

DOT Center for Climate Change and Environmental Forecasting

The Potential Impacts of Climate Change on Transportation

Federal Research Partnership Workshop

October 1-2, 2002

Summary and Discussion Papers

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U.S. Department of Transportation Center for Climate Change and Environmental Forecasting

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The opinions expressed in the discussion papers are those of the authors and do not necessarily represent the views of the U.S. Department of Transportation.

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Foreword



**U.S. Department of
Transportation**

Office of the Secretary
of Transportation

Assistant Secretary

400 Seventh St., SW
Washington, DC 20590

Dear Colleagues:

Climate change and climate variability are of great consequence to transportation. The workshop described in this report focused on the increasingly important issue of how future climate change might affect transportation, in contrast to other U.S. Department of Transportation efforts focused on how the transportation community might reduce greenhouse gas emissions.

Our national transportation network is key to our Nation's economic vitality and to the ability of individuals and families to lead full and productive lives. Local, State, and regional agencies work hard to ensure that communities and businesses have a safe and reliable transportation system that gets them where they need to go – whether that be across town or across the country. Meeting the country's future needs for this vast intermodal infrastructure requires thoughtful planning, close work with communities and industry, and the best information and data we can gather about past trends and what the future may hold.

The prospect of a changing climate adds a new element to this complex equation. Climate scientists are projecting changes in sea levels, weather patterns, temperatures, and other climate variables that could affect transportation decisions. The *Potential Impacts of Climate Change on Transportation* research workshop brought together top transportation professionals and climate change experts to explore what is known about the interaction between climate change and transportation, and to identify the key research questions needed to better understand the potential risks to our transportation system. The recommendations generated by workshop participants will be invaluable to the Department of Transportation, and to the broader research community, as we pursue research on this critical topic.

Sincerely,

Emil Frankel
Assistant Secretary for
Transportation Policy

Part 1: Workshop Summary

Workshop Summary

By **Joanne R. Potter**

In October 2002 the U.S. Department of Transportation Center for Climate Change and Environmental Forecasting (the Center) hosted a workshop of leading experts and decision makers in transportation and climate change. The purpose was twofold: to discuss the potential impacts of climate change on transportation, and to gain input and perspectives on the research necessary to better understand these impacts. The workshop marked a new area of investigation for the Center, which, since its creation in 1998, has concentrated on understanding and mitigating the effects of transportation on our global climate. The Center is now expanding its research to consider the implications a changing climate might have for the future of transportation and how the transportation community might be better prepared to avoid or adapt to any potential impacts.

The Center enlisted the support of key Federal partners in this effort: the Environmental Protection Agency, the Department of Energy, and the U.S. Global Change Research Program (under the auspices of the U.S. Climate Change Science Program). An interagency working group provided technical support and guidance to the Department of Transportation and was instrumental in the workshop's success.

The *Potential Impacts of Climate Change on Transportation Research Workshop* was held October 1-2, 2002, at the Brookings Institution in Washington D.C. The sixty-four invited participants included transportation professionals, regional and national stakeholders, and experts in climate change and assessment research, the environment, planning, and energy (Table 1). Appendix A provides a complete list of participants and their affiliations. Throughout the day and a half long event, participants explored the key challenges climate change may pose for transportation in specific regions and for specific modes, and identified priority areas for research, through interdisciplinary breakout sessions.

This report provides a summary of the workshop and the research recommendations generated by participants. This summary is followed by eighteen discussion papers that address various aspects of the relationship between climate change and transportation, and suggest opportunities for further study.

Table 1. Workshop participants.

U.S. Federal Agencies	
U.S. Climate Change Science Program	National Aeronautics and Space Administration
U.S. Department of Energy	National Oceanic and Atmospheric Administration
U.S. Department of Transportation	U.S. Army Corps of Engineers
U.S. Environmental Protection Agency	U.S. Geological Survey
State and Local Governments	
Alaska Department of Transportation and Public Facilities	Delaware Valley Regional Planning Commission
Chicago Area Transportation Study	New York State Department of Transportation
International Government Agencies	
Environment Canada	Transport Canada
Non-Governmental Organizations	
Researchers	Environmental non-profit organizations
Consultants	Transportation non-profit organizations
Industry representatives	
Expertise Represented	
Climate and Environment	Transportation
Air quality	Economics
Climate change	Emergency management
Environmental impact assessment	Engineering
Meteorology	Transportation operations
Water resources	Transportation planning
	Urban planning
Transportation Modes Represented	
Aviation	Rail
Highway	Transit
Marine	

Summary of Workshop Findings

Workshop participants strongly agreed that there is significant need for research to build understanding about the connections between climate change and transportation. The results of further research – if appropriately focused – will help transportation planners and managers better prepare for and manage the impacts of climate change on the transportation system. In addition, greater attention should be given to making current research findings available to inform trans-

portation decision makers. The key themes that emerged through the workshop discussions are summarized below.

Key Research Needs

- *Climate and Weather Projections at Regional and Local Levels.* Because transportation decisions and investments are most often made at local and regional levels, a regional research approach is essential to provide information at a level of specificity that is meaningful to local and regional decision makers, and to reflect the different

risks to transportation in different parts of the country.

- *Assessment of Potential Impacts on Critical Infrastructure Locations and Facilities.* Planners and transportation managers require research that helps identify the key facilities and locations that may be impacted by climate change. Impacts of particular interest to transportation could result from hydrologic changes, changes in the patterns and location of extreme events, changes in coastal geography and storm activity, and changes in prevailing climate and weather.
- *Analysis of Impacts on Operations, Maintenance, and Safety.* Long-term climate change may affect adverse weather conditions, shift temperature patterns, and alter seasonal precipitation. Future research is needed to better understand what these shifts may mean for safe and efficient management and operation of the transportation network.
- *Improved Tools for Risk Assessment and Decision Making.* Transportation managers need improved tools to effectively incorporate climate change data and projections into their planning, asset management, and operations decisions. Decision makers need techniques and methods that can be used to assess the relative risks of climate change to different aspects of the transportation network, to evaluate response strategies, and to target limited resources.
- *Integration of Climate Change Assessment with Other Transportation Decisions.* Transportation decision makers need frameworks to integrate consideration of climate changes with other key dynamics, including development patterns, technological advances, economic trends, and ecological changes. Tools are needed to

integrate impacts assessment with environmental assessments and transportation planning processes across all modes of transportation.

- *Assessment of Response Strategies.* Research is needed to better understand the range of potential response strategies available to transportation managers to avoid or adapt to the potential impacts of climate changes. Research should also develop new responses, evaluate tradeoffs among strategies, and assess the benefits, disbenefits, and costs of these options.

Coordination, Communication, and Public Awareness

- *Improved Sharing of Data and Knowledge.* Increased focus should be given to the dissemination and customization of existing data and knowledge for use by transportation managers, policy makers, the broader research community, and the general public.
- *Integration into CCSP Strategic Priorities.* DOT and other Federal agencies should coordinate the research priorities identified through this workshop with the activities of the U.S. Climate Change Science Program (CCSP). DOT, a Federal partner in CCSP, plays an active role in the development of the federal strategic plan for climate change research.¹
- *Leveraging Existing Research Activities.* The transportation community should work more closely with the climate and weather research communities to share knowledge and resources in this emerging field of research. DOT should collaborate with research partners to tap expertise in other fields, to provide transportation perspectives and expertise, and to leverage the research investments of other Federal agencies, international agencies, industry, and academia in climate change research.



Emil Frankel, Assistant Secretary for Transportation Policy at the Department of Transportation, addresses the importance of DOT research on climate change impacts in his opening address.

- *Public Education and Outreach.* Public access to and awareness of research findings needs to be improved. Information needs to be disseminated using formats readily understandable by the general public. Improved availability of information on the range of potential climate changes will provide the basis for the public to more effectively participate in transportation planning processes.

The following report gives a brief background on climate change research as it relates to transportation, provides an overview of the background papers and activities of the workshop, and summarizes the findings and recommendations of the *Potential Impacts of Climate Change on Transportation Research Workshop*.

Background

Current Research on Climate Change Impacts

Considerable research is being conducted on the effects that climate change might have on the U.S. and on the world. At the request of Congress, the U.S. Global Change Research Program (USGCRP) organized the U.S. National Assessment, a multi-year research effort to understand and assess the potential consequences of climate variability and change on the nation. In November 2000, the USGCRP



Panelist David Easterling, NOAA, makes a presentation on climate changes in the United States.

released the National Assessment Report: *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*.² This report provides a national level snapshot of potential impacts of climate change on the US and the relative degree of certainty researchers have in their projections, based on current scientific understanding. Table 2 provides a summary of the range of potential impacts identified in this report. In addition, under the auspices of USGCRP, various partnerships of universities, government agencies, and stakeholders have undertaken impact assessments on regional and sectoral levels. As of February 2003 reports on 11 regional assessments have been published that examine the potential impacts of climate change on specific regions of the United States; additional studies are forthcoming.³ Five sectoral assessments have also been completed, exploring impacts on water resources, human health, coastal areas and marine resources, forests, and agriculture.⁴ Other USGCRP research initiatives are profiled in *Our Changing Planet: The Fiscal Year 2003 U.S. Global Change Research Program and Climate Change Research Initiative*.⁵

Elaborating on the USGCRP assessments, other studies have explored various aspects of climate change impacts.⁶ For example, the National Research Council provided an overview of potential impacts as part of a larger examination in *Climate Change Science: An Analysis of Some Key Questions*.⁷ A related series of studies has been sponsored by The Pew

Table 2. Projected impacts of climate change on the United States, adapted from *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, by the National Assessment Synthesis Team.⁸

1. Increased warming and more intense precipitation will characterize the 21st century.
2. Differing regional impacts will occur, with greater warming in the western US, but a greater rise in heat index in the east and south.
3. Vulnerable ecosystems, particularly alpine areas, barrier islands, forests in the Southeast, and other vulnerable ecosystems will be significantly impacted.
4. Water will be a concern across the country, with increased competition for available resources, and the potential for more droughts and floods and reduced winter snowpack in some areas.
5. Food availability will increase because of increased crop productivity, although lowered commodity prices will stress farmers in marginal areas.
6. Forest growth will increase in the near-term, but some forests will be threatened over the long-term by increased susceptibility to fire, pests, and other disturbances.
7. Increased damage is very likely in coastal regions due to sea-level rise and more intense storms, while damage in other areas will result from increased melting of permafrost.
8. Adaptation will determine the importance of health outcomes, so that strengthening of the nation's community and health infrastructure will become increasingly important.
9. The impacts of other stresses will be magnified by climate change, with multiple factors causing adverse impacts on coral reefs, wildlife habitats, and air and water quality.
10. Uncertainties remain in current understanding and there is a significant potential for unanticipated changes.



Center Steering Committee member James Shrouds, Federal Highway Administration, introduces the speakers in the second panel.

Center on Global Climate Change, including reports discussing changes in precipitation patterns and the water cycle, sea-level rise, forests, and agriculture.⁹ Finally, studies such as the Federal Emergency Management Agency (FEMA) study on the effects of shoreline erosion in coastal communities and the Great Lakes regions¹⁰ have investigated the possible effects of climate and weather phenomena on emergency preparedness and property loss.

Impacts have been the subject of studies outside the United States as well, such as assessments prepared in Canada¹¹ and the United Kingdom.¹² On an even larger scale, the Intergovernmental Panel on Climate Change (IPCC), an organization formed by the United Nations (UN) and the World Meteorological Organization (WMO) to provide international assessments of climate change issues, published an examination of global impacts in *Climate Change 2001: Impacts, Adaptation, and Vulnerability*.¹³

Implications for Transportation

Few studies of climate impacts have been conducted that focus primarily on transportation concerns in the United States, but assessments such as those discussed above suggest potentially far-reaching implications for transportation. For example, changing coastlines and rising sea levels could, over the long-term, require the relocation of roads, rail lines, or airport runways, and could have major consequences for port facilities and coastal



Panelist Virginia Burkett, United States Geological Survey, speaks about climate impacts and transportation in the Gulf region.



Michael Savonis, Federal Highway Administration.

shipping. Underground tunnels for transit systems, roads, and rail could be subject to more frequent or severe flooding.¹⁴ In Alaska, thawing permafrost could damage roads, rail lines, pipelines, and bridges. Declining water levels in the Great Lakes could adversely impact shipping operations. A possible increase in the number of hurricanes and other extreme weather events would have implications for emergency evacuation planning, facility maintenance, and safety management for surface transport, marine vessels, and aviation. Changes in rain and snowfall and in seasonal flooding patterns could affect safety and maintenance operations as well.

In addition to these direct implications for planning, siting, design, and management of transportation facilities, the prospect of climate change raises other, less obvious, questions. For example, some research suggests that increasing temperatures could exacerbate near-surface ozone concentrations, making it more difficult for metropolitan areas to maintain air quality standards. Shifts in climate that affect ecosystems and the viability of natural resources are projected to impact agriculture, fisheries, and forestry production, which could, in turn, have long-term implications for freight transport. If climate change causes the relocation of major industrial and business activities, this would be expected to require significant investments in transportation and other infrastructure.



James Mahoney, Assistant Secretary of Commerce and Director of the Climate Change Science Program Office, delivers remarks on the importance of research on climate change and transportation.

Because of the many possibilities, assessing the implications of climate change for transportation will not be a straightforward task. Social and economic factors – including technology development, demographic shifts, and the rate of economic growth or contraction – will influence our future transportation needs, where transportation networks are located, and our investment in sustaining the nation's infrastructure. Furthermore, while the state of science in modeling climatic changes has advanced rapidly, there remain significant uncertainties about how global climate change will ultimately unfold. As studies attempt to project what could happen at specific regional and local areas, the level of uncertainty increases. In addition, the National Assessment notes that there is a high potential for "surprises" – major, unexpected events that will have significant impacts.

Need for Research on Transportation Impacts

The complexity of projecting the potential impacts of climate change presents a huge challenge for transportation decision makers. Ultimately, managers may need to incorporate a range of possible effects into their transportation investment decisions and management strategies. These decisions need to be informed by solid information about the range of potential effects on the transportation system and the



Panelist Martin Wachs, University of California at Berkeley, discusses the future of transportation.

probability of these effects. Further, long-range transportation plans and investment strategies must be sufficiently robust to accommodate unanticipated future events. Transportation decision makers need to know what policy and management options they have to prepare for these possible effects, and be able to assess the strengths and weaknesses of these options.

Recognizing transportation decision makers' need for more comprehensive projections of coming changes in climate, the DOT Center for Climate Change has decided to initiate research in this area and to encourage others in the research community to consider transportation concerns in their own research. The *Potential Impacts of Climate Change on Transportation* workshop launched this new research focus.

The Potential Impacts of Climate Change on Transportation Research Workshop

Discussion Papers

In preparation for the workshop several experts developed papers providing background information and introducing case examples of issues and current research related to climate changes and infrastructure. Final versions of these discussion papers are included in this report. These eighteen informative and thought-provoking papers provide both the research community and transportation decision makers an introduction to the wide variety of potential



Panelist Brian Mills, Meteorological Service of Canada, addresses the intersection of climate change and transportation.

connections between climate change and transportation, and open the door to further interdisciplinary study and dialogue.

Overviews

The first five papers provide summary background information on current climate change science and transportation services. In *Global Warming: A Science Overview*, Michael MacCracken presents six key aspects of the scientific findings on global warming. David Easterling then discusses the observational evidence for climate change in the United States and globally, in his paper *Observed Climate Change and Transportation*. Next, in *National Assessment of the Consequences of Climate Variability and Change for the United States*, MacCracken describes the process used to conduct the National Assessment, and summarizes the climate concerns for different regions of the United States as identified in the Assessment Report. Donald Trilling takes a look at the future of transportation in his paper *Notes on Transportation into the Year 2025*. Brian Mills and Jean Andrey then offer an introduction to the ways that trends in climate change and transportation may intersect in their paper *Climate Change and Transportation: Potential Interactions and Impacts*, which is based on studies conducted as part of Canada's national assessment.

Regional Case Studies

Following these overviews, six researchers provide more detailed examinations of regional effects of climate change in the United States, and what future changes may mean for transportation systems in these areas. Rae Zimmerman discusses climate change implications for infrastructure in the metropolitan New York region in *Global Climate Change and Transportation Infrastructure: Lessons from the New York Area*. Virginia Burkett describes how climate change dynamics may play out in the Gulf Coast / Mississippi Delta region – and the risks for transportation of these changes in storm events, sea level, precipitation, and other factors – in her paper *Potential Impacts of Climate Change and Variability on Transportation in the Gulf Coast / Mississippi Delta Region*.

In *The Potential Impacts of Climate Change on Great Lakes Transportation*, Frank Quinn provides an overview of how climate variability and change are projected to affect water levels in the Great Lakes – “one of the most intensively used fresh water systems in the world” - and discusses the implications for ports and marine transport. Turning to the west, Pierre duVair, Mary Jean Burer, and Douglas Wickizer discuss some of the ways climate change can be expected to impact transportation networks in California in their paper *Climate Change and the Potential Implications for California's Transportation System*. Jim Titus takes an East Coast perspective, posing the question *Does Sea Level Rise Matter to Transportation Along the Atlantic Coast?*. Finally, Orson Smith and George Levasseur examine the ongoing and potential effects of climate change in arctic regions in their discussion, *Impacts of Climate Change on Transportation in Alaska*.

System Impacts

The next group of papers looks at the potential implications of climate change for specific aspects of transportation, examining the issue either through an operational lens or modal perspective. In their paper *Surface Transportation Safety and Operations: The Impacts of*

Weather within the Context of Climate Change, Paul Pisano, Lynette Goodwin and Andrew Stern explain how adverse weather affects the safety and effectiveness of surface transportation operations, and how these effects may become even more important under climate change. Freight and transportation specialists Harry Caldwell, Kate H. Quinn, Jacob Meunier, John Suhrbier, and Lance Grenzeback examine the potential effects of climate change on the reliability and efficiency of freight transport in their discussion *Impacts of Global Climate Change on Freight*. Gloria Kulesa discusses how weather affects the safety and operations of airports and aviation and describes current research activities in the aviation community in her paper *Weather and Aviation*. Michael Rossetti considers the effects of weather and climate factors on rail operators in his paper *Potential Impacts of Climate Change on Railroads*.

Environment and Planning

The final group of papers addresses some of the environmental implications of climate change for transportation, and suggests considerations the transportation planning process may need to incorporate. In *Climate Change and Air Quality*, Anne Grambsch discusses the interaction between rising temperatures and air quality concerns in metropolitan areas and the implications of these effects on transportation. Paul Marx considers how climate changes may affect agriculture, industry and commerce, and residential land uses – and the issues that these effects may raise for transportation – in *Potential Climate Impacts on Land Use*. Finally, Erika S. Mortenson and Fred G. Bank explain the environmental roles and responsibilities of federal and state highway agencies, and explore how climate change may affect transportation agencies’ efforts to protect water quality, wetlands and ecosystems in their paper *Potential Impacts of Climate Change on Transportation: Water Quality and Ecosystems*.

These background papers offered workshop participants an array of thoughts to spark discussion when they arrived at the workshop on October 1, 2002.

Opening Session and Panel Presentations

Emil Frankel, Assistant Secretary for Transportation Policy, Department of Transportation, welcomed the distinguished group of experts. In the opening presentation, James Mahoney, Director of the Climate Change Science Program Office, Department of Commerce, stressed the importance of cooperation across Federal agencies on climate change research, and expressed his enthusiasm for research that would inform policy makers about the connections between climate changes and transportation. The full group then engaged in a brainstorming discussion, led by workshop facilitator Douglas Brookman, to explore the broader context for future research. The context map that quickly evolved through this dialogue highlighted the connections of transportation to broader social, political and economic drivers, the key roles of science and technology to the future of transportation, and the multiple challenges facing both the research and transportation communities (Figure 1). The

group recognized that we face significant uncertainties about the future – ranging from how technology is likely to unfold to the prospects of terrorism and international conflict. Potential changes in climate need to be considered as one factor among many in this dynamic context. The reality of an unpredictable future increases the challenges inherent in planning for a reliable and resilient transportation system.

