/variability can be integrated  
31 into existing transportation policy- and decision-making processes toward the development  
32 of adaptation strategies. Even at the conceptual level, this process can assist transportation  
33 decision-makers in considering the potential impacts from climate change and variability  
34 on a wide range of transportation infrastructure components of any type, including air, rail,  
35 marine, transit, or highway, as well as the overall intermodal system. It is intended to be  
36 implemented primarily at the state or local scale, since climate impacts differ by region of  
37 the country.

1 The framework can help direct local decision-makers in raising and to some extent  
2 answering such questions as: what are the likely changes in sea level (for example) in my  
3 area, how vulnerable is the transportation infrastructure related to this probability in my  
4 area, and at what point should decision-makers seek adaptive strategies to address this?  
5 The resulting information can then be utilized for making adaptation decisions.

### 6 ***Needed Data***

7 Previous chapters outlined the physical, infrastructure, and socioeconomic data that was  
8 collected and aggregated specifically for the Gulf Coast study area. This section discusses  
9 how this data serves to help assess the exposure and vulnerability of any transportation  
10 network. While not all of the data collected for this project would be available to local  
11 transportation stakeholders, much of the data is available and is being update on a regular  
12 basis.

13 Within this conceptual framework, the analysis begins with an assessment of what climate  
14 impacts can be determined with a relatively high degree of confidence. This is the basis for  
15 the exposure analysis, including some idea as to the probability that transportation facilities  
16 will be exposed to particular impacts. For the Gulf Coast Study, various climate scenarios  
17 were analyzed and probable impacts identified at the regional level, including sea level  
18 rise, increased storm intensity, extreme temperature increases, and potential ranges  
19 quantified. The infrastructure and services will be exposed to these impacts.

20 The vulnerability of specific portions of the transportation infrastructure will depend on its  
21 location relative to the location of the impacts, as well as other characteristics. Sea level  
22 rise is a good example, as coastal infrastructure will be more vulnerable than inland  
23 facilities. Based on location, the physical characteristics of the region, and socioeconomic  
24 data, the vulnerability of transportation facilities can be assessed.

25 From the probability of an exposure to a climate impact and the assessment of  
26 vulnerability, some idea of the risk the facility or the system faces can be determined. In  
27 order to do this, repair or replacement costs, economic losses, or other metric of potential  
28 damage must be developed. In addition, precise estimates of risk would require  
29 quantitative estimates of exposure would be needed. Whether risk can be quantitatively  
30 determined remains to be seen.

31 Resilience was not addressed in the first phase of the Gulf Coast analysis, but will be in the  
32 second phase. The analysis of resilience requires different data for systems versus facility  
33 consideration. At the systems level, an in-depth knowledge of the movement of goods and  
34 people is necessary to assess the potential for redundant services that can at least minimally  
35 maintain service. For facilities, the time and cost needed to bring damaged infrastructure to  
36 full performance would be critical.

1        ***Outcomes***

2        Having considered how transportation facilities might be exposed and determined their  
3        vulnerability and the resilience of the network, decision-makers can then consider ways to  
4        improve transportation in the region to be more robust to the climate impacts identified.

5        The primary outputs from the conceptual framework are policy recommendations or  
6        changes derived from the decision-makers understanding and interpretation of the major  
7        factors (exposure, vulnerability, and resilience and adaptation) associated with climate  
8        change. Where appropriate, these recommendations should lead to capital, maintenance, or  
9        operational improvements that will result in a more robust and resilient network.

10       The process of following the framework can be used to characterize the exposure of  
11       particular facility or system component to climate hazards, the vulnerability, and resiliency  
12       of these elements, and the adaptation options available to the decision-maker. Examples of  
13       potential thresholds or tipping points indicated for each of these factors targeted at each  
14       relevant transportation infrastructure element can then be used as input into the planning  
15       and decision processes available to the user. This output from the conceptual framework  
16       could be designated for the local level or state DOT level of planning. It will be up to the  
17       stakeholder or decision-maker to determine how the assessment output would impact  
18       existing or proposed decision and planning processes at the relevant scale.

19       Figure 5.6 illustrates the relationship between risk assessment and the value of performance  
20       to the type of adaptation strategy that may be selected. As the importance of maintaining  
21       uninterrupted performance increases, the appropriate level of investment in adaptation  
22       should increase as well, taking into account the degree of risk facing the specific facility or  
23       system. For example, maintaining a specific bridge may be essential to ensure safe  
24       evacuation of a particular community, because no other feasible evacuation routes or back-  
25       up strategies are available. In this instance, transportation and regional planners may  
26       recommend that more conservative (and possibly more expensive) design standards be  
27       applied to protect that bridge in the event of a low probability – but high consequence –  
28       storm event in that location. Conversely, although a road segment may be assessed to be  
29       highly at risk, it may warrant less extensive adaptation investment because alternatives to  
30       that road are available to provide access and mobility, or a moderate disruption in service  
31       performance is not considered to be critical.

32       [INSERT FIGURE 5.6: Degree of risk and value of performance inform level of adaptation  
33       investment ]

34       ***Making Use of Risk Assessment in Transportation Decisions***

35       The concepts presented in this chapter can be employed to begin the assessment of climate  
36       impacts in transportation planning and investment. Additional detail will be required for  
37       implementation, but this discussion offers an initial step toward a more complete  
38       consideration of risk and uncertainty in this type of assessment. As demonstrated,  
39       probabilities for some climate impacts are now available on a regional level, but  
40       probabilities for specific impacts on individual facilities or network components cannot yet

1 be assigned with confidence. Furthermore, while some climate impacts can be reliably  
2 identified, data are lacking for others that may be important for transportation.  
3 Nonetheless, even at the conceptual level, this discussion may be useful for transportation  
4 planners as they begin to incorporate climate concerns in their consideration of new  
5 investments.

6 Consider the following example of a bridge located near the coast that is scheduled for  
7 rehabilitation in five years. Based on the conceptual framework, the first step is to  
8 determine its exposure to stressors that may significantly impede the service it provides.

9 If the bridge were located within the Gulf Coast study area, the analyses in Chapters 3.0  
10 and 4.0 indicate the four main stressors of concern: sea level rise, storm surge, temperature  
11 increases, and heavy downpours giving rise to flooding. There may be others as well, and  
12 the analyst would do well to consider other potential impacts in consultation with natural  
13 resource experts.

14 If the bridge falls within the area identified as likely to be flooded by a 61 to 122 cm (2- to  
15 4-foot) rise in sea level, more specific examination of the particular terrain is warranted to  
16 assess in greater detail the likelihood of flooding. If there are no mitigating factors, there is  
17 a relatively high probability that the area will flood within a 50- to 100-year time period.

18 The next step is to determine the bridge's vulnerability to sea level rise. How high is the  
19 bridge? How high are the approaches? How critical is the service it provides? Based on  
20 these and other considerations, the bridge's vulnerability, in the context of its role within  
21 the larger network, can be assessed. If the bridge, or critical elements of it, are below 122  
22 cm (4 feet), it will likely flood within its projected lifespan. While more objective  
23 measures of vulnerability to the service flowing over the bridge would be desirable, at a  
24 minimum the analyst should be able to derive a qualitative determination of the bridge's  
25 vulnerability.

26 Judgment must be applied to assess the risk (probability of exposure x vulnerability) posed  
27 by flooding with current knowledge. Precise estimates of its components are not possible  
28 but the direction and likely ranges are known and from this a general sense of the risk can  
29 be inferred. If the bridge is heavily trafficked and it is vulnerable, the risk is high because  
30 the sea is rising leading to permanent flooding and the bridge's period of service will be cut  
31 short before it reaches the end of its useful life. Since in the example, the bridge is  
32 scheduled for rehabilitation, now would be an appropriate time to consider options.

33 The adaptation options are to protect, accommodate, or retreat. Accommodation, which  
34 might include operational strategies to work around the flooding or simply living with it,  
35 does not appear to be viable since the flooding is permanent and operational strategies like  
36 pumping the water out do not seem viable. Protection may include raising the bridge or its  
37 approaches or relocating the facility. Retreat, which in this case amounts to abandonment  
38 of the bridge, is likely the option of last choice since the bridge presumably provides a  
39 critical service. Engineering, design, landscape, and regional considerations will play  
40 crucial roles in the determination of the best option, as will the consideration of the

1 additional resources necessary to best protect the bridge. Transportation agencies have  
2 extensive experience in exercising the judgment necessary to make these determinations.

3 In similar fashion, each of the stressors can be assessed for their likelihood and the bridge  
4 examined for its vulnerability. Risk can be determined and options identified to prolong  
5 the bridge's useful life and minimize disruptions to the critical service it provides. For  
6 stressors whose impacts are well understood, a higher level of analysis can and should be  
7 done to consider the potential for synergistic impacts that may be more severe than the  
8 individual effect. The end result of the analysis will be recommendations for investment  
9 whose implementation will result in a more robust and reliable transportation facility and  
10 system. Experience indicates that the total cost to transportation agencies will probably be  
11 lower than failing to consider these impacts when the full costs – capital, operating and  
12 economic loss due to disrupted service – are included.

### 13 ■ 5.3 Conclusions

14 Climate change and variability have not historically been considered in the planning and  
15 development of transportation facilities, and this was clearly expressed in the interviews  
16 conducted as part of this study. Until recently, it may not have been possible to effectively  
17 use climate data to serve as the basis of considerable capital investment due to its relative  
18 uncertainties. That appears to be changing. The destructive force of Hurricanes Katrina  
19 and Rita have underscored the need to carefully consider the effects of the natural  
20 environment on transportation to a much higher degree. State, local, and possibly private  
21 (though less is known about their myriad approaches) transportation agencies are beginning  
22 to incorporate more information about the natural environment, including those effects  
23 wrought or exacerbated by climate change.

24 With the advent of increasingly greater certainty about the regional effects of climate  
25 change and better tools to assist their examination, the prospects for analyzing the impacts  
26 of climate and the natural environment has become possible. Clearly there is benefit to do  
27 so. Subsidence and climate-induced sea level rise, coupled with the likely increased  
28 severity of hurricanes, threaten infrastructure potentially causing severe disruptions to  
29 essential transportation services or cutting short the useful lives of important facilities.  
30 Transportation planners across the United States would do well to follow the lead of  
31 progressive agencies in the Gulf Coast and other places to begin immediately to consider  
32 the impacts of climate change on the natural environment and thus on transportation  
33 facilities under their purview.

34 This chapter introduces a taxonomy and conceptual approach toward incorporating climate  
35 change impacts in transportation planning. Standard deterministic approaches used in  
36 transportation planning will not suffice to address the timeframes and uncertainties that a  
37 changing climate poses. The approach is based on the quantitative or qualitative  
38 assessment of exposure to potentially disruptive impacts, examination of a facility's (or a  
39 network's) vulnerability, the risk of its loss, and possible adaptation strategies to mitigate

1 these impacts and prolong service. It is premature to consider any formal changes to the  
2 established Federal transportation planning process. If for no other reason, the timeframes  
3 and other requirements such as fiscal constraint do not mesh well. Nonetheless, the  
4 consideration of climate impacts is possible and useful to transportation plans at all levels  
5 of government and the private sector. For instance, in the planning process shown in  
6 Figure 5.3, climate change could be considered early on as part of a visioning process and  
7 later in the development and evaluation of alternative improvement strategies which  
8 consider future services and their location. Climate change could be considered in the  
9 project development process when design and engineering are addressed. Likewise, the  
10 concept of uncertainty and the use of risk analysis could be incorporated into the entire  
11 planning and project development process.

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16



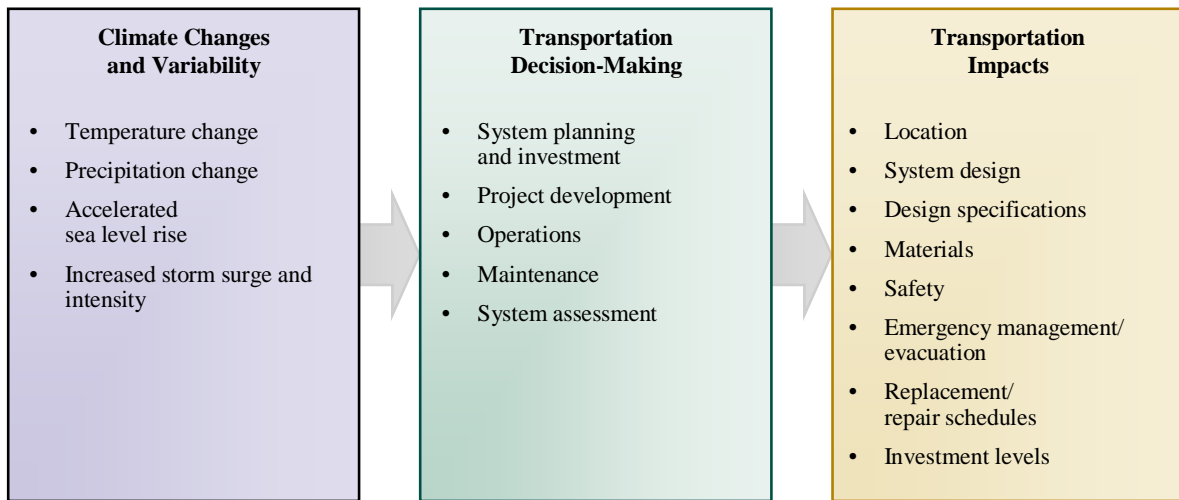
**Table 5.1 Urbanized area metropolitan planning organizations (MPO) in the Gulf Coast study area.**

<b>Urbanized Areas</b>	<b>2000 Population</b>	<b>Metropolitan Planning Organizations</b>
Mobile, Alabama	354,943	Mobile Area Transportation Study
Baton Rouge, Louisiana	516,614	Capital Regional Planning Commission
Houma, Louisiana	108,474	Houma-Thibodaux MPO
Lake Charles, Louisiana	183,577	Imperial Calcasieu Regional Planning and Development Commission
Lafayette, Louisiana	215,061	Lafayette MPO
New Orleans, Louisiana; Slidell, Louisiana; Mandeville-Covington, Louisiana	1,193,847	Regional Planning Commission of New Orleans
Gulfport-Biloxi, Mississippi; Pascagoula, Mississippi	363,987	Gulf Regional Planning Commission
Hattiesburg, Mississippi	80,798	Hattiesburg-Petal-Forest-Lamar MPO
Houston, Texas; Galveston, Texas; Lake Jackson-Angleton, Texas; Texas City, Texas; The Woodlands, Texas	4,669,571	Houston-Galveston Area Council
Beaumont, Texas; Port Arthur, Texas	385,090	South East Texas Regional Planning Commission MPO

**Table 5.2 Level of decision maker concern about climate stressors.**

<b>Research Subjects</b>	<b>Sea Level</b>	<b>Precipitation</b>	<b>Temperature</b>	<b>Storm Frequency and Magnitude</b>
Transtar	Moderate	Moderate	High	High
Emergency Management	High	Limited	Limited	High
Toll Authority	Low	Limited	Limited	High
Aviation	Limited	Moderate	Highest	High
Aviation	Limited	Moderate	Moderate	High
County Engineer	High	Limited	Limited	Highest
Port Engineer	High	High	Limited	Highest
Port Engineer	Low	High	Limited	Highest
Flood Control – Houston	Limited	Limited	Low	Highest
TX-DOT Engineer	Highest	Limited	Low	High

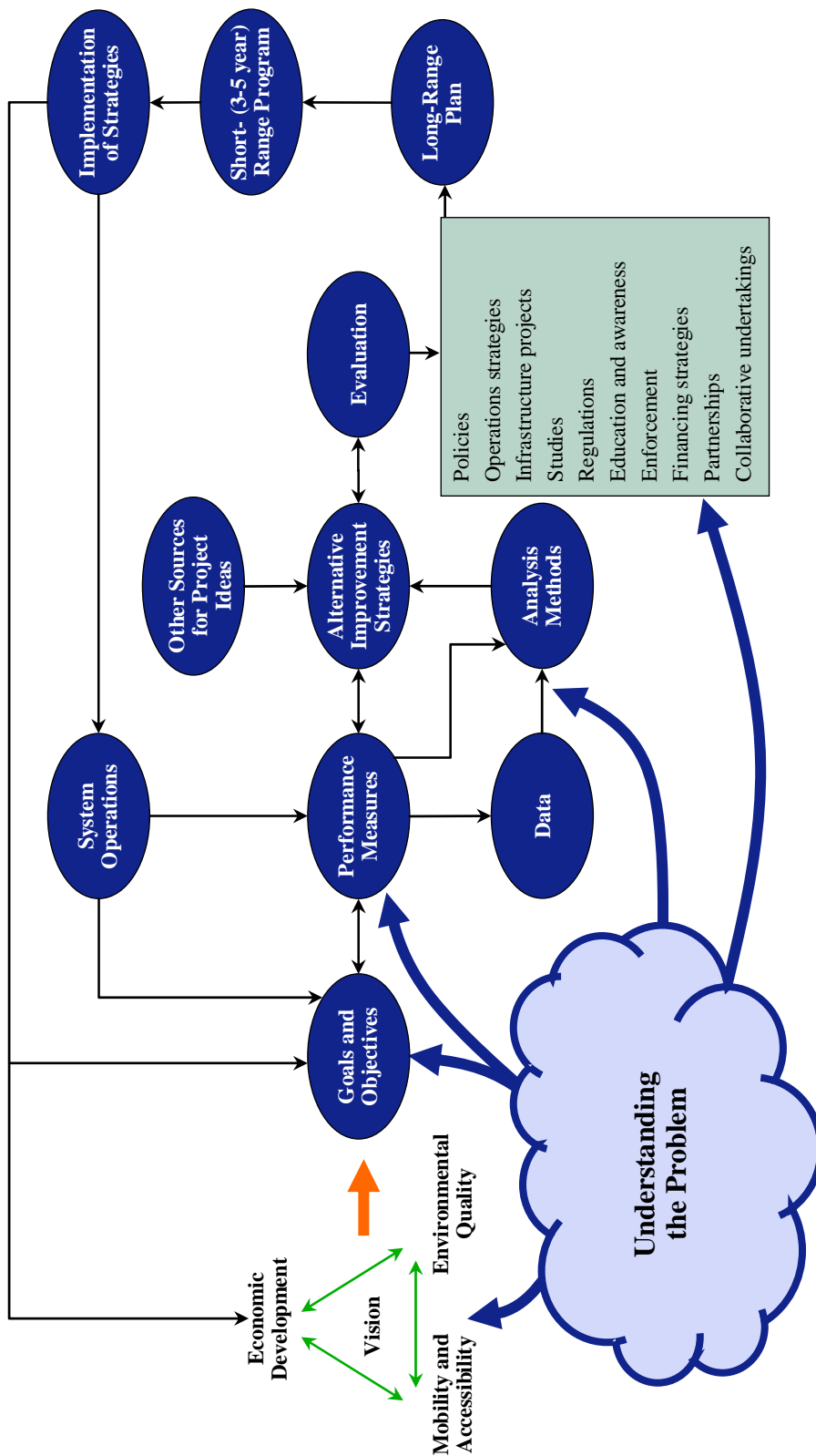
**Figure 5.1 How will climate change affect transportation decisions?**



