TRANSPORTATION ASSET MANAGEMENT AND CLIMATE CHANGE: AN ADAPTIVE RISK-ORIENTED APPROACH

A Dissertation
Presented to
The Academic Faculty

by

John Patrick O'Har

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Civil and Environmental Engineering

Georgia Institute of Technology
August 2013

TRANSPORTATION ASSET MANAGEMENT AND CLIMATE CHANGE: AN ADAPTIVE RISK-ORIENTED APPROACH

Approved by:

Dr. Adjo Amekudzi, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Michael D. Meyer
Parsons Brinckerhoff, Inc.
Strategic Advisor

Dr. Kari Watkins
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Sue McNeil
Department of Civil and Environmental Engineering
University of Delaware

Dr. Catherine Ross
College of Architecture
Georgia Institute of Technology

Date Approved: May 3, 2013

DEDICATION

Para mi costilla

ACKNOWLEDGEMENTS

Although there is only one author of this document, completing a dissertation and a doctoral degree requires the hard work, guidance, and dedication of many individuals. The thorough leadership, advice, and wisdom of my advisor, Dr. Adjo Amekudzi, was indispensable in drafting this document. I would not be in the graduate transportation systems engineering program at Georgia Tech were it not for the inspiration and encouragement of Dr. Michael D. Meyer. I cannot thank these two individuals enough.

During my tenure here at Georgia Tech, the advice and knowledge of my fellow graduate students not only improved my research, but also made this process more enjoyable. In addition, the friendships I developed in graduate school will be invaluable both personally and professionally. Even though I least expected it, I met the most beautiful and amazing person here at Georgia Tech, my girlfriend Lucrecia Martinez. Without her patience, gentle encouragement, and support I would not have finished my degree. I must also thank my parents and my brother for their support.

The National Science Foundation funded this research under grant number DGE-0644493 and the Dwight David Eisenhower Transportation Fellowship Program provided travel support so that I could attend workshops and conferences. I would not have been able to conduct the case studies for this research effort without the cooperation and support of agency staff from MARTA, MPC, and GDOT. In particular, I would like to thank Mark Wilkes from MPC and Kevin Schwartz and Georgene Geary at GDOT.

I have many good memories at Georgia Tech after eight years and three degrees, but I am excited to start the next chapter in my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

Risk:	Effect of uncertainty on objectives
Uncertainty:	Inherent component of the decision-making process when choices are made based on incomplete knowledge
Criticality:	Relative importance of transportation infrastructure assets based upon user-defined criteria
Vulnerability:	Those transportation infrastructure assets that are identified as both highly-critical and susceptible to higher-risk climate change impacts

LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AOGCMs	Atmosphere-Ocean General Circulation Models
ASCE	American Society of Civil Engineers
CAT	Chatham Area Transit
CIP	Capital Improvement Planning
CSC	Coastal Services Center
CNG	Compressed Natural Gas
DOT	Department of Transportation
EMIC	Earth Model of Intermediate Complexity
ESCM	Earth System Climate Model
ESRI	Environmental Systems Research Institute
FHWA	Federal Highway Administration
GASB	Government Accounting Standards Board
GCM	Global Circulation Model
GIS	Geographic Information Systems
GDOT	Georgia Department of Transportation
GDP	Geo Data Portal
HVAC	Heating, Ventilation, and Air Conditioning
ICLEI	International Council on Local Governments for Sustainability
ISO	International Organization for Standardization
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991

LaDOTD	Louisiana Department of Transportation and Development
LRFD	Load and Resistance Factor Design
MAP-21	Moving Ahead for Progress in the 21st Century Act
MARTA	Metropolitan Atlanta Rapid Transit Authority
MPC	Chatham County – Savannah Metropolitan Planning Commission
MPO	Metropolitan Planning Organization
NCADAC	National Climate Assessment and Development Advisory Committee
NHS	National Highway System
NPCC	New York City Panel on Climate Change
NSTC	National Science and Technology Council
NOAA	National Oceanic and Atmospheric Administration
NBI	National Bridge Inventory
NCA	National Climate Assessment
SERAP	Southeast Regional Assessment Project
SGR	State of Good Repair
SLOSH	Sea, Lake, and Overland Surges Hurricanes Storm Surge Model
SRES	Special Report on Emissions Scenarios
STRAHNET	Strategic Highway Network
TAM	Transportation Asset Management
TAMP	Transportation Asset Management Plan
TIP	Transportation Improvement Program
TMA	Transportation Management Area

TRB	Transportation Research Board
USGCRP	United States Global Change Research Program

SUMMARY

Transportation Asset Management (TAM) systems are in use at many transportation agencies both in the United States and around the world. These asset management systems serve as strategic resource allocation frameworks and their degree of implementation and maturity varies. Climatic change, with its potentially adverse impacts on both the built and natural environments, has become of increasing concern around the globe. Given the uncertainties associated with changing climatic conditions, transportation agency stakeholders utilize risk-based decision-making approaches to identify climate change impacts that pose the greatest risk to transportation infrastructure assets. In conjunction with criticality assessments, emerging conceptual frameworks seek to identify higher-risk infrastructure assets, which are both critical to system operations and vulnerable to potential climate change impacts, through standalone study efforts.

This research develops a risk-oriented decision-making framework to identify vulnerable, higher-risk transportation infrastructure assets within the context of existing transportation asset management systems. The framework assesses the relative maturity of an agency's transportation asset management system and provides guidance as to how an agency's existing tools and processes can be used to incorporate climate change considerations. This risk-based decision-making framework is applied to three case studies: one at the Metropolitan Atlanta Rapid Transit Authority, another at the Metropolitan Planning Commission in Savannah – Chatham County, and a statewide case study at the Georgia Department of Transportation.

The results of this research demonstrate that readily-available climate projection data can be analyzed and displayed geospatially so that the potential impacts of climatic change on transportation infrastructure can be determined for specific geographic regions. In addition, existing roadway and bridge infrastructure datasets can also be displayed geospatially. The framework uses geospatially-referenced roadway and bridge asset data and multi-criteria decision analysis procedures to develop and visually display criticality scores. Overlaying climate projection data and criticality data helps identify higher-risk transportation infrastructure assets. This research demonstrates that climate change considerations can be effectively incorporated in existing decision-making processes at various levels of maturity of formal TAM systems, making this more broadly accessible to agencies and communities with potential climate hazards.

CHAPTER 1

INTRODUCTION

Climate change, and its potentially adverse impacts on both the built and natural environments, has become of increasing concern around the globe. The Intergovernmental Panel on Climate Change (IPCC), which is comprised of prominent climate scientists from around the globe, confirmed that both temperature and sea levels are expected to increase to unprecedented levels through the end of this century (Solomon et al. 2007). Recent research has suggested that the assumptions in the 2007 IPCC report were in fact too conservative, and that climate change is happening more rapidly than thought (Tin 2008). Thus far the transportation community's response to climate change has consisted of two main strategies: mitigation of greenhouse gases (GHGs) through reductions in emissions, of which the transportation sector is a large contributor (EPA 2010), and adaptation to the impacts of climate change.

With respect to climate change adaptation, it is understood that even if we were to drastically reduce our GHG emissions today, climate change and its impacts will still continue decades into the future (TRB 2008). Thus, transportation agencies will play an important role in the adaptation of transportation infrastructure to potential climate change impacts. This research focuses on how transportation asset management systems, already in place at many agencies, could provide a strategic platform for incorporating climate change considerations into the transportation investment decision-making process, and how risk-oriented methods can be used to assess the relative importance of adaptation strategies.

Because transportation agencies have limited resources and the potential impacts of climate change will be varied and uncertain, a risk-oriented approach towards adapting transportation infrastructure is prudent. A risk-oriented approach allows agencies to identify the most critical transportation infrastructure assets that are also the most vulnerable to the potential impacts of climate change. However, risk-oriented decision making is a term that is now used by managers in a variety of organizations and it is often unclear what a decision maker means when he or she states that risk-oriented decision making is an integral part of the management process (Haimes 2004).

It is one thing to say that risk-oriented decision making is part of an organization's business process, but another to specify how exactly risk is a factor in everyday decision making. This dissertation examines how existing Transportation Asset Management (TAM) systems can incorporate a risk-oriented approach to climate change adaptation and presents three case studies that demonstrate this conceptual model. In particular, these three case studies show the scalability and flexibility of this conceptual model; one case study is at the local transit agency level with the Metropolitan Atlanta Rapid Transit Authority (MARTA), another is at the regional level with Savannah's Metropolitan Planning Commission (MPC), and the third is at the statewide level with the Georgia Department of Transportation (GDOT).

Formal TAM systems are already in use at a significant number of transportation agencies, especially in larger agencies, such as state Departments of Transportation (DOTs). A recent National Cooperative Highway Research Program (NCHRP) Synthesis Report surveyed 43 state DOTs in regards to their TAM systems. This survey revealed that 60% of the respondents have an agency asset management group or task force that coordinates all TAM activities (Hawkins and Smadi 2013). These TAM systems provide a cost-effective platform to incorporate climate change considerations. However, these agencies are at various stages of implementing TAM systems. An international transportation asset management scan tour revealed that some agencies outside the U.S. have particularly advanced TAM systems (Geiger et al. 2005). A 2006 scan tour in the United States, also on TAM systems, highlighted several state and local level agencies that were at various stages of implementation. The scan tour report identified best practices in TAM as found in the United States (Cambridge Systematics and Meyer 2007). Although much of the literature focuses on formal TAM systems, this research is applicable to the framework of TAM concepts.

Additionally, the use of the term “risk” as it relates to transportation infrastructure is not uniform and perhaps the most common use refers to the risk of failure of a transportation asset. However, such a use of risk of failure is not defined consistently given that performance measures for transportation infrastructure condition are often not standardized (Aktan et al. 2007). Also, catastrophic and non-catastrophic, i.e. level of service, failures tend to be treated differently. For this reason, the approach used in this research is termed “risk-oriented” since it is both a qualitative and quantitative process. Ultimately, this research develops a flexible, scalable conceptual model that can be used to identify the most critical transportation infrastructure assets that are also the most vulnerable to climate change impacts, allowing agencies to strategically target investments.

1.1 Research Objectives

Very little research has occurred on how to incorporate climate change-related risk into the transportation decision-making process and on how to incorporate risk assessment and risk management into transportation asset management systems. Given that most large transportation agencies, e.g. state DOTs, already have asset management systems in place, they could serve as a cost effective, strategic platform to incorporate climate change considerations. However, given the uncertainties associated with changing climatic conditions, it is essential to adopt a risk-oriented approach to the transportation investment decision-making process.

This research seeks to develop a risk-oriented decision-support framework to identify infrastructure assets that are vulnerable to potential climate change impacts within the context of existing transportation asset management systems. More specifically, the goals of this research are:

1. Review the state of practice as it relates to transportation-related climate change adaptation in the context of asset management systems,
2. Develop a risk-oriented methodology that utilizes existing transportation asset management systems to identify the most critical transportation infrastructure assets that are also the most vulnerable to potential climate change impacts,
3. Apply this methodology to case study agencies at the local, metropolitan and statewide level, and
4. Demonstrate the value of this methodology to stakeholders by strategically identifying transportation infrastructure assets that should be targeted for investment.

As described above, the methodology utilizes existing transportation asset management systems and thus existing agency resources. Therefore, the case studies are limited by the availability and quality of existing agency data. Furthermore, existing climate change projection data are utilized to develop climate projections. Over time, as the scientific community improves its understanding of climate change modeling, the selected agencies should continue to update their adaptation frameworks to account for newer climate projections.

The three agencies selected for case studies are at the local, regional, and state levels. Atlanta's Metropolitan Rapid Transit Authority (MARTA) was selected as a case study, which provides valuable insight into climate change adaptation within asset management systems at a transit agency. The Savannah, Georgia region's MPO, the Metropolitan Planning Commission (MPC), was selected for a second case study. In particular, this case study illustrates climate change considerations at the regional level in a coastal area. The Georgia Department of Transportation (GDOT) was selected for the final case study, which demonstrates how an existing asset management system can be used to account for climate change considerations at the statewide level.

Results of this research provide transportation decision makers with a risk appraisal framework that can be used within existing TAM systems to account for the potential impacts of climate change. The methodology developed through this research is flexible and scalable so that it is applicable to a variety of agencies and a variety of climate change impacts. Given that each agency faces unique challenges, stakeholder involvement is an important component of this methodology. The results of this research demonstrate how an agency can leverage existing resources to target specific transportation infrastructure assets for investment.

1.2 Dissertation Organization

This dissertation is organized in the following manner. Chapter 2 provides a literature review that summarizes TAM systems, discusses transportation and climate change, reviews how TAM systems can incorporate climate change considerations, and presents a basic overview of the concept of risk, risk assessment, and risk management. It then provides specific examples of risk applications in TAM systems and also specific examples of risk applications related to climate change adaptation that utilize existing TAM systems. Chapter 3 gives an overview of current climate change modeling, discusses climate change projections, and discusses transportation infrastructure data required for climate change adaptation. Chapter 4 details the methodology used in the three case studies and Chapter 5 describes the analysis performed in each case study. Chapter 6 presents the results of the analysis for each of the three case studies. Lastly, Chapter 7 provides conclusions and recommendations, identifies limitations of this research, and suggests areas for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Transportation Asset Management Systems – A Historical Context

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), among other things, placed emphasis on the management of existing infrastructure as opposed to the construction of new facilities. ISTEA required state transportation agencies to have six infrastructure management systems for road pavement, bridges, safety, congestion, public transportation, and intermodal facilities (Cambridge Systematics and Meyer 2007). Congress, however, did not provide funding to the states to establish these infrastructure management systems and this mandate was repealed in 1995 after state DOTs argued that the infrastructure management systems represented unfunded mandates. However, in many cases, states had developed infrastructure management systems prior to ISTEA, such as pavement and bridge management systems, and continued to use them. In the case of congestion management systems, such systems were still required for transportation management areas, defined as metropolitan areas over with 200,000 population (this approach is now called the congestion management process.)

In July of 2012 Congress enacted, and President Obama signed into law, the Moving Ahead for Progress in the 21st Century Act (MAP-21). This piece of legislation mandates a performance-based program for planning and programming. The most significant component of this legislation is the development of a performance management program, which establishes national goals and is outcome-based. One of these national goals seeks to maintain the Nation’s highway infrastructure system in a state of good repair. The Secretary of Transportation, in consultation with numerous stakeholders, will establish performance measures. States and MPOs will set performance targets associated with these performance measures, and states and MPOs must demonstrate how program and project selection will achieve these performance targets. In addition, MAP-21 requires States to develop a risk and performance-based asset management plan for the National Highway System (NHS) that improves or preserves asset condition; this plan must be reviewed and recertified at least every four years (FHWA 2012).

One of the distinguishing characteristics in the evolution of transportation asset management in the U.S. has been the use of conferences and workshops to develop and disseminate information on its application. A timeline of major conferences and workshops in the evolution of transportation asset management includes (two non-conference events are also included in the timeline because of their importance to the development of TAM):

- 1996: AASHTO and the FHWA co-sponsor a workshop in Washington D.C. entitled "Advancing the State of the Art into the 21st Century Through Public-Private Dialogue". The workshop included representatives from Chrysler, Wal-Mart, GTE Conrail, and a number of public utilities. The underlying theme of the workshop was that principles and tools of good asset management in private organizations could also apply to public organizations (USDOT and FHWA 1996).

- 1997: A workshop is held at the Center for Infrastructure and Transportation Studies at Rensselaer Polytechnic Institute further examining the practices, processes, and tools of asset management as they apply to state DOTs (AASHTO 1997).
- 1998: Federal Highway Administration (FHWA) creates the Office of Asset Management (USDOT 1999).
- 1999: A national conference is held in Scottsdale, Arizona that serves as a peer exchange for state DOTs (Cambridge Systematics 2002).
- 1999: The Government Accounting Standards Board (GASB) issues Statement No. 34. GASB 34 requires government agencies to report capital assets using a historical cost, a depreciation approach, or a modified approach for reporting on infrastructure assets. The modified approach requires government agencies to use some sort of asset management process (PB Consult Inc. et al. 2004).
- 2001: A national conference is held in Madison, Wisconsin with a theme of “Taking the Next Step” (Cambridge Systematics 2002).
- 2003: National conferences are held in Atlanta and Seattle with the theme “Moving from Theory to Practice” (Wittwer et al. 2003).
- 2005: A national conference is held in Kansas City with the theme “Making Asset Management Work in Your Organization” (Zimmerman and Sweet 2005).

- 2007: A national conference on transportation asset management is held in New Orleans with the theme “New Directions in Asset Management and Economic Analysis” (TRB 2007).
- 2009: A national conference on Transportation Asset Management is held in Portland with the theme “Putting the Asset Management Pieces Together” (TRB 2009).

These conferences and workshops occurred in parallel with an evolving literature on transportation applications in asset management that laid the foundation for today’s state of practice. For example, the Federal Highway Administration (FHWA), American Association of State Highway and Transportation Officials (AASHTO), Transportation Research Board (TRB) of the National Academies, and consultants from private industry have published various primers, reports, scans, and case studies regarding TAM (see USDOT and FHWA 1996; USDOT 1999; Cambridge Systematics 2002; Wittwer et al. 2003; PB Consult Inc. et al. 2004; Cambridge Systematics, et al. 2005; Geiger et al. 2005; Zimmerman and Sweet 2005; Cambridge Systematics et al. 2006; USDOT 2007; Cambridge Systematics and Meyer 2007; Cambridge Systematics et al. 2009; AASHTO 2011).

2.2 Transportation Asset Management Systems- System Components

The term “asset management” means different things to different organizations, many of which undertake efforts that are really asset management, but may not refer to these efforts as such. The AASHTO Subcommittee on Asset Management developed the following definition of asset management (AASHTO 2006):

> "…a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well defined objectives."

Of importance to this thesis, NCHRP Report 551 identified the following core principles of a TAM system: policy-driven, performance-based, analysis of options and tradeoffs, decisions based on quality information, and monitoring to provide clear accountability and feedback (Cambridge Systematics et al. 2006).

For purposes of this dissertation, the AASHTO definition of a transportation asset management system (AASHTO 2006) is used as a common point of departure. TAM systems are already in use in a large number of transportation agencies, especially in larger agencies, such as state DOTs. Most scans or other investigations of TAM systems show that implementation varies from one organization to another. Several international agencies, for example, have TAM systems that are quite advanced (Geiger et al. 2005). Others are just beginning to understand how agency decisions could be informed by such a system. This being the case, not all agencies use the term asset management, and similarly there is no single asset management system or framework that has been adopted uniformly. However, the FHWA has attempted to identify key steps or elements in a transportation asset management process, including: goals and policies, asset inventory, condition assessment and performance monitoring, alternatives analysis and program optimization, short and long range plans, program implementation, and performance monitoring . (See Figure 1, which shows the generic components of an asset management system.)

Some agencies enumerate specific goals and policies for their asset management systems before developing elements of a TAM system, while other agencies may develop certain elements of a TAM system before defining goals and policies. TAM best practice includes clearly defined goals and policies that can be translated into specific performance measures and targets, which depends upon the resources available to an agency (Cambridge Systematics 2002).

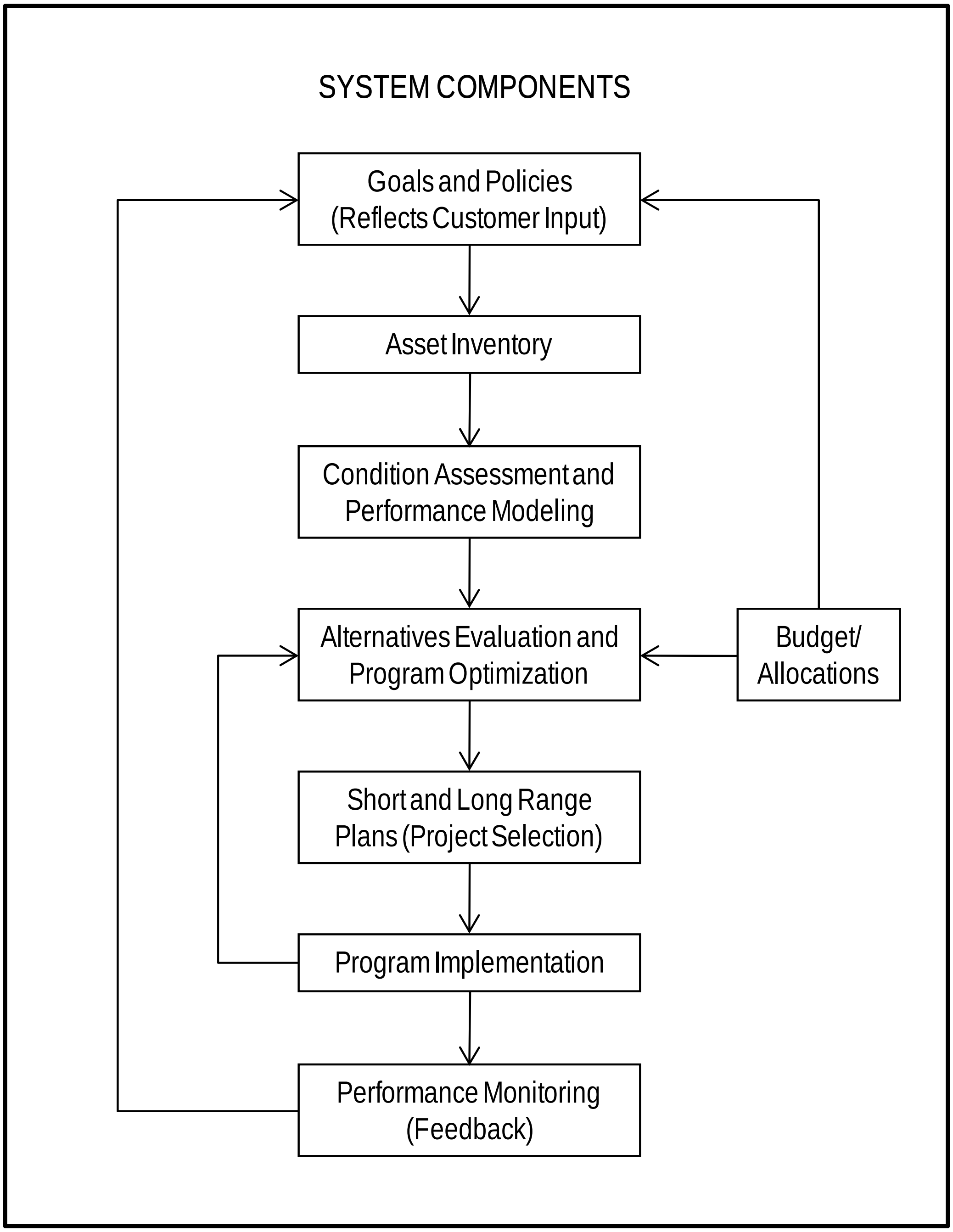


Figure 1. System components of a generic asset management system (USDOT 1999)

AASHTO's *Transportation Asset Management Guide* (Cambridge Systematics 2002) was produced after the FHWA Asset Management Primer (USDOT 1999) was developed, and looked to build upon previous work. The AASHTO Guide also presented the basic elements of an example resource allocation and utilization process in a TAM system as shown in Figure 2. Although similar to the FHWA process, the AASHTO framework is intentionally broader, incorporating fewer elements. This is to serve the needs of different agencies better, so that agencies do not feel the need to overhaul every aspect of their TAM systems (Cambridge Systematics et al. 2006). Nonetheless, the basic elements of the FHWA process are also captured in the AASHTO process.

An updated and accurate inventory of assets is an essential component of an effective TAM system. Inventory data may contain a variety of data related to a specific asset and will likely vary depending upon the class of the asset, i.e., roads versus bridges. An important component of an asset inventory system is the location referencing system used. Agencies have used Geographic Information Systems (GIS), Global Positioning Systems (GPS), or imaging technologies as part of their inventory system process. Ideally, an asset inventory should be updated on a regular basis, so that it can provide information on changing conditions for both newer and older assets.

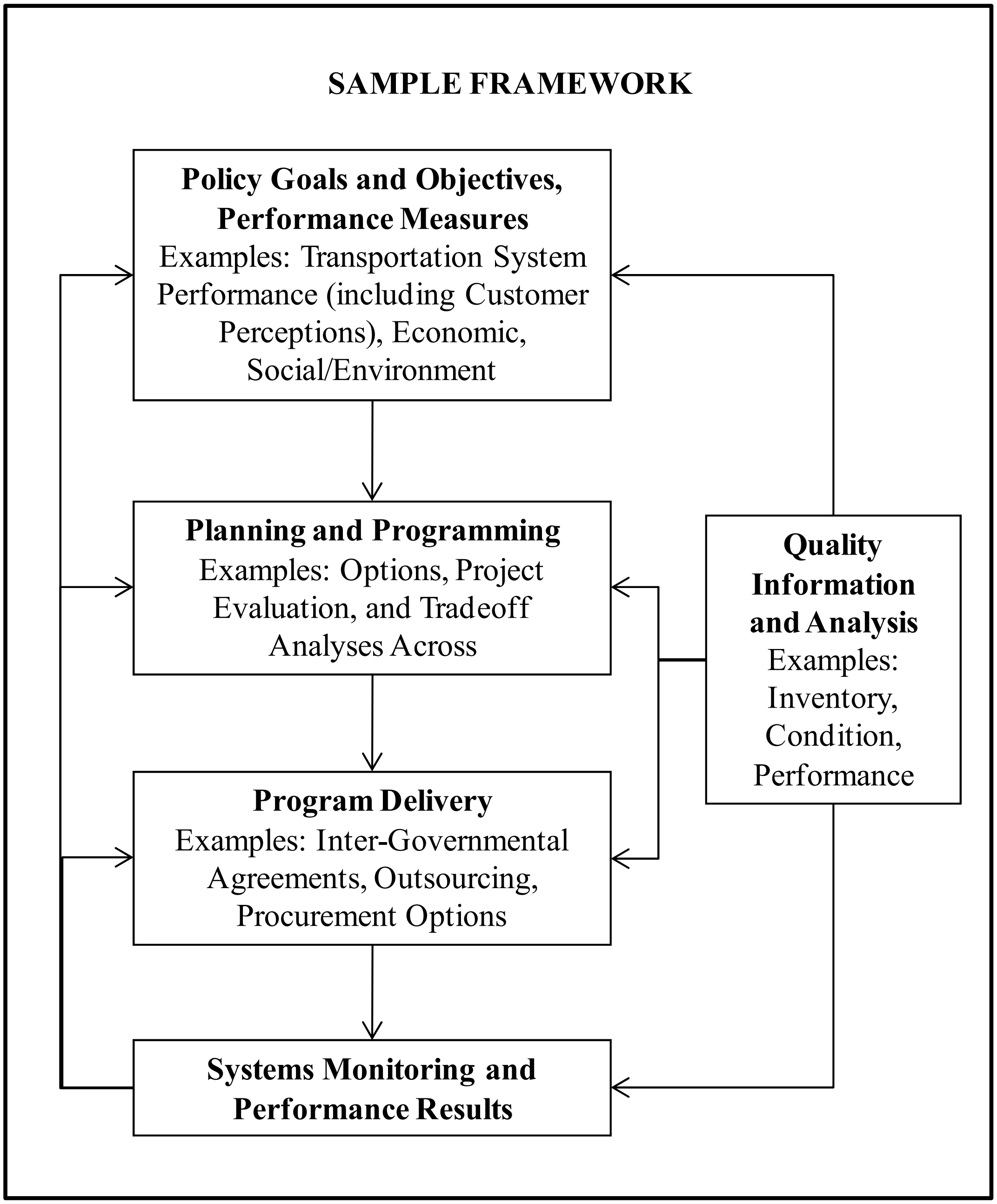


Figure 2. Sample resource allocation and utilization process in transportation asset management (Cambridge Systematics 2002)

Condition assessment is another critical component of an effective asset management system. Not only is it important for transportation agencies to maintain data on current asset condition, it is also critical to monitor trends in asset condition so as to identify how the transportation system is faring over time.

Performance modeling is a tool that allows transportation agencies to predict the future condition of assets. Oftentimes performance models depend upon the use of historic condition data to predict future asset condition. Many transportation agencies set a minimum defined condition level for their assets. For example, on a pavement condition scale of 0 to 100 an agency may set 85 as the minimally acceptable condition for interstate highways. In many instances, the level of funding directly impacts the condition of infrastructure assets.

Most TAM systems include some means of alternatives analysis and program optimization. Often an agency will develop a set of alternatives that meets its objectives given resource constraints. Program optimization can be used to identify the optimal set of alternatives that meet specified agency goals and objectives. However, there is not always an optimal alternative and as such, a decision maker selects one alternative based on his or her values and preferences. Sometimes agencies will evaluate various plans, programs, or project alternatives to assess tradeoffs involved in selecting one option over another. This implies that TAM systems should have procedures or processes for determining the relative value of one investment strategy versus another.

TAM systems are also significant components of many transportation organizations' short and long range plans in that TAM systems are used to both monitor current infrastructure asset condition and predict future asset condition. As part of their long-range planning efforts, several agencies with more advanced TAM systems have conducted scenario analysis to determine the effects of different funding levels on asset condition (Cambridge Systematics and Meyer 2007).

Plans lead to programs, documents that lay out the budget allocation and schedule of investment over time. Programs can focus on a range of investment categories such as regular maintenance, major rehabilitation or reconstruction. Programs perhaps are the most important part of a TAM in that this is where the ultimate decisions are made concerning where investment will be applied. Programs reflect an agency's priorities and overall strategy for keeping the transportation system in good condition and properly functioning.

Performance monitoring ensures that the asset management system is being provided some indication of whether the state of the transportation system is changing, and if so, in what direction. This is an important component of any TAM process as it ultimately relates to whether a transportation agency is meeting its stated goals and policies (assuming that transportation agency actions directly cause changes in performance). In order to ascertain the level of performance of transportation infrastructure, an agency needs to develop adequate performance measures.

2.3 Transit Asset Management

MAP-21also brings significant changes to public transportation provisions. Among other new requirements, MAP-21 requires the FTA to develop safety performance criteria for all modes of public transportation. The new State of Good Repair (SGR) program is a grant program that maintains public transportation systems in a state of good repair; to qualify for SGR funds projects must be contained in transit asset management plans. MAP-21 requires the FTA to define "state of good repair" and then based upon that definition, determine performance measures for grant recipients. Transit asset management plans must contain capital asset inventories, condition assessments, and investment prioritization. Additionally, recipients of FTA formula funds must report on asset condition and monitor and update changes in asset condition. Furthermore, reporting on performances and targets is required in metropolitan and statewide transportation plans, and also in transportation improvement programs (FTA 2012a).

To better facilitate efforts by transit agencies to develop transit asset management plans, the FTA released an *Asset Management Guide* (Rose, Isaac, and Blake 2013; Rose, Isaac, Shah, et al. 2013). A 2010 state of good repair assessment by the FTA determined that over 40 percent of bus assets and over 25 percent of rail assets were in marginal or poor condition. This assessment also found a SGR backlog of nearly $80 billion (FTA 2010). The Asset Management Guide aids transit system managers in the development and implementation of asset management frameworks for managing both individual assets and a portfolio of assets. In order to accomplish this the guide emphasizes the following areas (Rose, Isaac, Shah, et al. 2013):

- Explains asset management and its benefits to an agency
- Details best practice enterprise asset management frameworks and business models
- Lists the components of an asset management plan
- Describes the critical components of asset management for each asset class
- Provides organizations with a benchmark of current asset management practice and encourages movement towards advanced asset management

In addition, the guide provides lessons learned and examples of asset management implementation at several agencies (Rose, Isaac, Shah, et al. 2013).

2.4 Transportation and Climate Change Adaptation

As mentioned earlier, climate change has become of increasing concern around the globe (Solomon et al. 2007). GHG emissions from anthropogenic sources are widely recognized by the scientific community as the primary cause of global climate change. The transportation sector in the United States accounts for 29% of total U.S. GHG emissions and over 5% of global GHG emissions. These emissions estimates only account for vehicle tailpipe emissions, but if other transportation lifecycle processes such as vehicle manufacturing, extraction and refining of fuels, and construction of transportation infrastructure are also considered, U.S. transportation accounts for approximately 8% of global GHG emissions (EPA 2010). Given the significant contribution the U.S. transportation sector makes not only to U.S. GHG emissions but also to global GHG emissions, strategies to reduce GHG emissions, i.e. mitigation efforts, will undoubtedly be essential components of the transportation community's response to climate change. However, even if GHG emissions were significantly reduced today, the impacts of climate change would continue decades into the future (TRB 2008). This highlights the need for adaptation strategies.

The evidence supporting climate science and the anthropogenic influence on future climatic conditions is strong. A National Research Council pamphlet adequately summarizes the basic tenets underlying modern climate science (Huddleston 2012). It is beyond the scope of this dissertation to describe climate change science in detail, but in summary, scientists have concluded with greater than 90% certainty that the majority of the observed global warming trend of the past 50 to 60 years is due to anthropogenic emissions and other human activities. Furthermore, although there is uncertainty about climate change, further research cannot eliminate this uncertainty, which should not serve as a justification for inaction. There are simple steps society can take to protect its existing transportation infrastructure assets and future assets against both climate change and extreme weather (Huddleston 2012). A recent Transportation Research Circular further reiterates the scientific consensus on climate change and the important role the transportation sector plays in both mitigating and adapting to the impacts of climate change (Burbank et al. 2012).

The 1990 Global Change Research Act requires that the National Science and Technology Council (NSTC) reports to the President and Congress periodically on current scientific findings about the observed and projected impacts of climate change on the United States. Over 240 experts authored the 2013 National Climate Assessment under the oversight of the 60-member National Climate Assessment and Development Advisory Committee (NCADAC). This report draws on peer-reviewed scientific publications, and in addition to discussion of impacts on the U.S., the two primary responses to climate change impacts, mitigation and adaptation, are also discussed. Furthermore, authors of the report utilized risk-based framing, where risk is defined as likelihood and consequence, to identify key vulnerabilities for decision makers (NCADAC 2013).

Much like in the military and business worlds, scenario planning is commonplace in climate change science; emissions scenarios represent plausible future outcomes. The 2013 National Climate Assessment relies on two emissions scenarios from the Special

Report on Emissions Scenarios (SRES), the A2, which is a higher emissions scenario, and B1, which is a lower emission scenario. Although the fifth iteration of the Intergovernmental Panel on Climate Change (IPCC) assessment report relies on a new set of scenarios known as Representative Concentration Pathways (RCPs), new models are currently under development utilizing these new RCPs (NCADAC 2013). For this reason, which is discussed further in Chapter 3, this research also relies on SRES emissions scenarios.

2.4.1 Potential Climate Change Impacts on U.S. Transportation Infrastructure

The climate is changing in the United States and there is considerable scientific evidence to support this. A warming trend is clear and the frequency of extreme weather events is increasing, which is consistent with model predictions. In addition, over the last century, sea level rose approximately 8 inches after relatively little change over the previous two thousand years. Within this century, sea level is expected rise one to four feet. This has significant implications for coastal communities and infrastructure (NCADAC 2013). Much like other sectors of the U.S. economy, climate change will impact the transportation sector. The following impacts are decreasing the reliability and capacity of the U.S. transportation system:

- Sea level rise and storm surge
- Extreme weather events
- Higher temperatures and heat waves
- Precipitation changes
- Arctic warming

In particular, coastal transportation infrastructure is especially vulnerable to the combined impacts of sea level rise and storm surge, including the inundation of ports and harbors, roads, rail lines, tunnels, and bridges. Extreme weather continues to disrupt the normal provision of transportation infrastructure and these extreme events are projected to increase. Although climate change impacts will increase transportation system user costs, these costs can be mitigated by adaptive actions; transportation asset management systems are identified in this report as tools that can be used in adaptive actions identified in this report (H. G. Schwartz et al. 2013).

Climate change can lead to a number of climatic and weather phenomena that have the potential to impact transportation infrastructure. Some of the predicted impacts of climate change are expected to occur over such lengthy time horizons, i.e., 100 years, that they would not be of particular interest to infrastructure system managers when considering certain classes of infrastructure assets, roadway pavements, for example. However, for infrastructure assets with a long design life, such as bridges, these climate change phenomena could provide significantly different environmental conditions in the future than what is experienced today. Although the potential impacts of climate change are varied, many will impact transportation infrastructure assets and as such will be of interest to transportation officials. Increases in storm frequency and intensity may increase the risk of flooding in certain areas. In coastal and low-lying communities, sea level rise and storm surge pose a significant risk. Increased temperatures can negatively impact concrete and asphalt roadways by causing premature cracking and buckling. These are several examples from many possible climatic changes. Table 1 gives a more comprehensive list of climate change impacts and potential adaptation strategies.

Table 1. Climate Change Impacts and Adaptation Strategies (Adapted from Meyer et al. 2010)

Impact Category	Adaptation Strategies
Precipitation: accelerated asset deterioration	Conduct early vulnerability assessments Give greater weight to potential for ground subsidence in design of infrastructure Accelerate replacement cycles Shift to materials with greater resistance to moisture and heat/cold cycles Incorporate design features such as increased pavement sloping to improve resistance to precipitation
Precipitation and sea level rise: Increased incidence of flooding events	Re-site or floodproof infrastructure Provide greater protections and construction limitations for floodplains and coastal areas.
Precipitation: Water scarcity and loss of winter snowpack	Shift to less water-intensive construction methods Shift ROW plantings to drought-resistant species and designs that reduce runoff
Precipitation: Increased incidence of wildfires	Incorporate vulnerability assessments in infrastructure location decisions Use of fire-resistant construction materials and landscaping
Precipitation: Shift in ranges of endangered species	Keep abreast of ecological studies on a regional basis to detect observed shifts in habitat
Temperature: Arctic asset and foundation deterioration	Install insulation or cooling systems in roadbeds to prevent thawing Relocate facilities to more stable ground Remove permafrost before construction for new facilities
Temperature: Increase in the frequency and severity of heat events	Plan for more frequent maintenance Use heat-resistant roadway materials Make greater use of expansion joints in roadways, bridges, and rail guideways.
Temperature: Reduction in frequency of severe cold	Capitalize through the extension of construction and maintenance season
Sea level rise: Inundation of infrastructure	Relocate assets Develop redundancy in travel routes near the shoreline Disinvest in infrastructure too costly to protect Elevate or hardscape the most critical infrastructure Expand drainage and pumping capacity
Sea level rise: Storm surges	Use protective designs Relocate facilities
More intense weather events: Damage to assets	Retrofit assets early for greater resistance to extreme weather Incorporate storm resistant features into future designs Minimize water-impervious surfaces in designs and design infrastructure to slow run-off from heavy rain events
More intense weather events: Increased frequency of road traffic disruption, including interruption of emergency routes	Use more stringent design, operations standards Develop redundancy in travel routes near the shoreline Elevate or hardscape the most critical infrastructure Create Transportation Management Centers, improve monitoring of conditions and real-time information made available to the public Place greater emphasis on emergency evacuation procedures, making them routine

Different classes of infrastructure assets may be affected over the long term by changes in climate and over the short term by changes in weather. Many transportation agencies are already well-versed in managing the impacts of short-term extreme weather events. However, over time these extreme weather events today may well become a normal occurrence in the future. Additionally, over the long term, infrastructure assets may experience accelerated deterioration as a result of changes in climate. Sea level rise may inundate low-lying transportation facilities such as ports, coastal roadways, tunnels, and underground metro systems. Increased intensity of storms, such as hurricanes, can result in stronger winds and greater storm surges, which could be exacerbated by rising sea levels. High temperatures can soften asphalt pavements, leading to rutting, buckling, and subsidence; high temperatures can also cause sagging in overhead catenary wires and soften railways, leading to buckling and decreased operational speeds and capacity.

2.4.2 Climate Change Adaptation Efforts in Transportation Organizations

A Transportation Research Board circular, sponsored by the TRB Special Task Force on Climate Change and Energy, focused on the state of practice in adapting transportation to the impacts of climate change (Wegner et al. 2011). This circular reiterates the need for adaptation activities related to transportation infrastructure and briefly describes summaries from TRB Special Report 290 (TRB 2008). However, the majority of this circular contains articles highlighting climate change adaptation at the federal and state levels in the U.S. and in the United Kingdom at various levels of government. One article discusses the FHWA’s climate change adaptation activities (Wegner et al. 2011); the FHWA-sponsored adaptation pilot studies are highlighted later in Section 2.10.

Another article describes UK requirements for addressing climate change with an emphasis on coordination amongst numerous sectors. One article discusses adaptation strategies implemented by several states in the U.S. and another article focuses on the specific adaptation challenges airport operators face. The final article emphasizes the need for cooperation among and between transportation planners and operators at all levels of government and also with weather forecasters and emergency planners. Lastly, the circular concludes with research needs and opportunities drafted by the TRB Special Task Force on Climate Change and Energy (Wegner et al. 2011).

A workshop sponsored by the Center for Clean Air Policy (CCAP) and the Environmental and Energy Study Institute (EESI) held in November of 2011 specifically focused on climate change adaptation and transportation (Winkelman et al. 2012). Transportation infrastructure managers across the country see the importance of effectively managing and adapting to climatic changes and extremer weather events, which set records in terms of economic damage in 2011. This workshop focused specifically on what kinds of information and assistance transportation professionals need from the climate science community to more effectively adapt to climatic changes and extreme weather. Key takeaways from this workshop are that understanding local conditions and context is crucial; and infrastructure operators and service providers can identify vulnerabilities, interactions, and interdependencies in the transportation network. There is also a need for improved communication between the climate science community and transportation professionals. Existing climate models can provide sufficient information to inform transportation decision making. However, transportation professionals require additional guidance in terms of how management systems, and asset management systems in particular, can incorporate climate change impacts. Additionally, there is need for education and outreach regarding climate change adaptation actions; several agencies have already taken common sense steps to adapt their infrastructure networks (Winkelman et al. 2012).

Rail operators in the United Kingdom (UK) have already experienced the impacts of high heat on railways and the UK's National Health Service released a *Heatwave Plan for England* that specifically discusses impacts on transportation infrastructure and railway infrastructure in particular (Department of Health 2011). Thawing permafrost is already resulting in challenges related to roadway maintenance and design in Alaska. Areas that can expect increased frequencies of freeze/thaw cycles could also face significant transportation infrastructure design challenges. Precipitation patterns could change, which could affect network and facility operations, e.g. more frequent flooding, wetter soil and subsurface conditions, and earlier snowpack melting. Beyond direct impacts on transportation infrastructure, changing climatic conditions may affect the ecological functions of lands surrounding transportation infrastructure, which may alter environmental mitigation strategies used by transportation agencies in the project development process.

Many local governments are at the forefront of mitigating and adapting to climate change. The International Council on Local Environmental Initiatives, known as ICLEI – Local Governments for Sustainability, was founded in 1990 and now represents over 1,000 governments around the world and over 250 in the United States. ICLEI launched its Cities for Climate Protection Campaign in 1993, which assists local and regional governments in the integration of sustainability and climate change mitigation into decision-making processes. Then in 2005, ICLEI launched the Climate Resilient Communities Program to help local governments develop tools to protect communities from potential climate change impacts. As part of the Climate Resilient Communities Program, ICLEI developed a guidebook to aid local, regional, and state governments in preparing for climate change (Snover et al. 2007).

This guidebook identifies transportation infrastructure as a primary area of concern. Initially the guide provides context as to why it is important to plan for climate change. The planning process described in this guide is comprehensive and iterative. Additionally, the guide presents several examples of climate change preparedness plans, with King County Washington serving as the primary example. The following key steps are enumerated in the guide (Snover et al. 2007):

- Scope the climate change impacts to your major sectors
- Build and maintain support among stakeholders to prepare for climate change
- Build your climate change preparedness team
- Identify planning areas relevant to climate change impacts
- Conduct a vulnerability assessment
- Conduct a risk assessment
- Establish a vision and guiding principles for a climate resilient community
- Set preparedness goals in each priority planning area based on the aforementioned guiding principles
- Develop, select, and prioritize potential preparedness actions
- Identify a list of important implementation tools
- Develop an understanding of how to manage risk and uncertainty

- Develop measures of resilience to allow tracking of actions over time
- Review assumptions to ensure relevance of plan
- Update plan frequently

This guide emphasizes that there is no "one size fits all" approach and each community should customize its plans. Although this plan is not transportation-specific, the transportation sector is identified as a priority and several case studies specifically mention the inclusion of transportation officials in planning efforts (Snover et al. 2007). In fact, King County in Washington State states that the county, "…will protect the integrity and safe operation or regional transportation infrastructure from climate change impacts" (King County 2007).

National Cooperative Highway Research Program (NCHRP) Project 20-83(5) entitled "Climate Change and the Highway System: Impacts and Adaptation Approaches" focuses on how climate change adaptation activities can be incorporated into environmental analysis and engineering design, but also describes how adaptation can be incorporated into transportation planning processes. Adaptive management principles inform a diagnostic framework, which focuses on identifying and managing assets that are vulnerable to climate change impacts. In this case, vulnerability is defined as exposure to climate stressors that may result in asset failure or damage that impedes asset functionality (Meyer et al. 2013).

This guide emphasizes the importance of adopting a risk-oriented approach when considering climate risks. Climate-related risk is defined beyond the scope of asset failure; it also accounts for the cost of consequences of asset failure. The following equation defines climate-related risk:

Risk = Probability of Climate Event Occurrence x Probability of Asset Failure x Consequence or Costs

The guide discusses how climate change adaptation can be incorporated into asset management processes, recognizing that in many cases TAM systems provide a resource-effective manner to incorporate adaptation considerations into an existing platform. Final results of this project, a practitioner's guide to climate change adaptation and an associated software tool, are forthcoming (Meyer et al. 2013).

2.5 Transportation Asset Management and Climate Change

The effects of climate change could be considered in each component of an asset management system. As of January 2011, 36 states had or were creating Climate Action Plans. Most of these plans focus on mitigation and only 13 states have completed or are in the progress of completing adaptation plans (Pew Center 2011). Some examples include Alaska where the melting of permafrost makes it particularly vulnerable to the effects of climate change; "Public Infrastructure" is one of the four Technical Work Groups (TWGs) formed by Alaska's Climate Change Adaptation Advisory Group. California, Florida, Maryland, and Washington State have also recognized infrastructure as important components of their respective state adaptation plans.

Some cities and counties in the U.S. are also developing adaptation plans or strategies. New York City's Plan, *PLANYC*, recognized critical infrastructure as one of three adaptation specific initiatives (Zimmerman and Faris 2010). The city created an Intergovernmental Task Force; among its tasks is to develop an inventory of existing infrastructure that is at risk and develop design guidelines for new infrastructure. None of the adaptation plans in the U.S. specifically mentions TAM, nor do any of the states' asset management systems incorporate climate change. Nonetheless, several adaptation plans do mention components of an asset management system, such as *PLANYC*'s initiative to develop an inventory of existing infrastructure that is at risk (City of New York 2011).

New York City also prepared a climate change adaptation report that focuses on risk management (Rosenzweig and Solecki 2010). This report recognizes that densely populated urban areas along the coast will disproportionately suffer the impacts of climatic change. This report emphasizes both the short-term and long-term benefits of adaptation planning and adaptive activities, despite a fiscally-constrained environment today. Taking adaptation action now will provide immediate benefits and substantive savings in the long-term. One product of this report is the identification of critical infrastructure, which also includes a risk assessment, strategy prioritization, and recommendations on possible changes to existing standards and regulations (Rosenzweig and Solecki 2010).

The New York City Panel on Climate Change (NPCC) recommends the adoption of so-called "Flexible Adaptation Pathways", which are designed to evolve over time as climate knowledge and adaptation strategies evolve through monitoring. Several keys to success of the NPCC include proactive upper-level leadership, linkages to larger sustainability goals, involvement of multiple agencies across a variety of sectors, effective use of expert knowledge and opinion, and the development of an evolving dynamic process. Although the City of New York is confident in its robust adaptation planning process, the NPCC made the following recommendations (Rosenzweig and Solecki 2010):

- Adopt a risk-based approach
- Mandate an ongoing body of experts
- Establish a climate change monitoring program
- Incorporate government agencies across numerous sectors and various levels
- Leverage both public and private sector experts
- Review standards and codes
- Work with insurance industry
- Focus on strategies
- Emphasize early win-win adaptation strategies

It is a premise of this research that asset management systems can be used to monitor and warn transportation agency decision makers when climate change impacts need to be considered seriously as part of an agency's decision-making process. Table 2 shows how the individual components of an asset management system can be used to monitor and/or adapt to climate change.

Table 2. Climate Change Monitoring Techniques or Adaptation Strategies for TAM System Components (Adapted from Meyer et al. 2010)

Asset Management System Component	Monitoring Technique(s)/Adaptation Strategy(s)
Goals and policies	Incorporate climate change considerations into asset management goals and policies; these could be general statements concerning adequate attention of potential issues, or targeted statements at specific types of vulnerabilities (e.g., sea level rise)
Asset inventory	Map, potentially using GIS, infrastructure assets in vulnerable areas; Inventory critical assets that are susceptible to climate change impacts
Condition assessment and performance modeling	Monitor asset condition in conjunction with environmental conditions (e.g., temperature, precipitation, winds) to determine if climate change affects performance, Incorporate risk appraisal into performance modeling and assessment; Identify of high risk areas and highly vulnerable assets; Use “smart” technologies to monitor the health of infrastructure assets
Alternatives evaluation and program optimization	Include alternatives that use probabilistic design procedures to account for the uncertainties of climate change; Possibly apply climate change-related evaluation criteria, smart materials, mitigation strategies, and hazard avoidance approaches.
Short and long range plans	Incorporate climate change considerations into activities outlined in short and long range plans; Incorporate climate change into design guidelines; Establish appropriate mitigation strategies and agency responsibilities.
Program implementation	Include appropriate climate change strategies into program implementation; Determine if agency is actually achieving its climate change adaptation/monitoring goals
Performance monitoring	Monitor asset management system to ensure that it is effectively responding to climate change; Possibly use climate change-related performance measures; “Triggering” measures used to identify when an asset or asset category have reached some critical level.

At the highest level of an asset management system, climate change considerations can be incorporated into a transportation organization's goals and policies. For example, an organization can include adaptation to climate change in its mission statement or vision. Climate change considerations can be incorporated into the inventorying of assets, which is a vital component of an effective asset management system. Although an agency's asset inventory process is not likely to change much due to climate change considerations, data gathered during the asset inventory process could be useful for adaptation. Low-lying areas that are prone to flooding can be mapped using existing inventories, potentially with GIS, to create hazard maps. These hazard maps can identify areas that require special consideration when considering new infrastructure investments. Asset inventories could also note which infrastructure is considered critical, such as roadways in low-lying areas that serve as evacuation routes, and more carefully monitor these assets.

Condition assessment and performance modeling is another system component that can be used to monitor and adapt to the impacts of climate change. Many transportation organizations continuously monitor the condition of their assets, primarily roadways and bridges. Condition assessments of roadways and bridges are often tied to the remaining service lives of these assets. These condition assessments are then used to aid in the development of deterioration curves and models that can be used to predict an asset's performance in the future. Many transportation organizations also have Intelligent Transportation Systems (ITS) that monitor weather conditions in addition to traffic flows. Observed weather conditions could be tied to existing performance monitoring systems to determine if the impacts of climate change have a negative impact on infrastructure asset performance. For example, through a TAM it could be observed that pavement in a particular region is subject to increased temperatures over time, increased precipitation, and increased extreme weather events. If it is observed that these climate change phenomenon negatively impact asset performance, a transportation organization could then take actions to reduce the negative impact on its asset condition. A potentially promising area for such monitoring of infrastructure assets is the use of "smart" technologies to monitor the health of assets.

Climate change considerations could also be incorporated into alternatives evaluation and program optimization. Oftentimes uncertainties associated with the impacts of climate change are not accounted for in the design of infrastructure assets. Probabilistic design methods can be used to account for this uncertainty (Meyer 2008). During the alternatives analysis, or scenario analysis, designs that take the uncertainties of climate change into account could be considered. Asset management systems can also account for climate change considerations in project selection and implementation. If agencies incorporate climate change considerations into their TAM processes then they will be able to identify and implement strategies in direct response to climate change impacts, such as new height design standards for bridges over coastal rivers.

Short and long-range plans of transportation organizations are important products of an agency's planning and decision-making process that should consider potential changes in climate. Long-term plans in particular should take climate change considerations into account since much of the climactic changes are expected to occur over longer time horizons. However, in areas that are already experiencing the impacts of climate change, such as Alaska, short term plans will also need to account for climate change considerations. Given the uncertainty associated with future climate conditions, both short and long-term plans, and in particular long-term plans, will need to be flexible enough to respond to climatic changes. If a transportation organization chooses to incorporate climate change considerations into its asset management system it will be necessary to monitor the asset management system to determine if the organization is still following its policies and meeting its goals. This can be done with self-assessments, which some agencies already conduct, to ensure that actual operating procedures are aligned with the asset management system's goals and policies. A key function of any transportation organization is maintaining an acceptable level of asset performance.

2.5.1 Transportation Asset Management and Extreme Weather Risk

Similar to the impacts of climate change on transportation infrastructure, extreme weather events also affect the provision of transportation infrastructure. Furthermore, recent evidence suggests that extreme weather events are increasing in frequency (Lubchenco and Karl 2012). Volume Two of the Transportation Asset Management Guide enumerates 14 steps that transportation agency officials can take to implement a TAM program (AASHTO 2011a). A white paper for AASHTO (Meyer et al. 2012) details how several of these 14 steps can incorporate extreme weather risks, much in the same way that TAM systems can incorporate climate change considerations (Meyer et al. 2010). In particular, this paper emphasizes the importance of the use of life-cycle costing in TAM systems. Since the costs and benefits of an asset are considered throughout its useful life, a stressor such as extreme weather becomes an important consideration in terms of asset rehabilitation, reconstruction or replacement (Meyer et al. 2012).

Given that extreme weather events are by their nature infrequent, adopting an effective risk management approach as it relates to mitigating the risk of extreme weather events is crucial. TAM systems typically contain a wealth of information regarding transportation infrastructure, especially roadways and bridges. Much, if not all, of this infrastructure asset attribute information is also geospatially referenced. This allows for efficient monitoring of the locations of the network that are regularly affected by extreme weather events. If certain locations continue to experience severe impacts from extreme weather, transportation agencies can develop appropriate response, such as making certain infrastructure elements more resilient to extreme weather or changing design standards. Furthermore, if a particular segment of the transportation infrastructure is identified as vulnerable to extreme weather, infrastructure providers can also look to climate projections to assist in determining what weather can be expected in the future. This sorts of projections are even more valuable when designing and planning new transportation infrastructure (Meyer et al. 2012).

2.6 Adaptive Management

The environmental management community has used so-called adaptive management approaches to solve complex, interdisciplinary problems that involve multiple stakeholders. This sort of approach advocates using scientific evidence to develop well-quantified models that inform decision-making processes through iterative hypothesis testing. However, using systems-models to quantify complex processes has proven difficult, and often fails to account for unquantifiable information. Furthermore, failure to use a modeling approach that is open to input from all stakeholders can result in a lack of confidence in model results. For this reason, it is valuable to gather input from a range of stakeholders and develop models that produce multiple results based on varying input scenarios (McLain and Lee 1996).

Despite its shortcomings from a purely scientific perspective, adaptive management approaches provide valuable input in decision-making processes. Adaptive management allows policymakers to develop multiple scenarios and therefore multiple alternatives; oftentimes this process can result in alternatives policymakers would not consider otherwise and allow for the use of what-if scenarios. If only one model is used, then it is likely that the considerations of certain stakeholders will be overshadowed. Thus, the use of multiple complex models with a multitude of results may return problem discussion to a political forum, where the societal and cultural components of decision-making are more adequately addressed. Adaptive management approaches also require flexible institutional structures since adaptive approaches are experimental and long-term (McLain and Lee 1996).

Given the flexibility of adaptive management and its interdisciplinary nature, this term has entered the lexicon of the climate change adaptation community (Thompson et al. 2006). Adaptation to climatic changes will be continuous and long-term, requiring frequent responses by organizations. Like other complex, dynamic environmental challenges, the response to climatic change is also well suited to adaptive management. Furthermore, since climate science is multidisciplinary and the potential impacts of climate change are far-reaching, adaptive management approaches can foster the interdisciplinary dialogue required for more effective adaptation strategies (Thompson et al. 2006). Adaptive management approaches are flexible, incorporate iterative hypothesis testing, and involve input from a variety of stakeholders. For these reasons, adaptive management approaches can serve as an effective platform to incorporate climate change considerations, and their associated risks, into the transportation asset management process.

2.7 Risk and Transportation Asset Management Systems

Risk assessment and risk management are important components of any asset management process (Amekudzi 2009). For example, risk is inherent to the transportation planning and development process. Transportation plans reflect political risks, such as the adverse reaction of a community to the impacts of a transportation project in the plan, potential changes in direction from newly elected officials, and uncertainty in the availability of funds. Risk can be considered in any part of the TAM process shown in Figure 1 or during any portion of the life cycle of an infrastructure asset. Often it is best to consider risk throughout the entire transportation planning and development process, but sometimes it is more appropriate to consider risk during the latter stages of the process (Amekudzi 2009).

The Federal Highway Administration recognizes the importance of incorporating risk into the TAM process and released a series of five reports on this topic (Proctor and Varma 2012a; b, 2013; Varma and Proctor 2012, 2013). Transportation agencies in the U.S. typically incorporate risk at the project level, but often fail to do so at an organizational or enterprise level, while leading transportation organizations outside the U.S. do incorporate risk at these broader, strategic levels. FHWA has adopted the following steps in a risk management process from the International Organization for Standardization (ISO): establishing the context, risk identification, risk analysis, risk evaluation, and risk treatment. Many U.S. transportation agencies do practice risk management strategies but may not have formal, established risk management policies and goals defined at the institutional or enterprise level. However, many transportation agencies will be required to develop formal risk-based asset management plans as required by Congress in MAP-21 (Proctor and Varma 2012a).

