

# 1.0 Why Study Climate Change Impacts on Transportation?

Lead Authors: Robert C. Hyman, Joanne R. Potter, Michael J. Savonis, Virginia R. Burkett, and Jessica E. Tump

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

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

Four key questions guide this investigation:

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

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

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

## 16 ■ 1.1 The Climate is Changing

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1 information poses a major challenge to the scientific community: How can scientists  
2 effectively translate the findings of basic research into information that can be  
3 understood by other professions – and the general public – and be applied to the  
4 choices transportation managers need to make?

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

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

### 27 ■ **1.3 State of Science Regarding Climate Change Impacts on** 28 **Transportation**

29 What is the state of knowledge about climate change impacts on transportation? The  
30 research team undertook a review of the literature to assess the depth and breadth of  
31 existing research that specifically examines changes in climate and the resulting  
32 implications for transportation infrastructure and services. The technical report containing  
33 a full review and synthesis of can be found at: (forthcoming).

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

1 uneven; some aspects of climate change impacts on transportation have received much  
2 greater scrutiny than others depending on the particular concerns of individual authors and  
3 research sponsors.

### 4 **1.3.1 Overview of State of Practice**

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

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

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

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

1 In addition, some studies focused on specific urban areas (Kirsten et al., 2004; Suarez,  
2 2005; Greater London Authority, 2005).

3 • **Climate Zones Examined** – The literature does not examine all climate zones equally  
4 or in proportion to the amount of transportation infrastructure present. In particular,  
5 transportation in Arctic climates received substantial study, as warming impacts already  
6 are being observed in those regions. Many other studies looked at temperate climates,  
7 as in the United States or Europe. Australian studies were among the few that  
8 examined desert climates or hot climates. In addition, most of the literature focused on  
9 the industrialized world.

10 • **Timeframe Examined** – Most studies examined time horizons of 50- to 100-years into  
11 the future, consistent with the timescale of projections and scenarios often used in the  
12 climate literature. Though this is well beyond the 20- to 30-year planning horizons  
13 typically used in transportation planning, it was noted in the literature that some  
14 infrastructure (such as bridges) is designed with life expectancies of 100 years or more  
15 (Eddowess et al., 2003; Wooler, 2004; Norwell, 2004). Other researchers eschewed  
16 timescales and instead chose specific thresholds to consider. For instance, Marine  
17 Board (1987) chose to examine the impacts of 0.5, 1.0, and 1.5 meter rises in sea levels,  
18 without specifying a projected year for when these might take place. Finally, several  
19 Arctic studies focused on changes *presently* occurring, as in Grondin’s (2005) study of  
20 the effect of thawing permafrost on airfields and roads in Nunavik due to increasingly  
21 warmer winters.

### 22 1.3.2 Major Sponsors Conducting Related Research

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

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

35 Similarly, the U.S. National Assessment, which represents one of the broadest  
36 examinations of climate impacts to date in the U.S., did not include transportation as a  
37 sector of interest (National Assessment Synthesis Team, 2000). However, some of the  
38 regional studies conducted under the umbrella of the national assessment process did  
39 examine transportation impacts, most notably the Metro East Coast and Alaska studies  
40 (Zimmerman, 2002a; Weller et al., 1999). The 2002 DOT report, *The Potential Impacts of*



1 *Climate Change on Transportation: Summary and Discussion Papers*, contains 15  
2 discussion papers addressing potential climate impacts on various modes of transportation  
3 across the nation, and a summary of priority research needs identified.

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

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

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

### 30 **1.3.3 State of Technical Analysis**

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

---

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

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

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

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

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

1 increase the annual costs of flooding in the United Kingdom almost 15-fold by the  
2 2080s under high-emissions scenarios.

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

### 10 **1.3.4 Impacts, Assessment, and Adaptation**

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

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

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

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

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

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

### *Increasing Temperatures*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

## 6       *Environmental*

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

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

## 30      *Demographic*

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



1        ***Security***

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

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

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

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

27       ***Institutional Changes***

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

38 In addition, there are significant gaps in data collection and analysis for several modes and  
39 for transportation infrastructure in hot or tropical climates, such as are found in the

1 southwestern and southeastern portions of the United States. Most of the available  
2 literature addresses temperate or Arctic climates.

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

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

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

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

38 **Identifying Strategies for Adaptation and Planning.** Most studies dealt with adaptation  
39 from a facility engineering approach, rather than a strategic or systems performance level.  
40 Thus, it is largely specific design adaptations appropriate for particular types of facilities

1 that were identified in the literature (for instance, insulating railbeds to prevent permafrost  
2 melt, or raising roads to protect it against sea level rise).

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

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

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

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

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

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

### 1.5.1 Study Selection

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

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

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

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

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

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

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

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

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

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

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

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

36 [INSERT FIGURE 1.1 Gulf Coast Study Design]



### **1.5.3 Study Organization and Oversight**

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

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

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

### **1.5.4 Characterizing Uncertainty**

Some degree of uncertainty is inherent in any consideration of future climate change; further, the degree of certainty in climate projections varies for different aspects of future

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

9 [INSERT FIGURE 1.2 Uncertainty Lexicon]

## 10 ■ 1.6 References

11 **ABP Marine Environmental Research Ltd**, 2004: *Climate Change 2003 Port Template:*  
12 *Findings from the First Assessment*. Report Number R.1061, Associated British  
13 Ports – Head Office, March.