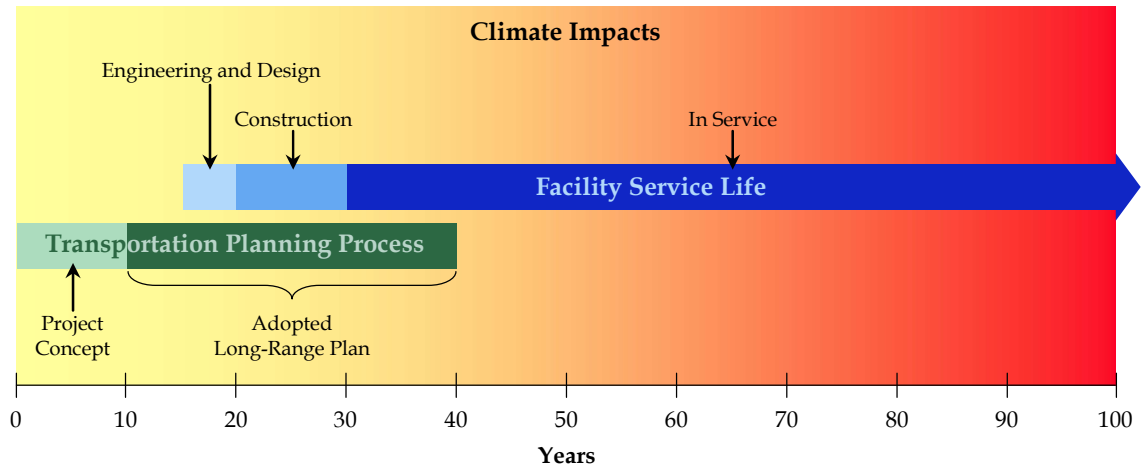
**Figure 5.2 SAFETEA-LU planning factors. Eight planning factors that should guide the development of plans, programs, and projects are identified in SAFETEA-LU. (Source: U.S. Department of Transportation)**



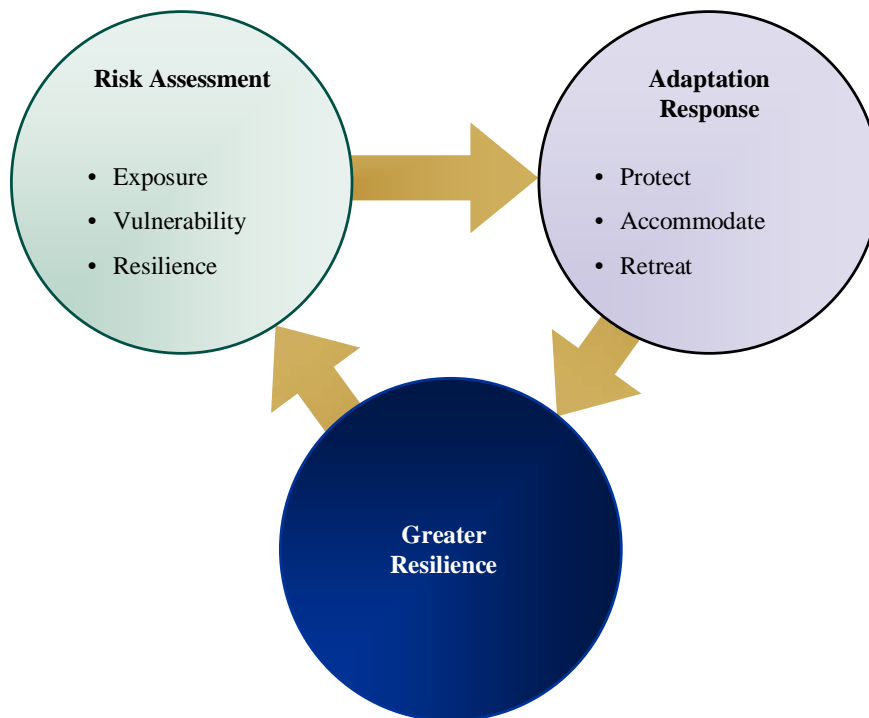
**Figure 5.3** Steps in the transportation planning process.  
 (Source: Michael Meyer, Georgia Institute of Technology)



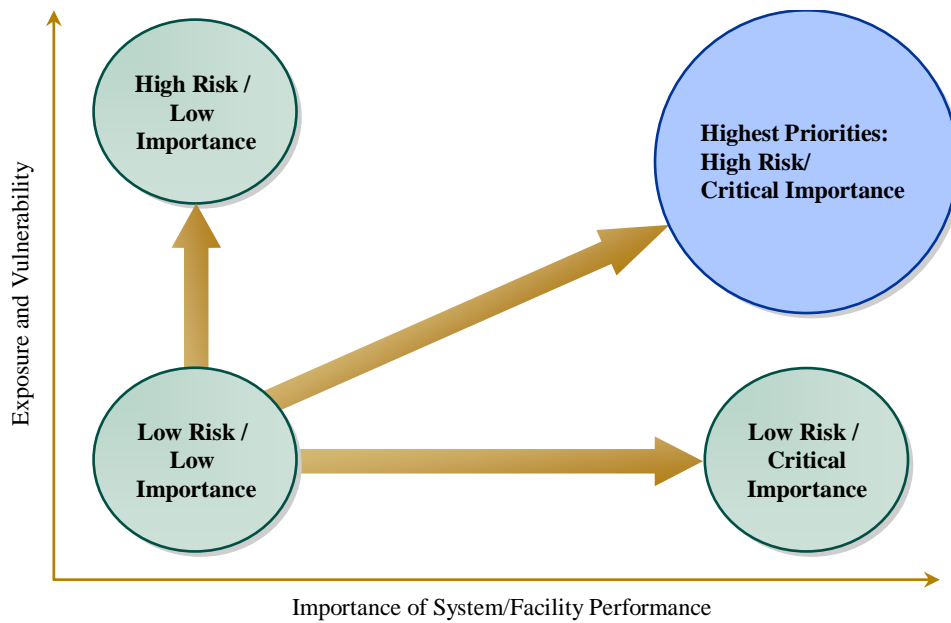
**Figure 5.4 Relationship of transportation planning timeframe and infrastructure service life to increasing climate change impacts**



**Figure 5.5 A risk assessment approach to transportation decisions.**



**Figure 5.6 Degree of risk and value of performance inform level of adaptation investment.**







## 6.0 What are the Key Conclusions of this Study?

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The primary objectives of this phase of the Gulf Coast Study were to assemble the data needed for an analysis of the potential impacts on transportation, determine whether climate and ecological data could be usefully employed in such an assessment, identify and implement an assessment approach, and provide an overview of the potential impacts. The results are striking. They show that the data can provide useful information to transportation decision-makers about the natural environment as it exists today, as well as the likely changes stemming from climate shifts. By using the historical data on the natural environment, an ensemble of climate models, a range of emission scenarios, well-established literature on climate impacts, and a conservative approach toward interpretation, this study indicates that the potential impacts on transportation in the Gulf Coast are highly significant, as summarized below.

While further study is needed to examine in more detail the impacts on specific transportation facilities, such as individual airports or rail terminals, this preliminary assessment finds that the potential impacts on infrastructure are so important that transportation decision-makers should begin immediately to assess them in the development of transportation investment strategies. Phase 2 of this effort will examine one small part of the Gulf Coast study region in much more detail. While the significance of climate factors will vary across regions of the U.S., responsible transportation agencies in other areas would do well to consider these types of impacts as well, since the decisions they make today may result in infrastructure that will last 50 to 100 years. While the timing and pace of these impacts cannot be specified with precision, the central Gulf Coast already is vulnerable to certain impacts, as demonstrated by the 2005 hurricane season.

Given the characteristics of the climate system – especially the long periods of time greenhouse gases remain in the atmosphere, and the virtually certain increases in carbon dioxide concentrations in the coming decades – some degree of impacts cannot be avoided. Based on analysis of different emission scenarios, the magnitude of future impacts will depend on the amount of greenhouse gases emitted. While the modeled scenarios demonstrate very similar levels climate impacts over the next 40 years, lower emission scenarios show lesser impacts in the longer term (60 to 100 years). If aggressive measures

1 result in reduced emission levels globally, the climate impacts identified here may be on  
2 the lower end of the anticipated ranges.

3 The study authors believe that prudent steps can be taken to fortify the existing  
4 transportation system, as warranted, after an evaluation of impacts on critical transportation  
5 facilities and systems. Structures can be hardened, raised, or even relocated as need be  
6 and – where critical to safety and mobility – expanded redundant systems may be  
7 considered as well. What adaptive strategies may be employed, the associated costs, and  
8 the relative effectiveness of those strategies will have to be determined on a case-by-case  
9 basis, based on studies of individual facilities and systemwide considerations. As  
10 transportation agencies struggle to meet the challenges of congestion, safety, and  
11 environmental mitigation – as well as maintaining transportation infrastructure in good  
12 repair – meeting the challenges posed by a changing climate poses a new and major hurdle  
13 toward creation of a more resilient transportation network in a time of increasingly scarce  
14 resources. Phase 3 of this effort will examine potential response strategies and develop  
15 methods to assist local decision-makers in assessing the relative merits of various  
16 adaptation options.

## 17 ■ 6.1 Trends in Climate and Coastal Change

18 The central Gulf Coast is particularly vulnerable to climate variability and change because  
19 of the frequency with which hurricanes strike, because much of its land is sinking relative  
20 to mean sea level, and because much of its natural protection – in the form of barrier  
21 islands and wetlands – has been lost. While difficult to quantify, the loss of natural storm  
22 buffers will likely intensify many of the climate impacts identified in this report,  
23 particularly in relation to storm damage.

- 24 • **Relative Sea Level Rise** – Since much of the land in the Gulf Coast is sinking, this area  
25 is facing much higher increases in relative sea level rise (the combination of local land  
26 surface movement and change in mean sea level) than most other parts of the U.S.  
27 coast. Based on the output of an ensemble of General Circulation Models (GCM) run  
28 with a range of IPCC emissions scenarios, relative sea level in the study area is very  
29 likely to increase at least 0.3 meter (1 foot) across the region and possibly as much as 2  
30 meters (6 to 7 feet) in some parts of the study area over the next 50 to 100 years. The  
31 analysis of even a “middle range” of potential sea level rise of 0.3 to 0.9 meters (2 to 4  
32 feet) indicates that a vast portion of the Gulf Coast from Houston to Mobile may be  
33 inundated in the future. The projected rate of relative sea level rise for the region  
34 during the next 50 to 100 years is consistent with historical trends, region-specific  
35 analyses, and the IPCC 4<sup>th</sup> Assessment Report (2007) findings, which assume no major  
36 changes in ice sheet dynamics.

37 Protective structures, such as levees and sea walls, could mitigate some of these  
38 impacts, but considerable land area is still at risk to permanent flooding from rising  
39 tides, sinking land, and erosion during storms. Subsidence alone could account for a

1 large part of the change in land area through the middle of this century, depending on  
2 the portion of the coast that is considered. Sea level rise induced by the changing  
3 climate will substantially worsen the impacts of subsidence on the region.

- 4 • **Storm Activity** – The region is vulnerable today to transportation infrastructure  
5 damage during hurricanes and, given the potential for increases in the number of  
6 hurricanes designated as Category 3 and above, this vulnerability will likely increase.  
7 This preliminary analysis did not quantitatively assess the impact of the loss of  
8 protective barrier islands and wetlands, which will only serve to make storm effects  
9 worse. It also did not consider the possible synergistic impacts of storm activity over a  
10 sea that has risen by 0.6 to 1.2 meters (two to four feet). This potential would likely  
11 make a bad situation even worse, as well.
- 12 • **Average Temperature Increase** – All GCMs used by the IPCC in its Fourth  
13 Assessment Report (2007) indicate an increase in average annual Gulf Coast  
14 temperature through the end of this century. Based on GCM runs under three different  
15 IPCC emission scenarios (A1B, A2, and B1), the average temperature in the Gulf Coast  
16 region appears likely to increase by at least  $1.5^{\circ}\text{C} \pm 1^{\circ}\text{C}$  ( $2.7^{\circ}\text{F} \pm 1.8^{\circ}\text{F}$ ) during the next  
17 50 years, with the greatest increase in temperature occurring in the summer.
- 18 • **Temperature Extremes** – With increases in average temperature also will come  
19 increases in extreme high temperature. Based on historical trends and model  
20 projections, it is very likely that the number of days above  $32.2^{\circ}\text{C}$  ( $90^{\circ}\text{F}$ ) will increase  
21 significantly across the study area; this has implications for transportation operations  
22 and maintenance. The number of days above  $32.2^{\circ}\text{C}$  ( $90^{\circ}\text{F}$ ) could increase by as much  
23 as 50 percent during the next 50 years.
- 24 • **Precipitation Change** – Future changes in precipitation are much more difficult to  
25 model than temperature. Precipitation trends in the study area suggest increasing  
26 values, with some climate divisions, especially those in Mississippi and Alabama,  
27 having significant long-term trends. Yet while some GCM results indicate that average  
28 precipitation will increase in this region, others indicate a decline in average  
29 precipitation during the next 50 to 100 years. Because of this ambiguity, it is difficult  
30 to reach conclusions about what the future holds regarding change in mean  
31 precipitation. Even if average precipitation increases slightly, average annual runoff in  
32 the region could decline as temperature and evapotranspiration rates increase.
- 33 • **Extreme Rainfall Events** – Average annual precipitation increased at most recording  
34 stations within the study area since 1919 and the literature indicates that a trend towards  
35 more rainfall and more frequent heavy downpours is likely. At this stage, climate  
36 modeling capacity is insufficient to quantify effects on individual precipitation events,  
37 but the potential for temporary flooding in this region is clear. In an area where  
38 flooding already is a concern, this tendency could be exacerbated by extreme rainfall  
39 events. This impact will become increasingly important as relative sea level rises,  
40 putting more and more of the study area at risk.

## 1 ■ 6.2 Transportation Impacts

2 Based on the trends in climate and coastal change, transportation infrastructure and the  
3 services that require them are vulnerable to future climate changes as well as other natural  
4 phenomena. While more study is needed to specify how vulnerable they are and what steps  
5 could be taken to reduce that vulnerability, it is clear that transportation planners in this  
6 region should not ignore these impacts.

- 7 • **Inundation from Relative Sea Level Rise** – While greater or lesser rises in relative  
8 sea level are possible, this study analyzed the effects of relative sea level rise of 0.6 and  
9 1.2 meters (2 and 4 feet) as realistic scenarios.. Based on these levels, an untenable  
10 portion of the region’s road, rail, and port network is at risk of permanent flooding.

11 Twenty-seven percent of the major roads, 9 percent of the rail lines, and 72 percent of  
12 the ports are at or below 122 centimeters (4 feet) in elevation, although portions of the  
13 infrastructure are guarded by protective structures such as levees and dikes. While  
14 flood protection measures will continue to be an important strategy, rising sea levels in  
15 areas with insufficient protection may be a major concern for transportation planners.  
16 Furthermore, the crucial connectivity of the intermodal system in the area means that  
17 the services of the network can be threatened even if small segments are inundated.

18 While these impacts are very significant, they can be addressed and adaptive strategies  
19 developed if transportation agencies carefully consider them in their decisions. The  
20 effectiveness of such strategies will depend on the strategies selected and the magnitude  
21 of the problem, as scenarios of lower emissions demonstrate lesser impacts. It may be  
22 that in some cases, the adaptive strategy may be wholly successful, while in others  
23 further steps may need to be taken. Adaptive strategies that can be undertaken to  
24 minimize adverse impacts will be assessed in Phase 3 of this study.

- 25 • **Flooding and Damage from Storm Activity** – As the central Gulf Coast is already is  
26 vulnerable to hurricanes, so is its transportation infrastructure. This study examined the  
27 potential for short-term flooding associated with a 5.5- and a 7.0-meter (18- and 23-  
28 foot) storm surge. Based on these relatively common levels, a great deal of the study  
29 area’s infrastructure is subject to temporary flooding. More than half (64 percent of  
30 Interstates; 57 percent of arterials) of the area’s major highways, almost half of the rail  
31 miles, 29 airports, and virtually all of the ports are subject to flooding.

32 The nature and extent of the flooding depends on where the hurricane makes landfall  
33 and its specific characteristics. Hurricanes Katrina and Rita demonstrated that that this  
34 temporary flooding can extend for miles inland.

35 This study did not examine in detail the potential for damage due to the storm surge,  
36 wind speeds, debris, or other characteristics of hurricanes since this, too, greatly  
37 depends on where the hurricane strikes. Given the energy associated with hurricane  
38 storm surge, concern must be raised for any infrastructure in its direct path that is not  
39 designed to withstand the impact of a Category 3 hurricane or greater.

1 Climate change appears to worsen the region's vulnerability to hurricanes, as warming  
2 seas give rise to more energetic storms. The literature indicates that the intensity of  
3 major storms may increase 5 to 20 percent. This indicates that Category 3 storms and  
4 higher may return more frequently to the central Gulf Coast, and thus cause more  
5 disruptions of transportation services.

6 The impacts of such storms need to be examined in greater detail; storms may cause  
7 even greater damage under future conditions not considered here. If the barrier islands  
8 and shorelines continue to be lost at historic rates and as relative sea level rises, the  
9 destructive potential of tropical storms is likely to increase.