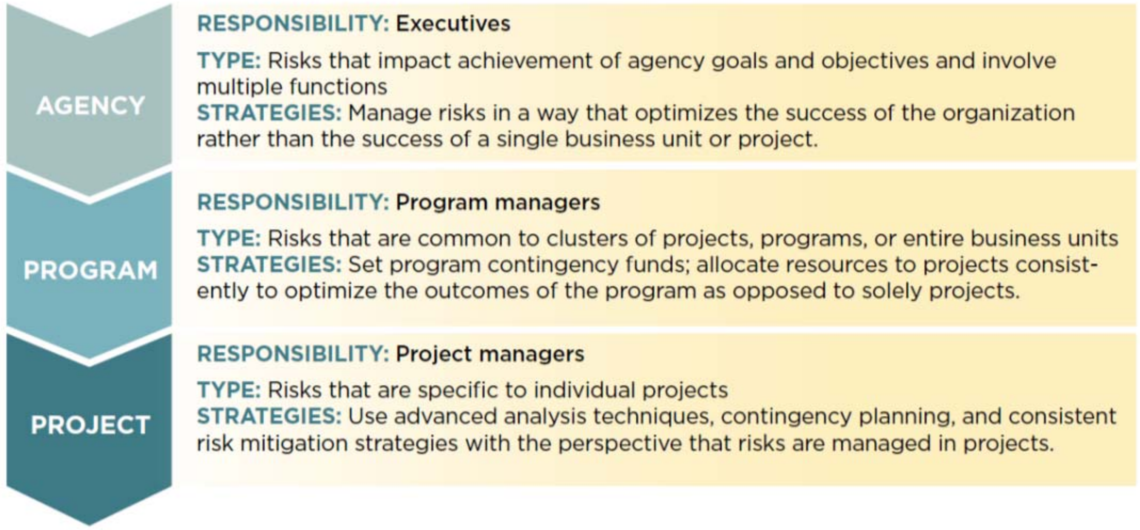
The second report in the series, *Managing Asset Risks at Multiple Levels in a Transportation Agency* (Varma and Proctor 2012), highlights the fact that risk management is required at agencies in Australia and New Zealand. Furthermore, risk management is an ongoing process of monitoring and managing risks, not a one-time activity. According to a NCHRP survey out of 43 state DOTs only 13 have formal agency-wide risk management procedures (D'Ignazio et al. 2011). Climate change risk and natural disaster risk are specifically discussed in this report (Varma and Proctor 2012). FHWA sponsored an international scan tour that examined best practices in risk management in Australia, New Zealand, the Netherlands, Germany, Scotland, and England (Curtis et al. 2012). Perhaps the most important message from this scan tour is that risk management is an integral part of transportation agency business activities (Curtis et al. 2012). Figure 3 shows how risk management relates to agency strategic objectives, asset management, and performance management.

Figure 3. Relationship between risk management and other transportation agency management functions (Curtis et al. 2012)

The international risk management scan defined enterprise risk management as a term that executives use when referring to risk; enterprise risk management occurs across three levels: agency, program, and project risk management. Figure 4 illustrates the three levels of enterprise risk management. Key recommendations from the report's scan team include (Curtis et al. 2012):

- Develop executive support for risk management
- Define risk management leadership and organizational responsibilities
- Formalize enterprise risk management approaches
- Use risk management to reexamine existing policies, processes, and standards
- Embed risk management in existing business processes
- Identify risk owners and manage risk at appropriate level
- Use risk management processes to support risk allocation

- Build trust with transportation stakeholders by using risk management to make the business case
- Deploy complex risk analysis tools but communicate results in a simple manner



RESPONSIBILITY: Executives

TYPE: Risks that impact achievement of agency goals and objectives and involve multiple functions

STRATEGIES: Manage risks in a way that optimizes the success of the organization rather than the success of a single business unit or project.

RESPONSIBILITY: Program managers

TYPE: Risks that are common to clusters of projects, programs, or entire business units

STRATEGIES: Set program contingency funds; allocate resources to projects consistently to optimize the outcomes of the program as opposed to solely projects.

RESPONSIBILITY: Project managers

TYPE: Risks that are specific to individual projects

STRATEGIES: Use advanced analysis techniques, contingency planning, and consistent risk mitigation strategies with the perspective that risks are managed in projects.

Figure 4. Description of the three levels of enterprise risk management (Curtis et al. 2012)

The third report in the risk-based transportation asset management series, *Achieving Policy Objectives by Managing Risks*, focuses on strategic risk management, which are defined as those risks to key agency objectives and policies (Proctor and Varma 2012b). In the private sector, strategic risk management is a crucial component of an executive’s responsibilities. However, this is typically not the case at transportation agencies. Instead, oftentimes transportation executives find themselves managing crises instead of risks. In this context, strategic risks are those risks to mission-critical agency objectives. Typically, these risks are out of the control of lower-level employees and are therefore the responsibility of executives. Some examples of strategic risks include political risks, e.g., changes in leadership, financial risk, e.g., regulatory risks, workforce risks, technology risks, decreases in revenues, and climate and weather risks, e.g., natural disasters and the impacts of global climate change. However, strategic risks can be managed, mitigated, and treated with appropriate frameworks (Proctor and Varma 2012b).

The fourth report in the series, *Managing Risks to Critical Assets*, focuses on risk-based asset management of critical corridors. Adopting a risk-based approach on critical corridors allows transportation agencies to strategically focus limited resources to improve the safety and condition of a greater number of transportation infrastructure assets. The definition of critical networks and corridors typically involves the use of certain functional classifications, such as the National Highway System (NHS) or Strategic Highway Network (STRAHNET). Risk-based approaches at the network and corridor levels allow agencies to focus on a more limited number of assets. This approach also allows transportation agencies to better justify trade-offs and communicate needs to both the traveling public and elected officials (Varma and Proctor 2013).

The fifth and final report in the series, *Managing External Threats Through Risk-based Asset Management*, addresses how physical, climatic, seismic, and other external threats can be incorporated into risk-based TAM processes. A premise of this report is that agency Transportation Asset Management Plans (TAMPs) typically rely on projected asset condition without accounting for the possibility of damage from external threats, such as extreme weather and climatic change. To minimize the impact of these external threats on transportation system operations this report focuses on redundancy, robustness, and resiliency. Although negative risks, such as hurricanes and floods, are often unpredictable in both timing and severity of occurrence, risk-based TAM can allow agencies to more quickly respond to and recover from negative risks (Proctor and Varma 2013).

NCHRP Report 525 develops the Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA) tool, which is computer-based and implemented with spreadsheets. The CAPTA methodology develops a common framework to analyze assets, threats and hazards, and consequence levels. This approach requires that users identify relevant assets, threats, and threshold levels at which these threats result in adverse consequences. The CAPTA process is iterative and allows decision makers to determine the impacts of various threshold levels on resource allocation. Ultimately, the CAPTA process results in a capital planning and budgeting tool that allows users to identify investment levels required for improvements in asset protection (SAIC and PB Consult Inc. 2009).

As illustrated by the 2007 collapse of the I-35W bridge in Minneapolis (NTSB 2008), a more systematic and performance-based approach for evaluating infrastructure condition is necessary. The use of risk-based approaches to evaluate infrastructure condition can lead to investments that are targeted at higher risk assets. For example, a highly traveled Interstate bridge could receive inspections with greater frequency. Additionally, in order to assess properly the risks associated with civil engineering infrastructure, a comprehensive approach towards defining infrastructure performance is needed.

2.7.1 Performance-based Design Standards for Civil Engineering Systems

The American Society of Civil Engineers (ASCE) has established a committee to develop a more complete definition of performance of engineered infrastructure. This committee has also investigated performance limit-states and performance-based design of infrastructure (Aktan et al. 2007). It was recognized that although performance-based engineering is not a new concept in engineering (see for example the automotive, aerospace, and space industries, that are not driven by code-based designs), it is a relatively new concept in civil engineering. If the civil engineering profession establishes performance definitions and develops quantitative, measurable indices, the benefits could be substantial (Aktan et al. 2007). For example, does it make sense to design a bridge in a low-risk seismic region to the same prescriptive code-based requirements as in a high-risk seismic region such as California?

Designs for modern bridges and buildings are based on limit states or load and resistance factor design (LRFD) concepts. Although these limit states are based on the basic LRFD concept of achieving predetermined reliability levels for typical limit states such as yielding, fracturing, and instability, limit state functions will vary for different building types such as bridges, tunnels, and dams (Aktan et al. 2007). Table 3 shows the limit-states, limit-events, and expected performance goals recommended by the ASCE Committee on Performance-Based Design and Evaluation of Constructed Facilities. Standardization of limit-states, limit-events, and expected performance goals is an important step in the development of performance-based design guidelines. Performance-based design would consider risk of failure, which reflects both the probability of failure, i.e., the inability to meet stated performance objectives, and the consequences of failure (Aktan et al. 2007).

Since the expected life of transportation infrastructure can be long, around 100 years for bridges, it can become difficult to establish performance limit-states for various stages throughout the life of an infrastructure asset. Asset management systems provide an effective platform for monitoring the condition or performance of infrastructure assets throughout their life-cycle. As such, these TAM systems would be an effective platform for incorporating the risks associated with such infrastructure.

Table 3. Limit-states, Limit Events, and Expected Performance Goals of Constructed Facilities (Aktan et al. 2007)

Limit state	Life-cycle utility, functionality, sustainability	Serviceability and durability	Life safety and stability of failure	Substantial safety at conditional limit states
Limit events	• Environmental impacts and sustainability • Societal impacts • Functionality throughout the life cycle • Financing mechanisms for initial *and* life-cycle costs • Operational capacity, safety, efficiency, flexibility, and security • Feasibility of construction, protection, and preservation aesthetics	• Excessive: displacements, deformations, shifts • Deterioration • Local damage • Vibrations • Lack of durability (Special limit state that should govern aspects of global design, detailing, materials, and construction)	• Excessive movements, settlements, geometry changes • Material failure • Fatigue • Local and member stability failure • Stability of failure(Incomplete and premature collapse mechanisms without adequate deformability and hardening) • Undesirable (sudden, brittle) failure mode(s)	• Lack of multiple escape routes in buildings • Lack of post-failure resiliency, leading to progressive collapse of buildings, bridges • Cascading failures of interconnected infrastructure systems • Failures of infrastructure elements critical for emergency response, medical, communication, water, energy, transportation, logistics, command, and control
Goals	• Constrained multi-objective function for integrated asset management (Functions relating to operations, security, and life-cycle cost)	• Constrained multi-objective function for integrated asset management (Functions relating to operations, security, and life-cycle cost)	• Multi-hazards risk management (Assurance of life safety and quick recovery of operations during days and months following an extreme event)	• Disaster response planning, and emergency management (protection of escape routes, evacuation, search and rescue needs, minimizing casualties, and economic recovery within years)

2.8 Risk Concepts

Risk is typically part of every individual's daily decision-making process. Risk-based decision making, however, suggests a different concept. This terminology, risk-based approaches to decision making, typically describes a systematic process that evaluates uncertainties, develops policies based on these uncertainties, and addresses the possible consequences of these policies (Haimes 2004). Risk-based decision making is not a simple undertaking. Risk is defined as the probability that a negative event occurs, along with the consequences of this negative event (Haimes 2004; Piyatrapoomi et al. 2004).

Although closely related to risk, uncertainty carries a different meaning. Uncertainty is an inherent component of the decision-making process when choices are made based on incomplete knowledge (Piyatrapoomi et al. 2004). Decision makers often do not have complete knowledge of every facet of every decision; some level of uncertainty is present in nearly all decision making. This type of uncertainty is generally termed subjective uncertainty, contrasted with objective uncertainty arising from the randomness of systems, which is irreducible (Helton and Burmaster 1996; Winkler 1996).

In terms of infrastructure assets, uncertainty arises from both the randomness of events and sources of error. Three primary sources of error for infrastructure assets are data errors, forecasting errors, and modeling errors. Data errors are due to measurement error or simple human error. These types of errors can be measured through the use of statistical techniques and can be reduced by collecting more complete historical data. Forecasting errors relate to the uncertainty associated with future events. There are limitations on the ability to decrease forecasting errors since it is not possible to predict, with certainty, future events. Model errors are a result of the difference between observed or real-world values and model estimates. Since it is almost impossible to represent the complexity of actual conditions with one hundred percent accuracy in a mathematical model, there are also limitations on the extent to which model errors can be reduced (Piyatrapoomi et al. 2004). Various studies have shown forecasting uncertainties are relatively larger than model and other data uncertainties (see for example (Amekudzi and McNeil 2000; Aktan and Moon 2010)).

2.8.1 Risk Assessment and Risk Management

At first, risk assessment and risk management may appear to be similar, or maybe even interchangeable; but they are distinct. Risk assessment refers to the scientific process of measuring risks in a quantitative and empirical manner (Haimes 2004; Piyatrapoomi et al. 2004). Risk management is a qualitative process that involves judging the acceptability of risks (Haimes 2004) within applicable legal, political, social, economic, environmental, and engineering considerations (Piyatrapoomi et al. 2004). The literature suggests that agencies, both public and private, that adequately address risk in their activities will be successful leaders in their respective fields (Haimes 2004).

Risk assessment and risk management are elements of nearly all engineered systems. For example, a building is designed to withstand greater than average wind loads, otherwise a building would topple each time there was a strong wind gust. It is rare that transportation infrastructure suddenly and unexpectedly fails; a testament to the civil engineering profession. The public trusts that the roads and bridges will not fail unexpectedly. However, there are catastrophes, such as the collapse of the Interstate 35W bridge in Minneapolis in 2007. Thirteen people were killed and over one hundred persons injured (NTSB 2008).

Most would consider this sort of catastrophic failure to be unacceptable. However, making sure that every possible failure contingency is incorporated into design is infeasible or possibly too costly. Decision makers must therefore determine an acceptable level of risk. This acceptable level of risk is often influenced by public perceptions of risk. Society perceives certain risks at different levels. For example, the risk of a traffic accident is far greater than the risk of an earthquake, but society is more willing to tolerate the risk of a traffic accident than the risk of a bridge failure due to natural events (Aktan and Moon 2010). This indicates the subjective nature of risk management. A risk assessment of the I-35W bridge at the time prior to its collapse could have quantitatively measured the risk of failure of the bridge; risk management actions would have determined appropriate actions to reduce or otherwise manage the existing risks. The failure of roadways and bridges in the Gulf Coast during Hurricane Katrina would be considered catastrophic by most. In anticipation of future storms and a rise in sea level, several bridges in the Gulf Coast area have already been reconstructed at higher elevations (Meyer 2008).

An FHWA hydraulic engineering circular highlighted the fact that 60,000 miles of highway nationwide lie within the Federal Emergency Management Agency's (FEMA) 100-year floodplain (Douglass and Krolak 2008). This circular also points out that more than 1,000 bridges may be vulnerable to failure modes that have been associated with recent coastal storms such as Hurricane Katrina.

These examples are cited to illustrate some of the risks associated with transportation infrastructure. It is possible to mitigate some of these risks through the use of proper risk assessment and risk management techniques. Given that many transportation agencies have asset management systems, it seems that these systems would provide a strategic platform for incorporating a risk-oriented approach into the investment decision-making process. In particular, in light the 2012 national surface transportation legislation's (MAP-21's) requirement for risk-based asset management plans in state Departments of Transportation, asset management systems should evolve to address risk if they are not already doing so. Figure 5 shows a proposed risk assessment framework for the investment decision-making process, with the last step of this framework being risk management, which is done by the decision maker.

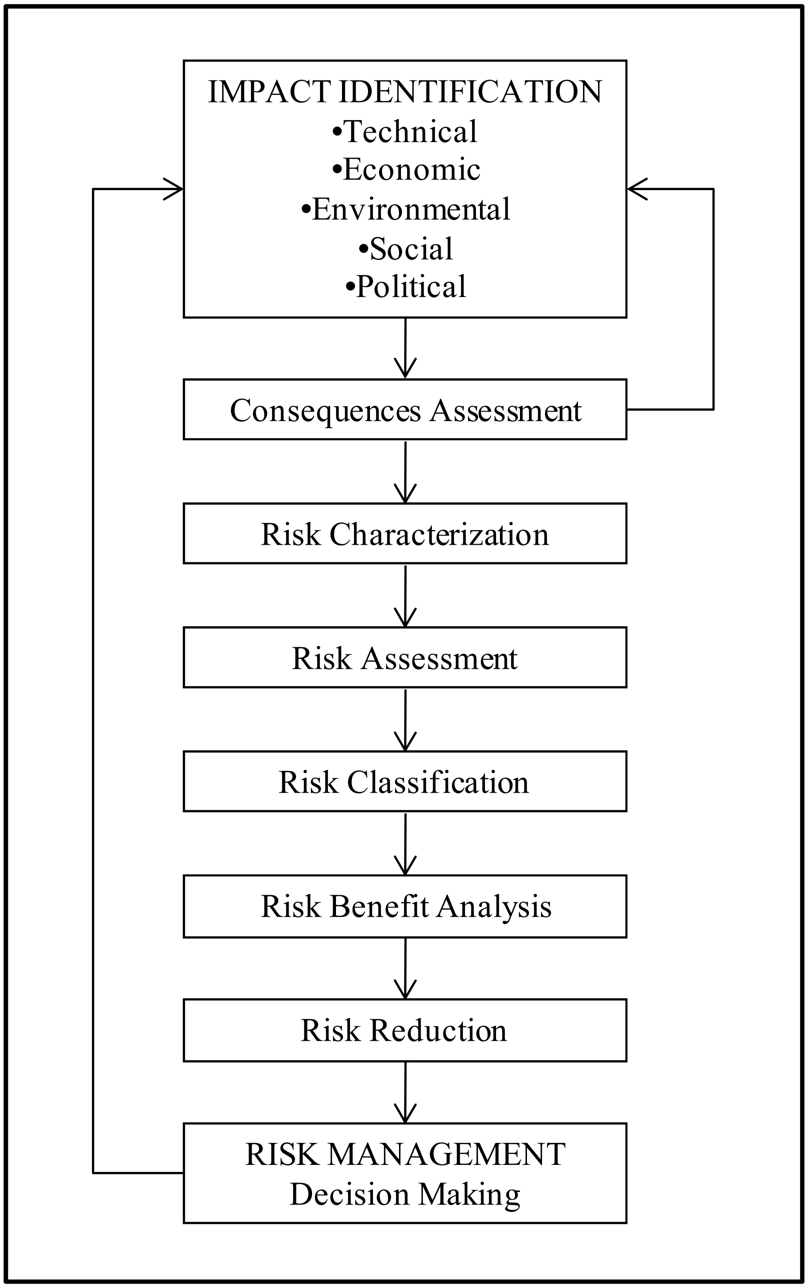


Figure 5. A framework for investment decision making under risk and uncertainty (Piyatrapoomi et al. 2004)

2.8.2 International Organization for Standardization Risk Management Principles and Guidelines

The International Organization for Standardization is a widely recognized international federation of national standards bodies, known as ISO member bodies. Technical committees typically prepare international standards; ISO Technical Management Board Working Group on risk management prepared ISO 31000, Risk management – Principles and guidelines. Two other widely known ISO standards include ISO 9000 – Quality management and ISO 14000 – Environmental management. ISO 31000 defines risk as the effect uncertainty has on an organization's objectives. Since this is an international standard that applies to a breadth of organizations, the generic approach detailed in ISO 31000 enumerates the principles and guidelines for managing any form of risk in a systematic, transparent, and credible manner all within any scope and context (ISO 2009). Figure 6 shows the generic ISO 31000 risk management process.

The ISO 31000 standard lists the following risk management principles:

- a) Creates value
- b) Integral part of organizational processes
- c) Part of decision making
- d) Explicitly addresses uncertainty
- e) Systematic, structured and timely
- f) Based on the best available information
- g) Tailored
- h) Takes human and cultural factors into account
- i) Transparent and inclusive

- j) Dynamic, iterative, and responsive to change
- k) Facilitates continual improvement and enhancement of the organization

The principles listed above and the risk management process shown in Figure 6 are related by the risk management framework shown in Figure 7. In broad terms, the risk management process should be an integral part of management, embedded in the culture and practices, and tailored to the business processes of the organization. Risk management is defined as the systematic application of management policies, procedures, and practices to the activities of communicating, consulting, establishing the context, and identifying, analyzing, evaluating, treating, monitoring and reviewing risk; risk assessment is the overall process of risk identification, risk analysis, and risk evaluation; risk treatment is selecting one or more options for modifying risks and then implementing those options. Lastly, risk management processes should be iterative with regular monitoring and reviewing. Furthermore, keeping records of risk management activities serves to enhance the process, serving as a foundation for improvement (ISO 2009).

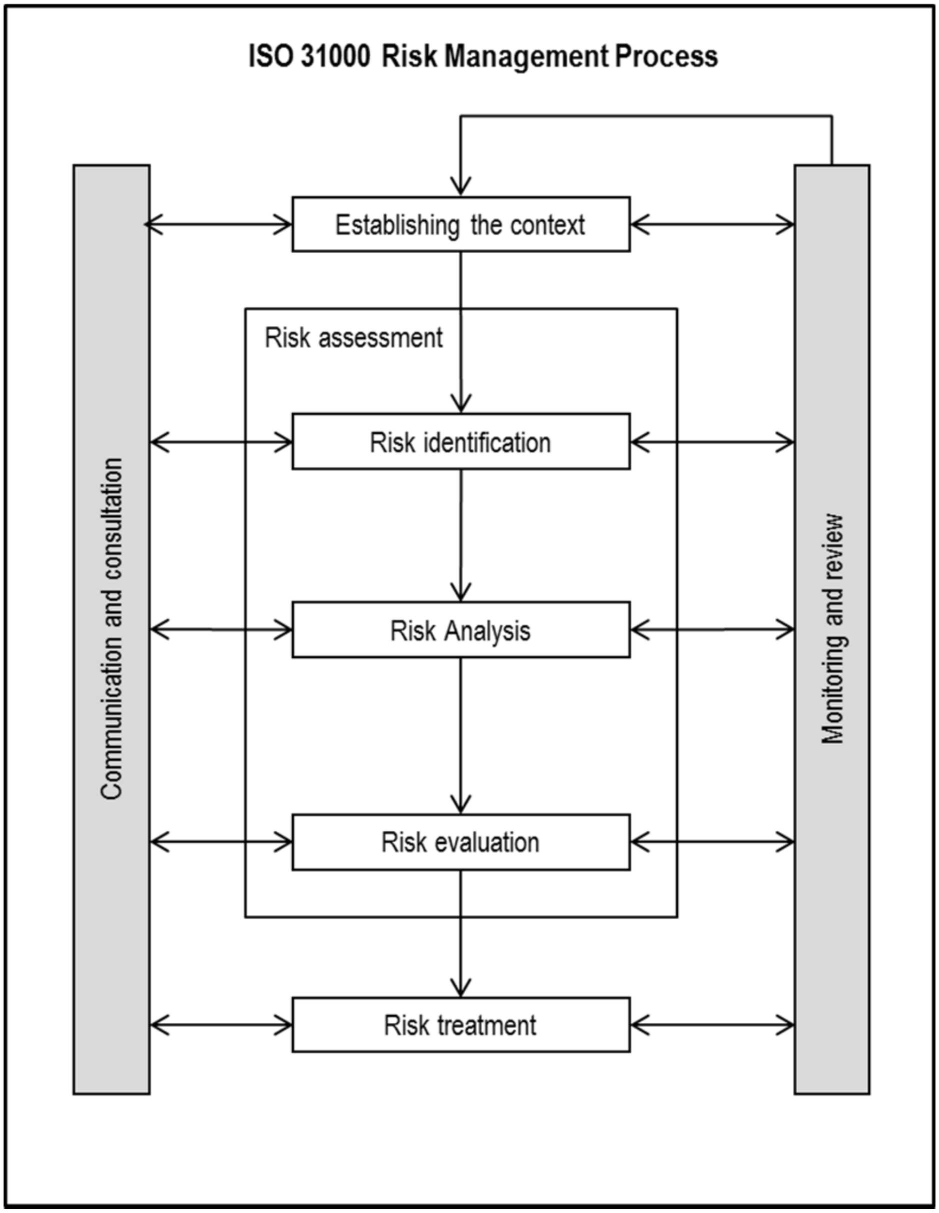


Figure 6. ISO 31000 Risk management process (ISO 2009)

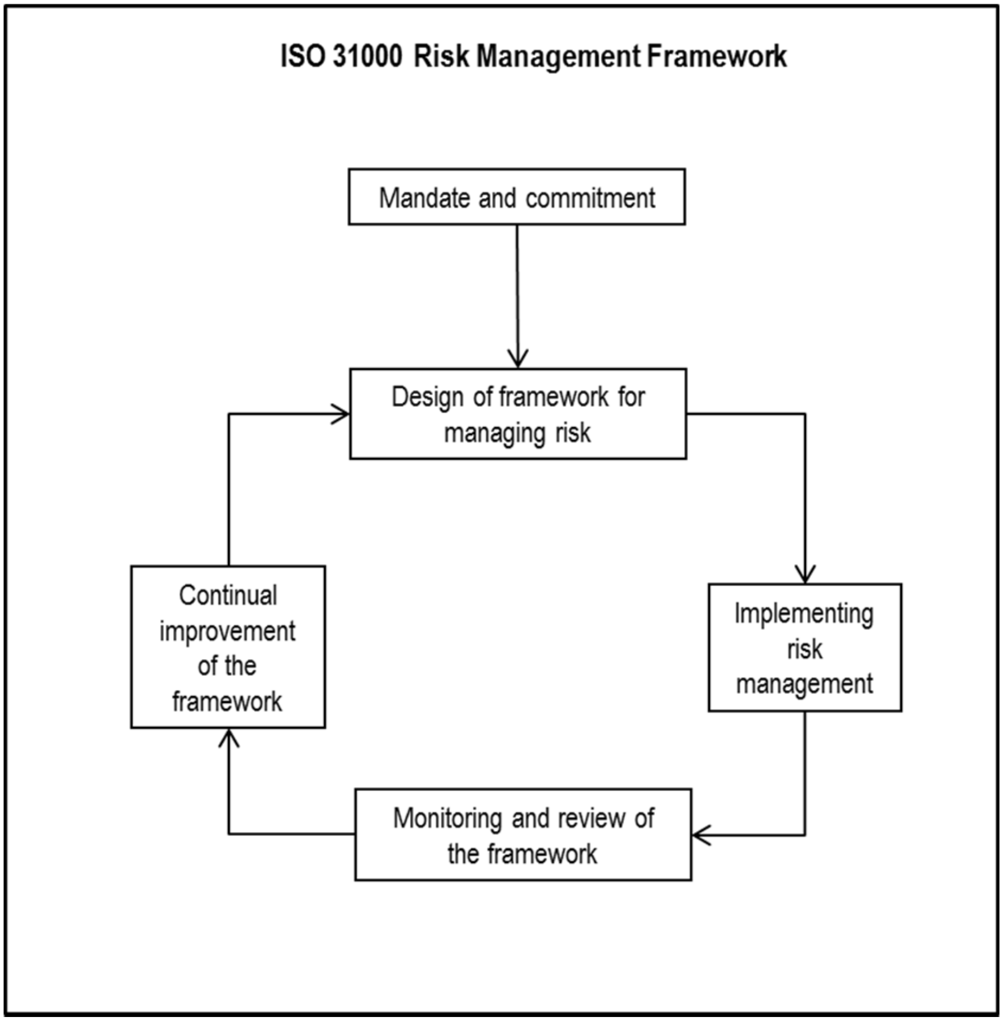


Figure 7. ISO 31000 Risk management framework (ISO 2009)

2.9 Risk Applications in Transportation Asset Management

The number of examples of risk applications in TAM is increasing in the literature. These applications use various methodologies to predict infrastructure asset performance while also addressing uncertainties. Several risk applications utilize methodologies for incorporating uncertainties in project prioritization, while other methodologies use risk as an investment decision-making criterion. The following sections describe a number of applications of risk in TAM systems.

2.9.1 Performance-Based Asset Management Framework

Atkan and Moon (2010) emphasize the importance of performance monitoring in an effective asset management system. They present specific steps that are necessary for performance-based asset management. In their asset management framework, prioritization is driven by the risk of failure, or non-performance. The first step is to gather all relevant stakeholders so they can determine a definition for infrastructure performance that is based on societal, cultural, and technical values. (Technical values should be included since stakeholders developing societal and cultural values may not be able to articulate technical values. The technical agency should be responsible for developing these technical values, which are a critical component of infrastructure performance.)

Next, an organization should determine the geographic and organizational boundaries of the infrastructure assets in a system that is interconnected and interdependent. Performance requirements should then be established at the network, regional, and local levels for different infrastructure types. Performance requirements that are established at the network level can also be used at the regional and local levels. The funding that is available at the network, regional, and local levels should also be determined. Infrastructure should next be identified and documented (e.g. using geographic information system, or GIS tools) at least at the regional level.

Asset performance requirements should be specific to different groups or classes of assets. For example, roadway asset groups may include users, traffic flows, pavements, and bridges. However, the performance of different groups of assets should be related to one another, e.g., determining how bridge performance affects pavement performance (if the condition of a bridge requires that loads be restricted then the loads experienced on the roadways approaching the bridge will be affected). Organizational resources, such as knowledge, experience, core personnel, and buildings, can also be considered an asset group. Data related to the current condition and performance of assets in each asset group should be collected.

Once the preceding steps have been completed, the system should be tested in a way that allows for the identification of the most critical factors that affect system-wide performance. Once this has been done, resources can be strategically targeted at the identified critical factors. The final step involves considering the effects of the failure of one infrastructure asset on another, or the interdependencies among infrastructure assets (Aktan and Moon 2010). Ultimately, these steps will provide an asset management framework that identifies critical assets where the risk of non-performance of these assets is minimized.

2.9.2 Scenario Analysis, Sensitivity Analysis, and Uncertainty in TAMs

Scenario analyses, scenario planning methods, or scenario assessment represent a collection of tools that is used to evaluate risk and uncertainty (Amekudzi 2009;

Piyatrapoomi et al. 2004). One of the original applications was to identify plausible alternatives based on realistic future scenarios. This was done to develop and implement a plan that resulted in acceptable or superior conditions independent of which future scenario materialized, therefore accommodating prevailing uncertainties (Schwartz 1996). Often, scenario analyses tools are used in the earlier stages of planning where transportation agencies consider several alternatives or scenarios and evaluate the possible outcomes of each alternative. First, alternative scenarios need to be defined and the different factors affecting each scenario, such as forecasted growth, congestion mitigation, economic development, and air quality impacts, need to be determined (Amekudzi 2009). Typically, some sort of scoring method is used to rank alternative scenarios. The alternative that provides the greatest benefit with minimal risk is usually the superior alternative. A scenario analysis serves as a means to evaluate different alternatives in project development. It is not a forecast, nor does it calculate the specific probability that a given event will occur (Piyatrapoomi et al. 2004). Scenario planning methods may prove to be the most useful for large-scale projects, given the potential for large negative consequences that may result from an alternative that is high-risk or worst-case (Amekudzi 2009).

A sensitivity analysis identifies the primary source of variability and can determine whether there are variables that contribute greater uncertainty to model results than others. Input parameters having the greatest impact on the variability of model results and that have insufficient data contribute significant uncertainty to model results. In 1983, the World Road Congress Committee on Economic and Finance examined approaches to a sensitivity analysis methodology. The Committee analyzed the uncertainties associated with data errors and with forecasting errors. Several input variables for a traffic model were considered and the range of possible values was determined for these variables. The Committee found that forecasting errors contributed significantly more to uncertainty than did data errors or model errors (Piyatrapoomi et al. 2004). This illustrates the fact that it is more difficult to predict accurately future events than to record data and develop models based on recorded historical data. While it would not be possible to eliminate uncertainty completely from forecasting, the input variables and model parameters that have the greatest impact on model outputs can be identified using sensitivity analysis.

A study by Amekudzi and McNeil (Amekudzi and Sue McNeil 2000) analyzed uncertainty in highway performance modeling at the federal level. Since 1968, the U.S. Congress has mandated that the FHWA produce a biennial highway investment needs estimate. The FHWA satisfies this mandate by producing a “Conditions and Performance” Report. Given the scope and scale of this effort, there is likely some uncertainty associated with the needs estimate, where this uncertainty can be grouped into two major categories, epistemic (non-variable phenomena in a real world system about which there is incomplete information) and aleatory (variable phenomena in a real world system).

This paper also examined the impacts of analysts’ uncertainties about model inputs on model outputs through the use of Monte Carlo simulation techniques. The predominant source of model output variability in the Highway Economic Requirements System (HERS), the national highway investment model, was determined to be traffic forecasts. The approaches presented in this paper allow decision makers to determine changes in asset performance as a function of changes in input data (Amekudzi and Sue McNeil 2000). It is important for decision makers to be aware of which model inputs have the greatest uncertainty and the impact of these inputs on model outputs. A better understanding of uncertainty leads to better uses of the results of infrastructure performance models.

2.9.3 Project Prioritization, Project Programming, and Modeling

Program prioritization, also referred to as project optimization, is another component of the asset management process that typically incorporates some level of risk assessment. Prioritization techniques can be used at a number of different levels in the asset management process, ranging from a broader network level to a more specific project level. Project programming, or project selection, involves analyzing a range or combination of alternatives to determine which alternative(s) provide the best investment. This process usually involves scenario analysis, which presents decision makers with trade-offs among different alternatives (Amekudzi 2009).

There are different levels of project programming, with the most basic being simple subjective ranking based on judgment. More complex project programming processes use mathematical models to perform a comprehensive analysis, taking into account a variety of factors that influence project selection. Although these models are more complex and more difficult to develop and interpret, they provide a more optimal solution than more basic subjective project rankings (Haas and Raymond 1999).

The more effective project programming models will take into account user benefits, in addition to project costs. Using this methodology, and accounting for user benefits, allows for the most successful project optimization. These more advanced project programming models, however, are not in widespread use for the selection of new projects. More advanced project programming methods are widely used in a transportation agency’s maintenance activities (Amekudzi 2009). For example, an agency may monitor the condition of its pavement assets on a regular basis, and depending upon the condition and age of pavement, perform certain preventive maintenance activities, such as surface overlays.

Many transportation agencies have well-developed project programming techniques in place for maintenance activities, which include repair and rehabilitation efforts. Project programming methods for maintenance activities should answer the following three questions: what portions of a particular asset should be targeted for maintenance, repair, or rehabilitation? How can these areas be reconstructed or repaired, i.e. which particular alternatives apply to these areas? And when should these areas be reconstructed or maintained, i.e. what is the appropriate timing? (Amekudzi 2009) Given that there may be a large number of alternatives and that agencies often have different priorities for different projects, such as safety improvements or capacity expansion, it is often difficult to determine which is the best alternative or set of alternatives.

Comparing alternatives across different classes of assets, such as transit projects versus highway projects, is another area of interest for an alternatives analysis. Cross asset trade-off analysis presents additional challenges, such as standardizing the values of costs and benefits across asset classes (Amekudzi 2009). Focusing solely on comparing alternatives within the same asset class, such as roadway projects versus other roadway projects, can result in less-than-optimal resource allocation.

If uniform values can be established for roadway projects, bridge projects, and transit projects, then a more accurate cross-asset trade-off analysis can be performed. This would allow agencies to move away from dedicating funds specifically for highway improvements or bridge improvements, and permit agencies to determine what the optimal project is among a set of alternatives that encompasses multiple classes of assets. Where uniform values cannot be established, decision makers must consider the value tradeoffs that would occur from investing in different asset classes.

The aforementioned project programming methods typically incorporate some form of risk analysis. Several agencies, particularly those in other countries, use some form of risk assessment in their project prioritization methods (AASHTO 2011a; Amekudzi 2009; Geiger et al. 2005).

Probabilistic models consider risk by taking uncertainty into account (Amekudzi 2009; Piyatrapoomi et al. 2004). These models use statistical methods in which mathematical functions of decision-making factors are developed. Uncertainties of the model inputs are calculated using probability distributions and statistical parameters, such as coefficient of variation and mean. In order to conduct a probability-based risk assessment the uncertainties associated with the input variables, such as variation in user demand, need to be estimated.

Monte Carlo simulation techniques are one method to estimate model outputs. These simulations intend to capture the range of errors associated with each variable and typically result in a range of errors associated with the model outputs (Piyatrapoomi et al. 2004). Outputs of Monte Carlo simulations present decision makers with a range of possible outcomes, and the probabilities associated with each of these outcomes. Since the results of the simulation are presented in this manner, decision makers are made aware of the uncertainties associated with the outputs, and of which inputs have the greatest impact on model outputs.

Another method for predicting the future condition of infrastructure assets is the use of Markov models or Markov chains (AbouRizk and Siu 2008; Amekudzi 2009). This method incorporates asset deterioration curves into its predictions. Markov models typically use historic data on asset condition, asset rehabilitation, asset repairs, and asset replacement. An asset element starts at its ideal condition, A if using an ordinal A to F rating system, such as the rating system using by the ASCE in its Report Card for America's Infrastructure (ASCE 2009). Through the course of its life an asset is likely to deteriorate from A to B and then B to C, and so on, with A representing an asset's optimal condition and F representing an asset's failed state. An asset will deteriorate from one condition state to another, for example, A to B, in a particular time-frame with some level of probability. This probability is referred to as a transition probability and can be obtained from a deterioration curve. Of course, over its lifetime the condition of an asset will continue to deteriorate, but various repair and rehabilitation policies can have a positive impact on asset condition. For example, a repair can move an asset from condition state C to condition state A. After a Markov model is developed based on historical condition state and repair and rehabilitation data, condition states of assets can be predicted at a given time period in the future (AbouRizk and Siu 2008).

An emerging risk assessment method called 'real options models' presents a new way of considering risk in the transportation analysis process (Amekudzi 2009). This approach accounts for the fact that while transportation projects are considered to have benefits, these predicted benefits are not always realized. In other cases, project results may be different from those that were predicted at the time when the investment decision was made. For this reason, it may be valuable to delay certain transportation investment decisions until additional information becomes available.

By doing this, decision makers may be able to decrease their risks. However, projects can lose value by waiting for new information to present itself. This potential lost value should be accounted for in calculations of project net present value. Since it may be more valuable to defer certain projects, it is useful when considering alternatives to consider those alternatives that can be phased in over time (Brand and Mehndiratta 2000).

2.9.4 Risk Application Examples in TAMs

In AbouRizk and Siu's (AbouRizk and Siu 2008) work risk severity is defined as the probability of failure multiplied by the consequences of failure on the local community (AbouRizk and Siu 2008). This keeps with the traditional technical definition of risk as the probability of occurrence of a negative event and the severity of the consequences of this negative event (Haimes 2004). In order to determine accurately the probability of failure of a particular infrastructure asset, it is necessary to ascertain certain information about this asset. Some valuable pieces of information include the asset's replacement value, the physical attributes of the asset, such as age, dimensions, and quantity, and perhaps most importantly, the condition of the asset. The type and amount of information collected about infrastructure assets varies from agency to agency. For example, a transportation agency whose jurisdiction includes areas that are prone to rock slides will likely collect data about retaining walls, when rock-fall events occur, the severity of the rock-fall, etc.

The condition rating system used in the AbouRizk and Siu study is ASCE's ordinal scale for Infrastructure Report Cards: very good "A", good "B", fair "C", poor "D", or very poor "F" (AbouRizk and Siu 2008). In their study (AbouRizk and Siu 2008), these alphabetical grades are converted to a numerical rating from 1(F) to 5(A), with 5 being the best. Based on this system, estimates for expected failure of assets are determined by multiplying the elements of an asset in a certain condition by the probability of failure of the element, and summing the elements in each condition state. A sample equation is shown below (AbouRizk and Siu 2008):

$$E(L) = E(L_A) + E(L_B) + E(L_C) + E(L_D) + E(L_F)$$

where

$$E(L_j)=\text{Probability(asset failing while in condition j)x(\# of elements in condition j)}$$

This methodology has its limitations, as the ASCE condition rating system tends to be very subjective. The next step after determining the expected failure of an asset is determining the impact of failure of the asset, and the product of these two values is the risk severity of an asset. Determining the impact of asset failure is also somewhat subjective in nature, and will vary depending on what risk factors an agency considers to have most impact. AbouRizk and Siu (2008) provide an example from the City of Edmonton that uses five areas to measure impact of failure and assigns the following weights (in parentheses) to each area: safety and public health (33%), growth (11%), environment (20%), monetary value required to replace an infrastructure element (20%), and services to people (16%). As these impact areas and their weights demonstrate, the impact of failure relates to the values of the communities that an agency serves.

Once the expected failure of an asset and the impact of failure are determined, the risk severity can be calculated as the product of the two values. AbouRizk and Siu (2008) define risk severity zones as shown in Table 4. Once again, the specified risk severity zones show the subjective nature of both the expected failure of an asset and the impact of failure.

Table 4. Sample Risk Severity Zones (AbouRizk and Siu 2008)

Zone	Description
Acute	An *acute* level of severity is one in which both the expected failure and the impact of each unit of failure are intolerably high. At this level, there is the potential for loss of life if an asset fails combined with a high likelihood that an element asset will fail.
Critical	If the asset is deemed to be at a *critical* level of risk, then either the expected failure will be high and the impact substantial or the impact of an asset's failure will be devastating and the probability of failure still moderate.
Serious	Assets with a *serious* level of risk may have severe or substantial levels of impact; however, these tend to be combined with a low level of expected failure. As such, assets at this level of risk will require attention, yet their needs do not necessarily require immediate rehabilitation or repair.
Important	An asset considered to be at an *important* level of risk corresponds to a situation where the levels of expected failure and impact can be addressed in keeping with a municipality's strategic approach. An important level of risk has been anticipated for most elements.
Acceptable	The *acceptable* level of risk represents a situation in which the combined expected failure and level of impact are manageable.

In light of the 2007 collapse of the I-35W bridge in Minneapolis there has been increasing interest in incorporating risk into transportation asset management as these systems relate to bridge management. Cambridge Systematics, Inc., in collaboration with Lloyd’s Register, a firm that specializes in risk management in the marine, oil, gas, and transportation sectors, developed a highway bridge risk model for 472,350 U.S. highway bridges, based on National Bridge Inventory (NBI) data (Maconochie 2010).

The model developed in this paper used Lloyd’s Register’s Knowledge Based Asset Integrity (KBAI™) methodology, which was implemented in Lloyd’s Register’s asset management platform, Arivu™ (Maconochie 2010). In this case, risk was defined as the product of failure multiplied by the consequence of failure. However, a failure was not defined as a catastrophic failure. Failure was defined as a bridge service interruption, which included emergency maintenance or repair, or some form of bridge use restriction. The model then predicted the mean time until a service interruption. A so-called highway bridge risk universe, as shown in Figure 8, can be visualized using the Arivu™ platform (Maconochie 2010).

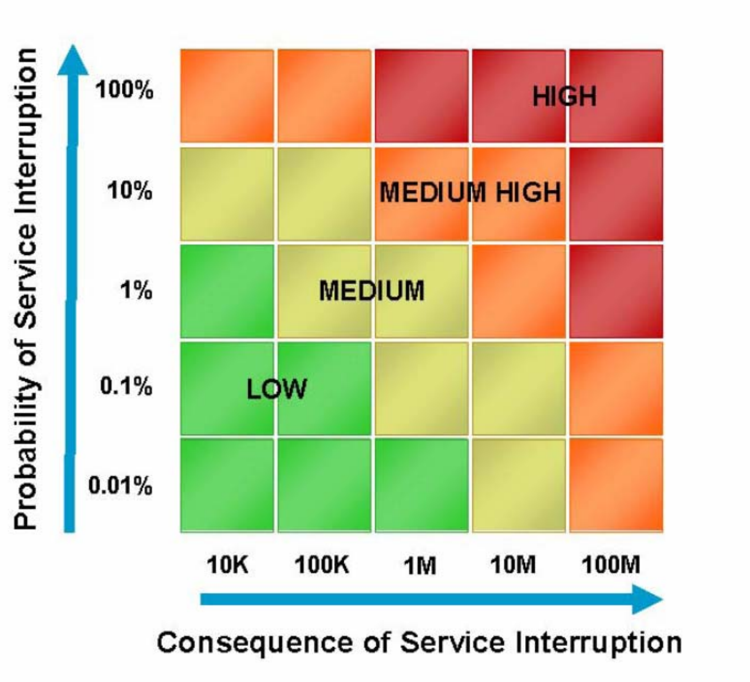


Figure 8. Highway bridge risk universe (Maconochie 2010)

The probability of service interruption is calculated based on three risk units: deck, superstructure, and substructure. The probability that each one of these units would cause a service interruption is calculated, then these probabilities are added together to determine the overall probability that a bridge will experience a service interruption in the next year. Consequence of service interruption is determined using a number of bridge characteristics, such as ADT, percentage of trucks, detour distance, public perception, and facility served, that indicate the relative importance of the bridge to the network. It should be noted the consequence of service interruption is dimensionless and allows the user flexibility in that the characteristics used to determine the relative importance of the bridge can be modified (Maconochie 2010). This model has a variety of potential applications. It can be used to prioritize bridge investments, to minimize risk, and prioritize bridge inspections.

An analysis of past NBI ratings to predict bridge system preservation needs was done for the Louisiana Department of Transportation and Development (LaDOTD) by Sun et al. (2004). At the time, the LaDOTD was in the process of transitioning to the use of AASHTO's PONTIS bridge management software. PONTIS requires detailed element level bridge inspection data known as Commonly Recognized elements (CoRe). Collecting element level bridge inspection data takes years; so, an innovative approach was developed using readily available historic NBI data. Deterioration processes of three NBI elements were studied to develop element deterioration models. Bridge preservation plans and cost scenarios were developed using this readily available NBI data along with current LaDOTD practice and information (Sun et al. 2004). This illustrated that NBI data can be used to evaluate long-term performance of bridges under various budget scenarios.

For capital budgeting needs, decision makers often use rankings to prioritize investment in transportation projects. Several different methods can be used to prioritize bridge projects, including benefit cost ratio (BCR) analysis, the California Department of Transportation's Health Index (Johnson and Shephard 1999), or the FHWA's Sufficiency Rating (SR) formula (FHWA 1995).

Dabous and Alkass (Dabous and Alkass 2010) developed a method to rank bridge projects based on Multi-attribute Utility Theory (MAUT). Based on interviews with bridge engineers and transportation decision makers, the authors selected MAUT as the prioritization methodology since it allowed decision makers to include multiple and conflicting objectives, incorporating both qualitative and quantitative measurements. Utility functions were developed using the Analytical Hierarchy Process (AHP) and the

Eigenvector approach. A case study was used to demonstrate the potential application of this method (Dabous and Alkass 2010).

As mentioned earlier, many international agencies incorporate risk assessment into various components of their TAM processes. There are several local, state, and national level examples of risk applications in TAM systems. For example, the City of Edmonton places infrastructure assets, such as recreational facilities, buildings, parks, roads, drainage, traffic control devices, street lighting, and transit (AbouRizk and Siu 2008) into various risk severity zones.

England's Department for Transport (DfT) has incorporated risk assessment methods into its project prioritization process. Projects or project types are assigned a score that is based on a risk matrix. Projects that have a higher score are given more attention in the investment decision making process. Risk of failure of a project is based on the probability, or likelihood, of individual components that contribute to the overall probability of failure. These components are cause, defect, exposure, and effect. DfT defines the likelihood (L) of a risk event using the following equation:

$$L(\text{Risk Event}) = L(\text{Cause}) * L(\text{Defect}) * L(\text{Exposure}) * L(\text{Effect})$$

For roadway assets, Highways Agency look-up tables provide the values of likelihood of failure. Typically, projects would have different likelihood values for each component (cause, defect, exposure, and effect), which would be determined from separate tables (Geiger et al. 2005). The likelihood of a risk event can be determined for a variety of projects by using the aforementioned process. Performing this sort of standardized risk assessment allows for the identification of the highest risk projects. This type of assessment can be used to calculate a risk score for a variety of projects so that projects with the greatest risk can be identified, and investment can be focused on these high risk projects (Amekudzi 2009).

The DfT prioritizes roadway maintenance projects through the use of a scoring matrix. Highways agency managers determine a score for each project. This score is reviewed at value management workshops, which include representatives from project sponsors, pavement treatment specialists, and Highways Agency program development staff. Projects also must be analyzed with a software package known as SWEEP. This software analyzes current conditions and future life-cycle treatments over a 60 year time horizon. SWEEP calculates an Incremental Economic Indicator (IEI), user costs, and estimated project costs for various treatment options.

Table 5 shows the value management scoring framework for maintenance projects. Ultimately, the analysis used in this scoring methodology results in a four year program of investment.

An example of incorporating risk as it applies to bridge maintenance is a program called *Whichbridge*, which was developed by Main Roads in Queensland, Australia (Amekudzi 2009). This program assesses the risks related to the condition of a bridge and assigns a numerical score to each bridge. Some of the factors used in the determination of bridge condition include: the condition of bridge components, the effects of defective components, component materials, environmental impacts, traffic volumes, and others. The program uses data from inspection reports and ranks structures based on risk exposure and safety considerations. It should be noted that this ranking is relative, not absolute (Geiger et al. 2005).

Keeping with the standard definition, risk is calculated as the product of the probability of failure and the consequence of failure. The probability of failure is determined using a function, whose inputs include loading, resistance, condition, inspection date, and exposure. In this case, consequence of failure refers to cost of failure. Many factors are used to determine cost of failure, including traffic access, road significance, human factors, environmental factors, and others. Risk score results for each region are presented to management personnel. Additionally, the ratio of current scores to the best scores possible in each region allows managers to easily see which region requires the most investment (Geiger et al. 2005).

Many officials at Main Roads believe that risk is a concept that elected officials can easily understand. As such, Main Roads officials have been able to get the attention of elected officials to consider funding allocations that reduce risk. Aiding in this process, Main Roads officials have impressive scenario analyses capabilities. A number of software programs allow Main Roads officials to determine the impact various input factors, such as funding levels, have on network performance (Geiger et al. 2005). An important capability of the programming methods used by Main Roads officials is the ability to determine reductions in risk based on funding allocations. Risk reduction is also a concept that is easily understood by elected officials, who often make funding allocations.

As mentioned in the previously, Edmonton, Alberta, Canada incorporates risk analysis in the transportation decision-making process. First, assets with similar characteristics are grouped together. Data about the present and previous condition states, and rehabilitation and repair work, is collected for the assets. Asset condition is then determined using a standardized condition rating approach. Infrastructure assets are presumed to fail in one of two ways, suddenly and unexpectedly or gradually and expectedly. This approach uses over 150 deterioration curves and probabilities to determine expected failure. The severity of asset failure is then compared to that asset's replacement value so that the highest priority assets can be identified (Amekudzi 2009).

Table 5. Value Management Scoring Framework for Maintenance Projects in England (Geiger et al. 2005)

Score	Justification	Safety (0.2)	Value for money (0.3)	Reduction of disruption (0.4)	Environment (0.1)
80-100	Fully justified	Substantial deficiencies and linked high accident rating, supported by analysis	Proposed option is appropriate for the defects and has an IEI > 5.0 compared to "do minimum" option	Reduction of user costs > 50% relative to "do minimum" option	Projects will have a strong positive impact on a significant and clearly defined environmental problem
50-79	Good justification	Moderate deficiencies and linked, above average accident rating, supported by analysis OR substantial deficiencies and average accident rating	Proposed option is appropriate for the defects and has an IEI > 2.5 and ≤ 5.0 compared to "do minimum" option	Reduction of user costs > 25% and ≤ 50% relative to "do minimum" option	Projects will have a moderate positive effect on a significant and clearly defined environmental problem
30-49	Moderate justification	Moderate deficiencies and linked, average accident rating, supported by analysis OR substantial deficiencies and low accident rating	Proposed option is appropriate for the defects and has an IEI > 1.0 and ≤ 2.5 compared to "do minimum" option	Reduction of user costs > 10% and ≤ 25% relative to "do minimum" option	Projects will have a slight positive effect on an identified environmental problem
10-29	Poor justification	Slight deficiencies and average accident rating OR moderate deficiencies and low accident rating	Proposed option is questionable for the defects and/or has an IEI > 0.4 and ≤ 1.0 compared to "do minimum" option	Reduction of user costs > 0% and ≤ 10% relative to "do minimum" option	Projects are expected to have a neutral effect on the environment
0-9	No justification	Slight deficiencies and low accident rating OR no deficiencies – Project will have neutral effect on safety	Proposed option is unnecessary or inappropriate and/or has an IEI ≤ 0.4 compared to "do minimum" option	Reduction of user costs < 0% relative to "do minimum" option	Projects are likely to have a negative impact on the environment

As shown above, risk can be incorporated into TAM in various areas to achieve different objectives. For example, the framework developed by Cambridge Systematics can be used to prioritize bridge inspections or to minimize the risk of service interruption. Another feature of the frameworks highlighted above is that decision maker input is an important consideration. This is very important, because as mentioned in the international scan, risk assessment can be used as a way to inform and garner support from elected officials (Geiger et al. 2005).

2.10 Risk Frameworks in Transportation Climate Change Adaptation

Wall and Meyer present a synthesis of leading risk-based frameworks for infrastructure for climate change adaptation. Many of these selected leading frameworks are from Australia, Canada, and the United Kingdom. Three primary motivations served as the impetus for adaptive framework development, legislative mandates, extreme weather events, and internal agency initiatives. Since climate change inherently involves considerable uncertainty, many of the frameworks relied upon existing risk management practices, particularly the ISO 31000:2009 Standard, which was discussed earlier. It should be noted that the ISO 31000:2009 standard was primarily informed by the AS/NZS 4360:2004 – *Risk Management* (Wall and Meyer 2013).

The frameworks reviewed by the authors emphasized three different types of adaptation, physical infrastructure and assets, operations and maintenance, and organizational management. However, the frameworks tend to place the greatest emphasis on physical infrastructure and assets, followed by operations and maintenance and then organizational management. Commons barriers and limitations identified that occur frequently are data limitations, treatment of risk, availability of sufficient resources; those barriers and limitations that do not occur as frequently included legal, political, regulatory barriers, and uncertain future demand. To address some of these barriers and limitations the authors recommend incorporating infrastructure asset data needs into existing transportation asset management programs; incorporating these frameworks into existing TAM programs can also reduce required resources. Public outreach and input from elected officials can aid in the definition of acceptable levels of risk, types of risk, and thresholds. Lastly, although many reports and agency directives and policies exist that detail frameworks, there are limited case studies available that detail the successes and failures of implementation of these frameworks (Wall and Meyer 2013).

Oswald and McNeil developed a methodology that can be used to incorporate climate change adaptation into the transportation planning process. This process utilized a spreadsheet-based tool known as the Climate Change Adaptation Tool for Transportation (CCATT), which is a decision-support tool. Utilizing the Long Range Transportation Plan (LRTP) timeline, the CCATT recognizes uncertainty and utilizes multiple climate change scenarios. The CCATT involves a step-by-step approach that evaluates climate change scenarios and impacts, inventories and identifies at-risk existing and proposed infrastructure, and identifies potential adaptation strategies. Since climate change impacts vary based on geographic region, the CCATT is applied in a case study in the Mid-Atlantic region at a Metropolitan Planning Organization in northern Delaware. This case study demonstrates that this tool and approach can be used in a real world transportation planning environment (Oswald and McNeil 2012; Oswald et al. 2013).

As it relates to climate change adaptation activities in the transportation sector, there are a variety of risks to address and a number of different strategies to manage and mitigate these risks. Many transportation agencies address climate change adaptation within the context of managing extreme weather events and natural disasters. Extreme weather events and natural disasters do not include the words climate change, nor global warming, and are therefore more palatable to elected officials and executive leadership at agencies in jurisdictions that are not as progressive when it comes to climate change adaptation. This was reflected in AASHTO's 2012 Spring Meeting; three state DOTs shared their experiences related to extreme weather response and although ostensibly these agencies may not be adapting to climate change, in reality they are incorporating adaptation into their business processes (AASHTO 2012).

Outside of the transportation profession, other groups within the scientific community now also terminology related to managing extreme weather. The IPCC released a Summary for Policymakers that discusses the important findings from the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), which examines the scientific literature related to climate change, extreme weather, and climate events (Field et al. 2012). In particular, this summary emphasizes the impact of exposure and vulnerability to the severity of climate change impacts; exposure is defined as the assets (persons, infrastructure, social and cultural assets, etc.) and vulnerability as the susceptibility to adverse impacts. For example, well-developed coastal communities are both more vulnerable and more exposed. Naturally, wealthy nations and communities possess more resources to mitigate and respond to adverse impacts (Field et al. 2012).

Exposure and vulnerability determine the risk of disaster and disaster response can serve to improve resilience and adaptive capacity. Climatic changes can alter the frequency, intensity, spatial extent, duration, and timing of extreme weather events. Although many extreme weather events continue to occur due to natural variability, anthropogenic climate change will also affect future extreme weather events. Given that by their nature extreme events are a rarity, limited data is available to make proper assessments regarding their frequency or intensity. Nonetheless, there is evidence that extremes have changed due to anthropogenic causes, particularly increases in atmospheric concentrations of greenhouse gases (Field et al. 2012).

Economic disasters related to weather and climate increased over the past few decades, but with a large degree of spatial and temporal variability. Even so, the primary cause of increased economic losses is increased exposure of persons and economic assets to weather and climate disasters. Understanding the temporal and spatial influences on vulnerability is critical to the development of appropriate adaptation and risk management strategies. Furthermore, national systems are the most essential component of building effective risk management capabilities (Field et al. 2012).

Adaptation and risk management strategies that account for both current and future climate change scenarios are known as so-called “low-regrets” measures since they offer a beneficial starting point while also providing the capacity to address future projections. Additionally, effective risk management strategies include a broad range of mechanisms to reduce and transfer risk while simultaneously accounting for multiple hazards. Since the state of knowledge regarding climate science changes regularly, iterative risk management strategies improve adaptation efforts (Field et al. 2012).