Panel A – Overview of Trends

Joel M. Szabat, Deputy Assistant Secretary for Transportation Policy, Department of Transportation, moderated the first panel. Panelists provided an overview of trends in both the climate science and transportation communities as a starting point for workshop discussions.

David R. Easterling, of the National Climatic Data Center, summarized key observational data on temperature and precipitation in the U.S. and presented model-



Figure 1. Climate impacts on transportation context map. This chart was used to brainstorm lists of relevant issues for the workshop, highlighting: seasonal trends, political factors, the economic climate, accessibility and mobility trends, technology factors, customer needs, and uncertainties.



Panelist Rae Zimmerman responds to a question following her presentation on New York area impacts.

derived projections for future changes in climate. Measurements of near-surface temperature for the twentieth century document warming of approximately 0.6 degrees Celsius since 1880, both globally and in the United States. More significant is the change in daily maximum and minimum temperatures: minimum temperatures have warmed at a rate approximately twice that of maximum temperatures. Changes also appear to be occurring in the hydrologic cycle. Observations indicate that precipitation has increased in higher latitudes, and heavy rainfall events have become more common across the United States. Easterling also summarized the findings of the National Assessment, focusing particularly on potential changes in hydrological regimes and risks to coastal communities and marine resources.

Martin Wachs, from the University of California at Berkeley, provided a picture of what lies ahead for transportation. Much of the change in transportation is expected to come from outside the United States, as other countries develop and as globalization increasingly influences what U.S. consumers purchase. Critical issues include growth in international air travel and goods movement, increases in non-commuting travel, and environmental concerns. Demands on transportation facilities and services are growing prodigiously in both the passenger and freight sectors, placing strains on a network already beyond capacity in some areas. Much of the nation's infrastructure is aging and obsolete, and



Panelist John Gambel, Federal Emergency Management Administration, gives an overview of FEMA's National Hazard Programs.

as funds are used to maintain the existing network there will be fewer resources for new capital investment. Transportation agencies are challenged to maintain and optimize the use of existing infrastructure even as demands for access and services grow and costs increase. Information technologies may help to increase the capacity of the US transportation system, but the need is already large and growing. Finally, a new emphasis on safety and security places additional challenges on the transportation community.

Brian Mills, from the Meteorological Service of Canada, presented an analytic approach that Jean Andrey and he developed to examine the potential interactions between climate change and transportation. In order to identify and evaluate possible impacts, one must first define the scale and scope of the transportation system or activity, and determine its sensitivities to weather and climate. It is then possible to explore how anthropogenic climate change and variability might alter those interactions, and the implications for future vulnerability. Adaptation options can then be considered based on this assessment of risk. In weighing the priority that should be given to research on a potential impact, both the significance of the impact and the level of confidence in the climate change projection should be considered. Mills illustrated the approach by presenting examples of climate change impacts that have been experienced recently in northern Canada and the Great Lakes-St. Lawrence River Watershed.

Panel B – Assessing the Impacts of Climate Change and Variability on Transportation

James Shrouds, Director of the Office of Natural and Human Environment for the Federal Highway Administration (FHWA), moderated the second panel. This panel provided examples of the implications of climate change for two regions of the United States and on Federal emergency management programs.

Rae Zimmerman, of New York University, described the findings of the regional assessment of the New York metropolitan area, including specific vulnerabilities of infrastructure to flooding and storm surges. Climate change model projections for increases in sea level and temperature as well as for changes in precipitation patterns indicate that much of the metropolitan area's transportation infrastructure will be at risk of more frequent flooding, and higher flood levels. Higher temperatures also pose risks to pavement and structures. These potential impacts call for multiple mitigation and adaptation responses that may include redesign or retrofitting of critical infrastructure, operational strategies, relocation of facilities, and land use planning. Zimmerman emphasized the interrelationships between development patterns, transportation's contributions to greenhouse gas emissions, and the impacts of climate change on transportation. She argued that climate change needs to be considered as a factor in urban development and infrastructure management. Zimmerman noted the research challenges inherent in translating global projections of climate change phenomena to local levels and the institutional challenges of developing adequate response strategies when multiple local governments and agencies must be involved.

John Gambel of the Federal Emergency Management Administration (FEMA) presented the connections between emergency management and transportation, and gave an overview of FEMA's National Hazard Programs. FEMA has studied the hazards of erosion in coastal areas, along with the significant – and growing – economic impacts of these hazards. Gambel indicated that insurance

rate structures for high-risk areas are already insufficient to cover the projected costs of property losses in erosion hazard areas. This situation could be exacerbated by the increase in erosion due to rising sea level and increased storm surge projected by climate change models.



Center Steering Committee Chair Joel Szabat, Office of the Secretary of Transportation.



Center Steering Committee members engaged in discussion. From left: Linda Lawson (Office of the Secretary), Robert Tucillo (Federal Transit Administration), and James Shrouds (Federal Highway Administration).

Furthermore, FEMA's National Hurricane Program is working to improve hurricane emergency planning, including mitigation, preparedness, and response and recovery activities. As seen in recent emergencies, inland flooding from hurricanes is a serious public safety concern requiring improved coordination between states and communities during evacuation. Use of real-time technology in managing transportation systems during evacuations could serve to improve this communication, but closer coordination between emergency management and transportation agencies is needed and will become even more necessary in the future.

Virginia Burkett, of the USGS National Wetlands Research Center, discussed the implications of climate change for transportation in the Gulf Coast. She highlighted several key climate change variables, described the impacts of these factors for the transportation sector, and explored adaptation strategies that could be considered. She noted that more frequent and intense rainfall events, higher storm surges, loss of coastal wetlands and barrier shoreline, and land subsidence all pose significant risks for transportation in many areas of the Gulf Coast. Surface roads and rail networks, ports, offshore and near-shore oil and gas production facilities, and onshore processing and pipeline systems may each be affected. The risks to the densely populated city of New Orleans – which is located below sea level and has limited evacuation routes – are particularly high. According to Burkett, Gulf Coast transportation managers need to incorporate weather and climate change projections into mitigation and adaptation strategies. These strategies may include changes in construction and design, hurricane preparedness plans, wetland and water quality mitigation planning, and energy transport. Given the vulnerability of the Gulf Coast to extreme weather events, significantly worse weather could lead to disastrous conditions.

Breakout Sessions: Creating a Framework for Research Analysis

Following these plenary sessions, the participants broke into interdisciplinary working groups to discuss in detail specific aspects of the research challenge. Six groups were defined, each with a particular geographic and modal perspective. This framework, illustrated in Figure 2, enabled the workshop as a whole to cover a broad spectrum of research concerns. Each working group was asked to address three questions:

- What are the most significant potential problems that climate change poses for transportation?
- Based on this, what are the priority research topics?
- Who should take the lead in this research?

Modal Focus	Regional Focus		
	National		
	Coastal	Interior	Great Lakes and Rivers
Marine	X		X
Rail, Road, and Pipeline	X	X	
Aviation		X	
Transportation Systems Perspectives		X	

Figure 2. A research framework for regional and modal analysis.

Two groups considered the research needs raised for transportation in coastal areas; one focused on marine issues and the other on surface transportation. A third group looked at the issues raised for surface transportation in interior regions. A Great Lakes and rivers group examined research issues raised for marine transportation on waterways throughout the country, as well as the related implications for surface modes. The aviation breakout group

considered research needs related to aviation on a nationwide basis. The sixth group was asked to consider the “big picture” by exploring the research challenges posed by climate change for the nation’s transportation systems as a whole.

A summary of the research recommendations of each group is provided in the following section.

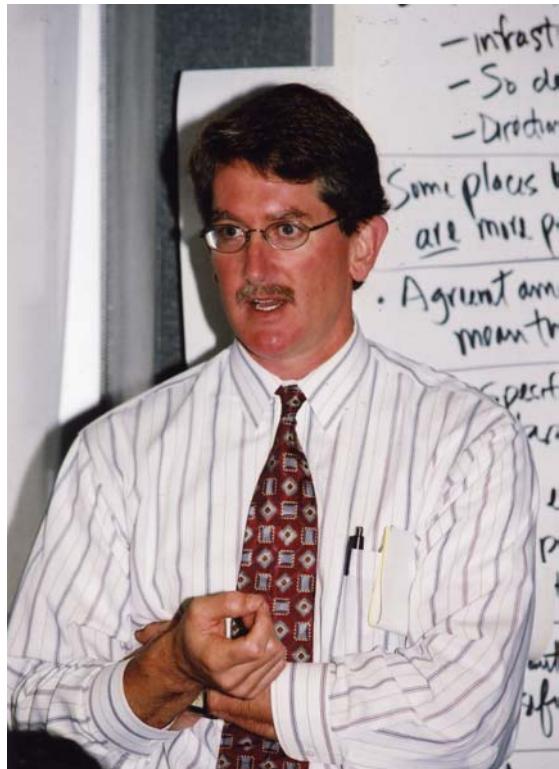
Research Recommendations

Analysis Focus Area: Coastal Regions/Marine

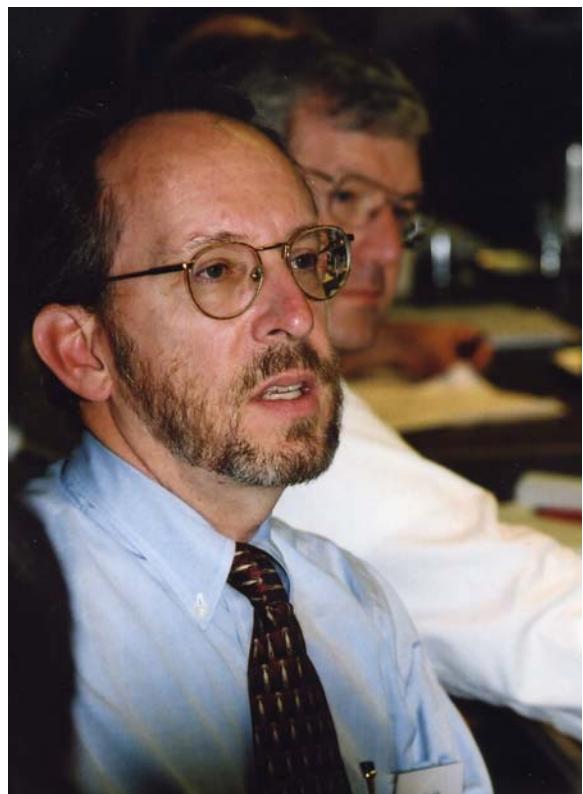
The group addressing marine issues in coastal areas identified six major research topics (Table 3). Several research challenges must be met to achieve a better understanding of the potential effects on ports and marine shipping of storms, sea level rise, sedimentation and erosion rates and mechanisms, and changes in key variables such as prevailing winds, waves, currents, and precipitation rates. Research should improve projections of the most likely changes with local and regional resolution. Participants emphasized that the need for research on climate variability is just as important as research on long-term climate change.

Specific research needs include enhancing climate models to simulate storm events, identifying the impact of severe events on ports and shipping, and modeling local sea level rise near ports and shipping channels. Participants recommended studies to identify the most likely impacts of climate change on river hydrology and sedimentation rates (including how varying rainfall could affect erosion into waterways), and case studies of actual sedimentation rates and impacts. Additional research on changes in Arctic shipping should detail the changes in sea ice extent and thickness that may result in longer shipping seasons or new routes.

These advances in scientific modeling and projections would provide the information transportation planners and managers need to prepare or respond to changes in coastal weather and coastline geography. The group also recognized the need for improved tools for



Michael Carter, Maritime Administration, presenting the findings of the Coastal Regions / Marine breakout group.



Orson Smith, University of Alaska at Anchorage.

Table 3. Summary of research priorities - coastal/marine.

Coastal / Marine	
Research Challenge	Specific Research Needs
• Storms and sea level rise	<ul style="list-style-type: none"> – Climate change effects on storm intensity, location, track – Clarification of projected trends – Exploration of local sea level changes and land movements – Simulation of storm events – Impact of severe events at different geographic scales
• Sedimentation and erosion	<ul style="list-style-type: none"> – Impact on wave- and current-induced sedimentation – Changes to rainfall and river hydrology; sedimentation rates – Case studies at ports – Dredging disposal options
• Changes in prevailing winds, waves, currents, and precipitation	<ul style="list-style-type: none"> – Improved monitoring, modeling – Relation to shipping, port design
• Shipping routes	<ul style="list-style-type: none"> – Monitor extent and thickness of sea ice – Arctic and Great Lakes
• Decision making and policy tools	<ul style="list-style-type: none"> – Improved models, elevation maps, GIS; communication tools
• Socio-economic patterns, legal issues	<ul style="list-style-type: none"> – Localized land use, watershed, transport development trends

decision making – improved models, geographic information systems (GIS), and communications that could enable planners and policy makers to better understand and incorporate scientific data. They further recommended that research be conducted to better understand socio-economic patterns – including land use and development trends – and the implications of these trends for marine transport.

Analysis Focus Area: Coastal Regions/Rail, Road and Pipeline

The second group turned landside, to consider the key research questions concerning surface transportation in coastal areas. Participants identified four major research challenges that examine the potential impacts of weather events and climate changes on the full range of transportation decision making, from short-term operational decisions to long-range planning and investment decisions.

At the operational level, research should consider the effects of weather-related travel delays on rail and road system performance. Participants noted that studies to date on weather delays have focused on aviation, rather than on surface transportation. Research on the effects of weather on travel times, and on travelers' responses to adverse weather can help inform real-time operational and maintenance decisions of transportation managers. A better understanding of weather activity and its effects on surface transportation could support better planning and investment for longer-term climate impacts, reducing delays and enhancing user satisfaction with the transportation network.

The group also highlighted the need for a better understanding of the potential impacts of climate change on both infrastructure and ecosystems, coupled with efforts to capture best practices in road design and construction that

respond to these changes. The effect of sea level rise on coastal infrastructure provides one striking example of these impacts. Growing development on coasts compounds the risks of sea level rise. Because of the inter-relationships of development, sea level change, and changes in severe weather, research is needed to enable transportation decision makers to incorporate these factors into planning for coastal development and transportation infrastructure. These efforts should include assessments of the economies of coastal development and the impacts of climate change, and development of local planning tools, such as GIS tools to create location-specific overlays of sea level rise on critical infrastructure and services.

As coastal conditions change, the impacts of existing coastal roads and other infrastructure on

local environments can change as well. Border roads can, for example, become barriers to wetland migration, acting as unintended dikes. Suggested research includes the identification and development of best practices for the construction and modification of coastal roads to avoid or mitigate environmental damage. This could include GIS overlays of coastal roads and elevations and regional case studies.

Finally, the group suggested measures to improve public understanding of the consequences of climate change. These could include better dissemination of existing information about climate change – and options for state and local responses – as well as research to develop improved methodologies for public education on this topic.

Table 4. Summary of research priorities – coastal/rail and road.

Coastal / Rail and Road	
Research Challenge	Specific Research Needs
<ul style="list-style-type: none"> • Weather-related travel time delays • Impact of climate change on roads and ecosystems • Smart growth • Lack of public awareness of climate change consequences 	<ul style="list-style-type: none"> – Regional effects on transportation system performance – Travel behavior response to delays – GIS overlay of coastal roads and elevations – impacts of sea level rise on roads and habitat – Regional case studies of road design that minimize environmental impacts – Best practices for road construction and location – Economies of coastal development and impacts of climate change – Analysis of anticipated sea-level rise and local development plans, using GIS technologies – State and local case studies – Website development on potential climate change impacts



Stanley Riggs, East Carolina University.

Analysis Focus Area: Interior Regions/Rail, Road and Pipeline

This expert group focused on research to address projected climate changes in interior regions and their implications for surface transportation and pipelines. The group identified four priority research challenges.

A lack of tools to support decision making related to local and regional scale impact projections creates a significant challenge. The group felt that it is currently very difficult to get useful information developed through climate research to transportation planners. They recommended the development of tools to specifically support transportation decision making at the local and regional level, and tools that integrate climate and impact models at comparable resolutions of current transportation planning. These tools should include risk analysis information and the ability to translate impact research findings into meaningful data used by decision makers. The availability of such tools and information would enable transportation managers to better project and plan for service interruptions, develop design parameters to accommodate expected impacts, and make improved decisions about the location and scale of new infrastructure.

The experts also recognized the need to understand how climate change is likely to affect the hydrologic cycle, and the implications of



John Zamurs, New York State Department of Transportation.

such changes on road, rail and pipeline infrastructure. For example, changes in precipitation, soil moisture, groundwater, and flooding may indicate the need to adjust engineering standards, location of infrastructure, maintenance schedules, and safety management. Suggested research includes the evaluation of existing hydrologic models under climate change scenarios, with a particular focus on groundwater issues, landslides, flooding, and sediment transport.

The group also recommended a focus on research to better understand and project risks from potential changes in the frequency and intensity of extreme events. Specifically, because projections based on historic trend lines are expected to be increasingly less accurate as the climate changes, research to develop methods to characterize risks *without* complete reliance on historical data becomes increasingly necessary. In addition, models need validation at multiple geographic and temporal scales.

Finally, the participants noted that there could be shifts in demand for natural resources due to changes in climate. These shifts may have impacts for transportation, depending on the timeframe over which these changes occur and the useful life of the related infrastructure. The group recommended evaluations of the timing and location of shifts in demand, and their intermodal implications.

Table 5. Summary of research priorities - interior/rail, road and pipeline.

Interior / Rail, Road, and Pipeline	
Research Challenge	Specific Research Needs
<ul style="list-style-type: none"> • Tools to support local / regional scale impacts projection and decision making • Hydrologic impacts on road, rail and pipeline infrastructure • Extreme events and impacts on roads, rail and pipelines • Spatial and temporal shifts in demand 	<ul style="list-style-type: none"> – Service interruptions – Development of appropriate design parameters for new facilities – Integration of climate and impact models at comparable resolution – Data “info mining” – Evaluation of existing hydrologic models (under climate change scenarios) – Effects of hydrological changes on groundwater table / quality – Landslides / washout, flooding impacts on transportation facilities – Effects of sediment transport on infrastructure, and response strategies – Methods to characterize risks without complete reliance on historical data – Validation of climate, hydrological and impacts models at multiple scales – Timing and location of shifts in transportation demand, relative to life of infrastructure – Impacts on port facility capacities and inter-modal flows

Analysis Focus Area: Great Lakes and Waterways/All Modes

The Great Lakes and Waterways group considered potential climate change impacts on the nation's waterway system, including the Great Lakes and the Ohio, Mississippi,

Columbia, and Missouri river basins. This network of waterways provides the basis for intermodal transport systems for both freight and passenger movement. In addition, these lakes and rivers support fisheries, industries, and recreation, and have important ecological functions. Recognizing the diverse set of



George Levasseur, Alaska Department of Transportation and Public Facilities.



Roger King, Mississippi State University.

interests involved, the group focused both on the specific research priorities and on the need to promote improved communication and systems for sharing information among all interests and stakeholders. The group identified three priority challenges for research: projection and analysis of future climate events; analysis of potential responses to these events; and comprehensive analysis of competing interests for water.

Researchers project that climate change may result in lower water levels throughout the Great Lakes system. Lower water levels would have significant implications for freight transport and recreational boating. The group suggested that the effect of climate changes on rainfall and fisheries should also be examined. Continuing to improve modeling and projections of changes in seasonal water levels will be an important ongoing research activity. In addition, further research is recommended that could help to indicate how the characteristics of extreme events are likely to change. Given the number of diverse interests involved, a special effort should be made to develop a common architecture with customers to disseminate research results in usable formats to the range of users of the lakes and rivers.

The results of these modeling efforts should be used to analyze the advantages and costs of possible responses to these events, including assessments of alternative passenger and freight

routes, redundancy, recovery time, and longer shipping seasons. These analyses should include market research, and should have the capability to model intermodal responses to climate changes and events. Research should be initiated to help inform governmental responses to climate changes and events, including the identification of critical infrastructure needs for public sector investment.