- 10 • **Effects of Temperature Increase** – As the average temperature in the central Gulf  
11 Coast is expected to rise by 0.5°C to 2.5°C (0.9°F to 4.5°F), the daily high  
12 temperatures, particularly in summer, and the number of days above 32.2°C (90°F) also  
13 will likely increase. These combined effects will raise costs related to the construction,  
14 maintenance, and operations of transportation infrastructure and vehicles. Maintenance  
15 costs will increase for some types of infrastructure as they deteriorate more quickly at  
16 temperatures above 32°C (90°F). Increase in daily high temperatures could increase  
17 the potential for rail buckling in certain types of track. Construction costs could  
18 increase because of restrictions on days above 32°C (90°F) since work crews may be  
19 unable to be deployed during extreme heat events and concrete strength is affected by  
20 the temperature at which it sets. Increases in daily high temperatures would affect  
21 aircraft performance and runway length, as runways need to be longer when daily  
22 temperatures are higher, all other things being equal. While potentially costly and  
23 burdensome, these impacts may be addressed by transportation agencies by absorbing  
24 the increased costs and increasing the level of maintenance for affected facilities.
- 25 • **Effects of Change in Average Precipitation** – It is difficult to determine how  
26 transportation infrastructure and services might be impacted by changes in average  
27 precipitation since models project either a wetter or a drier climate in the southeastern  
28 U.S. In either case though, the changes in average rainfall are relatively slight and the  
29 existing transportation network may be equipped to manage this.
- 30 • **Effects of Increased Extreme Precipitation Events** – Of more concern is the potential  
31 for short-term flooding due to heavier downpours. Even if average precipitation  
32 declines, the intensity of those storms can lead to temporary flooding as culverts and  
33 other drainage systems are overloaded. Further, Louisiana DOT reports that prolonged  
34 flooding of one to five weeks can damage the pavement substructure and necessitate  
35 rehabilitation (Gaspard et al., 2007). The central Gulf Coast already is prone to  
36 temporary flooding; and transportation representatives struggle with the disruptions  
37 these events cause. As the climate changes, this will probably become more frequent  
38 and more disruptive as the intensity of these downpours will likely increase. As  
39 relative sea level rises, it appears likely that even more infrastructure will be at risk  
40 because overall water levels already will be so much higher. While these impacts  
41 cannot be quantified at present, transportation representatives can monitor where  
42 flooding occurs and how the sea is rising as an early warning system about what  
43 facilities are at immediate risk and warrant high-priority attention. In a transportation

1 system that already is under stress due to congestion, and with people and freight  
2 haulers increasingly dependent on just-in-time delivery, the economic, safety, and  
3 social ramifications of even temporary flooding may be significant.

## 4 ■ 6.3 Implications for Planning

5 The network in the study area provides crucial service to millions of people and transports  
6 enormous quantities of oil, grain, and other freight. It is a network under increasing strain  
7 to meet transportation demand as the American public's desire for travel and low-cost  
8 goods and services continues to grow. Even minor disruption to this system causes ripple  
9 effects that erode the resources of transportation agencies as well as the good will and trust  
10 of the public. Good stewardship requires that the transportation network be as robust and  
11 resilient as possible within available resources.

12 This preliminary assessment raises clear cause for concern regarding the vulnerability of  
13 transportation infrastructure and services in the central Gulf Coast due to climate and  
14 coastal changes. These changes threaten to cause both major and minor disruptions to the  
15 smooth provision of transport service through the study area. Transportation agencies –  
16 bearing the responsibility to be effective stewards of the network and future investments in  
17 it – need to consider these impacts carefully.

18 Steps can be taken to address the potential impacts to varying degrees. This study  
19 demonstrates that there is benefit to examining the long-term impacts of climate change on  
20 transportation. Climate data and model scenarios may be productively employed to better  
21 plan for transportation infrastructure and services, even if there is not as much information  
22 or specificity as transportation planners might prefer. State and local planners need to  
23 examine these potentialities in greater detail within the context of smaller study areas and  
24 specific facilities. But to effectively consider them, changes are likely necessary in the  
25 timeframes and approaches taken.

26 • **Planning Timeframes** – Current practice limits the ability of transportation planners to  
27 examine potential conditions far enough into the future to adequately plan for impacts  
28 on transportation systems resulting from the natural environment and climate change.  
29 As such, insufficient attention is paid to longer-term impacts in some cases. The  
30 longevity of transportation infrastructure argues for a long timeframe to examine  
31 potential impacts from climate change and other elements of the natural environment.

32 The current practice for public agencies of examining 20 to 30 years in the future to  
33 plan for transportation infrastructure may represent the limits of our sight for social,  
34 economic, and demographic assessments; as well as for consideration of fiscal  
35 constraint and other Federal planning requirements. However, the natural environment,  
36 including the climate, changes over longer time periods and warrants attention –  
37 perhaps as part of a long-term visioning process that helps to determine where

1 transportation investments are needed and should be located. Such an approach would  
2 inform the long-range planning process with valuable supplementary information.

3 This study could not examine transportation decision-making in the private sector in  
4 detail due to proprietary concerns and the numerous companies involved. Clearly,  
5 some companies, such as CSX, have responded to issues posed by the 2005 hurricane  
6 season and made contingency plans to reroute service. Since the concerns are every bit  
7 as real for the private sector, these companies also would do well to plan for and  
8 implement adaptive strategies related to climate and other natural environment impacts.

- 9 • **Connectivity** – In addition to analysis at the level of particular facilities – such as an  
10 airport, bridge, or a portion of rail line – it would be useful for planners to examine the  
11 connectivity of the intermodal system for vulnerability assessed at the local, regional,  
12 national, and international levels to long-term changes in the natural environment,  
13 including changes induced by climate. This helps to identify critical links in the system  
14 and ways to buttress them against exposures to climate factors or other variables, or to  
15 create redundancies to maintain critical mobility for directly and indirectly affected  
16 populations alike.
- 17 • **Integrated Analysis** – From a transportation planning perspective, it is unnecessary  
18 and irrelevant to separate impacts due to climate change from impacts occurring from  
19 other naturally occurring phenomena like subsidence or storm surge due to hurricanes.  
20 In fact, such impacts are integrally related. Climate change is likely to increase the  
21 severity or frequency of impacts that already are occurring. Any impact that affects the  
22 structural integrity, design, operations, or maintenance that can be reasonably planned  
23 for should be considered in transportation planning. Efforts to restore ecological  
24 systems to redevelop protective buffers and reverse land loss may likewise help to  
25 protect transportation infrastructure from future climate impacts.

## 26 ■ 6.4 Future Needs

27 The analysis of how a changing climate might affect transportation is in its infancy. While  
28 there is useful information that can be developed, the continued evolution of this type of  
29 study will serve to enhance the type of information planners, engineers, operators, and  
30 maintenance personnel need to create an even more robust and resilient transportation  
31 system, ultimately at lower cost. This study begins to address the research needs identified  
32 in Chapter 1.0 based on the current literature, but much more investigation is required.  
33 Based on the experience gained in conducting this study, research gaps are indicated in  
34 several chapters and specifically identified in Chapter 4.0. Taken together, they indicate  
35 the following areas where more information is critical to the further estimation of the  
36 impacts of a changing climate on transportation infrastructure and services.

- 37 • **Climate Data and Projections** – The transportation community would benefit from  
38 the continued development by climatologists of more specific data on projected future

1 impacts. Higher resolution of climate models for regional and subregional studies  
2 would be useful. More information about the likelihood and extent of extreme events,  
3 including temperature extremes, storms with associated surges and winds, and  
4 precipitation events could be utilized by transportation planners.

- 5 • **Risk Analysis Tools** – In addition to more specific climate data, transportation  
6 planners also need new methodological tools to address the uncertainties that are  
7 inherent in projections of climate phenomena. Such methods are likely to be based on  
8 probability and statistics as much as on engineering and material science. The  
9 approaches taken to address risk in earthquake-prone areas may provide a model for  
10 developing such tools.

11 This study proposes a conceptual framework that may provide one way of approaching  
12 the development of new tools. More effort is needed to make the concepts presented  
13 here operational and thus useful to planners in the region. Specifically, more effort is  
14 needed to identify thresholds at which adaptive actions are warranted and taken.  
15 Monitoring short-term flooding due to increased downpours, relative sea level rise, and  
16 operating, maintenance, and construction costs serves as a good first step toward the  
17 identification of these thresholds. Eventually, it would be most useful to have  
18 standards of transportation service based on societal needs to guide future investments.  
19 And in some instances, changes in design standards may be indicated to ensure the  
20 desired levels of service.

- 21 • **Region-Based Analysis** – Future phases of this study will examine in more detail the  
22 potential impacts specific to the Gulf Coast and determine possible adaptation  
23 strategies. In addition, information developed either in this or subsequent studies  
24 would be valuable on freight, pipelines, and emergency management, in particular.  
25 Additional analysis on demographic responses to climate change, land use interactions,  
26 and secondary and national economic impacts would help elucidate what impacts  
27 climate will have on people and the nation as a whole should critical transportation  
28 services in the region be lost. However, the impacts that a changing climate might have  
29 depends on where a region is and the specific characteristics of its natural environment.  
30 The research conducted in this study should be replicated in other areas of the country  
31 to determine the possible impacts of climate change on transportation infrastructure and  
32 services in those locations. Transportation in northern climates will face much  
33 different challenges than those in the south. Coastal areas will similarly face different  
34 challenges than interior portions of the country.

- 35 • **Interdisciplinary Research** – This study has demonstrated the value of cross-  
36 disciplinary research that engages both the transportation and climate research  
37 communities. Continued collaboration will benefit both disciplines in building  
38 methodologies and conducting analysis to inform the nation’s efforts to address the  
39 implications of climate change.



1 ■ **6.5 References**

- 2 **Gaspard, K., M. Martinez, Z. Zhang, Z. Wu., 2007:** *Impact of Hurricane Katrina on*  
3 *Roadways in the New Orleans Area.* Technical Assistance Report No. 07-2TA, LTRC  
4 Pavement Research Group, Louisiana Department of Transportation and Development,  
5 Louisiana Transportation Research Center, March 2007, 73 pages.
- 6 **IPCC, 2007:** *Climate Change 2007: The Physical Science Basis, Summary for Policy-*  
7 *Makers.* Contribution of Working Group I to the Fourth Assessment Report of the  
8 Intergovernmental Panel on Climate Change. Geneva, Switzerland, 21 pages.



# 1 Appendix A: Gulf Coast Study

## 2 GIS Datasets

3 **Table A.1 Datasets in the Geographical Information System for the**  
 4 **Gulf Coast study area.**

Topic	Dataset
Elevation/Subsidence	National Elevation Dataset (NED) for Gulf Coast Study Area
	LIDAR for coastal Louisiana
	LSRC/NGS Subsidence Measurement Network for LMRV (NOAA Tech Report 50)
Transportation Infrastructure	Pipeline data obtained from the U.S. DOT OPS National Pipeline Mapping System
	Road networks from TIGER data, 2003
	Individual state evacuation routes
	Railway network from TIGER data
	Rail networks (Source: Federal Railroad Administration, 2005)
	Amtrak stations (Source: Federal Railroad Administration, 2005)
	Fixed guideway transit facilities (Source: Bureau of Transportation Statistics, Federal Transit Administration)
	Airports (Source: Federal Aviation Administration, 2005)
	Ports (Source: U.S. Army Corps of Engineers, 2005)
	Intermodal freight terminals (Source: Bureau of Transportation Statistics, 2004)
	Navigable waterways (Source: U.S. Army Corps of Engineers)
Imagery and Topographic Maps	Thematic Mapper (TM) Landsat 5 satellite data at 90-meter resolution
	Aerial Photography at one-meter resolution from the 1998 DOQQ
	Topographic Maps (DRG) at 1:24,000, 1:100,000, and 1:250,000 scales
Earth Sciences	Geology at 1:2,000,000 covering study area
	1:500,000 for Louisiana
	State Soil Geographic Database (STATSGO) for Gulf Coast Study Area
	Soil Survey Geographic Database (SSURGO) in tabular form available for Gulf Coast Study Area
	National Land Cover Dataset (NLCD)
	EcoRegions

1 **Table A.1 Datasets in the Geographical Information System for the Gulf**  
 2 **Coast study area (continued).**

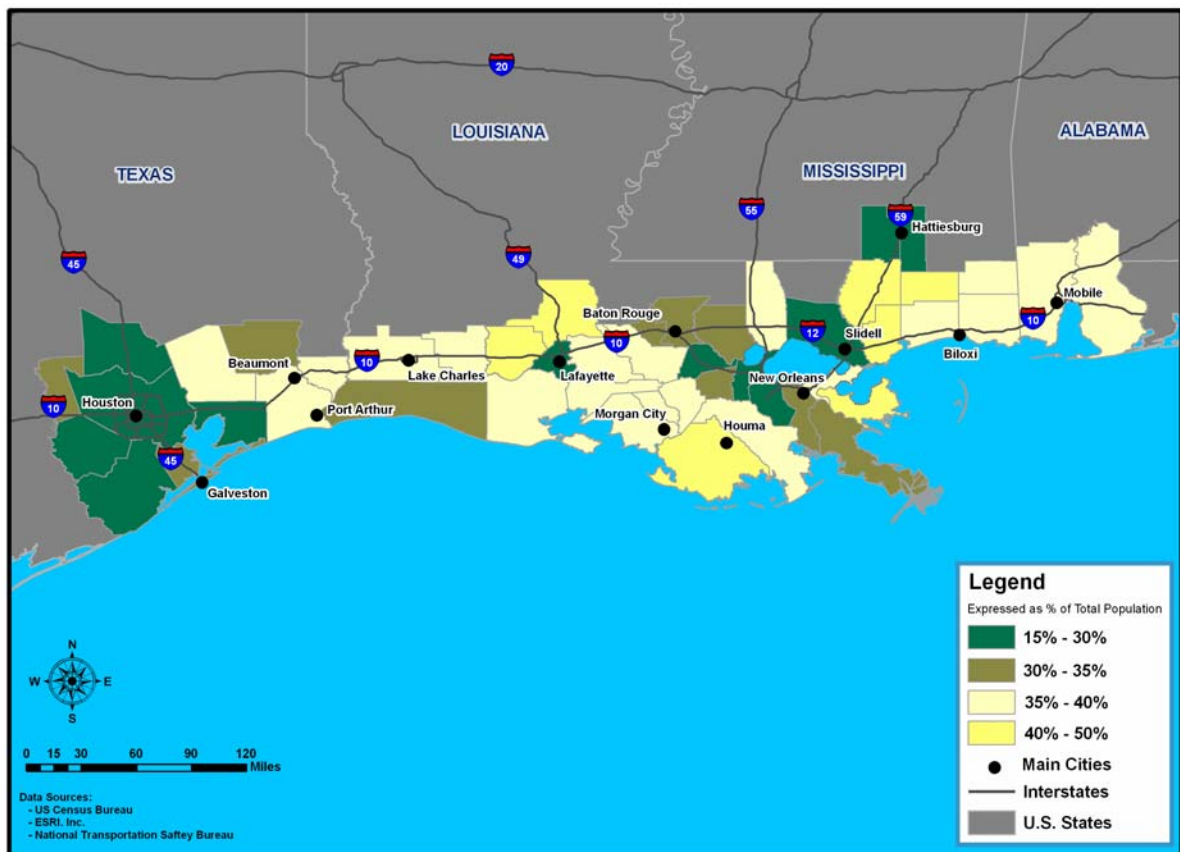
Topic	Dataset
Hydrology	National Hydrographic Dataset (NHD)
	Federal Emergency Management Agency (FEMA) Q3 flood data
	Hydrologic Unit Watershed coverage of Gulf Coast drainage
<b>Administrative Geography and Other Infrastructure</b>	
Political boundaries (Source: U.S. Census)	
Demographic data (Source: U.S. Census)	
Urbanized areas (Source: U.S. Census)	
MPO planning boundaries (Source: BTS)	
Coastal and hazard planning districts (Source: FEMA)	
Petrochemical and energy resources (Source: EPA/CENSUS)	
Industrial centers (Source: EPA/CENSUS)	
Employment centers (Source: CENSUS)	
Government/Federal facilities (Source: USGS)	
Military bases (Source: MTMCTEA)	
Public health, education, service facilities (Source: CENSUS)	
Emergency response and safety facilities (Source: FEMA)	

3

# 1 Appendix B: Additional Data

## 2 on Social and Economic Setting

3 **Figure B.1 Persons reporting disabilities.**



4

5 Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.2 Children age 14 and under.**

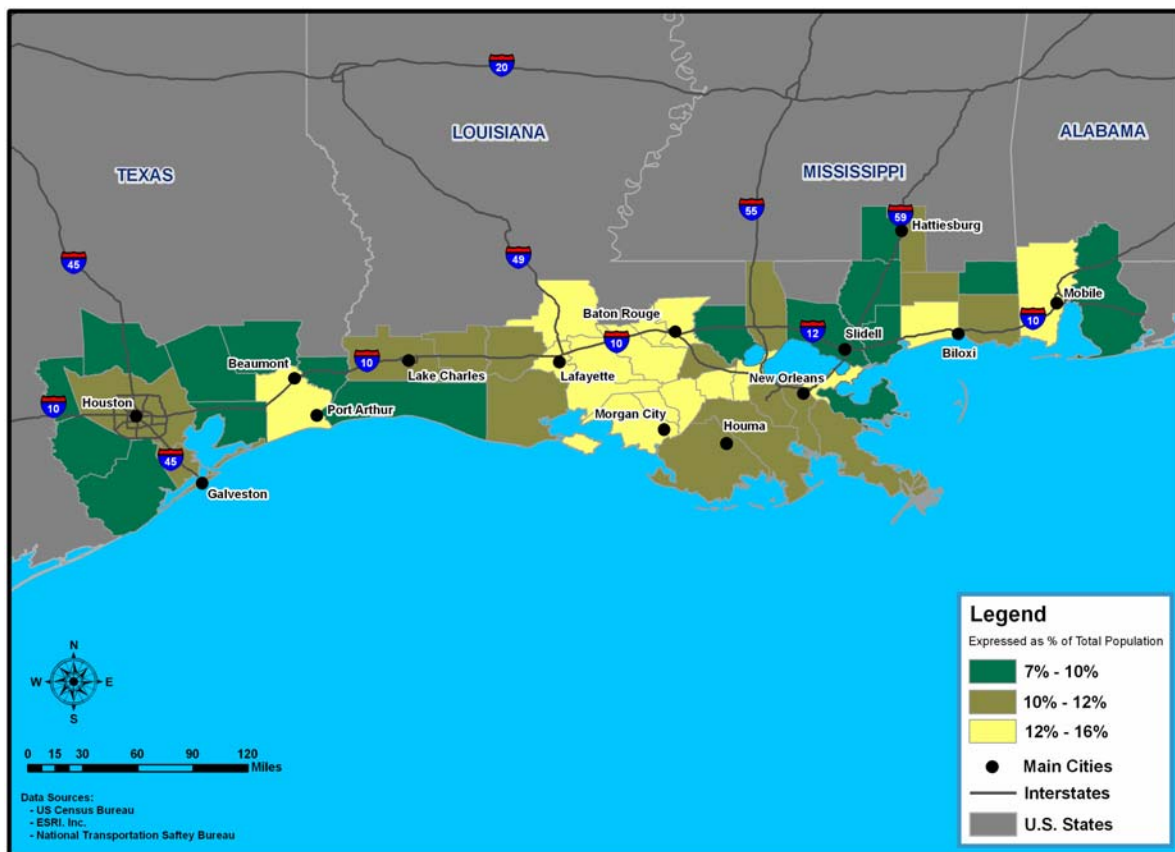


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.3 Single adult households with children.**