A risk appraisal is a critical element of an asset management system when a TAM system is used as a platform for climate change-related decision making. As previously discussed, many different approaches exist that can be utilized to perform a risk appraisal, including but not limited to the use of Bayesian decision theory, fuzzy theory, scoring methods and Delphi process. An example taken from the UK Highways Agency effort at developing a climate adaptation strategy is given below (Parsons Brinckerhoff 2008). The primary criteria used to assess vulnerabilities included:

- "Uncertainty – compound measure of current uncertainty in climate-change predictions and the effects of climate change on the asset/activity
- Rate of climate change – measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity
- Extent of disruption – measure taking into account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important if it affects a high proportion of the network, or a small number of highly strategic points on the network
- Severity of disruption – measure of the recovery time in the event of climate-related event, e.g., flood or land slip. This is separate from "how bad" the actual event is when it occurs, e.g., how many running lanes you lose; it focuses on how easy/difficult it is to recover from the event, i.e., how long it takes to get the running lanes back into use."

Each of these criteria was ranked on the basis of a high (3 points), medium (2 points) or low (1 point). For example, for extent of disruption, three points were assigned if the disruption was expected to affect 80 percent of the network, or any strategic route in the network; two points for 20 to 80 percent disruption; and one point for less than 20 percent disruption. Relating to the severity of disruption, three points are assigned if the duration is greater than one week; two points if it lasts one day to one week; and one point if it lasts less than one day. Based on the risk appraisal and a combination of the different risk factors, the Highways Agency identified the following vulnerabilities as being highly disruptive and time critical with high levels of confidence in the appraisal (Parsons Brinckerhoff 2008):

First Tier

- Pavement skid resistance
- Identifying best ways of investing resources/investment appraisals

Second Tier

- Wind actions (loads) applied to superstructures
- Designs for increased scour for foundations
- Pavement material integrity
- Strategic geographic importance of a region
- Network resilience
- Budgeting
- Staffing

Third Tier

- Pavement materials specification and construction details
- Design of pavement foundations
- Design of bearings and expansion joints

- Surface water drainage
- Attenuation and outfalls
- Pavement maintenance
- Flooding

The basics steps required in any climate change-related vulnerability assessment include: identifying what changes in climate and weather are likely to occur that will affect the environmental conditions associated with the assets under an agency's control; estimating the vulnerability of the different assets to these changes; and conducting a risk appraisal for each asset category and likely climate change scenarios. The next step would include what adaption strategies an agency might consider and the level of climate/weather change that would trigger the use of these strategies, and an assessment of the cost effectiveness of these strategies in the context of different asset categories. Similar to the UK Highways Agency report, it is also important to identify the units or managers in an agency that would be responsible for implementing these strategies.

2.11 Climate Change Adaptation Applications in Transportation Asset Management

In 2010 the United States Federal Highway Administration (FHWA) released a memorandum requesting applications to conduct climate change adaptation pilot studies at several state departments of transportation and metropolitan planning organizations (FHWA 2010). The goal of the pilot studies was to conduct climate change vulnerability and risk assessments of transportation infrastructure at the selected transportation agencies. Furthermore, the FHWA also released a proposed conceptual model to guide this systems-level vulnerability and risk assessment process. Please see Figure 3 for a flowchart that details the structure of the proposed risk assessment model. This conceptual model consists of three main steps: development of an asset inventory, gathering climate information, and risk assessment of individual assets and the transportation system as a whole from projected climatic changes. The following five agencies were selected to pilot the aforementioned conceptual model: Metropolitan Transportation Commission – San Francisco Bay; New Jersey DOT/North Jersey Transportation Planning Authority – Coastal and Central New Jersey; Virginia DOT – Hampton Roads; Washington State DOT – State of Washington; Oahu Metropolitan Planning Organization – Island of Oahu, Hawaii (FHWA 2010).

These five agencies are both geographically diverse, and diverse in terms of the size of the areas and populations served by the agencies. Additionally, these five agencies can expect a variety of potential climate change impacts, from sea level rise, to increased intensity of coastal storms, to increased precipitation and so on. The Metropolitan Transportation Commission (MTC) of the San Francisco Bay area released a report discussing the results of the pilot (MTC et al. 2011). San Francisco's report is named "Adapting to Rising Tides". Although the region can expect other climate change impacts, the one of most significant interest is sea level rise (SLR). The efforts for this pilot project were aided by a study completed by the San Francisco Bay Conservation and Development Commission (BCDC) that examined SLR-related impacts and vulnerabilities for the entire San Francisco Bay region (BCDC 2011). However, this analysis was performed at a broad level and did not reach the detailed, localized level of analysis of the FHWA pilot, which examines shoreline impacts and vulnerabilities, risks, identifies adaptation strategies, and develops adaptation planning tools for communities in the Bay Area (MTC et al. 2011).

Current projections predict that by midcentury the San Francisco Bay will rise 16 inches (0.41 m) and 55 inches (1.4 m) by the end of the century. A competitive process was used to select the Alameda County shoreline as the sub-region of the Bay Area to be assessed for the pilot project. This sub-region contains significant transportation infrastructure assets such as railways, highways, bridges, the Oakland International Airport, and the Bay Area Rapid Transit (BART) system. Inventorying the selected assets was the first step in the pilot process. Given the seismic risk that the Bay Area faces, seismic vulnerability assessments examined the combined risk of both SLR and seismic phenomena such as ground shaking and liquefaction. The underlying climate science and specific climate impacts expected to affect the sub-region are discussed. Vulnerability assessments were conducted and risk profiles were created for the assets selected for study. Additionally, detailed inundation and overtopping maps were created. Lastly, a detailed adaptation approach methodology discusses how to use the risk profiles to determine appropriate adaptation measures (MTC et al. 2011).

The Hampton Roads region in the State of Virginia was also selected for analysis of potential climate change impacts on transportation infrastructure. Although each pilot is part of the broader FHWA study examining the vulnerability of critical transportation infrastructure to climate change impacts, each pilot is allowed flexibility in its implementation. The Hampton Roads pilot developed a decision model and support tool that aids in the prioritization of elements of the region’s long range transportation plan (LRTP). LRTPs are required by the federal government and must cover a minimum time horizon of 25 years and be updated every four to five years. Like the San Francisco Bay area, the Hampton Roads region is most vulnerable to impacts related to SLR; unlike the San Francisco Bay Area, Hampton Roads is home to the largest naval base on the eastern seaboard of the United States (VDOT et al. 2011).

In order to examine a variety of impacts on the LRTP, multiple scenarios were developed that capture a number of different climate-related and other impacts. The framework used in this pilot study is supported by a quantitative model that is available on the web and implementable via a Microsoft Excel workbook. This model captures scenarios that combine projected climate change impacts with economic conditions, national security events, and additional population growth. Additionally, given the uncertainties associated with climate projections, four types of prioritization are addressed by the model: future transportation projects, existing transportation assets, long-term multimodal transportation policies, and transportation analysis zones, which are typically used to inform regional travel demand models. The results of this pilot study are already being used by the Hampton Roads Planning District Commissions as the regional LRTP is updated (VDOT et al. 2011).

Washington State's pilot study was the only one conducted at the larger statewide level of analysis. The Washington State Department of Transportation (WSDOT) also used scenario planning methods to conduct its pilot study. WSDOT inventoried its assets and obtained climate data from University of Washington climate scientists, both using GIS. WSDOT has a decade of experience performing project risk management using its proprietary Cost Estimate Validation Process ® and also through cost risk assessment workshops, which were used to develop a risk assessment method for the climate change analysis. Fourteen workshops engaged a variety of stakeholders from around the state and resulted in qualitative vulnerability assessments. WSDOT developed scenarios, using spreadsheets to display climate impact ratings and criticality, and GIS to display maps of climate impacts (Maurer et al. 2011).

The Oahu Metropolitan Planning Organization (OahuMPO) undertook its pilot in three stages. In the first stage climate change factors were analyzed. 2050 and 2100 were selected as time horizons and a baseline of 1970 to 2000 was set as a basis for comparison. Next, a two day workshop was held that included representatives from the City of Honolulu, the State of Hawaii, the Federal Highway Administration, and the private sector. This workshop led to the selection of five transportation assets for analysis. Lastly, the vulnerability of these five assets to climate stressors was analyzed. OahuMPO was able to extensively leverage local climate and transportation expertise in its pilot (SSFM International 2011).

The North Jersey Transportation Planning Authority (NJTPA) pilot study examines the jurisdiction of all three MPOs in New Jersey, essentially covering the geographic area of the entire state. This pilot study consisted of three key steps, building an asset inventory and identifying critical assets, gathering information on potential future climate scenarios, and finally, assessing the vulnerability and resilience of critical assets. The asset inventory and criticality assessments involved using GIS with the best available transportation infrastructure asset data. A vulnerability analysis was performed by superimposing climate datasets and transportation infrastructure datasets. This pilot study highlighted the difficulties presented by the uncertainties associated with climate change projections, data availability and data quality, and a lack of guidance from

Federal authorities on adaptation planning (Cambridge Systematics 2012a). Lessons learned from the aforementioned pilot studies will inform the case studies in the State of Georgia.

Outside the United States, particularly in the United Kingdom (UK) and New Zealand (NZ), several national, regional, and local governments have already incorporated climate change considerations into their TAM systems. As noted earlier, the UK's Highways Agency recognized that climate change may hinder the agency's ability to provide an effective road network, and developed its adaptation strategy (Parsons Brinckerhoff 2008). This strategy identifies over 80 agency activities that may be affected by climate change and sixty percent of these activities are expected to occur within a relatively short time period. The UK Highways Agency's plan also considers climate change everyday decision-making processes, particularly in the Agency's TAM systems (Parsons Brinckerhoff 2008).

Additional recommendations from the Highways Agency include changing design standards for assets with a long design life, such as bridges, to account for predicted climatic changes. This strategy also recognizes the uncertainties associated with climate change and notes that these uncertainties should not hinder the decision-making process. Higher temperatures and increased rainfall intensity are specifically noted as factors that may reduce asset performance. An interesting concept mentioned in the Highways Agency strategy is climate analogues. A climate analogue is a current climate that is similar to the future predicted climate of a specific location, i.e., the south of the UK and Lisbon, Portugal. Looking at the climate analogue can help determine the amount of adaptation that might be necessary for a given region (Parsons Brinckerhoff 2008).

Also at the national level, the New Zealand Transport Agency (NZTA) incorporates climate change into its asset management system. An internal assessment found that NZTA's asset management practices have the ability to adjust standards for assets in order to manage the impacts of climate change (Kinsella and McGuire 2005). NZTA determined that its current asset management system is able to manage the impacts on most of the network, but assets with a design life greater than 25 years, such as bridges and culverts, may require further analysis. An economic analysis concluded that assets with a design life of 25 years or less did not need changes in design, construction, or maintenance standards. NZTA suggests that the standards for these shorter design life assets can be modified as the impacts of climate change are observed. Furthermore, NZTA modified its Bridge Manual to account for the impacts of climate change as a design factor (Kinsella and McGuire 2005).

In the UK, local highway authorities must develop a Transport Asset Management Plan (TAMP), which became mandatory in the UK in 2006 as part of the Whole of Government Accounting initiative, if they want to raise money through public sector borrowing (Webster and Allan 2005). At the regional level, a joint report that includes ten local highway authorities and other transportation organizations, regarding the development of TAMPs in the Greater Manchester Area, UK contains a section on climate change (Greater Manchester Passenger Transport Executive 2008). Many climate models predict increases in the occurrence of extreme weather events in the next 20 years, which is accounted for in a TAMP since a TAMP covers approximately 20 years. The Great Manchester Plan identifies six actions listed below in the climate change section, with the most important being the need to develop risk models to better inform long term planning (Greater Manchester Passenger Transport Executive 2008):

1. Establish service levels and renewals strategies in line with carbon reduction targets in particular for street lighting and traffic signals
2. Identify carbon reduction measures through procurement and construction management
3. Adaptive strategies – incorporate climate change forecasts into costed risk models for transport network
4. Drainage – develop joint working group to address data sharing with United Utilities and Environment Agency
5. Investigate potential for further enhancing system performance/deficiency criteria
6. Ensure climate change and biodiversity considerations are incorporated into grounds maintenance strategies

At the local level, Transport for London and the London Climate Change Partnership incorporated TAM into their climate change strategy, the *Climate Change Adaptation for London's Transport System* (Greater London Authority 2005). The London Climate Change Partnership is a stakeholder group coordinated by the Greater London Authority that consists of over 30 organizations with representation from national, regional, and local government. As part of its asset management system, London Underground (LU) has mapped its assets against 200 identified risks and opportunities from climate change, identified critical points and their impacts on business, and developed correlation graphs between climate change parameters, effects on asset management, and predicted costs and savings (Woolston n.d.). LU has also developed a systematic approach to mapping identified system failure counts with weather patterns, such as sunshine, rainfall, humidity, and temperature, and has also developed a financial analysis of these results.

As shown in the aforementioned international examples, prior to incorporating climate change into an asset management system, the owners of the asset management system need to understand the potential impacts of climate change on the infrastructure assets they manage. After these impacts are determined, climate change considerations can be incorporated into the various components of an asset management system. However, this requires the sharing of information and cooperation between the scientific community, in particular those with expertise in climate science, and transportation officials. At the very least, efforts to incorporate climate change into asset management systems will foster better communication between transportation officials and members of the scientific community with expertise in climate science.

CHAPTER 3

CLIMATE CHANGE PROJECTIONS

3.1 Historic Climate and Climate Stressors

Prior to assessing the future climate for the case studies areas under consideration, it is important to understand the existing climatic conditions. This step will include assessing the climatic conditions that currently inform the design standards in use at the case study agencies. As discussed by Meyer (2008), oftentimes it is difficult to alter existing design standards that are based on historical climate conditions. However, as discussed previously, agencies cannot expect historic climate conditions to continue into the future. Nonetheless, average temperature and precipitation conditions do not result in negative impacts on transportation networks. It is significantly more likely that shorter-term extreme weather events, e.g., a heat wave, torrential precipitation over the span of several hours, intense precipitation over several days, a coastal storm or hurricane, etc., will adversely affect the provision of transportation infrastructure services. Thus, a critical component of this research is the development of a survey for agency managers that assesses which climate stressors pose the greatest threat to the operations of transportation infrastructure and determining at what thresholds or triggers, e.g., three hours of rainfall at a rate greater than one inch per hour or three consecutive days of temperatures greater than 100°F, agency operations will be adversely affected.

The impact of extreme weather conditions on the Nation's infrastructure was particularly evident in the summer of 2012. In Washington, D.C. 100-degree heat caused a jet airliner to sink into softened asphalt and rail lines buckled in the heat, derailing a subway train. In Texas the combination of extreme heat and drought impacted roadway subsurface conditions, causing clay-rich soils to shrink and led to extreme cracking. Extreme heat in the Northeast and Midwest caused sections of roadway to expand beyond their design limitations, leading to "pop-ups" and potentially hazardous speed bumps. So-called one hundred year events continue to occur with greater frequency and climatic changes could lead to potentially catastrophic failures of highway segments. However, transportation agencies are taking steps to adapt; transit operators now conduct more frequent inspections of railways, levees in New Orleans are higher, and culverts were resized in Vermont after damage from Hurricane Irene, just to name a few examples (Wald and Schwartz 2012).

3.2 Climate Analogues

An interesting concept discussed in the UK Highways Agency report is climate analogues. This report defines a climate analogue as a current climate that is similar to a projected future climate of a given location. These analogous climates serve as an intuitive manner in which to conceptualize the potential future impacts of climatic change on a particular location and also provide insight into the scope and magnitude of adaptations that a particular locale may require (Parsons Brinckerhoff 2008). In the United States several regional climate change reports elude to this concept of climate analogues, one in the Midwest (Katharine Hayhoe et al. 2010) and another in the Northeast (Frumhoff et al. 2007). Figure 9 and Figure 10 show climate analogues for these two regions, respectively.

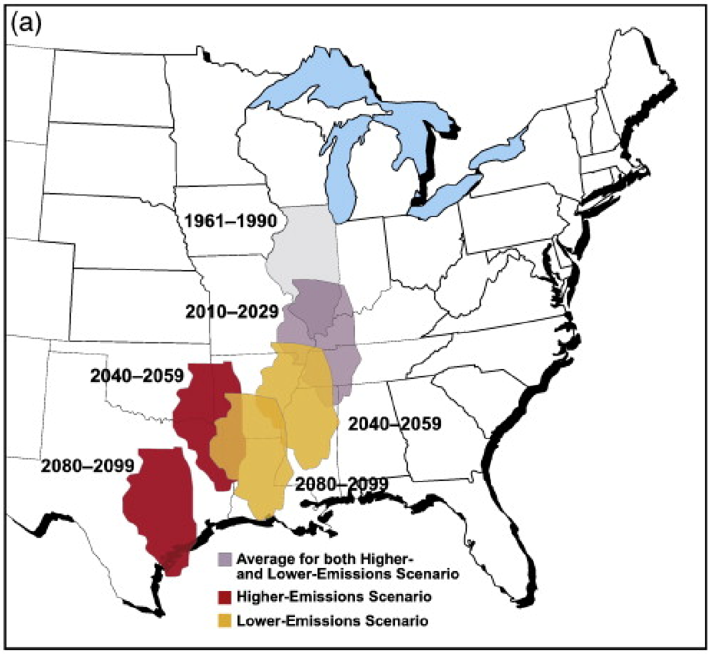


Figure 9. Projected future climate of Illinois under various emissions scenarios based on temperature and precipitation (Katharine Hayhoe et al. 2010)

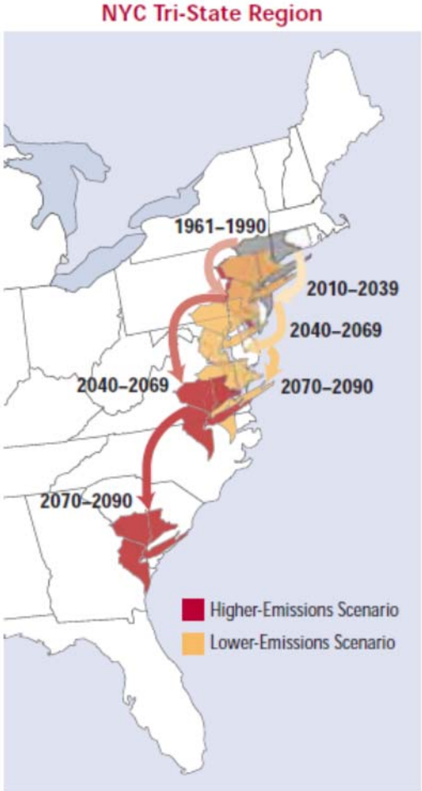


Figure 10. The migration of NYC Great Metro Area climate based on heat index (Frumhoff et al. 2007)

In Australia the National Climate Adaptation Research Facility commissioned a year-long study to examine the potential of learning from climate analogues for three selected target communities. This analysis focused on several sectors: land use planning, infrastructure, housing and building, health services, and ecosystem services. Although there are many similarities between the target and analogue communities, there are also significant differences; many of the similarities are attributed to state-based regulations (Kellett et al. 2011). Researchers at the CGIAR Research Program on Climate Change, Agriculture and Food Security developed an open-source software tool, which is also available via a web interface, that connects sites with statistically similar climates spatially and temporally (Ramirez-Villegas et al. 2011). Even though this tool focuses on agriculture, crops, and food security, it provides an impactful way to view potential future climates.

3.3 Climate Projections

Notwithstanding shorter-term impacts, in the longer-term, climatic changes that affect average seasonal or monthly values of temperature, precipitation, and sea level 25, 50, or 100 years in the future may very well have a significant impact on transportation infrastructure provision. In order to adequately assess the impacts of climate change on transportation infrastructure, transportation professionals must understand both current climatic conditions and climate projections. Since transportation professionals are not climate scientists, this requires significant assistance and input from the climate science community. However, climate projection data is available that can inform the transportation investment decision-making process, although this data is typically not in the most user-friendly format nor easily accessible.

Complex, mathematical formulas inform the climate models that are used to develop climate projections used in adaptation planning. The consensus within the scientific community is that climate models provide credible projections of future climatic conditions, particularly at continental and global scales. In the words of the IPCC (Randall et al. 2007):

“There is considerable confidence that climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above. This confidence comes from the foundation of the models in accepted physical principles and from their ability to reproduce observed features of current climate and past climate changes. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation). Over several decades of development, models have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases”.

By definition, a climate model is a mathematical representation of real world conditions and as such cannot predict future climate with complete accuracy. However, climate models are regularly analyzed by comparing their outputs with current climatic conditions. Current climate models skillfully represent numerous mean climate features such as the large-scale distributions of temperature, precipitation, radiation, wind, oceanic temperatures, currents, and sea ice cover. Climate models used to forecast the weather several days out use a significantly different type of prediction than the techniques these models utilize to predict long-term climate change (Randall et al. 2007).

3.4 Climate Models

Climate models take into account both anthropogenic and natural influences in their projections. Modern climate models can accurately simulate global temperatures over the past century, warming in the Arctic, and short-term global cooling that follows volcanic eruptions. Ultimately, the climate models derive their confidence from the fact that they are based upon well-established physical principles. Even so, these models still contain significant errors. It is particularly difficult to simulate small-scale processes and their interaction with larger features. Models thus far cannot accurately represent clouds, and the confidence of global models decreases at smaller scales. These models also result in a significant range of uncertainty in global temperature change associated with various levels of greenhouse gases. Nonetheless, all the models predict significant warming associated with increases in the amounts of greenhouse gases. The predicted warming is also consistent with observed conditions and reconstructions of past climate (Randall et al. 2007).

So-called Atmosphere-Ocean General Circulation Models (AOGCMs) reproduce observed features of recent climate. Physical laws inform AOGCMS, which can more accurately simulate future climate at continental and larger scales. However, there is greater confidence in certain variables, such as temperature, than in others, such as precipitation. In particular, it is difficult for the AOCGMs to accurately simulate cloud cover, sea ice, and model albedo (Randall et al. 2007). By definition, the Global Circulation Models (GCMs) produce results on a global scale, i.e. at large spatial scales. Earth Models of Intermediate Complexity (EMIC) are not as computationally intensive as

GCMs and are used in conjunction with GCMs to assess the parametric uncertainties of climate projections in the U.S.

3.4.1 Model Downscaling Techniques

In order to inform transportation decision making, higher resolution so-called downscaled models must be used. There are two primary downscaling techniques, dynamic downscaling and statistical downscaling. Dynamic downscaling produces regional models, is significantly more complex, and computationally intensive (Dalton and Jones 2010). Additionally, present-day dynamically downscaled models do not produce results at a resolution that is detailed enough for transportation decision making.

There is debate amongst the climate science community as far as what GCMs are the most accurate, since there are a number of research centers around the world that produce GCMs, and also debate over which downscaling techniques are the most appropriate. However, the scientific community recognizes this. Both the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Global Change Research Program (USGCRP), via the National Climate Assessment (NCA) address this issue. NOAA held a workshop whose goal was to identify high priority areas for further research. In particular, the focus of this workshop was regional and local scale impacts since regions and localities will be the entities primarily responsible for adapting to climatic change. This being the case, there is an urgent need for high quality actionable climate projections at the regional level since the impacts of extreme weather, such as coastal storms along the Gulf and East Coasts are particularly acute. Nevertheless, the understanding of global climate change on regional extreme weather events needs improvement, as does the understanding of regional climate trends and multi-decadal variations (NOAA 2011).

While the participants in the NOAA workshop acknowledge that there is significant economic impact from extreme weather events, which also garner significant public interest, they also mention that the science underlying regional models requires improvement. The mechanisms that inform regional models are numerous and complex. NOAA recognizes that high-quality, credible science should inform decision making related to climate change adaptation. In particular, there is not a comprehensive understanding of the mechanisms that influence the Arctic Ocean, nor an adequate understanding of the impact of the Arctic on other regions. As an agency NOAA views this area as mission critical since it directly relates to the agency's science mission, which is "to understand and predict changes in climate, weather, oceans, and coasts" (NOAA 2011).

The Global Change Research Act of 1990 mandates that at least every four years a scientific assessment known as the National Climate Assessment (NCA) must be developed and delivered to both the President and Congress; the next iteration is the NCA 2013 Report. NCA 2013 also recognizes that regional models at multiple temporal scales are required in the future. These regional models must be downscaled to a spatial resolution that permits the identification of climate change impacts at the local level. However, while utilizing downscaled climate projections is a critical component of assessment and adaptation, so is an understanding of the variability associated with global climate models, the downscaling methodology, and the range of variability captured by the downscaled results (NCA 2010).

3.4.1.1 Dynamical Downscaling

As mentioned previously, Regional Climate Models (RCMs) are based upon the outputs of global models and developed using dynamical or statistical downscaling methods. Dynamical downscaling requires global model outputs of high temporal resolution to inform regional simulation models, which are computationally intensive. Additionally, a limited number of global models are available that produce results of a high enough temporal resolution. However, dynamically downscaled models incorporate the relationship and feedbacks between large-scale global circulation patterns and local climate.

3.4.1.2 Statistical Downscaling

Statistical downscaling on the other hand, although less resource-intensive and quicker, assumes little or no change in the relationship between large-scale circulation mechanisms and local-scale climate over time. However, statistical downscaling does incorporate local historical observed data into projections. Statistically downscaled datasets can be generated at the scale of any observational dataset, both station-based and gridded. There is no standardized approach to assess and compare downscaling techniques, but the downscaling technique used is the most significant contributor to data quality (NCA 2010).

3.4.2 Global Climate Models

Naturally, the underlying data that feeds into the global climate models and the associated global circulation models also significantly impact model results. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) established formal structures to compare models and evaluate their outputs in comparison with the recent past. Most climate models currently in use are based upon the Phase 3 Coupled Model Intercomparison Project (CMIP3), which is well-established and supported with a significant amount of literature and the CMIP3-based models utilize the scenarios from the IPCC Special Report on Emission Scenarios (SRES). However, the IPCC's upcoming *Fifth Assessment Report* will utilize Phase 5 Coupled Model Intercomparison Project (CMIP5) stabilization pathways, which are known as Representative Concentration Pathways (RCPs). Since the CMIP3 generation of models represent the largest and most well-established collection of global climate models, the CMIP3 generation of global models will inform this research (NCA 2010).

3.4.3 Climate Model Uncertainties

Of course modeling complex, interconnected global climate systems and then downscaling the results of these global models to regional scales results in uncertainty. Thus far, the climate science community has focused primarily on the uncertainties associated with the science underlying the climate models, but not the climate variable outputs and impacts (NCA 2010). However, transportation engineers in particular are primarily concerned about the uncertainties related to the climate variable outputs that most significantly impact transportation infrastructure. For example, transportation engineers will pay close attention to temperature, precipitation, and extreme weather events since these directly impact daily operations and design standards, whereas ecological impacts, such as lengthened growing seasons, will be of concern to the agricultural community.

3.4.4 Emissions Scenarios

A critical input in global climate models are so-called emissions scenarios. The IPCC Special Report on Emissions Scenarios (SRES) has thus far been the source of emissions scenarios for CMIP3 models (Nakicenovic et al. 2000). As mentioned previously, although the forthcoming *Fifth Assessment Report* will utilize RCPs and CMIP5, this research utilizes climate projections from CMIP3 models and the SRES. The set of SRES emissions scenarios cover a broad range of the driving forces of future emissions and these scenarios are based upon an assessment of the literature, six alternative modeling approaches, and an open process that solicited participation of numerous expert groups and individuals. However, none of the scenarios developed account for future policies that specifically address climate change, i.e., none of the scenarios assume a comprehensive global agreement or system that explicitly reduces GHGs, sulfur, and other driving forces of climate change, e.g. land-use changes (Nakicenovic et al. 2000).

The driving forces of future GHG emissions include, but are not limited to, demographic, social, economic, technological, and environmental developments. Four qualitative storylines consistently describe the relationship between the driving forces and the emissions scenarios quantification. These four storylines cover a broad range of driving forces and the scenarios within each storyline are known as a scenario family. Figure 11 shows a breakdown of the storylines and scenarios. The A1 family describes a future with rapid economic growth, a global population peak mid-century followed by a decline, and rapid introduction of new, more efficient technologies. Within the A1 storyline, the A1FI scenario details a future that is fossil fuel intensive, the A1T describes a non-fossil fuel intensive future, and the A1B describes a balance across energy sources. A2's storyline is one of a heterogeneous world with gradually increasing population and fragmented, regional economic growth. The B1 storyline describes a population peak and decline similar to that of the A1 storyline, but this storyline describes rapid changes in economic structure toward a service and information economy, reducing material intensity and emphasizing the use of clean and efficient technologies. B2's storyline emphasizes environmental preservation and social equity. This storyline focuses on the local and regional scales, describing a future with continuous population growth, albeit at a rate lower than the A2 storyline, intermediate levels of economic development, and diverse technological change (Nakicenovic et al. 2000).

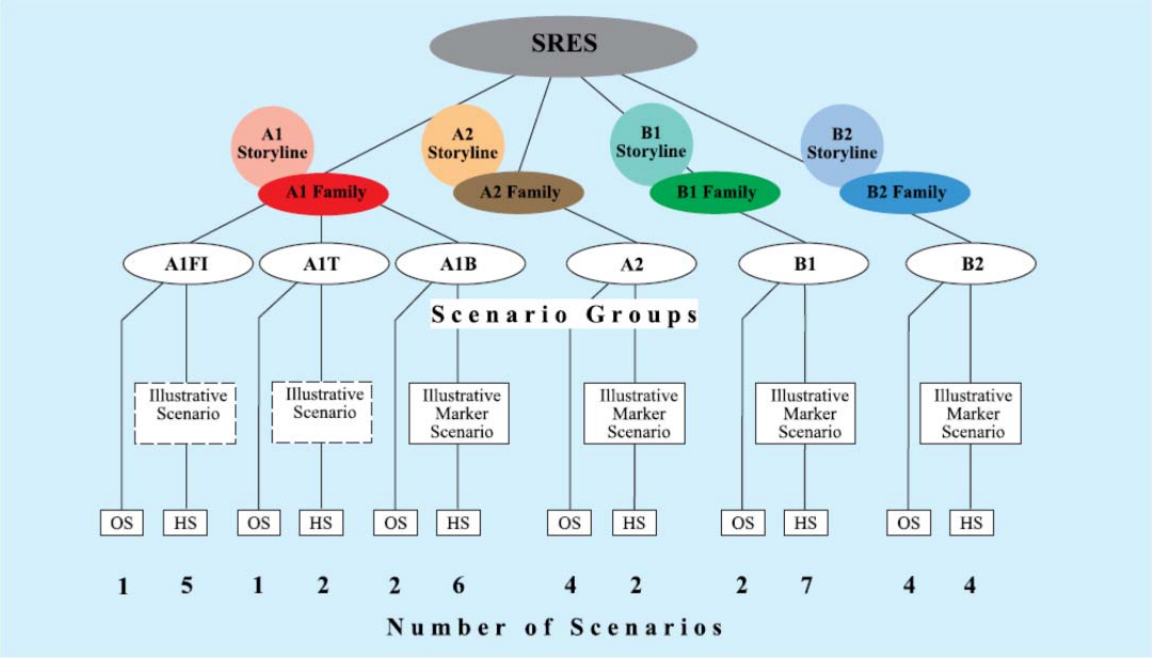


Figure 11. Primary characteristics of the four SRES storylines and scenarios (Nakicenovic et al. 2000)

There are six scenario groups, which feed into the global climate models: A1FI, A1T, A1B, A2, B1, and B2. Given the variety of SRES scenarios and their driving forces, any analysis should consider more than one storyline and several scenarios to capture the range of uncertainties associated with the driving forces behind the storylines and the emissions scenarios. These scenarios are projections through the end of the century and as such, there is inherent uncertainty associated with these long-term projections. Thus, the climate models are better suited for longer-term analysis, i.e. greater than a decade (Nakicenovic et al. 2000).

Given the complexities and uncertainties associated with both the global-scale and downscaled climate models, this analysis will utilize the best available dataset at the time. Given the uncertainties associated with the SRES storylines, this research utilizes three different scenarios from three different storylines, A1FI, A2, and B1. The A1FI scenario is a "high" emissions scenario, the A2 scenario is "moderately high", and the B1 scenario is a "low" scenario. For purposes of this research, each scenario is equally probable in order to account for the inherent range of uncertainty associated with climate projections. To account for the uncertainties associated with the different scenarios, where available, the results of multiple climate models are averaged to capture the range of uncertainties. This analysis utilizes downscaled climate projections, adding additional uncertainty. As mentioned previously, climate change adaptation is an iterative risk management process so it is imperative that decision makers constantly revisit adaptation issues as climate science continues to advance.

3.4.5 USGS Southeast Regional Assessment Project Climate Projections

Notwithstanding, the best available downscaled climate projections are those developed by the United States Geological Survey (USGS) as part of its Southeast Regional Assessment Project (SERAP). Although the purpose of SERAP is to produce high-resolution regional climate projections to aid in determining ecosystem impacts, the high-resolution temperature and precipitation datasets will also be useful to transportation infrastructure managers. SERAP recognizes that although GCMs reasonably predict global-scale climate change, there is considerable uncertainty associated with both the climate models themselves and with the downscaling methodology used. Frequently impact assessments utilize multiple GCMs to develop climate projections based on SRES emissions scenarios and estimate uncertainty as the range of model outputs. However, this can lead to an underestimation of the actual structural and parametric uncertainties associated with climate models, which can propagate to the regional level. This has the potential to give decision makers a false sense of security due to their failure to consider low probability, high-impact events. Even so, as mentioned previously, a central tenet of climate change adaption management is an iterative risk management process that adequately accounts for these large uncertainties (Dalton and Jones 2010).

As mentioned previously, the two primary approaches used to develop high-resolution projections from global-scale models are statistical and dynamic downscaling. These approaches mitigate model biases and correct for undersampling the tails of the distribution in order to better account for uncertainty. Similar to global and regional climate models, downscaled models are also subject to the same structural and parametric uncertainty. The primary objectives of SERAP are to: design and run an EMIC to describe the impacts of parametric uncertainty on climate projections in the U.S.; downscale EMIC and IPCC projections of variables relevant to ecosystem impacts; perform a Bayesian data-model fusion that weights downscaled climate projections according to their performance and structural uncertainty between models; and lastly, to disseminate high-resolution downscaled temperature and precipitation datasets (Dalton and Jones 2010).

3.4.5.1 SERAP Climate Projection Methodology

SERAP's methodology utilizes well-established models, data, and statistical tools. These include coupled AOGCMs from the CMIP3 database and an EMIC developed by the University of Victoria called Earth System Climate Model (ESCM). The following boundary conditions force the statistically downscaled simulations: 16 GCMs, the ESCM, and long-term daily historical weather records and reanalysis data at stations and grid points archived by the National Climatic Data Center (NCDC) and the National Center for Environmental Prediction (NCEP). Furthermore, Bayesian ensemble dressing methods address the structural uncertainty and accuracy of the AOGCMs. Historical simulations from the 16 different groups that contributed to the IPCC's Fourth Assessment Report provide a complete overview of climate from 1900 to 1999. The ability of these GCMs to simulate North America's regional atmospheric dynamics and surface climate patterns has been previously analyzed in the literature and generally speaking, the GCMs reproduce seasonal patterns and climate features (Dalton and Jones 2010).

3.4.5.2 SERAP Emissions Scenarios

AOCGMs from 2000 to 2099 are based upon the SRES A1FI, A2, A1B, and B1 emissions scenarios. The A1FI scenario can be considered a "higher" emission scenario, A2 a "mid-high" scenario, A1B a "mid" scenario, and B1 a "lower" emissions scenario. The EMIC used is the ESCM, which although not fully coupled to an AOGCM, requires fewer computation resources. However, the ESCM still contains many of the dynamic features of a GCM, which allows for exploration of the full probability density function of critical parameters that significantly influence the climate system. Additionally, the use of the ECSM as opposed to one the GCMs results in additional confidence that the uncertainty bounds around the climate projections will contain the actual climate change pathway (Dalton and Jones 2010).

3.4.5.3 SERAP Downscaling Techniques

Temperature downscaling is done with the statistical-asynchronous regression approach, which was originally developed by O'Brien, Sornette, and McPherron (2001). However, this approach was modified to allow for improved simulation of the most impact relevant extremes and the tails of the daily temperature distribution. This asynchronous regional regression model (ARRM) utilizes piecewise regression to reconcile observed quantiles with modeled quantiles and then downscale future projections (Stoner et al. 2012). Precipitation downscaling utilizes the methodology developed by Vrac, Stein, and Hayhoe (2007). This methodology uses a mixture model clustering approach that includes nonhomogeneous transition probabilities that models the occurrence and intensity of daily precipitation. Coupled together, this dual-downscaling approach is applied to the simulation outputs from the 16 GCMs to develop projections to 2100. Retrospective downscaling and observational training utilize long-term cooperative weather station locations in the Southeast from the U.S. Global Historic Climate Network (GHCN). Lastly, this dual-downscaling approach is applied to the ESCM simulation outputs to correct for model bias and better estimate the entire range of temperature values that are excluded due to the EMIC's inability to simulate local-scale processes (Dalton and Jones 2010).

Bayesian model averaging procedure (BMA), or "model dressing" (Draper 1995; Hoeting et al. 1999), is applied to the downscaled GCMs and ESCM simulations to produce more accurate projections of future climate in the Southeast. This Bayesian statistical approach allows for a more comprehensive treatment of the structural uncertainty in projections that are products of the limited sample size of the GCMs. Furthermore, this approach reduces predictive uncertainty since the data-model fusion properly weights the climate projections according to how well the models reproduce historical observations (Dalton and Jones 2010). The downscaled temperature and precipitation projections are available via a web-delivered computer application, the Geo Data Portal (GDP), http://cida.usgs.gov/climate/gdp. Nationally downscaled temperature and precipitation projections were the first datasets made available via the GDP.

3.4.5.4 <u>SERAP Climate Projection Datasets for the State of Georgia</u>

Since temperature and precipitation are the climate stressors with the most significant impact on transportation infrastructure, temperature and precipitation datasets for the State of Georgia are obtained via the GDP. The temperature and precipitation datasets are available with a spatial resolution of 1/8° or approximately 7.5 miles (12 km). These projections are available with a number of GCMs and SRES emissions scenarios.

It should be noted that the downscaled climate projection datasets are still in review (A. Stoner et al. 2012). Although the SERAP Open File Report (Dalton and Jones 2010) is currently available, additional documentation is forthcoming. Chapter 4 provides additional details on the projections used in this research.

CHAPTER 4

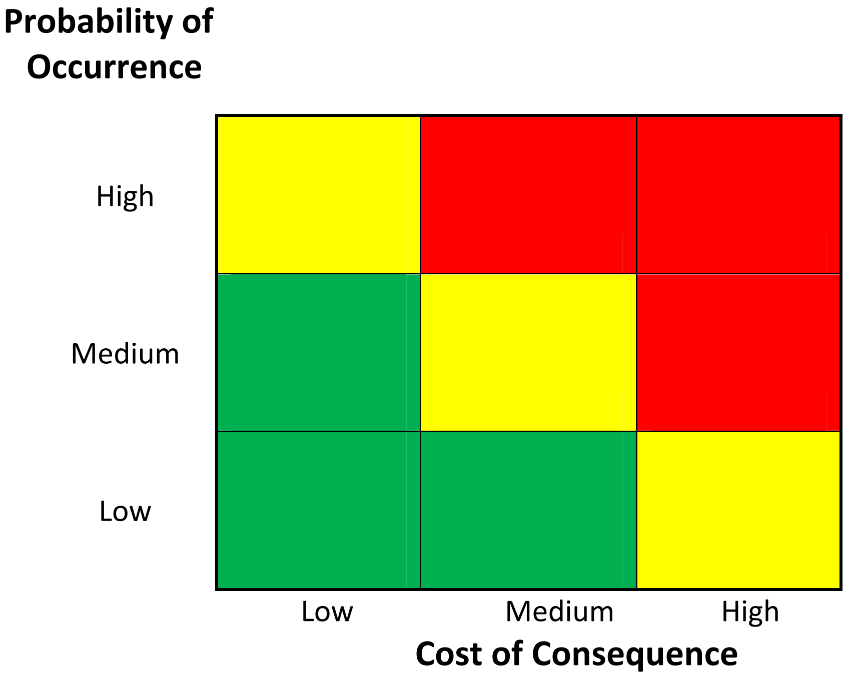
METHODOLOGY

4.1 Background

This research is based on the premise that existing asset management systems can be utilized to incorporate climate change-related considerations into the investment decision-making process. All three case studies agencies have asset management systems of various levels of maturity. An assessment of each agency's asset management system using the maturity scale developed in the *Transportation Asset Management Guide Volume 2* (AASHTO 2011b) will determine the maturity of each system. Another premise of this research is that regardless of the maturity of the asset management system, certain components in the system can be utilized to incorporate climate change-related considerations.

After assessing the maturity of the asset management systems, this methodology involves four primary steps. First, a criticality assessment determines what transportation infrastructure assets are most critical to a given transportation network. Secondly, potential climate change impacts for a particular geographic region assist in the identification of climate stressors. Given the uncertainty of climate projections, climate projections identify plausible future trends, and temperature and precipitation scenarios. Third, using GIS, critical transportation infrastructure is spatially superimposed over various climate stressors and scenarios. Lastly, the most vulnerable, i.e. critical and susceptible to potential climate change impacts, transportation infrastructure assets are identified. These assets can be strategically targeted for additional analysis and potential adaptation activities.

In order to facilitate the identification of adaptation strategies, each case study agency aids in the development of a climate risk matrix. Afterwards, short-term and long-term adaptation strategies are identified based upon the climate risks/stressors identified in the matrix. Figure 12 below shows a sample climate risk matrix for the agency stakeholders to fill in. After identifying impacts with the risk matrix, agency stakeholders can identify different short-term and long-term adaptation strategies. Table 1 provides an illustrative listing of climate impacts and adaptation strategies.



Probability of Occurrence	Low	Medium	High
High	🟨	🟥	🟥
Medium	🟩	🟨	🟥
Low	🟩	🟩	🟨
	Cost of Consequence		

Figure 12. Sample climate change impacts risk matrix

4.2 Criticality Assessment

Given the variation in the scope of the case studies and the size of the agencies, the criticality assessments are not identical. Even so, since the State of Georgia and Savannah – MPC case studies focus on roadways and bridges, these two cases share a similar criticality assessment. This is to say the criticality assessment varies from one agency to another. As was shown in the FHWA climate change adaptation pilots (Cambridge Systematics 2012a; Maurer et al. 2011; MTC et al. 2011; SSFM International 2011; VDOT et al. 2011), the criticality assessment approaches varied across agencies.

Typically, MPOs and agencies that oversee a smaller number of assets or a smaller geographical area, may be able to identify a limited number of specific assets which are considered critical; this was the case with the Oahu MPO, which only examined five assets (SSFM International 2011). It is also likely that the forthcoming FTA climate adaptation pilot studies will utilize different approaches to assess criticality at transit agencies when compared to the approaches used at agencies which primarily manage roadway and bridge assets (FTA 2011). This is also the case with the MARTA case study.

4.2.1 GDOT Statewide and Savannah – MPC Case Studies Methodology

Using Multiple Criteria Decision Making (MCDM) principles, transportation infrastructure assets are scored. These scores determine which criticality category the assets fall into. Using MCDM principles, certain variables or attributes are scored and weighted based upon their relative levels of importance. This approach will allow users to select the attributes they wish to weight, i.e., include in the criticality analysis. In order to accomplish this, a template in Excel is created. For the roadway network, users are able to select from the following attributes:

- STRAHNET Designation
- NHS Designation
- Functional Classification
- Traffic Volume (AADT)
- Condition
- Truck Percentage
- Total Lanes

Attribute data for the roadway links in both Savannah and across the State of Georgia are provided by GDOT's Office of Transportation Data.

Similarly, MCDM principles are used to weight, score and then categorize bridges throughout the state. Once again, users are able to select which attributes they wish to weight and include in the criticality analysis. For bridges, users can select to weight the following attributes:

- Inventory Rating
- Weight Posting
- Scour Criticality
- Fracture Criticality
- Bypass Length
- Condition

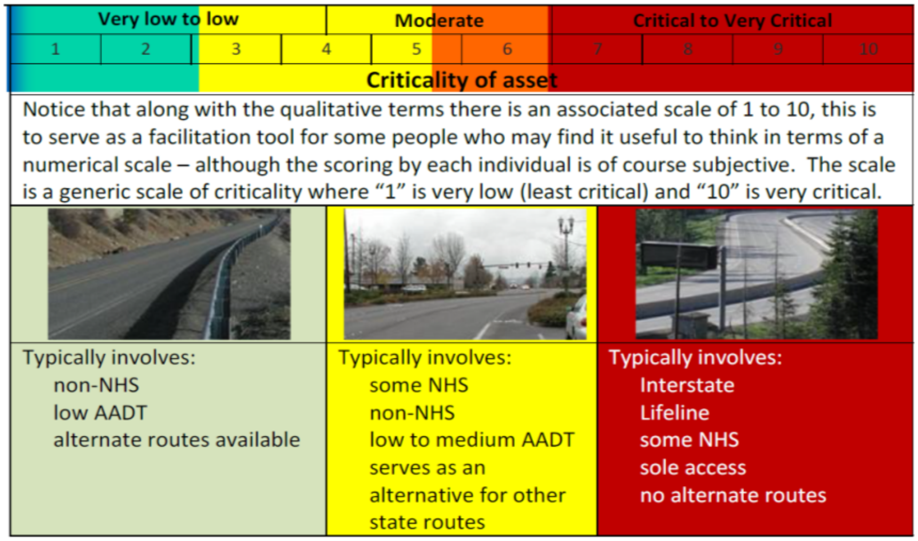
Bridge attribute data is provided by GDOT's Bridge Design & Maintenance Office.

In order to account for the relationship between roadway and bridge criticality, i.e., to ensure that the greatest criticality score is utilized on roadway segments that also contain bridges, a geospatial analysis is performed in ArcGIS. Since the criticality score for the roadway network accounts for AADT, percent trucks, and number of lanes, the bridge score does not. Thus, it is assumed that the AADT, percent trucks, and number of lanes on a roadway segment that contains a bridge are the same on the bridge as on the roadway segment.

As discussed in detail in Chapter 2, it is difficult, and beyond the scope of this research, to assign quantitative failure probabilities to transportation infrastructure assets. Rather than assign quantitative probabilities, critical assets are grouped into three different categories: high, medium, and low. For purposes of this criticality assessment, only interstates and arterials are analyzed. Details for the criticality classification system are shown below.

- Three categories (High, Medium, Low)
  - High – STRAHNET and Interstates
  - Medium – NHS and medium AADT
  - Low – Rural/low AADT

This methodology results in a criticality scoring from ranging from 1 to 10, with 1 being the least critical and 10 being the most critical, that is similar to the scoring scheme utilized in the WSDOT pilot (Maurer et al. 2011), shown below in Figure 13.



Very low to low				Moderate		Critical to Very Critical			
1	2	3	4	5	6	7	8	9	10

Criticality of asset

Notice that along with the qualitative terms there is an associated scale of 1 to 10, this is to serve as a facilitation tool for some people who may find it useful to think in terms of a numerical scale – although the scoring by each individual is of course subjective. The scale is a generic scale of criticality where "1" is very low (least critical) and "10" is very critical.

Typically involves: non-NHS low AADT alternate routes available	Typically involves: some NHS non-NHS low to medium AADT serves as an alternative for other state routes	Typically involves: Interstate Lifeline some NHS sole access no alternate routes

Figure 13. Rating scale for asset criticality in WSDOT climate adaptation pilot (Maurer et al. 2011)

4.2.1.1 MPC Incorporation of Climate Change into 2040 LRTP

This research coincides with MPC's LRTP update. Officials from MPC already identified critical corridors in the Savannah Chatham County Area (O'Har 2012). The following transportation infrastructure assets along these corridors are considered critical: hurricane evacuation routes, airports, seaports, and military facilities. In order to facilitate the consideration of climate change risks in the 2040 LRTP and to identify adaptation strategies, a climate change adaptation workshop was conducted in Savannah. The results of the workshop determine which climate impacts are of greatest concern to the Savannah area, and what short-term and long-term adaptation strategies are viable.

4.2.2 MARTA Criticality Assessment

MARTA was selected by the FTA as one of the climate change adaptation pilots (FTA 2011) with a specific focus on incorporating climate change considerations into its existing asset management systems. MARTA's asset management database contains an inventory of its physical assets, which number over 53,000. The agency intends to conduct a condition assessment of its physical assets, but given that assessing 53,000 assets would require significant resources, a statistically significant sample size was determined for each asset category. MARTA considers criticality in terms of three aspects, life criticality, safety criticality, and mission criticality. So-called "mission critical" facilities and services will be defined and prioritized over non-mission-critical facilities and services (Amekudzi and Crane 2012).

Assessing criticality for MARTA is a process that is significantly different from the GDOT and MPC case studies since MARTA is a transit agency and thus concerned with climate change impacts on its bus and rail facilities and services. As required by Federal law, rails are inspected at least once every two weeks to ensure they are in safe, operable condition. For purposes of this research, all of MARTA's railways are critical. The impacts of precipitation and temperature on rail stations and railways were assessed. Bus routes and bus stops were analyzed. However, given that bus routes can be modified, whereas modifying fixed railways is near impossible, this analysis identifies which bus facilities and services are most susceptible to precipitation impacts. Furthermore, this approach allows for the identification of bus stops that are vulnerable to climate change impacts.

4.3 Potential Climate Change Impacts

Since the three case studies vary in scope and geographic location, different climate stressors are relevant for each case study. The statewide case study is at a macro level and thus does not consider climate change impacts at finer spatial resolutions. Furthermore, since the Georgia coastline is heterogeneous, and local relative sea level rise can vary significantly, sea level rise is not specifically addressed at the statewide level. Given the complexities associated with sea level rise and coastal flooding, NOAA's Coastal Services Center (CSC) Digital Coast serves as a resource for sea level rise information (NOAA 2012). NOAA's CSC also continually updates its Sea Level Rise and Coastal Flooding Impacts Viewer, which is a web portal that allows users to visualize how sea level rise impacts coastal communities (Marcy et al. 2011).

4.3.1 Climate Projections

As mentioned in Chapter 3, the state of climate science and climate models is constantly improving. The projections utilized in this research were the best, state-of-practice projections made readily available by the USGS via the Geo Data Portal. This is to say that as improved projections become available, this input into this analysis framework can be updated.

4.3.1.1 Climate Ensembles

As discussed in more detail in Chapter 3, three emissions scenarios are utilized for this research, A1FI as a high emissions scenario, A2 as a moderate emissions scenario, and B1 as a low emissions scenario. Also discussed in Chapter 3, there is considerable uncertainty associated with climate projections; however, this is no reason for inaction. Using multiple emissions scenarios gives decision makers a more complete perspective on possible outcomes (Field et al. 2012). By their nature, engineering design standards for transportation infrastructure tend be conservative; this tends to favor the more conservative emissions scenarios. Even so, presenting decision makers with multiple emissions scenarios will allow these decision makers to update adaptation frameworks over time as the state of climate science improves; this is consistent with the adaptive management approach described in Section 2.6.

Typically, multiple individual climate models for a given emissions scenario are averaged to produce an ensemble. This approach reduces uncertainty through the use of multiple climate models. The individual climate models used in each ensemble are listed in Table 6, Table 7, and Table 8.

However, taking simple averages across multiple models ensures that many extreme values are lost. Since engineering design does not account for average conditions and is more concerned with extremes, this methodology utilizes a different approach to ensure that more extreme values are captured (Webster et al. 2012). For each grid square across each day of the modeling time period, the maximum (temperature and precipitation) or minimum (temperature) value is preserved across all of the climate models utilized for a particular emissions scenario. This more conservative approach ensures that for each date and each grid square the extreme value is utilized to develop projections. Raw climate data from the USGS Geo Data Portal was modified using scripts in MATLAB. Using the methodology described above, MATLAB scripts can be used to produce temperature and precipitation projections for user-defined time periods.

Table 6. High Emissions Scenario Model Listing for A1FI Ensemble (Lawrence Livermore National Laboratory 2007)

A1FI Emissions Scenario Ensemble		
Model Nickname	Originating Group	Country
CCSM3	National Center for Atmospheric Research	USA
GFDL-CM2.1	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA
HadCM3	Hadley Centre for Climate Prediction and Research/Met Office	UK
PCM	National Center for Atmospheric Research	USA

Table 7. Mid-high Emissions Scenario Model Listing for A2 Ensemble (Lawrence Livermore National Laboratory 2007)

A2 Emissions Scenario Ensemble		
Model Nickname	Originating Group	Country
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway
CCSM3	National Center for Atmospheric Research	USA
CGCM3.1(T47)	Canadian Centre for Climate Modeling & Analysis	Canada
CGCM3.1(T63)	Canadian Centre for Climate Modeling & Analysis	Canada
CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques	France
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	Germany
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	Germany Korea
GFDL-CM2.0	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA
HadGEM1	Hadley Centre for Climate Prediction and Research/Met Office	UK
PCM	National Center for Atmospheric Research	USA

Table 8. Low Emissions Scenario Model Listing for B1 Ensemble (Lawrence Livermore National Laboratory 2007)

B1 Emissions Scenario Ensemble		
Model Nickname	Originating Group	Country
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway
CCSM3	National Center for Atmospheric Research	USA
CGCM3.1(T47)	Canadian Centre for Climate Modeling & Analysis	Canada
CGCM3.1(T63)	Canadian Centre for Climate Modeling & Analysis	Canada
CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques	France
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	Germany
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA	Germany Korea
GFDL-CM2.0	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA
GFDL-CM2.1	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA
PCM	National Center for Atmospheric Research	USA

4.3.1.2 USGS SERAP Projections

The USGS projections include daily minimum temperature, maximum temperature, and precipitation. Spatially, these projections are available in an eighth of a degree resolution, or 7.5 miles (12 km) square per grid cell. The projections result in a daily temporal resolution and this high level of detail is used to examine the number of consecutive days of extreme heat or cold during the summer and winter seasons. Since the projections are suitable for analysis time periods of a decade or more (Nakicenovic et al. 2000), seasonal averages of mean temperature for summer and winter are projected for the following time periods for planning purposes, 2010 to 2039, 2040 to 2069, and 2070 to 2099. Projections of average maximum daily, i.e., 24-hour cumulative, precipitation are also provided.

4.3.1.3 Baseline Climate Information

Baseline seasonal temperature values and thresholds for extreme temperature values are determined from historical, 1981 to 2010, seasonal averages and normals. The National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) provides baseline historical climate data via the climate data online access portal (NOAA 2013a). For this research, historical weather data for Atlanta and Savannah were also utilized (NOAA 2013b; c). Relevant thresholds for temperature include:

- Days over 90 degrees Fahrenheit
- Days over 100 degrees Fahrenheit
- Days with greater than 1 inch of precipitation

These thresholds are standards utilized by NOAA in its record keeping. For the winter season, thresholds include:

- Number of freezing days, i.e., days when the minimum temperature is at or below freezing
- Days with greater than 1 inch of precipitation

In order to provide further insight, these projections also include consecutive days at, above, or below the aforementioned thresholds. This information is not recorded in NOAA's seasonal records so there are no historical baselines.

Given the uncertainties associated with the climate projections, particularly the precipitation projections, these potential future temperature and precipitation levels intend to provide illustrative examples of potential future climates. With the large levels of uncertainty, calculating storm event probabilities, e.g., increase in frequency of 100-

year storm events, can be a statistically daunting, and some would argue, futile, exercise. However, climate analogues, which are current climates that are similar to the projected climates of a particular locale, provide insight into the level of adaptation that may be necessary. With this sort of adaptive mindset, extreme storm events and their frequencies at climate analogues can inform decision making.

As a basis for comparison, climate projections need a historic baseline. Historic climate and weather records from 1980 through 2010 serve as a baseline, where available, to develop historic averages. The availability and continuity of historic weather data for the Atlanta and Savannah metropolitan regions dictates the accuracy of the baseline. At the statewide level, NOAA's climate divisions for the state of Georgia serve as a comparative baseline. It is also important to note that as discussed in Chapter 3, the USGS projections, i.e., climate models and statistical downscaling technique, utilize historic climate records to validate the models.

4.3.2 Statewide Climate Change Impacts

At the regional, i.e. Southeast, level climate stressors include (Karl et al. 2009; NCADAC 2013):

- Increased number of days over 90°F each year
- Decrease in the number of freezing days
- Increased extreme temperatures
- Increased intensity and frequency of high-precipitation events
- Decreased overall precipitation and therefore increased droughts
- Sea level rise
- Increased hurricane intensity and surge

At the statewide level, Georgia can expect to experience all of these climate impacts, although the impacts will vary across the climate divisions of the state.

4.3.3 Atlanta Region Climate Impacts

The Atlanta Region can expect to experience all of the impacts seen at the statewide level except for those impacts associated with coastal communities, i.e. sea level rise, increased storm surge, and increased intensity of coastal storms. Thus, the Atlanta area can expect the following climate impacts:

- Increased number of days over 90°F each year
- Decrease in the number of freezing days
- Increased extreme temperatures
- Increased intensity and frequency of high-precipitation events
- Decreased overall precipitation and therefore increased droughts

For purposes of this research, Fulton and DeKalb counties define the Atlanta Region since this comprises MARTA's service area. As described in Section 4.3.1, detailed projections for the Atlanta Region were developed for each emissions scenario and planning time horizon.