14 **Andrey, J.** and B.N. Mills, 2003: Chapter 9 – Climate Change and the Canadian  
15 Transportation System: Vulnerabilities and Adaptations. In: *Weather and*  
16 *Transportation in Canada* [Andrey, J. and C. Knapper (Eds.)], Department of  
17 Geography, University of Waterloo, Ontario, Canada.

18 **Barrett, Byrd Associates**, 2004: *Weathering The Changes. Transportation Professional*  
19 (Bba Linden House, Linden Close, Tunbridge Wells, Kent, United Kingdom),  
20 Volume 10, page 13.

21 **Black, W.R.**, 1990: *Global Warming: Impacts On The Transportation Infrastructure. TR*  
22 *News No. 150*, Transportation Research Board, pages 2-8, 34.

23 **Brennan, D.**, U. Akpan, I. Konuk, and A. Zebrowski, 2001: *Random Field Modeling of*  
24 *Rainfall Induced Soil Movement*. Geological Survey of Canada, February.

25 **Board on Atmospheric Sciences and Climate (BASC)**, 2004. *Where the Weather Meets*  
26 *the Road: A Research Agenda for Improving Road Weather Service*. National  
27 Academies Press, Washington, D.C.

28 **Brigham, L.** and B. Ellis (Eds.), 2004. *Arctic Marine Transport Workshop: September*  
29 *28-30*. Held at Scott Polar Research Institute, Cambridge University, United Kingdom  
30 Hosted by: Arctic Research Committee, Arlington, Virginia. Institute of the North,  
31 Anchorage, Alaska, and International Arctic Science Committee, Oslo, Norway.  
32 Northern Printing, Anchorage Alaska.

33 **Brown, J.L.**, 2005: *Cold Region Design: High-Altitude Railway Designed to Survive*  
34 *Climate Change. Civil Engineering – ASCE*, Volume 75, Number 4, April, page 28.

- 1 **Burkett, V.R.**, 2002: Potential Impacts Of Climate Change And Variability On  
2 Transportation in the Gulf Coast/Mississippi Delta Region. In: *The Potential Impacts*  
3 *of Climate Change on Transportation Workshop, October 1-2, 2002*. Washington,  
4 D.C.
- 5 **Caldwell, H., K.H. Quinn, J. Meunier, J. Suhrbier, and L. Grenzeback**, 2002: Potential  
6 Impacts Of Climate Change On Freight Transport. In: *The Potential Impacts of*  
7 *Climate Change on Transportation Workshop, October 1-2, 2002*. Washington, D.C.
- 8 **Cheng, G.**, 2005: Permafrost Studies in the Qinghai-Tibet Plateau for Road Construction.  
9 *Journal of Cold Regions Engineering*. Volume 19, Number 1, pages 19-29.
- 10 **Choo, K.** 2005: Heat Wave. *Planning*. Volume 71, Number 8, August, pages 8-13.
- 11 **Clayton, A., Montufar, J., Regeher, J., Isaacs, C. and McGregor, R.**, 2005: *Aspects of the*  
12 *Potential Impacts of Climate Change on Seasonal Weight Limits and Trucking in the*  
13 *Prairie Region*. Climate Change Impacts and Adaptation Directorate, Natural  
14 Resources Canada, June.
- 15 **Climate Risk Management** and Metroeconomica, 2005: *Financial Risks of Climate*  
16 *Change – Summary Report*. The Association of British Insurers (ABI), June.
- 17 **Committee on Engineering Implications of Change in Realitive Mean Sea Level**, 1987:  
18 *Responding to Changes in Sea Level – Engineering Implications*. Marine Board  
19 Commission on Engineering and Technical Systems, National Research Council,  
20 National Academy Press, Washington, D.C.
- 21 **D’Arcy, P.** 2004: *Response Strategy to maintain shipping and port activities in the face of*  
22 *climate change – reduced water levels in the Great Lakes/St. Lawrence Seaway*.  
23 Navigation Consensus Building Committee, Transport Canada.
- 24 **Dewar, J.A. and M. Wachs**, 2006: *Transportation Planning, Climate Change, and*  
25 *Decision-Making Under Uncertainty*. Draft Working Paper. The National Research  
26 Council, National Academy of Science, Transportation Research Board DELS Study,  
27 October.
- 28 **Dlugolecki, A.**, 2004: *A Changing Climate for Insurance – A Summary Report for Chief*  
29 *Executives and Policy-Makers*. The Association of British Insurers (ABI), June.
- 30 **DuVair, P., D. Wickizer and M.J. Burer**, 2002: Climate Change and the Potential  
31 Implications for California’s Transportation System. In: *The Potential Impacts of*  
32 *Climate Change on Transportation Workshop, October 1-2, 2002*. Washington, D.C.
- 33 **Easterling, D.R.**, 2002: Observed Climate Change And Transportation. In: *The Potential*  
34 *Impacts of Climate Change on Transportation Workshop, October 1-2, 2002*.  
35 Washington, D.C.