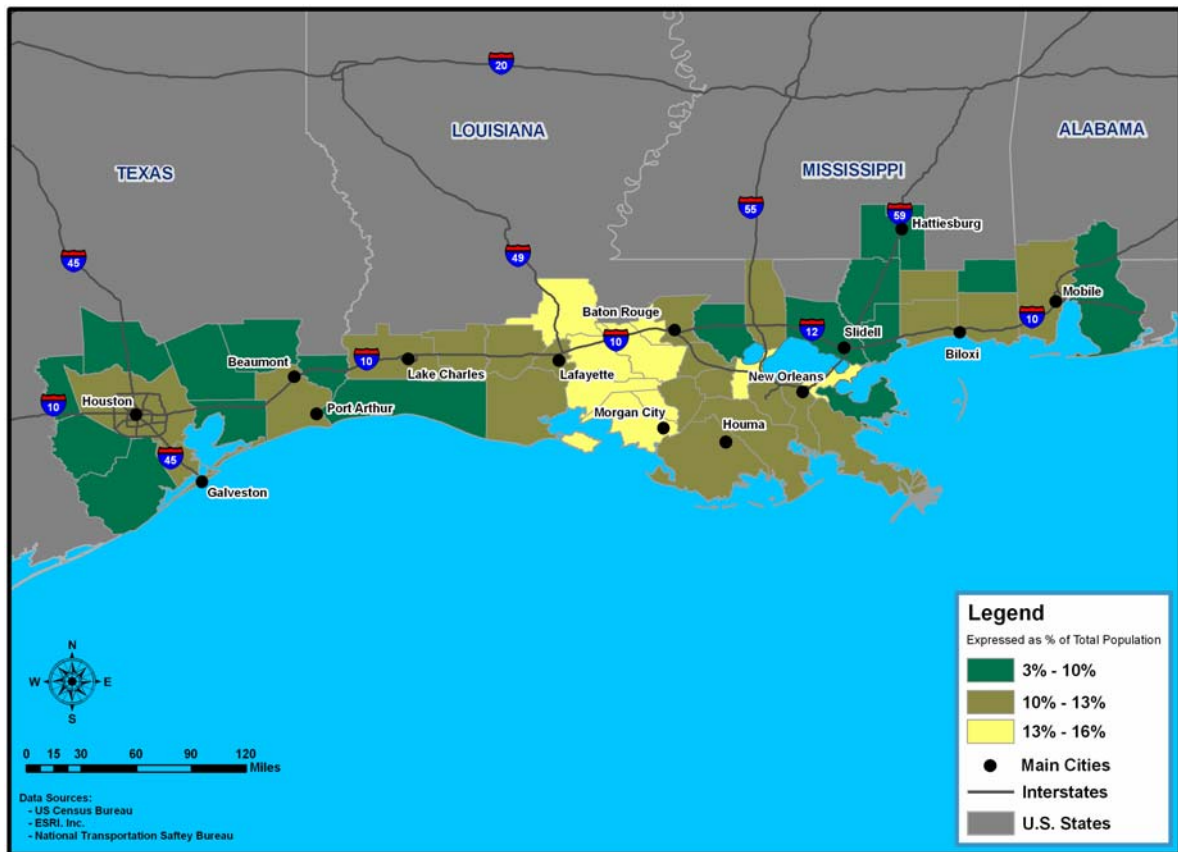


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.4 Linguistically isolated.**



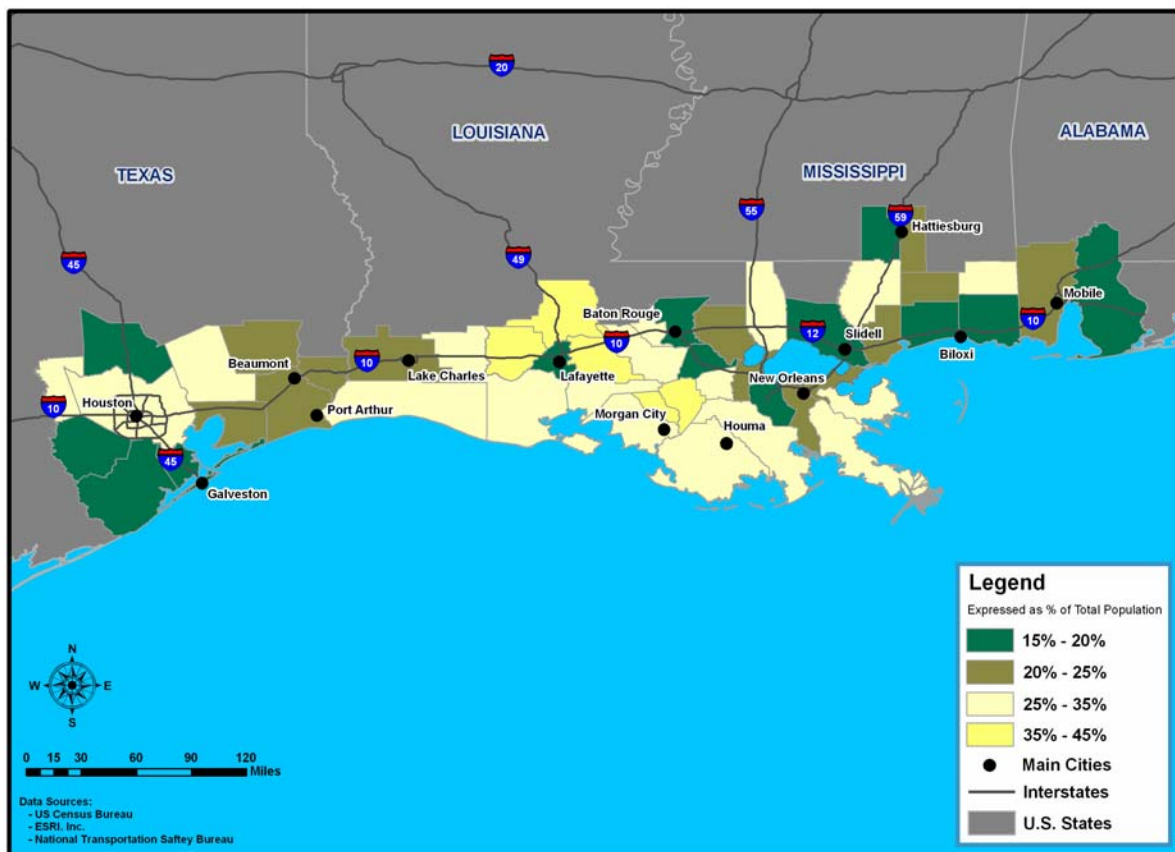
2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.



1 **Figure B.5 Percent of population with no high school diploma or equivalent.**

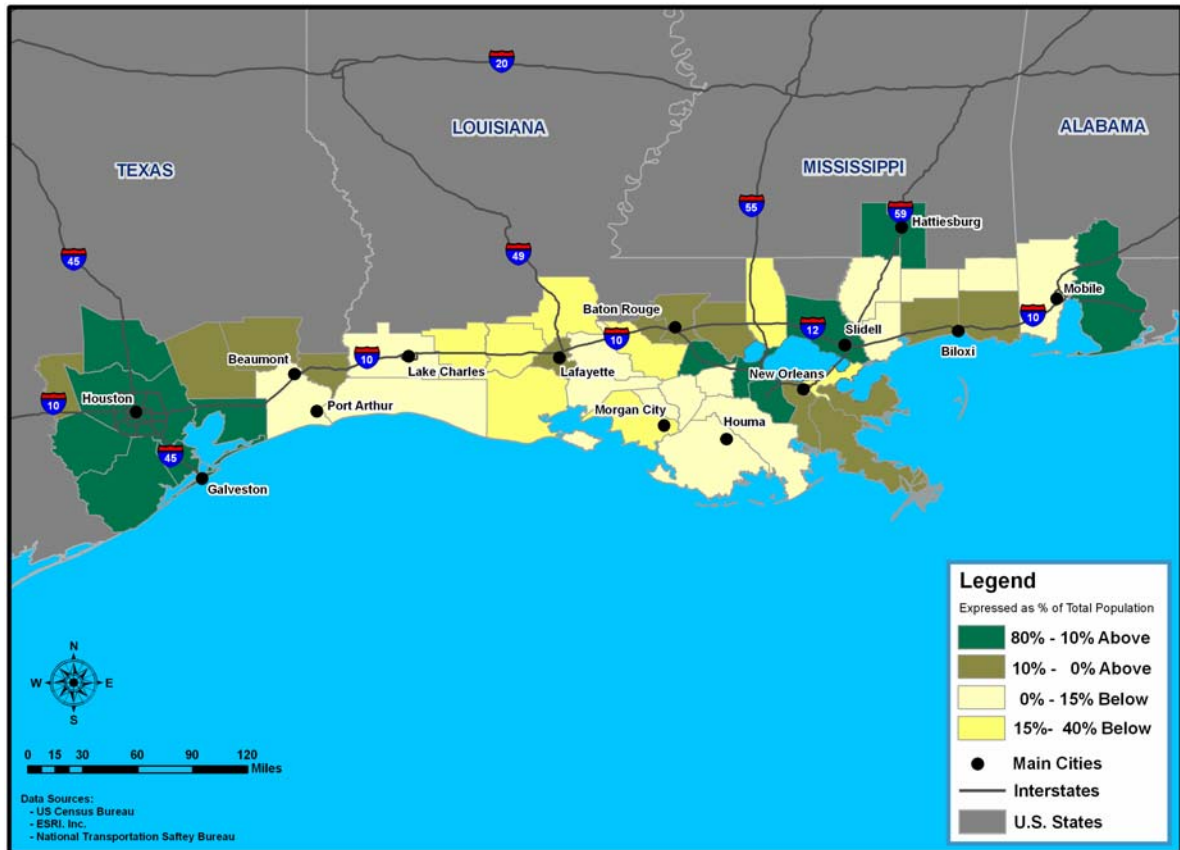


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.6 Percent of population below/above median study area income.**

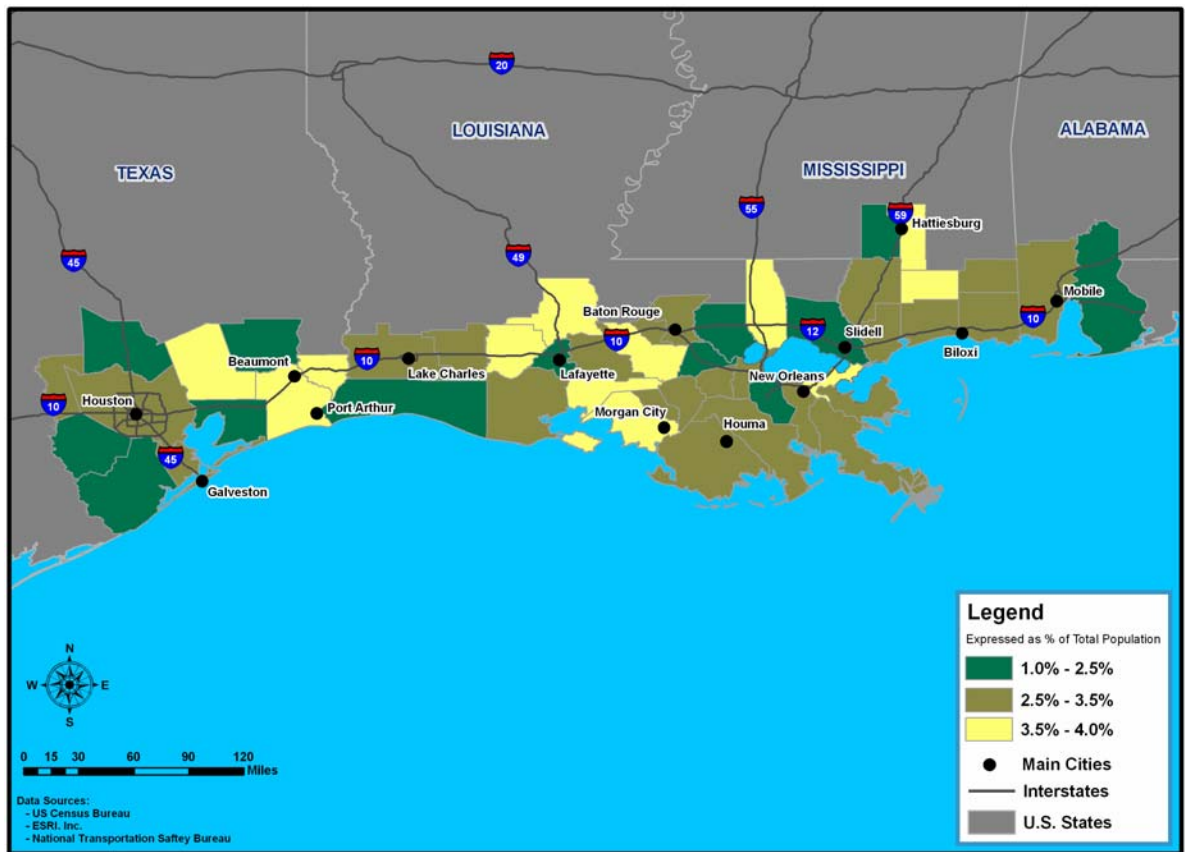


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.7 Public assistance income.**

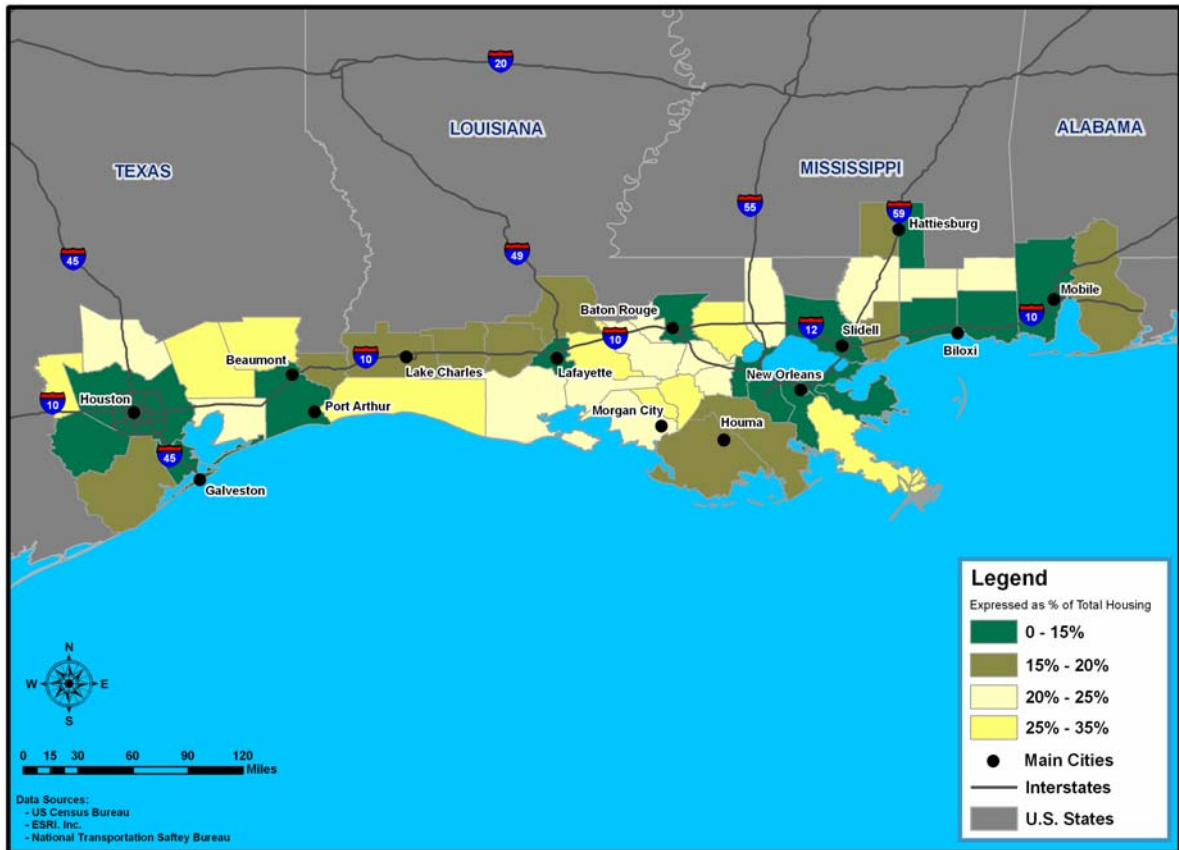


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.8 Percent of housing units that are mobile homes.**

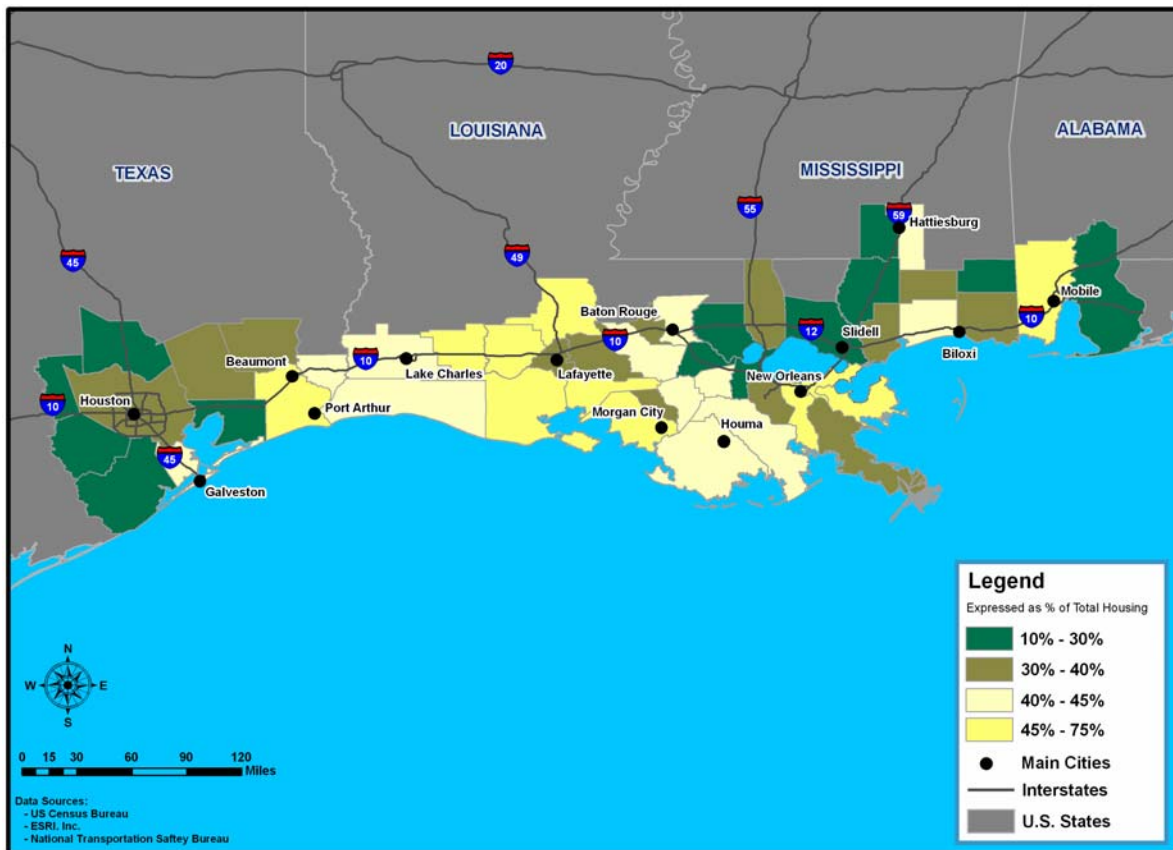


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.9 Percent of housing built prior to 1970.**