4.3.4 Savannah/Chatham County Impacts

Since Savannah/Chatham County lies along the coast, all of the aforementioned climate stressors in 4.3.2 are considered for the MPC case study. Therefore, Chatham County can expect the following climate change impacts:

- Increased number of days over 90°F each year
- Decrease in the number of freezing days

- Increased extreme temperatures
- Increased intensity and frequency of high-precipitation events
- Decreased overall precipitation and therefore increased droughts
- Sea level rise
- Increased hurricane intensity and surge

Since many of the metropolitan areas in Chatham County are low-lying, sea level rise, increased coastal storm intensity, and storm surge are of particular concern. The impacts of sea level rise and surge will be particularly acute since certain roadways in Chatham Count regularly flood during higher high tides (O'Har 2012).

NOAA's Coastal Services Center worked with the Chatham County Emergency Management Agency to conduct a comprehensive hurricane preparedness study. This exercise involved remapping storm surge zones through the utilization of improved lidar-derived elevation data and data from the Sea, Lake, and Overland Surges Hurricanes (SLOSH) storm surge model (NOAA CSC 2006). Although no formal published study resulted from this effort, the CSC regularly updates maps along the coast as improved data and funding are made available. For the Chatham County area, the Carl Vinson Institute of Government's Office of Information Technology Outreach Services (ITOS) at the University of Georgia created improved storm surge maps (NOAA CSC and CEMA 2006).

4.3.5 Impacts of Historical Extreme Weather

Where data is available, the impact of historical extremes on transportation infrastructure in the case study regions is analyzed. Oftentimes engineering design of transportation infrastructure requires that infrastructure be able to withstand a 100 year storm. Although recent research suggests that basing modern designs for new infrastructure on historical 100-year storms may be inadequate (Meyer 2008), it is valuable to know how transportation infrastructure withstood so-called 100-year storms if they have occurred. Although official documentation on responses to historical extreme weather events may not always exist, certain officials at transportation agencies possess this knowledge. For example, interviews with MARTA personnel revealed how the agency responded to extreme weather in the past and what the most significant concerns for the future were (Crane and Amekudzi 2012), and discussions with MPC staff revealed that certain roadways already inundate during higher tides (O'Har 2012).

4.4 Vulnerability Assessment

This key final step in this research process identifies those infrastructure assets that are both critical and susceptible to the impacts of climate change; these assets are the so-called high-risk assets. Since the MARTA and MPC case studies are at a micro level, individual infrastructure assets that are high risk can be identified. However, the statewide case study evaluates infrastructure at a broader scale. Critical segments of the roadway network, and bridges along this network, are identified in those climate divisions with larger projected temperature increases. Average temperatures and average temperature ranges are key inputs in the design and materials selection process for transportation infrastructure.

Using coastal surge maps, critical infrastructure susceptible to various levels of storm surge are identified. Given the greater uncertainties associated with the precipitation projections when compared to the temperature projections, it is assumed that critical transportation infrastructure throughout the state can expect increased frequent and intense precipitation events. Lessons learned from the MARTA case study could be applied to transit agencies in other regions of the state. Since MARTA is the only heavy rail operator in Georgia, other transit agencies will be concerned with how climate impacts affect bus facilities and services. However, the MARTA case study does not provide insight into adaptation for sea level rise, coastal storms, and surge. Even so, implications of intense precipitation and inundation could be applied to coastal transit agencies for the purposes of sea level rise, coastal storms, and surge.

CHAPTER 5

ANALYSIS

5.1 Maturity of Transportation Asset Management Systems

As mentioned earlier, each agency's asset management system is at a different level of maturity. For purposes of this research, the asset management maturity scale from *Volume 2* of the *Transportation Asset Management Guide* (AASHTO 2011a) is used as a basis for comparison and analysis. This maturity scale detailed in Table 9 consists of five levels:

- Initial
- Awakening
- Structured
- Proficient
- Best Practice

The goal of this scale is not to categorize an agency's TAM system as good or bad, but rather to indicate where an agency lies in terms of improving its TAM program. This maturity scale does not replace gap analysis tools, rather it describes an agency's position along a continuum of TAM practices. In general, an agency must maintain a particular level for some amount of time and make significant improvements prior to advancing to the next level. Typically this involves a multi-year asset management implementation process (AASHTO 2011a).

Table 9. Transportation Asset Management Maturity Scale (AASHTO 2011a)

TAM Maturity Scale Level	Generalized Description
Initial	No effective support from strategy, processes, or tools. There can be lack of motivation to improve.
Awakening	Recognition of a need, and basic data collection. There is often reliance on heroic effort of individuals.
Structured	Shared understanding, motivation, and coordination. Development of processes and tools.
Proficient	Expectations and accountability drawn from asset management strategy, processes, and tools.
Best Practice	Asset management strategies, processes, and tools are routinely evaluated and improved.

5.1.1 Georgia Department of Transportation

The Georgia Department of Transportation (GDOT) has one of the more mature asset management systems in the United States, as evidenced in a recent NCHRP Synthesis report (Hawkins and Smadi 2013). This report assessed the state of practice in asset management at state highway agencies. Along with New Jersey, Georgia's Department of Transportation was one of two agencies in the country with a transportation asset management plan (GDOT 2011a) that meets the guidelines set forth in *Volume 1* of the *Transportation Asset Management Guide* (Cambridge Systematics 2002; Hawkins and Smadi 2013). Presumably, GDOT's plan also would meet the standards that are yet to be finalized in MAP-21 (FHWA 2012).

GDOT officially began its asset management program in 2009 but had been conducting strategic planning since 1994 (Amekudzi and Meyer 2011). Since 2009, the Department has conducted multiple research studies related to asset management (Amekudzi and Meyer 2011; Amekudzi et al. 2011) and also released official transportation asset management policy from the Chief Engineer's Office (Division of the

Chief Engineer 2012). The Department conducted a TAM self-assessment survey as the first step in its implementation process (GDOT 2011a), and also conducted a TAM workshop for its board members (GDOT 2011b).

GDOT has well-documented asset management tools and processes (Amekudzi and Meyer 2011; Amekudzi et al. 2011; Division of the Chief Engineer 2012; GDOT 2011a; b) and one of the leading asset management plans in the U.S., as evidenced in a recent NCHRP synthesis report (Hawkins and Smadi 2013). Additionally, the Department maintains a webpage which contains a performance management dashboard (GDOT 2012). This dashboard consists of three performance measurement categories, safety investments and improvements, taking care of what we have, and planning and constructing. Within these categories there are 12 performance measures. The target audience for these performance measures is the general public (GDOT 2012).

GDOT has a relatively mature asset management system. The Department's asset management program formally started in 2009 and in the years since, asset management has been institutionalized. The Office of Organizational Performance Management is responsible for the implementation and administration of the Department's asset management program, strategic planning, and maintenance and development of the transportation performance dashboard (GDOT 2012; Hawkins and Smadi 2013). GDOT's asset management program utilizes well-documented and well-established tools and processes, which drive accountability and expectations. Along the maturity scale shown in Table 9, the Department is "Proficient", advancing towards "Best Practice".

5.1.2 Metropolitan Atlanta Rapid Transit Authority

During the climate change adaptation pilot study selection process, the Metropolitan Atlanta Rapid Transit Authority (MARTA) was recognized by the Federal Transit Administration (FTA) for the relative maturity of its asset management system (FTA 2011). MARTA has one of the leading transit asset management systems in the U.S, recognized for its software-based decision support tools (Springstead et al. 2012). This TAM system also supports the agency's state-of-good-repair (SGR) initiative (Amekudzi and Meyer 2012). Given the new SGR and transit asset management plans requirements in MAP-21 (FTA 2012a), MARTA is well-positioned to comply with forthcoming regulations from this new legislation.

Nonetheless, MARTA is still developing its formal asset management tools and processes, which will eventually drive expectations and increase accountability. Figure 14 below displays an evolution of asset management-related activities throughout MARTA's history. In the 1990s MARTA implemented its maintenance management information system. Then in 2006 MARTA's leadership recognized that an improved asset management program would lead to improved decision making. This led to the development of the Enterprise Asset Management (EAM) system, which links all resource allocation systems together in a single system (MARTA 2012).

In 2009 MARTA joined the FTA's SGR workgroup and attended the first SGR roundtable. Following up on this workshop, MARTA decided to expedite agency efforts to improve the existing asset management plan. A new condition assessment was then completed in 2011. The agency also moved forward with the selection of a software vendor to develop a new capital planning module for the EAM system. In addition, MARTA began to implement a decision making software package that prioritizes projects under budget constraints (MARTA 2012).

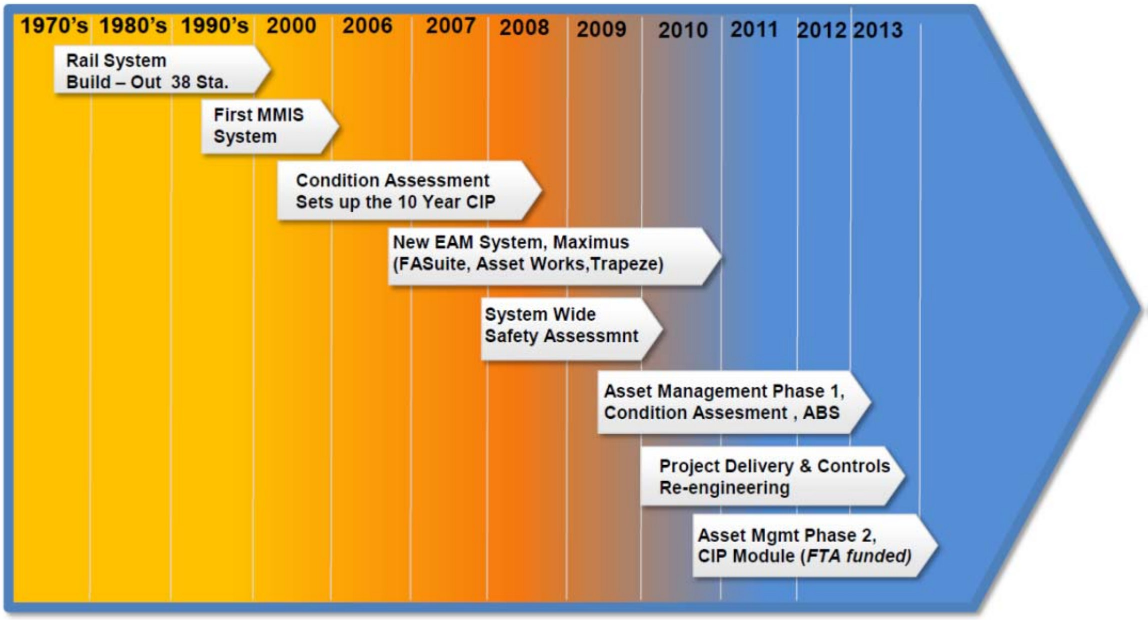


Figure 14. Evolution of MARTA's Asset Management Program (Springstead et al. 2012)

MARTA does have a relatively mature asset management system among transit agencies in the U.S. (Amekudzi and Meyer 2012), and also has an official agency transit asset management plan (MARTA 2012). Furthermore, the FTA chose to focus the MARTA climate change adaptation study on implementation through the use of its asset management system (FTA 2011). Even so, MARTA is still refining and finalizing its tools and processes that will eventually inform decision making. The Transit *Asset Management Guide* provides an asset management maturity scale (Rose, Isaac, Shah, et al. 2013) with five levels as shown in Figure 15.

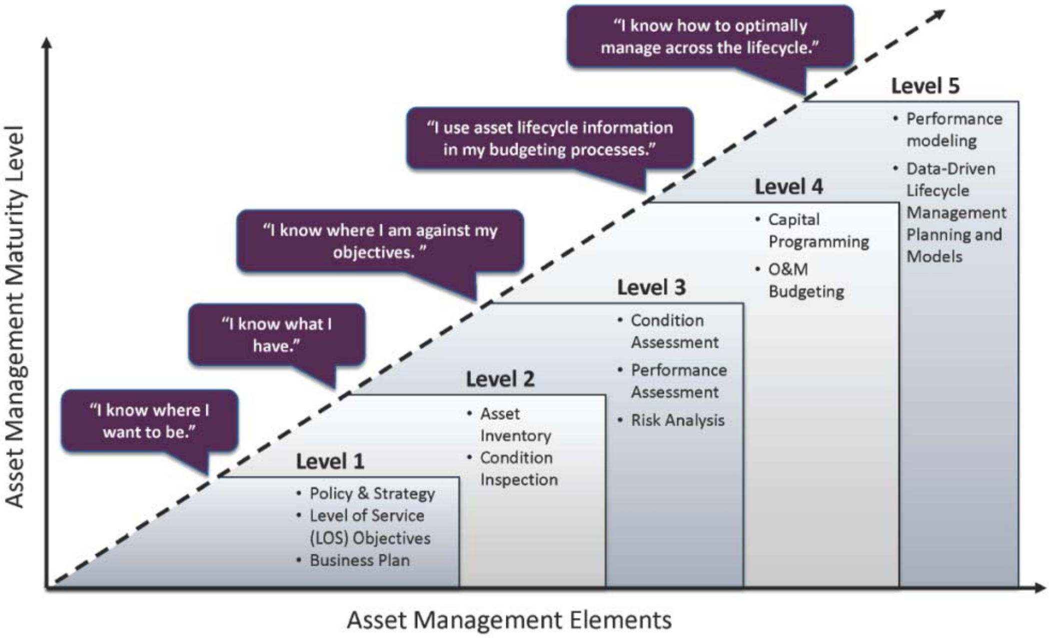


Figure 15. Transit asset management maturity scale (Rose, Isaac, Shah, et al. 2013)

Similar to the maturity scale described in Table 9, the transit asset management maturity scale in Figure 15 also consists of five different levels, with level five being the most mature. These scales align, and MARTA's TAM system is at level three in the transit asset management scale and at the "Structured" level, or third level, in the *Transportation Asset Management Guide Volume 2* scale. Once the aforementioned asset management processes and tools are finalized and used to develop expectations and accountability, MARTA's TAM system will advance to the fourth level of maturity.

5.1.3 Metropolitan Planning Commission – Savannah, GA/Chatham County

Unlike GDOT and MARTA, the MPC does not have a formal asset management program, plan, strategy, or champions. Given the resource constraints that many MPOs around the U.S. face, this is not surprising. Even so, the MPC does practice some degree of transportation asset management. Although it is not the owner of significant amounts of asset data, one the primary processes the MPC is involved with is short and long-range planning efforts. This is a crucial step of the generic asset management process described in Figure 1.

By Federal law, the Coastal Region Metropolitan Planning Organization (CORE MPO), also referred to as the Metropolitan Planning Commission (MPC), is the designated MPO for the Savannah urbanized area, which is defined by the U.S. Census Bureau. For all urban areas with a population greater than 50,000 persons MPOs are required to organize and direct transportation planning processes. In addition, since the population of the Savannah urbanized area exceeds 200,000 persons, the MPO is also a designated Transportation Management Area (TMA). This means that the MPO must develop congestion management processes, perform Transportation Improvement Program (TIP) project selection, and receive federal certification and approval of transportation planning processes at least every four years (MPC and RS&H 2009).

In addition to these existing legislative requirements, and although MAP-21 does not require that MPOs produce Transportation Asset Management Plans (TAMPs), MPOs must establish performance measures for pavement conditions and performance (for Interstates and the NHS), bridge conditions, injuries and fatalities, traffic congestion, on-road mobile source emissions, and freight movement on the Interstates (FHWA 2012). MPOs will work with states to establish performance targets for the aforementioned performance measures. MPO plans will demonstrate how programs and project selection will support achieving performance targets. State DOTs and MPOs will report this information to the USDOT, which in turn is required to report to Congress five years after the enactment of MAP-21, or in 2017 (FHWA 2012).

The MPC already engages in the federally mandated Long Range Transportation Plan (LRTP) process and the TIP project selection process. MAP-21 requires that these existing LRTP and TIP planning processes incorporate performance measures and targets (FHWA 2012). In light of the new risk-based TAMP requirements for state DOTs, the MPC, along with other MPOs around the country, is aware of the new asset management requirements associated with MAP-21. MPC also develops the LRTP every four years for the Savannah – Chatham County region. Development of the LRTP and the travel demand model for the region requires the MPC to collect, analyze, and utilize transportation data to create processes and tools. Given this information, the MPC is at the "Awakening" level of the asset management maturity scale described in Table 9.

5.2 Interpretation of Raw Climate Data

As described in Section 3.4.5, the United States Geological Survey's (USGS) Southeast Regional Assessment Project's (SERAP) Geo Data Portal (GDP) is the source of climate projection data for this research (Dalton and Jones 2010). The raw climate data is stored in netCDF, or Network Common Data Form, format. NetCDF is used to store multidimensional scientific data, and is commonly used in atmospheric sciences to store variables such as temperature, precipitation, humidity, etc (Rew and UCAR n.d.). Typically, these variables are associated with a time dimension. Thus, the variables are stored as three-dimensional data, two-dimensional arrays associated with latitude and longitude values for grid squares that vary over time (ESRI 2010). Figure 16 below displays a graphic illustration of how a variable would be stored as a 3D array in a netCDF file.

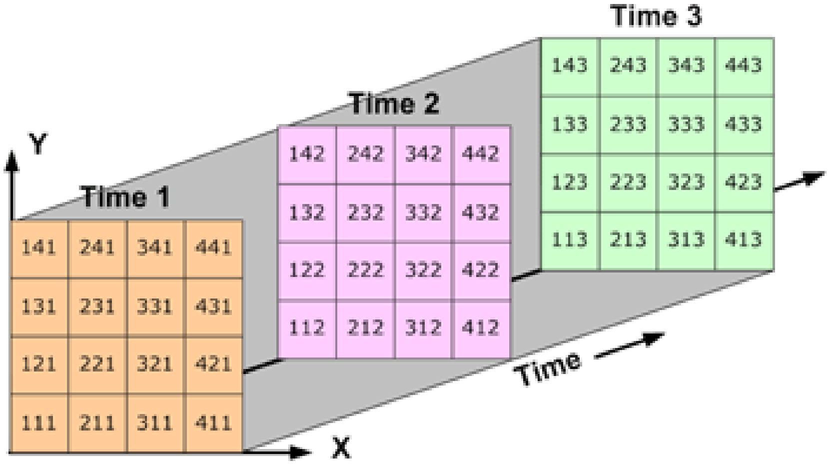


Figure 16. Graphic illustration of 3D netCDF data varying over time stored as an array (ESRI 2010)

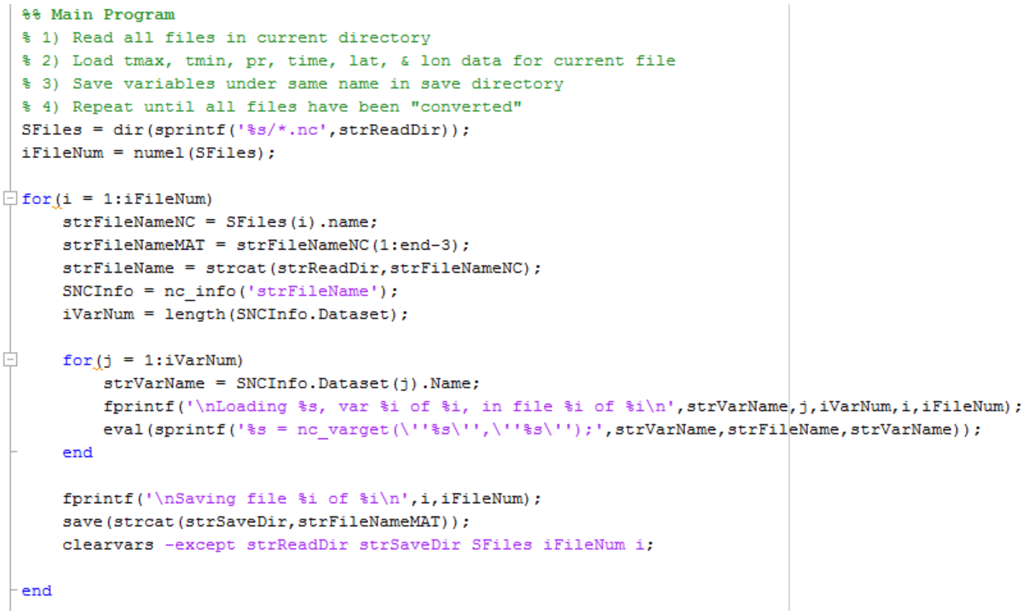
Although netCDF is a standard format that is self-describing and sharable, it is not user-friendly. There is not a software package that can easily manipulate and create netCDF files. MATLAB is the most user-friendly, but is still unwieldy. A software package called SNCTOOLS is a collection of MATLAB programs for accessing netCDF data (Evans n.d.). SNCTOOLS was utilized to read-in the netCDF files and their associated variables. Each individual netCDF file contains the results of one climate model for one particular emissions scenario for the State of Georgia for the time period 2010 to 2099. Each of these netCDF files contains the following variables:

- Maximum daily temperature
- Minimum daily temperature
- Cumulative 24 hour daily precipitation
- Time, i.e., days

- Latitude
- Longitude

5.2.1 Scripts in MATLAB to Import and Manipulate netCDF Data

The MATLAB code required to import, convert, and export the netCDF files in a usable format involves several steps. First, a script imports all of the netCDF files, which contain “.nc” extensions, and converts these files to MATLAB files, which contain a “.mat” extension. This script simply identifies which files in a particular directory contain the “.nc” extension, i.e., files that are in netCDF format. Next, the script reads in the six variables enumerated in Section 5.2.1. Figure 17 shows a screenshot of this code. Please see Appendix A for the complete text of the MATLAB code.



```
%% Main Program
% 1) Read all files in current directory
% 2) Load tmax, tmin, pr, time, lat, & lon data for current file
% 3) Save variables under same name in save directory
% 4) Repeat until all files have been "converted"
SFiles = dir(sprintf('%s/*.nc',strReadDir));
iFileNum = numel(SFiles);

for(i = 1:iFileNum)
    strFileNameNC = SFiles(i).name;
    strFileNameMAT = strFileNameNC(1:end-3);
    strFileName = strcat(strReadDir,strFileNameNC);
    SNCInfo = nc_info('strFileName');
    iVarNum = length(SNCInfo.Dataset);

    for(j = 1:iVarNum)
        strVarName = SNCInfo.Dataset(j).Name;
        fprintf('\nLoading %s, var %i of %i, in file %i of %i\n',strVarName,j,iVarNum,i,iFileNum);
        eval(sprintf('%s = nc_varget(\''%s\'',\''%s\'');',strVarName,strFileName,strVarName));
    end

    fprintf('\nSaving file %i of %i\n',i,iFileNum);
    save(strcat(strSaveDir,strFileNameMAT));
    clearvars -except strReadDir strSaveDir SFiles iFileNum i;

end
```

Figure 17. Screenshot of MATLAB code to convert “.nc” to “.mat”

The next MATLAB script contains the code that produces the climate ensembles for each emissions scenario by merging the data from the individual climate models. This code requires user input insofar as the date ranges over which to produce the ensembles. As described in Section 4.3.1, when producing the climate ensembles, which consist of individual models for each emissions scenario, the extreme value for each grid square across all of the models feeding into the ensemble is preserved. This is to say that for a particular date range, e.g., ten years, for each day, each grid square will contain the extreme value across all of the models used to develop a particular ensemble.

Since there are two temperature variables, maximum and minimum, associated with each climate model, for maximum temperature the maximum value is preserved and for minimum temperature the minimum value is preserved. For 24-hour cumulative precipitation, the maximum precipitation value is preserved. In order to reduce the computational intensity of these calculations, the extreme values are compared on a step-by-step basis. Therefore, the first model in the ensemble is set as the temporary extreme value. Next, each subsequent model is compared with the previous model so that the extreme value is preserved.

In order to compare the projected temperatures with baseline temperatures, averages of the extreme maximum and minimum temperature values are utilized to calculate a mean temperature value across a specified time range. For purposes of this research, 30 year time horizons are used due to the fact that NOAA’s baseline climatological data is from 1981 to 2010 (NOAA 2013a) and since 30 year time horizons coincide with transportation planning time horizons. The climate projections are available from 2010 to 2099 so the three time horizons used are:

- 2010 to 2039
- 2040 to 2069
- 2070 to 2099

Extreme temperature and precipitation values concern transportation infrastructure planners and designers. Thus, temperature and precipitation values and thresholds are calculated for the summer, which consists of June, July, and August, and winter, which consists of December, January, and February. In terms of coding, defining the date range for the winter months is more challenging. MATLAB and netCDF files store numbered dates beginning from one, e.g., January 1st, and ending with 365, e.g., December 31st. The summer months range from day 152 (June 1st) through day 243 (August 31st) while the winter months range from day 335 to 365 in December and from day one (January 1st) through 59 (February 28th).

Since the winter months do not comprise a consecutive date range, the January and February dates are concatenated with the December dates. The full code for the script to convert the winter ".mat" files into user-defined ".nc" files can be found in Appendix B. Unlike the script for the winter months, the script for the summer months does not require this additional step since the date range is consecutive. The full code for the script for the summer months to produce user-defined ".nc" from ".mat" files can be found in Appendix C.

In addition to defining the date range for different seasons, users also input the desired range of years. As discussed earlier, each time period for analysis in this research is 30 years, 2010 to 2039, 2040 to 2069, and 2070 to 2099. Since the ".nc" files range from 2010 to 2099, in terms of the MATLAB code the years range from one, i.e., 2010 to

90, i.e., 2099. Since the summer and winter scripts operate in one directory, in order to construct the ensembles, the user must place the ".mat" file for each model in a particular ensemble into the same folder, e.g., a folder named A1FI.

As discussed in section 4.3.1.3, these scripts calculate the following threshold information:

- Number of freezing days, i.e., days when the minimum temperature is at or below freezing
- Days over 90 degrees Fahrenheit
- Days over 100 degrees Fahrenheit
- Days with greater than 1 inch of precipitation

After running the scripts to determine mean temperature and calculate threshold data, ".nc" or netCDF output files are created. The climate data is geospatial in its nature. Each temperature, precipitation, and threshold value is associated with a corresponding grid square. The next section describes how ArcGIS mapping software converts this geospatial climate projection data into actionable data to inform decision making.

5.2.2 Use of ArcGIS to Geospatially Analyze Climate Projections

Given that the climate projection data is geospatial in nature, i.e., each temperature, precipitation, and threshold value corresponds with a grid square, ESRI's ArcGIS software generates maps and relevant climate data for planning purposes. Since each grid square is 7.5 square miles, temperature, precipitation, and threshold data for particular geographic regions, i.e., statewide, Atlanta metro area, and Savannah metro area, are calculated as average values of the grid squares that comprise each geographic area.

ESRI's ArcMap software contains a Multidimension Tools toolbox that reads in netCDF files and converts them into spatially-referenced raster files. However, transportation infrastructure asset data is typically stored in shapefiles or personal geodatabases. Thus, several models were created in ArcMap that convert netCDF or ".nc" files into shapefiles. ArcMap software requires that values be in integer format when they are converted from raster data into polygon or shapefile data. In order to maintain the precision of two decimal places, prior to converting the climate projection and threshold data, it is multiplied by 100. Then after it is converted into a shapefile this data is divided by 100 to yield the actual result.

Four models were created in ArcMap; one for converting temperature, another for converting precipitation, one for converting threshold data, and yet another for creating the statewide temperature projection maps for the various climate divisions. Although these four models differ, fundamentally they are very similar. The basic steps in each model are shown in Figure 18. The model used to create the temperature projections for the climate divisions throughout the state differs in that it contains an additional step in which the "Union" tool is used to insert the climate division borders into the map. Figure 19 shows the graphical representation of the models for converting temperature, precipitation, and thresholds in the ArcMap software, while Figure 20 shows the graphical representation of the model for creating the statewide temperature projection maps.

The first step in the process is selecting a netCDF file and variable, e.g., temperature, from that file. Next, the "Make NetCDF Raster Layer" tool converts the ".nc" file and selected variable into a raster layer. This raster layer is then projected in the appropriate coordinate system, which is GCS WGS 1984 in this case. After projection, the “Raster Calculator” tool converts the data from metric into English units where applicable, multiplies this value by 100, and then converts this value into an integer. Once this new raster layer is created, since the values are in integer format, the “Raster to Polygon” tool converts this raster file into a shapefile. This shapefile is then projected in the relevant coordinate system, which is NAD 1983 Georgia Statewide Lambert for the State of Georgia. Finally, the “Clip” tool is used to develop the final shapefile for the selected geographic region.

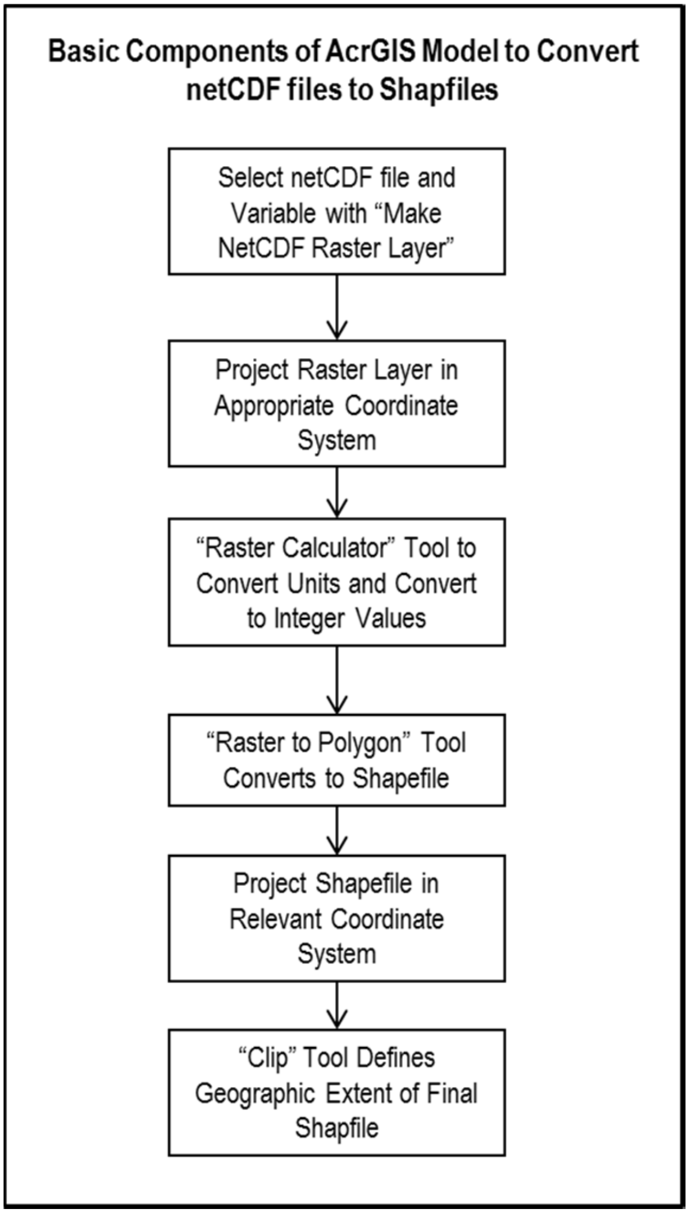


Figure 18. Basic steps in the ArcGIS model that creates shapefile outputs from netCDF file inputs

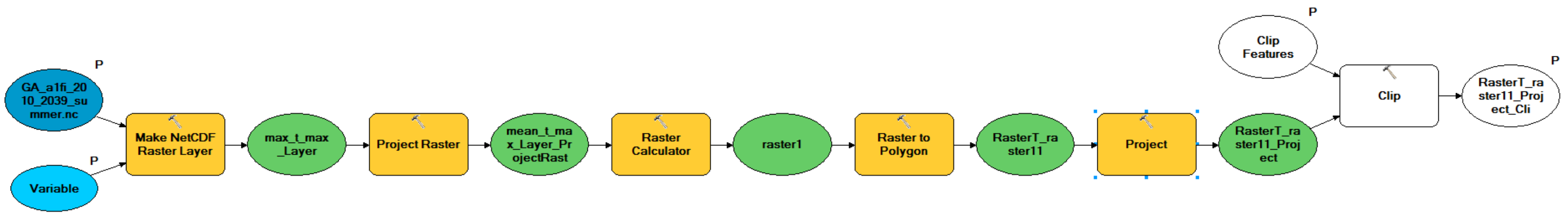


Figure 19. Screenshot of netCDF to shapefile model in ArcMap for converting temperature, precipitation, and threshold values

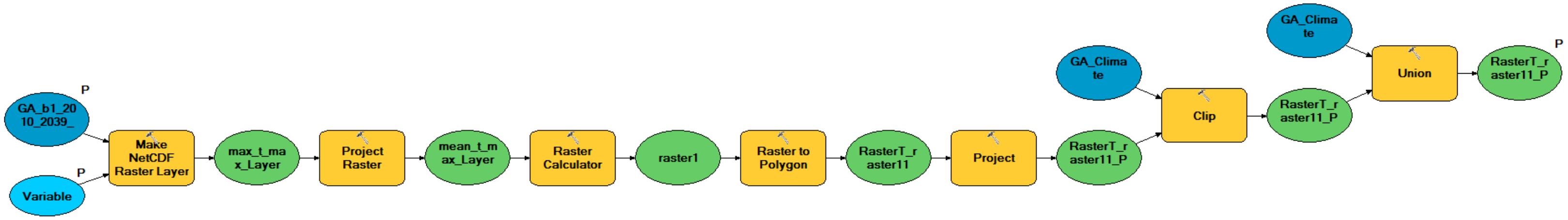


Figure 20. Screenshot of netCDF to shapefile model in ArcMap for creating statewide temperature projection maps for different climate divisions

5.3 Development of Excel Tool for MCDM Criticality Assessment

Roadway and bridge attribute data are spatially referenced in personal geodatabases. The spatially-referenced attribute data is exported from the personal geodatabase into an Excel Spreadsheet. Risk factors defined in Section 4.2.1 are used to select the attributes that will be used to define risk factors in the Excel tool. Users also have the option of utilizing fewer risk factors by weighting irrelevant factors zero.

Two separate Excel tools are created, one for roadway assets and another for bridge assets. Both Excel tools have the same layout, consisting of three worksheets. Users enter the weights for the risk factors on the first worksheet, the second worksheet contains the attribute data that will be used to develop the risk factors, and the third worksheet contains the calculations and final criticality score.

5.3.1 Roadway MCDM Criticality Scoring Tool

For the roadway criticality scoring tool, the first worksheet contains a brief description of the tool and instructions for the users. The following attributes are listed as potential criticality factors for weighting and scoring:

- STRAHNET Classification
- NHS Classification
- Traffic Volume (AADT)
- Condition (PACES Rating)
- Total Lanes
- Truck Percentage

There are three additional factors listed, which are blank, and serve as placeholders for users who wish to customize the tool further. Users are only permitted to enter weight values between zero and one. In addition, a warning messages alerts users when the factor weights do not sum to one. The second worksheet contains the input data, which consists of the columns of attribute data from the personal geodatabase that correspond with the criticality factors. To ensure that the attribute data in the Excel tool corresponds with the appropriate roadway segments in the personal geodatabase, the first column of the input worksheet contains the unique identifier, or object ID, from the personal geodatabase.

The third and final worksheet in the roadway MCDM criticality scoring tool consists of the calculations and final criticality scores. The scoring for the STRAHNET and NHS attributes is binary; roadways segments do or do not have these designations. It should be noted that all STRAHNET roadway segments are also on the NHS. Functional classification is scored in three categories; interstates, freeways, or expressways receive a score of three, principal arterials receive a score of two, and minor arterials receive a score of one. For AADT, volumes greater than or equal to 25,000 receive a score of three, volumes greater than 10,000 receive a score of two, and other volumes receive a score of one. These AADT categories are based upon an FHWA study which classified roadways with an AADT of greater than 25,000 as large arterials (BATTELLE 2006). A roadway with an AADT of greater than 10,000 but less than 25,000 can be considered a moderate volume roadway.

Criticality scores for the PACES ratings are based upon GDOT standards which define “good” roadway condition as a PACES rating greater than 75, “fair” as between

65 and 75, and “poor” as 65 and below (GDOT 2012). Based upon this classification scheme, roadway segments with a PACES rating of 75 or greater receive a score of one, PACES ratings between 65 and 75 receive a score of two, and PACES ratings below 65 receive a score of three. To score total lanes, the number of lanes on a given roadway segment is simply normalized by the maximum value in the state, which is 14. Roadways with greater than 25% truck traffic are considered heavy commercial corridors (E. Jones et al. 2013), so roadways with a truck percentage greater than or equal to 25% receive three points, roadways with truck percentage greater than 10% but less than 25% receive two points, and roadways with less than 10% trucks receive one point.

All of the score values described above, except for the binary scores, are then normalized. To calculate the final score the sum of the products of the attribute weights and score values is calculated. The values from the criticality score column are then copied and pasted into the corresponding personal geodatabase. This allows for the graphic display and visualization of the criticality scores. Users can also adjust the attributes used to calculate the criticality scores and can also adjust the attribute weights. The Excel VBA code required for the scoring functions is shown in Appendix D.

5.3.2 Bridge MCDM Criticality Scoring Tool

The bridge MCDM criticality scoring tool utilizes the same layout as the roadway MCM scoring tool described above. Users weight selected criticality factors on the first worksheet, which also contains a brief description of the tool and instructions. The following criticality factors are listed on the first worksheet:

- Inventory Rating
- Weight Posting

- Scour Criticality
- Fracture Criticality
- Bypass Length
- Condition

These factors represent the default attributes utilized to define risk factors in the tool and can be altered by users. Users are permitted to enter weights between zero and one and are prompted when the weights do not sum to one.

The second worksheet contains the attribute data or inputs. To ensure that the attribute data correlates with the appropriate bridge, the first column of this second worksheet is a unique identifier, or object ID, from the personal geodatabase. The additional columns in the second worksheet correspond to the attribute data from the personal geodatabase. To determine the value for the condition attribute, an average value for the deck, superstructure, and substructure condition ratings is calculated. Bridge condition ratings range from zero to nine, with a rating greater than or equal to six indicating satisfactory condition (FHWA 1995).

Inventory rating, also known as the capacity rating, refers to the load level that a structure can support safely for an indefinite period of time (FHWA 1995). GDOT considers bridges with an inventory rating less than 24 short tons as load limited since an inventory rating less than 24 short tons limits truck loads (Schwartz and O'Har 2010). Scoring for posting is binary. Posting is required when the legal load limits of a state exceed the load allowed by a bridge's operating rating. The operating rating is the maximum permissible load based on the type of vehicle used in the rating (FHWA 1995). If posting is required, a bridge receives a score of one.

Scour criticality and fracture criticality are also coded as binary values. If a bridge is considered scour critical, it receives a score of one. Similarly, if a bridge is fracture critical it receives a score of one. The condition rating system used for the deck, superstructure, and substructure of bridges ranges from zero, which indicates a failed bridge, to nine, which indicates a bridge in excellent condition. Six is the minimum value required for a bridge to be in satisfactory condition (FHWA 1995). Therefore, if the average of the deck, superstructure, and substructure values is below six, one of these components is not in satisfactory condition. Using the average of the bridge condition components, if this average is below six, a bridge receives a score of one.

Finally, a bridge's overall criticality score is calculated as the sum of the products of the attribute weights and score values. These final criticality score values are then copied and pasted into the corresponding personal geodatabase, which allows for the graphic display and visualization of the criticality scores. The attributes utilized to determine the criticality scores, along with the weighs of the attributes, can be customized by the user. Please see Appendix E for the Excel VBA code required for the scoring functions.

5.3.3 Use of ArcGIS to Visualize Criticality

The criticality scores for roadway and bridge assets are then inserted as columns into their respective personal geodatabases using Microsoft Access. This approach allows the user to customize the criticality scoring methodology and then insert the scores into ArcMap through the personal geodatabase. Within ArcMap the criticality scores are categorized, i.e., low, medium, and high, and displayed visually.

Once the scores are geospatially referenced within ArcMap, overlays can be performed utilizing various maps of climate hazards. In particular, the maps created on a statewide basis for temperature projections can be superimposed onto the criticality maps. Overlays can also performed using flood, abnormal high tide, and hurricane storm surge layers in coastal communities, such as Savannah – Chatham County.

5.3.4 Interdependency of Roadways and Bridges

Many state transportation agencies in the U.S. maintain separate asset databases for roadways and bridges; GDOT is no exception. Displaying criticality geospatially allows for the identification of the interdependencies between roadways and bridges. Roadway assets are linear whereas bridge assets are points. Since the roadway and bridge criticality scores are developed separately, displaying the scores in ArcMap allows users to identify interdependencies on the roadway and bridge network. Mapping roadway and bridge criticality concurrently allows for the visual identification of roadway segments that may not be as critical, yet contain critical bridges, and vice versa. The ability to identify this interrelationship between roads and bridges was specifically mentioned by GDOT's state maintenance engineer (O'Har 2013).

5.4 Climate Risk Matrices

In order to gather stakeholder input as to which climate impacts or stressors were considered to be the greatest risks, for the GDOT and MPC case studies, stakeholders were asked to fill in the climate risk matrix shown in Figure 12. Although this matrix was not utilized for the MARTA case study, relevant climate stressors of the greatest potential risk were identified through stakeholder interviews. This risk-oriented approach allows stakeholders to identify those climate impacts that are considered the highest risk. To facilitate filling in the climate risk matrices, stakeholders at GDOT and MPC were given the illustrative listing of climate impacts shown in Table 1. The list from Table 1 is not exhaustive and is simply meant to foster discussion among the stakeholders.

5.5 Identification of Adaptation Strategies

After identifying which climate impacts an agency can expect to experience, and which impacts are highest risk, stakeholders are asked to identify potential short-term and long-term adaptation strategies. Similar to the climate risk matrix exercise, possible adaptation strategies listed in Table 1 are illustrative and meant to foster discussion. This is to say that the list in Table 1 is not exhaustive. Adaptation strategies will vary from one agency to another depending on an agency's mission, jurisdiction, and resource constraints. For example, transit agencies will likely focus on adaptation strategies that differ from those strategies developed by agencies who primarily manage roadway assets.

5.6 Vulnerability Assessment and Identification of High-risk Assets

This is the step where the identification of relevant climate stressors, risk categorization of climate impacts, and criticality assessment of transportation infrastructure merge. Results of the climate impacts risk analysis are utilized in conjunction with mapping software. Assets that are identified as most critical are mapped along with potential climate impacts and hazards. After superimposing maps of climate impacts with criticality maps, the most vulnerable, i.e., high-risk, assets are identified as both highly critical and also susceptible to high-risk climate impacts.

CHAPTER 6

RESULTS

6.1 MARTA Case Study

As discussed earlier, the MARTA case study was part of an FTA-sponsored climate change adaptation assessment. Since MARTA has a relatively advanced asset management system, FTA specifically requested that the MARTA case study focus on incorporating climate change adaptation into its asset management processes. This process involved several steps, the first of which was identifying relevant climate stressors. Next, an assessment of the asset management system revealed how new processes, specifically asset management software tools, under development can incorporate climate change considerations. A matrix identifying potential adaptation strategies was developed and certain vulnerable areas of MARTA's network were identified. An important aspect of this case study is how the results can be applied to other transit agencies, specifically those agencies in Georgia.

6.1.1 Identification of Relevant Climate Stressors

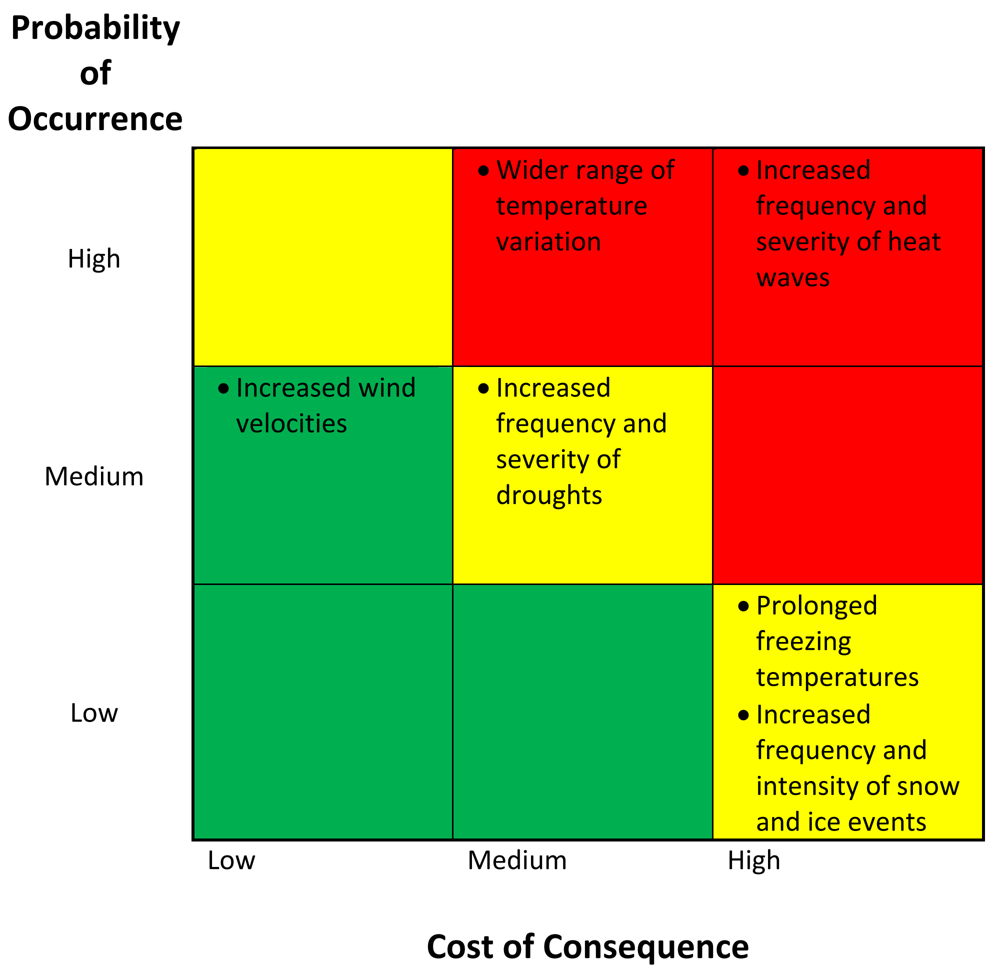
The Task 1 Report outlines which climate stressors MARTA can expect in its service area. Interviews with agency staff then revealed which of these stressors pose the greatest risks to the agency. MARTA can expect the following climate impacts in its service area (Amekudzi and Meyer 2012):

- Increased extreme heat and cold
- Increased duration of extreme heat, i.e., heat waves
- Increased average high temperatures

- Wider range of temperature variation
- Increased intensity of storm events

Interviews with agency staff revealed that while extreme cold, i.e., prolonged freezing temperatures and/or ice, is rare, it has the most significant impact on both bus and rail operations. During the snow and ice event of January 2011, MARTA acquired tire chains for buses and snow removal equipment. Prolonged freezing temperatures can causes rails to break and ice can freeze the third rail, which disrupts service and is costly and time-consuming to mitigate (Amekudzi and Crane 2012).

Prolonged periods of extreme heat, i.e., temperatures over 95 degrees Fahrenheit, can cause rails to buckle. Extreme heat can also cause Compressed Natural Gas (CNG) buses to overheat. The Heating, Ventilation, and Air Conditioning (HVAC) systems on buses also need to be closely monitored during periods of extreme heat. Flooding does not pose a significant risk to the bus route network but there are portions of the network that are vulnerable. Droughts can impact the ability to wash buses and clean other equipment if water restrictions are put in place. In addition, arcs from the electrified third rail do have the potential to ignite fires in extremely dry areas. Increased wind velocities are not expected to significantly impact rail operations since the majority of rail infrastructure is not at high elevations, the exception being the MLK Station, which is at the highest elevation on the network (Amekudzi and Crane 2012). A visual representation of the relative risk of the aforementioned climate impacts is shown below in Figure 21.



Probability of Occurrence			
High		• Wider range of temperature variation	• Increased frequency and severity of heat waves
Medium	• Increased wind velocities	• Increased frequency and severity of droughts	
Low			• Prolonged freezing temperatures • Increased frequency and intensity of snow and ice events
	Low	Medium	High

Cost of Consequence

Figure 21. Visual representation of climate risks for MARTA

6.1.2 Adaptation Strategies

A detailed list of short and long-term adaptation strategies for MARTA was developed as part of the climate adaptation assessment. This list of strategies is shown below in Table 10. This detailed list of adaptation strategies is applicable to many other transit agencies both in Georgia and beyond. However, it is limited to certain climate stressors and may lack stressors coastal transit systems may face. Application of these strategies in other contexts are discussed in Section 6.2 and Section 6.3.

Table 10. Draft Adaptation Strategies for MARTA (Amekudzi and Crane 2013).

Climate Stressor Department		Heat waves	More intense precipitation during storms[1]	Droughts	Wider temperature variations	More frequent high-wind events[2]
Bus Maintenance & Operations	**Short-Term**	-Establish explicit policies for conducting more frequent inspections of air conditioning systems and CNG buses during summer months and establishing temperature thresholds for increased inspections during other months -Evaluate existing policies on worker safety during hot days and update/clarify as necessary (thresholds) -Educate customers on ways to stay cool when waiting at a bus stop	-Identify all flood prone areas on all bus routes -Ensure all bus storage facilities are above existing floodplains and not in flash-flood prone areas. If not, identify temporary storage locations if flood conditions are expected -Establish a bus-rerouting procedure for flood prone areas and a communication plan for affected customers -Establish a combined emergency shut down and facility restart plan for any bus maintenance facility in a flood prone area and practice the plan with facility employees	-Establish modified bus washing plans for varying degrees of drought	-Establish thresholds for increased inspection of bus cooling systems for both extreme hot and cold days -Examine potential impacts of wider temperature ranges on bus tire pressures	-Establish thresholds for alternate routing or suspended service in areas vulnerable to high winds
	Long-Term	-Update design standard for new buses to have heat-resistant materials where feasible, more efficient and durable engine cooling systems (especially for CNG buses), and more durable air conditioning systems -Install air conditioning	-Develop an alternative route schedule/plan for all flood-prone areas and communicate plan to customers -Incorporate more redundant routing into future bus plans -Relocate or harden maintenance facilities	-Replace all bus washing equipment with more efficient systems (low-flow heads and water reclamation) -If efficient wash systems are already in place, utilize non-potable sources for	-Incorporate materials that better withstand greater temperature ranges	-Harden areas vulnerable to high winds -Harden bus storage facilities against damage from falling vegetation

Table 10 (continued).

		systems in maintenance facility areas where feasible -Retrofit or redesign maintenance facilities to utilize natural air flow to cool facilities during summer months where air conditioning is unfeasible	against flooding	wash water (rain barrels, groundwater, etc.) -Investigate new paints or coverings that could be applied to reduce the frequency of washing		
Rail Vehicle Maintenance & Operations	**Short-Term**	-Conduct more frequent inspections of air conditioning and electrical systems during summer months and establish thresholds for increased inspections during other months -Evaluate existing policies on worker safety during hot days and update/clarify as necessary (thresholds)	-Establish a combined emergency shut down and facility restart plan for any rail maintenance facility in a flood prone area and practice the plan with facility employees -Develop alternative techniques that train operators can employ to stop trains properly without enabling emergency braking mode	-Establish modified railcar washing plans for varying degrees of drought	-Identify materials and components that are most impacted by wider temperature ranges	-Establish thresholds for slow orders or suspended service on elevated track structures and stations
	Long-Term	-Update design standard for new railcars to have heat-resistant materials where feasible, increased ventilation for electrical components, and more durable air conditioning systems -Upgrade air conditioning on existing railcars with systems that	-Relocate or harden maintenance facilities against flooding	-Replace all railcar washing equipment with more efficient systems (low-flow heads and water reclamation) -If efficient wash systems are already in place, utilize non-potable sources for wash water (rain	-Incorporate materials that better withstand greater temperature ranges	-Institutionalize modified operating procedures for high wind conditions

Table 10 (continued).

		are designed for longer operating cycles		barrels, groundwater, etc.) -Investigate new paints or coverings that could be applied to reduce the frequency of washing		
Track & Structures	**Short-Term**	-Develop an explicit policy that establishes thresholds for conducting more frequent inspections during hot days or heat waves -Unify and re-evaluate policies regarding inspecting, maintaining, and replacing rail and track elements during extreme weather conditions	-Conduct more frequent inspection of drains and pipes located near tunnel entrances and on aerial structures to check for clogging	-Identify and remove vegetation that may pose a fire hazard during drought conditions in MARTA's ROW -Develop a plan with stakeholders located next to ROW for identifying and removing hazardous vegetation during drought conditions	-Identify track areas that are vulnerable to large temperature ranges and fluctuations	-Identify and remove vegetation within MARTA's ROW that may pose a falling or debris hazard -Develop a plan with stakeholders located next to ROW for identifying and removing hazardous vegetation -Establish wind speed thresholds for suspending service to King Memorial Station
	Long-Term	-Replace track elements and rail with more heat-resistant materials and expansion joints	-Increase drainage capacity near tunnel entrances and on aerial structures	-Establish a process for regularly identifying and removing hazardous vegetation within and near the ROW	-Install systems (e.g. expansion joints) that allow rail to expand and contract without compromising system speed or rail integrity	-Establish a process for regularly identifying and removing hazardous vegetation within and near the ROW -Retrofit King Memorial station to withstand higher wind speeds
Civil Engineering/Design	**Short-Term**	-Continue to monitor how extreme heat and heat waves affect	-Coordinate with future developers to reduce water runoff into	-Examine if subsurface conditions change in	-Identify and monitor structures and materials vulnerable	-Identify areas where further protection from strong winds is

Table 10 (continued).

		facilities, materials, and assets	MARTA's ROW -Establish policies and procedures for regularly inspecting and clearing clogged drains and pipes -Be aware of pending updates to FEMA floodplain maps	certain areas during prolonged drought conditions	to large temperature fluctuations	required
	Long-Term	-Update design standards as necessary to incorporate heat-resistant materials where possible and feasible	-Incorporate higher flood design standards for facilities, pipes, and drains -Incorporate low-impact developments (rain gardens, bioswales, etc.) into the design of new facilities to reduce runoff	-Incorporate water-saving mechanisms (e.g. low-flow toilets) and grey water usage into design standards -Modify design standards for subsurface structures	-Incorporate materials that can withstand a wider range of temperatures in design standards	-Modify design standards to account for greater wind velocities
Capital Facilities	**Short-Term**	-Coordinate all heat-related adaptation efforts from other departments -Conduct detailed analysis of the effect of heat waves on major capital assets	-Identify areas along MARTA's ROW with steep slopes and strategies for preventing mudslides during heavy precipitation events -Harden most vulnerable capital facilities against flooding	-In relevant areas (e.g. bathrooms), post information on how to conserve water	-Identify energy and water use metrics -Measure energy consumption and water usage	-Prepare an alternative communication plan and distribute back-up communication equipment to most critical staff and operators
	Long-Term	-Replace major capital facilities with new designs that incorporate heat-resistant materials	-Increasing pumping capacity at underground rail stations -Implement strategies for preventing mudslides on steep slopes	-Mandate water saving/reduction plans for new/rehabilitated facilities -Install water-efficient faucets,	-Retrofit existing buildings to meeting "green" building design standards; seek to certify new buildings to LEED or similar standards	-Install back-up communications systems that can be activated if primary systems fail

Table 10 (continued).

			-Abandon most-vulnerable major capital facilities and/or replace existing facilities with new facilities that incorporate more stringent flood design standards -Incorporate future floodplains when siting new major capital facilities -Evaluate feasibility of providing shelters at bus stops with no shelter	water fountains, and cleaning apparatuses		
Architecture	**Short-Term**	-Conduct an assessment of available shade near all bus stops and develop a plan for improving shade conditions near most vulnerable stops first -Similar shade assessment for rail stations -Evaluate methods for improving natural cooling in rail stations during hot days	-Develop and implement a coordination effort with local communities and governments to reduce runoff from existing and planned future developments -Develop a roof replacement prioritization plan for all rail station roofs that have no pitch and/or have exceeded their expected useful life	-Try to better protect newly-installed vegetation from customer abuse	-Develop a station floor replacement prioritization plan -Identify new materials and installation techniques that are more resistant to freeze-thaw cycles	-Identify potential landscape designs (natural or manmade) that can reduce or better withstand greater wind velocities
	Long-Term	-Increase shaded areas leading up to and around all bus stops, especially those without shelters (and rail stations)	-Incorporate low-impact developments (rain gardens, bioswales, etc.) into station design and areas	-Utilize rainwater captured from new roofs to water vegetation near stations	-Replace most exposed station platforms with more durable, weather-resistant materials	-Incorporate aesthetic elements that also block or reduce wind velocities

Table 10 (continued).

		-Employ methods for improving natural cooling in stations -If natural cooling methods are not feasible or possible, enclose rail stations and install air conditioning	leading up to bus stops -Replace original roofs with more durable, weather-resistant materials and a pitch to allow water to drain properly -Roof replacements should include installation of low-impact developments to capture and filter rainwater runoff			
General/Miscellaneous		• Adopt an agency-wide policy on climate change and climate adaptation and mitigation • Conduct climate vulnerability and risk assessment for assets and operations • Develop and implement a climate change adaptation and mitigation plan • Utilize existing agency processes and standard operating procedures to implement adaptation/mitigation strategies • Install sufficient generator capacity to entirely power bus maintenance facilities and their equipment during power outages • Review and update standard operating procedures for extreme weather conditions to incorporate emergency evacuation and restart plans for maintenance facilities and alternative communication plan • Develop a system accessibility plan which should establish what level of service will be provided during or after extreme weather events (ice storm, floods, etc.) as well as how access to that service will be maintained (e.g. snow/ice removal) • Coordinate with local weather services to identify extreme weather events within the service area in real time • Allow system users (passengers) to crowd source updates via social media (like Twitter) (e.g. flooded routes, broken A/C in train cars and buses) to key agency personnel				

6.1.2.1 Climate Projections for the Atlanta Region

Climate projections for Atlanta Region were developed using the approach detailed in Section 5.2. Table 11 and Table 12 show the climate projections for three emissions scenarios for the Atlanta Region for summer and winter seasons, respectively. For the 2010 to 2039 time horizon Atlanta is not expected to see no significant difference in temperature, i.e., more or less than 0.3°F. It is not until the 2040 to 2069 time horizon and the 2070 to 2099 time horizon that the mean temperature is projected to increase significantly. As expected, the mean temperature increases the most under the high emissions scenario.