Experts stressed the need for a greater understanding of competing interests in the Great Lakes system – particularly regarding the long-term viability of the freight network – as climate changes take place. Lowered water levels would be expected to dramatically change the important parameters used in determining water distribution, creating additional stress in the process of allocating water resources. In making these decisions, more definitive data and model results will be required, as well as an understanding of the legal regulations affecting water management, the impacts on ecosystems, and projections of economic impacts on different industries.

Finally, the group noted the importance of appropriate coordination of any research that is conducted. For research on the Great Lakes, DOT should work with the International Joint Commission (IJC) and ensure Canadian involvement on research topics of joint interest.



Donald Trilling, Office of the Secretary of Transportation, presenting the findings of the Great Lakes and Waterways breakout group.



Harry Caldwell, Federal Highway Administration.

Table 6. Summary of research priorities - Great Lakes and waterways/all modes.

Great Lakes and Waterways / All Modes	
Research Challenge	Specific Research Needs
<ul style="list-style-type: none"> • Future events that will impact the waterway system • Responses to events; government management of impacts • Understanding of competing interests for water after long-term climate changes, as related to freight viability 	<ul style="list-style-type: none"> – Projection of extreme events: severity, frequency, variability – Global and regional modeling to forecast: low flows, high rainfall events, impact on fisheries, impacts on navigation – Identification of alternative passenger and freight routes, modal splits, redundancy, recovery time – Modal interaction down river with events on the Great Lakes – Identification of demand network, supply network, defense network – Development of intermodal simulation capability to model changes, severe event frequency – Designation of critical infrastructure for investment decisions, and for government support – Legal analysis of moving water between basins – Impact on environment, endangered species, stakeholders – Comprehensive basin studies – Prediction of climate impacts

Analysis Focus Area: National/Aviation

The aviation breakout group discussed the relative needs of the industry for improved information regarding long-term changes in climate versus an improved understanding of near-term weather phenomena and climate variability. Research related to climate change and aviation has generally been regarded as a lower priority by both industry and government due in part to other, more immediate concerns confronting aviation, as well as to a lack of familiarity with the potential aviation risks posed by climate variability and change. Increased dialogue and communication among researchers, the FAA, and the range of public and private sector interests involved in aviation – owners and managers of airport facilities, airlines, manufacturers, and suppliers – will improve understanding of the aviation challenges stemming from climate change. The participants explored opportunities to advance research related to climate change and variability by building upon existing research activities in weather, environmental effects,

safety, and technology. Five priority research challenges were identified.

The group identified achieving a better understanding of the relationships between high altitude emissions and climate chemistry as the first major research challenge. This will require additional data collection through monitoring and field campaigns, building upon the ongoing observational work conducted by the Department of Defense, NOAA, NASA, and the National Science Foundation. These data need to be incorporated into global air quality models for analysis. Sensitivity studies are required to assess the potential efficacy of policy and technology options, in collaboration with FAA and industry.

The second major research challenge lies in improving predictability of weather phenomena (i.e. timing, confidence, location, frequency) in the face of a changing climate. Advances in weather prediction will support aviation decision making regarding location of facilities, flight paths, operations, and safety. Research in this

area should build upon the substantial weather research already underway through the FAA and Federal science agencies. Additional research is needed to understand the potential effects of climate change on convection, jet streams and turbulence, extreme events, winter weather conditions, visibility, and radiation.

The group also recommended research to identify technical strategies that will reduce aviation contributions to climate change. Research is needed, in particular, on the potential of advanced aircraft and engine technologies – both of alternative airframe and engines and improvements to existing technologies – to reduce greenhouse gas emissions from aviation, and research to promote higher efficiency and cleaner fuels.

Recognizing that the aviation community faces a range of environmental issues, the group highlighted the need to develop an integrated framework to assess these factors and the interaction of potential strategies intended to improve individual environmental effects, such as emissions, noise, and climate impacts. This analysis could assess costs and benefits of various strategies, reveal unintended counter-effects of some strategies, and potentially identify synergistic approaches to address multiple environmental needs.

Similarly, the group discussed how best to link ongoing research to improve aviation safety and efficiency with research and development to address environmental impacts. Research in this area needs to be conducted in close collaboration with industry, academia, and the FAA, and should be informed by an assessment of user needs, including identification of potential incentives to encourage research and development in this area. The group recommended that this assessment include examination of the potential effects on insurance costs. The experts stressed the importance of working with the entire aviation community to understand their priorities and concerns related to climate change – and to consider ways to integrate research on climate change with analysis of other concerns – including environmental issues, efficiency, and safety.

The experts also suggested several additional topics for specific research to provide aviation planners and operators improved data to support decision making. These topics include the potential effects of more hot days on lift pavement, the implications of sea level rise and storm surges on airport facilities and operations, the effects of climate variability and change on location and aviation route decisions, and the potential interaction between changing climate and aviation in the spread of diseases.



Linda Lawson, Office of the Secretary of Transportation, presenting the findings of the Aviation breakout group.



Anne Grambsch, Environmental Protection Agency.

Table 7. Summary of research priorities - national/aviation.

National / Aviation	
Research Challenge	Specific Research Needs
<ul style="list-style-type: none"> • High altitude aviation emissions and climate chemistry • Improved predictability of weather phenomena (timing, confidence, location, frequency) • Aircraft and engine technology • How to tie research and development in environment to safety, efficiency • Integrated framework to incorporate climate into environmental analysis 	<ul style="list-style-type: none"> – Monitoring of high altitude emissions, field campaigns – Incorporation of emissions data into global air quality models – Analysis of high altitude emissions impact on climate – Sensitivity and policy studies – Convection – Jet stream / turbulence – Extreme events – Winter weather conditions – Visibility / ceiling – Radiation – Alternative engines – Improvements to current engines – Fuels – New lightweight materials – Multidisciplinary design for operations – Use existing FAA network to assess user needs – Identification of incentives (e.g. potential increased insurance costs) – Tradeoffs between emissions, noise – Portfolio management tool to inform decision makers

Analysis Focus Area: National/Transportation Systems

The final breakout group examined the overriding topics of concern from a nationwide, transportation systems perspective. This group identified research priorities related to climate variability and change that would inform effective planning and investment decisions and support a strong and viable intermodal transportation network. The group identified four key challenges requiring research: improved understanding of weather effects, integration of climate change factors with environmental and transportation planning, institutional barriers and decision making processes involving multiple organizations and

stakeholders, and risk assessment techniques to support sound decisions.

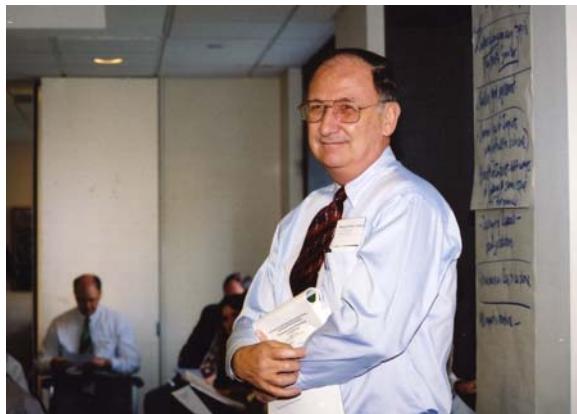
An increased research focus on regional and local effects of weather and climate variability would build an improved understanding and predictive capacity of weather impacts at a level appropriate and useful for transportation decision makers. This will require significant, long-term research, including development of data and models to support regional and local estimates; better scenario development; and study of the specific effects of weather and climate variability on infrastructure, patterns of development, transportation operations and services.

The participants identified a need for tools to integrate environmental and transportation plans to better understand and assess the interactions among climate change, air, and water quality in transportation decisions. They

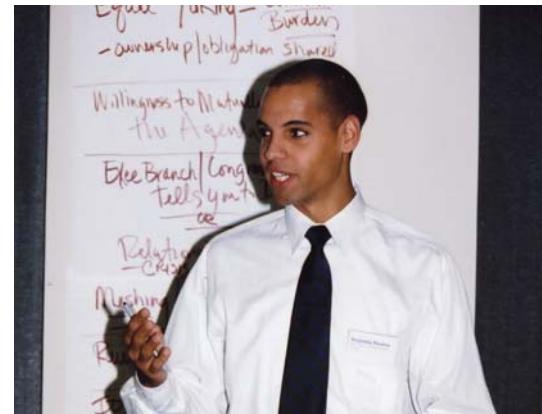
called for applied research to define and share best practices among transportation practitioners, focusing on win-win strategies that reduce risks associated with climate change, support sound transportation, and are environmentally beneficial.

Table 8. Summary of research priorities - national/transportation systems.

National / Transportation Systems	
Research Challenge	Specific Research Needs
<ul style="list-style-type: none"> • Uncertainties about science of climate variability and weather effects • Integrating environmental and transportation plans • Institutional barriers and decision making • How to do risk assessment 	<ul style="list-style-type: none"> – Data and models for regional / local estimates – Better climate scenario development – Effects on infrastructure, patterns of development, operations and services – Enhanced understanding of interactions, changes in air and water quality – Identification and dissemination of best practices – Search for environmentally-beneficial transportation strategies – Comparative analysis across government, private sector – How to elevate climate awareness in transportation – Better communication with decision making public – Scenario building, testing – Identification of vulnerable assets – Exploration of reinsurance industry experience



Michael MacCracken, U.S. Global Change Research Program (retired).



Benjamin Preston, Pew Center on Global Climate Change.

The group recognized that transportation decision making occurs at various levels of government, and involves multiple government agencies with different mandates and priorities, private sector entities, and the general public. Research to address institutional barriers would support improved communication and analysis across institutions. The group also recommended research to identify ways to elevate climate awareness both within the transportation community and with the public at large.

The ability to understand and evaluate levels of risk lies at the core of effective decision making. The group highlighted the need to advance the transportation community's capacity to assess risks associated with climate variability and change. This will involve scenario development and testing, development of modeling techniques, and identification of vulnerable transportation assets. The group recommends collaborating with the reinsurance industry in this work.

Conclusions

The research workshop on the *Potential Impacts of Climate Change on Transportation* helped spark a new level of dialogue between the climate change and transportation communities – the beginning of a multi-disciplinary discussion that can enrich scientists and practitioners working in both arenas.

Key Research Needs

There is a significant need for research to build knowledge and capacity about the connections between climate change and transportation. Such research holds great potential to help transportation planners and managers better prepare for and manage the impacts of climate change on the transportation system. At the same time, the research and transportation communities need to make existing research findings available to transportation decision makers. While a broad range of research challenges and needs were identified, some key themes for future research emerged through the day and a half of discussions.



Virginia Burkett, U.S. Geological Survey.



Center Steering Committee Chair Joel Szabat, Office of the Secretary of Transportation, addressing the workshop participants at the close of the event.

Climate and Weather Projections at Regional and Local Levels

The need for improved regional-level modeling and scenario development was a recurring theme in the recommendations of the breakout groups and in the full-group discussions. Because transportation decisions and investments are most often made at local and regional levels, a regional approach is essential to provide

information at a meaningful level of specificity. Further, analysis at the regional and local level can best reflect the variation in risks to transportation systems in different parts of the country. While better use of existing information can inform some transportation decisions today, transportation planners and managers need more refined models and projections.

Assessment of Impacts on Critical Infrastructure Locations and Facilities

The results from improved regional-level climate and weather projections would support improved modeling and analysis of the range of potential climate impacts on transportation infrastructure. This will help planners and transportation managers identify the key facilities and locations that may be impacted. Impacts of particular interest to transportation could result from hydrologic changes, changes in the patterns and location of extreme events, changes in coastal geography and storm activity, and changes in prevailing climate and weather.

Analysis of Impacts on Operations, Maintenance, and Safety

Changes in climate have implications not only for the built transportation infrastructure but also for the safe and efficient management and operation of the transportation network. Research to understand the potential effects of long-term climate change on adverse weather conditions, temperatures, and seasonal precipitation patterns – and the meaning of these shifts for seasonal and real-time management of the transportation system – will improve our understanding of challenges to system operation.

Improved Tools for Risk Assessment and Decision making

Transportation managers need improved tools to effectively incorporate climate change data and projections into their decisions regarding planning, asset management, and operations. Techniques to assess the relative risks of climate change to different aspects of the transportation network will allow decision makers to

appropriately target resources to the most significant infrastructure and systems. Use of geographic information system technologies and scenario modeling could assist in identification of key concerns and evaluate response strategies.

Integration of Climate Change Assessment with Other Transportation Decisions

Transportation decision makers need frameworks to integrate consideration of climate changes with other key dynamics, including development patterns, technological advances, economic trends, and ecological changes. Tools are needed to integrate impacts assessment with environmental assessments and with transportation planning processes across all modes of transportation.

Assessment of Response Strategies

Research is needed both to better understand the range of potential response strategies available to transportation managers to avoid or adapt to the impacts of climate changes on transportation, and potentially to develop new responses. Decision makers will need tools to evaluate an array of potential strategies – including changes in infrastructure location, engineering and design responses, operational strategies, and modal shifts – and to assess the direct costs and benefits, long-range effects on ecological systems, economic and social effects, and economic implications of each option.

Coordination, Communication, and Public Awareness

In addition to their recommendations on research priorities, workshop participants identified key actions that would advance the state of knowledge, help support transportation managers in making sound decisions, and enable researchers to be more effective. These include the following recommendations:

Improve Sharing of Data and Knowledge

Workshop discussions highlighted the considerable amount of research that has been accomplished by numerous Federal agencies and

private research organizations. This research has already produced a significant amount of valuable data and research products that transportation decision makers could use; yet much of this information has not reached transportation managers or the general public. Increased focus should be given to the customization and dissemination of existing data and knowledge so that it can be used both by policy makers and by other researchers.

Integration into CCSP Strategic Priorities

Participants noted that the research priorities identified for DOT and other Federal agencies through the workshop should be coordinated with the U.S. Climate Change Science Program, which is developing the interagency strategic plan for federal climate change research. DOT is a Federal partner of CCSP, and plays an active role in the development of the federal research strategic plan.¹⁵

Leveraging Existing Research Activities

Participants emphasized both the opportunities for the transportation community to work more closely with the climate and weather research communities to share knowledge and resources in this emerging field. In addition, they emphasized the importance of multi-disciplinary

approaches to research. They encouraged DOT to collaborate with research partners to tap expertise in other fields, and to leverage the investments of other organizations in climate change research. Working with other Federal agencies, international agencies, industry, and academia can help make the best use of limited DOT resources.

Public Education and Outreach

Participants stressed the need to improve public access to and awareness of research findings, and the responsibility of the transportation and research communities to provide this information to the general public through formats and tools that are readily understood. There is a broad diversity of economic, social and environmental interests that must be addressed as adaptation or mitigation strategies are developed. Outreach and education efforts will assume a growing importance as research produces results and the outlines of potential adaptation strategies begin to form. Improved availability of information on the range of potential climate changes and adaptation options will help the public effectively participate in transportation planning processes and support sound community decisions and investments.

¹ For further information, see: US Climate Change Science Program, 2003. *Strategic Plan for the U.S. Climate Change Science Program*. <http://www.climatescience.gov/Library/stratplan2003/final/default.htm>. A National Research Council evaluation of an earlier draft of the plan is also available: National Research Council, 2003. *Planning Climate and Global Change Research: A Review of the Draft U.S. Climate Change Science Program Strategic Plan*, Washington, DC: The National Academies Press.

² National Assessment Synthesis Team, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, Cambridge, UK: Cambridge University Press, 2001. See: <http://www.usgcrp.gov/usgcrp/Library/nationalassessment/foundation.htm>.

³ See USGCRP National Assessment webpage for links to regional assessment homepages: <http://www.usgcrp.gov/usgcrp/nacc/default.htm>. Links to regional assessment reports can be found at <http://www.usgcrp.gov/usgcrp/nacc/allreports.htm>.

⁴ See USGCRP National Assessment webpage for links to sectoral assessments; <http://www.usgcrp.gov/usgcrp/nacc/default.htm>.

⁵ Climate Change Science Program and the Subcommittee on Global Change Research, *Our Changing Planet: The Fiscal Year 2003 U.S. Global Change Research Program and Climate Change Research Initiative*, 2003.

⁶ For example, several studies of impacts on the New York City area have been released. See Gornitz, V., S. Couch, and E.K. Hartig, 2001, "Impacts of sea level rise in the New York City metropolitan area." *Global Planetary Change* 32, pp 61-88. See also Bloomfield, J., Smith, M. and Thompson, N., *Hot Nights in the City: Global Warming, Sea-Level Rise and the New York Metropolitan Region*, Environmental Defense, 2001.

⁷ National Research Council, *Climate Change Science: An Analysis of Some Key Questions*, Washington DC: National Academy Press, 2001.

⁸ Condensed and adapted from the National Assessment Synthesis Team, *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, Cambridge, UK: Cambridge University Press, 2001.

⁹ See the Environmental Impacts Reports series on the Pew Center website for a complete listing, at http://www.pewclimate.org/projects/index_environment.cfm.

¹⁰ *Evaluation of Erosion Hazards*, prepared for the Federal Emergency Management Agency by the H. John Heinz III Center for Science, Economics and the Environment, April 2000.

¹¹ See *The Canada Country Study: Climate Impacts and Adaptation*, conducted by Environment Canada.

¹² See the many regional reports of the United Kingdom Climate Impacts Programme, <http://www.ukcip.org.uk/>.

¹³ IPCC, *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge, UK: Cambridge University Press, 2001.

¹⁴ See for example, *Climate Change and a Global City: An Assessment of the Metropolitan East Coast Region*, Assessment Synthesis, http://metroeast_climate.ciesin.columbia.edu/sectors.html.

¹⁵ For further information, see: U.S. Climate Change Science Program, 2003. *Strategic Plan for the Climate Change Science Program*. <http://www.climatescience.gov/Library/stratplan2003/final/default.htm>. A National Research Council evaluation of an earlier draft of the plan is also available: National Research Council, 2003. *Planning Climate and Global Change Research: A Review of the Draft U.S. Climate Change Science Program Strategic Plan*, Washington, DC: The National Academies Press.

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Part II: Discussion Papers

Overviews

Global Warming: A Science Overview

By Michael C. MacCracken

Fossil fuels (i.e., coal, oil, and natural gas) provide about 85% of the world's energy, sustaining the world's standard-of-living and providing much of the power for transportation, generation of electricity, home heating, and food production. Compared to other sources of energy, fossil fuels are relatively inexpensive, transportable, safe, and abundant. At the same time, their use contributes to environmental problems such as air pollution and acid rain, which are being addressed through various control efforts, and to long-term climate change, which governments have begun to address through adoption of the UN Framework Convention on Climate Change negotiated in 1992.

Drawing primarily from international assessment reports (see references for reports by the Intergovernmental Panel on Climate Change (IPCC)), this paper summarizes six key elements of the science of climate change (often referred to simply as "global warming" although the projected changes involve changes in many variables in addition to a rise in global average temperature). These results are presented as context for considering the challenges of both limiting long-term warming and adapting to the warming that will occur as a result of past use of fossil fuels and the inevitable future use over coming decades.

Human Activities are Changing Atmospheric Composition by Increasing the Concentrations of Radiatively Active (Greenhouse) Gases and Particles

Observations from global measurement stations and reconstructions of the composition of the atmosphere in the past clearly indicate that human activities are increasing the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and of various halocarbons (HCFCs and, until very recently, CFCs). These gases are collectively referred to as greenhouse gases because of their warming influence on the climate.