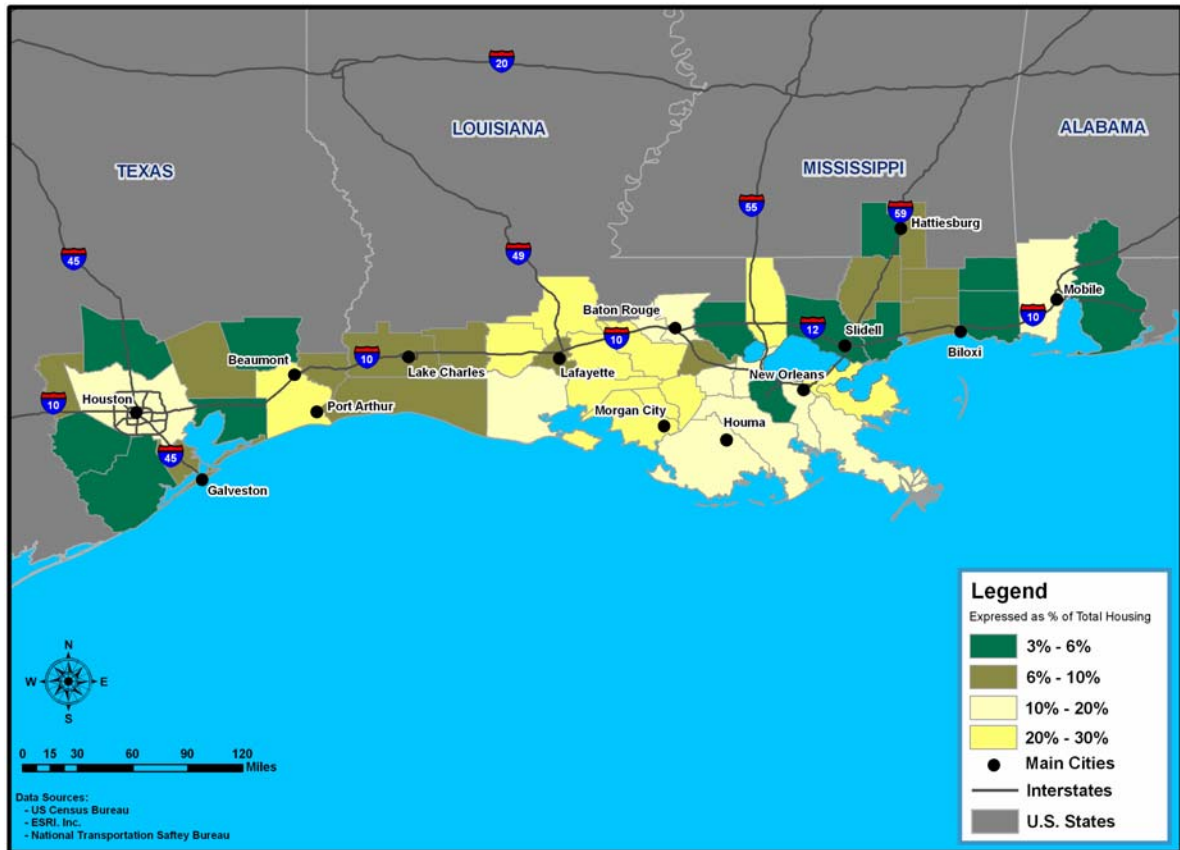


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.10 Percent of housing units reporting no vehicle.**

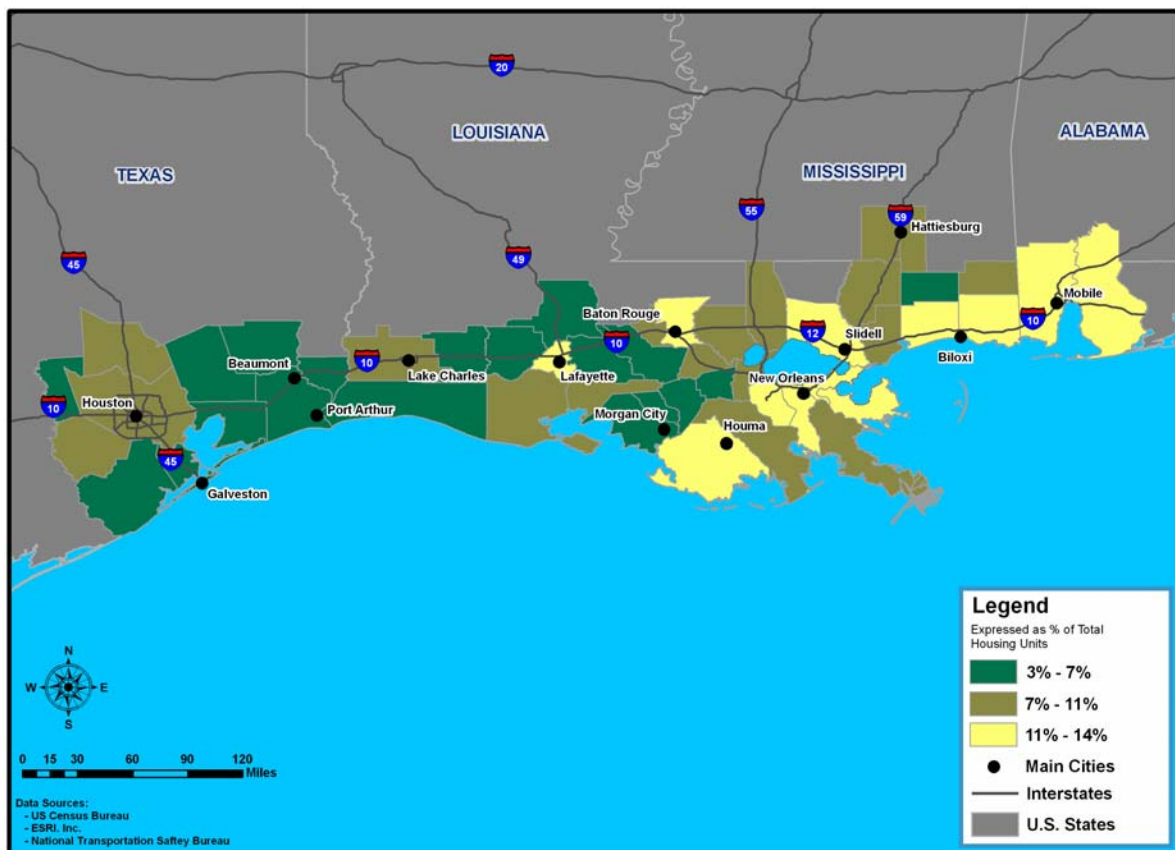


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.11 Percent of housing units with a second mortgage or home equity loan.**

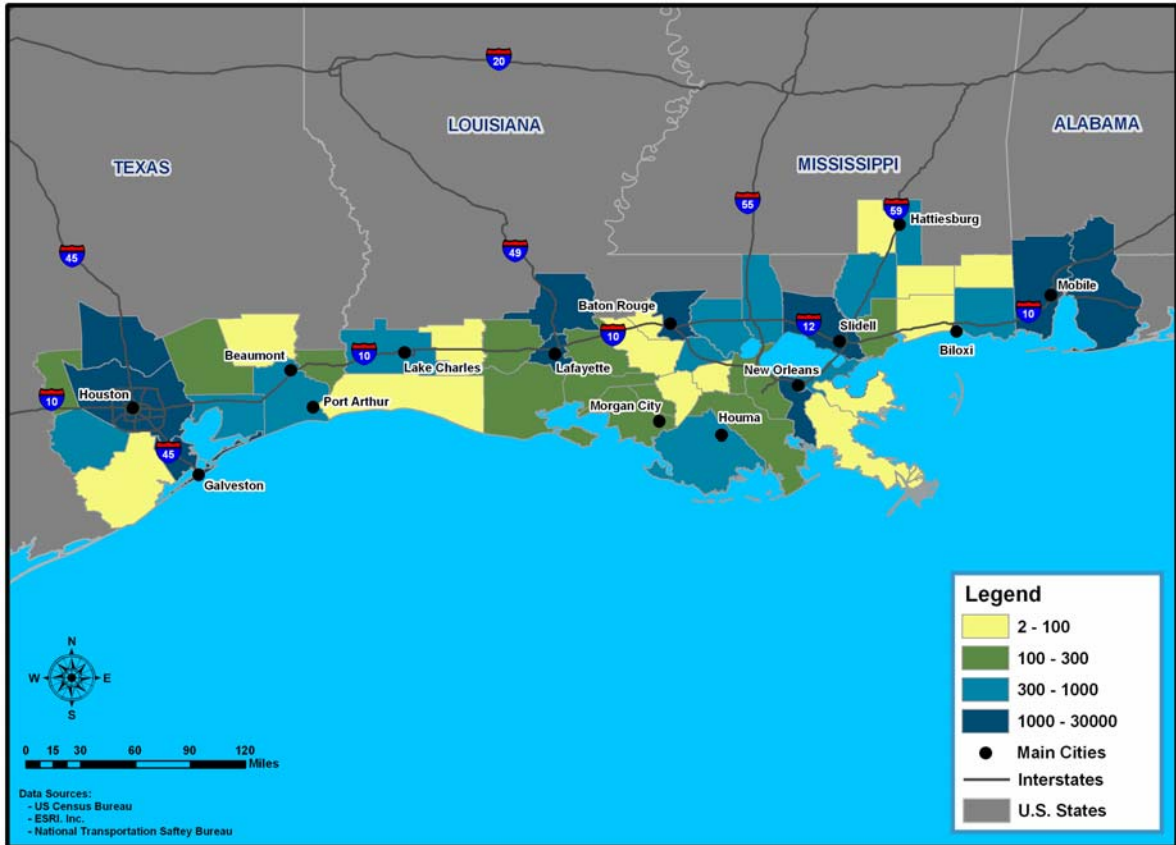


2

3

Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.

1 **Figure B.12 Number of building permits issued, 2002.**  
2



3  
4 Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.



1 **Figure B.13 Percent change in building permits issued, 1997 to 2002.**  
2



3  
4 Source: U.S. Census Bureau; ESRI, Inc.; National Transportation Safety Bureau.



# 1 Appendix C: Additional Rail Data

2 **Table C.1 Freight rail facilities in the Gulf Coast study area.**

Name	Mode Type	City	State	Gridcode
Kansas City Southern-Metairie-LA	Rail & Truck	Metairie	LA	0
Larsen Intermodal, Inc.-Metairie-LA	Rail & Truck	Metairie	LA	0
New Orleans Cold Storage & Warehouse Company, Ltd	Rail & Truck	Metairie	LA	0
Port of Gulfport	Truck - Port - Rail	Gulfport	MS	0
Port of Galveston	Truck - Port - Rail	Galveston	TX	0
NS-New Orleans-LA	Rail & Truck	New Orleans	LA	1
Up-Avondale-La-Intermodal Facility	Rail & Truck	Avondale	LA	1
Port of Freeport	Truck - Port - Rail	Freeport	TX	1
Dry Storage Corporation of Louisiana	Rail & Truck	Kenner	LA	2
DSC Logistics-Kenner-LA	Rail & Truck	Kenner	LA	2
Yellow-New Orleans-LA Terminal	Rail & Truck	New Orleans	LA	2
BNSF-New Orleans-LA	Rail & Truck	Westwego	LA	3
BNSF-New Orleans-LA-539 Bridge	Rail & Truck	Westwego	LA	3
BNSF-New Orleans-LA-Intermodal Facility	Rail & Truck	New Orleans	LA	3
Intermodal Cartage Company-New Orleans-LA	Truck - Port - Rail	New Orleans	LA	3
Transflo-New Orleans-LA	Rail & Truck	New Orleans	LA	3
BNSF-Avondale-LA-101 Avonda	Rail & Truck	Avondale	LA	4
Down South Transfer, Inc.-Avondale-LA	Rail & Truck	Avondale	LA	4
Port of New Orleans	Truck - Port - Rail	New Orleans	LA	4
CSX Intermodal-New Orleans-LA	Rail & Truck	New Orleans	LA	5
Dupuy Storage and Forwarding Corporation	Rail & Truck	New Orleans	LA	5
Port of Iberia	Truck - Port - Rail	New Iberia	LA	5
BNSF-Mobile-AL	Rail & Truck	Mobile	AL	6
CN-Mobile-AL	Truck - Port - Rail	Mobile	AL	6
Miller Transporters, Inc.-Mobile-AL	Rail & Truck	Prichard	AL	6
CN-New Orleans-LA	Truck - Port - Rail	New Orleans	LA	6
Continental Grain Co.-Westwego-LA	Rail & Truck	Westwego	LA	6
Hayes Dockside, Inc.-New Orleans-LA	Rail & Truck	New Orleans	LA	6
Illinois Central Railroad-New Orleans-LA	Rail & Truck	New Orleans	LA	6
Lake Charles Harbor and Terminal District-Lake CHA	Rail & Truck	Lake Charles	LA	6
LST (Floating Elevator)-Belle Chasse-LA	Rail & Truck	Belle Chasse	LA	6
NS Independent Bulk Transfer Terminal-Arabi-LA	Rail & Truck	Arabi	LA	6
Port of Lake Charles	Rail & Port	Lake Charles	LA	6
Port of South Louisiana	Rail & Port	Laplace	LA	6
Port of Pascagoula	Truck - Port - Rail	Pascagoula	MS	6
Houston Fuel Oil Terminal Co.-Houston-TX	Rail & Truck	Houston	TX	6
Miller Transporters, Inc.-Beaumont-TX	Rail & Truck	Beaumont	TX	6
Port Arthur-TX	Rail & Truck	Port Arthur	TX	6
Port of Orange	Truck - Port - Rail	Orange	TX	6
Port of Port Arthur	Truck - Port - Rail	Port Arthur	TX	6
Mobile Moving and Storage	Rail & Truck	Mobile	AL	7
Yellow-Mobile-AL Terminal	Rail & Truck	Mobile	AL	7
Aimcor Galveston Marine Terminal-Texas City-TX	Rail & Truck	Texas City	TX	7
ASW Supply Chain Services, LLC-Beaumont-TX	Truck - Port - Rail	Beaumont	TX	7
GATX Terminals Corporation-Galena Park-TX	Rail & Truck	Galena Park	TX	7

1 **Table C.1 Freight rail facilities in the Gulf Coast study area (continued).**

Name	Mode Type	City	State	Gridcode
PCI Transportation, Inc.-Houston-TX	Rail & Truck	Houston	TX	7
Port of Beaumont	Truck - Port - Rail	Beaumont	TX	7
UP-Laporte-TX	Rail & Truck	Strane	TX	7
Walton Barge Terminal-Houston-TX	Truck - Port - Rail	Houston	TX	7
Wilson Warehouse Co. of Texas, Inc.-Beaumont-TX	Rail & Truck	Beaumont	TX	7
Yellow-Beaumont-TX Terminal	Truck - Port - Rail	Beaumont	TX	7
Cargill Marketing Co. Inc.	Truck - Port - Rail	Eight Mile	AL	8
Meador Warehousing and Distribution, Inc.-Mobile-A	Rail & Truck	Mobile	AL	8
The Finch Companies-Mobile-AL	Rail & Truck	Mobile	AL	8
Acme Transfer-Baton Rouge-LA	Rail & Truck	Baton Rouge	LA	8
Agway Systems Inc.	Rail & Truck	Baton Rouge	LA	8
Branch Warehousing and Distribution Center, Inc.-l	Rail & Truck	Lafayette	LA	8
Innovative Waste Systems, Inc-Baton Rouge-LA	Rail & Truck	Baton Rouge	LA	8
Miller Transporters, Inc.-Baton Rouge-LA	Rail & Truck	Baton Rouge	LA	8
Port Manchac Distribution Center	Rail & Truck	Ponchatoula	LA	8
Yellow-Lafayette-La Terminal	Rail & Truck	Broussard	LA	8
Miller Transporters, Inc.-Hattiesburg-MS	Rail & Truck	Hattiesburg	MS	8
Miller Transporters, Inc.-Lumberton-MS	Rail & Truck	Lumberton	MS	8
Yellow-Gulfport-MS Terminal	Rail & Truck	Gulfport	MS	8
Adams Distribution Center, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
BNSF-Houston-TX	Rail & Truck	Houston	TX	8
BNSF-Houston-TX-10000 Wal	Rail & Truck	Houston	TX	8
BNSF-Houston-TX-5500 Walli	Rail & Truck	Houston	TX	8
Care Terminal	Truck - Port - Rail	Houston	TX	8
Charles Emmons Pulpwood Co.-Cleveland-TX	Rail & Truck	Cleveland	TX	8
CSX Intermodal-Houston-TX	Rail & Truck	Houston	TX	8
General Stevedores, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Gulf Winds International, Inc.-Mykawa-TX	Rail & Truck	Mykawa	TX	8
Guthrie Lumber Sales Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Intercontinental Terminals Co.-Houston-TX	Rail & Truck	Houston	TX	8
Intermodal Cartage Company-Houston-TX	Truck - Port - Rail	Houston	TX	8
International Distribution Corp.-Houston-TX	Rail & Truck	Houston	TX	8
MCC Transport, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Miller Transporters, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Oil Tanking Houston, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Palmer Logistics-Houston-TX	Rail & Truck	Houston	TX	8
Port of Houston Authority	Truck - Port - Rail	Houston	TX	8
Quality Carriers-Houston-TX	Rail & Truck	Houston	TX	8
South Coast Terminals, I.P.-Houston-TX-3730fm 196	Rail & Truck	Houston	TX	8
Southern Warehouse Corporation-Houston-TX	Rail & Truck	Houston	TX	8
Tencon Industries, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Texas Rice Inc.	Rail & Truck	Houston	TX	8
Thompson Cargo Specialists, Inc.-Houston-TX	Rail & Truck	Houston	TX	8
Union Pacific Bulk Tainer Service-Spring-TX	Rail & Truck	Spring	TX	8
United DC, Inc Corporate Headquarters-Houston-TX894	Rail & Truck	Houston	TX	8
United DC, Inc.-Houston-TX-1200 Lathr	Rail & Truck	Houston	TX	8
UP-Houston-TX-5500	Rail & Truck	Houston	TX	8
Western Intermodal Services, Ltd.-Houston-TX	Rail & Truck	Houston	TX	8
Yellow-Houston-TX Terminal	Truck - Port - Rail	Houston	TX	8