Extreme temperatures are expected to increase under all emissions scenarios and for all time horizons. For purposes of this research, extreme temperatures are defined by the thresholds utilized in NOAA's record-keeping. The summer temperature thresholds include days over 90°F and days over 100°F; the winter temperature threshold is number of freezing days, or days below 32°F. In addition, the projected numbers of consecutive days exceeding these thresholds are also provided. For precipitation, the extreme value includes days with one inch or greater precipitation. In addition, the mean maximum daily 24 hour cumulative precipitation is also provided. The number of days with more than one inch of precipitation is expected to increase significantly under all emissions scenarios but the maximum daily precipitation is expected to remain similar to present extremes.

Table 11. Atlanta Region (Fulton and DeKalb Counties) Summer (June, July, & August) Temperature & Precipitation Projections

A1FI Emissions Scenario Ensemble “High Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	79.0	79.3	82.3	84.5
Mean Days Over 90°F	32.2	80.7	90.4	91.8
Mean Max Consecutive Days Over 90°F	N/A	39	82.0	85.7
Mean Days Over 100°F	0.4	1.23	7.41	20.7
Mean Max Consecutive Days Over 100°F	N/A	3.10	1.13	17.8
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.44	3.28	3.11	3.15
Mean Days with 1" or more precip	3.9	6.72	8.51	10.40
A2 Emissions Scenario Ensemble “Moderate Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	79.0	79.1	81.1	83.0
Mean Days Over 90°F	32.2	90.0	91.7	92.0
Mean Max Consecutive Days Over 90°F	N/A	75.7	82.5	91.0
Mean Days Over 100°F	0.4	6.59	20.0	45.5
Mean Max Consecutive Days Over 100°F	N/A	0.67	9.48	5.56
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.44	4.86	5.00	5.21
Mean Days with 1" or more precip	3.9	15.7	17.9	19.50
B1 Emissions Scenario Ensemble “Low Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	79.0	79.2	79.8	80.2
Mean Days Over 90°F	32.2	89.4	91.4	91.2
Mean Max Consecutive Days Over 90°F	N/A	74.8	91.0	88.0
Mean Days Over 100°F	0.4	8.85	11.2	16.5
Mean Max Consecutive Days Over 100°F	N/A	5.00	4.06	7.30
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.44	4.74	3.96	4.91
Mean Days with 1" or more precip	3.9	16.5	17.1	19.40

Table 12. Atlanta Region (Fulton and DeKalb Counties) Winter (December, January, & February) Temperature & Precipitation Projections

A1FI Emissions Scenario Ensemble “High Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	45.2	45.0	46.7	48.8
Mean Freezing Days (Low <= 32°F)	30.6	80.8	76.4	70.3
Mean Max Consecutive Freezing Days	N/A	36.7	38.7	30.5
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.02	4.21	4.55	5.06
Mean Days with 1" or more precip	3.6	11.7	10.6	11.2
A2 Emissions Scenario Ensemble “Moderate Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	45.2	45.1	46.5	48.6
Mean Freezing Days (Low <= 32°F)	30.6	89.2	88.6	86.8
Mean Max Consecutive Freezing Days	N/A	83.5	65.7	55.2
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.02	3.66	3.84	3.84
Mean Days with 1" or more precip	3.6	24.5	25.4	26.6
B1 Emissions Scenario Ensemble “Low Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	45.2	44.9	45.9	46.4
Mean Freezing Days (Low <= 32°F)	30.6	89.2	89.0	88.4
Mean Max Consecutive Freezing Days	N/A	60	86.5	74
Mean Max Daily (cumulative 24 hr.) precip (in.)	4.02	3.76	4.39	4.61
Mean Days with 1" or more precip	3.6	24.9	25.4	27.2

6.1.3 Incorporation of Climate Change Considerations into TAM Processes

As mentioned in Section 5.1.2, MARTA is in the procurement process for new transit asset management databases and tools. In particular, the Enterprise Asset Management (EAM) software is undergoing an update that will include the addition of a software-based decision support tool, which will optimize project prioritization for MARTA's Capital Improvement Planning (CIP). In terms of project prioritization, MARTA currently considers an asset's age, its condition, and its life, safety, and operation criticality. This decision framework can be used to incorporate climate factors as well (Amekudzi and Crane 2012).

Given that MARTA already has a formalized asset management program and institutionalized asset management processes, these existing processes and tools can also formally incorporate climate change considerations. The agency's policy, goals, and objectives can be modified to include climate change-related considerations. Incorporating climate change considerations at this higher level would also facilitate periodic staff meetings to assess climate change considerations. The aforementioned asset databases and decision support tools can also account for climate change-related factors. Since climatic change also poses significant extreme weather risks, MARTA could also develop formal disaster management and recovery plans and procedures that would account for plausible future extreme weather scenarios. In light of the ice events of January 2011 (Crane and Amekudzi 2012) and the impact to New York City's transit system from Hurricane Sandy, MARTA could develop disaster response plans (Amekudzi and Crane 2012). Table 13 details how MARTA's existing TAM system components can incorporate climate change considerations.

Table 13. Draft Illustrative listing of how components of MARTA's existing TAM system can incorporate climate change (A. Amekudzi and Crane 2012)

Organizational Element	Climate-Sensitive Retrofit	Notes
Policy, Goals and Objectives	Develop climate change policy with supporting goals and objectives	The process of developing a formal climate change policy will assist agencies in developing their knowledge on the real risks of climate change to their operations and assets.
	Organizational Factors	
Staffing	Assess the value of staff time to address climate change issues on a periodic/consistent basis.	Agencies that address climate issues proactively will be better informed to develop climate risk management capabilities proactively.
	Asset Management	
Asset Management System Database (Data Collection)	Expand organizational capabilities to include expert or staff time for climate assessment and action plan with respect to agency assets and services.	E.g., Condition assessment can be conducted in collaboration with expert to integrate climate forecasts for service area and assess vulnerability of system to anticipated climate risks.
Enterprise Asset Management (EAM) system (Analysis of Alternatives including Tradeoffs)	Develop a code for climate-sensitivity of assets and input information first for mission-critical assets and then for other assets. While several transit agencies consider the age of an asset for repair and replacement decisions, MARTA considers asset condition and criticality (i.e., life safety criticality, operation criticality, etc.) as well. A climate sensitivity code can be developed with respect to the level of severity, extent of impact and probability of climate-related failure of an asset.	The EAM system comes with the capability for adding fields that can designate particular asset groups, types or components as being vulnerable to different climate stressors, to different degrees.
Expert Choice Decision-Making Software (Resource Allocation Decision Making)	The Expert Choice decision-making tool will assist the CIP committee in making decisions based on a set of agency goals and objectives that can be accorded different levels of importance based on the agency's changing priorities. A climate-related goal can be included in the current goals capturing MARTA's desire to make assets and operations more resilient to the effects of climate change. The relative importance of climate considerations can be managed by the weight given to climate factors in the model.	Infrastructure resilience to climate hazards and disasters is a desirable attribute for a transit agency in this modern climate era. However, the relatively high levels of uncertainty associated with predicting climate changes makes an adaptive management framework desirable; one that can respond to changes and new information revealed with better data over time. The weighting approach used in the decision-making software is a good platform on which to implement such an adaptive approach
Design Standards	Engineering design standards may be developed to address changing climate, e.g., higher frequency and intensity of storms.	

Table 13 (continued).

Disaster Management and Recovery		
Disaster Recovery Plan	Where it makes sense, develop Disaster Recovery Plan (DRP) that outlines MARTA's role in different realistic disaster scenarios.	Agencies that develop DRPs proactively will be better prepared for quick and effective recovery in the aftermath of a disaster.
Post-Disaster Smart Rebuilding	Transit agencies that experience disasters such as the 2012 Super Storm will be better prepared to rebuild smart, relative to climate risks, if they have spent some time thinking through the potential impacts of climate risks on their operations and services and identified how they can modify their actions to achieve a higher level of resilience in their transit facilities and operations.	Post-Disaster rebuilding, while all disasters remain undesirable, may be viewed as an opportunity to rebuild and renew infrastructure in smarter ways to improve resilience in the face of changing climate patterns.

6.1.3.1 Criticality

MARTA’s asset management database contains over 53,000 data items. In order to identify which assets are most critical, the agency can follow a hierarchy that prioritizes mission-critical assets. Given the importance of the agency’s State of Good Repair (SGR) efforts, climate change factors could be considered within the existing prioritization hierarchy of mission-critical and SGR critical assets. Since there is considerable uncertainty associated with climate projections, MARTA can utilize an adaptive management approach to incorporate climate change considerations into existing asset management processes. As knowledge of climate change impacts improves over time, MARTA can modify its asset management policies and procedures.

6.1.4 Vulnerability

To identify which portions of its network and which assets are most vulnerable, MARTA can utilize the relative risk of the climate impacts shown in Figure 21, and the potential adaptation strategies detailed in Table 10. Based on this information, the impacts of prolonged extreme heat and increased intensity of precipitation events are of greatest concern to MARTA. The most vulnerable portions of the rail and bus networks include those segments that are most susceptible to inundation during extreme precipitation events. In addition, those rail segments and rail stations at higher elevations susceptible to the impacts of high wind velocities are also vulnerable. MARTA can plan contingency routes on its bus system for use during extreme precipitation events.

Increased extreme heat poses a risk not only to the structural integrity of the rails, but also to the safety and comfort of both MARTA employees and passengers. Maintenance and effectiveness of HVAC systems on bus and rail vehicles will be imperative during heat waves. In addition, the productivity of MARTA's employees who work in non-air conditioned areas will be affected. Passenger comfort and safety should also be considered. Where feasible, MARTA can ensure that shaded areas are available at bus stops, and fans can be used to augment natural cooling provided by proper air circulation.

Although MARTA's service network is vulnerable to the impacts of snow and ice events, these events are rare in occurrence. The agency also required snow and ice removal equipment in January of 2011. Lessons learned from the January 2011 snow and ice event, and the development of formal response procedures, can be utilized to respond to future snow and ice events. In the event that snow and ice conditions become more frequent and/or intense in the future, the agency can account for this consideration within the context of its asset management policies and procedures as part of its overall adaptive management process.

6.2 MPC/Savannah Case Study

Although the CORE MPO in Savannah – Chatham County does not have a mature asset management system relative to MARTA and GDOT, climate change considerations can be incorporated into the short and long-range planning component of the asset management process shown in Figure 1. This approach has also been used at the MPOs in Asheville, North Carolina (Fox et al. 2010) and Chattanooga, Tennessee (Cambridge Systematics 2012b). Furthermore, MAP-21 requires that MPOs develop plans that detail performance measures and performance targets. These plans must also demonstrate how project selection meets performance targets (FHWA 2012). At present, LRTPs are not required to incorporate climate change considerations, but the FHWA released a report that describes model language in transportation plans that do consider climate change (ICF International 2010).

Beyond the possibility of federal requirements that LRTPs include climate change considerations, Savannah is a low-lying community and its vulnerability to sea level rise is well-documented (Baden et al. 2012; Landers 2009; Peralta 2012). Furthermore, the CORE MPO planned to conduct a formal climate change assessment, but funding did not materialize. Thus, CORE MPO staff was willing to host a climate change adaptation workshop in conjunction with this research effort. The climate change adaptation workshop was conducted at the MPC in Savannah on April 2nd, 2013.

6.2.1 CORE MPO Climate Change and Adaptation Workshop Summary and Results – April 2nd, 2013

Twenty-five persons from a variety of industries attended the workshop. The list of attendees included four MPC staff members, three city staff members, three county staff members, four educational institution representatives, four consultants and private sector representatives, one military representative, one transit agency representative, one media representative, and four advisory board and interest group representatives. The workshop consisted of two parts; the first was a presentation by Dr. Michael Meyer of Transport Studio, LLC and the second was a brief presentation by Georgia Tech Ph.D. Candidate J.P. O'Har. The presentations were followed by group breakout sessions to identify climate risks and potential adaptation strategies.

The workshop began with a presentation entitled "Climate Change and Transportation-related Adaptation Planning". This presentation set the broader context for climate change adaptation planning in transportation. To begin the presentation, the difference between adaptation and mitigation was discussed. Mitigation largely deals with strategies to reduce Greenhouse Gas (GHG) emissions and therefore reduce the impacts of climate change. Adaptation relates to planning for and coping with expected impacts.

Extreme weather events, particularly Hurricanes Katrina, Irene, and Sandy, have significantly affected transportation infrastructure. A brief discussion of the scientific evidence behind climate change followed. Recent scientific data points towards warming trends and increased frequency of extreme weather events in the United States. Impacts of climate change, such as increased frequency and duration of extreme heat, sea level rise, and permafrost thaw, present long-term environmental challenges. Many coastal roadways in the U.S. are vulnerable to storm surge. To provide context in terms of transportation, critical components of transportation infrastructure design and the typical roadway segment were defined. Several climate stressors, their impacts on transportation infrastructure, and potential adaptation strategies were given as illustrative examples.

Criticality is an important component of the transportation community's response to climate change. However, different stakeholders may define criticality in different ways. It is important to identify what role transportation plays in the community, i.e., what critical activities does transportation infrastructure provide access to? The Chattanooga Metropolitan Planning Organization (MPO) conducted a climate change adaptation workshop in 2012 as part of its 2040 Long Range Transportation Plan (LRTP) development. One component of this workshop was the identification of critical transportation infrastructure assets by stakeholders (Cambridge Systematics 2012b).

Asheville, North Carolina is another community that has identified likely impacts of climate change on its transportation infrastructure. Climate stressors that are expected to affect Asheville include increased frequency of hazards associated with wildfires, flooding, landslides, and dam breaches. Given the elevation differences in parts of this community, the valley roads can expect increased severity of extreme heat, while roads at higher elevations can expect colder temperatures and icing events. In addition, Asheville can expect increased risk of flooding and of landslides (Fox et al. 2010).

In order to account for these risks, Asheville advocated reviewing design standards and identifying roads and bridges that are especially susceptible to flooding. To identify areas particularly vulnerable to climate change impacts, analyses were conducted using GIS. In addition, the use of future scenarios to inform transportation and land use planning was advocated. Proposed projects in the 2040 LRTP were mapped and superimposed on climate risks to identify projects that could be impacted by climate hazards (Fox et al. 2010).

An ongoing National Cooperative Highway Research Program (NCHRP) Project 20-83(5) entitled “Climate Change and the Highway System: Impacts and Adaptation Approaches” develops a conceptual framework which can be used to incorporate climate change adaptation activities at transportation agencies. Preliminary findings of this research project were presented; the final results of this project, a practitioner’s guide to climate change adaptation and an associated software tool, are forthcoming. A pre-publication, unedited version of this guide is available online (Michael Meyer et al. 2013). The NCHRP Project focuses on impacts throughout the U.S. As such, temperature and precipitation projections for the U.S. in 2050, with a baseline of 2010 were displayed.

An overview of the progress on Phase 2 of the Federal Highway Administration (FHWA) – sponsored Gulf Coast Study, which examines climate impacts on the Gulf Coast Region and also identifies adaptation strategies, was presented. The second phase of the Gulf Coast Study provides a detailed analysis of potential impacts in the Mobile, Alabama area. Infrastructure assets are assigned vulnerability scores based on indicators related to asset exposure, sensitivity, and adaptive capacity (ICF International et al. 2012).

The final part of the presentation involved going through the individual steps in the adaptation framework defined in NCHRP Project 20-83(5), which is shown below in Figure 22. To further illustrate potential risk appraisal approaches, several examples of how agencies are performing risk assessments were discussed. In conclusion, a list of ten recommended operations and maintenance activities to better prepare for extreme weather and climatic change were enumerated.

The subsequent presentation discussed what climate impacts the Savannah – Chatham County region can expect. The climate models used to develop the climate ensembles for three emissions scenario were discussed. Downscaled climate projection data used to develop these projections is made available via the United States Geological Survey's (USGS) Geo Data Portal (GDP) (Stoner et al. 2012). For illustrative purposes, several maps of the statewide climate divisions in Georgia showing baseline climate data and projected summer and winter temperatures were shown.

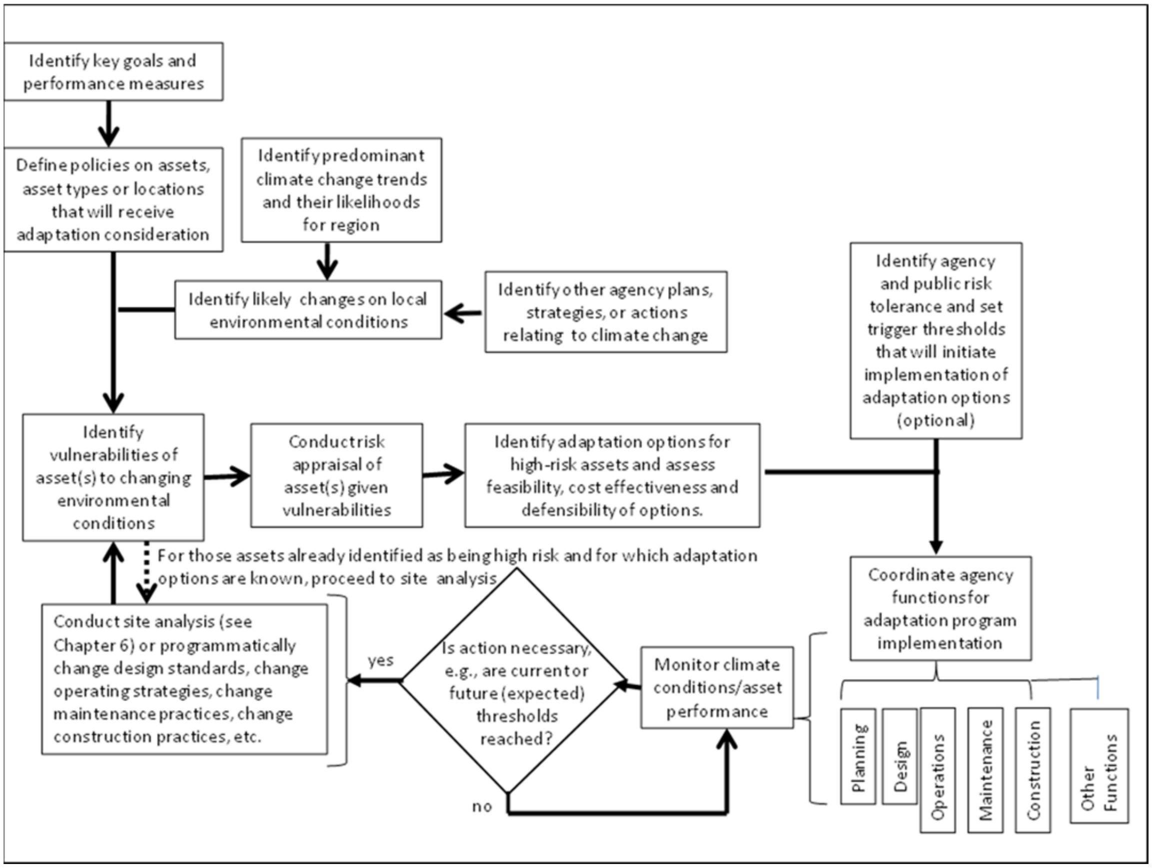


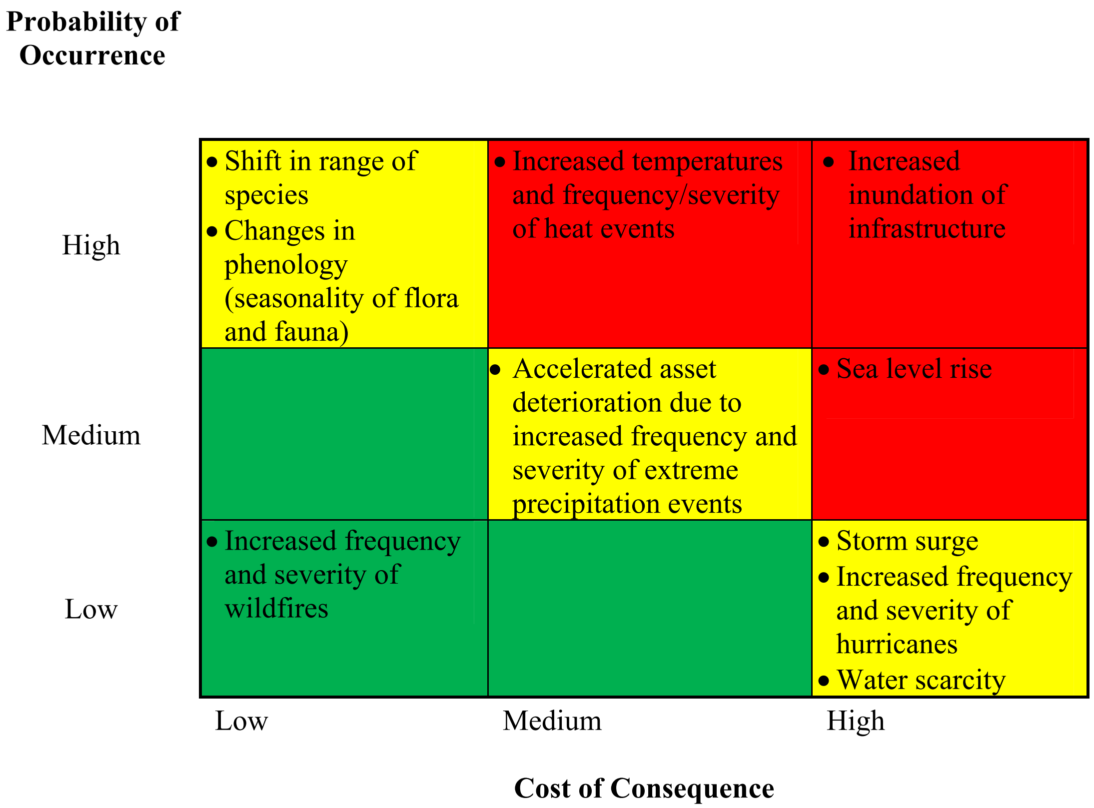
Figure 22. Adapted from NCHRP 20-83(5) (Meyer et al. 2013) climate change adaptation framework

The following climate impacts in Chatham County were listed for illustrative purposes:

- Sea Level Rise
- Coastal Storms and Surge
- Increased Wind Velocities
- Increased Temperatures
- Increased Frequency/Intensity of Precipitation
- Increased Extreme Temperatures
    - But Decreased Extreme Cold Over Time

Savannah has been identified as being particularly vulnerable to sea level rise in several studies and several major news media outlets, such as the New York Times and National Public Radio, have singled out Savannah as especially vulnerable to sea level rise (Peralta 2012; Wald and Schwartz 2012). Information Technology Outreach Services (ITOS) at UGA's Carl Vinson Institute for Government, in conjunction with the National Oceanic and Atmospheric Administration (NOAA)'s Coastal Services Center (CSC), created hurricane surge maps and above normal tide maps for Chatham County's Emergency Management Agency (CEMA) as part of its Comprehensive Hurricane Preparedness Study (NOAA CSC and CEMA 2006).

Several maps display above normal tides and hurricane surge levels in conjunction with transportation infrastructure, and also with transit bus routes and bus stops. These maps illustrate the potential inundation of critical transportation infrastructure from above normal tides and hurricane storm surge. Attendees were provided handouts that contained the projection data in Table 15 and Table 16. Given the information provided in both presentations, and the projections in the handouts, attendees were divided into four breakout groups and asked to fill in the climate change impacts risk matrix and the adaptation strategies table. See Figure 23 and Table 14 below for the results of this exercise.



Probability of Occurrence

	Low	Medium	High
High	• Shift in range of species • Changes in phenology (seasonality of flora and fauna)	• Increased temperatures and frequency/severity of heat events	• Increased inundation of infrastructure
Medium		• Accelerated asset deterioration due to increased frequency and severity of extreme precipitation events	• Sea level rise
Low	• Increased frequency and severity of wildfires		• Storm surge • Increased frequency and severity of hurricanes • Water scarcity

Cost of Consequence

Figure 23. Climate risk matrix from CORE MPO workshop

Table 14. Adaptation strategies from CORE MPO workshop

Potential Climate Impacts	Adaptation Strategies	
	Short-term	Long-term
• Increased frequency of inundation of infrastructure	• Increase public awareness • Install tide gates • Increase drainage pipe capacity • GIS analysis of potential hazards/identification of vulnerable areas • Condition assessment of aging infrastructure	• Alter zoning and land use • Change building codes • Relocation of bus shelters • Elevation of infrastructure • Prioritization of investment
• Sea level rise	• Develop living shorelines • Identify routes impacted at various sea level increases • Identify transit routes impacted • Retrofit and deepen bridge footings	• Elevate critical infrastructure, i.e., Hwy 80 • Eco-armoring • Plan reroutes
• Storm surge • Increased frequency and severity of hurricanes	• Flood-proof/harden existing infrastructure	• Elevate critical infrastructure, i.e., Hwy 80 • Relocation of facilities
• Water scarcity	• Increase use of recycled/grey water • Protect drinking water sources • Identify salt-resistant plants	• Public education • Alter project prioritization • Analysis of trade-offs/balance with economic development
• Increased temperatures and frequency/severity of heat events	• Accelerate asset maintenance • Identify critical linkages in transportation infrastructure	• Explore alternative energy sources • Improve efficiency of buildings • Research heat resistant materials • Change design standards
• Accelerated asset deterioration due to increased frequency/severity of precipitation events	• Conduct vulnerability assessment • Accelerate asset replacement cycles	• Research new materials, e.g., permeable materials • Change design standards • Construction of transportation management/control center
• Shift in range of species • Changes in phenology (seasonality of flora and fauna)	• Monitor changes in ecosystem	• Public education
• Increased frequency/severity of wildfires	• Analyze evacuation routes and identify critical linkages	• Procure new fire-fighting equipment • Conduct disaster preparedness planning

6.2.2 Climate Risk Matrix and Potential Adaptation Strategies

As mentioned above, participants of the workshop were provided with handouts that contained climate projections for Chatham County, a blank climate risks matrix (see Figure 12), and a blank adaptation strategies table that contains columns for both short and long-term adaptation strategies.

6.2.2.1 Climate Projections for the Savannah – Chatham County Region

The approach detailed in Section 5.2 was utilized to develop the temperature and precipitation projections for Chatham County. Table 15 and Table 16 show the climate projections for three emissions scenarios for the Savannah – Chatham County Region for summer and winter seasons, respectively. For the 2010 to 2039 time horizon Chatham County can expect a two degree Fahrenheit increase in mean summer temperatures and a one degree Fahrenheit increase in winter temperatures under all emissions scenarios. In the 2040 to 2069 time horizon and the 2070 to 2099 time horizon there is greater variation in the expected temperature increases among the emissions scenarios. As expected, the mean temperature increases the most under the high emissions scenario.

Extreme temperatures are expected to increase under all emissions scenarios and for all time horizons. For purposes of this research, extreme temperatures are defined by the thresholds utilized in NOAA's record-keeping. The summer temperature thresholds include days over 90°F and days over 100°F; the winter temperature threshold is number of freezing days, or days below 32°F. In addition, the projected numbers of consecutive days exceeding these thresholds are also provided. For precipitation, the extreme value includes days with one inch or greater precipitation and in addition, the mean maximum daily 24 hour cumulative precipitation is also provided. The number of days with more than one inch of precipitation is expected to increase significantly under all emissions scenarios. The maximum daily precipitation is expected to increase approximately 20% or more in the summer under all emissions scenarios and 10% or more in the winter under all emissions scenarios.

Table 15. Savannah Region (Chatham County) Summer (June, July, & August) Temperature & Precipitation Projections

A1FI Emissions Scenario Ensemble “High Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	81.3	83.3	86.4	88.7
Mean Days Over 90°F	56.3	90.8	92.0	92.0
Mean Max Consecutive Days Over 90°F	N/A	66.5	91.0	91.0
Mean Days Over 100°F	1.8	10.20	37.80	70.8
Mean Max Consecutive Days Over 100°F	N/A	3.25	6.80	33.8
Mean Max Daily (cumulative 24 hr.) precip (in.)	5.41	6.35	7.26	6.64
Mean Days with 1" or more precip	5.4	18.0	22.1	25.1
A2 Emissions Scenario Ensemble “Moderate Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	81.3	83.2	85.2	87.1
Mean Days Over 90°F	56.3	91.9	92.0	92.0
Mean Max Consecutive Days Over 90°F	N/A	89	91.0	91.0
Mean Days Over 100°F	1.8	27.30	57.2	85.0
Mean Max Consecutive Days Over 100°F	N/A	5.60	17.2	32.4
Mean Max Daily (cumulative 24 hr.) precip (in.)	5.41	6.43	6.84	6.64
Mean Days with 1" or more precip	5.4	33.6	36.7	35.60
B1 Emissions Scenario Ensemble “Low Emissions”				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	81.3	83.3	84.0	84.6
Mean Days Over 90°F	56.3	92.0	92.0	92.0
Mean Max Consecutive Days Over 90°F	N/A	91.0	91.0	91.0
Mean Days Over 100°F	1.8	30.0	39.2	54.3
Mean Max Consecutive Days Over 100°F	N/A	9.50	8.00	22.00
Mean Max Daily (cumulative 24 hr.) precip (in.)	5.41	7.29	6.27	7.28
Mean Days with 1" or more precip	5.4	33.9	35.1	35.70

Table 16. Savannah Region (Chatham County) Winter (December, January, & February) Temperature & Precipitation Projections

A1FI Emissions Scenario Ensemble "High Emissions"				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	51.4	52.3	54.2	56.2
Mean Freezing Days (Low <= 32°F)	19.5	52.1	41.2	30.2
Mean Max Consecutive Freezing Days	N/A	18.5	2.16	9.6
Mean Max Daily (cumulative 24 hr.) precip (in.)	3.30	3.17	3.14	3.08
Mean Days with 1" or more precip	2.6	9.41	7.97	7.79
A2 Emissions Scenario Ensemble "Moderate Emissions"				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	51.4	52.4	53.8	55.7
Mean Freezing Days (Low <= 32°F)	19.5	76.0	67.1	55.0
Mean Max Consecutive Freezing Days	N/A	19.6	19.3	11.5
Mean Max Daily (cumulative 24 hr.) precip (in.)	3.30	3.78	3.82	3.66
Mean Days with 1" or more precip	2.6	17.5	19.6	21
B1 Emissions Scenario Ensemble "Low Emissions"				
Time Horizon	1981-2010	2010-2039	2040-2069	2070-2099
Mean Temp °F	51.4	52.2	53.0	53.5
Mean Freezing Days (Low <= 32°F)	19.5	76.5	72.7	69.9
Mean Max Consecutive Freezing Days	N/A	16.7	39.8	15.7
Mean Max Daily (cumulative 24 hr.) precip (in.)	3.30	3.37	3.49	3.70
Mean Days with 1" or more precip	2.6	20.4	20.0	20.4

6.2.2.2 Hazard Maps for Critical Infrastructure

Using ArcMap software and coastal hurricane surge and abnormal high tide maps produced as part of the CHPS (NOAA CSC and CEMA 2006), overlays of critical transportation infrastructure in Chatham County were created. One set of maps displays critical infrastructure, which includes evacuation routes, airports, and bridges, in Chatham County. Another set of maps focuses on the transit system and includes bus routes and bus stops. The hazard layers include two abnormal high tide levels and hurricane storm surge. These layers illustrate potential inundation from higher than normal tides and storm surges. The tidal hazard layers display Mean Lower Low Water (MLLW), which is the average of the lower low water height of each tidal day (NOAA n.d.), levels of 10 feet and 18.4 feet. 18.4 feet is the highest water level on record at the Fort Pulaski tide gauge (NOAA CSC and CEMA 2006). A 10 foot MLLW is considered a major flood stage at this Fort Pulaski tide gauge by the NWS (NWS 2013). Since this is an average of low tides, potential inundation from high tide is even greater. Figure 24, Figure 25, Figure 26, and Figure 27 show the tidal hazard layer maps. The hurricane surge maps completed as part of the CHPS are shown in Figure 28 and Figure 29.

The tidal hazard map layers show that with a 10 foot MLLW there is a significant level of inundation. U.S. Route 80, which connects Tybee Island to the mainland, is inundated under 10 foot MLLW, cutting off access to the island. An 18.4 foot MLLW is catastrophic to the Savannah – Chatham County area. Access to downtown Savannah and to the airports is cut off under these conditions. The 18.4 foot MLLW is approximately equivalent to the storm surge associated with a category three storm, which would pose similarly disastrous consequences for the Savannah – Chatham County region.

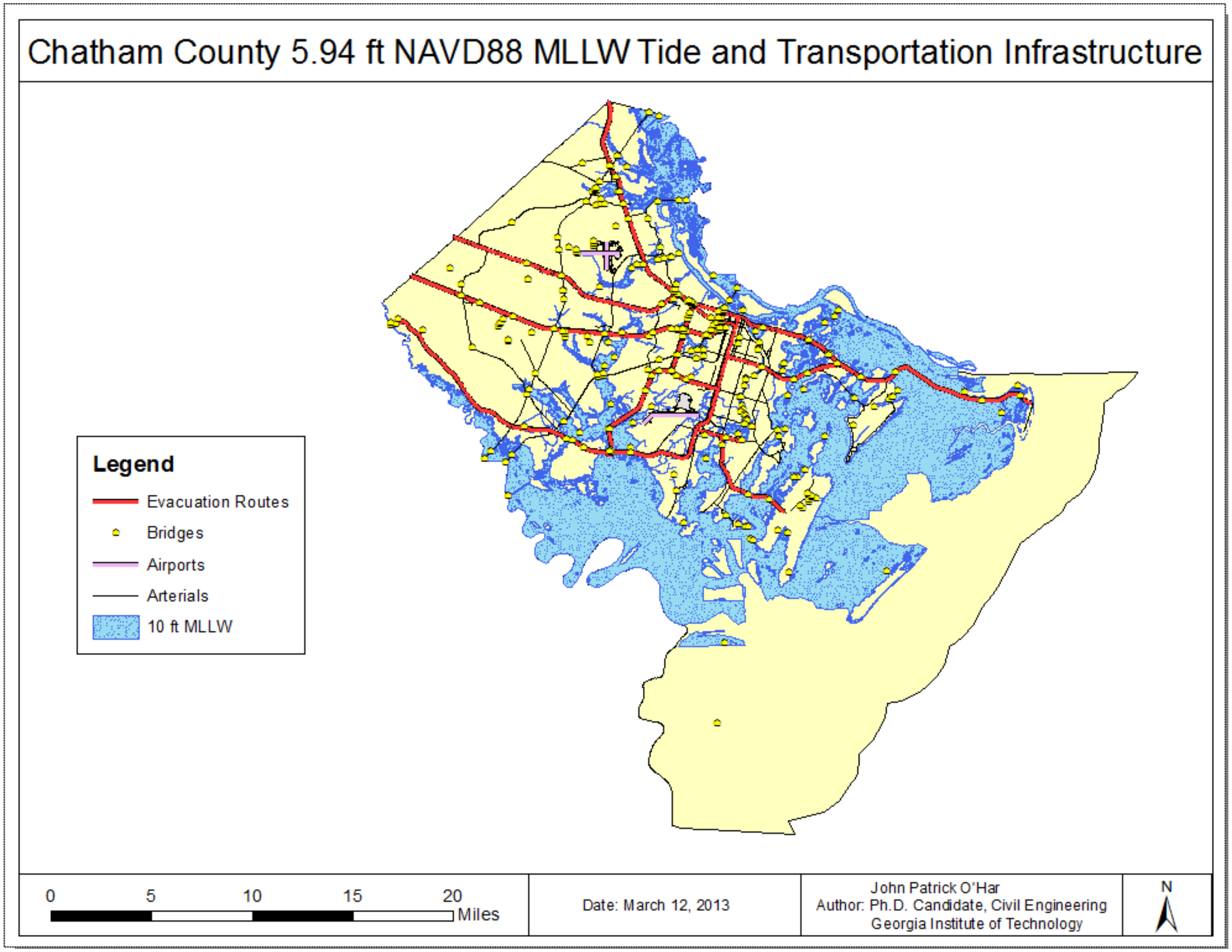


Figure 24. Chatham County 10 ft. MLLW tidal inundation and critical transportation infrastructure

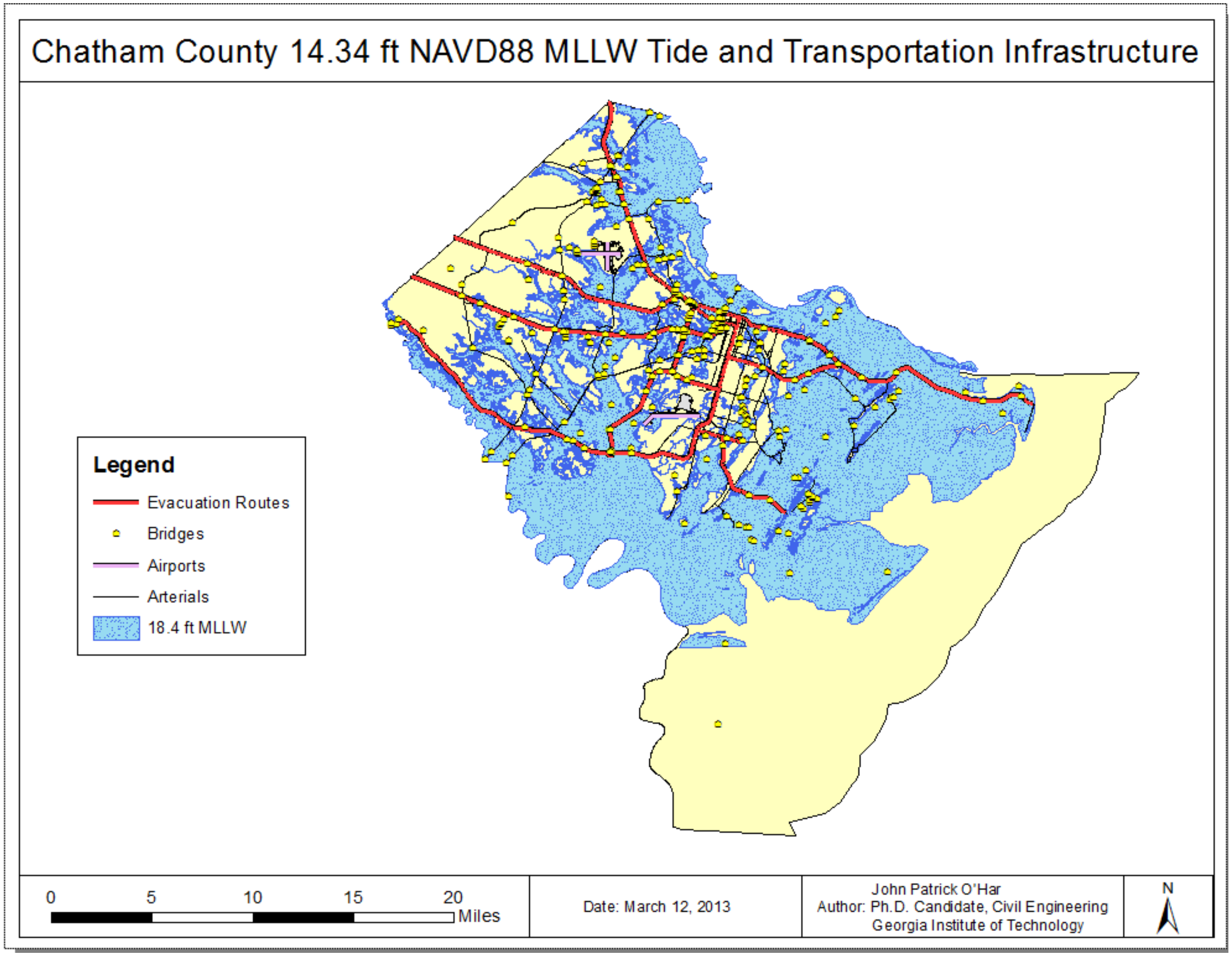


Figure 25. Chatham County 18.4 ft. MLLW tidal inundation and critical transportation infrastructure

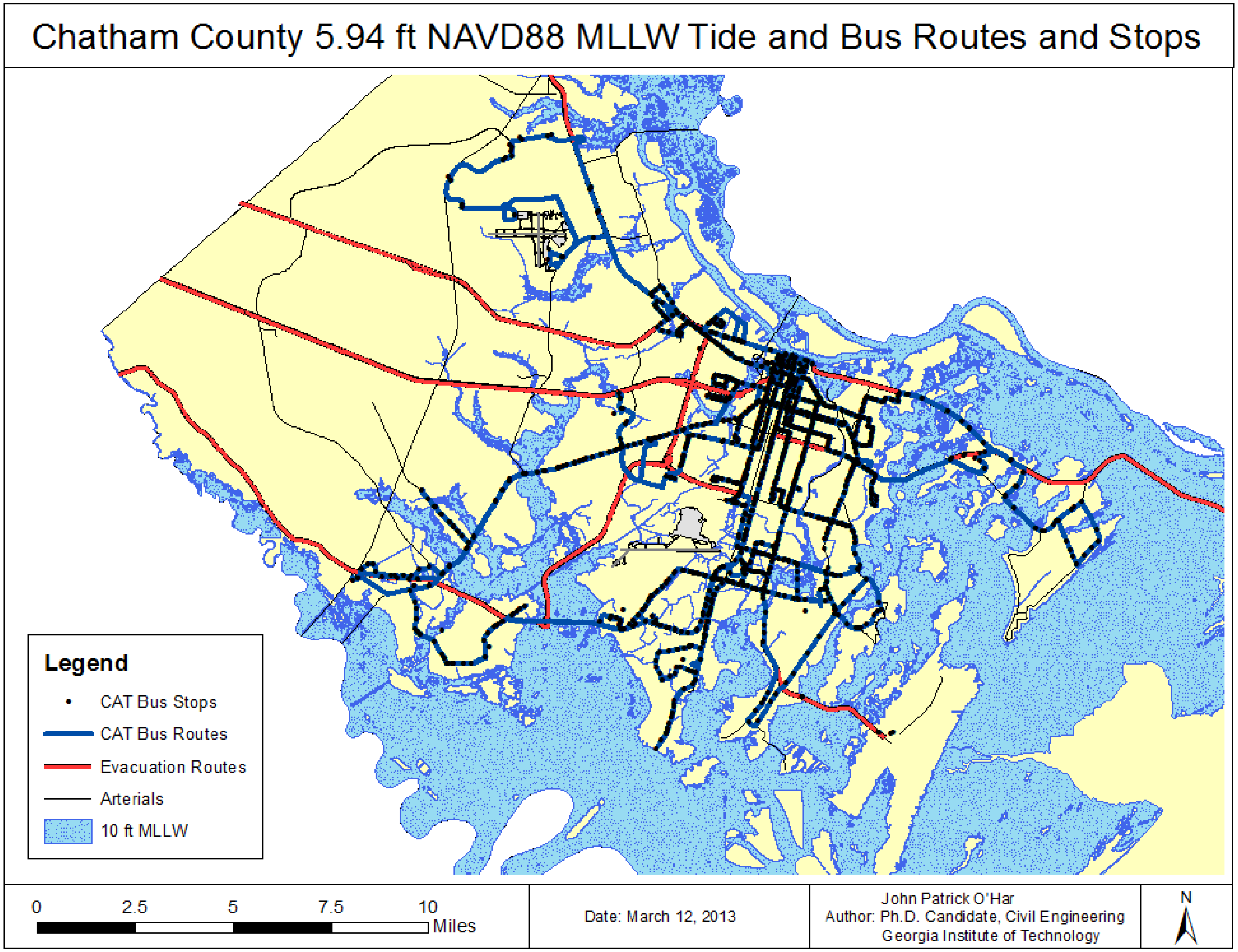


Figure 26. Chatham County 10 ft. MLLW tidal inundation and bus routes and bus stops

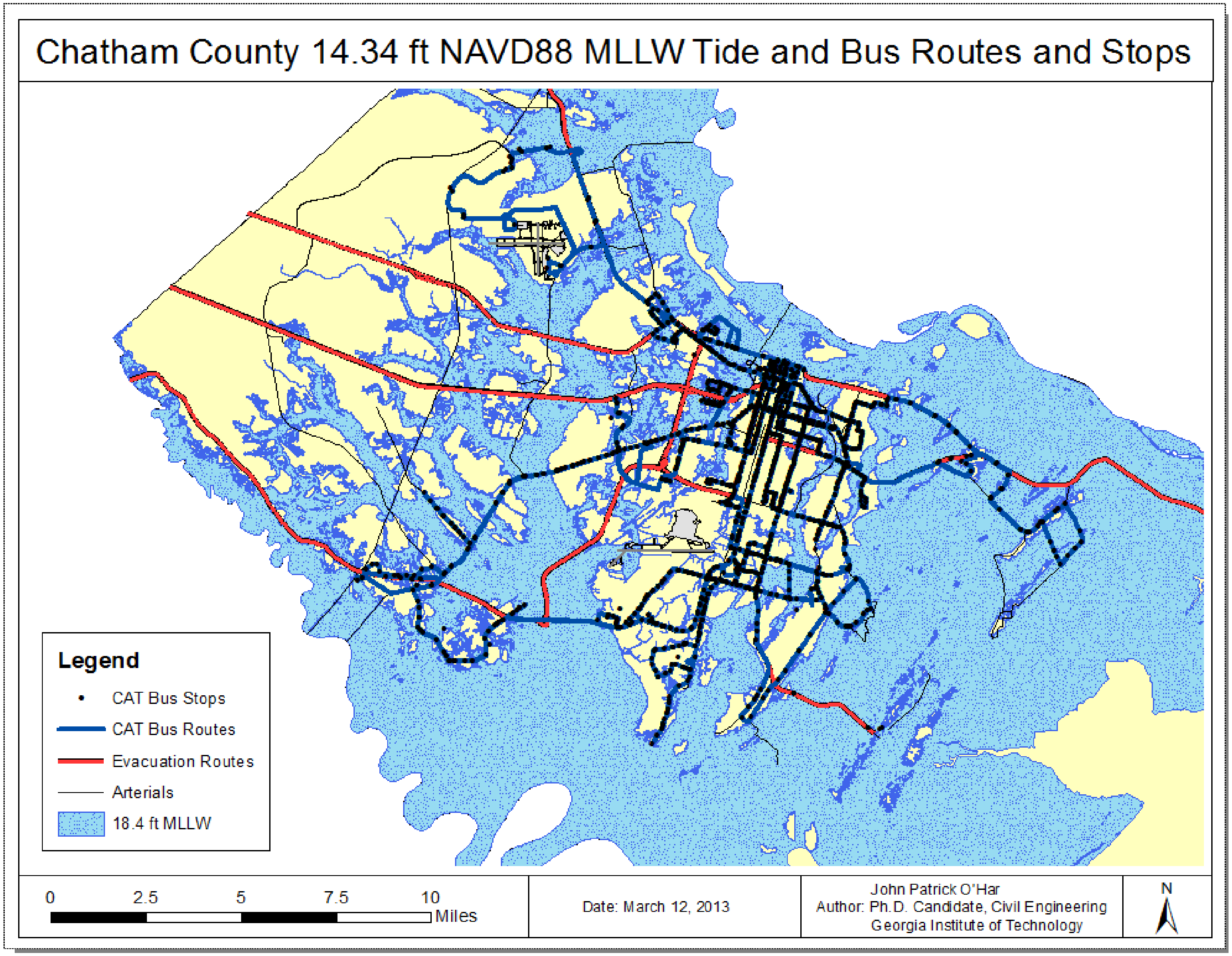


Figure 27. Chatham County 18.4 ft. MLLW tidal inundation and bus routes and bus stops

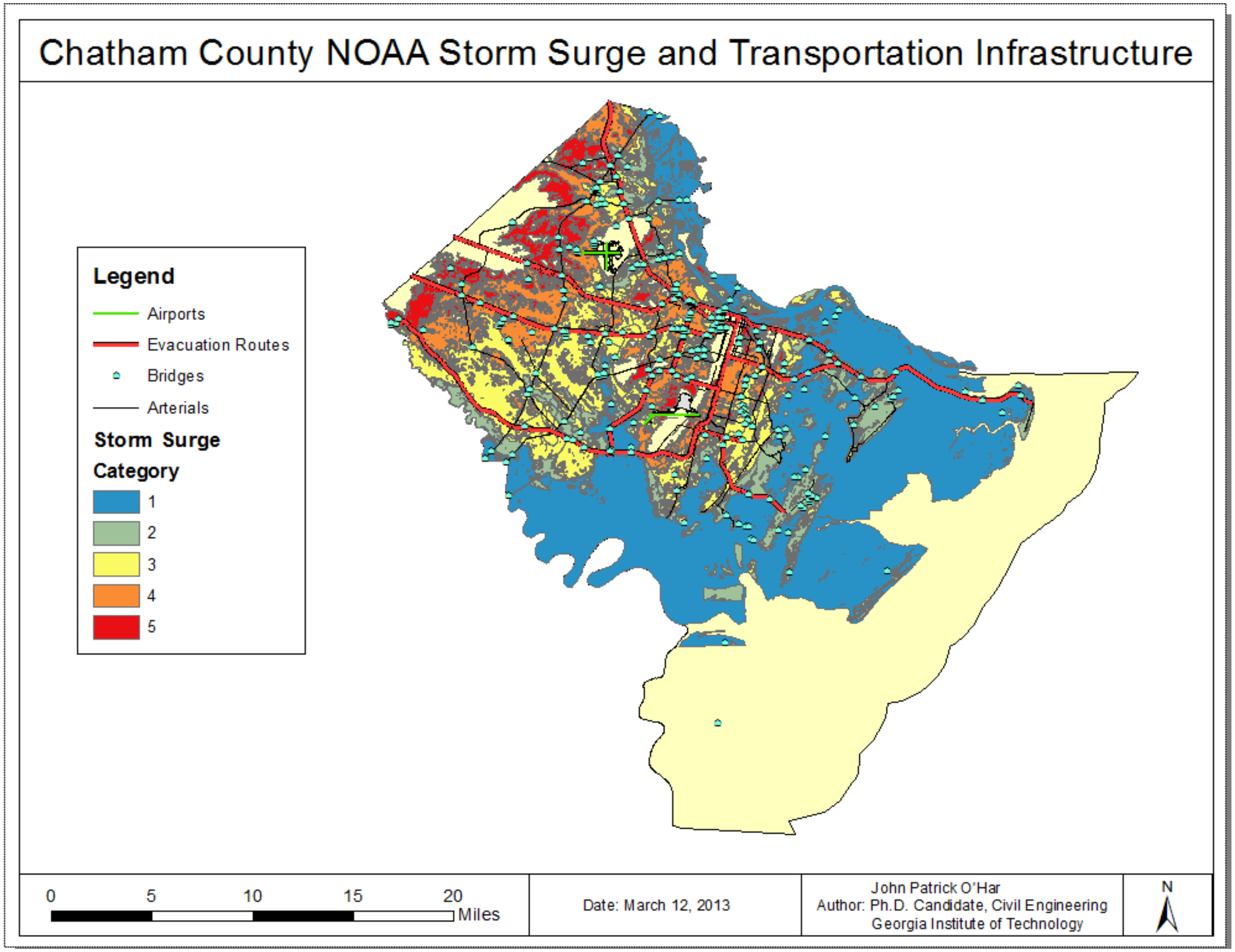


Figure 28. Chatham County hurricane storm surge and critical transportation infrastructure

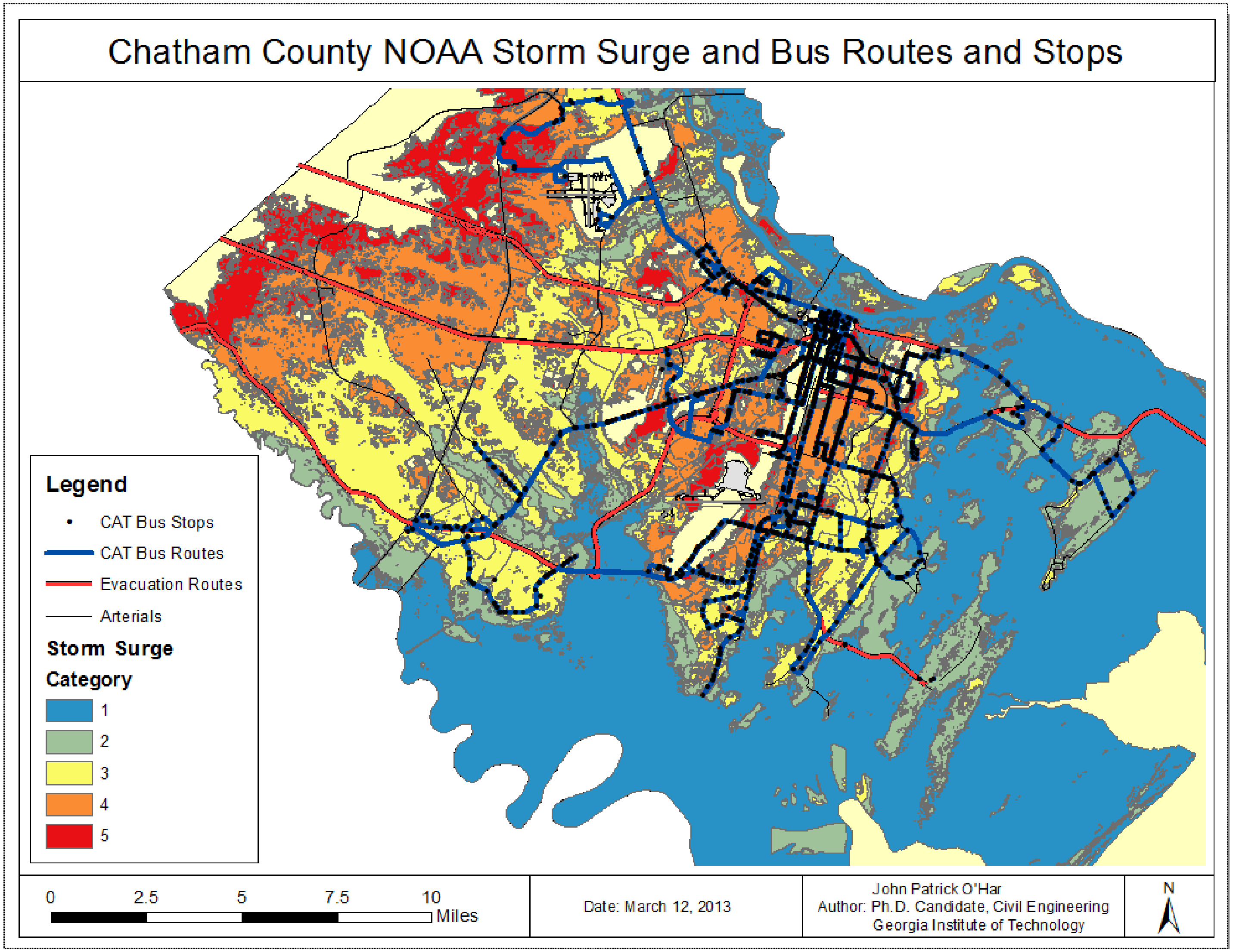


Figure 29. Chatham County hurricane storm surge and bus routes and bus stops

6.2.3 Incorporation of Climate Change Considerations into 2040 LRTP

Results of this workshop will be incorporated into the 2040 LRTP (Landers 2013). Representatives from the consultant preparing the 2040 LRTP, RS&H, were present at the workshop. Although there is currently no federal mandate to include climate change considerations in LRTPs, MPC staff anticipate future federal requirements, and the FHWA released a report describing examples of language used to incorporate climate change in LRTPs and TIPs (ICF International 2010).

6.2.3.1 Criticality and Project Prioritization

The most critical transportation infrastructure asset in the Savannah – Chatham County region is U.S. Route 80 since it provides the only access to Tybee Island. If sea levels rise approximately one foot by 2060, U.S. Route 80 could be inundated approximately half of the days out of the year (Landers 2013). Clearly some sort of project related to elevating U.S. Route 80 by mid-century should be high priority. During the project prioritization component of the 2040 LRTP, using the results of this research, climate impacts can be incorporated into the project selection process.

6.2.4 Vulnerability

Those areas or infrastructure assets that are both critical and at high risk from climate change impacts are identified in the hazard maps. U.S. Route 80 is a low-lying evacuation route that is highly susceptible to sea level rise and inundation; this is the most critical piece of infrastructure in the region. In addition, with a category three storm surge, the airport runways and access to the airports are at high risk of inundation. Further study regarding the possibility of elevating runways and airport access roads may be warranted. Although the Port of Savannah was not explicitly addressed as part of this research, it would be susceptible to sea level rise, storm surge, inundation, and limited access due to inundated roadways. An unintended benefit for the Port, which is undergoing a channel deepening project (Morris 2013), could be sea level rise allowing for vessels with larger drafts to call in Savannah.