While these gases occur naturally, records going back many thousands of years indicate that the present concentrations are well above natural levels. The history of emissions versus concentrations, analyses of carbon isotopes, and other scientific results all confirm that these changes are occurring as a result of human activities rather than because of natural processes. For example, the CO_2 concentration is currently about 370 parts per million by volume (ppmv), which is about 30% above its preindustrial value of about 280 ppmv (see Figure 1b). This increase has been due primarily to the combustion of fossil fuels and secondarily to the release of carbon occurring in the clearing

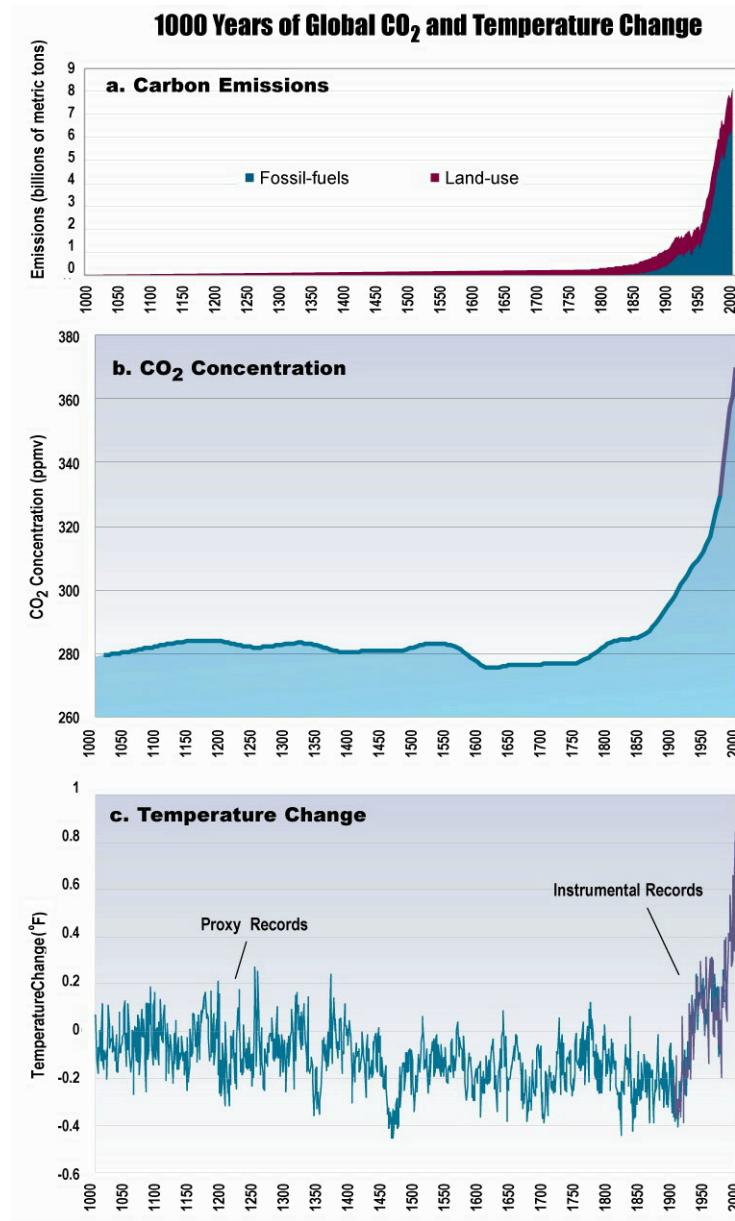


Figure 1. Carbon emissions, CO₂ concentrations, and temperature change over the past millennium. (a) Over the past 1000 years, but especially since 1850, the emissions of carbon dioxide (expressed in terms of carbon emitted) have grown from near zero to over 7 GtC/year (billions of tonnes of carbon per year); of this total, approximately 6 GtC/yr are from combustion of coal, oil, and natural gas and approximately 1 GtC/yr are from net changes in land use. (b) As a result of the CO₂ emissions, its concentration has increased from about 280 ppmv to about 370 ppmv over the past 1000 years, especially since 1850. (c) Reconstruction of the global-scale record of temperature departures from the 1961-90 average (primarily from proxy records from the Northern Hemisphere) suggests a relatively slow and steady cooling of about 0.2°C (0.4°F) that extended over most of the last 1000 years; beginning in the late 19th century and continuing through the 20th century, an unusually rapid warming of about 0.6°C (1.0°F) has taken place (from NAST, 2000, which contains primary references).

of forested land and the plowing of soils for agriculture (see Figure 1a). The CH₄ concentration is up over 150%. Its increase is due primarily to emissions from rice agriculture, ruminant livestock, biomass burning, landfills, and fossil fuel development, transmission, and combustion. The concentrations of many halocarbons are entirely new to the atmosphere—many of these compounds are solely a result of human activities. The persistence (or lifetimes) of the excess contributions of these gases in the atmosphere range from decades (for CH₄) to centuries (for CO₂ and some halocarbons) to thousands of years (for some perfluorocarbons). Thus, with ongoing emissions, the excesses of their concentrations above natural levels are likely to persist for many centuries.

Human activities are also contributing to an increase in the atmospheric concentrations of small particles (called aerosols), primarily as a result of emissions of sulfur dioxide (SO₂), soot, and some various organic compounds. The emissions of these human-induced aerosols result primarily from use of fossil fuels (primarily from coal combustion and diesel and 2-stroke engines) and from biomass burning. Once in the atmosphere, these compounds can be transformed or combined in various ways. For example, SO₂ is transformed into sulfate aerosols that create the whitish haze common over and downwind of many industrialized areas. This haze tends to exert a cooling influence on the climate by reflecting away solar radiation. Soot aerosols can combine with organics and form mixed aerosols that can exert warming or cooling influences. Changes in land cover, especially where this leads to desertification, can also lead to increased lofting of particles into the atmosphere. Dust lofted in this way generally has a cooling influence on the climate while also decreasing visibility; dust can also be carried to intercontinental scales as a result of long-distance transport.

Of critical importance is that the typical lifetime of aerosols in the atmosphere is less than 10 days (for example, sulfate and nitrate compounds are often rained out, causing the

acidification of precipitation known popularly as “acid rain”). Because of their relatively short lifetime in the atmosphere, emissions must be quite substantial for global concentrations to build up to the level that will have a long-term climatic influence that is as great as for the greenhouse gases with their longer atmospheric lifetimes. However, concentrations can become quite high in particular regions, and the pollution effects that result can cause regional disturbances of the climate. For example, aerosols lofted in southern Asia are suspected to be contributing to the diminishment of the monsoon.

Although natural processes can also affect the atmospheric concentrations of gases and aerosols, observations indicate that this has not been an important cause of changes over the past 10,000 years. Thus, it is well-established that human activities are the major cause of the dramatic changes in atmospheric composition since the start of the Industrial Revolution about 200 years ago.

Increasing the Concentrations of Greenhouse Gases will Warm the Planet and Change the Climate

From laboratory experiments, from study of the atmospheres of Mars and Venus, from observations and study of energy fluxes in the atmosphere and from space, and from reconstructions of past climatic changes and their likely causes, it is very clear that the atmospheric concentrations and distributions of radiatively active gases play a very important role in determining the surface temperature of the Earth and other planets. Figure 2 provides a schematic diagram of the energy fluxes that determine the Earth’s temperature (and climate).

Of the solar radiation reaching the top of the atmosphere, about 30% is reflected back to space by the atmosphere (primarily by clouds) and the surface; about 20% is absorbed in the atmosphere (primarily by water vapor, clouds,

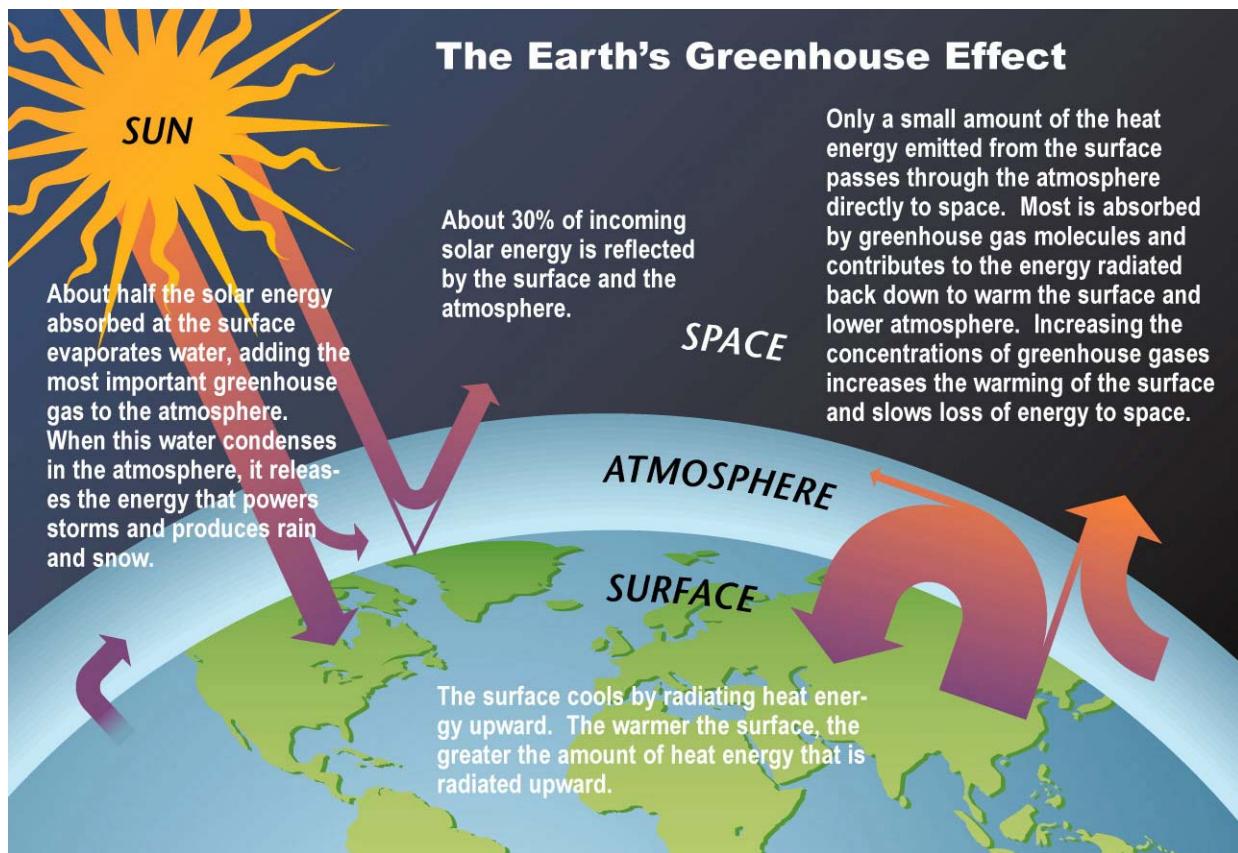


Figure 2. Schematic diagram of the Earth's greenhouse effect, with arrows proportional in size to the fluxes of energy by the particular process (NAST, 2000). Of incoming solar radiation, about 30% is reflected back into space by clouds and the surface, about 20% is absorbed in the atmosphere, and about 50% is absorbed at the surface. Most of the infrared (heat) radiation emitted by the surface is absorbed in the atmosphere and the atmosphere in turn then emits about 90% of this amount back to the surface, adding to its heat gain from the Sun. The extra energy at the surface is used to evaporate water or heat the near surface atmosphere. In the atmosphere, the extra energy it receives from the Sun, from absorbed infrared radiation, from latent heating released during precipitation, and from sensible heating, is emitted to space to balance the net solar radiation absorbed by the surface and atmosphere.

and aerosols), and about 50% is absorbed at the surface. For a system to come to a steady state temperature, the energy absorbed must be balanced by radiation that is emitted away as infrared (or heat) radiation. Were the Earth's atmosphere transparent and its surface a simple radiator of energy to space, the Earth's average surface temperature would equilibrate at close to 0°F (-18°C), given the current reflectivity of the Earth-atmosphere system. Such a temperature would be much too cold to sustain life as we know it.

However, the Earth's atmosphere is not transparent to infrared radiation, being able to recycle some of it in a way that creates a warming influence. This warming effect occurs because much of the infrared radiation emitted by the surface and by the greenhouse gases and low clouds in the atmosphere is absorbed by various radiatively active gases in the atmosphere. For example, less than 10% of the infrared radiation emitted by the surface gets through directly to space without being absorbed. A significant fraction of the absorbed energy is radiated back to the surface by the atmosphere's greenhouse gases and clouds,

providing additional energy to warm the surface. This radiation in turn causes the surface to warm, which raises its temperature and causes more radiation to be emitted upward, where much of it is again absorbed, providing more energy to be radiated back to the surface. This emission-absorption-reemission process is popularly called the *greenhouse* effect, even though the processes involved are different than keep a greenhouse warm and humid. The effect of this natural greenhouse effect is to raise the average surface temperature of the Earth from about 0°F (-18°C) to almost 60°F (15°C).

An additional warming influence results because the atmospheric temperature decreases with altitude up to the tropopause (about 8-10 miles up) before temperatures start to rise again in the stratosphere, which is warmed by the solar absorption by ozone (O_3) molecules. As a result of this temperature structure, when the concentrations of greenhouse gases are increased and the atmosphere becomes more opaque to infrared radiation, the absorption and reemission of infrared radiation to the surface comes from lower and warmer layers in the atmosphere. Because the emission of infrared energy is proportional to the fourth power of temperature, this has the effect of increasing the downward emitted radiation, tending to enhance the natural greenhouse effect. Similarly, emission outward to space occurs from higher and colder layers when the concentrations of greenhouse gases are increased. As a result, the surface-atmosphere system has to warm even more to achieve a planetary energy balance with the incoming solar radiation.

The most important radiatively active (or greenhouse) gas is water vapor (to be radiatively active, molecules need to have at least 3 atoms so that various rotational and vibrational bands can be activated by the radiation). Not only does water vapor absorb infrared radiation emitted by the Earth's surface, but it also absorbs infrared radiation from the Sun. In addition, under appropriate conditions, water vapor can condense and form clouds that absorb and emit infrared radiation as well as absorbing and scattering solar radiation. In addition to water

vapor, other greenhouse gases in the atmosphere that are present in significant concentrations include CO_2 , CH_4 , N_2O , and many chlorofluorocarbons, the concentrations of all of which are being directly affected by human activities, and O_3 , the tropospheric and stratospheric concentrations of which are being indirectly affected through chemical reactions caused by the emissions of other gases. Because of their connection to human activities, these greenhouse gases are usually referred to as the anthropogenic greenhouse gases (strictly speaking, their concentrations are being anthropogenically modified).

Observations from space-based instruments clearly indicate that the rising concentrations of the anthropogenic greenhouse gases are tending to enhance the natural greenhouse effect. Even though the greenhouse effect of the anthropogenic greenhouse gases is exceeded by the positive greenhouse effect of atmospheric water vapor, their effect is not overwhelmed by it. Instead, the warming caused by the increases in concentrations of CO_2 , CH_4 and other anthropogenic greenhouse gases is significantly amplified by a positive water-vapor feedback mechanism. This positive feedback occurs because more water vapor can be present in a warmer atmosphere, so that warming leads to an increase in atmospheric water vapor and a further warming. At the same time, however, changes in atmospheric water vapor and in atmospheric circulation can change the extent and distribution of clouds, and this can in turn affect the extent of the absorption and scattering of solar radiation and the absorption and reemission of infrared radiation through relatively complex and uncertain cloud feedback mechanisms.

Overall, there is no scientific disagreement that increases in the atmospheric concentrations of the anthropogenic greenhouse gases will tend to raise the Earth's average surface temperature—the key questions are by how much and how rapidly.

Increases in the Concentrations of Greenhouse Gases Since the Start of the Industrial Revolution are Already Changing the Climate, Causing Global Warming

The evidence is clear-cut that the concentrations of greenhouse gases have risen significantly since the start of the Industrial Revolution and that increasing the concentrations of greenhouse gases will induce a warming influence on the Earth's climate. A key test of scientific understanding is to determine if the time history and magnitude of climatic changes that are occurring match those expected to be occurring, based on theoretical and numerical analyses, as a result of past emissions and the resulting changes in atmospheric composition. Complications in this analysis arise because other influences on the Earth's radiation balance (referred to as *radiative forcings*) also can be affecting the climate. These radiative forcings include natural influences, such as changes in the output of solar radiation or in stratospheric particle loadings caused by volcanic eruptions, and human-induced changes, such as depletion of stratospheric ozone, enhancement of tropospheric ozone, changes in land cover, and changes in the amount of aerosols in the atmosphere.

To have the best chance of identifying the human influence, it is most useful to look at the longest records of the climatic state. Instrumental records of average temperature for large areas of the Earth go back to the mid-19th century. These records indicate a warming of over 1°F (about 0.6°C) over this period. Extensive proxy records (i.e., records derived from tree rings, ice cores, coral growth, etc.) for the Northern Hemisphere going back about 1000 years also indicate very significant warming during the 20th century compared to the natural variations apparent over earlier centuries. As shown in Figure 1c, a sharp rise in the temperature began during the late 19th century and continued through the 20th century. This warming appears to be much more persistent than the earlier natural fluctuations that were

likely caused by the inherent natural variability of the ocean-atmosphere system (i.e., internal variability) and the natural variations in solar radiation and the occasional eruption of volcanoes (i.e., external variability). That warming is occurring is also confirmed by rising temperatures measured in boreholes (i.e., dry wells), retreating mountain glaciers and sea ice, increasing concentrations of atmospheric water vapor, rising sea level due to melting of mountain glaciers and thermal expansion in response to recent warming (augmenting the natural rise due to the long-term melting of parts of Antarctica), and related changes in other variables.

The key question is whether these changes might be a natural fluctuation or whether human activity is playing a significant role. Among the reasons that the effect is being attributed largely to human activities is the coincidence in timing with the changes in greenhouse gas concentrations, the very large and unusual magnitude of the changes compared to past natural fluctuations, the warming of the lower atmosphere and cooling of the upper atmosphere (a sign of a change in greenhouse gas concentrations rather than in solar radiation), and the global pattern of warming. Some uncertainty is introduced because some of the warming occurred before the sharpest rise in greenhouse gas concentrations during the second half of the 20th century. Some analyses indicate that as much as 20-40% of the overall warming may be due to a coincidental increase in solar radiation, although other factors, such as changes in land cover or in soot emissions, may also have had an influence. In addition, some uncertainty has been introduced because the rise in tropospheric temperatures over the past two decades may have been a bit slower than the rise in surface temperature. Whether this difference is real or arises from, for example, calibration issues with the satellite instrumentation, natural variations in Earth-surface temperatures, the confounding influences of ozone depletion, volcanic eruptions, and atmosphere-ocean interactions, or other factors is not yet clear.

Taking all of the scientific results into consideration, the Intergovernmental Panel on Climate Change (IPCC, 1996a) concluded in its Second Assessment Report in 1995 that "The balance of evidence suggests a discernible human influence on the global climate." This conclusion, in essence, is equivalent to the criterion for a civil rather than a criminal conviction. In its Third Assessment Report (IPCC, 2001), the IPCC indicated even more clearly that the magnitude and timing of the warming during the 20th century, especially during the last 50 years, quite closely matches what would be expected from the combined influences of human and known natural influences.

Future Emissions of Greenhouse Gases and Aerosols Will Lead to Significant Further Climate Change, Including Much More Warming and Sea Level Rise than Occurred During the 20th Century

With the global population of 6 billion and current average fossil fuel usage, each person on Earth is responsible, on average, for emissions of about 1 metric ton (tonne) of carbon per year. Per capita use varies widely across the world, reaching nearly 6 tonnes per year in the US and about 3 tonnes per year in Western Europe, but amounting to only about 0.5 tonne per person per year in developing countries such as China and India. Projections for the year 2100 are that the global population may increase to 8 to 10 billion. As a result of the rising standard-of-living and the necessary energy required to sustain it, average per capita emissions across the globe may double as fossil fuel use grows significantly in the highly populated, but currently underdeveloped, emerging economies. If this happens, total annual emissions would more than triple from about 6 billion tonnes of carbon per year to about 20 billion tonnes of carbon per year. New estimates by the IPCC suggest emissions in 2100 could range from about 6 to over 30 billion tonnes of carbon per year (IPCC, 2000).

