STATEMENT OF
DR. VIRGINIA BURKETT
CHIEF SCIENTIST FOR GLOBAL CHANGE RESEARCH
U.S. GEOLOGICAL SURVEY
U.S. DEPARTMENT OF THE INTERIOR

BEFORE THE
COMMITTEE ON ENERGY AND NATURAL RESOURCES
UNITED STATES SENATE
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SAP 4.7: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I

May 13, 2008

Mr. Chairman and Members of the Committee, as a Lead Author and Editor of the U.S. Climate Change Science Program assessment of climate change and its impacts on Gulf Coast transportation, I am pleased to present a summary of our findings about trends in the physical environment and the climate variables that have implications for the transportation sector. I would like to acknowledge the other editors and co-authors of the report, with whom I have collaborated over the past four years to develop this broad regional assessment upon which my testimony is based (CCSP 2008):

Editors: Michael J. Savonis (FHWA) and Joanne R. Potter (Cambridge Systematics)

Lead Authors: Michael J. Savonis, Joanne R. Potter, Robert C. Hyman (Cambridge Systematics), Barry D. Keim (Louisiana State University), Thomas W. Doyle (USGS), Robert S. Kafalenos (FHWA), Kenneth J. Leonard (Cambridge Systematics), Ron Hagelman (Texas State University), Stephen B. Hartley (USGS), Matthew Sheppard (IBM), John H. Suhrbier (Cambridge Systematics), Eric Lindquist (Texas A&M Univerisity), and Jessica E. Tump (Cambridget Systematics)

Contributing authors: Claudia Tebaldi (National Center for Atmospheric Research), Daniel M. Beagan (Cambridge Systematics), Alan Meyers (Cambridge Systematics), Michael F. Wehner (Lawrence Berkeley National Laboratory), Tamara G. Houston (NOAA), David T. Hunt (Cambridge Systematics), Michael K. Maynard (Wilbur Smith Associates), Barbara Fritsche (Wilbur Smith Associates), Russell H. Henk (Texas Transportation Institute), Edward J. Seymour (Texas Transportation Institute), Leslie E. Olson (Texas Transportation Institute) , Wesley R. Dean (Texas A&M University), Ivor Van Heerden (Louisiana State University), S. Ahmet Binselam (Louisiana State University), and Nanda N. Srinivasan (Cambridge Systematics)

These authors collectively represent three Federal agencies, five universities and research institutions, and two transportation planning and engineering firms. In addition to the contributions from these co-authors, the study was guided by a 16-member advisory committee formally chartered by the Secretary of Transportation under the Federal Advisory Committee Act of 1972. This committee included transportation experts representing the various modes (e.g., rail, ports, highways) and several additional physical scientists and risk assessment experts.

The Gulf Coast project was sponsored by the U.S. Department of Transportation (DOT) in partnership with the U.S. Geological Survey (USGS) under the auspices of the U.S. Climate Change Science Program (CCSP). The study, Synthesis and Assessment Product (SAP) 4.7 titled "Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I" is one of 21 "synthesis and assessment" products planned and sponsored by the CCSP with the Department of Transportation as the lead agency. This SAP was completed by the CCSP in March 2008. This project demonstrates how our understanding of climate change and other physical processes can be integrated with knowledge of transportation engineering and planning to produce an assessment of risks and vulnerability that is relevant to this important sector of the U.S. economy.

The ultimate goal of this 3-phased research project is to provide knowledge and tools that will enable transportation planners and managers to better understand climate change and associated risks, adaptation strategies, and tradeoffs involved in planning, investment, design, and operational decisions. The objective of Phase I of this project, which we have now completed, was to conduct a preliminary assessment of the risks and vulnerabilities of transportation in the region, after collecting and integrating the range of data needed to characterize the region – its physiography and hydrology, land use and land cover, past and projected climate, current population and trends, and transportation infrastructure. Subsequent phases will involve a more detailed analysis. Phase II will involve an in-depth assessment of risks to transportation in a selected location, reporting on implications for long-range plans and impacts on safety, operations, and maintenance. This phase will also develop a risk assessment methodology and identify techniques to incorporate environmental and climate data in transportation decisions. Phase III will identify and analyze adaptation and response strategies and develop tools to assess these strategies, while enumerating future research needs.

My comments this morning will focus on the major drivers of change in the central Gulf Coast, considering the natural physical setting as well as the historical and projected changes in climate. The Lead Author of the study from the DOT, Mike Savonis, is with me to answer any questions that you might have about potential impacts on the wide range of transportation modes within the regions, such as pipelines, highways and ports.

The Gulf Coast study area (Figure 1) includes 48 contiguous coastal counties in four States, from Houston/Galveston, Texas, to Mobile, Alabama. This region is home to nearly 10 million people living in a range of urban and rural settings and contains critical transportation infrastructure that provides vital service to its constituent States and the Nation as a whole. It is also highly vulnerable to sea level rise and storm impacts. A variety of physical datasets were compiled for review and use by the project research team. Most of the spatial data was organized in geographic information system (GIS) formats or "layers" that can be used to assess the vulnerability and risks of the transportation infrastructure in the study area and inform the development of adaptation strategies. In cooperation with DOT's Bureau of Transportation Statistics we developed a GIS that allows us to overlay elevation, storm surge, census data, and other attributes of the study area with transportation infrastructure.

The Central Gulf Coast region is a low-lying sedimentary coast with low topographic relief; the great majority of the study area lies below 30 m (100 ft) in elevation (Figure 2). Much of the central Gulf Coast region is prone to flooding during heavy rainfall events, hurricanes, and lesser tropical storms. Land subsidence is a major factor in the region, particularly in the Galveston region and the Mississippi River deltaic plain. Subsidence is influenced by both landform characteristics of specific locations as well as by human activities, such as ground-water withdrawals. Most of the coastline is also highly vulnerable to erosion and wetland loss, particularly in association with tropical storms and passing storm fronts. It is estimated that 56,000 ha (217 mi^2) of land were lost in Louisiana during Hurricane Katrina. Further, many Gulf Coast barrier islands are retreating and diminishing in size. The Chandeleur Islands, which serve as a first line of defense for the New Orleans region, lost roughly 85 percent of their surface area during Hurricane Katrina. As barrier islands and mainland shorelines erode and submerge, human communities and onshore infrastructure in low-lying coastal areas become more susceptible to inundation and destruction.