6.3 Statewide Case Study

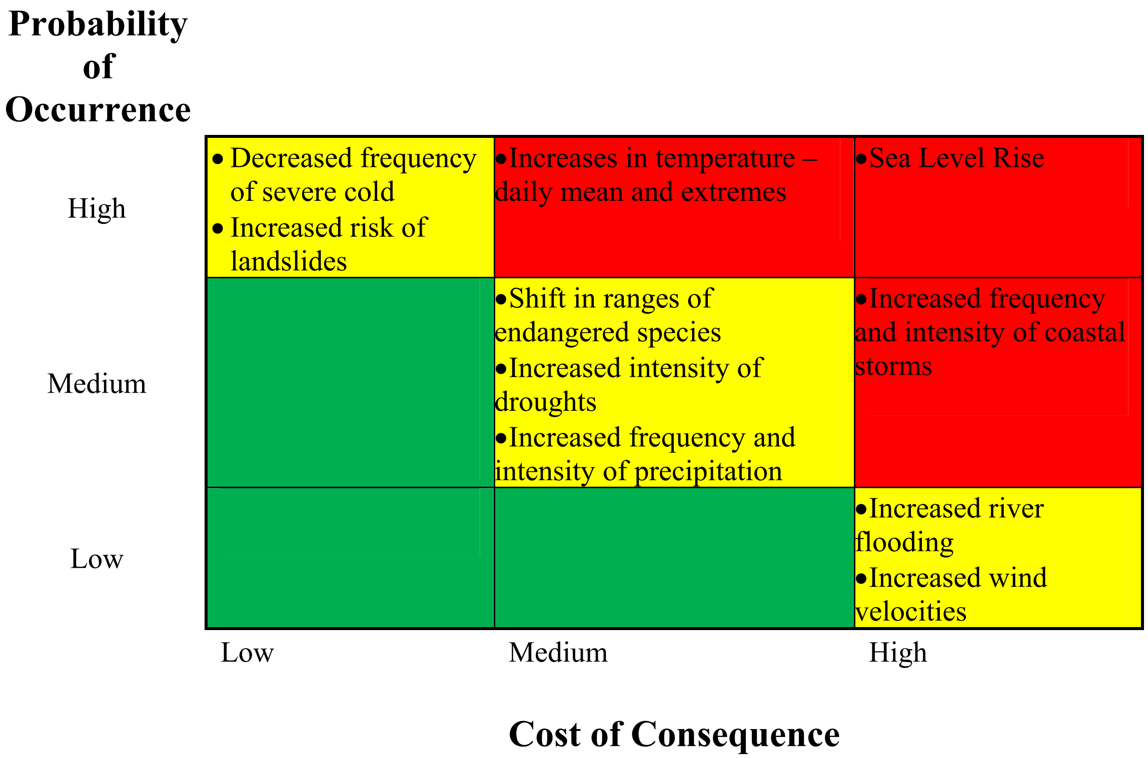
GDOT has a relatively mature asset management system, tools, processes, and an asset management plan (see Section 5.1.1). However, thus far the Department has not made an attempt to incorporate climate change considerations into is TAM processes, although it has performed studies related to risk-based asset management. Nonetheless, GDOT officials, including the director of organizational performance management, the state research engineer, the state maintenance engineer, and the assistant state bridge engineer expressed interest in both criticality assessments and climate impacts on the transportation network (O'Har 2013).

According to GDOT officials, some form of criticality assessments are ongoing but within the separate divisions or offices of the Department. The state maintenance engineer expressed interest in a criticality assessment tool that displays both roadways and bridges since the Department typically analyzes roadways and bridges separately. During the meeting, GDOT officials analyzed the statewide temperature projections and also filled in a climate risk matrix similar to the one in Figure 12. Next, the Department officials discussed potential short and long-term adaptation strategies.

6.3.1 Climate Risk Matrix and Potential Adaptation Strategies

Similar to the workshop conducted at the MPC in Savannah, GDOT officials were presented with climate projection data for temperature and also with illustrative results of the climate projections at a more localized scale for the Atlanta Region. Table 11 and Table 12 were presented to the GDOT officials. These tables, along with other climate change studies (Karl et al. 2009; NCADAC 2013), indicate that the Southeast and Georgia can expect increased frequency and intensity of precipitation events.

Sea level rise and storm surge will impact the coastal communities in Georgia. The impacts of sea level rise and storm surge in Chatham County are discussed in Section 6.2. Other research utilizing SLOSH models and analysis in ArcGIS demonstrates the potential risks associated with inundation along the coast in Georgia (Restrepo 2011). Due to the variability of local conditions related to sea level rise and storm surge, these impacts should be assessed on a more localized scale. Nonetheless, Department officials identified the relative risks of various other climate impacts. See Figure 30 and Table 17 for the climate risk matrix and adaptation strategies identified by the GDOT stakeholders during the meeting.



Probability of Occurrence	Low	Medium	High
High	🟨 • Decreased frequency of severe cold • Increased risk of landslides	🟥 •Increases in temperature – daily mean and extremes	🟥 •Sea Level Rise
Medium	🟩	🟨 •Shift in ranges of endangered species •Increased intensity of droughts •Increased frequency and intensity of precipitation	🟥 •Increased frequency and intensity of coastal storms
Low	🟩	🟩	🟨 •Increased river flooding •Increased wind velocities

Cost of Consequence

Figure 30. Climate risk matrix from meeting with GDOT stakeholders

Table 17. Adaptation strategies identified by GDOT stakeholders

Potential Climate Impacts	Adaptation Strategies	
	Short-term	Long-term
• Sea Level Rise • Increased frequency and severity of coastal storms	• Retrofit existing bridges with deeper foundations and shear keys • Improve drainage/increase culvert capacity	• Elevate new bridges and build with deeper foundations
• Increased Temperatures • Wider temperature ranges • Decrease in frequency of extreme cold	• Utilize materials with greater thermal capacity	• Research materials that can better withstand heat
• Increased flooding	• Identify low-lying areas that are susceptible to increased risk of flooding • Monitor flooding and other extreme weather events using GDOT's Emergency Operations Center Application	• Elevate and/or flood-proof critical infrastructure in vulnerable areas
• Increased Wind Velocities	• Restrict loads and traffic on bridges once wind velocity is too great • Identify areas expected to experience increased wind velocities	• Install natural and manmade barriers to block wind at vulnerable locations
• Shift in Endangered Species	• Prepare to conduct more in-depth environmental impact statements as species shift • Identify endangered species whose habitats are expected to shirt with warmer temperatures	• Install mitigation infrastructure in areas where species will likely shift • Public education and outreach about shift in species
• Increased intensity of droughts	• Monitor Department water use • Identify maintenance and other activities that are water-intensive	• Install more efficient fixtures in Department facilities • Utilize rain water capture/grey water for activities where appropriate
• Increased risk of landslides	• Identify areas of that State that are susceptible to landslides • Examine earth retaining structures in areas prone to landslides	• Install improved earth retaining structures that better withstand landslide • Relocate roadways to areas not as prone to landslide where feasible

6.3.1.1 Statewide Baseline Temperature and Temperature Projections

To develop climate projections for the State of Georgia, NOAA’s climate divisions for the State were used as a baseline. Mean temperature values, using a baseline of 1981 to 2010, for each division for both summer and winter were displayed graphically. Figure 31 and Figure 32 show these baseline climate maps. Utilizing the methods detailed in Section 5.2, temperature projection values were calculated for each climate division. Summer and winter temperature projection maps were created for each time horizon, i.e., 2010 to 2039, 2040 to 2069, 2070 to 2099, and for each emissions scenario, A1FI, A2, B1. Including the baseline maps, there are 20 maps total. In addition to the baseline maps, the 2070 to 2099 maps for the A1FI, or high, emissions scenario are shown below in Figure 33 and Figure 34. These are the most conservative projections, i.e., the greatest potential increase in mean temperatures. Maps for other time horizons and emissions scenarios are in Appendix G:.

The baseline temperature maps show that southern and southeastern Georgia experience the highest mean temperatures in summer and winter. Although these areas are expected to get warmer, the northeastern and eastern parts of the state can expect to see the most significant increases in mean temperature through the end of the century. Since the southern and southeastern portions of the State are more accustomed to warmer temperatures, the implications of increased temperatures in the eastern and northeastern portions of the State could be more severe.

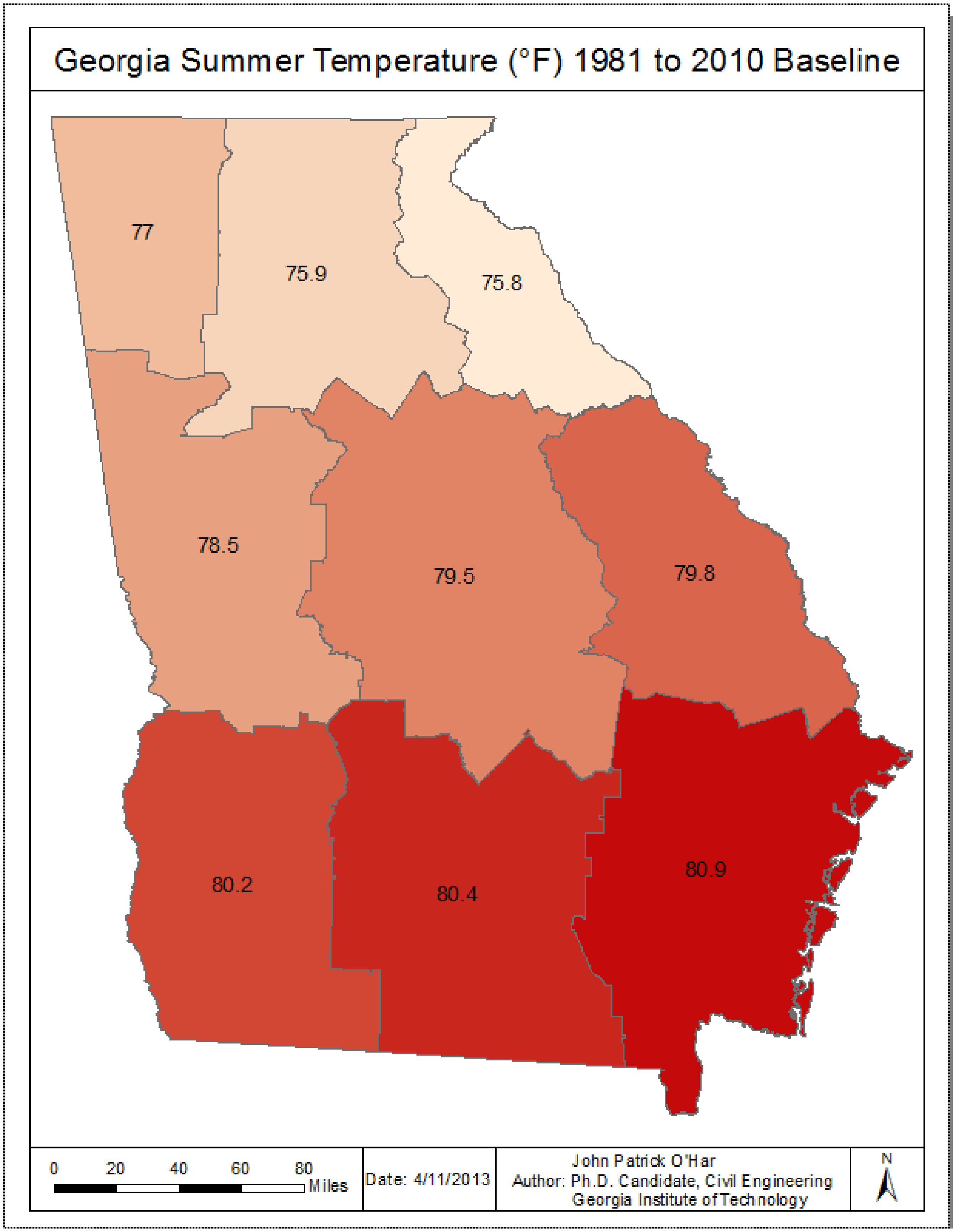


Figure 31. State of Georgia summer (June, July, August) baseline temperatures for NOAA climate divisions

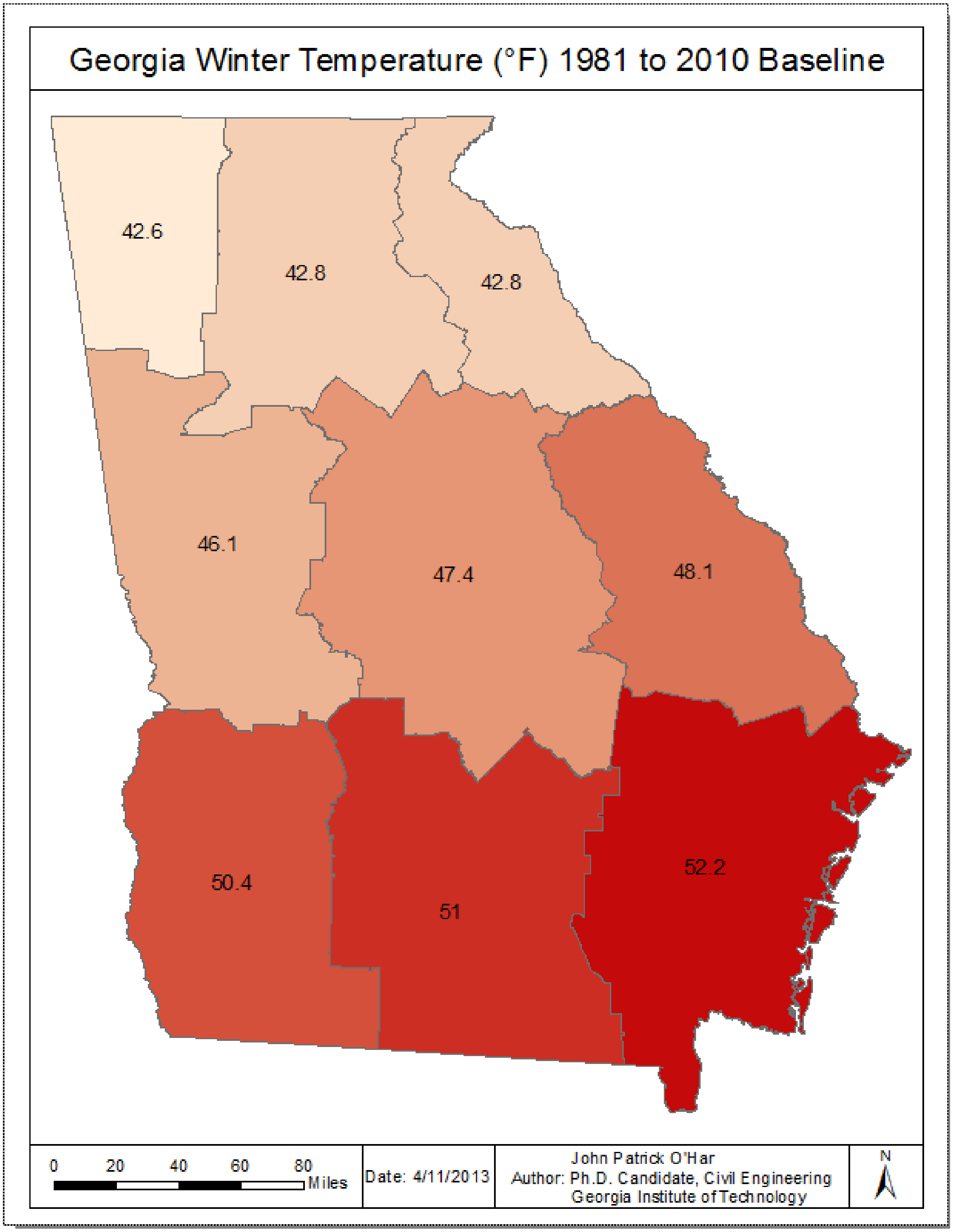


Figure 32. State of Georgia winter (December, January, February) baseline temperatures for NOAA climate divisions

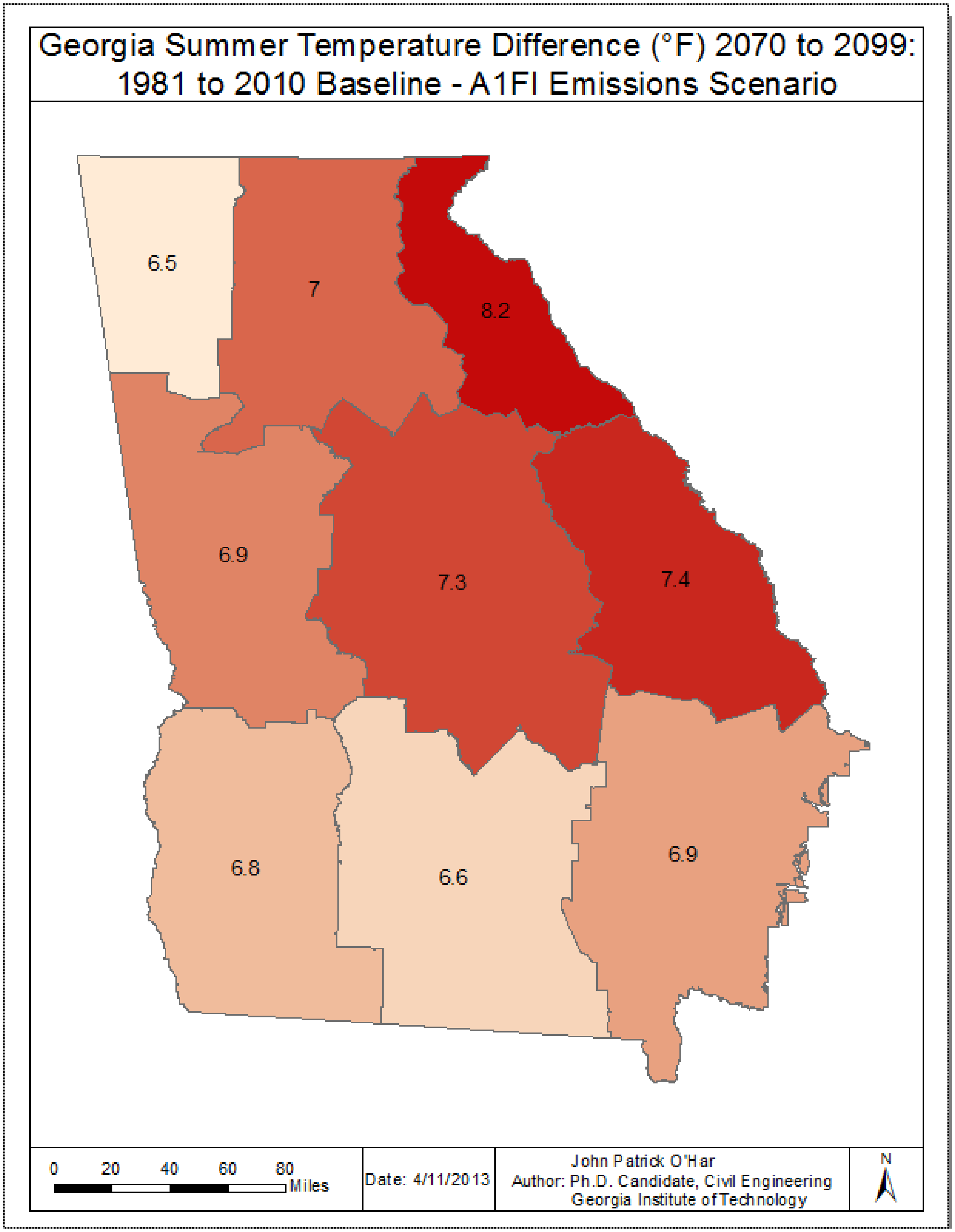


Figure 33. State of Georgia summer (June, July, August) temperature difference projection for 2070 to 2099 for the A1FI emissions scenario

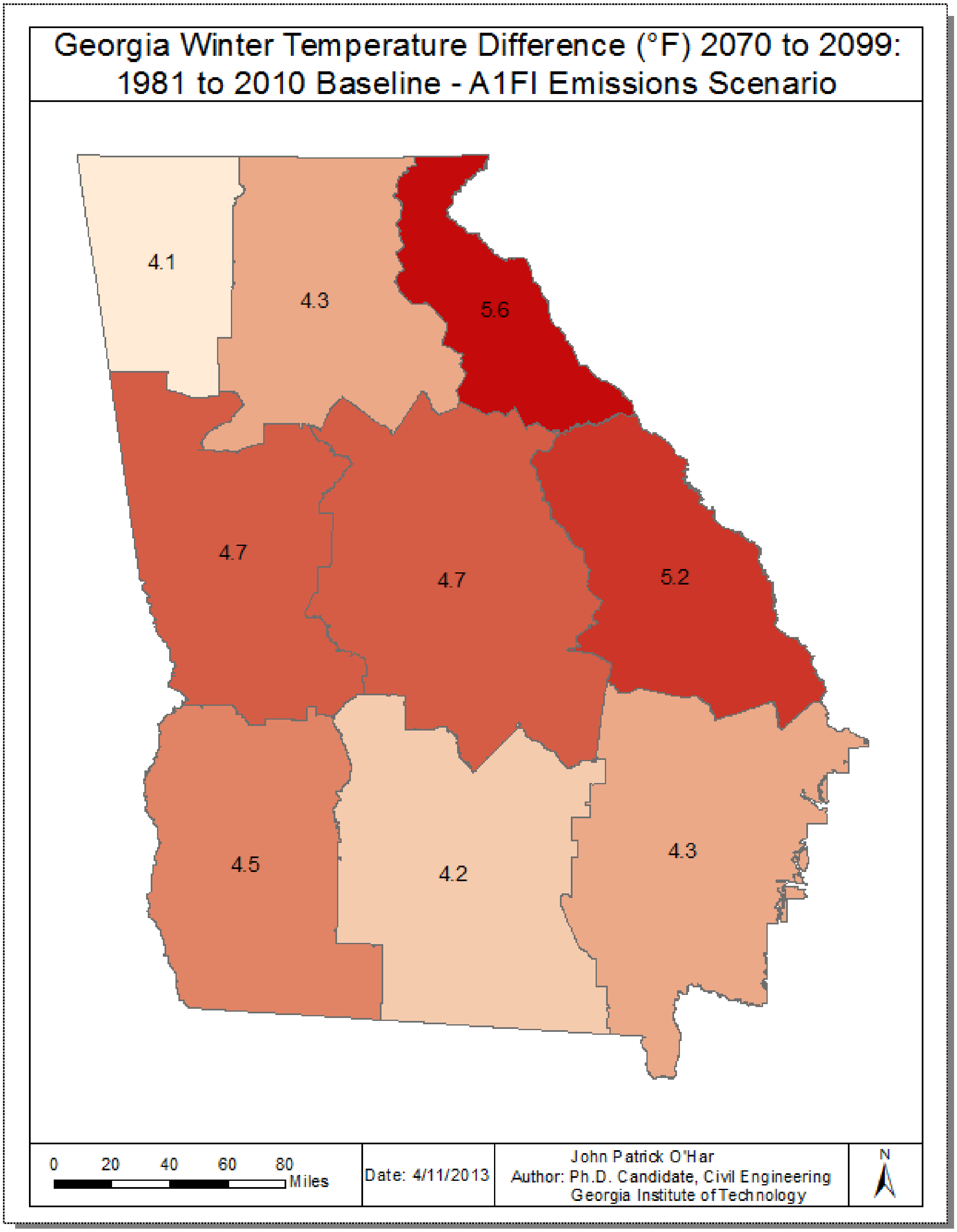


Figure 34. State of Georgia winter (December, January, February) temperature difference projection for 2070 to 2099 for the A1FI emissions scenario

6.3.2 Criticality – MCDM Tool for Roadways and Bridges

In addition to the temperature projection maps, climate risks matrix, and adaptation strategies table, GDOT stakeholders were also presented with the results of the MCDM criticality scoring tools. Department officials expressed interest in this sort of tool. This tool was presented to GDOT stakeholders as an illustrative example of its capabilities. Users of the tool can select which attributes will define risk factors, define the relative levels of risk for each factor, and then the tool will calculate a criticality score for roadways and bridges. This information can then be displayed geospatially to identify interdependencies between critical roadways and bridges. Please see Appendix F: for sample criticality score calculations.

6.3.2.1 Roadway MCDM Criticality Tool Results

As discussed in Section 5.3.1 the following attributes defined the risk factors used in this research:

- STRAHNET Classification
- NHS Classification
- Traffic Volume (AADT)
- Condition (PACES Rating)
- Total Lanes
- Truck Percentage

The risk factor weights utilized in this research are shown below in Table 18. Figure 35 displays the visualization of the final criticality scores developed using these factors. Criticality scores were divided into three different ranges representing low, medium, and high, two to three, four to six, and seven to nine respectively. Table 19 shows the length of centerline miles of roadway in each criticality score category. The largest length of miles is in the low criticality category, with fewer miles in the medium category and the fewest miles in the high criticality category. Further information regarding the definition of relative risk and the methodological approach used to develop this tool is available in Section 4.2 and Section 5.3.1. Results of this tool should be used at the network level to identify critical corridors and portions of the roadway network. Project-level analysis would require a more detailed approach.

Table 18. Risk Factor Weights for Roadway MCDM Tool

Risk Factor	Weight
STRAHNET	0.2
NHS	0.1
Functional Classification	0.1
Traffic Volume (AADT)	0.2
Condition (PACES Rating)	0.2
Total Lanes	0.1
Truck Percentage	0.1

Table 19. Roadways in Each Criticality Category

Criticality Category	Centerline Miles (mi.)
High	1365
Medium	5707
Low	9703

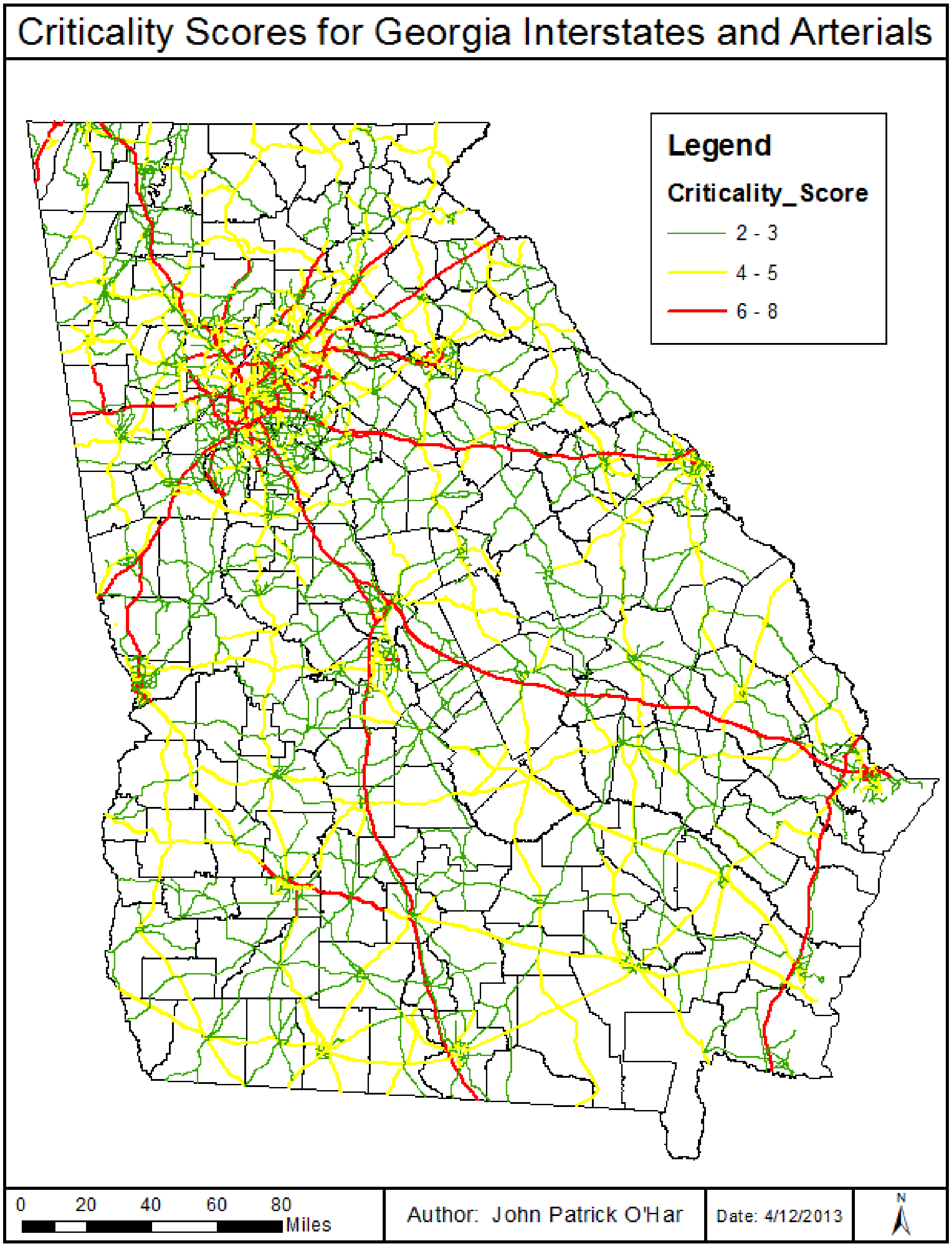


Figure 35. Map of criticality scores for interstates and arterials in Georgia

6.3.2.2 Bridge MDCM Criticality Tool Results

As mentioned in Section 5.3.2 the risk factors used to develop the criticality scores for bridges in the State of Georgia are:

- Inventory Rating
- Weight Posting
- Scour Criticality
- Fracture Criticality
- Bypass Length
- Condition

Table 20 shows the risk factors used to calculate the criticality scores for the bridges. A visual representation of the criticality scores is shown in Figure 36. Similar to the roadways, bridges were categorized into low, medium, and high criticality using the following score ranges, zero to three for low, four to six for medium, and seven to nine for high. The number of bridges in each category is shown below in Table 21. The vast majority of bridges are in the low criticality category, a moderate number of bridges are in the medium category, and relatively few bridges are in the high criticality category. This tool should be used at the network level; more detailed analysis should be done at the project level. Section 4.2 and Section 5.3.2 provide details regarding the definitions of relative risk and the methodological approach utilized to calculate these criticality scores.

Table 20. Risk Factor Weights for Bridge MCDM Criticality Tool

Risk Factor	Weight
Inventory Rating	0.3
Weight Posting	0.2
Scour Criticality	0.05
Fracture Criticality	0.05
Bypass Length	0.2
Condition	0.2

Table 21. Number of Bridges in Each Criticality Category

Criticality Category	Number of Bridges
High	93
Medium	567
Low	1625

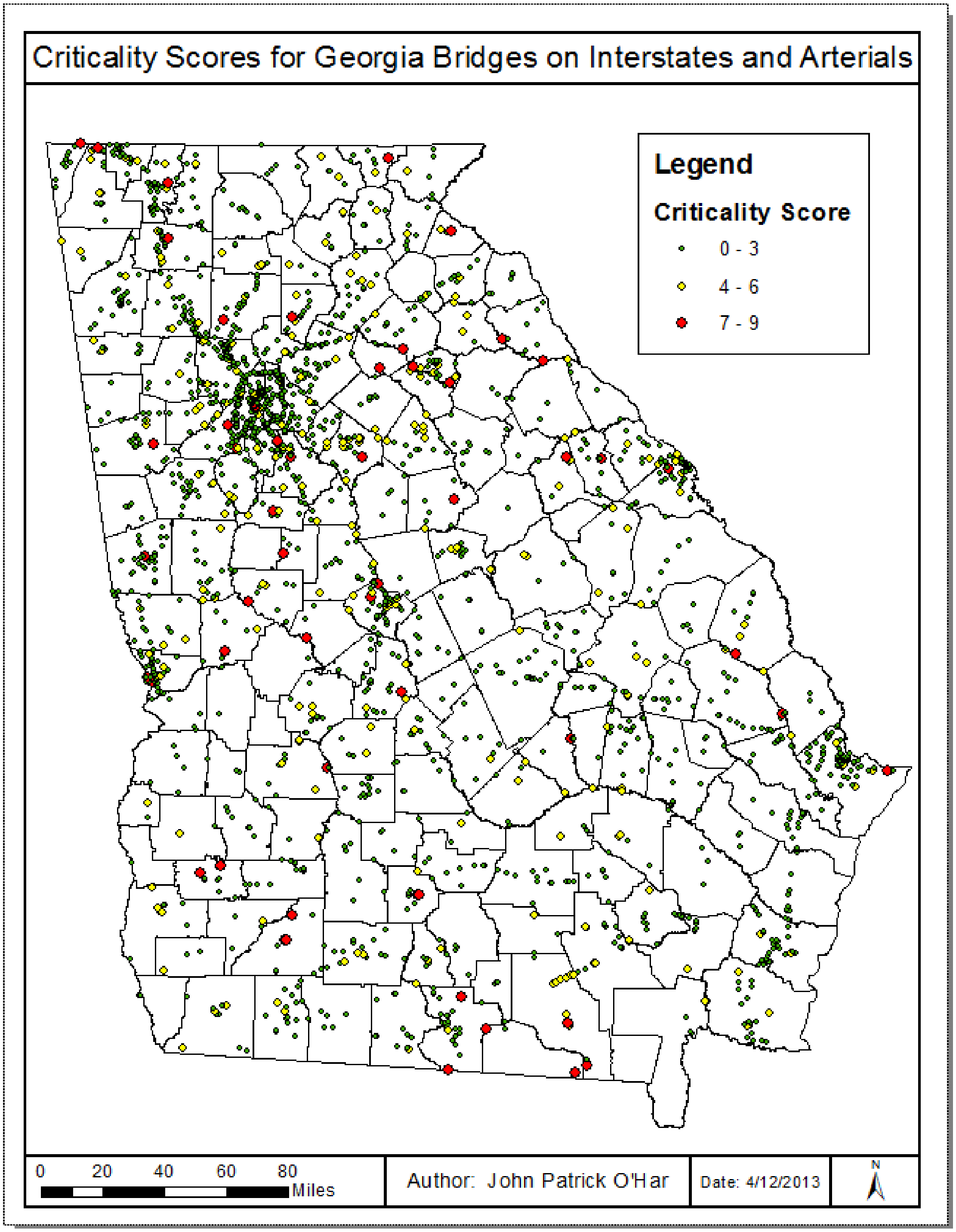


Figure 36. Map of criticality scores for Georgia bridges on interstates and arterials

6.3.2.3 Interdependency of Roadways and Bridges

An important component of the geospatial analysis conducted using the results of the roadway and bridge MCDM tools is determining the interdependency of roadways and bridges. In particular, the user can identify where highly critical bridges intersect with portions of the roadway network that are not classified as highly critical. This is crucial because if a bridge is highly critical its access roadways should also be classified as highly critical. Given the risk factor weights used for roadways and bridges in this analysis, there is only one bridge that is highly critical and lies on portion of the roadway network that is also classified as highly critical.

Figure 37 shows a map of the highly critical roadways and bridges in Georgia. As mentioned above, all but one of the highly critical bridges are on portions of the roadway network that are classified as medium or low criticality. Special attention should be given to portions of the roadway network that intersect with highly critical bridges. Detour routes and the condition of these roadways should be analyzed. Although analyses for roadways and bridges are often performed separately, the interaction between these two components of the roadway network is critical to the effective, efficient function of the transportation network.

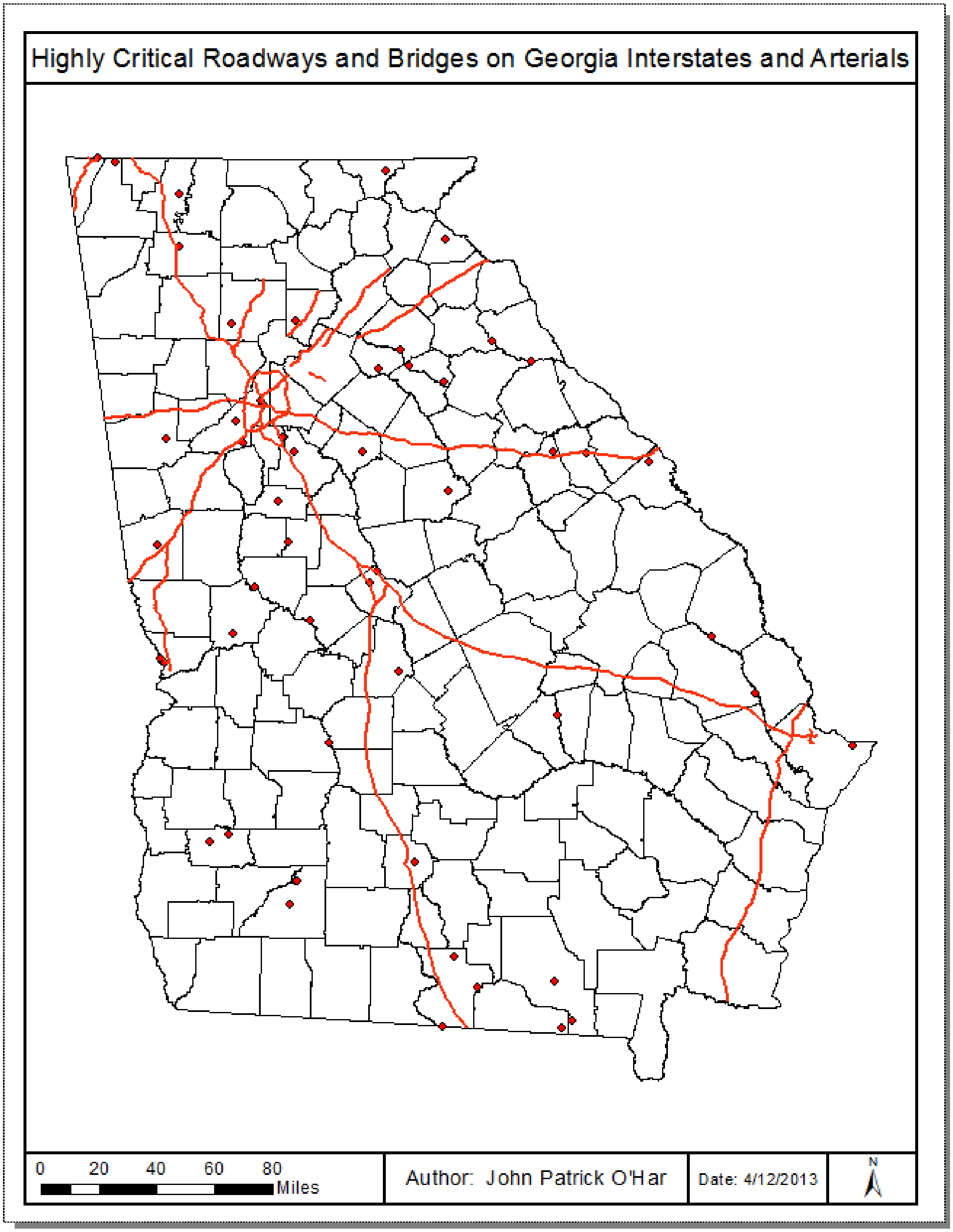


Figure 37. Map of highly critical roadways and bridges on Georgia interstates and arterials

6.3.3 Vulnerability

The map shown above in Figure 37 displays those portions of the roadway network and those bridges that are highly critical as defined by the risk factors and approach used in this research. This higher-level criticality assessment in conjunction with the climate maps shown in Figure 33, Figure 34, and Appendix G: indicate that highly critical roadways and bridges in the northeastern and eastern portions of the State can expect the largest increases in mean temperature. As such, the Department should begin planning and conducting research as it relates to adapting the infrastructure in these areas.

In addition to the highly critical roads and bridges that can expect the most significant increase in temperature, procedures can be put in place to adapt to increased frequency and intensity of extreme weather events throughout the state. These efforts can be targeted at those highly critical components of the transportation infrastructure network. Additional analyses should be conducted to identify vulnerable areas along the coast that will be subject to sea level rise, storm surge, and increased intensity of coastal storms. Data was readily available for the Chatham County region (see Section 6.2), but not for all of the coastal counties in the State of Georgia.

6.3.3.1 Implications for Transit Agencies in the State of Georgia

Results of the MARTA case study (see Section 6.1) can be applied to other transit agencies throughout the state. As mentioned by a staff member from Chatham Area Transit (CAT), it would be valuable to conduct an inundation hazard analysis using ArcGIS to identify bus stops and portions of the CAT network that are especially susceptible to the impacts of flooding. Given that CAT operates in a coastal community, a similar analysis can be conducted as it relates to sea level rise, storm surge, and coastal storms.

Table 22 lists the five largest transit agencies by annual passenger miles in the State of Georgia; this ranking excludes transit systems within the Atlanta Regional Commission-defined ten county Atlanta metropolitan area, university transit systems, and rideshare programs (FTA 2012b). Certain results from the MARTA case study can be applied to all of these agencies. Similar to MARTA and CAT, identification of portions of bus networks that are prone to flooding can be performed. The impact of increased temperatures and heat waves on transit agency staff can also be analyzed by all transit agencies. Similar to efforts undertaken at MARTA, these agencies can examine their bus shelters or consider installing bus shelters to provide passengers with additional shade. Where feasible, fans and natural cooling mechanisms can be used to improve passenger comfort. The impact of increased temperatures and heat waves on bus engines and HVAC equipment should also be considered at all transit agencies in the State.

Table 22. Five largest transit operators in Georgia outside metro Atlanta (FTA 2012b)

Transit Agency	Annual Passenger Miles
Chatham Area Transit Authority	13,252,495
Athens Transit System	5,229,446
Albany Transit System	5,106,612
City of Rome Transit Department	4,531,045
Augusta Richmond County Transit Department	2,285,202

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This research examined whether or not existing transportation asset management systems, along with existing climate projection information, could be utilized to strategically inform investment decision making through a risk-based approach. Three case studies, one at MARTA, one at the MPC, and one statewide case study at GDOT were conducted. The same decision-making processes and framework were utilized in each case study. An assessment of each agency's asset management system revealed its relative maturity and also revealed which existing databases, tools, and processes were in place. These three case studies were conducted at agencies of various size and scope. MARTA is large transit system, the MPC oversees a metropolitan area of moderate population, and GDOT oversees transportation assets throughout the State of Georgia. Each of these agencies is also along a different point in the continuum of the asset management maturity scale, with MARTA and GDOT possessing relatively mature TAM systems and the MPC possessing an emerging system.

Regardless of the maturity of an organization's asset management system, this research demonstrates that existing transportation asset management system components e.g., project prioritization, asset inventory and condition data, short and long-range planning, in conjunction with readily available state-of-science climate projections, can be utilized to identify those transportation infrastructure assets that are the most critical, and also subject to potential climate change impacts, i.e., vulnerable. That being said, the level of maturity of an asset management system and the availability of agency staff resources have a direct impact on the quality of any climate change adaptation effort.

7.1 Impact of Maturity of TAM Systems

All three of the agencies examined in this research effort had asset management systems of varying levels of maturity, with GDOT possessing the most mature asset management system, MARTA possessing one of the more mature transit asset management systems in the country, and the MPC possessing an emerging asset management system. GDOT asset management efforts are well-documented, along with its asset management tools, databases and processes. In addition, GDOT was the only case study agency with an office and personnel dedicated explicitly to TAM activities.

GDOT's mature TAM system and its comprehensive and accurate roadway and bridge databases allowed for easy access to relevant transportation infrastructure data. Although MARTA also has databases with large amounts of data related to its transportation infrastructure assets, the agency's EAM databases and decision support software tools are proprietary and/or provided by outside vendors. Although this limits ease of access to infrastructure asset data at MARTA, the agency does have a well-documented, relatively mature transit asset management system.

Since GDOT and MARTA both have institutionalized, well-documented TAM systems, it would be relatively easy to incorporate climate change considerations into different components of the asset management systems. The MPC on the other hand does not have an institutionalized, well-established TAM program. With no opportunity to incorporate climate change considerations into existing TAM processes, the heroic efforts of individuals or climate change champions would be the most likely manner in which climate change considerations would be incorporated into agency investment decision-making processes, and even then it may be more difficult to sustain if these processes are not institutionalized before the original champions leave the agency.

7.2 Criticality Assessments

The criticality assessments conducted as part of this research effort were semi-quantitative in their nature. Although transportation infrastructure data was leveraged to inform the criticality assessments, expert opinion and engineering judgment were used to develop criticality scoring schemes. For example, MARTA considers mission critical assets to be those assets that are life, safety, and mission critical. Stakeholder involvement in criticality assessments is critical to obtaining buy-in from decision makers. Since MARTA staff determine which assets are mission-critical, this metric will be credible within the agency.

The MDCM roadway and bridge criticality tools require that users define risk factors, relative risks for these factors, and then weight the factors to calculate a final criticality score for assets. Not only can users define relative risk for different asset attributes, they can also see the impact of how they define relative risk and risk factor weights on the final criticality score. This sort of criticality assessment is a network-level screening. At smaller scales, such as the MPC case study or the MARTA case study, more detailed project level criticality assessments should be conducted where appropriate.

7.3 Identification of Potential Climate Change Impacts

Many efforts of identifying climate change impacts in the U.S. resulted in work that identifies impacts at broad, e.g., the Southeast, levels. Newer research led to the development of downscaled climate projections that can be used to inform decision making at local scales, e.g., county and city. However, it is important to have an understanding of the state of climate science and how precisely the outputs of climate projections should be used to inform decision making. For example, 24-hour cumulative precipitation projections may not inform many engineering design considerations; intense precipitation that occurs in intervals of minutes or hours and can lead to flash flooding is likely of more concern to design engineers.

Even with the uncertainty associated with climate projections, the results of these projections provide valuable insight into plausible future scenarios. Since climate models are based upon assumptions regarding emissions at a global level, multiple emission scenarios should be presented to decision makers. In this manner, decision makers will be able to assess the potential impacts from numerous emissions scenarios and adjust their responses over time depending upon their risk tolerance and the state of climate science. Over time, the understanding of climate change and its impacts on the transportation infrastructure network will improve, which is why an adaptive management approach should be utilized.

Assessing the relative risks of different climate change impacts is an important component of the strategic decision-making process. The climate risk matrices developed for the case study agencies in this research illustrate how different agencies perceive climate-related risks. GDOT for example is somewhat concerned about the potential impact of landslides, whereas the MPC is not since the topography of its jurisdiction makes landslides a less significant risk. Identifying which climate change impacts pose the greatest relative risk to an agency also allows the agency to focus on developing adaptation strategies for the climate impacts of higher relative risk.

7.4 The Importance of a Risk-based Approach

Both the criticality assessment and the climate risk assessment incorporate risk-based decision-making processes. Many transportation agencies manage databases that contain information on large numbers of assets. For example, this research revealed that MARTA's EAM database contains over 53,000 assets, GDOT's roadway database contains over 900,000 unique routes, and the Department's bridge database contains over 8,000 bridges. These agencies do not have the resources to perform climate change risk assessments for each asset and then develop adaptation strategies for each individual asset.

This is why it is important to define the criteria and approach that are used to determine asset criticality. Potential approaches range from expert opinion, scoring based risk factors, similar to the MCDM tools developed in this research, or more advanced mathematical models to analyze criticality. Whatever approach is chosen, once highly critical assets are defined, the potential impacts of climate change on these highly critical assets can then be determined. Identifying which potential climate impacts pose the greatest relative risk is also important. For example, U.S. Route 80 in Chatham County is a hurricane evacuation route and is the only way to access Tybee Island, clearly the relative risk of sea level rise and storm surge to this already low-lying roadway are more significant than the risk posed by a shift in endangered species.

Ultimately, adopting a risk-based approach also allows transportation agencies to identify those infrastructure assets that are most vulnerable. These vulnerable, high-risk assets are both critical and susceptible to climate change impacts. Then transportation agencies can develop adaptation strategies for the most vulnerable assets. This enables transportation agencies to target resources at a more limited number of critical assets.

7.5 Asset Management as Part of a Broader Adaptation Approach

At many transportation agencies, climate change considerations and climate change adaptation activities are not considered just in terms of TAM systems, but rather across many levels an organization. Many transportation agencies, from the local to national levels, undergo climate change assessments and develop climate action plans. A climate-related risk appraisal is typically a crucial component of any climate change assessment or action plan. Transportation infrastructure asset inventory and condition data are required to identify assets that are vulnerable to climatic changes. Transportation asset management systems contain databases with asset inventory and condition data that are required for climate change study efforts.

Thus, climate change adaptation activities within the context of existing TAM systems can be aligned with organizations broader climate change assessments or climate action plans. In a similar fashion, the incorporation of climate change considerations in TAM systems can encourage organizations to account for climate change considerations in other areas. TAM systems can then serve as a both a component of climate change adaptation efforts and also as a critical input in adaptation and risk appraisal efforts. Since maintaining accurate asset inventory and condition data allows for effective monitoring of the impacts of climatic change on transportation infrastructure, asset inventories and condition assessments are critical components of a TAM system in the context of climate change adaptation activities.

7.6 Limitations

One of the key limitations in this research is the considerable uncertainty associated with climate change projections. Civil engineering design standards are based upon established historical weather and climate data, but this historical weather and climate data is not likely to remain relevant 50 or 100 years into the future. Nonetheless, the climate science community encourages policymakers and decision makers to consider multiple emissions scenarios and to act upon the state-of-science readily available climate information. This may seem paradoxical to some decision makers, but incorporating climate change considerations into existing decision-making processes does not require a significant amount of resources.

The political environment in certain jurisdictions and at certain agencies can be an impetus for incorporating climate change considerations in the investment decision-making process or it can act as a deterrent. Incorporating climate change considerations at organizations where there are champions, is a process that is relatively easier than at organizations where such a political will does not exist. Whether or not funds are available can also affect efforts to incorporate climate change considerations.

Another limitation is the accuracy of the criticality assessments, which are semi-quantitative and incorporate some manner of expert opinion and engineering judgment. Nonetheless, the criticality assessments are based upon objective data and can be customized to the goals, needs, and objectives of an individual agency or organizations. That is a key strength of this methodology; this research develops a decision-support methodology, yet ultimately, the decision makers are responsible for appropriately leveraging the results of this research to influence investment decision-making processes at an agency.

7.7 Future Work

Interpretation of raw climate and weather data proved to be a time-consuming, challenging endeavor. Oftentimes, the climate science community conducts its research efforts in isolation and neglects to produce actionable data for policymakers and decision makers. The transportation community is also at fault for a lack of communication with the climate scientists in terms of what sorts of projection data are valuable for transportation infrastructure design and planning efforts. There is a need for increased dialogue between the climate science and transportation communities. In addition, it would be beneficial to the transportation community if the climate science community made the results of its climate projections available in a more user-friendly format.

Criticality assessments can be in-depth processes that go beyond the efforts of the MCDM network level screening tool developed in this research effort. Whatever method a transportation agency uses to identify its critical infrastructure will yield valuable results. In light of new federal legislation in the form of MAP-21, which requires risk-based asset management plans (FHWA 2012), transportation agencies throughout the country should consider what sort of risk-based planning approach they would like to adopt.

Currently the U.S. is lacking leadership and guidance as it relates to climate change adaptation at the federal level. In many respects, state, local, and regional governments are at the forefront of the climate change adaptation planning process. Systematic guidance, tools, and support from the federal government could result in more effective, efficient adaptation planning efforts throughout the country. The transportation community is becoming more active in terms of climate change adaptation planning. Even so, there is no central repository of climate change adaptation strategies nor a regular, e.g., biennial, forum for transportation agencies to exchange and share knowledge as it relates to climate change adaptation planning. Since climate change impacts are regional in nature, it would be even more valuable for various regions of the U.S. to host transportation climate change adaptation peer exchanges.

The risk-based decision-making framework developed and tested with three case studies in this research effort demonstrates that existing transportation asset management processes and systems, along with readily-available climate change projections, can be used to identify transportation infrastructure assets that are most vulnerable to climate change. This type of approach allows transportation agencies to leverage existing resources and processes to strategically target investment towards those transportation infrastructure assets and portions of the transportation network that are most vulnerable to potential climate change impacts. As the state of climate science continues to improve, transportation agencies will be able to regularly monitor and update their TAM systems and climate change adaptation plans in a manner that strategically allocates resources.