If global emissions of CO₂ gradually increase to about 20 billion tonnes of carbon per year by 2100, models of the Earth's carbon cycle that are verified against observations of past increases in concentration, project that the atmospheric CO₂ concentration would rise to just over 700 ppmv. This would be almost double its present concentration, and over 250% above its preindustrial value. Scenarios of future concentrations based on consideration of ranges in global population, energy technologies, economic development, and other factors project that the atmospheric CO₂ concentration could range from about 500 to over 900 ppmv in 2100, with concentrations rising even further in the next century. Depending on various control measures, this rise in the CO₂ concentration could also be accompanied by increases in the concentrations of CH₄ and N₂O, as well as of sulfate and soot aerosols, although it would take an unrealistically large (and unhealthy) amount of aerosols to limit radiative forcing to the extent that it is projected to rise as a result of the increases in the concentrations of the anthropogenic greenhouse gases.

Projections of the climatic effects of such changes in atmospheric composition are often based on use of computer-based climate models that are constructed based on the application of fundamental physical laws and results of extensive field investigations of how atmospheric processes work. To gain a level of confidence in the models, they are tested by comparing their simulations to the observed behavior of the climate from recent decades, recent centuries, and for geological periods in the past. Based on the model results and theoretical analyses, as well as on extrapolation of recent trends, the global average temperature is projected to rise by about 2.5 to 10°F (about 1.4 to 5.8°C) by 2100 (IPCC, 2001a). Such a warming would lead to temperatures that would far exceed those existing during the period in which society developed (see Figure 3). In addition to the warming influence of the rise in the CO₂ concentration, reduction in the

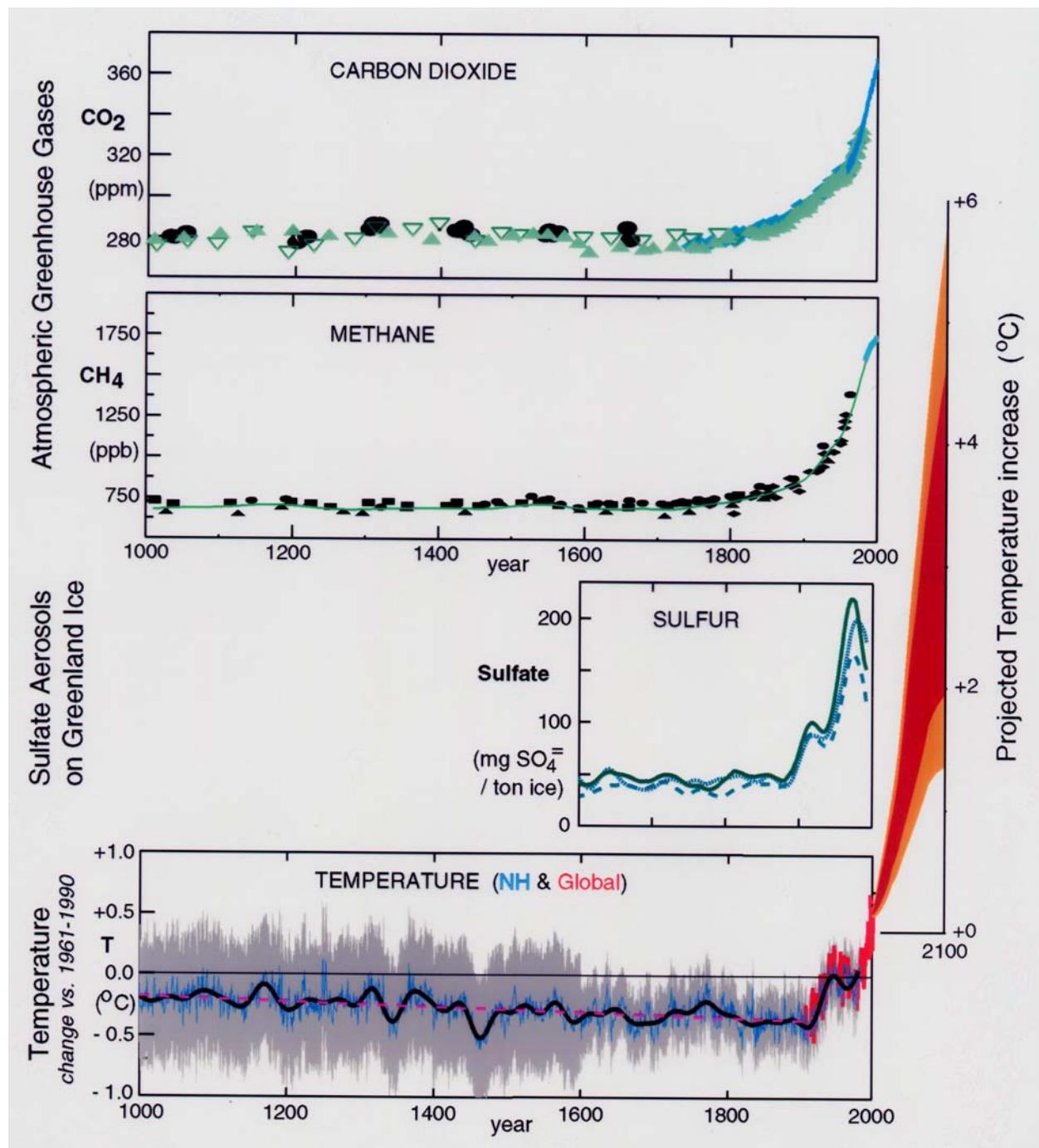


Figure 3. Projection of the increase in global average surface temperature during the 21st century in comparison to conditions that have existed during the past 1000 years. Concentrations of carbon dioxide, methane, and sulfate aerosols increased significantly during the industrial age. A sharp rise in temperature has been occurring since the late 19th century. Based on model simulations reinforced by theoretical and paleoclimatic analyses, global average temperatures are projected to rise 1.4 to 5.8 °C by 2100 (from IPCC, 2001a).

emissions of SO₂ in order to reduce acid precipitation and enhance air quality and public health could contribute to the warming, although an associated reduction in soot aerosol emissions might counteract this effect.

Based on these longer-range projections, it is very likely that the warming over the next several decades will be greater than the warming over the whole 20th century, even were there to be sharp reductions in CO₂ emissions. Associated with this warming would be shifts in precipitation zones and an intensification of evaporation and precipitation cycles, creating conditions more conducive to extremes of floods, droughts, and storms. In addition, projections are that the rate of sea level rise would increase from 4 to 8 inches/century (0.1 to 0.2 m/century) over the 20th century to a rate of 4 to 36 inches/century (0.1 to 0.9 m/century) during the 21st century. As was the case for the sudden appearance of the Antarctic ozone hole, there are likely to be surprises as well, given the presence of potential thresholds and nonlinearities. One of the possibilities is the potential disruption of the Gulf Stream and the global scale deep ocean circulation of which it is a part. The recurrence of a weakening such as apparently occurred as the world emerged from the last glacial about 11,000 years ago would be expected to cause a strong cooling centered over Europe (were this to happen during the 21st century, the cooling would likely only moderate somewhat the influence of global warming) and an acceleration in the rate of sea level rise (due to reduced sinking of cold water into the deep ocean).

The Environmental and Societal Consequences of Climate Change are Likely to be Diverse and Distributed, With Benefits for Some and Damages for Others

With fossil fuels providing important benefits to society, contemplating changes in the ways in which most of the world's energy is generated would seem appropriate only if the types of consequences with which societies will need to

cope and adapt are also quite significant. Several types of consequences for the US have been identified (NAST, 2000; NAST, 2001; Department of State, 2002). A similar summarization of scientific findings has been made for the world by the Intergovernmental Panel on Climate Change (IPCC, 1996b, 1996c, 2001b). The following sections summarize broad categories of impacts, particularly in terms of impacts for the US, recognizing that those in the US may be able to more readily adapt to these changes than those in developing nations.

Human Health

Sharp increases in summertime heat index would be likely to increase mortality rates in the US were it not for the expected offset of these conditions by the more extensive availability of air-conditioning. The poleward spread of mosquitoes and other disease vectors has the potential to increase the incidence of infectious diseases, but is likely to be offset by more attention to public health and enhancing building and community design and maintenance standards. The increased intensity of extreme events may injure or kill more people (and disrupt communities) unless steps are taken to enhance risk-adverse planning and construction.

Food Supplies

Higher CO₂ concentrations are very likely to enhance the growth of many types of crops and to improve their water use efficiency. If this happens widely (i.e., if other constraints on agriculture do not arise), agricultural productivity would be expected to rise, increasing overall food availability, and reducing food costs for the public. For farmers in some areas, the lower commodity prices that would be likely to result would reduce farm income, and farmers in marginal areas, even though benefiting from some gain in productivity, are unlikely to remain competitive. This could cause economic problems in nearby rural communities unless other profitable crops are identified.

Water Supplies

Changes in the location and timing of storms will alter the timing and amount of precipitation and runoff and warmer conditions will change snow to rain, requiring changes in how water management systems are operated. This will be especially the case in the western US because there is likely to be less snow and more rain in winter coupled with more rapid and earlier melting of the snowpack. These changes are likely to require a lowering of reservoir levels in winter and spring to provide a greater flood safety margin, even though this would risk reducing water availability in summer when demand will be rising. Across much of the US, the intensity of convective rainfall (e.g., from thunderstorms) is projected to increase, creating the potential for enhanced flooding in watersheds that experience frequent rainfall. Conversely, increased summertime evaporation may also reduce groundwater recharge in the Great Plains, and cause lower levels in the Great Lakes and in rivers such as the Mississippi, reducing opportunities for shipping and recreation.

Fiber and Ecosystem Services from Forests and Grasslands

While winter precipitation may increase in some areas, temperatures are likely to significantly increase in most areas. The increase in evaporation rates is likely to reduce summertime soil moisture. Some, but not all, of these effects may be offset by the increased CO₂ concentration that will help many types of plants grow better (if other factors such as nutrients are not limiting). As seasonal temperatures and soil moisture change, ecosystems will be affected, causing changes in prevailing tree and grass types and then associated changes in wildlife. As regions accumulate carbon in vegetation and dry out during persistent warm episodes, fire risk is likely to increase in many regions. Some climate model projections suggest a much drier southeastern US, stressing the current forests or even leading to their transformation into savanna (see Figure 4). At the same time, the southwestern deserts may get wetter and sprout

more vegetation (which may, however, increase fire risk in dry seasons). What is most important to understand is that the notion of ecosystem migration is a misconception—particular species will become dominant in different locations. However, this will likely mean the deterioration of existing ecosystems and the creation of new ones, albeit likely not with the complexity and resilience of current systems because there will not be sufficient time for adjustment and evolution to take place. If the climate changes at the rates projected, stresses on ecosystems over the next 100 years may be as great as over the last 10,000 years.

Coastal Endangerment

Mid-range projections suggest that the relatively slow rate of rise of sea level this century (about 4 to 8 inches, reduced or amplified by regional changes) may increase by a factor of 3 during the 21st century. For regions currently experiencing subsidence of their coastlines (e.g. Louisiana, the Chesapeake Bay, etc.), there could be a significant acceleration in inundation and loss of coastal lands, especially of natural areas such as wetlands and other breeding grounds where protective measures such as diking cannot be afforded. The rate of loss will be greatest during coastal storms when storm surges (and therefore damage) will reach further inland and further up rivers and estuaries. For developed areas, strengthening of coastal protection is needed, not just to protect against sea level rise, but also to reduce current vulnerability to coastal storms and hurricanes.

Transportation

While the US transportation system is very reliable and quite robust, impacts from severe weather and floods currently cause disruptive economic impacts and inconvenience that sometimes become quite important for particular regions. While information is only starting to emerge about how climate change might lead to changes in weather extremes, a range of possible types of impacts seem possible, including some that are location dependent and some that are event specific. Location-

dependent consequences might, for example, include: lower levels in the Great Lakes and the St. Lawrence River, and, particularly during the summer, in the Mississippi-Missouri-Ohio River systems. Lower levels could significantly inhibit shipping, even though reduction in the thickness and duration of lake ice in the Great Lakes during winter could lengthen the shipping season.

Along coastlines, reduction in ice cover could lead to more damage to coastal

infrastructure, especially because waves would be expected to be larger and cause more erosion. In addition, sea level rise could endanger barrier islands and coastal infrastructure while shifting sediments and channels in ways that might affect coastal shipping and require more frequent dredging and remapping. In the Arctic, warming is already reducing the extent of sea ice, and further warming could lead to the opening of Arctic waters for shipping while also causing more rapid melting of permafrost that could destabilize roads, pipelines, and other infrastructure.

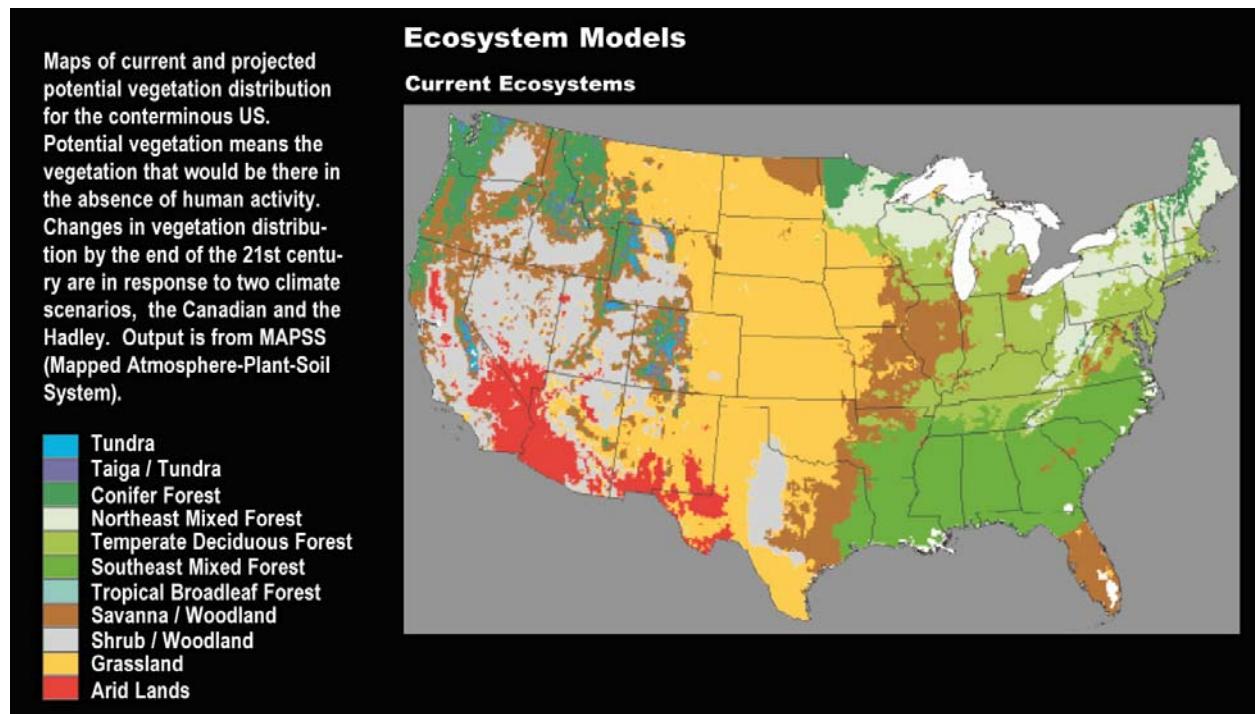


Figure 4a. Computer-based ecosystem models that associate the most likely type of ecosystem with the prevailing and future climatic conditions have been used to estimate the potential for changes in the predominant vegetation as a result of climate change. (a) Map of the prevailing vegetation of the conterminous US using vegetation models calibrated for the climatic conditions of the late 20th century.

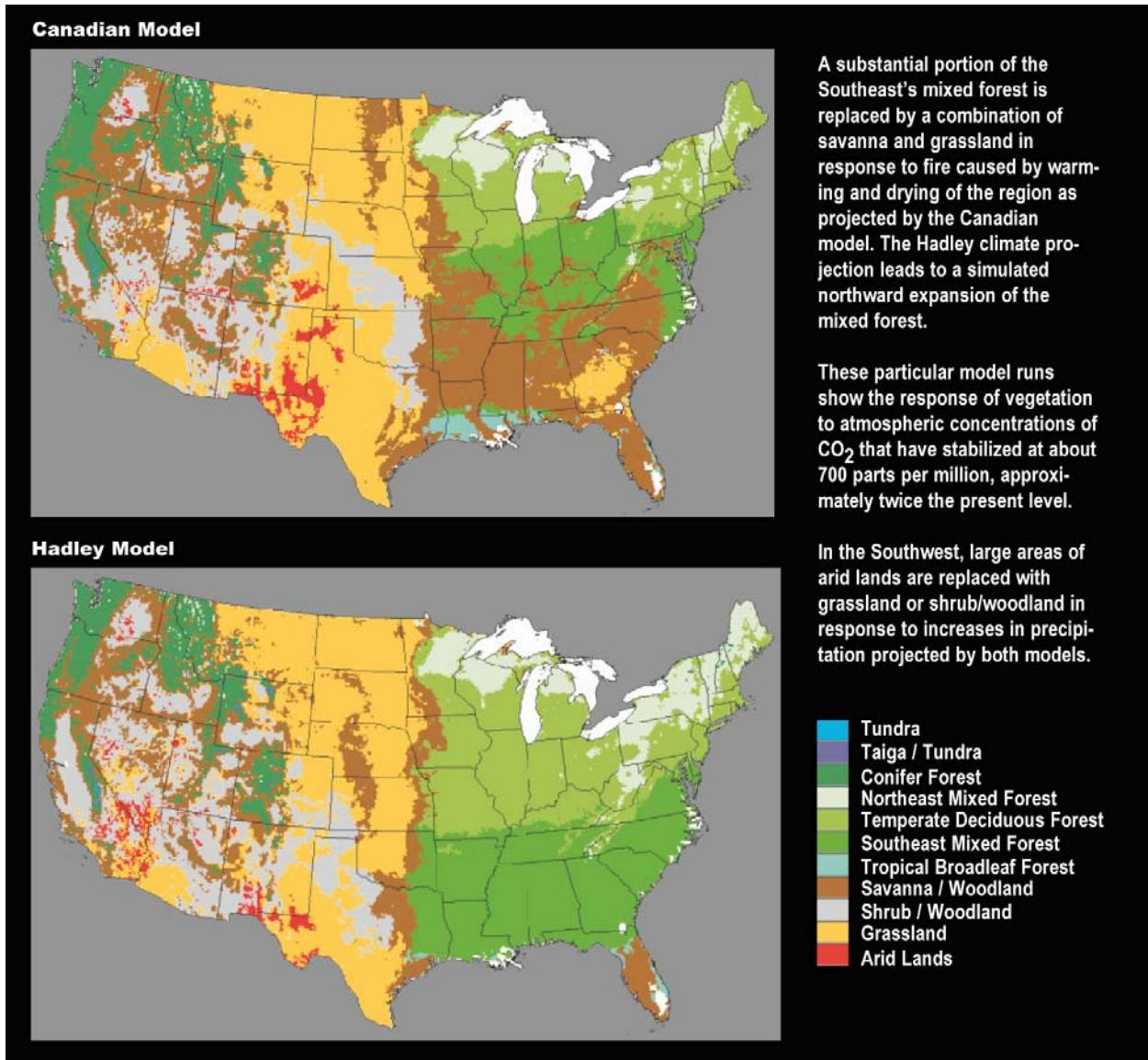


Figure 4b. (b) Maps of projected vegetation for the conterminous US based on two projections of climatic conditions for the latter part of the 21st century. The Canadian model scenario projects that the prevailing climatic conditions are likely to be relatively hotter and drier than present conditions, especially in the southeastern US and during the warm months, whereas the Hadley (U.K.) model projects that climatic conditions will tend to be warmer and moister. In both models, increased precipitation in the southwestern US tends to reduce the extent of arid lands. In the southeastern US the Hadley scenario projects continued coverage by a mixed forest, whereas the Canadian model projects that savanna and woodland conditions are likely to become predominant.

Event-specific consequences could include: more frequent occurrence of heavy and extreme rains (a trend already evident during the 20th century); reduced or shifted occurrence of winter snow cover that might reduce winter trucking and air traffic delays; altered frequency, location, or intensity of hurricanes accompanied by an increase in flooding rains; and warmer summertime temperatures that raise the heat index and may increase the need for air pollution controls. Early model projections suggest that the return period of severe flooding could also be significantly reduced (e.g., the baseline 100-year flood might occur as often, on average, as every 30 years by 2100). By reducing the density of the air, warmer temperatures will also cause reductions in combustion efficiency, which would both increase costs and require longer runways or a lower load for aircraft. Starting to consider climate variability and change now in the design of transportation systems could be a very cost-effective means of enhancing both short- and long-term resilience.