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 with:

- 27,000 km (17,000 mi) of major highways – about 2 percent of the Nation's major highways – that carry 83.5 billion vehicle miles of travel annually.
- Pipelines, bulk terminals, and other infrastructure that receive and transport two-thirds of all U.S. oil imports. 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 largest concentration of public and private freight handling ports in the United States, measured on a tonnage basis, which handle 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.
- The center of U.S. transcontinental trucking and rail routes with one of only four major points in the United States where railcars are exchanged between the dominant eastern and western railroads.
- The Nation's leading and third-leading inland waterway systems (the Mississippi River and the Gulf Intracoastal Waterway) based on tonnage and providing 20 States with access to the Gulf of Mexico.
- 61 publicly owned, public-use airports, including 11 commercial service facilities.

All of these transportation modes are vulnerable in some way to the changes in climate that are anticipated in this region during the next 50 to 100 years. The relative vulnerability of facilities is dependent, in large part, on elevation and distance from the coastline.

The Gulf Coast, like much of the world, has experienced significant changes in climate over the past century and is expected to change even more rapidly during the next century (IPCC, 2007). The four key climate drivers in the Central Gulf Coast region – rising temperatures, changing precipitation patterns, rising relative sea levels, and increasing storm intensity – present clear risks to existing infrastructure. These factors can be incorporated into decisions that enable communities to prepare for and adapt to changing climatic conditions. The research team's assessment of historical and potential future changes in these four variables draws on publications, analyses of instrumental records, and models that simulate how climate may change in the future.

Our assessment of the present climate and 20th century trends was built around climatic data from the United States Climate Division Datasets (CDD) and the United States Historical Climate Network (USHCN). Empirical trends and variability were analyzed for temperature and precipitation at the CDD level for the climate divisions along the Gulf Coast from Galveston, Texas, to Mobile, Alabama, including Texas Climate Division 8, Louisiana Divisions 6-9, Mississippi Division 10, and Alabama Division 8 (Figure 3).

Results from our analysis of temperature variability during 1905 to 2003 indicate that the 1920s or 1930s was generally the warmest decade for the various Gulf Coast climate divisions (Figure 3). After a step down in the temperature in the late 1950s, the coolest period occurs in the 1960s, while a warming trend is evident for all seven climate divisions beginning in the 1970s and extending through 2003. Of the seven climate divisions, LA6, LA8, and MS10 have slight but significant cooling trends over the 98-year period of record. Precipitation variability shows that the 1940s and 1990s were the wettest decades, while the 1950s was generally the driest (Figure 4). Although all of the climate divisions at least suggest long-term patterns of increasing rainfall, only MS10 and AL8 have significant trends.

A water balance model developed for the region suggests a long-term trend of increasing annual runoff (Figure 5). Over the entire record since 1919, there was an increase in rainfall that, combined with relatively cool temperatures, led to an estimated 36 percent increase in runoff. Modeled future water balance, however, suggests that runoff is expected to either decline slightly or remain relatively unchanged, depending upon the balance of precipitation and evaporation. Moisture deficits and drought appear likely to increase across the study area, though model results are mixed. These findings are consistent with the Intergovernmental Panel on Climate Change (IPCC, 2007), which concludes that it is very likely that heat waves, heat extremes, and heavy precipitation events over land will increase during this century and that the number of dry days (or spacing between rainfall events) will increase. Even in mid-latitude regions where mean precipitation is expected to decrease, precipitation intensity is expected to increase (IPCC, 2007).

Sea level has risen more than 120 m (395 ft) since the peak of the last ice age (about 20,000 B.P.) and over the 20th century by 1-2 mm/year (0.04-0.08 in/year). The rate of global sea level rise since 1963 is estimated at 1.8 mm/year (0.07 in/year) (IPCC, 2007). More recent analysis of satellite altimetry data for the period from 1993 to 2003 shows a global average rate of sea level rise of about 3.1 (2.4-3.8) mm per year (0.12 in/year). Whether the faster rate since 1993 reflects decadal variability or a long-term acceleration over the 20th century rate is unclear. There is high confidence, however, that the rate of observed sea level rise was greater in the 20th century compared to the 19th century (IPCC, 2007).

Changes in mean water level at a given coastal location are affected by a combination of changes in sea level in an ocean basin and by local factors such as land subsidence. Gulf Coastal Plain environments, particularly in the central and western parts of the Gulf Coast study area, are prone to high rates of land surface subsidence attributed to soil decomposition and compaction, deep fluid extraction, and the lack of sediment deposition. For example, the Mississippi River delta region demonstrates relative sea level rates of 10 mm/year (0.40 in/year), five-fold greater than the 20th century rate of global sea level rise. Subsidence rates for several Gulf Coast sites by previous investigators range from a low of 0.27 cm/year (0.11 in/year) in the Big Bend region of northwest Florida up to 2.39 cm/year (0.94 in/year) for coastal Louisiana.

The scenarios of future climate referenced in our report were generated by the National Center for Atmospheric Research (NCAR), a research center lead by a consortium of universities and international organizations, by using an ensemble of 21 different atmosphere-ocean coupled general circulation models (GCM) for the Gulf Coast region. Model results, climatic trends during the past century, and climate theory all suggest that extrapolation of the 20th century temperature record would likely underestimate the range of change that could occur in the next few decades. 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 regarding the direction of change for most of the climate variables that affect transportation in the Gulf Coast region.