- 1       **Easterling, W. III, B.H. Hurd, J.B. Smith, 2004:** *Coping with Global Climate Change:  
2           The Role of Adaptation in the United States.* Pew Center on Global Climate Change.  
3           June.
- 4       **Eddowess, M.J., D. Waller, P. Taylor, B. Briggs, T. Meade, and I. Ferguson, 2003:** *Rail  
5           Safety Implications of Weather, Climate and Climate Change: Final Report.* Rail  
6           Safety and Standards Board, United Kingdom, March.
- 7       **Entek U.K. Limited, 2000:** *The Potential Impacts of Climate Change on the East  
8           Midlands – Summary Report.* East Midlands Sustainable Development Round Table,  
9           Warwickshire, England, July.
- 10       **Entek U.K. Limited, 2004:** *The Potential Impacts of Climate Change in the West  
11           Midlands.* Sustainability West Midlands, United Kingdom, January.
- 12       **Frey, H.C. 2006:** *Incorporating Risk and Uncertainty into the Assessment of Impacts of  
13           Global Climate Change on Transportation Systems.* Draft, Submitted for  
14           consideration for publication and presentation at the 2<sup>nd</sup> Workshop on Impacts of  
15           Global Climate Change On Hydraulics and Hydrology and Transportation March 27,  
16           2006, Washington, D.C.
- 17       **Greater London Authority, 2005:** *Climate Change and London’s Transport Systems:  
18           Summary Report.* London, United Kingdom, September.
- 19       **Grenzeback, L.R. and A.T. Lukmann, 2006:** *Case Study of the Transportation Sector’s  
20           Response to and Recovery from Hurricanes Katrina and Rita.* Draft Working Paper.  
21           The National Research Council, National Academy of Science, Transportation  
22           Research Board and Department of Earth and Life Sciences Study, October.
- 23       **Grondin, G. 2005:** Impact of Permafrost Thaw on Airfield and Road Infrastructures in  
24           Nunavik, Quebec. *Routes = Roads*, Number 326, pages 42-49.
- 25       **Haas, R., L.C. Falls, D. Macleod, and S. Tighe, 2006:** Climate Impacts And Adaptation  
26           On Roads in Northern Canada. In: *Transportation Research Board 85<sup>th</sup> Annual  
27           Meeting*, Washington, D.C. January 22, page 19.
- 28       **Hyman, W., T.R. Miller, J.C. Walker, 1989:** Impacts of the Greenhouse Effect on Urban  
29           Transportation. *Transportation Research Record 1240.* Transportation Research  
30           Board, National Research Council, Washington, D.C., pages 45-50.
- 31       **Instanes, A., O. Anisimov, L. Brigham, D. Goering, L.N. Khrustalev, B. Ladanyi, J. Otto  
32           Larsen, O. Smith, A. Stevermer, B. Weatherhead, G. Weller, 2005:** Chapter 16 –  
33           Infrastructure: Buildings, Support Systems, and Industrial Facilities, In: *Arctic  
34           Climate Impact Assessment*, Cambridge University Press, 1042p.
- 35       **Institute for Water Resources, 2005:** *Climate Impacts on Inland Waterways (Final  
36           Report).* Report to U.S. Department of Transportation. Institute for Water Resources,  
37           U.S. Army Corps of Engineers, Alexandria, Virginia. July.

- 1 **Intergovernmental Panel on Climate Change (IPCC)**, 1996: *Climate Change 1995:*  
2 *Impacts, Adaptations, and Mitigation of Climate Change.* IPCC. Cambridge  
3 University Press, Cambridge, United Kingdom.
- 4 **Intergovernmental Panel on Climate Change (IPCC)**, 2001: *Climate Change 2001:*  
5 *Impacts, Adaptations, and Vulnerability.* IPCC. Cambridge Press. New York, New  
6 York.
- 7 **Intergovernmental Panel On Climate Change (IPCC)**, 2007, *Climate Change 2007:*  
8 *The Physical Science Basis, Summary for Policy-Makers, Contribution of Working*  
9 *Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate*  
10 *Change,* IPCC. Cambridge Press. New York, New York, February
- 11 **Irwin**, N.A. and W.F. Johnson, 1990: Implications of Long-Term Climatic Changes for  
12 Transportation in Canada. *Transportation Research Record*, Number 1267, pages  
13 12-25.
- 14 **Johnston**, D.M., 2002: The Northwest Passage Revisited. *Ocean Development &*  
15 *International Law.* April-June, Volume 33, Issue 2, pages 145-164.
- 16 **Karl**, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray, eds., 2006: *Temperature Trends in*  
17 *the Lower Atmosphere: Steps for Understanding and Reconciling Differences.* U.S.  
18 Climate Change Science Program, Synthesis and Assessment Product 1.1,  
19 Washington, D.C., page 164.
- 20 **Kerr**, A. and A. McLeod, 2001: *Potential Adaptation Strategies for Climate Change in*  
21 *Scotland.* Scottish Executive Central Research Unit, Scotland, U.K.
- 22 **Kerr**, A., S. Schackley, R. Milne, and S. Allen, 1999: *Climate Change: Scottish*  
23 *Implications Scoping Study.* The Scottish Executive Central Research Unit, Scotland,  
24 U.K.
- 25 **Kinsella**, Y. and F. McGuire, 2005: *Climate Change Uncertainty and the State Highway*  
26 *Network: A moving target.* Transit New Zealand, Auckland, New Zealand.
- 27 **Kirshen**, P.H., M. Ruth, W. Anderson, and T.R. Lakshmanan, 2004: *Infrastructure*  
28 *Systems, Services, and Climate Change: Integrated Impacts and Response Strategies*  
29 *for the Boston Metropolitan Area (CLIMB Final Report).* U.S. Environmental  
30 Protection Agency, Washington, D.C., August 13.
- 31 **Land Use Consultants**, CAG Consultants, and SQW Ltd., 2002: *Living with Climate*  
32 *Change in the East of England Summary Report.* East of England Sustainable  
33 Development Round Table, England, U.K., September.
- 34 **Lockwood**, S., 2006: *Operational Responses to Climate Change.* Draft Working Paper.  
35 The National Research Council, National Academy of Science, Transportation  
36 Research Board DELS Study, October.