2 Source: National Transportation Atlas Database (BTS, 2004).

1 **Table C.2 Amtrak facilities in the Gulf Coast study area.**

<b>Station</b>	<b>City</b>	<b>State</b>	<b>Gridcode</b>
Mobile	Mobile	AL	6
Lake Charles	Lake Charles	LA	6
New Orleans	New Orleans	LA	6
Schriever	Schriever	LA	6
Slidell	Slidell	LA	6
Pascagoula	Pascagoula	MS	6
Beaumont	Beaumont	TX	6
Galveston	Galveston	TX	6
Lamarque	Lamarque	TX	6
New Iberia	New Iberia	LA	7
Bay St. Louis	Bay St. Louis	MS	7
Biloxi	Biloxi	MS	7
Bay Minette	Bay Minette	AL	8
Baton Rouge	Baton Rouge	LA	8
Hammond	Hammond	LA	8
Lafayette	Lafayette	LA	8
Gulfport	Gulfport	MS	8
Hattiesburg	Hattiesburg	MS	8
Picayune	Picayune	MS	8
Houston	Houston	TX	8
South Houston	South Houston	TX	8

2 Source: National Transportation Atlas Database (BTS, 2004).



# Appendix D: Water Balance Model Procedures

Temperature and precipitation data were either the calculated historical values for the study area or the forecast-modified values under SRES scenario A1B. Reference evapotranspiration ( $ET_o$ ), was calculated using the Turc (1961) model (Jensen et al. 1997, Fontenot 2004). Turc was selected for use over the original Thornthwaite model because of its ability to more closely simulate FAO-56 Penman-Monteith  $ET_o$  with a limited set of meteorological data (Fontenot 2004). Allen (2003) defined the Turc equation for operational use:

$$ET_o = a_T 0.013 \frac{T_{mean}}{T_{mean} + 15} \frac{23.8856 R_s + 50}{\lambda} \quad (1)$$

where  $ET_o$  is evapotranspiration ( $\text{mm day}^{-1}$ ),  $T_{mean}$  is the mean daily air temperature ( $^{\circ}\text{C}$ ),  $R_s$  is solar radiation ( $\text{MJ m}^{-2} \text{day}^{-1}$ ), and  $\lambda$  is the latent heat of vaporization ( $\text{MJ kg}^{-1}$ ). The coefficient  $a_T$  is a humidity-based value. If the mean daily relative humidity ( $RH_{mean}$ ) is greater than or equal to 50 percent, then  $a_T = 1.0$ . If the mean daily relative humidity is less than 50 percent, then  $a_T$  has the value of:

$$a_T = 1 + \frac{50 - RH_{mean}}{70} \quad (2)$$

Humidity data (historical or forecast) were not available for the study area, so the assumption was made that the dew point temperature was equal to the mean monthly minimum temperature. This procedure is recommended by Allen et al. (1998) for approximating daily humidity values when measured values are not available. Solar radiation ( $R_s$ ) was estimated by using the Hargreaves model as described by Allen et al. (1998):

$$R_s = k_{RS} \sqrt{(T_{MAX} - T_{MIN})} R_a \quad (3)$$

where  $R_s$  is the solar radiation as stated above,  $k_{RS}$  is an adjustment coefficient,  $T_{MAX}$  and  $T_{MIN}$  are the mean daily maximum and minimum air temperatures ( $^{\circ}\text{C}$ ), and  $R_a$  is extraterrestrial radiation ( $\text{MJ m}^{-2} \text{day}^{-1}$ ). A value of 0.19 was used for  $k_{RS}$  as suggested by Allen et al. (1998) for use in coastal locations. The Turc model was run using the monthly temperature data and radiation data for the 15<sup>th</sup> – the midpoint – of each month. The values were then multiplied by the appropriate number of days in each month to create a monthly value for  $ET_o$ . For simplicity, leap days were not included.

1 After the basic input variables were prepared, the data were entered into the water balance.  
2 First, using the temperature data, the monthly precipitation was partitioned into rain and  
3 snow components where:

$$4 \quad RAIN_M = F_M \cdot P_M \quad (4)$$

$$5 \quad SNOW_M = (1 - F_M) \cdot P_M \quad (5)$$

6 Where  $P_M$  is the monthly precipitation and  $F_M$  is a melt factor which is computed using the  
7 following method:

$$8 \quad \text{If } T_M \leq 0^\circ \text{ C: } F_M = 0$$

$$9 \quad \text{If } 0^\circ \text{ C} < T_M < 6^\circ \text{ C: } F_M = 0.167 \cdot T_M$$

$$10 \quad \text{If } T_M \geq 6^\circ \text{ C: } F_M = 1 \quad (6)$$

11 where  $T_M$  is the mean monthly temperature (Dingman, 2002).  $F_M$  also is used to determine  
12 the monthly snowmelt amount:

$$13 \quad MELT_M = F_M \cdot (PACK_{m-1} + SNOW_m) \quad (7)$$

14 with  $PACK_{m-1}$  being the water equivalent of the snow pack at the end of the previous  
15 month and  $SNOW_m$  being the snow fall total of the current month. The previous month's  
16 pack amount is calculated as:

$$17 \quad PACK_m = (1 - F_M)^2 \cdot P_M + (1 - F_M) \cdot PACK_{m-1} \quad (8)$$

18 The overall hydrological input into the model is defined by  $W_M$  is:

$$19 \quad W_M = RAIN_m + MELT_m \quad (9)$$

20 In this study, the probability of the study region having any significant snow amounts is  
21 low, but the variable was included to provide for the possibility in the forecasted model  
22 runs.

23 Changes in soil moisture are calculated using the following logic. If  $W_M \geq ET_o$ , monthly  
24 evapotranspiration ( $ET_M$ ) occurs at the  $ET_o$  rate. If  $ET_M$  equals  $ET_o$ , then soil moisture  
25 would then increase or remain steady if the soil moisture already is at field capacity  
26 (Dingman, 2002). For the purposes of this study, field capacity ( $SOIL_{MAX}$ ) has been set to  
27 150 mm. The monthly value for soil moisture is therefore:

$$28 \quad SOIL_M = \min\{[(W_M - ET_o) + SOIL_{m-1}], SOIL_{MAX}\} \quad (10)$$

29 where the soil moisture value is the lesser of the two values in the equation (Dingman,  
30 2002). If  $W_M$  is less than  $ET_o$ , then  $ET_M$  is equal to the hydrological input ( $W_M$ ) and a  
31 drying factor:



$$ET_M = W_M + \left\{ SOIL_{m-1} \cdot \left[ 1 - \exp\left( -\frac{ET_{OM} - W_M}{SOIL_{MAX}} \right) \right] \right\} \quad (11)$$

where  $ET_{OM}$  is the monthly Turc  $ET_O$  value (Dingman, 2002).

After computing soil moisture change, any excess water in the budget was declared as surplus. The monthly surplus parameter is synonymous with runoff in these wetland environments, as long lags are not common between the generation of surplus water and the resultant streamflow. If  $W_M$  does not meet the environmental demand, then a deficit is created until  $W_M$  meets the environmental demand. In this study, we retained surplus as an index for runoff, and dismissed the modeled runoff term as invalid.

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# Appendix E:

## HURASIM Model Description

HURASIM is a spatial simulation model of hurricane structure and circulation for reconstructing estimated windforce and vectors of past hurricanes. The HURASIM model generates a matrix of storm characteristics (i.e., quadrant, windspeed, and direction) within discrete spatial units and time intervals specified by the user for any specific storm or set of storms. HURASIM recreates the spatial structure of past hurricanes based on a tangential wind function, inflow angle offset, forward speed, and radius of maximum winds. Figure E.1 (below) shows the graphic user interface of the HURASIM model for a windfield reconstruction of Hurricane Katrina (2005) making landfall southeast of New Orleans, Louisiana. Data input for the model includes tracking information of storm position, latitude and longitude, and maximum sustained wind speed every six hours or less. The model offers a suite of mathematical functions and parameter sets for the tangential wind profile taken from other hurricane studies (Harris 1963, Bretschneider and Tamaye 1976, Neumann 1987, Kjerfve et al. 1986, Boose et al. 1994). The user can specify the set of functions which provide more or less robust constructions of the range and extent of estimated winds.

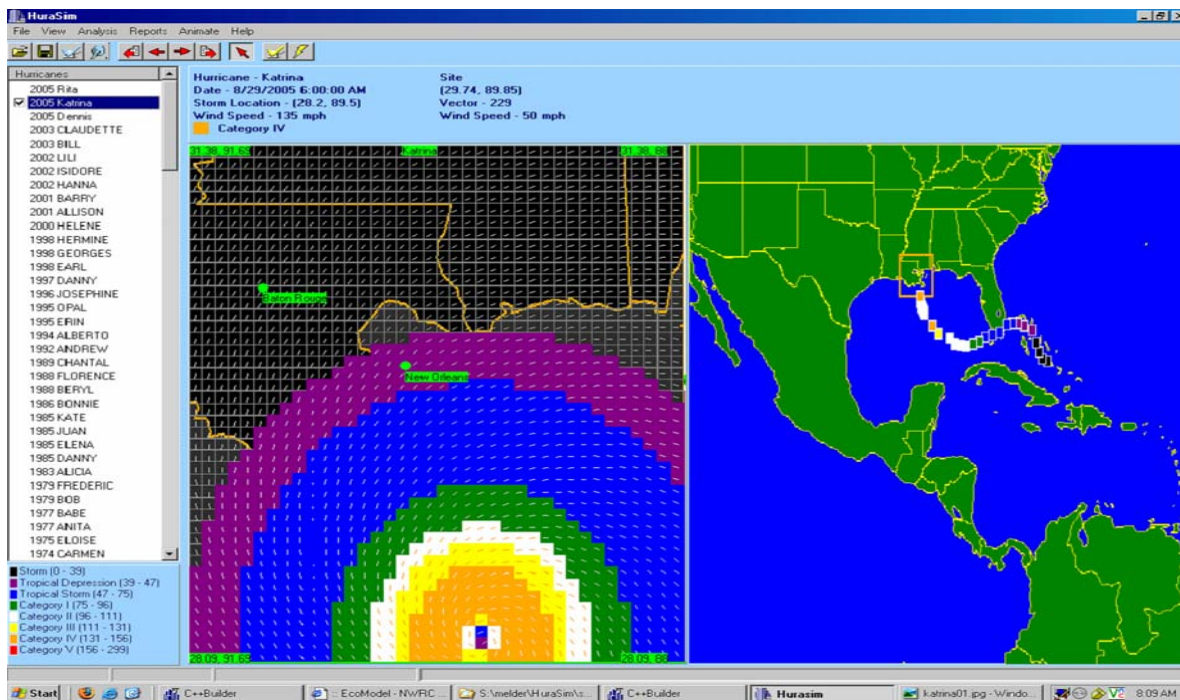
Model output is user-specified for given geographic locations assigned by a given point or boundary area. Latitude and longitude for each study site location was supplied to the model to create a log of hurricane activity at 15-minute intervals for predicted winds above 30 mph for the period of record (1851-2003). The model estimates a suite of storm characteristics (i.e., quadrant, wind speed, and direction) within discrete spatial units and time intervals specified by the user for designated storms, years, and study site locations. Profiles of estimated wind conditions for a given site application are stored by year and storm. Time intervals of storm reposition and speed for this study were generated every 15 minutes. Minimum conditions of windspeed or distance can be set to parse the data output if warranted. In this study, windspeed estimates for any point or grid location were retained for further analysis if greater than 30 mph or tropical depression status.

HURASIM has been used extensively for field and modeling studies to relate biological response to hurricane forcing. HURASIM model output from Hurricane Andrew was correlated with field data to construct data tables of damage probabilities by site and species and to determine critical windspeeds and vectors of tree mortality and injury (Doyle et al. 1995a, 1995b). HURASIM also has been applied to reconstruct probable windfields of past hurricanes for remote field locations and correlated with tree ring growth patterns and direction of leaning trees and downed logs (Doyle and Gorham 1996). HURASIM also has been used to construct landscape templates of past hurricane activity that are linked with landscape simulation models of coastal habitat (Doyle and Girod 1997).

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- 23       **Neumann, C.J.**, 1987: *The National Hurricane Center risk analysis program (HURISK)*.  
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1 **Figure E.1** Graphic user interface of the HURASIM model displaying storm track  
2 and windfield reconstruction of Hurricane Katrina (2005)  
3 at landfall south of New Orleans, Louisiana. Grid cell color schemes  
4 represent different categories of storm strength and a directional line  
5 of wind direction.



6

7



# Appendix F: Projecting Future Sea Level Rise with the SLRRP Model

SLRRP is a PC-Windows software package designed with a user-friendly interface to generate a suite of future sea level projections from various GCM models and scenario outputs obtained from IPCC (2001). The SLRRP acronym stands for Sea Level Rise Rectification Program. The SLRRP model allows the user to select a region-based tide station, GCM model, and SRES emission scenario to generate a graph and output file of future sea level change. SLRRP rectifies the historic tide record and future eustatic sea level rise into a common datum (default = NAVD88) to facilitate comparison with landbase features and elevations. The SLRRP model generates a sea level prediction by wrapping the historic mean monthly records for the period of record for all future years up to year 2100. Because the historic record retains the long-term trend of local subsidence and historic eustatic change, an adjustment of removing the historic eustatic rate is accomplished before adding the predicted future eustatic sea level rise based on a selected IPCC model and scenario. SLRRP uses a historic eustatic sea level rate of 1.8 mm/year conferred by several sources as the best estimate for the global-mean since 1963 (IPCC, 2001, Douglas, 1997).

The SLRRP model uses a series of sequential pop-up windows to facilitate user selection of GCM models, scenarios, and manual entries for projecting future sea levels (Figures F.1-F.3). The SLRRP and CoastCLIM models generate similar eustatic projections but SLRRP retains the local tidal fluctuations that will contribute to short-term flooding above mean tides. The advantage of using the historic record includes the retention of the local variability and seasonality of sea level heights and the interannual variability and long-term climatic autocorrelation.

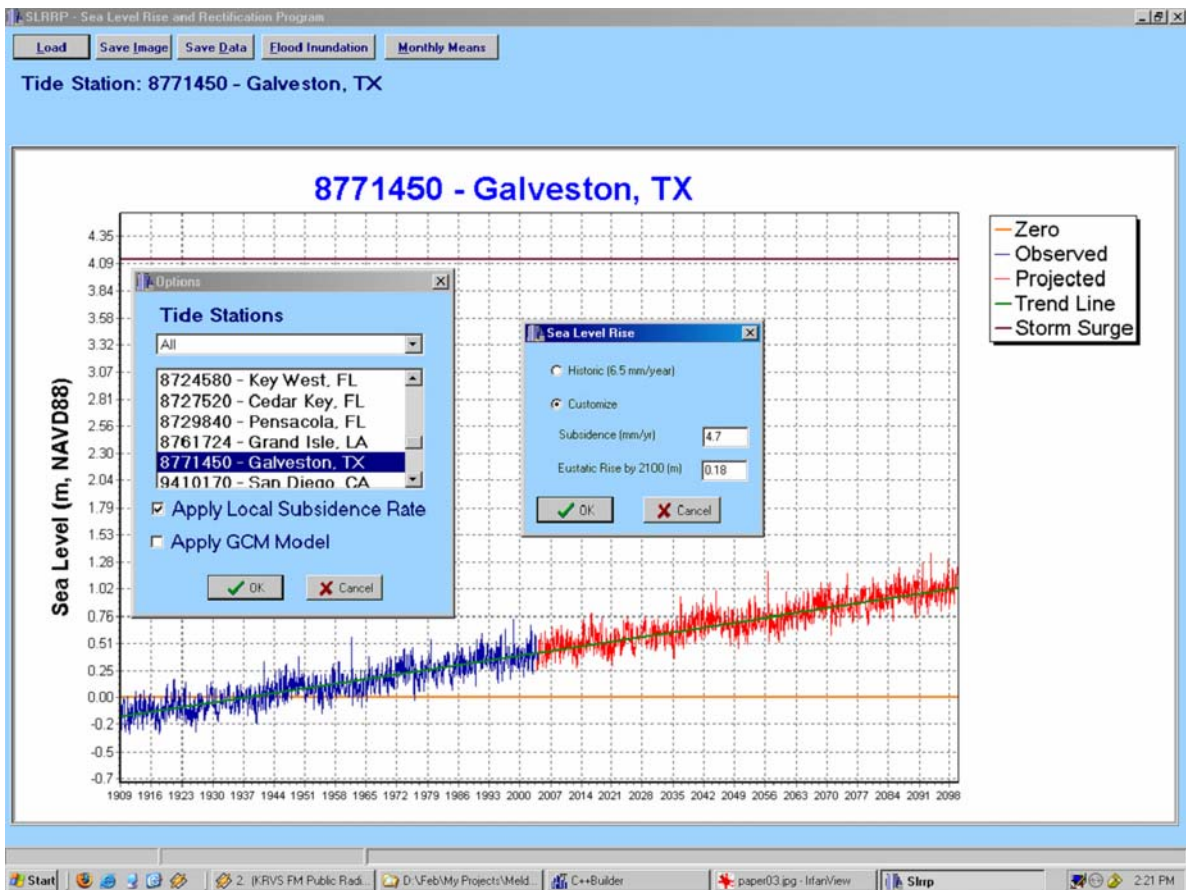
The program gives the user options for saving graphical and digital formats of SLRRP predictions and generating a supplemental graph to visualize the timing and extent of yearly flooding potential for a given elevation (NAVD88) for a transportation feature. After generating a future sea level projection, the user can execute a seawater inundation option that builds another graph that plots the timing and rate of flooding for a selected land elevation (Figure F.4). In effect, the model shows the prospective data and time period for which sea level will overtop a given landscape feature under a future changing climate. Flooding potential is the percentage of months within a year when there is inundation by seawater at a select land elevation determined by the user.