Climate models currently lack the detail needed to make confident projections or forecasts for a number of variables, especially on small scales, so plausible “scenarios” are often used to provide input to decision making (Parson et al., 2007). Output from an ensemble of 21 GCMs run with the three emissions scenarios indicate a wide range of possible changes in temperature and precipitation out to the year 2050. The models agree to a warmer Gulf Coast region of about 1.5 °C ± 1 °C (2.7 °F ± 1.8 °F), with the greatest increase in temperature occurring in the summer. Based on historical trends and model projections, we conclude that it is very likely that in the future the number of very hot days will substantially increase across the study area. Modeled outputs of potential temperature increase scenarios for August are presented in Table 1. Extreme high temperatures could be about 1^{o}C (1.8 °F) greater than the change in the average temperature simulated by the GCMs.

Scenarios of future precipitation are more convoluted, with indications of increases or decreases by the various models, but the models lean slightly toward a decrease in annual rainfall across the Gulf Coast. However, by compounding changing seasonal precipitation with increasing temperatures, average runoff is likely to remain the same or decrease, while deficits (or droughts) are more likely to become more severe. Each of the climate model and emissions scenarios analyzed in our report represents plausible future regional conditions.

Increased tropical storm intensity is likely to accompany global warming as a function of higher sea surface temperatures, which have been observed globally (Webster et al., 2005; IPCC 2007). The kinetic energy of tropical storms and hurricanes is fueled from heat exchange over warm tropical waters. An increase in sea surface temperature (SST) from global climate change is likely to increase the probability of higher sustained winds per tropical storm circulation (Emanuel, 1987; Holland, 1997; Knutson et al., 1998). Sea surface temperature has increased significantly in the main hurricane development region of the North Atlantic during the past century (Bell et al., 2007) (Figure 6) as well as in the Gulf of Mexico (Smith and Reynolds, 2004) (Figure 7).

Recent empirical evidence suggests a trend towards more intense hurricanes formed in the North Atlantic Basin, and this trend is likely to intensify during the next century (IPCC, 2007). In the Gulf region, there is presently no compelling evidence to suggest that the number or paths of tropical storms have changed or are likely to change in the future.

Change in the rate of sea level rise is dependent on a host of interacting factors that are best evaluated on decadal to centennial time scales. Two complementary modeling approaches were applied in this study to assess the potential rise in sea level and coastal submergence over the next century. Both models were used to estimate relative sea level rise (RSLR) by 2050 and 2100 under a range of greenhouse gas emissions scenarios. Both models account for global sea level change as estimated by the global climate models and also incorporate values for land subsidence in the region based on the historical record. One model, CoastClim, produces results that are closer to a simple measure of future sea level change under the scenarios of future climate. A similar model, SLRRP, also incorporates values for high and low tidal variation attributed to astronomical and meteorological causes, which are pulled from the historical record. The SLRRP model is rectified to the NAVD88 (North American Vertical Datum of 1988) that is commonly used by surveyors to calculate the elevations of roads, bridges, levees, and other infrastructure. The tide data used in the SLRRP model is based on a monthly average of the mean high tide (called mean high water) for each day of the month (Table 2). The SLRRP results capture seasonal variability and interannual trends in relative sea level change, while the CoastClim results do not.

The three long-term tide gauge locations analyzed in this study represent three subregions of the study area: Galveston, Texas (the chenier plain); Grand Isle, Louisiana (the Mississippi River deltaic plain); and Pensacola, Florida (Mississippi/Alabama Sound) (Figure 8). For each of these gauges, we examined potential range of relative sea level rise through 2050 and 2100 using the SRES B1, A1B, A2, and A1FI emissions scenarios based on the combined output of 7 GCMs. Results for the year 2100 generated with CoastClim range from 24 cm (0.8 ft) in Pensacola to 167 cm (5.5 ft) in Grand Isle. Results for the year 2100 from SLRRP (Table 3), which as noted above accounts for historical tidal variation, indicate relative sea level rise in the range of 70 cm (2.3 ft, NAVD88) in Pensacola to 199 cm (6.5 ft, NAVD88) in Grand Isle.

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

Changes in climate can have widespread effects on physical and biological systems of low-lying, sedimentary coasts. However, the large and growing pressures of development are responsible for most of the current stresses on Gulf Coast natural resources, which include: water quality and sediment pollution, increased flooding, loss of barrier islands and wetlands, and other factors that are altering the resilience of coastal ecosystems (U.S. Environmental Protection Agency, 1999). Human alterations to freshwater inflows through upstream dams and impoundments, dredging of natural rivers and engineered waterways, and flood-control levees also have affected the amount of sediment delivered to the Gulf coastal zone. Roughly 80 percent of U.S. coastal wetland losses have occurred in the Gulf Coast region since 1940, and predictions of future population growth portend increasing pressure on Gulf Coast communities and their environment. Sea level rise will generally increase marine transgression on coastal shorelines and the frequency of barrier island overwash during storms, with effects most severe in coastal systems that already are stressed and deteriorating. An increase in tropical storm intensity or a decrease in fresh water and sediment delivery to the coast would tend to amplify the effects of sea level rise on Gulf Coast landforms.

The global near-surface air temperature increase of the past 100 years is approaching levels not observed in the past several hundred years (IPCC, 2001). 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 regarding the direction of change for most of the climate variables that affect transportation in the Gulf Coast region. Key findings from our analysis and other published studies for the study region concerning future climate include:

Warming temperatures – All GCMs available from the IPCC (via the Coupled Model Intercomparison Project 3) used in this study indicate an increase in average annual Gulf Coast temperature through the end of this century. Based on GCM runs under three different emission scenarios developed by the IPCC Special Report on Emissions Scenarios (SRES) (the low-emissions B1, the high-emissions A2, and the mid-range A1B scenarios), the average temperature in the Gulf Coast region appears likely to increase by at least 1.5°C ± 1°C (2.7°F ± 1.8°F) during the next 50 years. Extreme high temperatures are also expected to increase – with the number of days above 32.2°C (90°F) very likely to increase significantly across the study area. Within 50 years the probability of experiencing 21 days a year with temperatures of 37.8°C (100°F) or above is greater than 50 percent (Figure 9).