- 1       **Lonergan, S., R. Difrancesco and M.-K. Woo, 1993:** Climate Change and Transportation  
2             in Northern Canada: An Integrated Impact Assessment. *Climate Change*, 24:4,  
3             August, pages 331-352.
- 4       **Marbek Resource Consultants Ltd., 2003:** *Impacts of Climate Change on*  
5             *Transportation in Canada – Transport Canada Canmore Workshop – Final Report.*  
6             Transport Canada, March.
- 7       **Marine Board, 1987:** *Responding to Changes in Sea Level – Engineering Implications.*  
8             Washington, D.C, National Academy Press, page 148.
- 9       **McRobert, J., N. Houghton and E. Styles, 2003:** Salinity impacts and roads – towards a  
10            dialogue between climate change and groundwater modelers. *Road and Transport*  
11            *Research.* Volume 12, Number 3, September, pages 45-60.
- 12       **Meyer, M.D., 2006:** *Design Standards for U.S. Transportation Infrastructure: The*  
13            *Implications of Climate Change.* Draft Working Paper. The National Research  
14            Council, National Academy of Science, Transportation Research Board DELS Study,  
15            October.
- 16       **Mills, B. and J. Andrey, 2002:** Climate Change And Transportation: Potential Interactions  
17            And Impacts. In: *The Potential Impacts of Climate Change on Transportation*  
18            *Workshop, October 1-2, 2002.* Washington, D.C.
- 19       **Ministry of Housing, Spatial Planning, and the Environment, 2001:** *Third*  
20            *Netherlands’ National Communication on Climate Change Policies: Prepared for the*  
21            *Conference of the Parties under the Framework Convention on Climate Change.*  
22            Directorate Climate Change and Industry/IPC 650, Climate Change and Acidification  
23            Department, October, pages 79-80.
- 24       **National Assessment Synthesis Team, 2000:** *Climate Change Impacts on the United*  
25            *States: The Potential Consequences of Climate Variability and Change.* U.S. Global  
26            Change Research Program, Cambridge University Press, New York.
- 27       **Ning, Z.H., R.E. Turner, T. Doyle, and K. Abdollahi, 2003:** *Integrated Assessment of the*  
28            *Climate Change Impacts on the Gulf Coast Region: Findings of the Gulf Coast*  
29            *Regional Assessment.* Report for the U.S. Global Change Research Program, GCRCC,  
30            Baton Rouge, Louisiana. June
- 31       **Norwell, G., 2004:** *Impact of Climate Change on Road Infrastructure.* Austroads Inc.,  
32            Sydney, Australia.
- 33       **Office of Naval Research, Naval Ice Center, Oceanographer of the Navy, and the Arctic**  
34            **Research Commission, 2001:** *Naval Operations in an Ice-Free Arctic Symposium,*  
35            *17-18 April 2001,* Washington, D.C. Office of Naval Research. Department of the  
36            Navy, Arlington, Virginia.

- 1 **Olsen, J.R., L.J. Zepp and C. Dager, 2005:** Climate Impacts on Inland Navigation.  
2 Conference Proceeding: Environmental and Water Resources Institute of ASCE:  
3 Impacts of Global Climate Change.
- 4 **Peterson, T., M. McGuirk, T. Houston, A. Horvitz and M. Wehner, 2006:** *Climate*  
5 *Variability and Change with Implications for Transportation.* Draft Working Paper.  
6 The National Research Council, National Academy of Science, Transportation  
7 Research Board DELS Study, October.
- 8 **Pisano, P., L. Goodwin, and A. Stern, 2002:** Surface Transportation Safety and  
9 Operations: The Impacts Of Weather Within The Context Of Climate Change. In:  
10 *The Potential Impacts of Climate Change on Transportation Workshop, October 1-2,*  
11 *2002.* Washington, D.C.
- 12 **Potter, J.R., 2002:** Workshop Summary. In: *The Potential Impacts of Climate Change on*  
13 *Transportation Workshop, October 1-2, 2002.* Washington, D.C.
- 14 **Potter, J.R. and M.J. Savonis, 2003:** Transportation in an Age of Climate Change: What  
15 are the Research Priorities? *TR News*, 227, July-August, 26-31.
- 16 **Quinn, F.H., 2002:** The Potential Impacts Of Climate Change On Great Lakes  
17 Transportation. In: *The Potential Impacts of Climate Change on Transportation*  
18 *Workshop, October 1-2, 2002.* Washington, D.C.
- 19 **Rosenzweig, C. and W.D. Solecki (Eds.), 2001:** *Climate Change and Global City: The*  
20 *Potential Consequences of Climate Variability and Change – Metro East Coast.*  
21 Report for the U.S. Global Change Research Program, National Assessment of the  
22 Potential Consequences of Climate Variability and Change for the United States,  
23 Columbia Earth Institute, New York, 224 pp.
- 24 **Rossetti, M.A., 2002:** Potential Impacts Of Climate Change On Railroads. In: *The*  
25 *Potential Impacts of Climate Change on Transportation Workshop, October 1-2, 2002.*  
26 Washington, D.C.
- 27 **Rossiter, L., 2004:** *Climate Change Impacts on the State Highway Network: Transit New*  
28 *Zealand's Position.* Transit New Zealand, Auckland, New Zealand, July.
- 29 **Ruth, M. (Ed.), 2006:** *Smart Growth and Climate Change: Regional Development,*  
30 *Infrastructure and Adaptation.* Edward Elgar Publishing, Cheltenham, United  
31 Kingdom.
- 32 **Sato, N. and S.M. Robeson, 2006:** Climate Change and Its Potential Impact on Winter-  
33 Road Maintenance: Temporal Trends in Hazardous Temperature Days in the United  
34 States And Canada. In: *TRB 85<sup>th</sup> Annual Meeting*, January 22, 2006, Washington,  
35 D.C., page 13.