APPENDIX A: MATLAB CODE ".nc" TO ".mat"

MATLAB Code to Convert ".nc" Files in a Directory to ".mat" Files

```
function nc2mat(strReadDir,strSaveDir)
% Filename:     nc2mat.m
% Date:         2012-10-30
% Author(s):    Ivan Caceres      (ivan.caceres@gmail.com)
% Description:  Reads a directory (strReadDir) for *.nc files and saves
the
%               data stored. Assume that variables in *.nc files are
all
%               the same (i.e. tmax, tmin, pr, time, lat, & lon)
% Requires:
% Parameters:   strReadDir - string containing the directory with the
*.nc
%                            files to be converted
%               strSaveDir - string containing the directory with the
*.mat
%                            files to be saved
% Returns:
% Example:      nc2mat('X:\Dissertation\Data\USGS
Projections\','X:\Dissertation\Data\USGS Projections\MATLAB\')
% Change Log:
%
%               Version:        1.1
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2012-11-06
%               Changes:        Inserted a test variable that replaces
%                               hypens in variable names with
underscores
%
%% Setup Default Variables
% Declare default values for arguments in case function is called
without
% some parameters. If this function has no default values, verify that
% number of input parameters is correct.
strDefaultDir = './';

if((nargin<2)||isempty(strReadDir))
    strSaveDir = strDefaultDir;
end
if((nargin<1)||isempty(strReadDir))
    strReadDir = strDefaultDir;
end

% Correct if '/' not in specified directory
if(~strcmp(strReadDir(end),'/'))
    strReadDir = strcat(strReadDir,'/');
end

if(~strcmp(strSaveDir(end),'/'))
    strSaveDir = strcat(strSaveDir,'/');
end
```

```
%% Main Program
% 1) Read all files in current directory
% 2) Load tmax, tmin, pr, time, lat, & lon data for current file
% 3) Save variables under same name in save directory
% 4) Repeat until all files have been "converted"
SFiles = dir(sprintf('%s/*.nc',strReadDir));
iFileNum = numel(SFiles);

for(i = 1:iFileNum)
    strFileNameNC = SFiles(i).name;
    strFileNameMAT = strFileNameNC(1:end-3);
    strFileName = strcat(strReadDir,strFileNameNC);
    SNCInfo = nc_info(strFileName);
    iVarNum = length(SNCInfo.Dataset);

    for(j = 1:iVarNum)
        strVarName = SNCInfo.Dataset(j).Name;
        %check for hypens in variable names and replace with
underscores
        test = strVarName;
        loc = find(test=='-');
        test2 = test;
        test2(loc) = '_';
        fprintf('\nLoading %s, var %i of %i, in file %i of
%i\n',strVarName,j,iVarNum,i,iFileNum);
        eval(sprintf('%s =
nc_varget(\''%s\'',\''%s\'');',test2,strFileName,strVarName));
    end

    fprintf('\nSaving file %i of %i\n',i,iFileNum);
    save(strcat(strSaveDir,strFileNameMAT));
    clearvars -except strReadDir strSaveDir SFiles iFileNum i;

end
```

APPENDIX B: MATLAB CODE FOR WINTER ENSEMBLES

MATLAB Code to Develop Ensembles and User-defined ".nc" Files from ".mat" Files for the Winter Months

```
% Filename:     temyr_winter.m
% Date:         2012-23
% Author(s):    Ivan Caceres      (ivan.caceres@gmail.com)
% Description:  Reads .mat files in a directory which contain climate
% projection data from .nc files that have already been converted to
.mat
% using the nc2mat function. Then creates and ensemble of climate
% projections by retaining the max or min values across multiple
% projections, i.e., .mat files. Also counts days over specified
% temperature thresholds and consecutive days over these thresholds.
Then
% writes out this information as a .nc file,
% Requires:
% Parameters:   iYrStart - start year of desired time frame
%               iYrEnd - end year of desired time frame
%
%               iDayStart - start date of desired time range, e.g.
season,
%               month, etc.
%               iDayEnd - end date of desired time range
%
%               ***Thresholds can be modified***
%
%               iF95 - Celsius conversion of 95 degree Farenheit
threshold
%               iF100 - Celsius conversion of 100 degree Farenheit
threshold
%               iF0 - Celsius conversion of 0 degree Farenheit
threshold
%
% Returns:
% Example:      .nc file with selected variables for output
% Change Log:
%
%               Version:        1.1
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2012-12
%               Changes:        Added write-out to ncfile capability
%               utilizing built-in MATLAB functions
%
%               Version:        1.2
%               Editor:         Ivan Caceres
(ivan.caceres@gmail.com)
%               Date Edited:    2013-2-4
%               Changes:        Automated process to load all .mat
files in
%               a particular director. Also added threshold check and
%               consecutive day check capabilities.
```

```
%               Version:        1.3
%               Editor:         Ivan Caceres
(ivan.caceres@gmail.com)
%               Date Edited:    2013-2-7
%               Changes:        Modified thresholds so that total count
of
%               days is given for each grid square. Also modified
%               consecutive day count so that only the final day, i.e.,
%               total count of consecutive days is the output. Added
%               additional .nc file creation with create and write of
%               threshold values.

%               Version:        1.4
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2013-2-28
%               Changes:        Modified consecutive temperature
threshold
%               analysis so the the maximum number of consecutive days
is
%               given for one season/year/date range at a time.
%
%               Version:        1.5
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2013-3-2
%               Changes:        Developed separate scripts for winter
and
%               summer since winter (Dec, Jan, Feb) is not continuous
%               throughout the year. Also caculated averages for temp,
%               precip, added precip > 1 in. count, and mean diurnal
%               temperature range. These values are consistent with
NOAA
%               National Climatic Data Center (NCDC) record-keeping.

%% Variable Delcaration (CHANGE)

rgFiles = dir('./*.mat');
iSimNum = length(rgFiles);

% Put years in range 1-90
iYrStart = 61;
iYrEnd = 90;

% Put days in term of 1st year
% If winter need two start and end dates
iDayStart_1 = 1;
iDayEnd_1 = 59;

%If non/winter set to 0
iDayStart_2 = 335;
iDayEnd_2 = 365;

iSeason = (iDayEnd_1 - iDayStart_1 + 1) + (iDayEnd_2 - iDayStart_2 +
1);

% Thresholds
```

```
iF90 = 32.22;
iF100 = 37.78;
iF0 = 0;
    %Precipitation 1 inch = 25.4mm
iP1 = 25.4;

% Day range generation
rgDays = [];
for(k = (iYrStart-1):(iYrEnd-1))
    rgDays =
[rgDays,(iDayStart_1+365*k):(iDayEnd_1+365*k),(iDayStart_2+365*k):(iDay
End_2+365*k) ];
end

%% File Loading & Get Max / Mins
pr_max = [];
t_max = [];
t_min = [];

iDateRange = length(rgDays);

for(z = 1:iSimNum)
    fprintf('\nLoading file %i of %i\n',z,iSimNum);

    % Load files and variables
    load(rgFiles(z).name);
    rgFileName = rgFiles(z).name(1:end-13);

    strPrName = strcat(rgFileName,'lat');
    rgIdx = find(strPrName=='-');
    strPrName(rgIdx) = '_';

    strPrName = strcat(rgFileName,'lon');
    rgIdx = find(strPrName=='-');
    strPrName(rgIdx) = '_';

    strPrName = strcat(rgFileName,'pr','(:,:,rgDays)');
    rgIdx = find(strPrName=='-');
    strPrName(rgIdx) = '_';

    strTmaxName = strcat(rgFileName,'tmax','(:,:,rgDays)');
    rgIdx = find(strTmaxName=='-');
    strTmaxName(rgIdx) = '_';

    strTminName = strcat(rgFileName,'tmin','(:,:,rgDays)');
    rgIdx = find(strTminName=='-');
    strTminName(rgIdx) = '_';

    % Set temp variables
    eval(sprintf('pr_temp(:,:,:,1) = %s;',strPrName));
    eval(sprintf('tmax_temp(:,:,:,1) = %s;',strTmaxName));
    eval(sprintf('tmin_temp(:,:,:,1) = %s;',strTminName));

    % Set new max & min
```

```
    if(z==1)
        pr_max = squeeze(pr_temp);
        t_max = squeeze(tmax_temp);
        t_min = squeeze(tmin_temp);
    else
        pr_temp(:,:,:,2) = pr_max;
        tmax_temp(:,:,:,2) = t_max;
        tmin_temp(:,:,:,2) = t_min;

        pr_max(:,:,:) = max(pr_temp,[],4);
        t_max(:,:,:) = max(tmax_temp,[],4);
        t_min(:,:,:) = min(tmin_temp,[],4);
    end

    % Clear memory
    clearvars -except rgFiles iYrStart iYrEnd iDayStart_1 iDayEnd_1
rgDays...
        iDayStart_2 iDayEnd_2 pr_total tmax_total tmin_total pr_max...
        t_max t_min iDateRange z...
        iSimNum iF90 iF100 iF0 iP1 lat lon iSeason;
end

%% Consecutive temperature analysis
fprintf('\nCalculating cumulative differences\n');

f90_count = zeros(size(t_max(:,:,1)));
f100_count = f90_count;
f0_count = f90_count;

p1_count = zeros(size(pr_max(:,:,1)));

f90_consec_max = [];
f100_consec_max = [];
f0_consec_max = [];

f90_consec_temp = zeros(size(t_max));
f100_consec_temp = f90_consec_temp;
f0_consec_temp = f90_consec_temp;

Season = iSeason;

for(t = 1:iDateRange)
    % Set temp variables
    f90_temp = zeros(size(t_max(:,:,1)));
    f100_temp = f90_temp;
    f0_temp = f90_temp;

    p1_temp = zeros(size(pr_max(:,:,1)));

    % Check thresholds
    rg90Idx = find(t_max(:,:,t)>=iF90);
    rg100Idx = find(t_max(:,:,t)>=iF100);
    rg0Idx = find(t_min(:,:,t)<=iF0);
```

```
    rg1Idx = find(pr_max(:,:,t)>=iP1);

    f90_temp(rg90Idx) = 1;
    f100_temp(rg100Idx) = 1;
    f0_temp(rg0Idx) = 1;

    p1_temp(rg1Idx) = 1;

    f90_count(:,:,1) = f90_count + f90_temp;
    f100_count(:,:,1) = f100_count + f100_temp;
    f0_count(:,:,1) = f0_count + f0_temp;

    p1_count(:,:,1) = p1_count + p1_temp;

    if(t==1)
        f90_consec_temp(:,:,t) = f90_temp;
        f100_consec_temp(:,:,t) = f100_temp;
        f0_consec_temp(:,:,t) = f0_temp;

    elseif(t==iSeason)
        f90_consec_max(:,:,:,2) = max(f90_consec_temp,[],3);
        f100_consec_max(:,:,:,2) = max(f100_consec_temp,[],3);
        f0_consec_max(:,:,:,2) = max(f0_consec_temp,[],3);

    elseif(t==Season)

        for(k = (iYrStart-1):(iYrEnd-1))
            Season = iSeason + (k*iSeason);

            f90_consec_max(:,:,:,1) = max(f90_consec_temp,[],3);
            f100_consec_max(:,:,:,1) = max(f100_consec_temp,[],3);
            f0_consec_max(:,:,:,1) = max(f0_consec_temp,[],3);

            f90_consec_max(:,:,:) = max(f90_consec_max,[],4);
            f100_consec_max(:,:,:) = max(f100_consec_max,[],4);
            f0_consec_max(:,:,:) = max(f0_consec_max,[],4);

            f90_consec_temp = zeros(size(t_max(:,:,1)));
            f100_consec_temp = f90_consec_temp;
            f0_consec_temp = f90_consec_temp;
        end

    else
        f90_consec_temp(:,:,t) = f90_consec_temp(:,:,t-1) + f90_temp;
        f100_consec_temp(:,:,t) = f100_consec_temp(:,:,t-1) +
f100_temp;
        f0_consec_temp(:,:,t) = f0_consec_temp(:,:,t-1) + f0_temp;

        rgSame = f90_consec_temp(:,:,t)==f90_consec_temp(:,:,t-1);
        f90_consec_temp(:,:,t) = f90_consec_temp(:,:,t) .* ~rgSame;

        rgSame = f100_consec_temp(:,:,t)==f100_consec_temp(:,:,t-1);
        f100_consec_temp(:,:,t) = f100_consec_temp(:,:,t) .* ~rgSame;
```

```
        rgSame = f0_consec_temp(:,:,t)==f0_consec_temp(:,:,t-1);
        f0_consec_temp(:,:,t) = f0_consec_temp(:,:,t) .* ~rgSame;
    end
end

%%Consecutive Threshold Final Matrix
f90_consec_max = squeeze(f90_consec_max);
f100_consec_max = squeeze(f100_consec_max);
f0_consec_max = squeeze(f0_consec_max);

f90_consec_max = max(f90_consec_max,[],3);
f100_consec_max = max(f100_consec_max,[],3);
f0_consec_max = max(f0_consec_max,[],3);

%% Get Maxs and Mins across specified time range
max_t_max = nanmax(t_max, [], 3);
min_t_min = nanmin(t_min, [], 3);
max_pr_max = nanmax(pr_max, [],3);

%% Get Means
mean_t_max = nanmean(t_max, 3);
mean_t_min = nanmean(t_min, 3);
mean_t = (mean_t_max + mean_t_min)/2;
mean_dutr = mean_t_max - mean_t_min;
mean_pr_max = nanmean(pr_max, 3);
mean_pr = times(mean_pr_max, iSeason)/iSimNum;

%% Save Data (Change)
save GA_B1_2070_2099_winter.mat

%% Create NetCDF File (Change)

nccreate('GA_b1_2070_2099_winter.nc', 'mean_t', 'Dimensions', {'lon' 40
'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter.nc', 'mean_pr', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter.nc', 'max_t_max', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter.nc', 'min_t_min', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter.nc', 'max_pr_max', 'Dimensions',
{'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter.nc', 'mean_dutr', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter_thresholds.nc', 'f0_count',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_winter_thresholds.nc', 'f0_consec_max',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_winter_thresholds.nc', 'p1_count',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_winter.nc', 'lon', 'Dimensions', {'lon' 40},
'Datatype', 'double', 'Format', 'classic');
```

```
nccreate('GA_b1_2070_2099_winter.nc', 'lat', 'Dimensions', {'lat' 41},
'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter_thresholds.nc', 'lon', 'Dimensions',
{'lon' 40}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_winter_thresholds.nc', 'lat', 'Dimensions',
{'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
ncwrite('GA_b1_2070_2099_winter.nc', 'mean_t', mean_t);
ncwrite('GA_b1_2070_2099_winter.nc', 'mean_pr', mean_pr);
ncwrite('GA_b1_2070_2099_winter.nc', 'max_t_max', max_t_max);
ncwrite('GA_b1_2070_2099_winter.nc', 'min_t_min', min_t_min);
ncwrite('GA_b1_2070_2099_winter.nc', 'max_pr_max', max_pr_max);
ncwrite('GA_b1_2070_2099_winter.nc', 'mean_dutr', mean_dutr);
ncwrite('GA_b1_2070_2099_winter_thresholds.nc', 'f0_count', f0_count);
ncwrite('GA_b1_2070_2099_winter_thresholds.nc', 'f0_consec_max',
f0_consec_max);
ncwrite('GA_b1_2070_2099_winter_thresholds.nc', 'p1_count', p1_count);
ncwrite('GA_b1_2070_2099_winter.nc', 'lon', lon);
ncwrite('GA_b1_2070_2099_winter.nc', 'lat', lat);
ncwrite('GA_b1_2070_2099_winter_thresholds.nc', 'lon', lon);
ncwrite('GA_b1_2070_2099_winter_thresholds.nc', 'lat', lat);
```

APPENDIX C: MATLAB CODE FOR SUMMER ENSEMBLES

MATLAB Code to Develop Ensembles and User-defined “.nc” Files from “.mat” Files for the Summer Months

```
% Filename:     temyr_summer.m
% Date:         2012-23
% Author(s):    Ivan Caceres      (ivan.caceres@gmail.com)
% Description:  Reads .mat files in a directory which contain climate
% projection data from .nc files that have already been converted to
.mat
% using the nc2mat function. Then creates and ensemble of climate
% projections by retaining the max or min values across multiple
% projections, i.e., .mat files. Also counts days over specified
% temperature thresholds and consecutive days over these thresholds.
Then
% writes out this information as a .nc file,
% Requires:
% Parameters:   iYrStart - start year of desired time frame
%               iYrEnd - end year of desired time frame
%
%               iDayStart - start date of desired time range, e.g.
season,
%               month, etc.
%               iDayEnd - end date of desired time range
%
%               ***Thresholds can be modified***
%
%               iF95 - Celsius conversion of 95 degree Farenheit
threshold
%               iF100 - Celsius conversion of 100 degree Farenheit
threshold
%               iF0 - Celsius conversion of 0 degree Farenheit
threshold
%
% Returns:
% Example:      .nc file with selected variables for output
% Change Log:
%
%               Version:        1.1
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2012-12
%               Changes:        Added write-out to ncfile capability
%               utilizing built-in MATLAB functions
%
%               Version:        1.2
%               Editor:         Ivan Caceres
(ivan.caceres@gmail.com)
%               Date Edited:    2013-2-4
%               Changes:        Automated process to load all .mat
files in
%               a particular director. Also added threshold check and
%               consecutive day check capabilities.
```

```
%               Version:        1.3
%               Editor:         Ivan Caceres
(ivan.caceres@gmail.com)
%               Date Edited:    2013-2-7
%               Changes:        Modified thresholds so that total count
of
%               days is given for each grid square. Also modified
%               consecutive day count so that only the final day, i.e.,
%               total count of consecutive days is the output. Added
%               additional .nc file creation with create and write of
%               threshold values.

%               Version:        1.4
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2013-2-28
%               Changes:        Modified consecutive temperature
threshold
%               analysis so the the maximum number of consecutive days
is
%               given for one season/year/date range at a time.
%
%               Version:        1.5
%               Editor:         J.P. O'Har    (johnpat714@gmail.com)
%               Date Edited:    2013-3-2
%               Changes:        Developed separate scripts for winter
and
%               summer since winter (Dec, Jan, Feb) is not continuous
%               throughout the year. Also caculated averages for temp,
%               precip, added precip > 1 in. count, and mean diurnal
%               temperature range. These values are consistent with
NOAA
%               National Climatic Data Center (NCDC) record-keeping.

%% Variable Delcaration (CHANGE)

rgFiles = dir('./*.mat');
iSimNum = length(rgFiles);

% Put years in range 1-90
iYrStart = 61;
iYrEnd = 90;

% Put days in term of 1st year
% If winter need two start and end dates
iDayStart = 152;
iDayEnd = 243;

iSeason = iDayEnd - iDayStart + 1;

% Thresholds
    %Temperature
iF90 = 32.22;
iF100 = 37.78;
iF0 = 0;
    %Precipitation 1 inch = 25.4mm
```

```
iP1 = 25.4;

% Day range generation
rgDays = [];
for(k = (iYrStart-1):(iYrEnd-1))
    rgDays = [rgDays,(iDayStart+365*k):(iDayEnd+365*k)];
end

%% File Loading & Get Max / Mins
pr_max = [];
t_max = [];
t_min = [];

iDateRange = length(rgDays);

for(z = 1:iSimNum)
    fprintf('\nLoading file %i of %i\n',z,iSimNum);

    % Load files and variables
    load(rgFiles(z).name);
    rgFileName = rgFiles(z).name(1:end-13);

    strPrName = strcat(rgFileName,'lat');
    rgIdx = find(strPrName=='-');
    strPrName(rgIdx) = '_';

    strPrName = strcat(rgFileName,'lon');
    rgIdx = find(strPrName=='-');
    strPrName(rgIdx) = '_';

    strPrName = strcat(rgFileName,'pr','(:,:,rgDays)');
    rgIdx = find(strPrName=='-');
    strPrName(rgIdx) = '_';

    strTmaxName = strcat(rgFileName,'tmax','(:,:,rgDays)');
    rgIdx = find(strTmaxName=='-');
    strTmaxName(rgIdx) = '_';

    strTminName = strcat(rgFileName,'tmin','(:,:,rgDays)');
    rgIdx = find(strTminName=='-');
    strTminName(rgIdx) = '_';

    % Set temp variables
    eval(sprintf('pr_temp(:,:,:,1) = %s;',strPrName));
    eval(sprintf('tmax_temp(:,:,:,1) = %s;',strTmaxName));
    eval(sprintf('tmin_temp(:,:,:,1) = %s;',strTminName));

    % Set new max & min
    if(z==1)
        pr_max = squeeze(pr_temp);
        t_max = squeeze(tmax_temp);
        t_min = squeeze(tmin_temp);
    else
        pr_temp(:,:,:,2) = pr_max;
```

```
        tmax_temp(:,:,:,2) = t_max;
        tmin_temp(:,:,:,2) = t_min;

        pr_max(:,:,:) = max(pr_temp,[],4);
        t_max(:,:,:) = max(tmax_temp,[],4);
        t_min(:,:,:) = min(tmin_temp,[],4);
    end

    % Clear memory
    clearvars -except rgFiles iYrStart iYrEnd iDayStart iDayEnd
rgDays...
        pr_total tmax_total tmin_total pr_max t_max t_min iDateRange
z...
        iSimNum iF90 iF100 iF0 iP1 lat lon iSeason;
end

%% Consecutive temperature analysis
fprintf('\nCalculating cumulative differences\n');

f90_count = zeros(size(t_max(:,:,1)));
f100_count = f90_count;
f0_count = f90_count;

p1_count = zeros(size(pr_max(:,:,1)));

f90_consec_max = [];
f100_consec_max = [];
f0_consec_max = [];

f90_consec_temp = zeros(size(t_max));
f100_consec_temp = f90_consec_temp;
f0_consec_temp = f90_consec_temp;

Season = iSeason;

for(t = 1:iDateRange)
    % Set temp variables
    f90_temp = zeros(size(t_max(:,:,1)));
    f100_temp = f90_temp;
    f0_temp = f90_temp;

    p1_temp = zeros(size(pr_max(:,:,1)));

    % Check thresholds
    rg90Idx = find(t_max(:,:,t)>=iF90);
    rg100Idx = find(t_max(:,:,t)>=iF100);
    rg0Idx = find(t_min(:,:,t)<=iF0);

    rg1Idx = find(pr_max(:,:,t)>=iP1);

    f90_temp(rg90Idx) = 1;
    f100_temp(rg100Idx) = 1;
    f0_temp(rg0Idx) = 1;
```

```
    p1_temp(rg1Idx) = 1;

    f90_count(:,:,1) = f90_count + f90_temp;
    f100_count(:,:,1) = f100_count + f100_temp;
    f0_count(:,:,1) = f0_count + f0_temp;

    p1_count(:,:,1) = p1_count + p1_temp;

    if(t==1)
        f90_consec_temp(:,:,t) = f90_temp;
        f100_consec_temp(:,:,t) = f100_temp;
        f0_consec_temp(:,:,t) = f0_temp;

    elseif(t==iSeason)
        f90_consec_max(:,:,:,2) = max(f90_consec_temp,[],3);
        f100_consec_max(:,:,:,2) = max(f100_consec_temp,[],3);
        f0_consec_max(:,:,:,2) = max(f0_consec_temp,[],3);

    elseif(t==Season)

        for(k = (iYrStart-1):(iYrEnd-1))
            Season = iSeason + (k*iSeason);

            f90_consec_max(:,:,:,1) = max(f90_consec_temp,[],3);
            f100_consec_max(:,:,:,1) = max(f100_consec_temp,[],3);
            f0_consec_max(:,:,:,1) = max(f0_consec_temp,[],3);

            f90_consec_max(:,:,:) = max(f90_consec_max,[],4);
            f100_consec_max(:,:,:) = max(f100_consec_max,[],4);
            f0_consec_max(:,:,:) = max(f0_consec_max,[],4);

            f90_consec_temp = zeros(size(t_max(:,:,1)));
            f100_consec_temp = f90_consec_temp;
            f0_consec_temp = f90_consec_temp;
        end

    else
        f90_consec_temp(:,:,t) = f90_consec_temp(:,:,t-1) + f90_temp;
        f100_consec_temp(:,:,t) = f100_consec_temp(:,:,t-1) +
f100_temp;
        f0_consec_temp(:,:,t) = f0_consec_temp(:,:,t-1) + f0_temp;

        rgSame = f90_consec_temp(:,:,t)==f90_consec_temp(:,:,t-1);
        f90_consec_temp(:,:,t) = f90_consec_temp(:,:,t) .* ~rgSame;

        rgSame = f100_consec_temp(:,:,t)==f100_consec_temp(:,:,t-1);
        f100_consec_temp(:,:,t) = f100_consec_temp(:,:,t) .* ~rgSame;

        rgSame = f0_consec_temp(:,:,t)==f0_consec_temp(:,:,t-1);
        f0_consec_temp(:,:,t) = f0_consec_temp(:,:,t) .* ~rgSame;
    end
end

%%Consecutive Threshold Final Matrix
```

```
f90_consec_max = squeeze(f90_consec_max);
f100_consec_max = squeeze(f100_consec_max);
f0_consec_max = squeeze(f0_consec_max);

f90_consec_max = max(f90_consec_max,[],3);
f100_consec_max = max(f100_consec_max,[],3);
f0_consec_max = max(f0_consec_max,[],3);

%% Get Maxs and Mins across specified time range
max_t_max = nanmax(t_max, [], 3);
min_t_min = nanmin(t_min, [], 3);
max_pr_max = nanmax(pr_max, [],3);

%% Get Means
mean_t_max = nanmean(t_max, 3);
mean_t_min = nanmean(t_min, 3);
mean_t = (mean_t_max + mean_t_min)/2;
mean_dutr = mean_t_max - mean_t_min;
mean_pr_max = nanmean(pr_max, 3);
mean_pr = times(mean_pr_max, iSeason)/iSimNum;

%% Save Data (Change)
save GA_B1_2070_2099_summer.mat

%% Create NetCDF File (Change)

nccreate('GA_b1_2070_2099_summer.nc', 'mean_t', 'Dimensions', {'lon' 40
'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer.nc', 'mean_pr', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer.nc', 'max_t_max', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer.nc', 'min_t_min', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer.nc', 'max_pr_max', 'Dimensions',
{'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer.nc', 'mean_dutr', 'Dimensions', {'lon'
40 'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'f90_count',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'f100_count',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'f90_consec_max',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'f100_consec_max',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'p1_count',
'Dimensions', {'lon' 40 'lat' 41}, 'Datatype', 'double', 'Format',
'classic');
nccreate('GA_b1_2070_2099_summer.nc', 'lon', 'Dimensions', {'lon' 40},
'Datatype', 'double', 'Format', 'classic');
```

```
nccreate('GA_b1_2070_2099_summer.nc', 'lat', 'Dimensions', {'lat' 41},
'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'lon', 'Dimensions',
{'lon' 40}, 'Datatype', 'double', 'Format', 'classic');
nccreate('GA_b1_2070_2099_summer_thresholds.nc', 'lat', 'Dimensions',
{'lat' 41}, 'Datatype', 'double', 'Format', 'classic');
ncwrite('GA_b1_2070_2099_summer.nc', 'mean_t', mean_t);
ncwrite('GA_b1_2070_2099_summer.nc', 'mean_pr', mean_pr);
ncwrite('GA_b1_2070_2099_summer.nc', 'max_t_max', max_t_max);
ncwrite('GA_b1_2070_2099_summer.nc', 'min_t_min', min_t_min);
ncwrite('GA_b1_2070_2099_summer.nc', 'max_pr_max', max_pr_max);
ncwrite('GA_b1_2070_2099_summer.nc', 'mean_dutr', mean_dutr);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'f90_count',
f90_count);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'f100_count',
f100_count);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'f90_consec_max',
f90_consec_max);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'f100_consec_max',
f100_consec_max);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'p1_count', p1_count);
ncwrite('GA_b1_2070_2099_summer.nc', 'lon', lon);
ncwrite('GA_b1_2070_2099_summer.nc', 'lat', lat);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'lon', lon);
ncwrite('GA_b1_2070_2099_summer_thresholds.nc', 'lat', lat);
```

APPENDIX D: VBA CODE FOR ROADWAY MCDM CRITICALITY TOOL

```
'Develop Criticality Score of 0 or 1 based on STRAHNET Designation

Function STRAHNET_Score(STRAHNET) As Double

        If STRAHNET = 1 Then
            STRAHNET_Score = 1
        ElseIf STRAHNET = 2 Then
            STRAHNET_Score = 1
        Else:
            STRAHNET_Score = 0
        End If

End Function

'Develop Criticality Score of 0 or 1 based on NHS Designation

Function NHS_Score(NHS) As Double

        If NHS = 1 Then
            NHS_Score = 1
        ElseIf NHS = 3 Then
            NHS_Score = 1
        Else:
            NHS_Score = 0
        End If

End Function

' Develop Criticality Score of 1, 2, or 3 based on Functional Classification

Function FC_Score(FUNC_CLASS) As Double
    Select Case FUNC_CLASS
        Case Is = 1, 11, 12
            FC_Score = 3
        Case Is = 2, 14
            FC_Score = 2
        Case Is = 6, 16
            FC_Score = 1
    End Select
End Function
```

```
'Develop Criticality Score of 1, 2, or 3 based on AADT

Function AADT_Score(AADT) As Double

        If AADT >= 25000 Then
            AADT_Score = 3
        ElseIf AADT > 10000 Then
            AADT_Score = 2
        Else:
            AADT_Score = 1
        End If

End Function

'Develop Criticality Score of 1, 2, or 3 based on COPACES Rating

Function PACES_Score(PACES_RATING) As Double

    If PACES_RATING >= 75 Then
        PACES_Score = 1
    ElseIf PACES_RATING > 65 Then
        PACES_Score = 2
    Else:
        PACES_Score = 3
    End If

End Function

'Develop Criticality Score of 1, 2, or 3 based on Truck Percentage

Function Truck_Score(TRUCK_PERCENT) As Double

    If TRUCK_PERCENT >= 25 Then
        Truck_Score = 3
    ElseIf TRUCK_PERCENT >= 10 Then
        Truck_Score = 2
    Else:
        Truck_Score = 1
    End If

End Function
```

APPENDIX E: VBA CODE FOR BRIDGE MCDM CRITICALITY TOOL

```
'Develop Criticality Score of 0 or 1 based on Inventory Rating

Function HSInv_Score(HSInv) As Double

        If HSInv < 24 Then
            HSInv_Score = 1
        Else:
            HSInv_Score = 0
        End If

End Function

'Develop Criticality Score of 0 or 1 based on whether or not posting is
required

Function Post_Score(Post) As Double

        If Post = 5 Then
            Post_Score = 0
        Else:
            Post_Score = 1
        End If

End Function

'Develop Criticality Score of 0 or 1 based on whether or not bridge is
scour critical
'Scour Critical if Sc_Crit = U, T, 3, 2, 1, 0
'Out  of possible cases 3,5,6,8,N,T,U

Function Sc_Crit_Score(Sc_Crit) As Double
     Select Case Sc_Crit
        Case Is = U, T, 3
            Sc_Crit_Score = 1
        Case Is = N, 5, 6, 8
            Sc_Crit_Score = 0
    End Select
End Function

'Develop Criticality Score of 0 or 1 based on whether or not bridge is
fracture critical
'Scour Critical if F_Insp = 1, 2
'Out  of possible cases 0,1,2

Function FC_Score(F_Insp) As Double
     Select Case F_Insp
        Case Is = 1, 2
            FC_Score = 1
        Case Is = 0
            FC_Score = 0
    End Select
```

```
End Function

'Develop Criticality Score of 1, 2, or 3 based on Bypass Length

Function BP_Len_Score(BP_Len) As Double

        If BP_Len >= 20 Then
            BP_Len_Score = 3
        ElseIf BP_Len >= 10 Then
            BP_Len_Score = 2
        Else:
            BP_Len_Score = 0
        End If

End Function

'Develop Criticality Score of 0 or 1 based on Condition Rating

Function BR_Cond_Score(BR_Cond_Avg) As Double

        If BR_Cond_Avg < 6 Then
            BR_Cond_Score = 1
        Else:
            BR_Cond_Score = 0
        End If

End Function
```

APPENDIX F: SAMPLE CALCULATIONS FOR ROADWAY AND BRIDGE CRITICALITY SCORES

Table 23. Sample Calculations for OBJECT ID 484 Shiloh Rd.

Risk Factor	Weight	Attribute Data	Raw Criticality Score	Normalized Score	Weighted Risk Factor Score
STRAHNET	0.2	No	0	0	0
NHS	0.1	No	0	0	0
Functional Classification	0.1	Minor Arterial	1	0.3333333	0.0333333
Traffic Volume (AADT)	0.2	15380	2	0.6666667	0.1333334
Condition (PACES Rating)	0.2	60	3	1	0.2
Total Lanes	0.1	2	2/14	0.1428571	0.0142857
Truck Percentage	0.1	N/A	1	0.3333333	0.0333333
Overall Criticality Score (Σ of Weighted Risk Factor Scores)					**0.414**
Final Criticality Score (Factored by 10)					**4.14**

Table 24. Sample Calculations for OBJECT ID 2 Withalacoochee River Bridge on State Route 31

Risk Factor	Weight	Attribute Data	Raw Criticality Score	Normalized Score	Weighted Risk Factor Score
Inventory Rating	0.3	13	1	1	0.3
Weight Posting	0.2	3	1	1	0.2
Scour Criticality	0.05	U	0	0	0
Fracture Criticality	0.05	2	1	1	0.05
Bypass Length	0.2	17	2	0.6666667	0.1333334
Condition	0.2	5.67	1	1	0.2
Overall Criticality Score (Σ of Weighted Risk Factor Scores)					**0.883**
Final Criticality Score (Factored by 10)					**8.83**

APPENDIX G: STATE OF GEORGIA TEMPERATURE DIFFERENCE PROJECTION MAPS

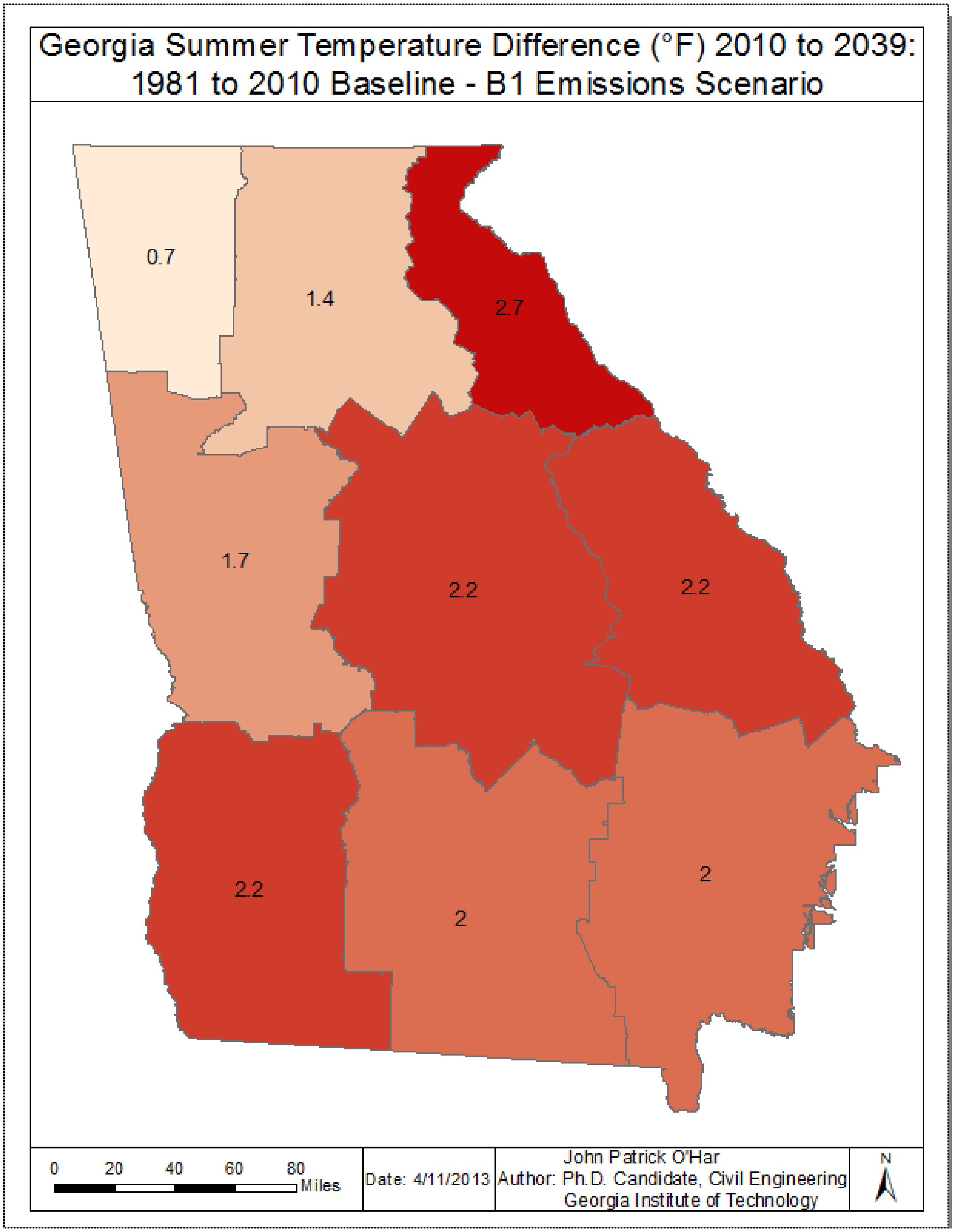


Figure 38. State of Georgia summer (June, July, August) temperature difference projection for 2010 to 2039 for the B1 emissions scenario

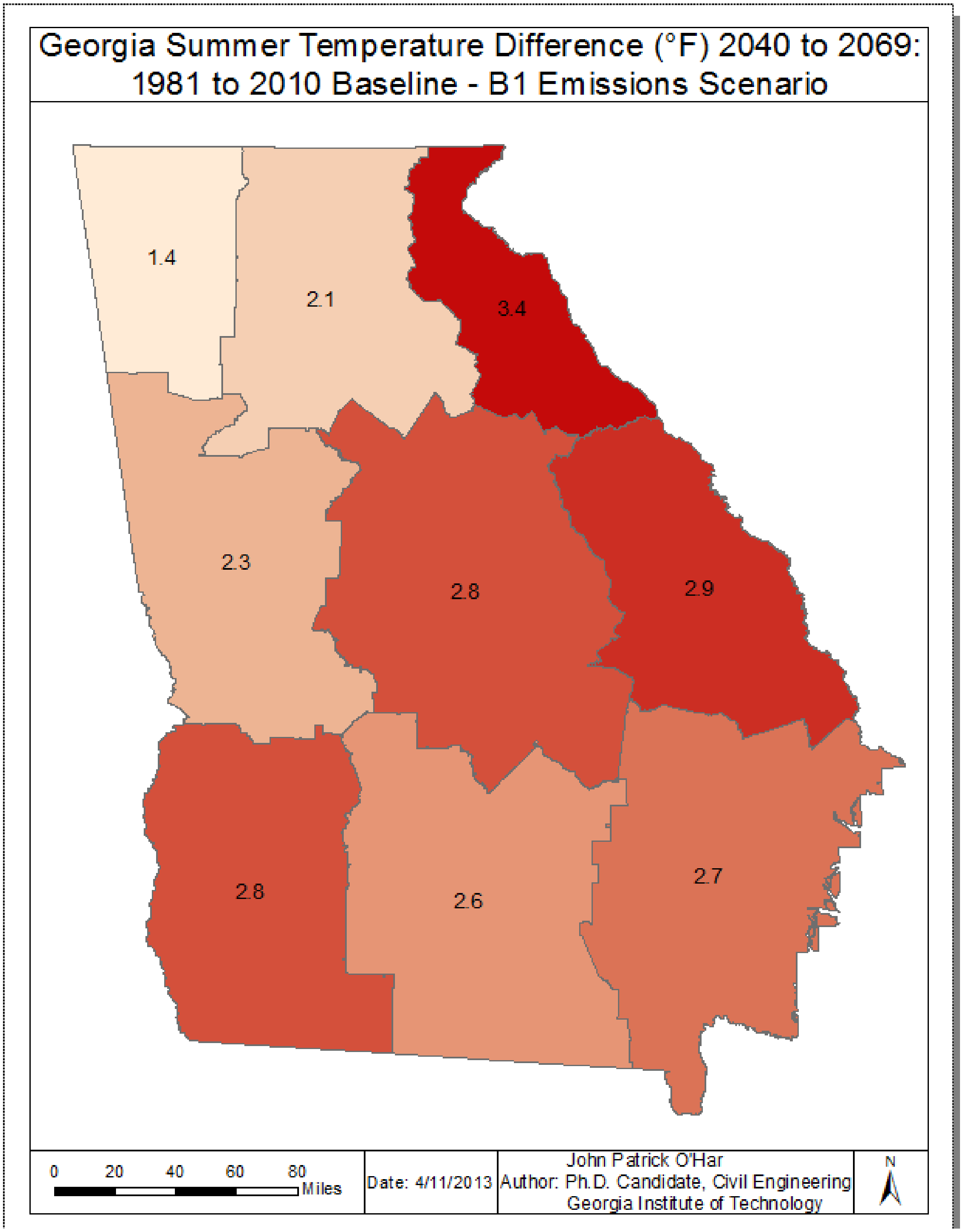


Figure 39. State of Georgia summer (June, July, August) temperature difference projection for 2040 to 2069 for the B1 emissions scenario

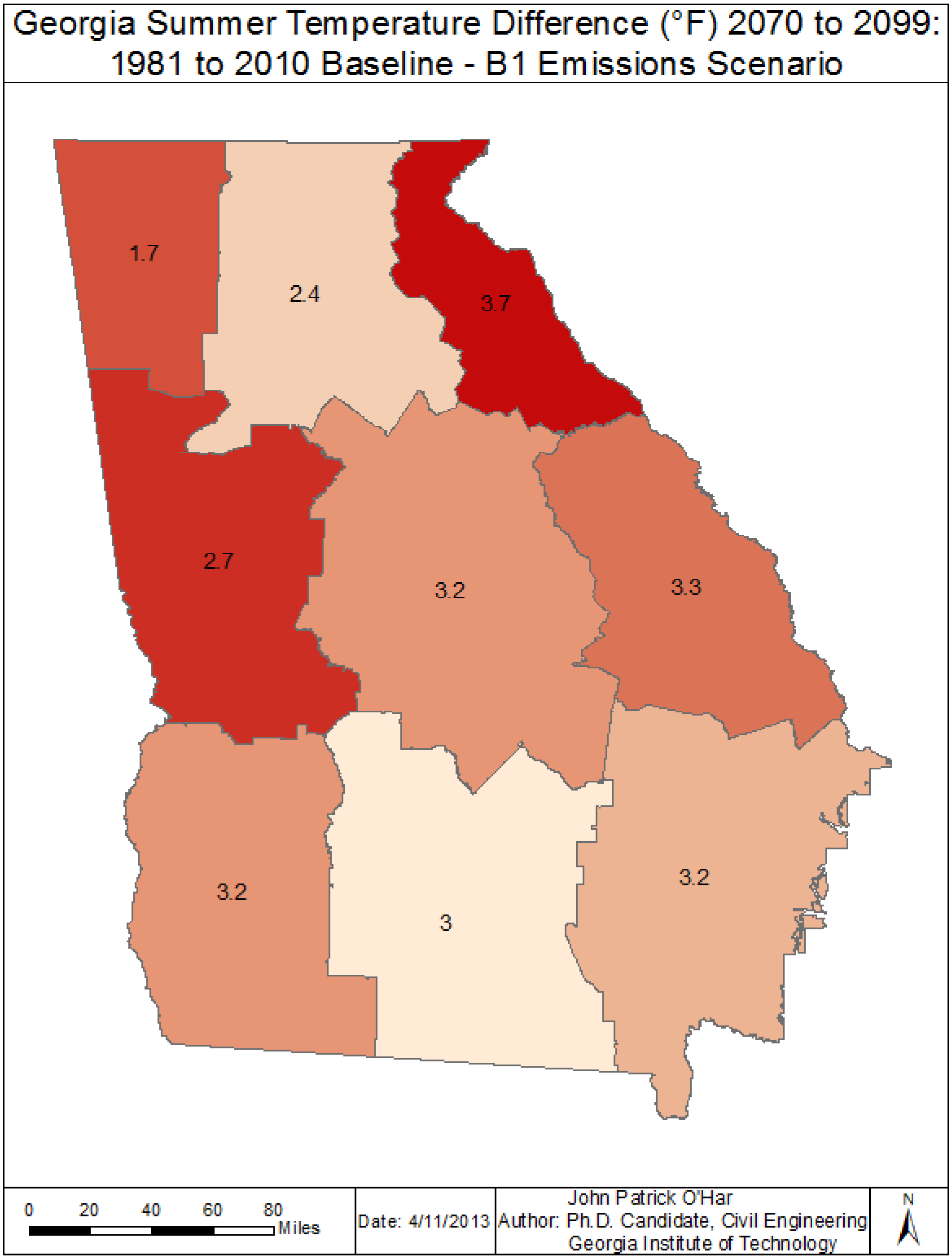


Figure 40. State of Georgia summer (June, July, August) temperature difference projection for 2070 to 2099 for the B1 emissions scenario

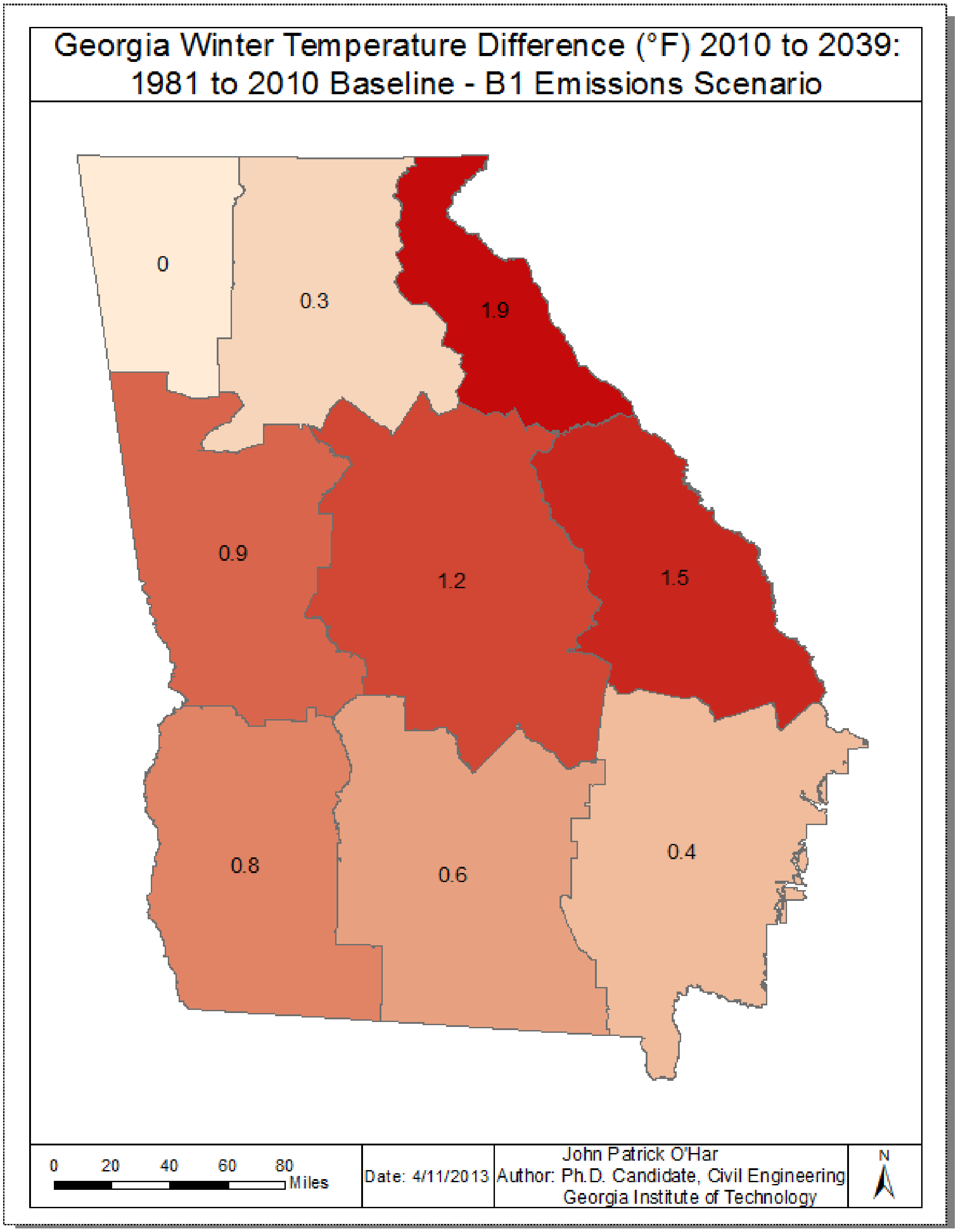


Figure 41. State of Georgia winter (December, January, February) temperature difference projection for 2010 to 2039 for the B1 emissions scenario

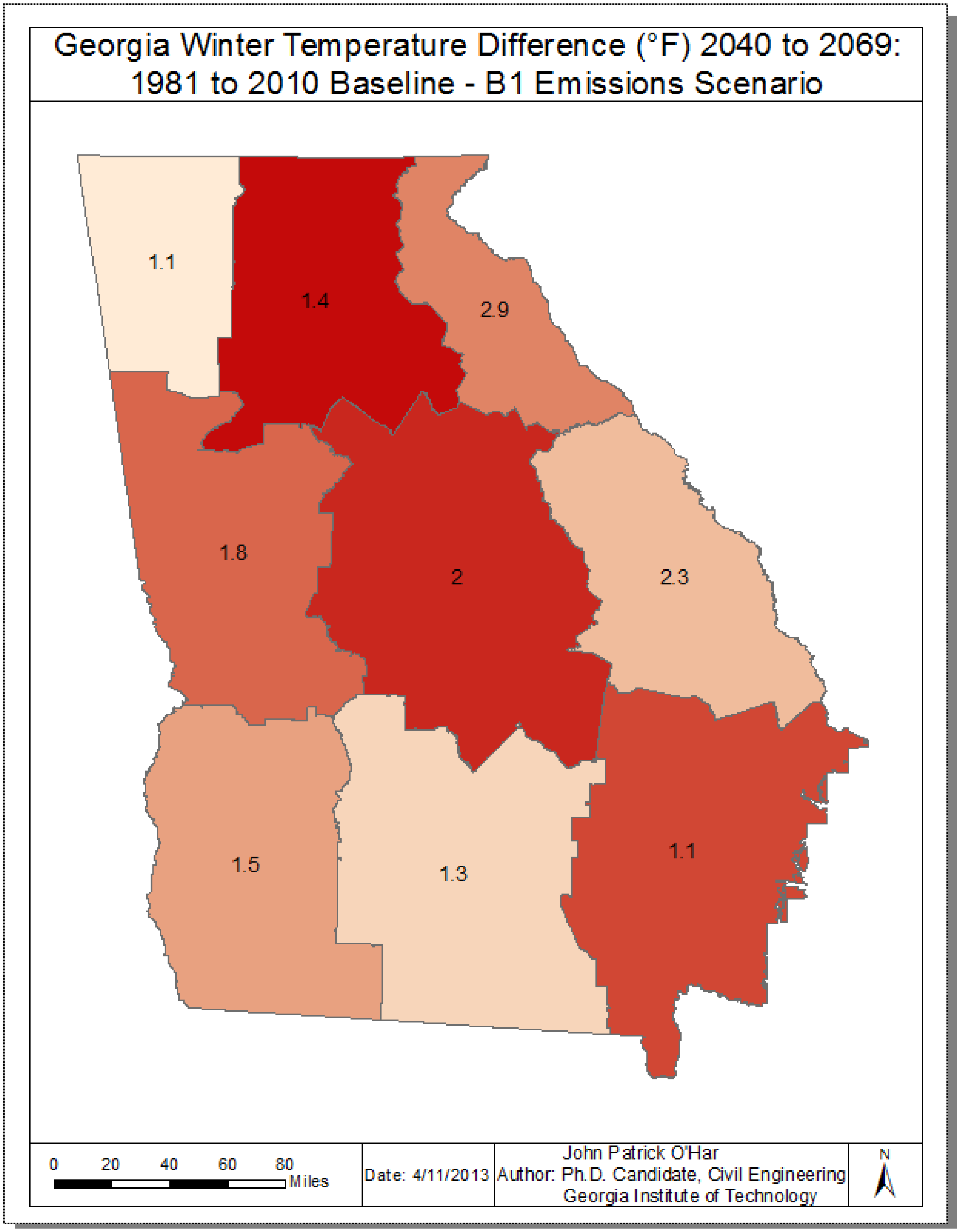


Figure 42. State of Georgia winter (December, January, February) temperature difference projection for 2040 to 2069 for the B1 emissions scenario

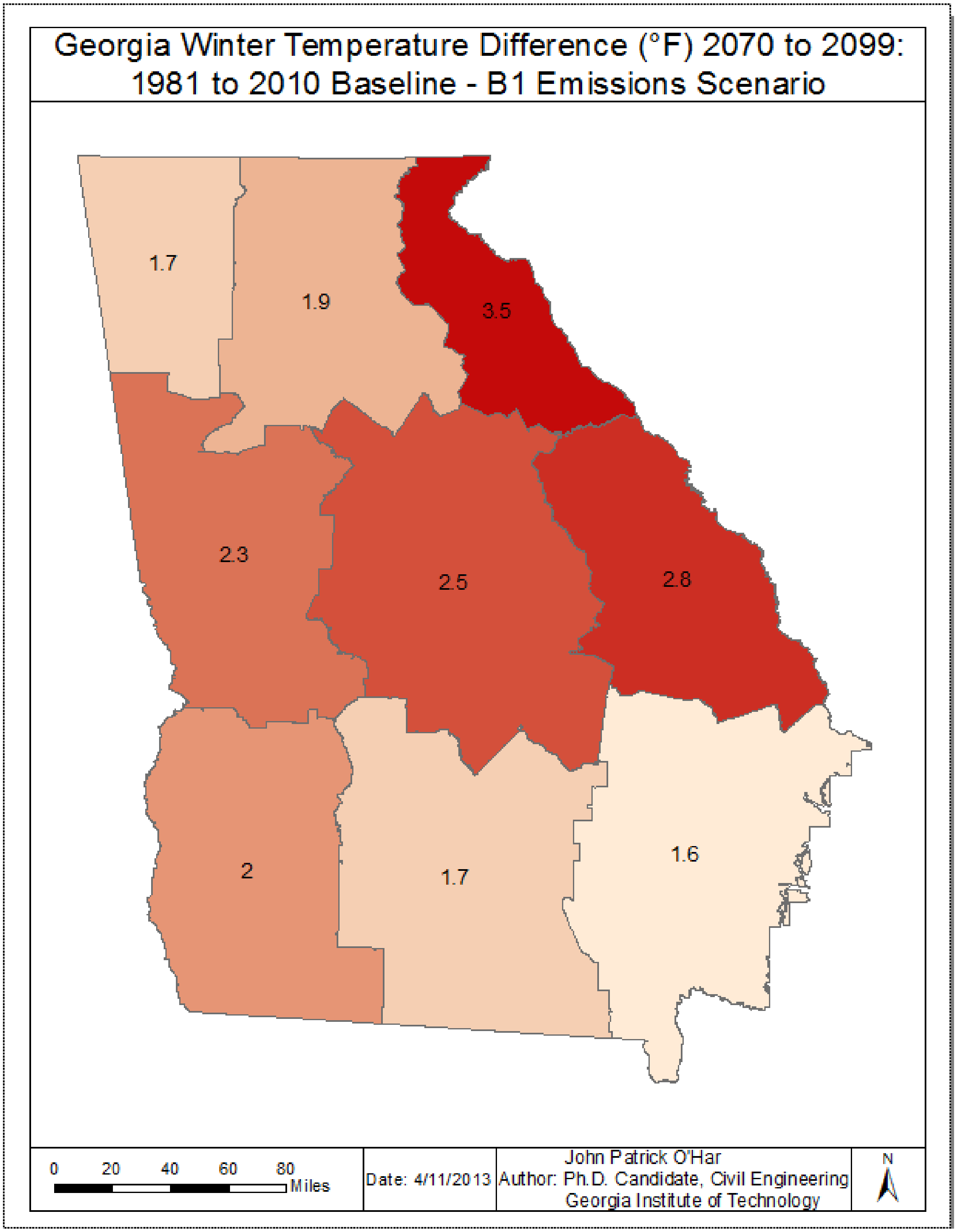


Figure 43. State of Georgia winter (December, January, February) temperature difference projection for 2070 to 2099 for the B1 emissions scenario

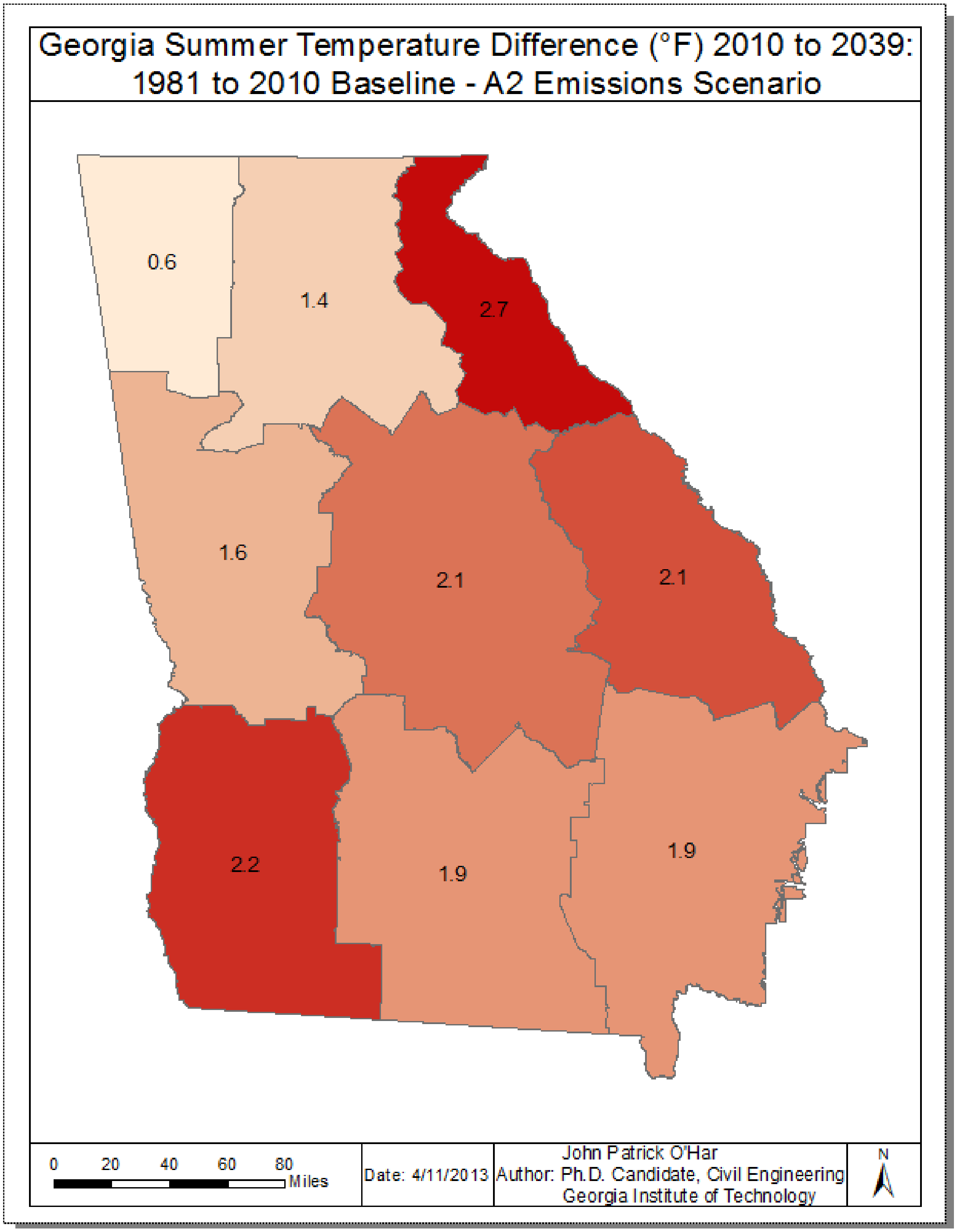


Figure 44. State of Georgia summer (June, July, August) temperature difference projection for 2010 to 2039 for the A2 emissions scenario

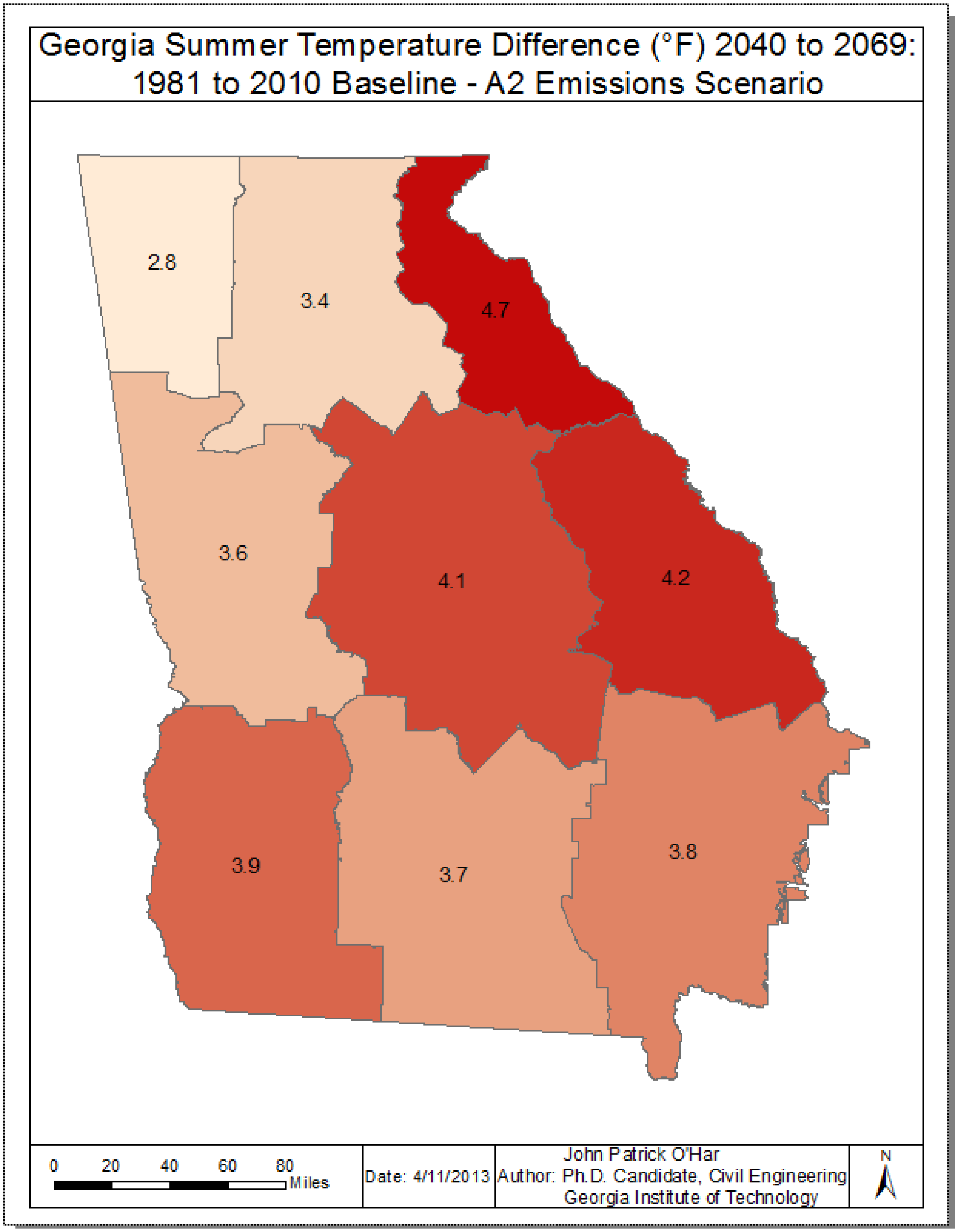


Figure 45. State of Georgia summer (June, July, August) temperature difference projection for 2040 to 2069 for the A2 emissions scenario