Changes in precipitation patterns – Some analyses, including the GCM results from this study, indicate that average precipitation will increase in this region while others indicate a decline of average precipitation during the next 50 to 100 years. In either case, it is expected that average soil moisture could decline, due to increasing temperatures and resulting higher evapotranspiration rates. While *average* annual rainfall may increase or decrease slightly, the *intensity* of individual rainfall events is likely to increase during the 21st century.

Rising Sea Levels – Relative sea level is likely to rise between 1 and 6 ft by the end of the 21st century, depending upon model assumption and geographic location. The highest rate of relative sea level rise will very likely be in the central and western parts of the study area

(Louisiana and East Texas) where subsidence rates are highest (Table 3). Relative sea level rise (RSLR) is the combined effect of the projected increase in the volume of the world's oceans (eustatic sea level change), which results from increases in temperature and melting of ice, and the projected changes in land surface elevation at a given location due to subsidence of the land surface. The highest rate of relative sea level rise will very likely be in the central and western parts of the study area (Louisiana and East Texas), where subsidence rates are highest (Table 3). The analysis of a "middle range" of potential sea level rise of 0.6 to 1.2 meters (2 to 4 feet) indicates that a vast portion of the Gulf Coast from Houston to Mobile may be inundated over the next 50 to 100 years. The projected rate of relative sea level rise for the region is consistent with historical trends, other published region-specific analyses, and the IPCC 4th Assessment Report findings, which assumes no major changes in ice sheet dynamics.

Storm Activity – The destructive potential of hurricanes is likely to increase as the sea surface temperature of the Atlantic and Gulf of Mexico continue to rise. Rising relative sea level will exacerbate exposure to storm surge and flooding. Depending on the trajectory and scale of individual storms, facilities at or below 9 m (30 ft) could be subject to direct storm surge impacts. Rising relative sea level will exacerbate exposure to storm surge and flooding.

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

Based on findings from the USGS-led research team about the physical setting and climatic trends, a regional-scale characterization of impacts on transportation systems and infrastructure was led by the DOT. The following summary of potential impacts is presented in the Executive Summary of the report:

Warming temperatures may require changes in materials, maintenance, and operations. The combined effects of an increase in mean and extreme high temperatures across the study region are likely to affect the construction, maintenance, and operations of transportation infrastructure and vehicles. Higher temperatures may also suggest areas for materials and technology innovation to develop new, more heat-tolerant materials. Some types of infrastructure deteriorate more quickly at temperatures above 32.2°C (90°F). As the number of very hot days increases, different materials may be required. Further, restrictions on work crews may lengthen construction times. Rail lines may be affected by more frequent rail buckling due to an increase in daily high temperatures. Ports, maintenance facilities, and terminals are expected to require increased refrigeration and cooling. Finally, higher temperatures affect aircraft performance and the runway lengths that are required. However, advances in aircraft technology are expected to offset the potential effects of the temperature increases analyzed in this report, so that current runway lengths are likely to be sufficient. The effects of increases in average temperatures and in the number of very hot days will have to be addressed in designing and planning for vehicles, facilities, and operations.

Changes in precipitation patterns may increase short-term flooding. The analysis of future annual precipitation change based on results of climate model runs is inconclusive: some models indicate an increase in average precipitation and some indicate a decrease. In either case, the hotter climate may reduce soil moisture and average run-off, possibly necessitating changes in right-of-way land management. The potential of changes in heavy rainfall may have more significant consequences for transportation; more frequent extreme precipitation events may result in more frequent flooding, stressing the capacity of existing drainage systems. The potential of extreme rainfall events and more frequent and prolonged flooding may disrupt traffic management, increase highway incidents, and impact airline schedules – putting additional strain on a heavily used and increasingly congested system. Further, prolonged flooding – inundation in excess of one week – can damage pavement substructure.

Relative sea level rise may inundate existing infrastructure. To assess the impact of relative sea level rise (RSLR), the implications of rises equal to 61 cm and 122 cm (2 and 4 ft) were examined. As discussed above, actual RSLR may be higher or somewhat lower than these levels. Under these scenarios, substantial portions of the transportation infrastructure in the region are at risk: 27 percent of the major roads, 9 percent of the rail lines, and 72 percent of the ports are at or below 122 cm (4 ft) in elevation, although portions of the infrastructure are guarded by protective structures such as levees and dikes. While protective structures will continue to be an important strategy in the area, rising sea levels significantly increase the challenge to transportation managers in ensuring reliable transportation services. Inundation of even small segments of the intermodal system can render much larger portions impassable, disrupting connectivity and access to the wider transportation network.

Increased storm intensity may lead to greater service disruption and infrastructure damage. This study examined the potential for flooding and damage associated with storm surge levels of 5.5 m and 7.0 m (18 ft and 23 ft). These modeled outputs are comparable to potential surge levels during severe storms in the region: Simulated storm surge from model runs across the central Gulf Coast demonstrated a 6.7- to 7.3-m (22- to 24-ft) potential surge for major hurricanes. These levels may be conservative; surge levels during Hurricane Katrina (rated a Category 3 at landfall) exceeded these heights in some locations. The specific location and strength of storm surges are of course determined by the scale and trajectory of individual tropical storms, which are difficult to predict. However, substantial portions of the region's infrastructure are located at elevations below the thresholds examined, and recent storms have demonstrated that major hurricanes can produce flooding miles inland from the location of initial landfall. With storm surge at 7 m (23 ft), more than half of the area's major highways (64 percent of Interstates; 57 percent of arterials), almost half of the rail miles, 29 airports, and virtually all of the ports are subject to flooding.