- 1 **Smith, O.P.** and G. Levasseur, 2002: Impacts Of Climate Change On Transportation  
2 Infrastructure in Alaska. In: *The Potential Impacts of Climate Change on*  
3 *Transportation Workshop, October 1-2, 2002.* Washington, D.C.
- 4 **Smith, O.**, 2006: *Trends in Transportation Maintenance Related to Climate Change.*  
5 Paper presented to the Climate Change Workshop, Center for Transportation and  
6 Environment, Washington, D.C: March 29.
- 7 **Smyth, A.**, W.I. Montgomery, D. Favis-Mortlock, and S. Allen (Eds.), 2002: *Implications*  
8 *of Climate Change for Northern Ireland: Informing Strategy Development.* Scotland  
9 and Northern Ireland Forum for Environmental Research (SNIFFER).
- 10 **Soo Hoo, W.K.**, M. Sumitani, and S. Cohen, 2005: *Climate Change Will Impact the*  
11 *Seattle Department of Transportation.* City of Seattle, Office of City Auditor, Seattle,  
12 Washington, August 9.
- 13 **Sousounis, P.J.** and J.M. Bisanz (Eds.), 2000: *Preparing for a Changing Climate: The*  
14 *Potential Consequences of Climate Variability and Change Great Lakes Overview.*  
15 Report for the U.S. Global Change Research Program. October.
- 16 **Struck, D.**, 2006: Melting Arctic Makes Way for Man: Researchers Aboard Icebreaker  
17 Say Shipping Could Add to Risks for Ecosystem. *Washington Post*, November 5,  
18 page A01.
- 19 **Suarez, P.**, W. Anderson, V. Mahal, T.R. Lakshmanan, 2005: *Impacts of Flooding and*  
20 *Climate Change on Urban Transportation: A Systemwide Performance Assessment of*  
21 *The Boston Metro Area.* Elsevier Transportation Research Part D 10. Pages 231-244.
- 22 **Three Regions Climate Change Group**, 2005: *Consultation Document – Adapting to*  
23 *Climate Change: A Checklist for Development, Guidance on Designing Developments*  
24 *in a Changing Climate.* London, United Kingdom, February.
- 25 **Titus, J.**, 2002: Does Sea Level Rise Matter To Transportation Along The Atlantic Coast?  
26 In: *The Potential Impacts of Climate Change on Transportation Workshop,*  
27 *October 1-2, 2002.* Washington, D.C.
- 28 **Trilling, D.R.**, 2002: Notes on Transportation into the Year 2025. In: *The Potential*  
29 *Impacts of Climate Change on Transportation Workshop, October 1-2, 2002.*  
30 Washington, D.C.
- 31 **U.S. Arctic Research Commission Permafrost Task Force**, 2003: *Climate Change,*  
32 *Permafrost, and Impacts on Civil Infrastructure.* Special Report 01-03, U.S. Arctic  
33 Research Commission, Arlington, Virginia.
- 34 **U.S. Department of State**, 2002: Chapter 6: Impacts and Adaptation. In: *U.S. Climate*  
35 *Action Report 2002.* Washington, D.C., May.



- 1 **U.S. Federal Highway Administration (FHWA)**, 1998: *Transportation and Global*  
2 *Climate Change: A Review and Analysis of the Literature*. Office of Environment and  
3 Planning, Federal Highway Administration, U.S. Department of Transportation,  
4 Washington, D.C. June.
- 5 **Wagner**, F.H. (Ed. and Principal Author), 2003: *Rocky Mountain/Great Basin Regional*  
6 *Climate-Change Assessment*. Report for the U.S. Global Change Research Program.  
7 Utah State University, Logan, Utah: IV + 240 pages.
- 8 **Warren**, F., E. Barrow, R. Schawartz, J. Andrey, B. Mills, D. Riedel, 2004: *Climate*  
9 *Change Impacts and Adaptation: A Canadian Perspective*, [Lemmen, D.S. and F.J.  
10 Warren, eds.]. Climate Change Impacts and Adaptation Directorate Natural Resources  
11 Canada. Ottawa, Ontario.
- 12 **Weller**, G., P. Anderson, and B. Wang, 1999: *Preparing for a Changing Climate – The*  
13 *Potential Consequences of Climate Variability and Change: Alaska*. Report for the  
14 U.S. Global Change Research Program, Center for Global Change and Arctic System  
15 Research, Fairbanks, Alaska, December.
- 16 **Wilkinson**, R., 2002: *Preparing for a Changing Climate – The Potential Consequences of*  
17 *Climate Variability and Change. A Report of the California Regional Assessment*  
18 *Group*. Report for the U.S. Global Change Research Program, September.
- 19 **Wooler**, S., 2004: *The Changing Climate: Impact on the Department for Transport*.  
20 Department for Transport, London, United Kingdom.
- 21 **Wright**, F., C. Duchesne, F.M. Nixon, and M. Cote, 2001: *Ground Thermal Modeling in*  
22 *Support of Terrain Evaluation and Route Selection in the Mackenzie River Valley –*  
23 *Summary Report*. Geological Survey of Canada, August.
- 24 **Wu**, S.-Y., B. Yarnal, and A. Fisher, 2002: Vulnerability of Coastal Communities to Sea  
25 Level Rise: A Case Study of Cape May County, New Jersey, USA. *Climate Research*  
26 22, 255-270.
- 27 **Zimmerman**, R., 2002a: Global Climate Change and Transportation Infrastructure:  
28 Lessons from the New York Area. In: *The Potential Impacts of Climate Change on*  
29 *Transportation Workshop, October 1-2, 2002*. Washington, D.C.
- 30 **Zimmerman**, R., 2002b: Global Warming, Infrastructure, and Land Use in the  
31 Metropolitan New York Area: Prevention and Response. In: *Global Climate Change*  
32 *and Transportation: Coming to Terms*. Eno Transportation Foundation, pages 55-63.