Air Quality

Warmer temperatures generally tend to accelerate the formation of photochemical smog. The rising temperature and rising absolute (although perhaps not relative) humidity are projected to raise the urban heat index significantly, contributing to factors that lead to breathing problems. Meeting air quality standards in the future is likely to require further reductions in pollutant emissions (although, of course, a move away from the combustion engine might make this change much easier). Increasing amounts of photochemical pollution could also have greater impacts on stressed ecosystems, although the increasing concentration of CO₂ may help to alleviate some types of impacts as the leaf's stomata close somewhat. Summertime dryness in some regions could exacerbate the potential for fire, creating the potential for increased amounts of smoke, while in other regions dust may become more of a problem.

International Coupling

While it is natural to look most intently at consequences within the US, our Nation is intimately coupled to the world in many ways. For example, what happens outside the US will affect economic markets, overseas investments, the availability of imported food and other resources, and the global environment that all countries share. Health-related impacts overseas are likely to be of importance to US citizens both because US citizens travel abroad for business and pleasure and because foreign travelers come to visit the US. Many resources, from water and hydropower-derived electricity to fisheries and migrating species, are shared across borders, or move and are transferred internationally. Finally, the US is largely a nation of immigrants, and when disaster strikes overseas, its citizens respond with resources and our borders are often opened to refugees. Clearly, all countries are connected to what happens outside their borders, and those of us in the US will be affected by what the societal and environmental consequences experienced by others.

Summary of Impacts

It is very difficult to accurately quantify the risk and importance of such a wide variety of impacts in a way that allows comparison with taking actions to change energy systems (IPCC, 1996c; IPCC, 2001c). At the international level, this is particularly difficult because issues of equity and cultural values more forcefully enter into consideration (e.g., what is the present economic value of the risk of the Marshall Islands being flooded over in 50 to 100 years?). Overall, there will likely be important consequences, some negative and some positive, that we are only starting to understand. Quite clearly, the present tendency to average across large domains is very likely to obscure rather large consequences for localized groups.

Reducing the Rate of Change of Atmospheric Composition to Slow Climate Change Will Require Significant and Long-Lasting Cutbacks in Emissions

In recognition of the potential for significant climatic and environmental change, the nations of the world in 1992 agreed to the United Nations Framework Convention on Climate Change (UNFCCC), which set as its objective the “stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” At the same time, the Convention called for doing this in a way that would “allow ecosystems to adapt naturally to climate change, ... ensure that food production is not threatened, and ... enable economic development to proceed in a sustainable manner.” Defining the meanings of these terms and accomplishing the objective are both formidable challenges. For example, stabilizing the atmospheric concentration at double the preindustrial level (about 550 ppmv) would require international stabilization of the present per capita CO₂ emission level at about 1 tonne of carbon per person per year throughout the 21st century rather than allowing per capita emissions to double over this period, as is projected to occur in the absence of controls (recall that the typical US citizen is now responsible for emission of 5-6 tonnes of carbon per year and Europeans are responsible for about 3 tonnes of carbon per year). Limiting the CO₂ concentration to 550 ppmv would also require that global emissions for the 22nd century would need to drop by at least a factor of 2 below current global average levels (i.e., to about half of the 6 billion tonnes of carbon now emitted each year), meaning that per capita emissions of carbon would have to be about one-third the level of developing countries today. This would not mean that per capita energy use would need to be this low, only that net per capita use of fossil fuels (so emissions minus sequestration) would need to be this low. The IPCC (IPCC, 2001c) suggests that such reductions could be accomplished by meeting

most of the world’s energy needs using renewables and nuclear, and if there is also significant effort to improve the efficiency of energy end uses.

The Kyoto Protocol was negotiated as a first step toward achieving the UNFCCC objective. Even though its goal is relatively modest (i.e., cutting developed country emissions to about 7% below their 1990 levels) and would only begin to limit the rate of increase in the global CO₂ concentration, it has been especially controversial in the US. Even if fully implemented by all the developed nations through the 21st century (including the US, which has rejected it), the increase in the CO₂ concentration by the year 2100 would be only about 15-20% less than the currently projected rise to about 710 ppmv, and much less than the 50% cutback in emissions needed to move toward stabilization at 550 ppmv. Such analyses make it clear that reducing CO₂ emissions to achieve stabilization at 550 ppmv would thus require a multi-faceted approach around the world as well as in the US, including significant introduction of non-fossil energy technologies, improvement in energy generation and end-use efficiencies, and switching to natural gas from coal.

Absent such efforts on a global basis, the CO₂ concentration could rise to about 800-1100 ppmv (about 3-4 times the preindustrial level). Were this to occur, projections indicate that the resulting warming would be likely to induce such potentially dangerous long-term, global-scale impacts as the initiation of the eventual melting of the Greenland and the West Antarctic ice sheets (each capable of inducing a sea level rise of up to about 15-20 feet, or 5-7 meters, over the next several centuries), the loss of coral reef ecosystems due to warming and rapid sea level rise, the disruption of the global oceanic circulation (which would disrupt the nutrient cycle sustaining ocean ecosystems), and extensive loss or displacement of critical ecosystems that societies depend on for many ecological services.

What is clear from present-day energy analyses is that there is no “silver bullet” that could easily accomplish a major emissions reduction (e.g., see Hoffert et al., 2002). Achieving the UNFCCC objective over the 21st century is therefore likely to require a much more aggressive (although not unprecedented) rate of improvement in energy efficiency, broad-based use of non-fossil technologies (often selecting energy sources based on local resources and climatic conditions), and accelerated technology development and implementation.

Conclusion

A major reason for controversy about dealing with this issue results from differing perspectives about how to weigh the need for scientific certainty, about ensuring a reliable source of energy to sustain and improve the national and global standard-of-living, about capabilities for improving efficiency and developing new technologies, about the potential risk to “Spaceship Earth” that is being imposed by this inadvertent and virtually irreversible geophysical experiment, about the economic costs and benefits of taking early actions to reduce emissions (including what factors to consider in the analysis and how to weigh the importance of long-term potential impacts versus better defined near-term costs), and about the weight to give matters of equity involving relative impacts for rich versus poor within a nation, the developed versus developing nations, and current generations versus future generations.

Moving toward a consensus on these issues will require that everyone become better informed about the science of climate change, about potential impacts, and about potential options for reducing emissions. Moving toward collective action will require that the political system focus on finding approaches that tend to balance and reconcile these (and additional) diverse, yet simultaneously legitimate, concerns about how best to proceed.

Acknowledgments

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U. S. Department of State (DOS), 2002, *U. S. Climate Action Report—2002*, U. S. Government Printing Office, Washington DC, 263 pp. (see especially Chapter 6 on Impacts).

This paper is updated from MacCracken, M. C., 2001, Global Warming: A Science Overview, pp. 151-159 in *Global Warming and Energy Policy*, Kluwer Academic/Plenum Publishers, New York, 220 pp.

Michael MacCracken retired from the University of California's Lawrence Livermore National Laboratory in the fall of 2002. His research there for the past 34 years had focused on numerical modeling of various causes of climate change (including study of the potential climatic effects of greenhouse gases, volcanic aerosols, land cover change, and nuclear war) and of factors affecting air quality (including photochemical pollution in the San Francisco Bay Area and sulfate air pollution in the northeastern United States). Most recently, he had been on assignment as senior global change scientist to the interagency Office of the U.S. Global Change Research Program (USGCRP) in Washington DC. From 1993 to 1997, he served as executive director of the Office, which is charged with helping to coordinate the combined research efforts of eleven federal agencies to understand and improve predictions of climate variability and change, depletion of stratospheric ozone, and the long-term, global-scale impacts of humans on the environment and society. From 1997-2001, Mike served as executive director of the National Assessment Coordination Office, a USGCRP-sponsored activity to facilitate regional, sectoral, and national assessments of the potential consequences of climate variability and change for the United States.

Observed Climate Change and Transportation

By David R. Easterling

Abstract

In this paper the current instrumental evidence regarding climate variations and change during the Twentieth Century is reviewed. The questions addressed include: (1) what is the observational evidence for a changing climate, both globally and in the United States, (2) what are the relevant results from the recently completed U.S. National Assessment examining the potential consequences of climate change in the U.S. Based on global near-surface temperature measurements for the Twentieth Century it is clear that a warming of approximately 0.6 deg C has occurred for the globe and a similar warming has occurred in the U.S. More importantly, however, are the observed asymmetric changes in daily maximum and minimum temperature, with the minimum temperatures increasing at a rate approximately twice that of the maximum temperature. Other temperature sensitive measures, such as glacial and snow cover extent reinforce the observed temperature trends.

Examination of the hydrologic cycle indicates that changes also appear to be occurring, although less confidence can be placed on these analyses than those for temperature. Recent studies suggest that precipitation has increased in higher latitudes, particularly in the Northern Hemisphere. The final question regarding climate extremes is much more difficult to assess due to a lack of high temporal resolution climate databases. Of the few studies that have been performed, however, there is evidence that precipitation extremes, particularly heavy rainfall events are increasing in the U.S., also suggesting an enhanced hydrologic cycle as the planet warms.

Introduction

Over the past decade considerable progress has been made in assembling databases, removing systematic biases from these data, and analyzing records for interannual variability and decadal changes in the mean for large sampling times (monthly to annual) and spatial extent. This paper reviews our base of knowledge about climate variability and change during the instrumental record and examines a few of the relevant results from the U.S.

National Assessment of the potential consequences of climate change in the U.S.

Is the Planet Getting Warmer?

There is little doubt that measurements show that near-surface air temperatures are increasing. Figure 1 shows the globally-averaged mean annual temperature time series including both land and ocean for 1880-2000. Although the overall trend of this time series is about 0.6 deg C/century, it shows a number of distinct periods with different trends. The characteristics of the

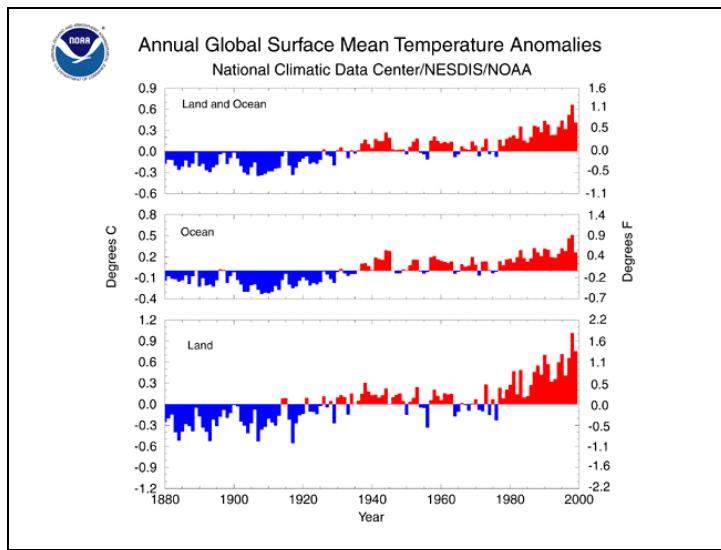


Figure 1. Global near-surface temperatures for land, ocean, and combined land and ocean.

time series, as calculated objectively by Karl et al. (1999) shows a cooling of -0.38 deg C / century from 1880-1910, then warming of 1.2 deg C/century from 1911 to 1945, a period of no change to 1975, then strong warming of 1.96 deg C/century since the 1970s. The period since the late 1970s has seen stronger and more frequent El Ninos, which have been shown empirically (Jones 1989, 1994) to add to any warming present due to other factors. One other feature about the time series is the large positive anomaly for 1998, making this the warmest year in the instrumental record due, in part, to the exceptionally strong 1997-1998 El Nino.

The rate and direction of temperature change has not been spatially uniform, as shown in Figure 2. Although much of the globe is warming, portions of the southern U.S., the North Atlantic Ocean, the Middle East and China actually cooled during the twentieth century. Some of the strongest warming is over the mid-to-high latitudes of the Northern Hemisphere, and it is also noteworthy that the magnitude of the warming on regional space scales is often much larger than the global mean.

The changes in mean temperature are a signal of a more interesting change in the mean daily maximum and minimum temperatures. Easterling et al. (1997) have shown that the rate

of temperature increase of the maximum temperature has been about one-half the rate of increase of the minimum temperature. Some regions, including Great Britain, have not shown this global signature of minimum temperatures rising faster than maximums. One other feature about these results is that the possibility of urban contamination of the time series was specifically addressed. This was done by excluding observing stations in larger urban areas ($> 50,000$ population), and comparing this analysis with the full data set, with the effect being only a very slight reduction in the temperature trends when urban areas are excluded.

The surface temperature warming has been greatest during the winter and spring seasons and least during the autumn. This is true in both global mean temperatures, and in trends in maximum and minimum temperatures (Easterling et al. 1997). Part of this seasonal disparity is related to the snow cover feedback effect as noted by Groisman et al. (1994) in an analysis of the ablation of spring snow cover in recent decades.

Is the Hydrologic Cycle Changing?

Global warming would very likely lead to changes in precipitation due to changes in

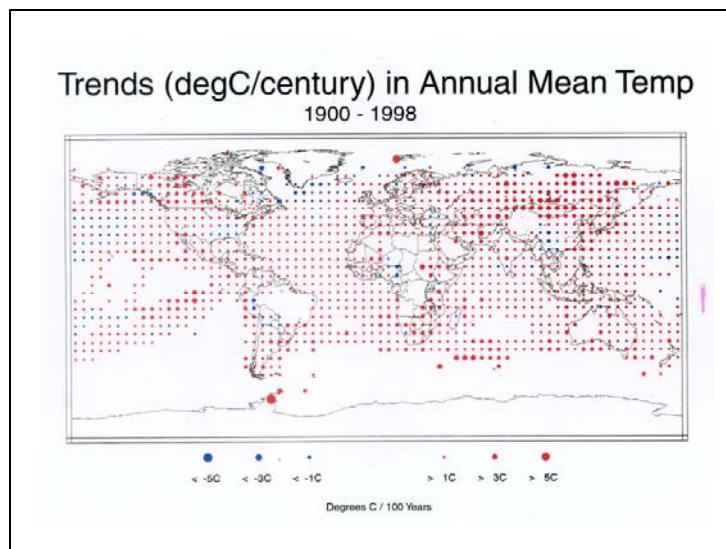


Figure 2. Map showing trends of temperature change for 1900-1998 in annual average temperature. Magnitude of the trends are reflected by the area of the circles. Red circles reflect increases and blue circles, decreases.

atmospheric circulation and a more active hydrologic cycle. This would be due, in part, to an increase in the water holding capacity of the atmosphere with an increase in temperature. Figure 3 reflects changes in precipitation for a variety of zones using the GHCN data set (Vose et al., 1992). There is an increase in the mid-to-high latitude precipitation and a notable decrease in subtropical precipitation. Some of the largest tropical decreases have occurred in the Sahel region in Africa due to long-term drought conditions from the 1960s to the mid-1990s. This region, however, has seen an increase in precipitation in the most recent years to a level approximately that of the 20th century average. There is also evidence to suggest that much of the increase of precipitation in mid- to-high latitudes arises from increased autumn and early winter precipitation in much of North America (Groisman and Easterling, 1994) and Europe (IPCC, 2001). Furthermore, large-scale coherent patterns of change in precipitation during the twentieth century are shown in Figure 4, which provides added confidence in the results. This figure shows the sometimes large, but spatially consistent patterns of decrease across the tropical and sub-tropical regions, and increases in most other areas. One other point about Figure 4 is that there are some large areas where we currently do not have reliable enough

data to calculate long-term trends. These areas include parts of high-latitude North America and Russia, as well as western China, and the Sahara.

Is the Weather and Climate Becoming More Extreme or Variable?

Perhaps one of the greatest interests in weather and climate relates to extremes of climate. Due to inadequate monitoring as well as prohibitively expensive access to weather and climate data held by the world's national weather and environmental agencies, only limited reliable information is available about large-scale changes in extreme weather or climate variability. The time-varying biases that affect climate means are even more difficult to effectively eliminate from the extremes of the distributions of various weather and climate elements. There are a few regions and climate variables, however, where regional and global changes in weather and climate extremes have been reasonably well-documented.

Interannual temperature variability has not changed significantly over the past century. However, on shorter time-scales and higher frequencies; e.g., days to a week, there is some

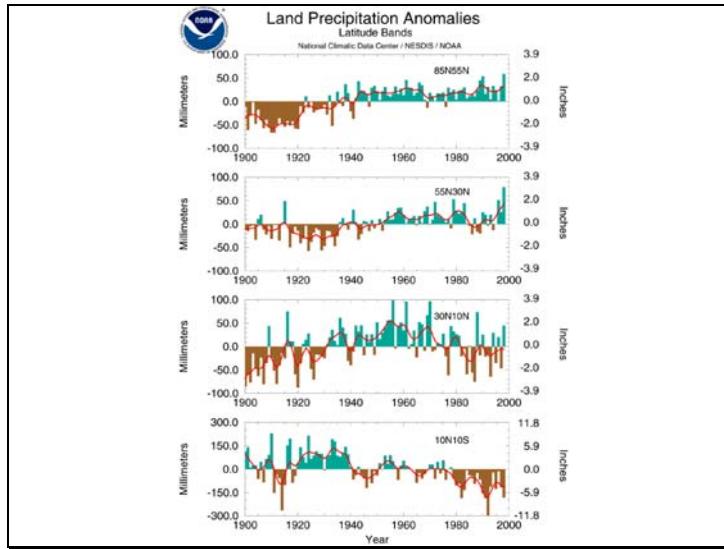


Figure 3. Zonally-averaged annual precipitation anomalies (using 1961-90 as base). Smooth curves were created using a nine-point binomial filter. Anomalies are based on the Global Historical Climatology Network data set.

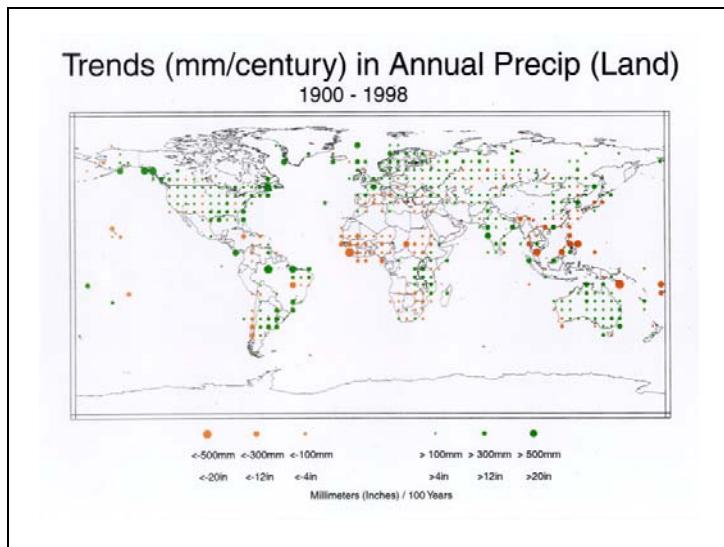


Figure 4. Map showing trends in annual precipitation over land, 1900-1998.

evidence for a decrease in temperature variability across much of the Northern Hemisphere (Karl and Knight, 1995). Related to the decrease in high-frequency temperature variability there has been a tendency for fewer low temperature extremes and a reduction in the number of freezes in disparate locations like the U.S. (Easterling 2002), and Queensland, Australia. Further, Easterling (2002) found a significant shift to an earlier date of the last spring freeze resulting in an increase in the frost-free season in most parts of the U.S. Widespread changes in extreme high temperatures, however, have not been noted.