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

Mr. Chairman, thank you for the opportunity to present the findings of Phase I of the Gulf Coast study. I will be happy to answer any questions that you and other Members of the Committee may have.

Table 1. Modeled outputs of potential temperature increase (°C [°F]) scenarios for August.

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	**5th**	**50th**	**95th**	**Scenario**	**5th**	**50th**	**95th**
A1B mid-range	1.6 (2.9)	2.5 (4.5)	**3.4 (6.1)**	**A1B mid-range**	3.0 (5.4)	3.9 (7.0)	5.0 (9.0)
B1 low	**0.9 (1.6)**	1.8 (3.2)	2.6 (4.7)	**B1 low**	**1.8 (3.2)**	2.7 (4.9)	3.6 (6.5)
A2 high	1.1 (2.0)	2.3 (4.1)	**3.4 (6.1)**	**A2 high**	3.3 (5.9)	4.7 (8.5)	**6.0 (10.8)**

Note: Lowest/highest changes in bold.

Table 2. USGS SLRRP model results showing the mean land surface elevations (cm [NAVD88]) 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 seven GCM models for the A1FI, B1, A1B, and A2 emissions scenarios.

Year 2050	**Low**				**Year 2100**	**Low**			
	A1FI	**B1**	**A1B**	**A2**		**A1FI**	**B1**	**A1B**	**A2**
Galveston, TX	83.0	80.9	83.4	83.4	Galveston, TX	130.7	117.0	124.9	127.0
Grand Isle, LA	107.5	106.0	108.8	106.3	Grand Isle, LA	171.2	159.7	168.7	167.6
Pensacola, FL	48.0	47.8	48.4	53.7	Pensacola, FL	83.9	70.1	78.2	75.2
Year 2050	**Mid**				**Year 2100**	**Mid**			
	A1FI	**B1**	**A1B**	**A2**		**A1FI**	**B1**	**A1B**	**A2**
Galveston, TX	88.9	86.7	88.7	88.8	Galveston, TX	146.0	129.5	137.1	140.8
Grand Isle, LA	113.6	111.8	114.2	111.8	Grand Isle, LA	185.3	171.4	180.2	181.3
Pensacola, FL	53.9	53.6	53.7	60.0	Pensacola, FL	99.2	82.6	90.3	89.3
Year 2050	**High**				**Year 2100**	**High**			
	A1FI	**B1**	**A1B**	**A2**		**A1FI**	**B1**	**A1B**	**A2**
Galveston, TX	94.8	92.5	93.9	94.3	Galveston, TX	161.3	142.0	149.3	154.5
Grand Isle, LA	119.6	117.6	119.6	117.3	Grand Isle, LA	199.6	183.1	191.7	195.1
Pensacola, FL	59.8	59.4	58.9	66.3	Pensacola, FL	114.5	95.0	102.5	103.5

Table 3. 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 seven GCM models for the A1FI emission scenario.

Model Parameters	**Scenarios**	**Louisiana-Texas Chenier Plain**	**Louisiana Deltaic Plain**	**Mississippi-Alabama Sound**
Tide Gauge		Galveston, TX	Grand Isle, LA	Pensacola, FL
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 1. Map of the study area, which extends from Mobile, AL, to Houston/Galveston, TX.

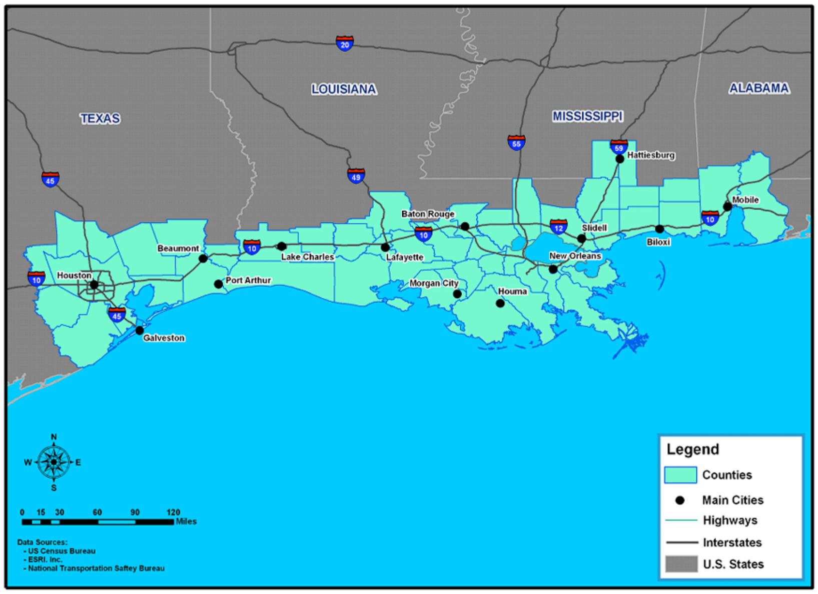


Figure 2. Relative elevation of counties in the study area (delineated in blue). All areas shown in bright orange are below 30–m elevation. (Source: U.S. Geological Survey)