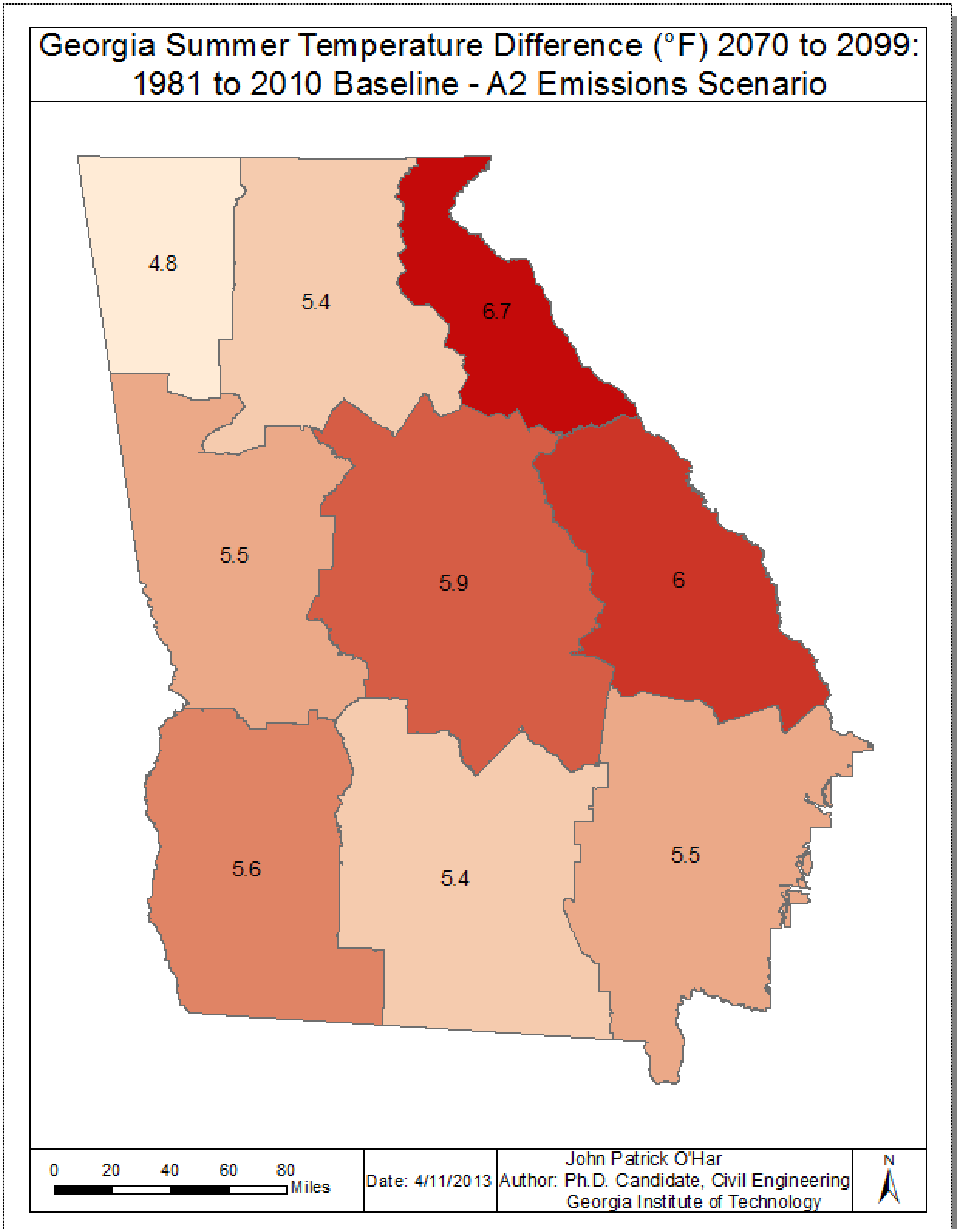


Figure 46. State of Georgia summer (June, July, August) temperature difference projection for 2070 to 2099 for the A2 emissions scenario

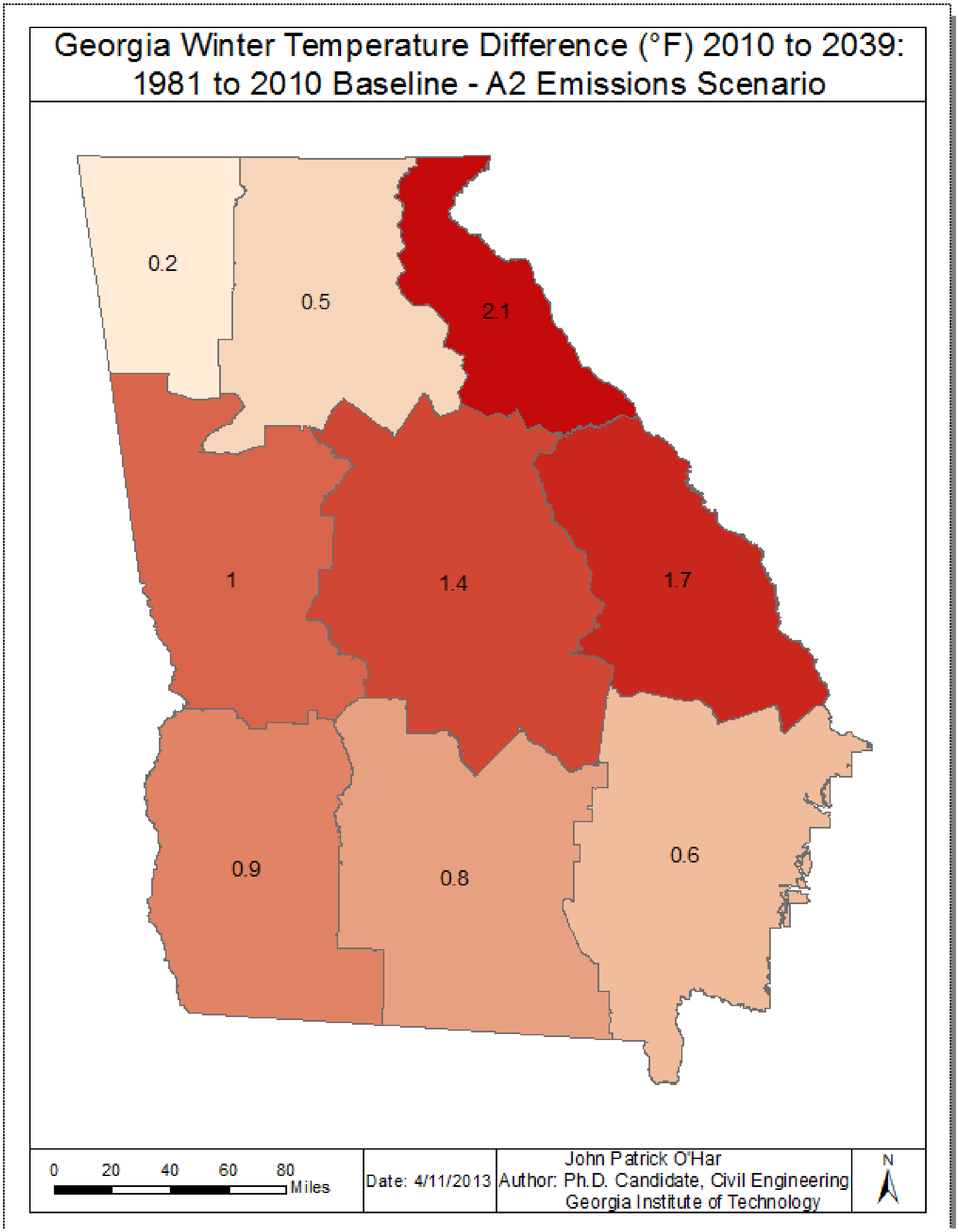


Figure 47. State of Georgia winter (December, January, February) temperature difference projection for 2010 to 2039 for the A2 emissions scenario

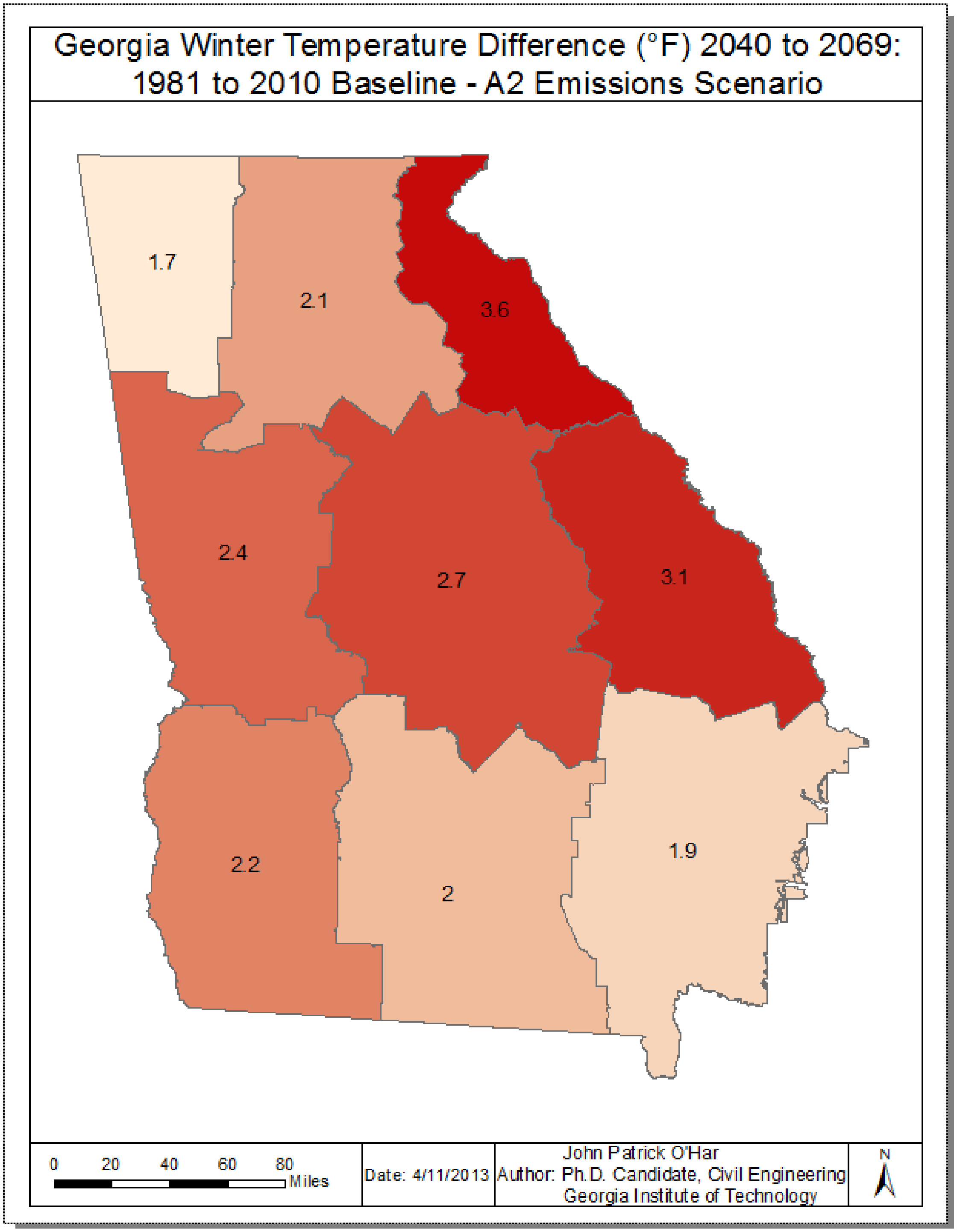


Figure 48. State of Georgia winter (December, January, February) temperature difference projection for 2040 to 2069 for the A2 emissions scenario

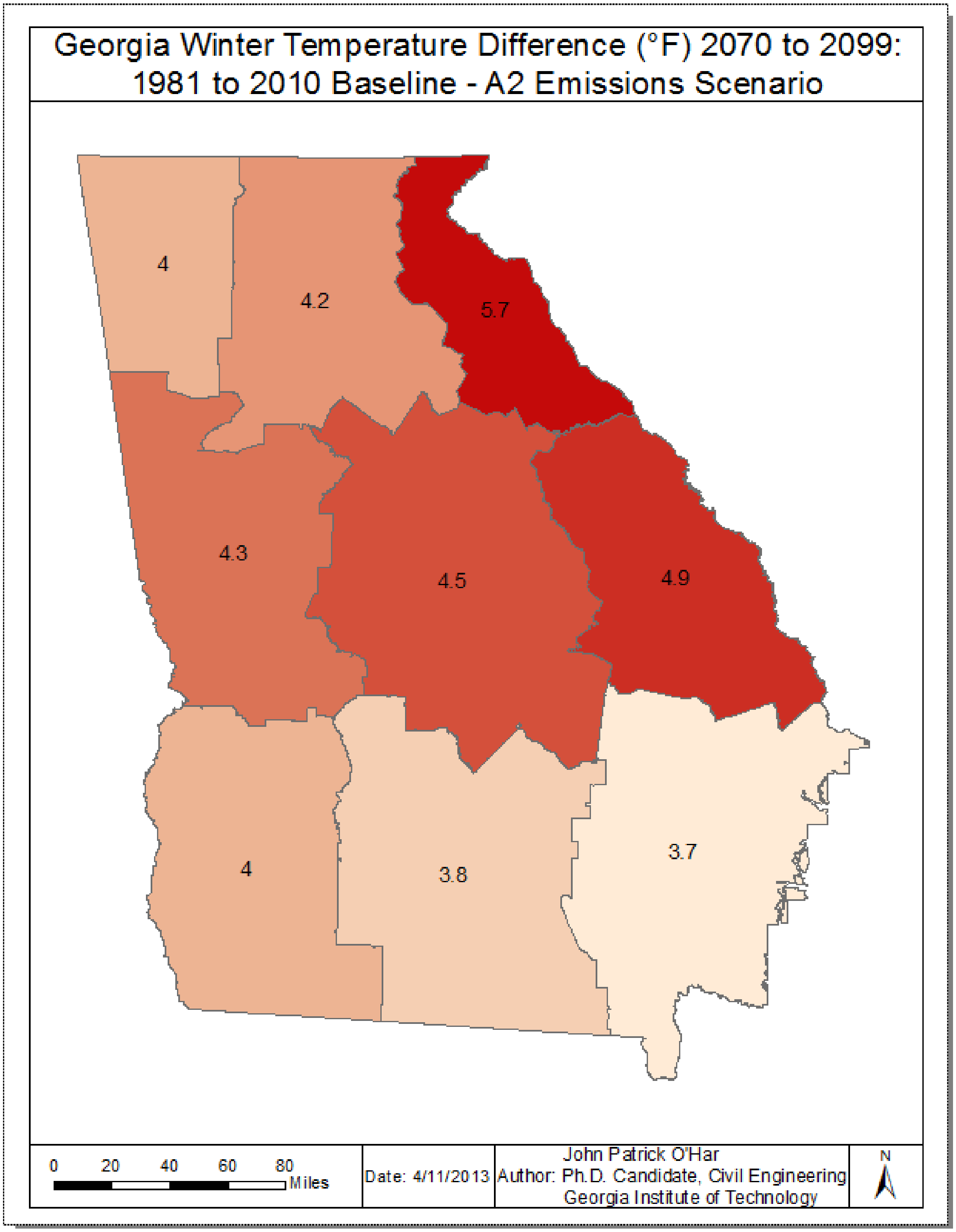


Figure 49. State of Georgia winter (December, January, February) temperature difference projection for 2070 to 2099 for the A2 emissions scenario

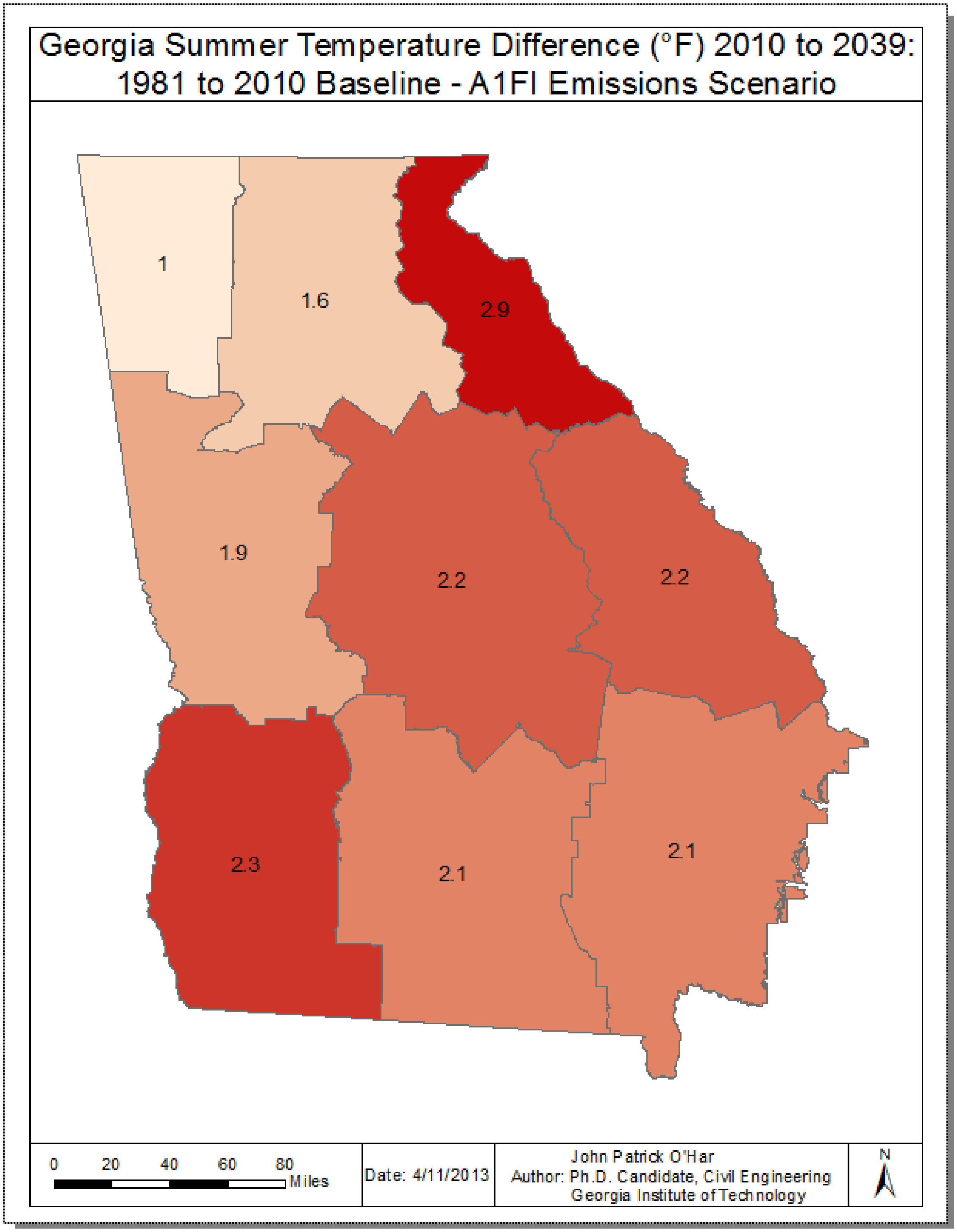


Figure 50. State of Georgia summer (June, July, August) temperature difference projection for 2010 to 2039 for the A1FI emissions scenario

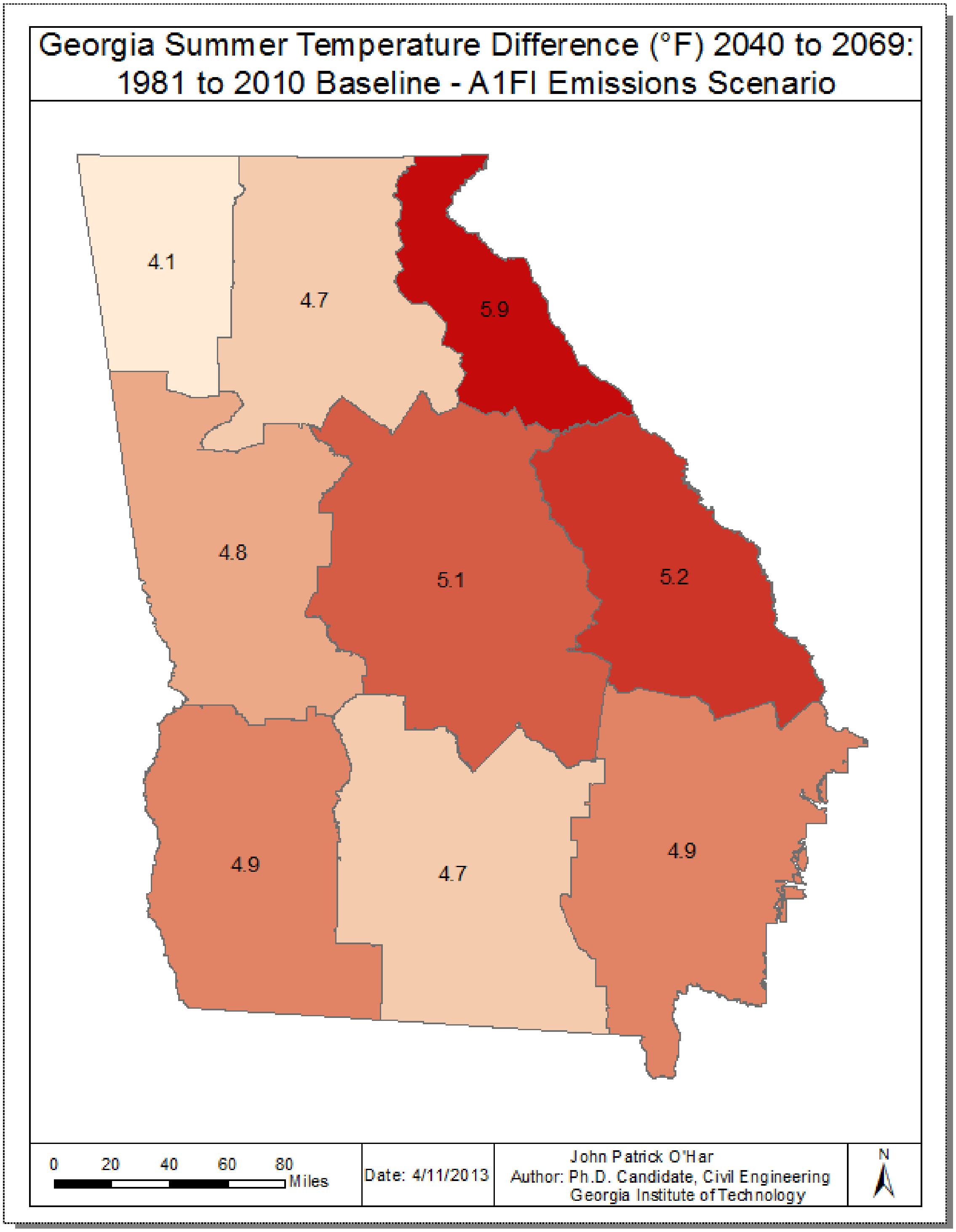


Figure 51. State of Georgia summer (June, July, August) temperature difference projection for 2040 to 2069 for the A1FI emissions scenario

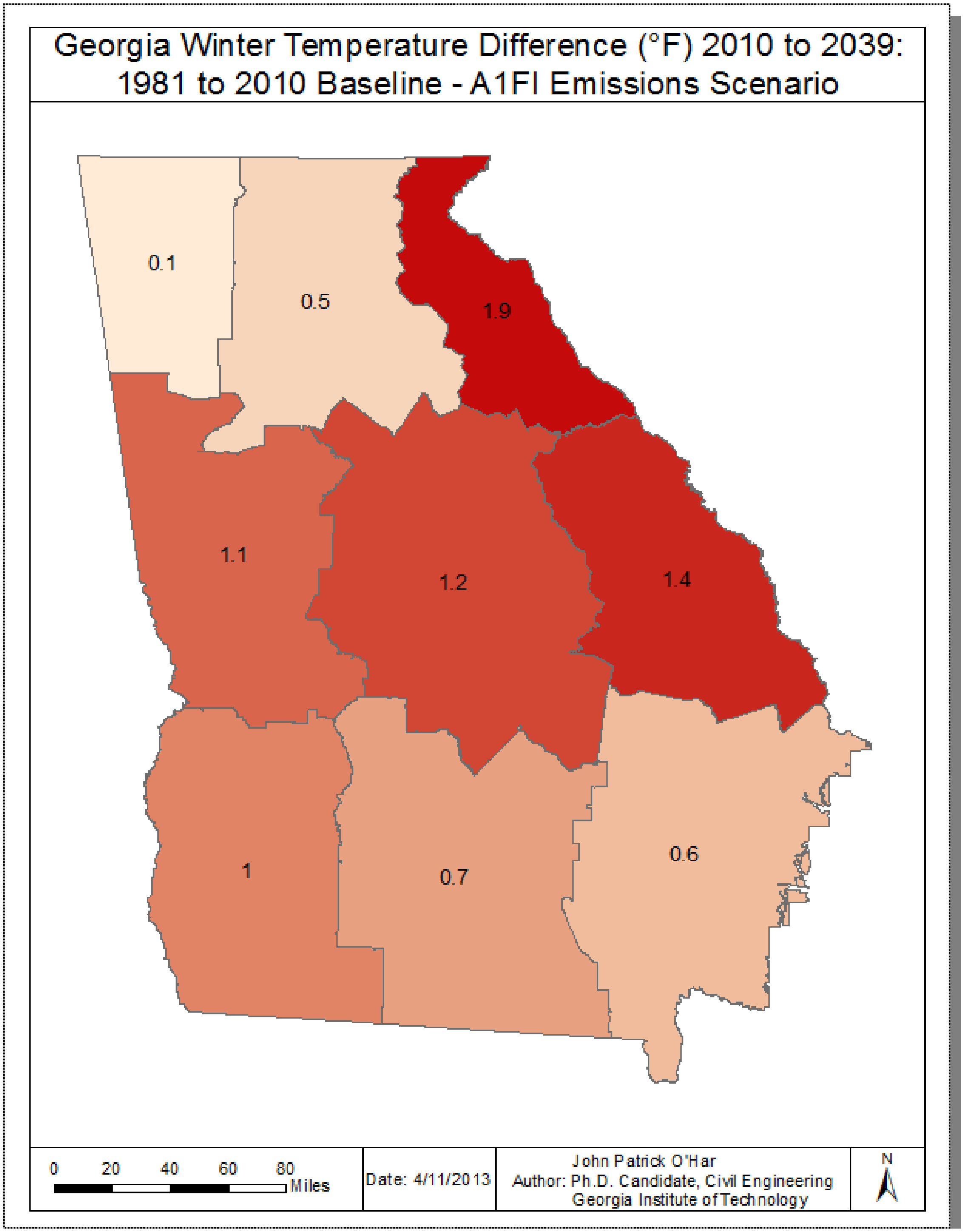


Figure 52. State of Georgia winter (December, January, February) temperature difference projection for 2010 to 2039 for the A1FI emissions scenario

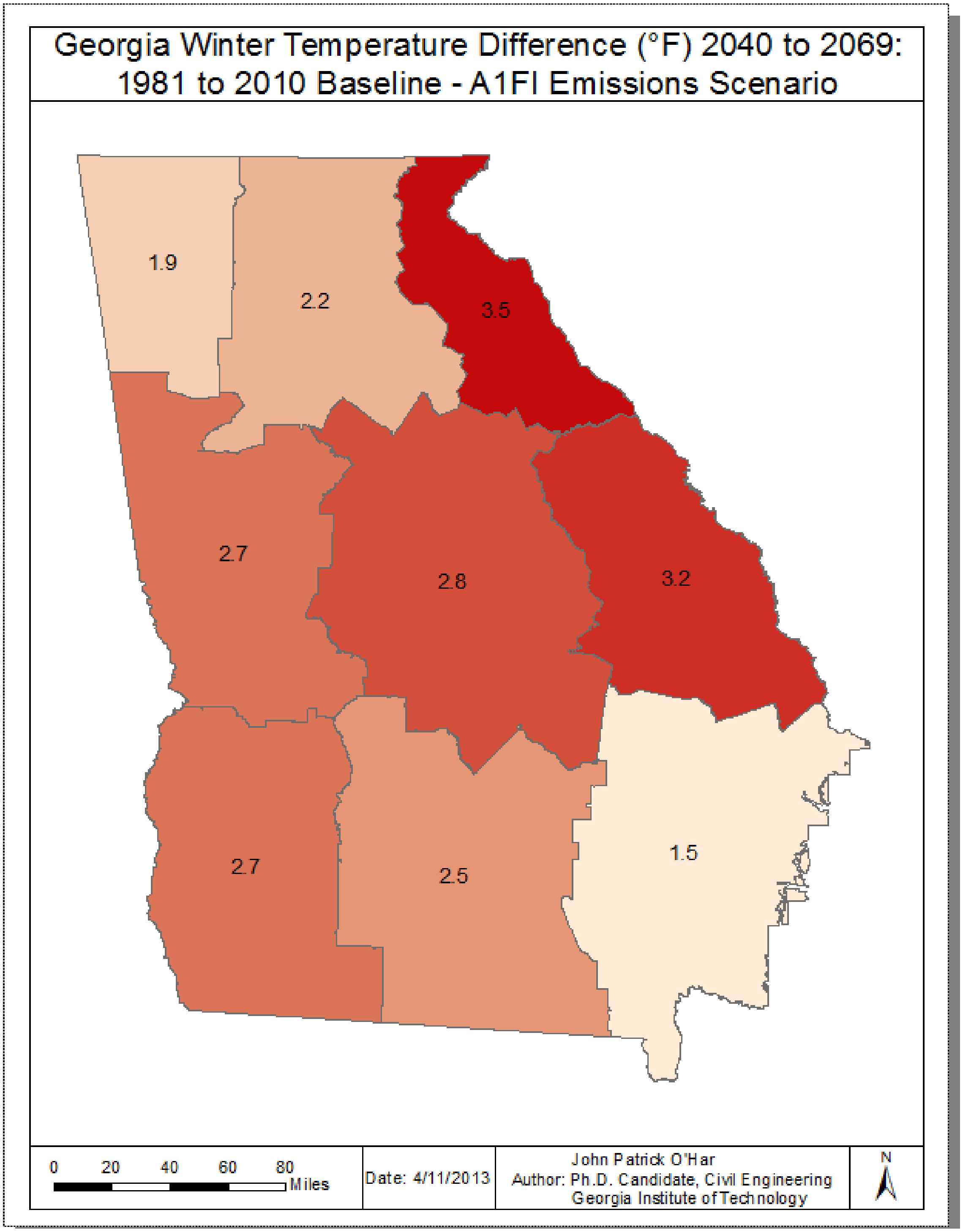


Figure 53. State of Georgia winter (December, January, February) temperature difference projection for 2040 to 2069 for the A1FI emissions scenario

REFERENCES

AASHTO. (1997). *21st Century Asset Management: Executive Summary*.

AASHTO. (2006). “Motion to Amend the Definition to Advocate the Principles of Transportation Asset Management.” Standing Committee on Highways, AASHTO, Jekyll Island, GA.

AASHTO. (2011a). *AASHTO Transportation Asset Management Guide: A Focus on Implementation*. *Focus*, Washington, D.C.

AASHTO. (2011b). *AASHTO Transportation Asset Management Guide: A Focus on Implementation*. Washington, D.C.

AASHTO. (2012). “States Discuss Adapting to Extreme Weather during AASHTO Spring Meeting Session.” *AASHTO Journal: Weekly Transportation Report*, Washington, D.C.

AbouRizk, S. M., and Siu, K. L. (2008). “Standardized Risk Analysis for Infrastructure Assessment.” *Infrastructure Reporting and Asset Management: Best Practices and Opportunities*, 131–140.

Aktan, A. E., Ellingwood, B. R., and Kehoe, B. (2007). “Performance-based engineering of constructed systems.” *Journal of Structural Engineering*, 311–323.

Aktan, A. E., and Moon, F. L. (2010). “Mitigating Infrastructure Performance Failures Through Risk-based Asset Management.” *Fifth International Conference on Bridge*

Maintenance, International Association for Bridge Management and Safety, Philadelphia, PA.

Amekudzi, A. A. (2009). “Asset Management.” *ITE Transportation Planning Handbook 3rd Edition*, M. D. Meyer, ed., Institute of Transportation Engineers, Washington, D.C., NP.

Amekudzi, A., and Crane, M. (2012). *Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Regional Transit Authority: Task 3 Draft Technical Memorandum Addressing Climate Change and Hazard’s using MARTA's Asset Management Program*. Atlanta, GA.

Amekudzi, A., and Crane, M. (2013). *Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Regional Transit Authority: Task 4/5 Draft Technical Memorandum Climate Change Adaptation Strategies for MARTA*. Atlanta, GA.

Amekudzi, A., and McNeil, Sue. (2000). “Capturing Data and Model Uncertainties in Highway Performance Estimation.” *Journal of Transportation Engineering*, 126(6), 455–463.

Amekudzi, A., and Meyer, Michael. (2011). *Best Practices in Selecting Performance Measures and Standards for Effective Asset Management*. Atlanta, GA.

Amekudzi, A., and Meyer, Michael. (2012). *Transit Climate Change Adaptation Assessment/Asset Management Pilot for the Metropolitan Atlanta Regional Transit Authority Task 1 Draft Technical Memorandum*. Atlanta, GA.

Amekudzi, A., Meyer, Michael, Akofio-Sowah, M., and Boadi, R. (2011). *Comprehensive Transportation Asset Management: Making a Business Case and Prioritizing Assets for Inclusion in Formal Asset Management Programs*. Atlanta, GA.

ASCE. (2009). *2009 Report Card for America's Infrastructure*. *Science (New York, N.Y.)*, Reston, Virginia.

Baden, C., Keller, Josh, and Marsh, B. (2012). "What Could Disappear." *New York Times*, online ed.

BATTELLE. (2006). *Detailed Monitoring Protocol for U.S. 95 Settlement Agreement*. Washington, D.C.

BCDC. (2011). *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*. *Development*, San Francisco, CA.

Brand, D., and Mehndiratta, S. (2000). "Options Approach to Risk Analysis in Transportation Planning." *Transportation Research Record*, (1706), 54–63.

Burbank, C. J., Wenger, J. A., and Sperling, D. (2012). *Transportation Research Circular: Climate Change and Transportation, Number E-C164*. Washington, D.C.

Cambridge Systematics. (2002). *Transportation Asset Management Guide, NCHRP Project 20-24. Prepared for National Cooperative Highway Research*, Washington, D.C.

Cambridge Systematics. (2012a). *Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure*. Newark, NJ.

Cambridge Systematics. (2012b). *Draft Report: Climate Change and Transportation Resiliency in the CHCRPA Region*. Chattanooga, TN.

Cambridge Systematics, Applied Research Associates, Arora and Associates, KLS Engineering, PB Consult Inc., and Lambert, L. (2009). *NCHRP Report 632 An asset-management framework for the Interstate Highway System. Planning And Administration*, Washington, D.C.

Cambridge Systematics, and Meyer, M. D. (2007). *U.S. Domestic Scan Program: Best Practices in Transportation Asset Management, SCAN-TOUR Report, NCHRP 20-68. Management*, Washington, D.C.

Cambridge Systematics, PB Consult Inc., and System Metrics Group Inc. (2005). *NCHRP Report 545 Analytical Tools for Asset Management. Transportation*, Washington, D.C.

Cambridge Systematics, PB Consult Inc., and Texas Transportation Institute. (2006). *NCHRP Report 551 Performance Measures and Targets for Transportation Asset Management. Planning And Administration*, Washington, D.C.

City of New York. (2011). *plaNYC: A Greener, Greater New York. New York*, New York.

Crane, M., and Amekudzi, A. (2012). “Transit Climate Change Adaptation Assessment/Asset Management Pilot for MARTA/Task 2 and 3 Interview Notes.” Atlanta, GA.

Curtis, J. A., Dailey, J. S., D’Angelo, D., DeWitt, S. D., Graf, M. J., Henkel, T. A., Miller, J. B., Milton, J. C., Molenaar, K. R., Richardson, D. M., and Rocco, R. E. (2012). *Transportation Risk Management: International Practices for Program Development and Project Delivery*. Washington, D.C.

D’Ignazio, J., Hallowell, M., and Molenaar, K. (2011). *Executive Strategies for Risk Management by State Departments of Transportation*. Washington, D.C.

Dabous, S. A., and Alkass, S. (2010). “A multi-attribute ranking method for bridge management.” *Engineering, Construction and Architectural Management*, 17(3), 282–291.

Dalton, M. S., and Jones, S. A. (2010). *Southeast Regional Assessment Project for the National Climate Change and Wildlife Science Center, U.S. Geological Survey. Science*, Reston, Virginia.

Department of Health. (2011). *Heatwave Plan for England: Protecting Health and Reducing Harm From Extreme Heat and Heatwaves*. London.

Division of the Chief Engineer. (2012). “GDOT Publications Policies & Procedures: 4B-1-Asset Management Policy.” Georgia Department of Transportation, Atlanta, GA.

Douglass, S. L., and Krolak, J. (2008). *Highways in the Coastal Environment: Hydraulic Engineering Circular 25, Second Edition*. *Contract*, Washington, D.C.

Draper, D. (1995). “Assessment and propagation of model uncertainty.” *Journal of the Royal Statistical Society. Series B (* …, 57(1), 45–97.

EPA. (2010). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2008*. *Environmental Protection*, Washington, D.C.

ESRI, I. (2010). “Fundamentals of netCDF data storage.” ESRI, Inc.

Evans, J. (n.d.). “SNCTOOLS.” *SourceForge Project MEXCDF*, <http://mexcdf.sourceforge.net/index.php> (Oct. 30, 2012).

FHWA. (1995). *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges*. Washington, D.C.

FHWA. (2010). “Highways and Climate Change: Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model.” Federal Highway Administration, Washington, D.C.

FHWA. (2012). *Moving Ahead for Progress in the 21st Century Act (MAP-21): A Summary of Highway Provisions*. *A Summary of Highway Provisions*, Washington, D.C.

Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M., and Midgley, P. M. (2012). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Summary for Policy Makers*. *Managing*, New York, 1–19.

Fox, J., Dobson, G., and Hutchins, M. (2010). *French Broad River MPO Long Range Transportation Plan Update DRAFT Climate Change Chapter*. Asheville, NC.

Frumhoff, P. C., McCarthy, J. J., Melillo, J. M., Moser, S. C., and Wuebbles, D. J. (2007). *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. Cambridge, MA.

FTA. (2010). *National State of Good Repair Assessment*. Washington, D.C.

FTA. (2011). "Announcement of Project Selections: Transit Climate Change Adaptation Assessment Pilots." Federal Transit Administration, Washington, D.C.

FTA. (2012a). *Moving Ahead for Progress in the 21st Century Act (MAP-21): A Summary of Public Transportation Provisions*. Washington, D.C., 1–11.

FTA. (2012b). "National Transit Database." *NTD 2011 Database*, <http://www.ntdprogram.gov/ntdprogram/datbase/2011_database/NTDdatabase.htm> (Apr. 11, 2013).

GDOT. (2011a). *Transportation Asset Management: The Strategic Direction of Georgia Department of Transportation*. Atlanta, GA.

GDOT. (2011b). "Transportation Asset Management GDOT Board Workshop: What is Transportation Asset Management?" Georgia Department of Transportation, Atlanta, GA.

GDOT. (2012). "GDOT Performance Management Dashboard." <http://www.dot.ga.gov/statistics/performance/Pages/default.aspx> (Mar. 27, 2013).

Geiger, D., Wells, P., Bugas-Schramm, P., Love, L., Mcneil, S., Merida, D., Meyer, Michael, Ritter, R., Steudle, K., Tuggle, D., and Velasquez, L. (2005). *Transportation Asset Management in Australia, Canada, England, and New Zealand*. *Transportation*, Washington, D.C., 160.

Greater London Authority. (2005). *Climate Change and London's Transport Systems Summary Report*. *Change*, London, UK.

Greater Manchester Passenger Transport Executive. (2008). *Transport Asset Management in Greater Manchester: Progress Update*. *Development*.

Haas, R., and Raymond, C. (1999). "Asset Management for Roads and Other Infrastructure." *Annual Asphalt Seminar*, Ontario Hot Mix Producers Association, Toronto, Ontario.

Haimes, Y. Y. (2004). *Risk Modeling, Assessment, and Management*. John Wiley & Sons, Inc., Hoboken, New Jersey.

Hawkins, N., and Smadi, O. (2013). *NCHRP Synthesis 439 Use of Transportation Asset Management Principles in State Highway Agencies: A Synthesis of Highway Practice*. Washington, D.C.

Hayhoe, Katharine, VanDorn, J., Croley, T., Schlegal, N., and Wuebbles, D. (2010). “Regional Climate Change Projections for Chicago and the US Great Lakes.” *Journal of Great Lakes Research*, 26(Supplement 2), 7–21.

Helton, J. C., and Burmaster. (1996). “Treatment of Aleatory and Epistemic Uncertainty in the Performance of Complex Systems.” *Reliability Engineering and System Safety*, 54, 91–94.

Hoeting, J., Madigan, D., Raftery, A., and Volinsky, C. (1999). “Bayesian model averaging: a tutorial.” *Statistical science*, 14(4), 382–401.

Huddleston, N. (2012). *Climate Change: Evidence, Impacts, and Choices*. Washington, D.C.

ICF International. (2010). *Climate Change – Model Language in Transportation Plans*. San Francisco, CA.

ICF International, PB Americas, USGS, and South Coast Engineers. (2012). *DRAFT The Gulf Coast Study, Phase 2: Climate Variability and Change in Mobile, Alabama Final Report, Task 2*. Washington, D.C.

ISO. (2009). “ISO 31000:2009(E) Risk management - Principles and guidelines.” International Organization for Standardization, Geneva, Switzerland.

Johnson, M. B., and Shephard, R. W. (1999). “California Bridge Health Index.” *8th International Bridge Management Conference*, Transportation Research Board, Washington, D.C.

Jones, E., Hsu, C.-J., and Xiang, I. (2013). “Heavy Vehicle Adjustment Factors for High Percentages of Trucks.” *Mid-America Transportation Center Research Projects*, <http://matc.unl.edu/research/research_projects.php?researchID=115> (Apr. 8, 2013).

Karl, T. R., Melillo, J. M., and Peterson, T. C. (2009). *Global Climate Change Impacts in the United States*. *Society*.

Kellett, J., Ness, D., Hamilton, C., Pullen, S., and Leditschke, A. (2011). *Learning from Regional Climate Analogues*. Adelaide, South Australia, Australia.

King County. (2007). *King County 2007 Climate Plan*.

Kinsella, Y., and McGuire, F. (2005). “Climate change uncertainty and the state highway network: A moving target.” *Transit New Zealand*, 1–20.

Landers, M. (2009). “As Seas Rise, Planning Starts.” *Savannah Morning News*, Savannah, GA.

Landers, M. (2013). “County to Adapt to a Warmer, Wetter Coast.” *Savannah Morning News*, Savannah, GA, 1A and 7A.

Lawrence Livermore National Laboratory. (2007). “CMIP3 Climate Model Documentation, References, and Links.” *About WCRP CMIP3 Model Output*, <http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php> (Feb. 7, 2013).

Lubchenco, J., and Karl, T. R. (2012). “Predicting and managing extreme weather events.” *Physics Today*, 65(3), 31.

Maconochie, J. A. (2010). “U . S . Highway Bridge Risk Model – Development, Summary Results, and Applications for Federal and State Transportation Agencies.” *TRB 2010 Annual Meeting*, Transportation Research Board, 1–14.

Marcy, D., Herold, N., Waters, K., Brooks, W., Hadley, B., Pendleton, M., Schmid, K., Sutherland, M., Dragonov, K., McCombs, J., and Ryan, S. (2011). *New Mapping Tool and Techniques for Visualizing Sea Level Rise and Coastal Flooding Impacts. … Solutions to Coastal …*, Charleston, SC.

MARTA. (2012). *MARTA’s State of Good Repair Asset Management Program*. Atlanta, GA.

Maurer, M., Roalkvam, C. L., Salisbury, S. L., Goss, E., and Gabel, M. (2011). *Climate Impacts Vulnerability Assessment*. *Assessment*, Olympia, Washington.

McLain, R., and Lee, R. (1996). “Adaptive Management: Promises and Pitfalls.” *Environmental management*, 20(4), 437–48.

Meyer, M. D., Amekudzi, A., and O'Har, J. P. (2010). "Transportation Asset Management Systems and Climate Change." *Transportation Research Record: Journal of the Transportation Research Board*, 2160, 12–20.

Meyer, M. D., Rowan, E., Savonis, M. J., and Choate, A. (2012). "Integrating Extreme Weather Risk into Transportation Asset Management."

Meyer, MD. (2008). "Design standards for US transportation infrastructure: The implications of climate change." *Transportation Research Board, Washington, DC*, 1–30.

Meyer, Michael, Flood, M., Keller, Jake, Lennon, J., McVoy, G., Dorney, C., Leonard, K., Hyman, R., and Smith, J. (2013). *NCHRP 20-83(5) Climate Change, Extreme Weather Events and the Highway System: A Practitioner's Guide*. Washington, D.C.

Morris, R. (2013). "Deal to Ink Budget with $50M More for Port Deepening." *Georgia Ports Authority*, <http://www.gaports.com/corporate/SavannahHarborExpansionProject/PressReleases.aspx> (Apr. 11, 2013).

MPC, and RS&H. (2009). *Coastal Regions MPO (CORE) Connections 2035 Volume 1 Framework Mobility Plan*. Savannah.

MTC, Caltrans, and BCDC. (2011). *Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project: Technical Report*. *Transportation*, San Francisco, CA.

Nakicenovic, N., Davidson, O., Davis, G., Grubler, A., Kram, T., Lebre La Rovere, E., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., and Dadi, Z. (2000). *Summary for Policymakers Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. New York, NY.

NCA. (2010). *Climate Change Modeling and Downscaling NCA Report Series, Volume 7: Issues and Methodological Perspectives for the U.S. National Climate Assessment*. Washington, D.C.

NCADAC. (2013). *Third National Climate Assessment Report (DRAFT).* Washington, D.C.

NOAA. (n.d.). "Mean Lower Low Water (MLLW)." *Tides and Currents*, <http://tidesandcurrents.noaa.gov/mllw.html> (Apr. 11, 2013).

NOAA. (2011). "Toward Understanding and Predicting Regional Climate Variations and Change." *Findings from the NOAA Science Challenge Workshop*, National Oceanic and Atmospheric Administration, Washington, D.C.

NOAA. (2012). *Benefits and Costs of the Digital Coast*. Charleston, SC.

NOAA. (2013a). "Climate Data Online: Text & Map Search." *National Climatic Data Center*, <http://www.ncdc.noaa.gov/cdo-web/> (Mar. 5, 2013).

NOAA. (2013b). “National Weather Service Forecast Office: Peachtree City, GA.” *NOWData - NOAA Online Weather Data*, <http://www.nws.noaa.gov/climate/xmacis.php?wfo=ffc> (Mar. 8, 2013).

NOAA. (2013c). “National Weather Service Forecast Office: Charleston, SC.” *NOWData - NOAA Online Weather Data*, <http://www.nws.noaa.gov/climate/index.php?wfo=chs> (Mar. 8, 2013).

NOAA CSC. (2006). *Products and Services Bulletin: National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center*. Charleston, SC.

NOAA CSC, and CEMA. (2006). “Official Chatham County Hurricane Storm Surge Zones (Categories 1-5).” University of Georgia Information Technology Outreach Services, Athens, GA.

NTSB. (2008). *Highway Accident Report: Collapse of I-35W Highway Bridge Minneapolis, Minnesota August 1, 2007. Transportation*, Washington, D.C.

NWS. (2013). “Fort Pulaski Tide Gauge.” *Advanced Hydrologic Prediction Service*, <http://water.weather.gov/ahps2/hydrograph.php?wfo=chs&gage=fpkg1> (Apr. 11, 2013).

O’Brien, T., Sornette, D., and McPherron, R. (2001). “Statistical asynchronous regression: Determining the relationship between two quantities that are not measured simultaneously.” *Journal of Geophysical Research*, 106(A7), 13,247–13,259.

O’Har, J. P. (2012). “Interview with MPC Staff Member Mark Wilkes.” Savannah, GA.

O’Har, J. P. (2013). *GDOT Stakeholders Climate Risks and Potential Adpatation Strategies Meeting Summary and Results*. Atlanta, GA.

Oswald, M. R., and McNeil, S. (2012). “Methodology for Integrating Adaptation to Climate Change Into the Transportation Planning Process.” *Public Works Management & Policy*, 18(2), 145–166.

Oswald, Michelle R, Asce, A. M., Mcneil, S., and Asce, M. (2013). “Climate Change Adaptation Tool for Transportation : Mid-Atlantic Region Case Study.” *Journal of Transportation Engineering*, (April), 407–415.

Parsons Brinckerhoff. (2008). *Climate Change Adaptation Strategy Volume 1. Highways*.

PB Consult Inc., PricewaterhouseCoopers, Cambridge Systematics, and NuStats, I. (2004). *NCHRP Report 522 A Review of DOT Compliance with GASB 34 Requirements*. Washington, D.C.

Peralta, E. (2012). “Sea Level Rising Much Faster Than U.N. Projections.” *National Public Radio*.

Pew Center. (2011). *Climate Change 101 Adaptation*. *Change*, Arlington, VA.

Piyatrapoomi, N., Kumar, a, and Setunge, S. (2004). “Framework for Investment Decision-Making Under Risk and Uncertainty for Infrastructure Asset Management.” *Research in Transportation Economics*, 8(04), 199–214.

Proctor, G., and Varma, S. (2012a). *Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities*. Washington, D.C.

Proctor, G., and Varma, S. (2012b). *Risk-Based Transportation Asset Management Report 3: Achieving Policy Objectives by Managing Risks*. Washington, D.C.

Proctor, G., and Varma, S. (2013). *Risk-Based Transportation Asset Management Report 5: Managing External Threats Through Risk-based Asset Management*. Washington, D.C.

Ramirez-Villegas, J., Lau, C., A-K, K., Signer, J., Jarvis, A., Arnell, N., Osborne, T., and Hooker, J. (2011). *Climate Analogues: Finding Tomorrow's Agriculture Today*. Cali, Colombia.

Randall, D. A., Wood, R. A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R. J., Sumi, A., and Taylor, K. E. (2007). "Climate Models and Their Evaluation." *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, eds., Cambridge University Press, New York, NY.

Restrepo, A. C. (2011). "Analysis of Storm Surge Impacts on Transportation Systems in the Georgia Coastal Area." Georgia Institute of Technology.

Rew, R., and UCAR. (n.d.). “NetCDF (Network Common Data Form).” *NetCDF FAQ*, <http://www.unidata.ucar.edu/software/netcdf/docs/faq.html#whatisit> (Mar. 28, 2013).

Rose, D., Isaac, L., and Blake, T. (2013). *Transit Asset Management Guide Supplement: Asset Class Overviews & Lifecycle Management*. Washington, D.C.

Rose, D., Isaac, L., Shah, K., and Blake, T. (2013). *Asset Management Guide: Focusing on the Management of Our Transit Invesments*. Washington, D.C.

Rosenzweig, C., and Solecki, W. (2010). *Climate Change Adaptation in New York City: Building a Risk Management Response. Annals of the New York Academy of Sciences*, New York, NY.

SAIC, and PB Consult Inc. (2009). *NCHRP Report 525 Surface Transportation Security Volume 15: Costing Asset Protection: An All-Hazards Guide for Transportation Agencies (CAPTA)*. Washington, D.C.

Schwartz, H. G., Meyer, Michael, Burbank, C. J., Kuby, M., Oster, C., Posey, J., Russo, E. J., and Rypinski, A. (2013). “Transportation.” *Third National Climate Assessment Report (DRAFT)*, National Climate Assessment and Development Advisory Committee, Washington, D.C.

Schwartz, K., and O’Har, J. P. (2010). “Bridge Prioritization Formula.” Atlanta, GA.

Schwartz, P. (1996). *The Art of the Long View: Planning for the Future in an Uncertain World*. Doubleday.

Snover, A. K., Whitely Binder, J., Lopez, J., Willmott, E., Kay, J., Howell, D., and Simmonds, J. (2007). *Preparing for Climate Change: A Guidebook for Local, Regional, and State Governments*. Oakland, CA.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L. (2007). *IPCC 2007, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. *Environment*, New York, 996.

Springstead, D. M., Thomas, S., and Bruno, P. (2012). "Streamlining Assessment and Capital Planning with Standardization, Coordination and New Technologies." *9th National Conference on Transportation Asset Management*, Transportation Research Board, San Diego, CA.

SSFM International. (2011). *Oahu Metropolitan Planning Organization Transportation Asset Climate Change Risk Assessment Project*. Honolulu, Hawaii.

Stoner, A., Hayhoe, Katharine, and Yang, X. (2012). "A Modified Statistical Asynchronous Regression Downscaling Method." *USGS Geo Data Portal*, <http//cida.usgs.gov/climate/hayhoe_projections.jsp> (Aug. 22, 2012).

Stoner, A. M. K., Hayhoe, Katharine, Yang, X., and Wuebbles, D. J. (2012). "An asynchronous regional regression model for statistical downscaling of daily climate variables." *International Journal of Climatology*, n/a–n/a.

Sun, X., Zhang, Z., Wang, R., Wang, X., and Chapman, J. (2004). "Analysis of Past National Bridge Inventory Ratings for Predicting Bridge System Preservation Needs." *Transportation Research Record*, 1866(1), 36–43.

Thompson, A., Robbins, P., Sohngen, B., Arvai, J., and Koontz, T. (2006). "Economy, Politics and Institutions: From Adaptation to Adaptive Management in Climate Change." *Climatic Change*, 78(1), 1–5.

Tin, T. (2008). *Climate Change: Faster, Stronger, Sooner*. *Natural Hazards*, Brussels, Belgium.

TRB. (2007). "TRB Final Program Transportation Asset Management New Directions in Asset Management and Economic Analysis." *7th National Conference on Transportation Asset Management*, Transportation Research Board, Washington, D.C.

TRB. (2008). *Transportation Research Board Special Report 290 Potential Impacts of Climate Change on U.S. Transportation*. *TRB*, National Rsearch Council of the National Academies, Washington, D.C.

TRB. (2009). "TRB Final Program Putting the Asset Management." *8th National Conference on Transportation Asset Management*, Transportation Research Board, 1–24.

USDOT. (1999). *Asset Management Primer*. *Management*, Washington, D.C.

USDOT. (2007). *Asset Management Overview*. *Management*, Washington, D.C.

USDOT, and FHWA. (1996). *Asset Management, Advancing the State of the Art into the 21st Century through Public-Private Dialogue, FHWA-RD-97-046*. Washington, D.C.

Varma, S., and Proctor, G. (2012). *Risk-Based Asset Management Report 2: Managing Asset Risks at Multiple Levels in a Transportation Agency*. Washington, D.C.

Varma, S., and Proctor, G. (2013). *Risk-Based Transportation Asset Management Report 4: Managing Risks to Critical Assets*. Washington, D.C.

VDOT, UVA, VCTIR, HRPDC, and HRTPO. (2011). *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot*. Charlottesville, VA.

Vrac, M., Stein, M., and Hayhoe, K. (2007). "Statistical downscaling of precipitation through nonhomogeneous stochastic weather typing." *Climate Research*, 34, 169–184.

Wald, M. L., and Schwartz, J. (2012). "Weather Extremes Leave Parts of U.S. Grid Buckling." *The New York Times*, New York Ed., A4.

Wall, T. A., and Meyer, Micha. (2013). "Risk-Based Adaptation Frameworks for Climate Change Planning in the Transportation Sector: A Synthesis of Practice." *2013 Transportation Research Board Annual Meeting*, Transportation Research Board, Washington, D.C.

Webster, J. S., and Allan, N. D. (2005). "Best practice in advanced asset management systems for the highway sector in the." *Proceedings. 2005 IEEE International Engineering Management Conference, 2005.*, Ieee, 861–867.

Webster, P., O'Har, J. P., and Wall, T. A. (2012). "Climate Models Discussion." Personal Communication, Atlanta, GA.

Wegner, J., Potter, J., Neudorff, L., Seskin, S., and Prey, S. (2011). *Transportation Research Circular E-C152: Adapting Transportation to the Impacts of Climate Change*. Washington, D.C.

Winkelman, S., Mueller, J., and Jue, E. (2012). *Climate Adaptation & Transportation Identifying Information and Assistance Needs: Summary of an Expert Workshop held November 2011*. *Energy*, Washington, D.C.

Winkler, R. L. (1996). "Uncertainty in Probabilistic Risk Assessment." *Reliability Engineering and System Safety*, 54(2-3).

Wittwer, E., Mcneil, S., Zimmerman, K., and Bittner, J. (2003). *KEY FINDINGS FROM THE FIFTH NATIONAL WORKSHOP ON TRANSPORTATION ASSET MANAGEMENT*. *Transportation Research*, Madison, WI, 50.

Woolston, H. (n.d.). "Climate Change Adaptation for London's Transport System." *Transport*.

Zimmerman, K. A., and Sweet, L. A. (2005). “6th National Conference on Transportation Asset Management.” *Transportation Research Circular Number E-C093*, Transportation Research Board.

Zimmerman, R., and Faris, C. (2010). “New York City Panel on Climate Change 2010 Report Chapter 4: Infrastructure impacts and adaptation challenges.” *Annals of the New York Academy of Sciences*, New York, 63–85.