Trends in intense rainfall events have been examined for a variety of countries (Karl et al., 1996; Suppiah and Hennesy, 1996). There is some evidence for an increase in intense rainfall events (U.S., tropical Australia, Japan, and Mexico), but analyses are far from complete and subject to many discontinuities in the record. Some of the strongest increases in extreme precipitation are documented in the U.S. Figure 5 shows annual trends in the contribution of heavy precipitation, defined as daily values above the 90 percentile, to the annual total for a number of countries. Results from this figure show that heavy precipitation amounts are increasing, in some areas by as much as 12 percent. However, in some areas of the U.S. this is being offset by decreases in more moderate events, and in other areas of the country (e.g. the Northwest, Southeast and Northeast) both amounts are increasing. Such increases, at least in the U.S., have been supported by an observed increase in water vapor (Ross and Elliott, 1997) and total precipitation.

The U.S. National Assessment: The Potential Consequences of Climate Variability and Change in the United States

In 1997 the U.S. Global Change Research Program (USGCRP) undertook the task of organizing a major assessment of the potential consequences of climate change on the United States. This report (NAST 2001) is the product of input from hundreds of researchers and

stakeholders in the U.S. and was first released in the fall of 2000. Below is a summary of some of the points relevant to this audience.

A unique aspect of the U.S. National Assessment is the combination of a national-scale analysis with an examination of potential impacts of climate change on a regional level. For example, in the southeastern U.S., increasing sea-level has already impacted coastal areas such as Louisiana by causing coastal wetlands losses, which then puts these areas at a greater risk from storm surges associated with tropical and extratropical storms.

What are some other aspects of this Assessment that are directly relevant to transportation? First, future conditions were evaluated by using results from state of the art climate model simulations in impacts studies, and by using results from the current scientific literature. Some of the relevant results include:

- Some climate models show a reduction in soil moisture in many areas resulting in decreases in ground and surface water supplies. This could result in a decrease in the levels of the Great Lakes by as much as a meter or more. However, other model results suggest little change in lake levels. Reductions in base stream flow could cause problems with transportation such as barge shipping, infrastructure, and reductions in water supply. However, warmer winter temperatures could result in a longer ice-free season thereby extending the shipping season on the Great Lakes.
- A possible reduction in Western U.S. snowpack that would impact water supply and streamflow. This could result in a seasonal redistribution of water availability.
- In Alaska, permafrost has already undergone extensive melting and if future projections of high-latitude warming hold, then melting would continue.
- Heavy precipitation events in the U.S. have increased over the 20th century, and could

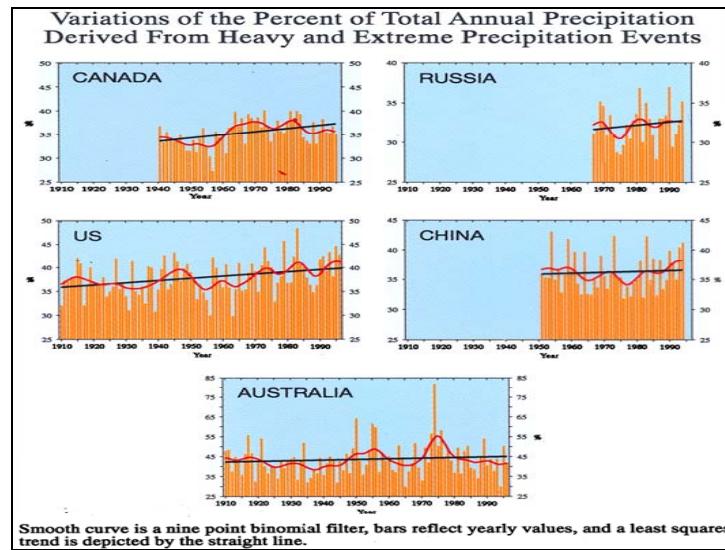


Figure 5. The trends in the percent of the annual total precipitation derived from heavy precipitation events for Canada, the United States, Russia, China, and Australia.

continue with a more vigorous hydrologic cycle as projected by model scenarios.

- Increasing summer temperatures, coupled with increasing water vapor, would likely result in increases in the summer-time heat index in many parts of the country.

Other Relevant Results

The U.S. National Climatic Data Center (NCDC) provides climate information in a variety of ways that are relevant to transportation. These include the calculation and distribution of Climate Normals, and climate data intended for engineering purposes. The NCDC has recently recalculated and released the 1971-2000 Normals of temperature and precipitation for the U.S. These Normals are used by a variety of industries for use in activities such as calculating energy demand and energy rate setting as well as the rapidly growing weather derivatives market. Figure 6 shows the difference between the 1961-1990 Normals of temperature and the 1971-2000 Normals. The decade of the 1990s in the U.S. was one of the warmest, only equaled by the Dust Bowl decade of the 1930s. The difference map (Figure 6) shows that the Normals of annual average temperature have increased by as

much as 0.6 deg C (1 deg F) or more in some areas with the biggest increases occurring in the winter. Precipitation Normals (Figure 7) have also shown increases over the previous Normal of as much as 50 mm (2 inches) or more.

Summary and Conclusions

The suite of available climate data can be used to assemble a coherent, quantitative description of variations and changes during the instrumental climate record. These data indicate that the planet has warmed by approximately 0.6 deg C during the past century, and this temperature increase has been strongest at night and over the mid-to-high latitude continental areas. The warming has tended to occur in jumps rather than in a continuous fashion with the most recent jump(s) occurring in the late 1970s and perhaps around 1990 (subsequent data will affirm or contradict this recent jump). Global data are available from these analyses, but are largely based on monthly means which are often unsatisfactory in capturing extreme climate and weather events. Exceptions to this occur primarily on a national basis. That is, high resolution daily temperatures are available on a country-by-country basis, but have not been assembled into a consistent long-term data base. In the U.S. reductions in the number of frost

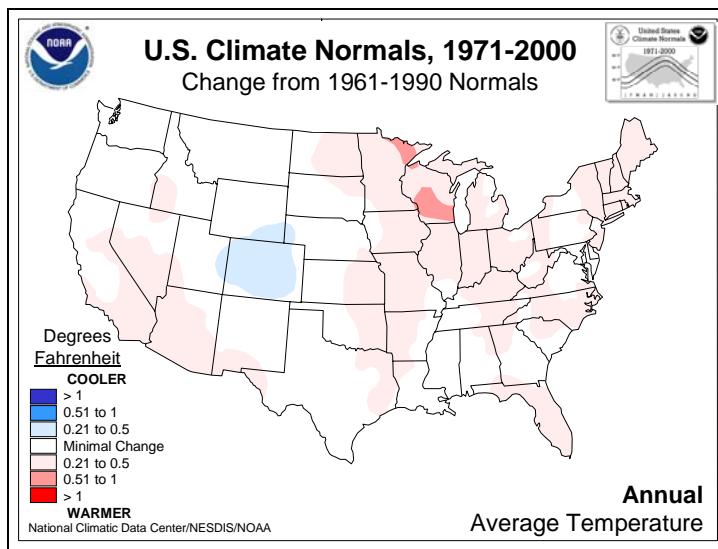


Figure 6. Map showing the difference between the 1961-1990 normals of temperature and the 1971-2000 normals. Areas in red show warming; blue shows areas with cooling.

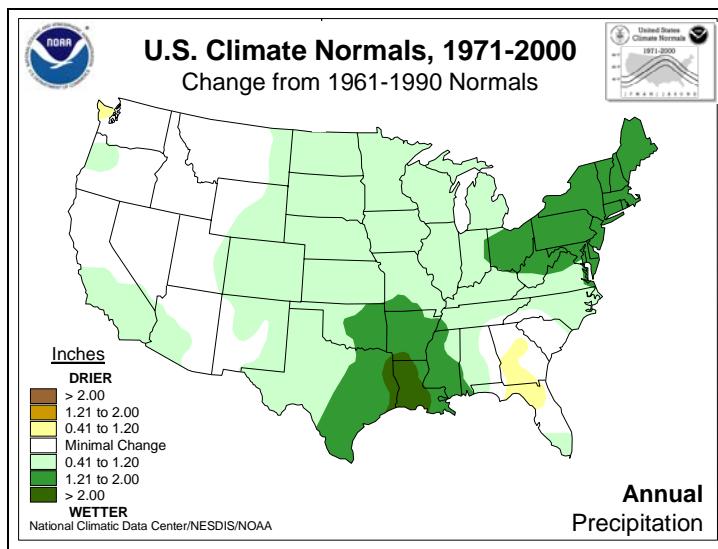


Figure 7. Map showing the difference between the 1961-1990 normals of annual precipitation and the 1971-2000 normals. Areas in green show precipitation increases and light brown show decreases. The western Gulf Coast and the Northeast have experienced the largest increases.

days and an increase in the length of the frost-free season have occurred over the latter half of the 20th century.

Precipitation has increased in the mid-to-high latitudes and has tended to decrease in the subtropics. High-resolution daily precipitation data is also available for a few countries, and has been analyzed for changes in extremes. Significant increases in extreme precipitation rates are apparent in the U.S.

Results from the U.S. National Assessment indicate that potential problems exist in sea-level rise, water supply, and warming in higher latitudes (Alaska) resulting in permafrost thawing. Warming winter temperatures also may lead to a decrease in winter-time energy demand but an increase in summer energy demands as the differences in the new U.S. Climate Normals suggest.

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National Assessment of the Consequences of Climate Variability and Change for the United States

By Michael C. MacCracken

Climate is an important influence on both the environment and society. Year-to-year variations are reflected in such things as the number and intensity of storms, the amount of water flowing in rivers, the extent and duration of snow cover, ocean-current induced changes in the height of sea level, and the intensity of waves that strike coastal regions and erode the shoreline. These factors in turn determine agricultural productivity, the occurrence of floods and droughts, the safety of communities, and the general productivity of society. Science now suggests that human activities are causing the natural climate to change, mainly by inducing global warming and an associated intensification of the global hydrologic cycle. Although the details are still emerging about the magnitude, regional pattern, and timing of the changes projected for the next century, that climate will be changing is widely recognized. Indeed, temperatures have increased in many areas, Arctic sea ice is much thinner, continental snow cover is not lasting as long in the spring, and total precipitation is increasing, with more rainfall occurring in intense downpours. These changes also appear to be affecting the distribution of plants and wildlife. There is evidence of a longer growing season in northern areas and changing ranges for butterflies and other species.

The Global Change Research Act of 1990 [Public Law 101-606] gave voice to early scientific findings that human activities were starting to change the global climate: “(1)

Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few generations; (2) Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being.”

To address these issues, Congress established the U.S. Global Change Research Program (USGCRP) and instructed the Federal research agencies to cooperate in developing and coordinating “a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural process of global change.” Further, the Congress mandated that the USGCRP *shall prepare and submit to the President and the Congress an assessment which*

- *integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;*
- *analyzes the effects of global change on the natural environment, agriculture, energy*

production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and

- *analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.*

The cycle of climate change assessments began in 1990 with USGCRP support for international assessments by the Intergovernmental Panel on Climate Change (IPCC). The IPCC assessments from 1990, 1996, and 2001 document existing global-scale changes and project that these changes will increase in magnitude over the next 100 years. As a consequence of the changes in climate, the IPCC also projects significant environmental change, generally at the continental scale. To provide a more focused picture of what climate change might mean for the U.S., the USGCRP initiated the *National Assessment of the Potential Consequences of Climate Variability and Change* in 1997. This Assessment focused on answering why people in the U.S. should care about climate change and how actions might be taken to effectively prepare for an average national warming of 5 to 9°F and significantly altered patterns of precipitation and soil moisture. It is just such changes that are simulated by global climate models assuming that global emissions of carbon dioxide and other greenhouse gases continue to climb as projected.

The overall goal of the Assessment has been to analyze and evaluate what is known about the potential consequences of such changes in the context of other pressures on the public, the environment, and the Nation's resources. By building broader understanding of the prospects for climate change and of the importance of these changes for the Nation, the USGCRP is aiming to promote an intensifying exploration of options that can help to reduce the vulnerability of individuals, public and private sector organizations, and the resource base on which society depends. With good information, these responses should be able to help build resilience

to climate variations and, to at least some extent, avoid or reduce the deleterious consequences of climate change while taking advantage of conditions that may be more favorable.

The Assessment process has been broadly inclusive in its approach, drawing on inputs from many sources. Support has been provided in a shared manner by the set of USGCRP agencies, including the departments of Agriculture, Commerce (National Oceanic and Atmospheric Administration), Energy, Health and Human Services, and Interior plus the Environmental Protection Agency, National Aeronautics and Space Administration, and the National Science Foundation. Although support for various activities has come mostly from the federal agencies, the conduct of the Assessment has been carried out in a highly distributed manner. Each of a diverse set of activities has been led by a team comprised of experts drawn from universities and government, from the public and private sectors, and from the spectrum of stakeholder communities. Through workshops and assessments, a dialogue has been started about the significance of the scientific findings concerning climate change and the degree to which existing and future changes in climate will affect issues that people care about, both at present and in the future. The reports that have been prepared have all gone through an extensive review process involving scientific experts and other interested stakeholders, ensuring both their technical accuracy and balance.

Three types of activities have underpinned the Assessment effort:

1. **Regional analyses and assessments:** An initial series of workshops provided the basis for characterizing the potential consequences of climate variability and change in regions spanning the U.S. A total of 20 workshops were held around the country in 1997 and 1998; sixteen of these groups then went on to prepare assessment reports focusing on the most critical issues identified. These activities focused on the implications of the patterns and texture of changes where people live. Although issues

considered often seemed to have a common thread, the implications often played out in different ways in different places. For example, various manifestations of the issue of water arose in virtually all regions. In some regions, it was changes in winter snowpack that project the need to adjust water allocations and the operational procedures for managing reservoir systems to ensure safety and supplies for electric generation, irrigation, industry, and communities; in other regions issues related to the potential influences of changes in precipitation amount on water quality, summertime drought, or river and lake levels. Table 1 highlights examples of issues as they arose across the country in nine consolidated regions.

- 2. Sectoral analyses:** To explore the potential consequences for sectors of national interest that cut across environmental, economic, and societal interests, the Assessment examined implications for agriculture, forests, human health, water, and coastal areas and marine resources. These sectoral studies analyzed how the consequences in each region would affect the nation, and how national level changes would affect particular areas. Key findings from each of the sectoral studies contributed to the findings at both the regional level and the national level (see Tables 1 and 2, respectively).
- 3. National overview:** A fourteen-member National Assessment Synthesis Team (NAST) drawn from academia, industry, government, and non-governmental organizations had responsibility for summarizing and integrating the findings of the regional and sectoral studies and then drawing conclusions about the importance of climate change and variability for the

United States. To document their findings, an extensive Foundation report was prepared that ties the findings to the scientific literature. To convey their message to the broader public and leading decision makers, an Overview report was prepared that describes the key issues facing nine regions across the U.S. and five sectors. The key findings from their report that apply to the nation as a whole are summarized in Table 2. An important advance was consistent use of a set of well-defined terms to indicate the relative likelihood of various outcomes based on the considered judgment of the experts that NAST represented. While some types of changes were found to be highly likely or unlikely, many were judged to be only possible based on current understanding. To gain better information, the NAST summarized key directions for research, urging particularly the strengthening of efforts to take an integrated look at the changing set of stresses facing regions and resource managers.

With the increasing level of understanding of global-scale environmental challenges, the conduct of assessments provides an important means for linking the emerging findings of the scientific community with the information needs of stakeholders. While also creating an urgency for new and elaborated scientific findings, these couplings in turn provide insights about potential vulnerabilities and response options for those responsible for economic development and societal welfare. The progress made in the initiation of the National Assessment and related activities in other nations is stimulating the beginning of a greater number of such activities around the world, building a society that is better informed and better prepared for not just climate change, but other long term issues of sustainability.

Table 1. Examples of important consequences of climate change affecting particular areas of the United States.

Regions and Subregions	Examples of Key Consequences Affecting:		
	The Environment	The Economy	People's Lives
Northeast New England and upstate NY Metropolitan NY Mid-Atlantic	Northward shifts in the ranges of plant and animal species (e.g., of colorful maples) Coastal wetlands inundated by sea-level rise	Reduced opportunities for winter recreation such as skiing; increased opportunities for warm-season recreation such as hiking and camping Coastal infrastructure will need to be buttressed	Rising summertime heat index will make cities less comfortable and require more use of air-conditioning Reduced snow cover
Southeast Central and Southern Appalachians Gulf Coast Southeast	Increased loss of barrier islands and wetlands, affecting coastal ecosystems Changing forest character, with possibly greater fire and pest threat	Increased productivity of hardwood forests, with northward shift of timber harvesting Increased intensity of coastal storms threaten coastal communities	Increased flooding along coastlines, with increased threat from storms Longer period of high heat index, forcing more indoor living
Midwest Eastern Midwest Great Lakes	Higher lake and river temperatures cause trend in fish populations away from trout toward bass and catfish	Increasing agricultural productivity in many regions, ensuring overall food supplies but possibly lowering commodity prices	Lowered lake and river levels, impacting recreation opportunities Higher summertime heat index reduces urban quality of life
Great Plains Northern Central Southern Southwest/Rio Grande Basin	Rising wintertime temperatures allow increasing presence of invasive plant species, affecting wetlands and other natural areas Disruption of migration routes and resources	Increasing agricultural productivity in north, more stressed in the south Summertime water shortages become more frequent	Altered and intensified patterns of climatic extremes, especially in summer Intensified springtime flood and summertime drought cycles
West California Rocky Mountains/Great Basin Southwest/Colorado River Basin	Changes in natural ecosystems as a result of higher temperatures and possibly intensified winter rains	Rising wintertime snowline leads to earlier runoff, stressing some reservoir systems Increased crop yields, but with need for greater controls of weeds and pests	Shifts toward more warm season recreation activities (e.g., hiking instead of skiing) Greater fire potential created by more winter rains and dry summers Enhanced coastal erosion
Pacific Northwest	Added stress to salmon populations due to warmer waters and changing runoff patterns	Earlier winter runoff will limit water availability during warm season Rising forest productivity	Reduced wintertime snow pack will reduce opportunities for skiing, increase opportunities for hiking Enhanced coastal erosion
Alaska	Forest disruption due to warming and increased pest outbreaks Reduced sea ice and general warming disrupts polar bears, marine mammals, and other wildlife	Damage to infrastructure due to permafrost melting Disruption of plant and animal resources supporting subsistence livelihoods	Retreating sea ice and earlier snowmelt alter traditional life patterns Opportunities for warm season activities increase

Table 1. Examples of important consequences of climate change affecting particular areas of the United States.

Regions and Subregions	Examples of Key Consequences Affecting:		
	The Environment	The Economy	People's Lives
Coastal and Islands Pacific Islands South Atlantic Coast and Caribbean	Increased stress on natural biodiversity as pressures from invasive species increase Deterioration of corals reefs	Increased pressure on water resources needed for industry, tourism and communities due to climatic fluctuations, storms, and saltwater intrusion into aquifers	Intensification of flood and landslide-inducing precipitation during tropical storms More extreme year-to-year fluctuations in the climate
Native People and Homelands	Shifts in ecosystems will disrupt access to medicinal plants and cultural resources	The shifting climate will affect tourism, water rights, and income from use of natural resources	Disruption of the religious and cultural interconnections of Native people and the environment

Table 2. Key consequences of climate change of importance to the United States.

1. Increased warming and more intense precipitation will characterize the 21st century.
2. Differing regional impacts will occur, with greater warming in the western U.S., but a greater rise in heat index in the east and south.
3. Vulnerable ecosystems, particularly alpine areas, barrier islands, forests in the Southeast, and other vulnerable ecosystems will be significantly impacted.
4. Water will be a concern across the country, with increased competition for available resources, and the potential for more droughts and floods and reduced winter snowpack in some areas.
5. Food availability will increase because of increased crop productivity, although lowered commodity prices will stress farmers in marginal areas.
6. Forest growth will increase in the near-term, but some forests will be threatened over the long-term by increased susceptibility to fire, pests, and other disturbances.
7. Increased damage is very likely in coastal regions due to sea-level rise and more intense storms, while damage in other areas will result from increased melting of permafrost.
8. Adaptation will determine the importance of health outcomes, so that strengthening of the nation's community and health infrastructure will become increasingly important.
9. The impacts of other stresses will be magnified by climate change, with multiple factors causing adverse impacts on coral reefs, wildlife habitats, and air and water quality.
10. Uncertainties remain in current understanding and there is a significant potential for unanticipated changes.