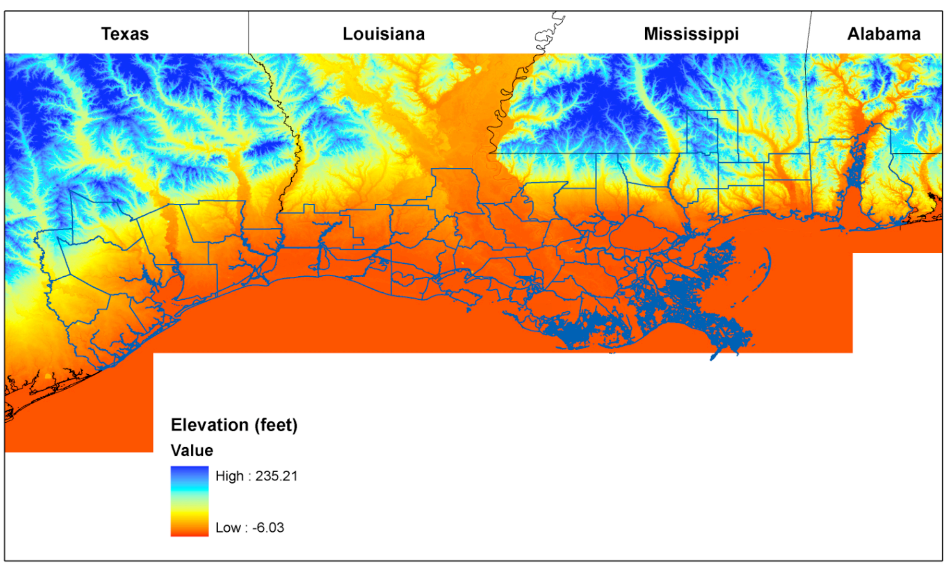


Figure 3. Temperature variability from 1905-2003 for the seven climate divisions making up the Gulf Coast study area. The level of significance in long-term temperature trend within each division was determined at α ≤0.05.

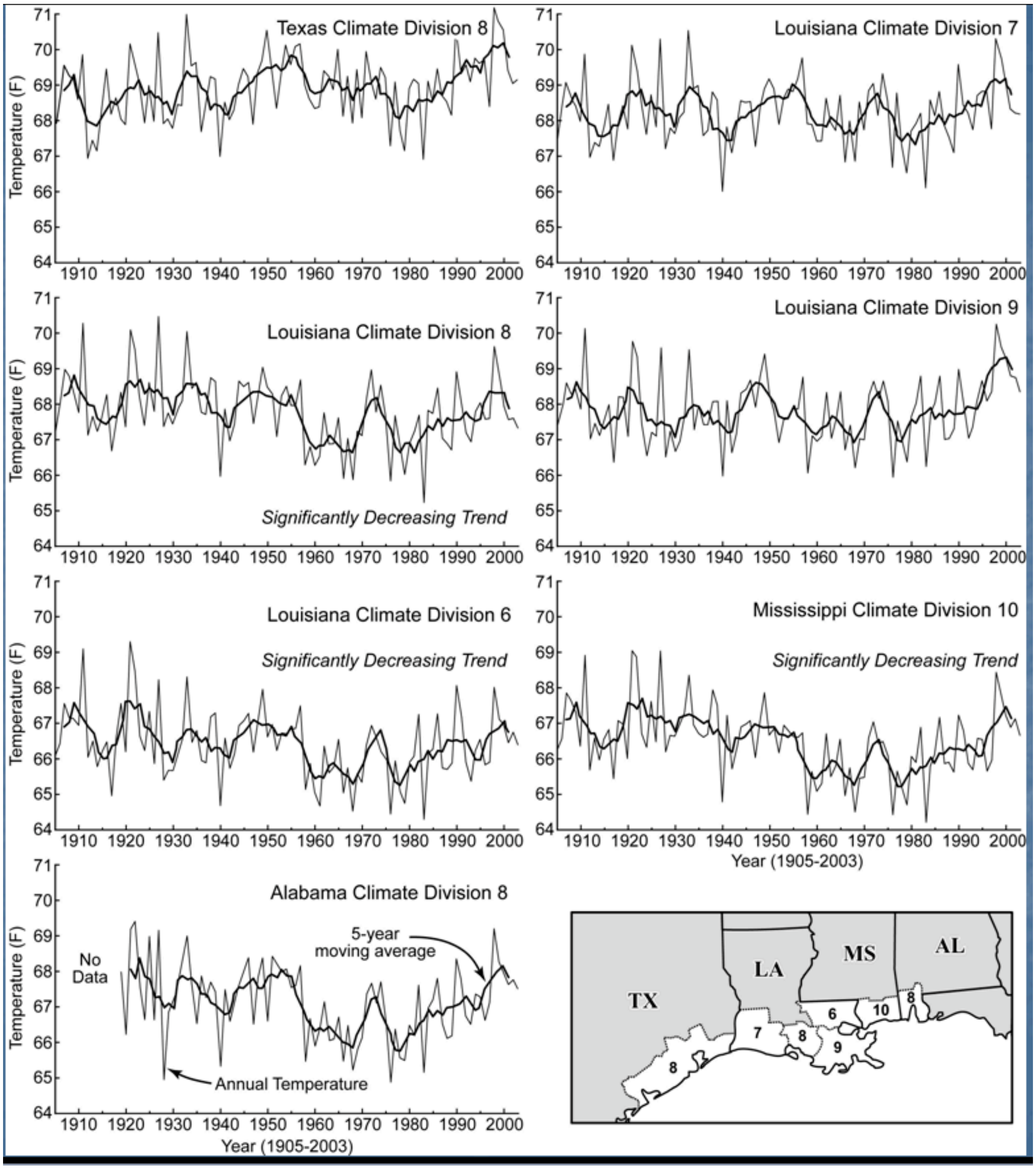


Figure 4. Precipitation variability from 1905 to 2003 for the seven climate divisions making up the Gulf Coast study area. The level of significance in long-term precipitation trend within each division was determined at α ≤0.05.