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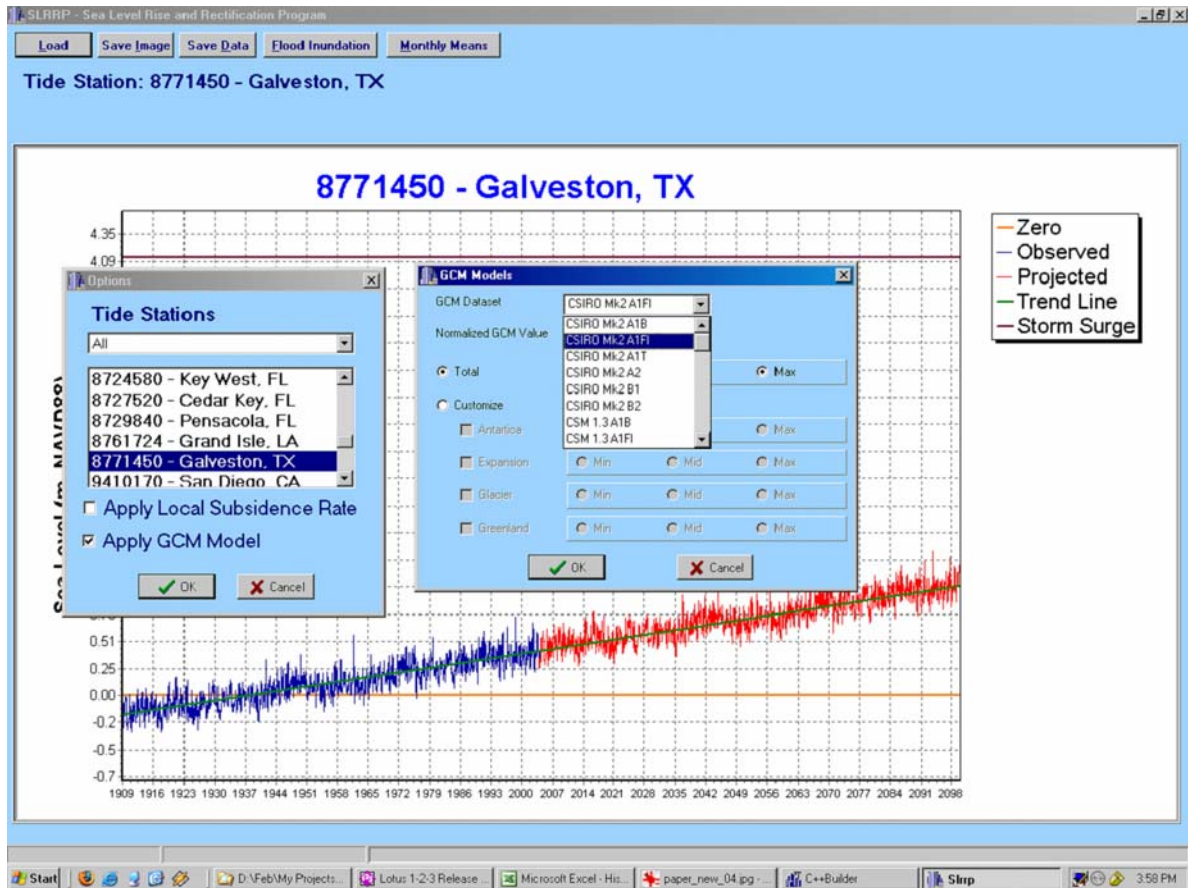
1 **Figure F.1** User interface and simulated graph of historic sea level rise from a  
2 sample SLRRP Model application displaying the pop-up windows  
3 for selecting tide gauge stations and constructing a sea level  
4 function based on local subsidence.



5

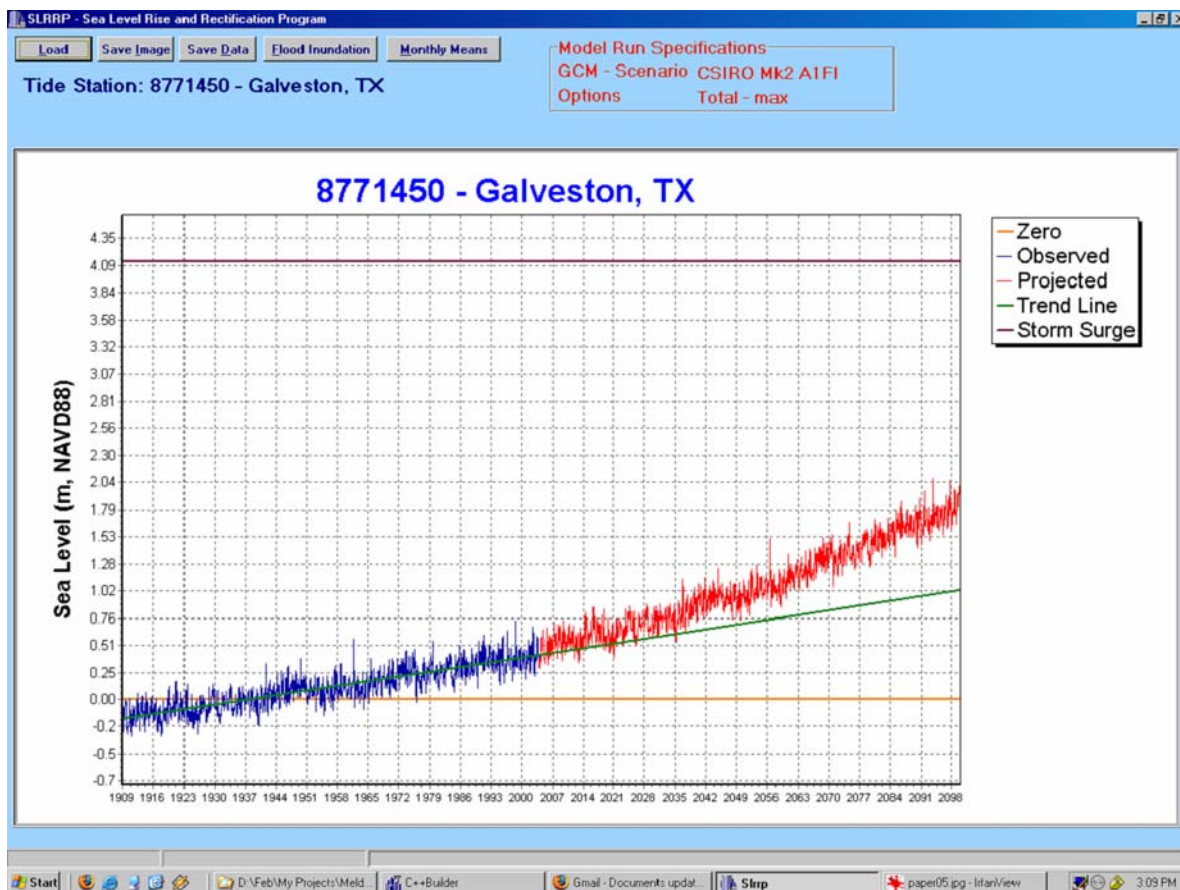


1 **Figure F.2** User interface and simulated graph of historic sea level rise from a  
2 sample SLRRP Model application displaying the pop-up window  
3 for selecting a GCM model and SRES emission scenario.



4

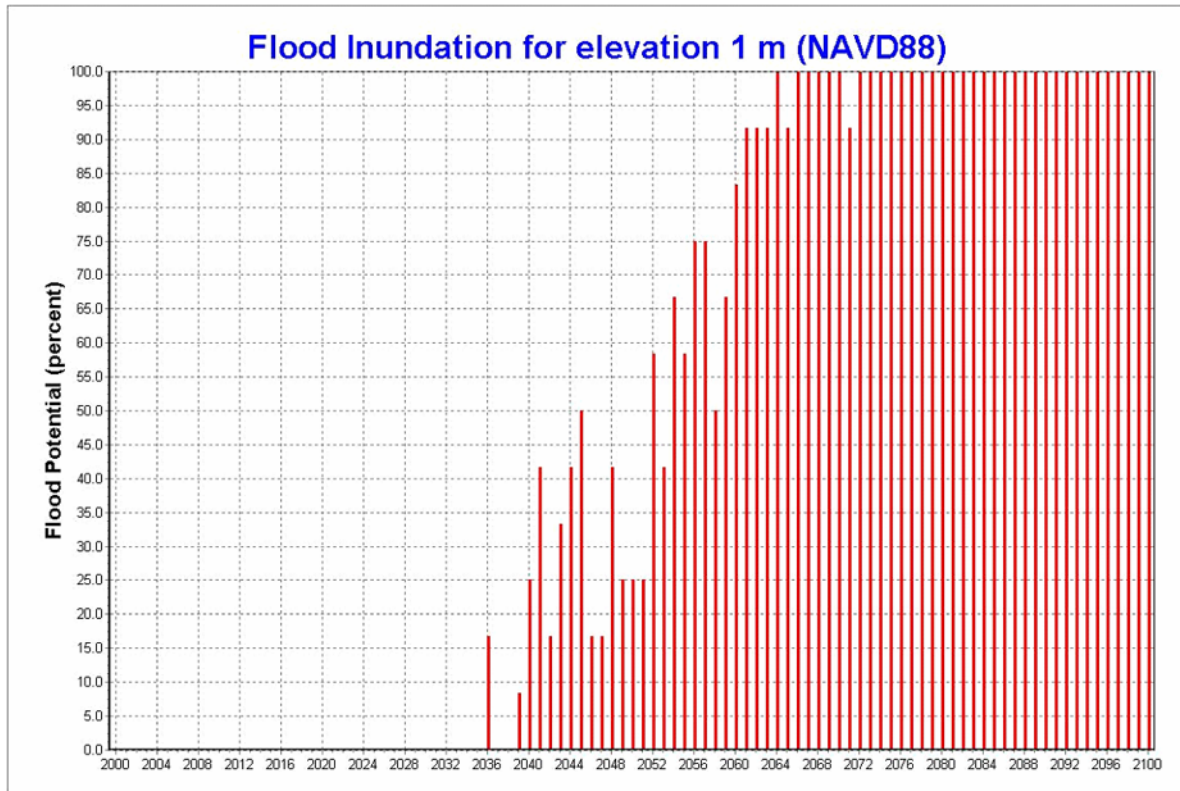
1 **Figure F.3** User interface and simulated graph of future sea level rise from a  
2 **sample SLRRP model application displaying the historic trend**  
3 **line (green), datum relationship (orange), and maximum historical**  
4 **storm surge stage for the select tide gauge location.**



5

DRAFT

1       **Figure F.4**   **Sample flood graph displaying flood timing and extent based on**  
2                   **the hydroperiod or percent of days within a calendar year that**  
3                   **flooding is likely to occur for a given land elevation and sea level**  
4                   **rise projection.**



5  
6

# 1 List of Acronyms

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AASHTO	American Association of State and Highway Transportation Officials
APTA	American Public Transit Association
BRT	Bus rapid transit
CCSP	Climate Change Science Program
CDIAC	Carbon Dioxide Information Analysis Center
CVI	Coastal Vulnerability Index
DEM	Digital Elevation Model
DOT	Department of Transportation
GCM	General Circulation Model
HURDAT	HURricane DATabase
IPCC	Intergovernmental Panel on Climate Change
MPO	Metropolitan planning organization
NAVD88	North American Vertical Datum 88
NED	National Elevation Dataset
NGVD	National Geodetic Vertical Datum
NHC	National Hurricane Center
NHS	National Highway System
NLCD	National Land Cover Dataset
NTD	National Transit Database
PDF	Probability density function
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLRRP	Sea Level Rise Rectification Program
SRES	Special Report on Emissions Scenarios
SST	Sea surface temperature
USCDD	U.S. Climate Division Dataset
USGS	United States Geological Survey
USHCN	U.S. Historic Climate Network
VMT	Vehicle Miles Traveled
WGNE-CMIP3	Working Group on Numerical Experimentation Coupled Model Intercomparison Project phase 3

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2



# 1 Glossary of Terms

## 2 **Accretion**

3 The process of soil buildup, generally through deposition.

## 4 **Adaptation**

5 Actions taken to reduce the vulnerability of natural and human systems against actual or  
6 expected climate change effects. Various types of adaptation can be distinguished, including  
7 anticipatory, autonomous, and planned adaptation.

8 • **Anticipatory Adaptation** – Adaptation that takes place before impacts of climate  
9 change are observed. Also referred to as proactive adaptation.

10 • **Autonomous Adaptation** – Adaptation that does not constitute a conscious response to  
11 climatic stimuli but is triggered by ecological changes in natural systems and by market  
12 or welfare changes in human systems. Also referred to as spontaneous adaptation.

13 • **Planned Adaptation** – Adaptation that is the result of a deliberate policy decision,  
14 based on an awareness that conditions have changed or are about to change and that  
15 action is required to return to, maintain, or achieve a desired state.

## 16 **Adaptation Assessment**

17 The practice of identifying options to adapt to climate change and evaluating them in terms  
18 of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.

## 19 **Adaptation Benefits**

20 The avoided damage costs or the accrued benefits following the adoption and implementa-  
21 tion of *adaptation* measures.

## 22 **Adaptation Costs**

23 Costs of planning, preparing for, facilitating, and implementing *adaptation* measures,  
24 including transition costs.

## 25 **Adaptive Capacity**

26 The ability of a system to adjust to climate change (including climate variability and  
27 extremes) to moderate potential damages, to take advantage of opportunities, or to cope  
28 with the consequences.

1        **Alluvium**

2        Sand, gravel, and silt deposited by rivers and streams in a valley bottom.

3        **Anthropogenic**

4        Resulting from or produced by human beings.

5        **Arterials**

6        Major streets or highways, many with multilane or freeway design, serving high-volume  
7        traffic corridor movements that connect major generators of travel. While they may provide  
8        access to abutting land, their primary function is to serve traffic moving through the area.

9        **Atmosphere**

10       The gaseous envelope surrounding the earth. The dry atmosphere consists almost entirely  
11       of nitrogen and oxygen, together with trace gases, including carbon dioxide and ozone.

12       **Baseline/Reference**

13       The baseline (or reference) is the state against which change is measured. It might be a  
14       “current baseline,” in which case it represents observable, present-day conditions. It might  
15       also be a “future baseline,” which is a projected future set of conditions, excluding the  
16       driving factor of interest. Alternative interpretations of the reference conditions can give  
17       rise to multiple baselines.

18       **Basin**

19       The drainage area of a stream, river, or lake.

20       **Bus Rapid Transit (BRT)**

21       A rapid mode of bus transportation that can combine the quality of rail transit and the  
22       flexibility of buses. There are a broad range of features that can be considered elements of  
23       a BRT system, including a dedicated bus-only right-of-way, bus lane reserved for buses on  
24       a major arterial road or freeway, on-line stops or stations (like light rail stations), other  
25       forms of giving buses priority in traffic, faster passenger boarding, faster fare collection,  
26       and a system image that is uniquely identifiable.

27       **Carbon Cycle**

28       The term used to describe the flow of carbon (in various forms, e.g., carbon dioxide)  
29       through the atmosphere, ocean, terrestrial biosphere, and lithosphere.



1       **Carbon Dioxide (CO<sub>2</sub>)**

2       A naturally occurring gas fixed by photosynthesis into organic matter. A by-product of  
3       fossil fuel combustion and *biomass* burning, it is also emitted from land use changes and  
4       other industrial processes. It is the principal *anthropogenic greenhouse gas* that affects the  
5       earth's radiative balance. It is the reference gas against which other greenhouse gases are  
6       measured, thus having a Global Warming Potential of one.

7       **Climate**

8       Climate in a narrow sense is usually defined as the “average weather,” or more rigorously,  
9       as the statistical description in terms of the mean and variability of relevant quantities over  
10      a period of time ranging from months to thousands or millions of years. These quantities  
11      are most often surface variables such as temperature, precipitation, and wind. Climate in a  
12      wider sense is the state, including a statistical description, of the *climate system*. The classical  
13      period of time is 30 years, as defined by the World Meteorological Organization (WMO).

14      **Climate Change**

15      A change in the mean state or variability of the climate, whether due to natural variability  
16      or as a result of human activity, that persists for an extended period, typically decades or  
17      longer. This usage differs from that in the *United Nations Framework Convention on*  
18      *Climate Change (UNFCCC)*, which defines “climate change” as: “a change of climate  
19      which is attributed directly or indirectly to human activity that alters the composition of the  
20      global atmosphere and which is in addition to natural climate variability observed over  
21      comparable time periods.” Also see *climate variability*.

22      **(Climate Change) Impact Assessment**

23      The practice of identifying and evaluating, in monetary and/or nonmonetary terms, the  
24      effects of climate change on natural and human systems.

25      **(Climate Change) Impacts**

26      The effects of climate change on natural and human systems. Depending on the considera-  
27      tion of adaptation, one can distinguish between potential impacts and residual impacts.

- 28      • **Potential Impacts** – All impacts that may occur given a projected change in climate,  
29      without considering adaptation.
- 30      • **Residual Impacts** – The impacts of climate change that would occur after adaptation.  
31      Also see *aggregate impacts*, *market impacts*, and *nonmarket impacts*.

1       **Climate Model**

2       A numerical representation of the climate system based on the physical, chemical, and  
3       biological properties of its components, their interactions and feedback processes, and  
4       accounting for all or some of its known properties. The climate system can be represented  
5       by models of varying complexity (i.e., for any one component or combination of compo-  
6       nents a hierarchy of models can be identified, differing in such aspects as the number of  
7       spatial dimensions, the extent to which physical, chemical, or biological processes are  
8       explicitly represented, or the level at which empirical parameterisations are involved.  
9       Coupled atmosphere/ocean/sea-ice General Circulation Models (*AOGCM* or *GCM*) provide  
10      a comprehensive representation of the climate system. More complex models include  
11      active chemistry and biology. Climate models are applied, as a research tool, to study and  
12      simulate the climate, but also for operational purposes, including monthly, seasonal, and  
13      interannual climate predictions.

14      **Climate Prediction**

15      A climate prediction or climate forecast is the result of an attempt to produce an estimate of  
16      the actual evolution of the climate in the future, e.g., at seasonal, interannual, or long-term  
17      time scales. Also see *climate projection* and *climate scenario*.

18      **Climate Projection**

19      The calculated response of the climate system to *emission* or concentration scenarios of  
20      *greenhouse gases* and *aerosols*, or *radiative forcing* scenarios, often based on simulations  
21      by climate models. Climate projections are distinguished from *climate predictions*, in that  
22      the former critically depend on the emission/concentration/radiative forcing scenario used,  
23      and therefore on highly uncertain assumptions of future socioeconomic and technological  
24      development.