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

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Temperature Increase</i>				
<b>Increased Summer Temperatures</b>	Highway asphalt rutting		Proper design/construction, milling out ruts, more maintenance, overlay with more rut resistant asphalt	1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Hass, et al. 2006. 4) Black, William. 1990. 5) Meyers, Michael. 2006. 6) Barrett, et al. 2004. 7) Marbek Resource Consultants Ltd. 2003. 8) Kerr, Andrew, et al. 1999. 9) Warren, et al. 2004. 10) Entek U.K. Limited. 2000. 11) Entek U.K. Limited. 2004. 12) Lockwood, Steve. 2006. 13) Kinsella, Y. and McGuire, E. 2005. 14) Mills and Andrey. 2002.
	Rail buckling	Speed restrictions could increase travel time	Speed restrictions, reducing frequency of some services, better air conditioning for signals	1) Wooler, Sarah. 2004. 2) Eddowes, M.J., et al. 2003. 3) Kerr, Andrew, et al. 1999. 4) Warren, et al. 2004. 5) Entek U.K. Limited. 2000. 6) Land Use Consultants, et al. 2002. 7) Smyth, et al. 2002. 8) Kerr, Andy. 2001. 9) Entek U.K. Limited. 2004. 10) Rossetti. 2002.
	More airport runway length and fuel needed because of less dense air		New planes designed to takeoff more efficiently	1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Irwin and Johnson. 1990. 4) Warren, et al. 2004. 5) Entek U.K. Limited. 2000. 6) Smyth, et al. 2002. 7) Entek U.K. Limited. 2004.
	Heat/Lack of ventilation on London Underground	Overcrowding, failed, or delayed service will only compound the problem. Could cause passengers to avoid taking public transportation (mode shift)	Install better ventilation systems	1) Wooler, Sarah. 2004. 2) Greater London Authority. 2005.

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

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Temperature Increase (continued)</i>				
	Low water levels on inland waterways	Increased shipping costs; shift to other modes (rail, truck)	Changes to navigation, dredging of channels, flow augmentation	1) Wooler, Sarah. 2004. 2) Andrey and Mills. 2003. 3) Olsen, et al. 2005. 4) Black, William. 1990. 5) Irwin and Johnson. 1990. 6) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 7) U.S. Department of State. 2002. 8) Institute for Water Resources, U.S. Army Corps of Engineers. 2004. 9) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000. 10) National Assessment Synthesis Team. 2000. 11) Marbek Resource Consultants Ltd. 2003. 12) D'Arcy, Pierre. 2004. 13) Warren, et al. 2004. 14) Entek U.K. Limited. 2000. 15) Ministry of Housing, Spatial Planning, and the Environment, The Netherlands. 2001. 16) Ruth, Matthais. 2006. 17) Quinn. 2002.
	Thermal expansion of bridges	Frequent detours, traffic disruptions	Increased ongoing maintenance	1) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005.
	Overheating of diesel engines		Adaptation of cooling systems	1) Entek U.K. Limited. 2000.
	Increased vegetation – leaf fall	Ineffective braking of rail cars, visual obstruction	Vegetation management, plant low-maintenance vegetation as buffer	1) Wooler, Sarah. 2004. 2) Eddowes, M.J., et al. 2003. 3) Land Use Consultants, et al. 2002. 4) Smyth, et al. 2002. 5) Kerr, Andy. 2001. 6) Entek U.K. Limited. 2004. 7) Kinsella, Y. and McGuire, E. 2005.
	Changes to landscape/biodiversity	Highway agency owns many medians. Increased pest management. Impact on wetlands commitments	Different types of vegetation may have to be considered	1) Wooler, Sarah. 2004. 2) Kinsella, Y. and McGuire, E. 2005. 3) Mortenson and Bank. 2002.