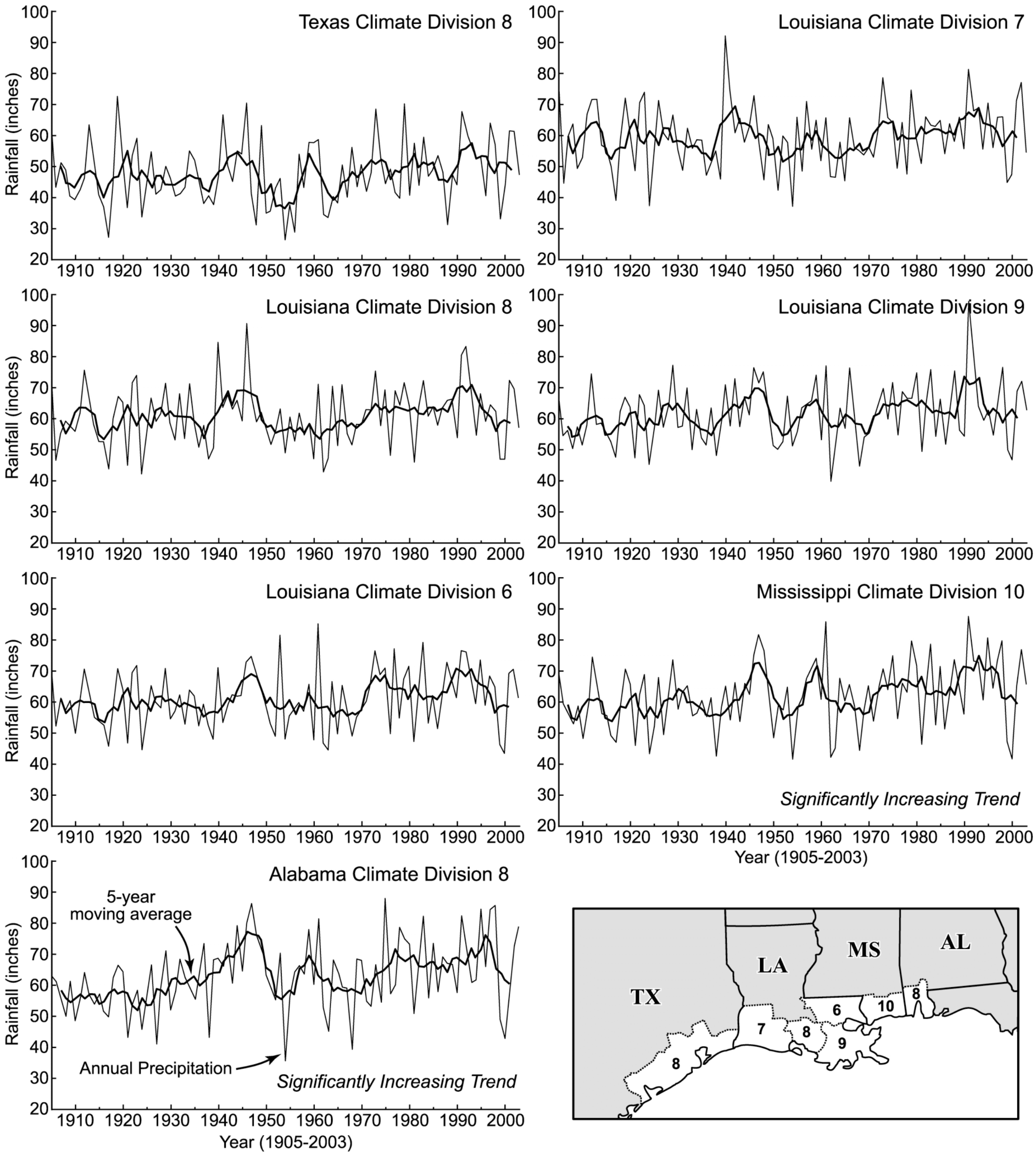


Figure 5. Variability and trends in model-derived surplus (runoff) and deficit from 1919 to 2003 for the Gulf Coast study area.

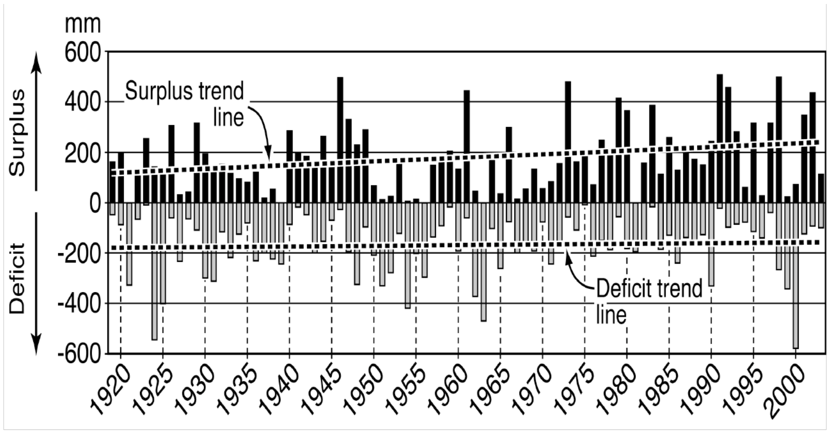


Figure 6. Sea surface temperature trend in the main hurricane development region of the North Atlantic during the past century. Red line shows the corresponding 5-yr running mean. Anomalies are departures from the 1971–2000 period monthly means.
(Source: Bell et al., 2007)

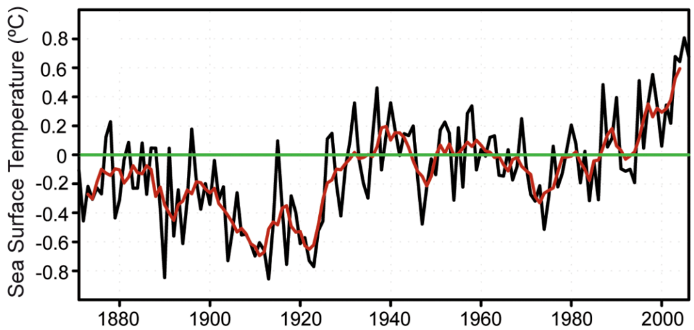


Figure 7. Sea surface temperature trends in the Gulf of Mexico region produced by using the ERSST v.2 database. The plot includes the SST anomalies averaged annually, as well as the anomalies determined from the averages for August only and the July-September peak of the hurricane season. (Source: Smith and Reynolds, 2004)