25      **Climate Scenario**

26      A plausible and often simplified representation of the future *climate*, based on an internally  
27      consistent set of climatological relationships and assumptions of *radiative forcing*, typi-  
28      cally constructed for explicit use as input to climate change impact models. A “climate  
29      change scenario” is the difference between a climate scenario and the current climate.

30      **Climate System**

31      The climate system is defined by the dynamics and interactions of five major components:  
32      atmosphere, hydrosphere, cryosphere, land surface, and biosphere. Climate system  
33      dynamics are driven by both internal and external forcing, such as volcanic eruptions, solar  
34      variations, or human-induced modifications to the planetary radiative balance, for instance  
35      via anthropogenic emissions of greenhouse gases and/or land use changes.

1       **Climate Variability**

2       Climate variability refers to variations in the mean state and other statistics (such as stan-  
3       dard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales  
4       beyond that of individual weather events. Variability may be due to natural internal proc-  
5       esses within the climate system (internal variability) or to variations in natural or anthropo-  
6       genic external forcing (external variability). Also see *climate change*.

7       **Collectors**

8       In urban areas, streets providing direct access to neighborhoods as well as direct access to  
9       arterials. In rural areas, routes serving intracounty, rather than statewide travel.

10       **Commercial Service Airport**

11       Airport that primarily accommodates scheduled passenger airline service.

12       **Convection**

13       Generally, transport of heat and moisture by the movement of a fluid. In meteorology, the  
14       term is used specifically to describe vertical transport of heat and moisture in the atmos-  
15       phere, especially by updrafts and downdrafts in an unstable atmosphere. The terms “con-  
16       vection” and “thunderstorms” often are used interchangeably, although thunderstorms are  
17       only one form of convection.

18       **Datum**

19       A reference point or surface against which position measurements are made. A vertical  
20       datum is used for measuring the elevations of points on the earth’s surface, while a hori-  
21       zontal datum is used to measure positions on the earth.

22       **Downscaling**

23       A method that derives local- to regional-scale (10 to 100 km) information from larger-scale  
24       models or data analyses.

25       **Drought**

26       The phenomenon that exists when precipitation is significantly below normal recorded lev-  
27       els, causing serious hydrological imbalances that often adversely affect land resources and  
28       production systems.

1       **El Niño-Southern Oscillation (ENSO)**

2       El Niño, in its original sense, is a warmwater current that periodically flows along the coast  
3       of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a  
4       fluctuation of the intertropical surface pressure pattern and circulation in the Indian and  
5       Pacific Oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenome-  
6       non is collectively known as El Niño-Southern Oscillation. During an El Niño event, the  
7       prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm  
8       surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru  
9       current. This event has great impact on the wind, sea surface temperature, and precipita-  
10      tion patterns in the tropical Pacific. It has climatic effects throughout the Pacific region  
11      and in many other parts of the world. The opposite of an El Niño event is called La Niña.

12      **Emissions Scenario**

13      A plausible representation of the future development of emissions of substances that are  
14      potentially radiatively active (e.g., *greenhouse gases, aerosols*), based on a coherent and  
15      internally consistent set of assumptions about driving forces (such as demographic and  
16      socioeconomic development, technological change) and their key relationships. In 1992,  
17      the IPCC presented a set of emissions scenarios that were used as a basis for the climate  
18      projections in the Second Assessment Report (IPCC, 1996). These emissions scenarios are  
19      referred to as the IS92 scenarios. In the IPCC Special Report on Emissions Scenarios  
20      (*SRES*) (Nakićenović et al., 2000), new emissions scenarios – the so-called SRES scenar-  
21      ios – were published.

22      **Enplanements**

23      The total number of passengers boarding an aircraft, including both originating and con-  
24      necting passengers.

25      **Ensemble**

26      A group of parallel model simulations used for *climate projections*. Variation of the results  
27      across the ensemble members gives an estimate of uncertainty. Ensembles made with the  
28      same model but different initial conditions only characterise the uncertainty associated with  
29      internal climate variability, whereas multimodel ensembles, including simulations by sev-  
30      eral models also include the impact of model differences.

31      **Erosion**

32      The process of removal and transport of soil and rock by weathering, mass wasting, and the  
33      action of streams, glaciers, waves, winds, and underground water.

34      **Evaporation**

35      The transition process from liquid to gaseous state.

1       **Evapotranspiration**

2       The combined process of water *evaporation* from the earth's surface and *transpiration*  
3       from vegetation.

4       **Exposure**

5       The combination of stress associated with climate-related change (sea-level rise, changes in  
6       temperature, frequency of severe storms) and the probability, or likelihood, that this stress  
7       will affect transportation infrastructure.

8       **Extreme Weather Event**

9       An event that is rare within its statistical reference distribution at a particular place. Defi-  
10      nitions of "rare" vary, but an extreme weather event would normally be as rare as or rarer  
11      than the 10<sup>th</sup> or 90<sup>th</sup> percentile. By definition, the characteristics of what is called "extreme  
12      weather" may vary from place to place. Extreme weather events may typically include  
13      floods and droughts.

14      **Fixed-Route Bus Service**

15      Service provided on a repetitive, fixed-schedule basis along a specific route with vehicles  
16      stopping to pick up and deliver passengers to specific locations; each fixed-route trip serves  
17      the same origins and destinations, unlike demand response and taxicabs.

18      **Fixed Transit Guideway**

19      A system of vehicles that can operate only on its own guideway constructed for that purpose  
20      (e.g., rapid rail, light rail). Federal usage in funding legislation also includes exclusive  
21      right-of-way bus operations, trolley coaches, and ferryboats as "fixed guideway" transit.

22      **Freight Handling Facility**

23      Marine facilities or terminals that handle freight. A given port or port area may contain  
24      multiple freight-handling facilities.

25      **General Aviation Airport**

26      Airport that primarily accommodates aircraft owned by private individuals and businesses.

27      **General Circulation Model (GCM)**

28      See *climate model*.

1       **Greenhouse Effect**

2       The process in which the absorption of infrared radiation by the atmosphere warms the earth.  
3       In common parlance, the term ‘greenhouse effect’ may be used to refer either to the natural  
4       greenhouse effect, due to naturally occurring greenhouse gases, or to the enhanced (anthro-  
5       pogenic) greenhouse effect, which results from gases emitted as a result of human activities.

6       **Greenhouse Gas**

7       Greenhouse gases are those gaseous constituents of the atmosphere, both natural and  
8       anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum  
9       of infrared radiation emitted by the earth’s surface, the atmosphere, and clouds. This prop-  
10      erty causes the *greenhouse effect*. Water vapor (H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), nitrous oxide  
11      (N<sub>2</sub>O), methane (CH<sub>4</sub>), and ozone (O<sub>3</sub>) are the primary greenhouse gases in the earth’s  
12      atmosphere. Beside CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>, the *Kyoto Protocol* deals with the greenhouse  
13      gases sulfur hexafluoride (SF<sub>6</sub>), hydrofluorocarbons (HFC), and perfluorocarbons (PFC).

14      **Gross-Ton Mile**

15      One ton of equipment or freight moved one mile.

16      **Hazardous Liquid**

17      Petroleum, petroleum products, liquefied natural gas (LNG), anhydrous ammonia, or a liq-  
18      uid that is flammable or toxic.

19      **Humidity**

20      Generally, a measure of the water vapor content of the air. Popularly, it is used synony-  
21      mously with relative humidity.

22      **Hurricane**

23      A tropical cyclone in the Atlantic, Caribbean Sea, Gulf of Mexico, or eastern Pacific, in  
24      which the maximum one-minute sustained surface wind is 64 knots (74 mph) or greater.

25      **Industrial Airport**

26      Airports which can accommodate both commercial and privately owned aircraft, and are  
27      typically used by aircraft service centers, manufactures, and cargo companies, as well as  
28      general aviation aircraft.

29      **Infrastructure**

30      The basic equipment, utilities, productive enterprises, installations, and services essential  
31      for the development, operation, and growth of an organization, city, or nation.

1       **Integrated Assessment**

2       An interdisciplinary process of combining, interpreting, and communicating knowledge  
3       from diverse scientific disciplines so that all relevant aspects of a complex societal issue  
4       can be evaluated and considered for the benefit of decision-making.

5       **Intermodal Connector**

6       Highway providing access to intermodal facilities and designated as a National Highway  
7       System (NHS) Intermodal Connector.

8       **Intermodal Passenger Terminal**

9       A passenger terminal which accommodates several modes of transportation, such as inter-  
10      city rail service, intercity bus, commuter rail, intracity rail transit and bus transportation,  
11      airport limousine service and airline ticket offices, rent-a-car facilities, taxis, private  
12      parking, and other transportation services.

13      **Intermodal Transportation**

14      Use of more than one type of transportation; e.g., transporting a commodity by barge to an  
15      intermediate point and by truck to destination. Often specifically refers to the use of cargo  
16      containers that can be interchanged between transport modes, i.e., motor, water, and air  
17      carriers, and where the equipment is compatible within the multiple systems.

18      **Interstate Highways**

19      Limited access divided facility of at least four lanes designated by the Federal Highway  
20      Administration as part of the Interstate System, a system of freeways connecting and  
21      serving the principal cities of the continental United States.

22      **Invasive Species**

23      An introduced species that invades natural habitats.

24      **Land Use**

25      The total of human activities implemented in a certain land-cover type (a set of human  
26      actions). The social and economic purposes for which land is managed (e.g., grazing, tim-  
27      ber extraction, conservation).

28      **LIDAR (Light Detection and Ranging)**

29      A remote sensing technology which determines the distance to an object or surface using  
30      laser pulses.

31      **Linguistically Isolated Household**

32      A household in which no person aged 14 and over speaks English at least “very well.”

1       **Local Road**

2       Roads that provide access to private property or low-volume public facilities.

3       **Long-Range Transportation Plan (LRTP)**

4       A 20- to 30-year plan that provides a long-range vision of the future of the surface trans-  
5       portation system, considering all passenger and freight modes and their interrelationships.  
6       LRTPs are developed by MPOs as part of the Federally mandated planning process.

7       **Metropolitan Planning Organization (MPO)**

8       The forum for cooperative transportation decision-making for a metropolitan planning area.  
9       Formed in cooperation with the state, it develops transportation plans and programs for the  
10      metropolitan area. For each urbanized area, a metropolitan planning organization (MPO)  
11      must be designated by agreement between the Governor and local units of government rep-  
12      resenting 75 percent of the affected population (in the metropolitan area), including the  
13      central cities or cities as defined by the Bureau of the Census or in accordance with proce-  
14      dures established by applicable state or local law (23 U.S.C. 134(b)(1)/Federal Transit Act  
15      of 1991 Section 8(b)(1)).

16      **Mitigation**

17      An anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it  
18      includes strategies to reduce *greenhouse gas sources* and emissions and enhancing *green-*  
19      *house gas sinks*.

20      **Morphology**

21      The form and structure of an organism or land form, or any of its parts.

22      **Nonfreight Marine Facility**

23      Marine facilities not used for transporting or handling freight. Includes unused berths;  
24      commercial fishing facilities; vessel construction, repair, and servicing facilities; marine  
25      construction services; etc.

26      **Nonlinearity**

27      A process is called “nonlinear” when there is no simple proportional relation between  
28      cause and effect.



1       **Paratransit**

2       Comparable transportation service required by the American Disabilities Act (ADA) for  
3       individuals with disabilities who are unable to use fixed-route transportation systems.  
4       Usually involves the use of demand-response systems, in which passengers or their agents  
5       contact a transit operator, who then dispatches a cars, vans, or bus to pick up the passengers  
6       up and transport them to their destinations (also called “Dial-a-Ride”).

7       **Partial Duration Series (PDS)**

8       A series composed of all events during the period of record that exceed some set criterion,  
9       for example, all floods above a selected base, or all daily rainfalls greater than a specified  
10      amount.

11      **Probability Density Function**

12      A statistical function that shows how the density of possible observations in a population is  
13      distributed.

14      **Projection**

15      The potential evolution of a quality or set of quantities, often computed with the aid of a  
16      model. Projections are distinguished from predictions in order to emphasize that projec-  
17      tions involve assumptions – concerning, for example, future socioeconomic and techno-  
18      logical developments, that may or may not be realized – and are, therefore, subject to sub-  
19      stantial uncertainty. Also see *climate projection* and *climate prediction*.

20      **Radiative Forcing**

21      Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square  
22      metre ( $Wm^{-2}$ )) at the tropopause due to an internal or external change in the forcing of the  
23      climate system, such as a change in the concentration of  $CO_2$  or the output of the sun.

24      **Relative Humidity**

25      A dimensionless ratio, expressed in percent, of the amount of atmospheric moisture present  
26      relative to the amount that would be present if the air were saturated. Since the latter  
27      amount is dependent on temperature, relative humidity is a function of both moisture con-  
28      tent and temperature. As such, relative humidity by itself does not directly indicate the  
29      actual amount of atmospheric moisture present.

30      **Resilience**

31      The capacity of a system to absorb disturbances and retain essential processes.

32      **Runoff**

33      That part of precipitation that does not evaporate and is not transpired.

1       **Saffir-Simpson Scale**

2       A scale from 1 to 5 that describes a hurricane’s strength, where Category 1 is the weakest  
3       and Category 5 is the strongest hurricane. The categories are defined by wind speed. The  
4       scale of numbers is based on actual conditions at some time during the life of the storm; as  
5       the hurricane intensifies or weakens, the scale number is reassessed accordingly.

6       **Scenario**

7       A plausible and often simplified description of how the future may develop based on a  
8       coherent and internally consistent set of assumptions about driving forces and key relation-  
9       ships. Scenarios may be derived from projections, but are often based on additional infor-  
10      mation from other sources, sometimes combined with a “narrative storyline.” Also see  
11      *climate scenario* and *emissions scenario* and *SRES*.

12      **Sea-Level Rise**

13      An increase in the mean level of the ocean. Eustatic sea-level rise is a change in global  
14      average sea level brought about by an increase in the volume of the world ocean. Relative  
15      sea-level rise occurs where there is a local increase in the level of the ocean relative to the  
16      land, which might be due to ocean rise and/or land-level subsidence. In areas subject to  
17      rapid land level uplift, relative sea-level can fall.

18      **Sea Surface Temperature**

19      The mean temperature of the ocean in the upper few meters.

20      **Socioeconomic Scenarios**

21      *Scenarios* concerning future conditions in terms of population, Gross Domestic Product,  
22      and other socioeconomic factors relevant to understanding the implications of climate  
23      change. Also see *SRES*.

24      **Specific Humidity**

25      In a system of moist air, the ratio of the mass of water vapor to the total mass of the system.

26      **SRES**

27      The storylines and associated population, GDP and emissions scenarios associated with the  
28      Special Report on Emissions Scenarios (SRES) (Nakićenović, 2000), and the resulting cli-  
29      mate change and sea-level rise scenarios. Four families of socioeconomic scenario (A1,  
30      A2, B1, and B2) represent different world futures in two distinct dimensions: a focus on  
31      economic versus environmental concerns and global versus regional development patterns.

1       **Storm Surge**

2       An abnormal rise in sea-level accompanying a hurricane or other intense storm, whose  
3       height is the difference between the observed level of the sea surface and the level that  
4       would have occurred in the absence of the cyclone. Storm surge is usually estimated by  
5       subtracting the normal or astronomic tide from the observed storm tide.

6       **Subsidence**

7       A sinking down of part of the earth's crust, generally due to natural compaction of sedi-  
8       ments or from underground excavation (such as the removal of groundwater).

9       **Surface Runoff**

10       The water that travels over the soil surface to the nearest surface stream; *runoff* of a drain-  
11       age basin that has not passed beneath the surface since precipitation.

12       **Thermal Expansion**

13       In connection with *sea-level rise*, this refers to the increase in volume (and decrease in den-  
14       sity) that results from warming water. A warming of the ocean leads to an expansion of the  
15       ocean volume and hence an increase in sea level.

16       **Threshold**

17       The level of magnitude of a system process at which sudden or rapid change occurs. A  
18       point or level at which new properties emerge in an ecological, economic, or other system,  
19       invalidating predictions based on mathematical relationships that apply at lower levels.

20       **Transpiration**

21       The evaporation of water vapor from the surfaces of leaves through stomates.

22       **Transportation Improvement Program (TIP)**

23       A prioritized program of transportation projects to be implemented in appropriate stages  
24       over several years (i.e., three to five years). The projects are recommended from those in  
25       the transportation systems management element and the long-range element of the planning  
26       process. This program is required as a condition for a locality to receive Federal transit and  
27       highway grants.

28       **Tropical Storm**

29       A tropical cyclone in which the maximum one-minute sustained surface wind ranges from  
30       34 to 63 knots (39 to 73 mph) inclusive.

1       **Uncertainty**

2       An expression of the degree to which a value (e.g., the future state of the climate system) is  
3       unknown. Uncertainty can result from lack of information or from disagreement about  
4       what is known or even knowable. It may have many types of sources, from quantifiable  
5       errors in the data to ambiguously defined concepts or terminology, or uncertain projections  
6       of human behavior. Uncertainty can therefore be represented by quantitative measures  
7       (e.g., a range of values calculated by various models) or by qualitative statements (e.g.,  
8       reflecting the judgment of a team of experts).

9       **United Nations Framework Convention on Climate Change (UNFCCC)**

10       The UNFCCC was adopted on May 9, 1992, in New York, and signed at the 1992 Earth  
11       Summit in Rio de Janeiro by more than 150 countries and the European Community. Its  
12       ultimate objective is the “stabilization of greenhouse gas concentrations in the atmosphere  
13       at a level that would prevent dangerous anthropogenic interference with the climate sys-  
14       tem.” It contains commitments for all Parties. Under the Convention, Parties included in  
15       Annex I aim to return greenhouse gas emissions not controlled by the Montreal Protocol to  
16       1990 levels by the year 2000. The Convention entered in force in March 1994. Also see  
17       *Kyoto Protocol*.

18       **Urbanisation**

19       The conversion of land from a natural state or managed natural state (such as agriculture)  
20       to cities; a process driven by net rural-to-urban migration through which an increasing per-  
21       centage of the population in any nation or region come to live in settlements that are  
22       defined as “urban centers.”

23       **Vehicle Miles of Travel (VMT)**

24       A unit to measure vehicle travel made by a private vehicle, such as an automobile, van,  
25       pickup truck, or motorcycle. Each mile traveled is counted as one vehicle mile, regardless  
26       of the number of persons in the vehicle. Generally, vehicle miles of travel are reported on  
27       an annual basis for a large area.

28       **Vulnerability**

29       The structural strength and integrity of key facilities or systems and the resulting potential  
30       for damage and disruption in transportation services from climate change stressors.

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