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

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

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

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

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

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<b>Precipitation Increase(continued)</b>				
<b>Increased Precipitation and Increased Summer Temperatures</b>	Highway, rail, and pipeline embankments at risk of subsidence/ heave	Landslides	Fill cracks and carry out more maintenance	1) Wooler, Sarah. 2004. 2) Instanes et al.. 2005. 3) Cohen, Susan, Soo Hoo, Wendy K., and Sumitani, Megumi. 2005. 4) Wilkenson, Robert. 2002. 5) Weller, Gunter, et al. 1999. 6) Eddowes, M.J., et al. 2003. 7) Konuk, Ibrahim. 2005. 8) Marbek Resource Consultants Ltd. 2003. 9) Kerr, Andrew, et al. 1999. 10) Warren, et al. 2004. 11) Entek U.K. Limited. 2000. 12) Land Use Consultants, et al. 2002. 13) Smyth, et al. 2002. 14) Entek U.K. Limited. 2004. 15) Kinsella, Y. and McGuire, E. 2005. 16) Rossiter, Lisa. 2004. 17) duVair et al. 2002.
	Concrete deterioration			1) Wooler, Sarah. 2004. 2) U.S. Department of State. 2002.
	More frequent and larger slush-flow avalanches (Arctic)		Incorporate potential risk into planning process for new settlements, detection systems, temporary closures	1) Instanes et al.. 2005. 2) Marbek Resource Consultants Ltd. 2003. 3) Warren, et al. 2004. 4) Stethem, Chris, et al. 2003.
	Altered runoff patterns (Arctic)	Disruption of the ice-water balance		1) Instanes et al.. 2005.
<b>Glacial Melting/Thermal Expansion of Oceans</b>				
<b>Sea Level Rise</b>	Erosion of coastal highways		Construction of sea walls	1) Wooler, Sarah. 2004. 2) Black, William. 1990. 3) U.S. Federal Highway Administration Office of Environment and Planning. 1998. 4) Marbek Resource Consultants Ltd. 2003. 5) Norwell, Gary. 2004. 6) Kinsella, Y. and McGuire, E. 2005. 7) Ruth, Matthais. 2006. 8) Hyman, William, et al. 1989. 9) Titus, 2002.

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

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

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

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



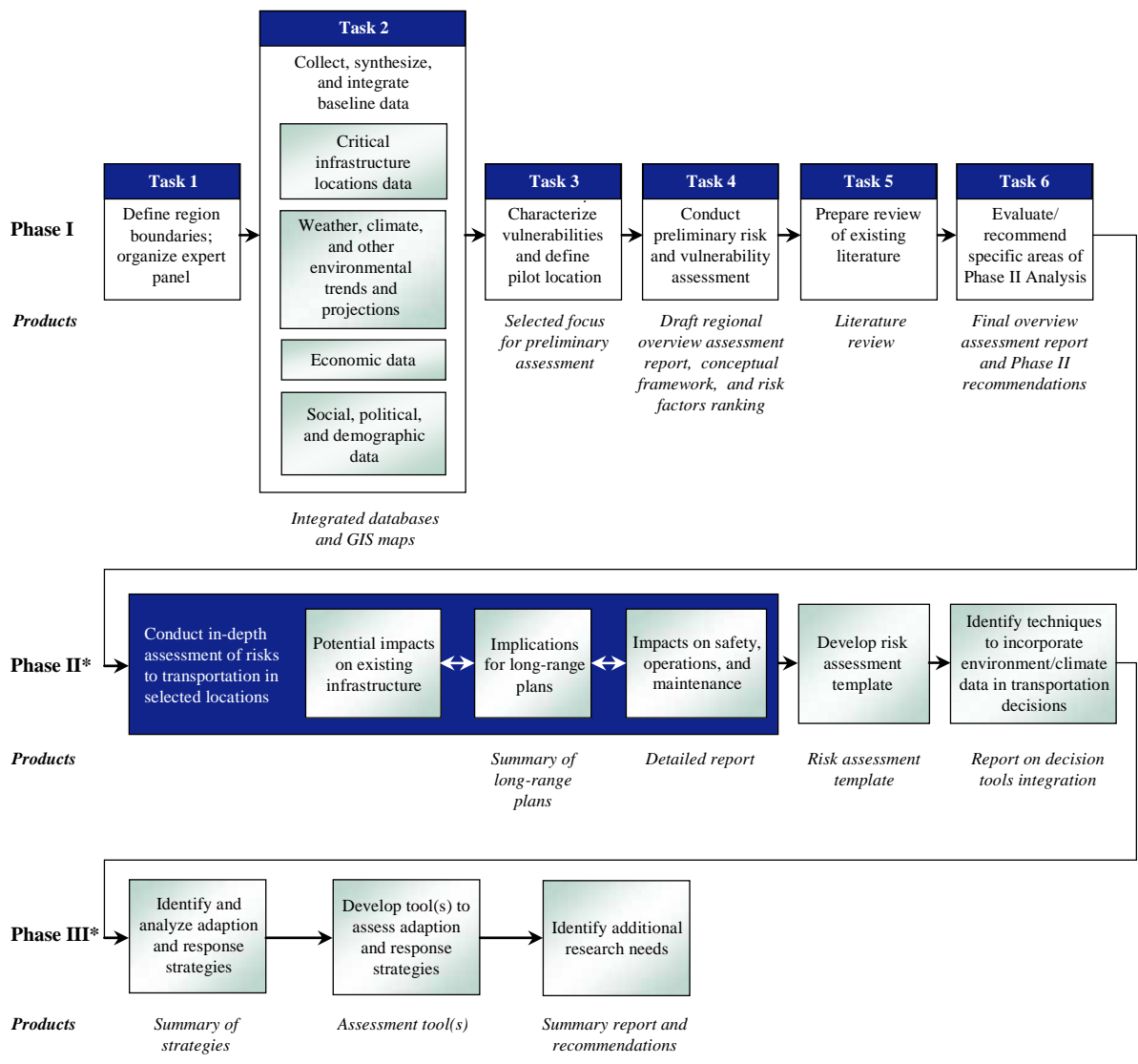
**Table 1.1 Impacts of climate change on transportation identified in the literature, 1987-2006. (continued)**

Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Storm Activity (continued)</i>				
<b>Lightning/Electrical Disturbance</b>	Disruption to transportation electronic infrastructure, signaling, etc.	Unknown	Unknown	1) Wooler, Sarah. 2004. 2) Eddowes, M.J., et al. 2003.
<b>Fewer Winter Storms</b>	Less snow/ice for all modes	Improved mobility/safety, reduced maintenance costs, less pollution from salt, decrease in vehicle corrosion		1) Andrey and Mills. 2003. 2) Black, William. 1990. 3) Irwin and Johnson. 1990. 4) Intergovernmental Panel on Climate Change. 2001. 5) Barrett, et al. 2004. 6) Marbek Resource Consultants Ltd. 2003. 7) Kerr, Andrew, et al. 1999. 8) Warren, et al. 2004. 9) Entek U.K. Limited. 2000. 10) Land Use Consultants, et al. 2002. 11) Entek U.K. Limited. 2004. 12) Wooler, Sarah. 2004. 13) Kinsella, Y. and McGuire, E. 2005. 14) Hyman, William, et al. 1989. 15) Pisano et al. 2002.
<i>Ice Melting</i>				
<b>Reduced Ice Cover (Canada, Alaska, Great Lakes)</b>	Reduced ice loading on structures, such as bridges or piers			1) Instanes et al.. 2005.
	New northern shipping routes	Shorten shipping distance and delivery time, security concerns, environmental risks, law-diplomacy issues, Inuit unease	Develop a "transit management regime" for area	1) Instanes et al.. 2005. 2) Johnston, Douglas. 2002. 3) Brigham, Lawson and Ben Ellis, Eds. 2004. 4) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001. 5) National Assessment Synthesis Team. 2000. 6) Marbek Resource Consultants Ltd. 2003. 7) Warren, et al. 2004. 8) Smith and Levasseur. 2002. 9) Caldwell et al. 2002.
		Lengthened season for float planes		1) Black, William. 1990. 2) Irwin and Johnson. 1990.

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

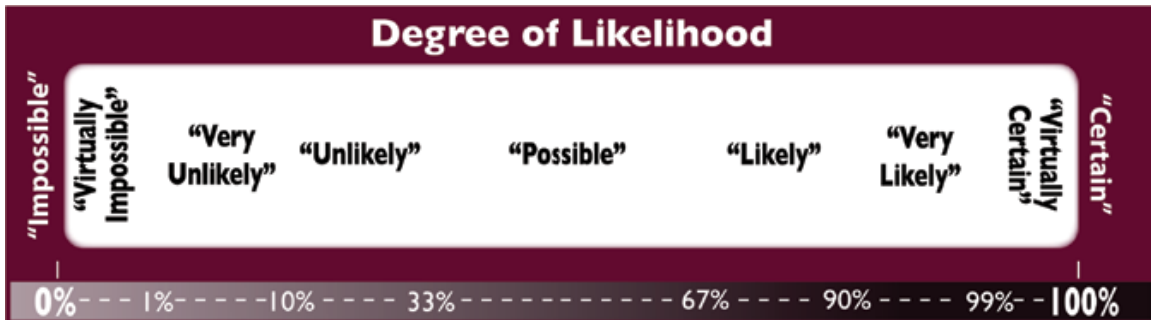
Climate Impact	Potential Infrastructure Impact	Potential Operations Impact	Adaptation	Source
<i>Ice Melting (continued)</i>				
		Longer shipping season		<ol style="list-style-type: none"> <li>1) Wooler, Sarah. 2004.</li> <li>2) Andrey and Mills. 2003.</li> <li>3) Black, William. 1990.</li> <li>4) Irwin and Johnson. 1990.</li> <li>5) U.S. Federal Highway Administration Office of Environment and Planning. 1998.</li> <li>6) Sousounis, Peter J. and Jeanne M. Bisanz, Eds. 2000.</li> <li>7) National Assessment Synthesis Team. 2000.</li> <li>8) Warren, et al. 2004.</li> <li>9) Ruth, Matthais. 2006.</li> <li>10) Caldwell et al. 2002.</li> </ol>
	Multi-year ice, in low concentrations, will be hazard to ships and naval submarines		New ship/submarine design or modifications	<ol style="list-style-type: none"> <li>1) Brigham, Lawson and Ben Ellis, Eds. 2004.</li> <li>2) Office of Naval Research, Naval Ice Center, Oceanographer of the Navy. 2001.</li> </ol>
<b>Earlier River Ice Breakup (U.S., Canada)</b>	Ice-jam flooding risk			<ol style="list-style-type: none"> <li>1) Instanes et al.. 2005.</li> <li>2) Hass, et al. 2006.</li> <li>3) Smith and Levasseur. 2002.</li> </ol>

**Figure 1.1 Gulf Coast Study Design**



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

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



Source: Karl *et al.* 2006.