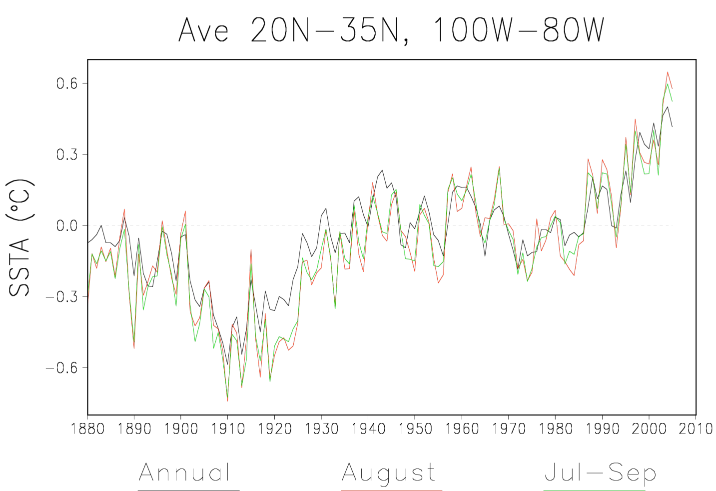


Figure 8. Tide gauge records and mean sea level trend line for three northern Gulf Coast tide stations at Pensacola, FL, Grand Isle, LA, and Galveston, TX, corresponding with the eastern, central, and western coverage of the study area. (NOAA tide gauges).

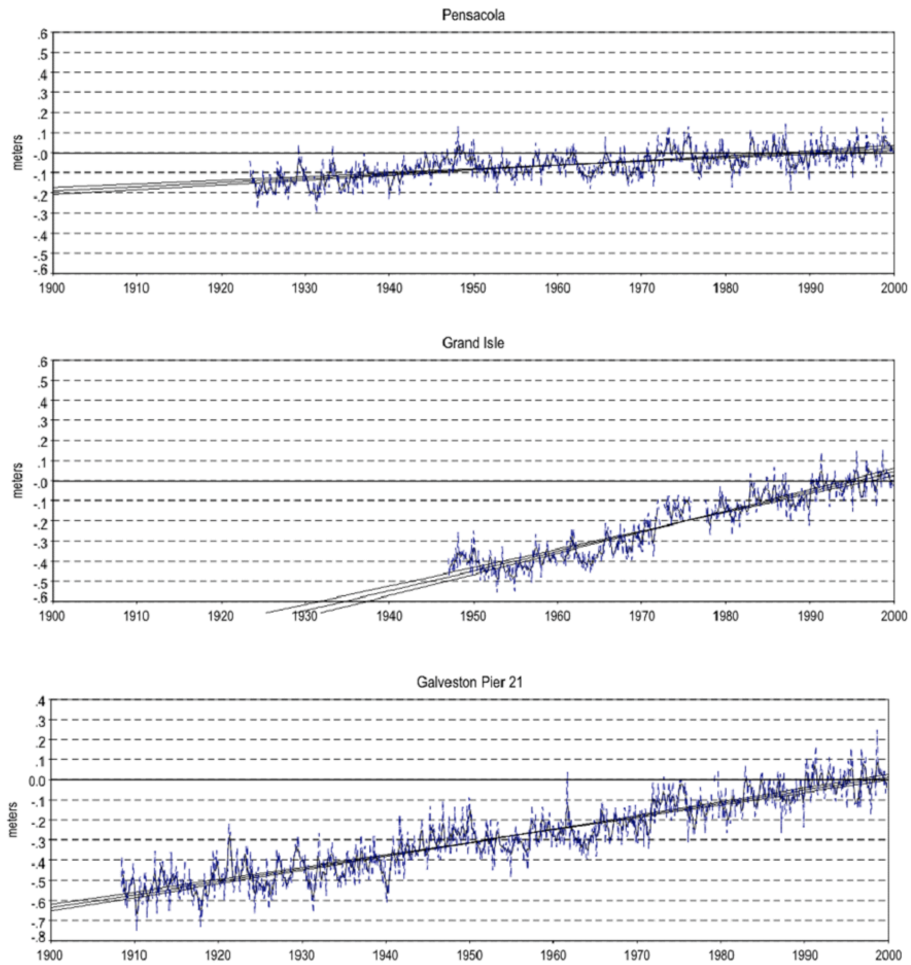
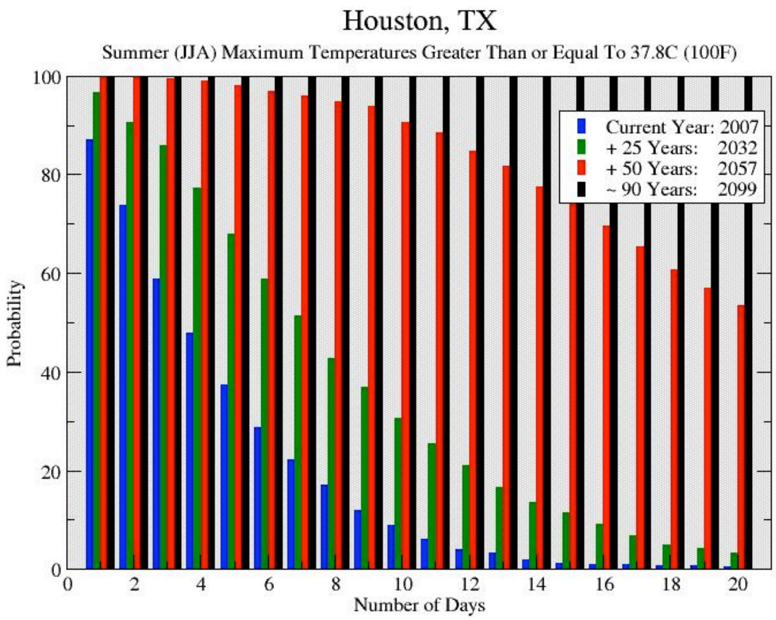


Figure 9. The current and future probabilities of having 1 to 20 days during the summer at or above 37.8 °C (100 °F) in or near Houston, TX, under the A2 emissions scenario.



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