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Michael MacCracken retired from the University of California's Lawrence Livermore National Laboratory in the fall of 2002. His research there for the past 34 years had focused on numerical modeling of various causes of climate change (including study of the potential climatic effects of greenhouse gases, volcanic aerosols, land cover change, and nuclear war) and of factors affecting air quality (including photochemical pollution in the San Francisco Bay Area and sulfate air pollution in the northeastern United States). Most recently, he had been on assignment as senior global change scientist to the interagency Office of the U.S. Global Change Research Program (USGCRP) in Washington DC. From 1993 to 1997, he served as executive director of the Office, which is charged with helping to coordinate the combined research efforts of eleven federal agencies to understand and improve predictions of climate variability and change, depletion of stratospheric ozone, and the long-term, global-scale impacts of humans on the environment and society. From 1997-2001, Mike served as executive director of the National Assessment Coordination Office, a USGCRP-sponsored activity to facilitate regional, sectoral, and national assessments of the potential consequences of climate variability and change for the United States.

Notes on Transportation into the Year 2025

By Donald R. Trilling

The following paper was background reading for a panel of experts who met to discuss research needs regarding the impacts of global climate change on the Nation's transportation system. It draws heavily on the first chapter of the U.S. Department of Transportation document *The Changing Face of Transportation*,¹ published in January 2001, and *Transportation in 2050*.² The paper assumes that global climate change is taking place, and that it will have impacts on the transportation system. The range and nature of potential effects are discussed in separate papers.

It is impossible, of course, to fully predict the timing and broad scope of changes in U.S. transportation over 25 years, or the social and economic shifts which drive them. The following projects a single scenario, among many scenarios which are possible. All of this material predated the horrific events of September 11, 2001. It is too soon to gauge what the long-term influence of those events will be on the trends depicted here.

Introduction

Table 1 provides forecasts for U.S. transportation activity to the year 2025.³ While it is two years old, it presents an authoritative, internally consistent set of projections, and unless otherwise noted, will be the basis for all numerical activity estimates cited below. It projects that over the next 25 years, the U.S. population is likely to continue growing at an average annual rate of change of about 0.82 percent, reaching a level of 338 million by 2025. The age distribution of the population, however, will continue to change significantly. The median age has risen from 28.8 in 1975 to 35.2 in 1999, and it is expected to reach 38.0 by 2025.⁴ These demographics will challenge

transportation managers to maintain system safety and efficiency, in the face of a changing makeup of the workforce, the numbers of youthful versus aging drivers, and shifts in consumer preferences for products and services.

Economic projections tend to be more near-term. The Congressional Budget Office 2000 estimates suggest growth in production at a substantially faster rate than population growth—about 2.7 percent compounded annually over the next 10 years. Projected forward, we might expect Gross Domestic Product (GDP) to reach \$29 trillion by 2025. In that event, per-capita GDP might well be close to 1.5 times today's level, even after adjustment for inflation.

Table 1. U.S. Transportation Activity, 1975 – 2025.

Forecasts Past and Future	1975	1990	2000	2025
	Actual	Actual	Estimated	Forecast ¹³
Transportation Context				
Population (millions) ¹	215	249	275	338
GNP (constant 1975\$, billions) ²	\$1,598	\$2,409	\$3,049	\$5,486
GNP Per Capita (1975\$) ²	\$7,417	\$9,675	\$11,087	\$16,240
GDP (constant 2000\$, billions) ³	NA	NA	\$9,942	\$18,258
Passenger Transportation				
Passenger-Miles (billions) ⁴	2,560	3,946	5,036	8,438
Passenger-Miles Per Capita ⁴	11,881	15,847	18,313	24,979
Licensed Drivers (millions) ⁵	130	167	190	243
Vehicles (millions) ⁶	138	193	219	262
Freight Transportation⁷				
(millions of Ton-Miles)	2,285,000	3,196,000	3,959,432	5,098,888
Rail	754,252	1,033,969	1,416,446	1,484,802
Water (domestic ton-miles)	565,984	833,544	763,540	NA
Water (domestic and foreign short tons)	1,695	2,164	2,453	3,429
Truck (intercity)	454,000	735,000	1,130,132	2,121,837
Air	3,470	9,064	15,904	33,925
Pipeline (hazardous liquids)	507,000	584,000	633,410	797,950
Safety⁸				
Transportation fatalities	49,214	47,248	42,600	40,300
Air Pollution⁹				
CO (millions of tons)	85.27	61.18	50.48	24.24
No _x (millions of tons)	9.45	8.51	8.66	7.98
Greenhouse gas emissions ¹⁰	350.00	420.00	500.00	600.00
Energy¹¹				
Btu ¹² (trillions)	16,998	24,070	25,200	36,600

¹Population projections are taken from U.S. Department of Commerce, Bureau of the Census, Annual Projections of the Total Resident Population as of July 1: Middle Series Projections for 2000 and 2025.

²Forecasts for GNP are based on 1975 through 1999 data, using log linear (Holt) exponential smoothing model, parameters optimized through SAS/ETS software.

³Forecasts for GDP are based on 1929 through 1999 data, using damped trend exponential smoothing, parameters optimized through SAS/ETS software. NA = not available.

⁴Forecasts are based on 1990 through 1997 data, using damped trend exponential smoothing, parameters optimized through SAS/ETS software.

⁵Forecasts are based on 1949 through 1998 data, using damped trend exponential smoothing, parameters optimized through SAS/ETS software. Forecasts for vehicles are based on 1990 through 1997 data, using double (Brown) exponential smoothing, parameters optimized through SAS/ETS software.

⁷Forecasts for total ton-miles are an aggregate of the individual forecasts by mode. Forecasts for rail ton-miles are based on 1990 through 1998 data, using damped trend exponential smoothing, parameters optimized through SAS/ETS software. (The FRA, however, forecasts a two percent average annual growth rate for the 2000-2025 period. This translates into 2.4 trillion ton-miles in 2025.) Forecasts for water ton-miles are based on two forecast models: log damped trend exponential smoothing based on 1990 through 1997 data, and log simple exponential smoothing based on 1960 through 1995 data in five year increments; the two forecasts are combined with equal weights. Forecasts for truck ton-miles are based on two forecast models: linear trend based on 1990 through 1997 data, and double (Brown) exponential smoothing based on 1960 through 1995 data in five year increments; the two forecasts are combined with equal weights. Forecasts for air ton-miles are based on two forecast models: linear trend based on 1990 through 1998 data, and damped trend exponential smoothing based on 1960 through 1995 data in five year increments; the two forecasts are combined with equal weights. Forecasts for pipeline ton-miles are based on 1990 through 1997 data using log linear trend. All forecast model parameters optimized through SAS/ETS software.

⁸Forecasts are based on 1990 through 1998 data, using damped trend exponential smoothing, parameters optimized through SAS/ETS software.

⁹Forecasts for CO are based on 1985 through 1997 data, using log linear trend parameters optimized through SAS/ETS software. Forecasts for NO_x are based on 1985 through 1997 data, using double (Brown) exponential smoothing, parameters optimized through SAS/ETS software. Forecasts for greenhouse gas emissions are based on expert opinion.

¹⁰Millions of metric tons of carbon equivalent, excluding bunker fuels.

¹¹Forecasts based on 1990 through 1997 data, using double (Brown) exponential smoothing, parameters optimized through SAS/ETS software.

¹²Btu: British thermal unit.

¹³The 2025 forecasts are purely statistical. For sources of data used in these forecasts see The Changing Face of Transportation, *ibid*, page 1-32.

Generally speaking, as population grows, travel rises. But changes in the age distribution, geographic distribution, and even immigration also affect travel volume and patterns. Economic well-being can also slow or accelerate use of the transportation system, while changing the mix of transportation modes or trip purpose. International factors such as the globalization of the economy and population change can further impact both trade and passenger flows. Thus, demographics and economics provide an important future context for transportation decision-making by individuals, governments, and private industry.

Economic location decisions are creating large metropolitan areas around one or more urban centers and their suburbs. This pattern is particularly evident along the Nation's coastal areas. If the changes in climate occur as projections indicate, then coastal areas will need to prepare their infrastructures for higher sea levels, more frequent extreme weather events, and higher levels of accompanying storm surges. The economic losses from such storms will grow, not only because of their increased frequency and intensity, but also because the trends for these areas are higher population densities and more elaborate and expensive construction. Climate change may also bring population shifts due to shoreline flooding, changes in agricultural patterns, and increased intensity in weather-related disasters.

Priorities

It is impossible to predict how the top priorities for the Nation's transportation system will change over the next 25 years but they will likely be close to those of today: safety, transportation security, congestion relief, environmental protection, energy usage, globalization, and more rapid deployment of new technology. These concerns will be addressed through experimentation in innovative solutions, creative management and planning, developing technologies such as Intelligent Transportation Systems (ITS), and new strategies for capital investment and financing. Although the transportation system could take many future forms, all improvements will be

designed to improve access and ensure the free flow of goods and people within and among all of the various modes of transportation, and to allow people to be even more productive with their time, to experience new things, and to always be connected.

Safety

Reductions in highway accidents have come from improvements in road and motor vehicle design, increased seat belt use, enactment and enforcement of drunk driving laws, improvements at rail grade crossings, and public awareness campaigns. Additional gains are expected from advances in roadway designs, in-vehicle technologies (particularly wide-spread deployment of collision avoidance systems), technology-enhanced traffic law enforcement, further pedestrian/cyclist separation, and advances in trauma response and medical treatment after crashes.

Aggressive safety programs are ongoing in other modes as well. NASA and FAA are engaged in a joint program with the goals of reducing the aircraft accident rate by a factor of 5 by 2010, and by a factor of 10 by 2025. Rail operation will benefit from wide use of advanced train control systems, along with improved locomotive and rail passenger car safety standards. Recreational boating and marine safety programs, and improvements in the general safety of vessels (e.g., structural safety, fire protection) will retain their importance, even with the Coast Guard moving to the newly formed Department of Homeland Security.

While it is impossible to forecast the results of continued high priority safety programs, the projections of Table 1 indicate that fatalities could be expected to decrease to about 40,300 per year by 2025, even with passenger miles increasing by 68 percent over 2000. Technology, innovation, and leadership will be the keys to major safety advances in the future. The safety implications of potential climate change are presently poorly understood, and need to be identified and quantified so that the Nation can begin to develop safety

countermeasures that will forestall its negative effects.

Transportation Security

On September 11th, 2001, an attack by a determined and remorseless enemy brought us to realize the vulnerability of our transportation system. As a result, changes will be made in all modes, to meet the significant security challenges facing the transportation system, beginning with terrorism, and the introduction of weapons of mass destruction, but also including smuggling of people and illegal drugs, and protection of natural resources. Working closely with the Department of Homeland Security, Secretary Mineta intends to assure that these investments in new infrastructure and technologies made to enhance security also will improve system efficiency. As the impacts of climate change on transportation become understood and identified, and possible measures to mitigate them are catalogued, the changes made to respond to security needs may offer concurrent opportunities to respond to climate change.

Congestion

Addressing problems related to congestion will be a major challenge over the next 25-year period. Highway vehicle-miles traveled exceeded 2.6 trillion per year in 2000 and continue to grow. Transit ridership reached 9 billion in 1999, the highest in 40 years. Commercial airports handled more than 8.5 million flights, nearly double the number of flights handled in the mid 1970s. By 1999, U.S. domestic revenue passenger-miles had climbed to 473 billion and will continue to increase.

With economic growth will come increasing demand for transportation services, exacerbating present capacity constraints. In the surface modes, we cannot build ourselves out of this situation. Population presence and the existing built environment limits our ability to construct enough lanes or roads in most places where capacity is needed. Given the large footprint of the current urban infrastructure, relatively little ground level addition will be possible, without

greatly increased expense. Possible alternatives by 2025 include: going underground for expanded subway systems to carry people and goods, multi-tier roadways, building new guideways above ground over existing rights-of-way for rapid rail, or better exploitation of existing infrastructure through new practices and technology.

No matter what the form of infrastructure, new or existing, the long-range transportation planning process should now consider the anticipated effects of climate change, potentially building-in more resilience to climate variability while recognizing that there will be different impacts in different areas. Increased temperature loading on construction materials, higher likelihood of extreme weather events and the destruction and flooding that accompanies them, the possible collapse of perma-frost based structures, land erosion and subsidence, impacts of sea level rise on our ports and in coastal areas, and water level changes in the Great Lakes will all pose significant challenges for transportation officials.

Options that can reduce congestion and the demand for transportation may receive higher priority for development, such as telecommuting, alternative work schedules, peak period pricing and various user fees. Information technology offers a variety of scenarios for congestion relief. Improved communications providing virtual reality phones could let us feel closer to business associates and friends, reducing the need for face-to-face contact and with no need for geographic proximity. This could mean higher dispersion, however, increasing freight distances, and with uncertain outcomes as to personal travel.

Passenger Travel – By 2025, travelers will have widespread, real-time access—any time, any place—to information of all types, such as transportation availability, geographic location, and operating conditions over various segments of a trip. Using a range of media, they will be able to request demand-responsive services from any location. Transportation will have more of a customer orientation, and provide relatively seamless intermodal trips. In absolute terms,

passenger-miles of travel will increase faster than the growth in travel experienced during the 1990s—from 5 trillion miles in 2000 to 8.4 trillion in 2025, provided that capacity issues can be adequately addressed. A corresponding rise in global travel is also expected.

Even before the events of September 11, 2001, **aviation** was beset with capacity problems and significant public concern about flight delays and cancellations. Technology to address weather-related delays and modernization of the nation's air traffic control system will be part of the solution. Continued investment in airport capacity will still be necessary, with forecast demand exceeding capacity in a substantial number of airports, presenting a major constraint on growth.

Today's market share of **transit**—and its capacity in some geographic areas—is small, and may be only a small part of the solution. Although transit ridership has been recently growing at a rate faster than automobile travel in some urban areas, its impact has been limited. As congestion continues to grow, as the frequency and convenience of service improves, and as residential and commercial development decisions become better integrated with transportation decisions, more of its benefits will accrue, even to non-users. In addition, its role in maintaining mobility in metropolitan areas may gain in importance and with it the economic vitality of these areas may hang in the balance.

Congestion on **highways** will also be addressed through capacity expansion or a variety of demand management policies and technological innovations. Peak period access pricing may gain in prominence and could help to spread the flow of travelers through choke-points throughout the day. New transponder technology will collect tolls without the need to stop, and efficiently distribute the revenues to all stakeholders. Metropolitan areas across the country are actively deploying Integrated ITS Infrastructure to improve the capacity of the highway system. The tools necessary to advance telecommuting are available, but it is impossible to predict at this point what its impact will be on the trends shown in Table 1.

The interest in high-speed, **rail**-based ground transportation, heralded by the unveiling of *Acela*, Amtrak's new high-speed train service (with speeds reaching 150 mph) in the Northeast Corridor, may continue to grow. By 2025 other corridors in the nation may have high-speed train service, but there are many barriers to overcome before rail provides intercity travel times that will rival those of air travel.

Increased use of **waterborne** systems could address congestion in certain metropolitan areas like San Francisco, New York City, and Seattle. Ferries traveling up to 50 knots using conventional engines can mitigate traffic, but will require auxiliary technologies to control their emissions.

There will be greater concern for the safe mobility of those over 65, who will make up almost one-sixth of the population by 2025. New technologies will be employed to keep them driving safely longer, balanced by additional, more user-friendly, mobility options.

While traveling in the future will be different, the basic modes we use are unlikely to change. What will change are the characteristics of these systems, how we use them (e.g., the growing trend for shared ownership and use of cars), and how we construct our daily routines. As noted above, technology, and the prospect for increased affluence will help enhance the quality of the transportation experience.

Freight - The next 25 years will be a challenging time for all sectors of the freight community. Congestion and capacity issues are already apparent in every mode, with much of the transportation infrastructure requiring modernization. Workforce shortages are projected. At the same time, e-commerce and increasing globalization of the economy will increase transportation demand, requiring both more system capacity and greater reliability. Buyers will enjoy a close consumer-factory relationship where they can instantly customize their ordered products electronically and have them shipped directly from the factory. The freight system must accommodate an increase in

GDP likely to grow by 84 percent, in 2000 dollars, and that is projected to grow to just over 5 billion ton-miles by 2025—a 29 percent increase. But there may be shifts in how freight is moved and how freight transportation is managed.

There will be a continuation in the trend to a high volume of smaller shipments to satisfy low or no inventory production and distribution requirements and express package delivery. Highly integrated freight transportation companies will provide full logistics/transportation services using multiple modes.

Trucks will continue to dominate the freight transportation market, and their share of the primary shipment tonnage transported in the United States is expected to remain relatively constant for at least the next 10 years even as total volumes increase. There will be continuing efforts to address empty backhauls and unnecessary stops using information technology. Nevertheless, increasing truck traffic will become even more of a source of congestion along the Interstate and urban arterials.

Domestic **water** freight movement is expected to increase moderately over the next quarter century; foreign waterborne commerce is expected to double. A significant increase in international freight movement will require much larger ships, deeper channels, and high-capacity efficient intermodal cargo-handling ports. As these ports are improved, they can also incorporate measures to mitigate the expected effects of climate change.

Air cargo growth is expected at a pace even greater than today's because of e-commerce and globalization. Larger aircraft, both dedicated freighters and passenger aircraft with excess storage capacity, are expected to accommodate the growth in freight demand.

Estimates of growth in **rail** ton-miles vary considerably, with the most robust estimate

putting the average at 2 percent per year between 2000 and 2025.

Pipeline movements are projected to grow by over 25% through the period.

The Environment

It will become increasingly challenging to balance the need for greater mobility with the need to protect the environment. Projected growth in the population and the economy, along with the associated increases in travel and shipping, might easily offset the gains that might be achieved by greater choices in transportation, improved land use patterns, reformulated fuels, or greater capture of pollutants. Today, 39 percent of the U.S. population lives in a “nonattainment” area—not meeting National Ambient Air Quality Standards—for one or more of six criteria pollutants. Ground-level ozone, in particular, remains an important problem for most people in these areas.⁵

Tailpipe emissions of criteria pollutants from automobiles have already diminished substantially due to Clean Air Act standards, and their continued reduction is anticipated through 2025. They will continue to improve for trucks of all sizes as the new Tier II⁶ and heavy-duty diesel regulations⁷ take effect. As long as light duty vehicles are fossil-fuel dependent however, actual reductions in greenhouse gas (GHG) emissions appear to be limited, although new efficiencies introduced into the conventional power train have the potential to improve fuel economy by 20-40 percent or even more over the coming years.⁸ While we look to fuel cell and hybrid vehicles to offer even sharper declines, the full pace of deployment of such vehicles into the fleet by 2025 will be limited by the major national investment in making fossil fuel powered engines and the long lead time necessary to introduce new technologies into manufacturers' product lines.

In 2000, transportation produced nearly 1900 teragrams (1 Tg = 1 million metric tons) of greenhouse gases per year. Table 2 shows the growth in these emissions over the past decade,

and the proportion of total national greenhouse gases they represent. Figure 1 shows how they were distributed among the modes over that period. Table 1 indicates that greenhouse gas emissions are projected to grow 20 percent by 2025.

Emissions from airports and aircraft will become a greater concern as air travel increases. New aircraft meeting international noise and emissions standards will result in even quieter aircraft by 2025. Most of the world's current commercial aircraft, however, still will be operating 20 years from now. Increased use of cleaner ground support equipment and other steps to reduce airport-related emissions are likely to be in place. New communications, navigation, surveillance, and air traffic management procedures will allow optimization of all phases of flight – from planning and surface operations to enroute flight paths with resultant fuel savings and environmental benefits.

Large oil spills into U.S. waters are becoming less common and a response regime is in place to minimize impacts. Eventually, shifts in automotive design away from fossil fuels could break the pattern of both U.S. reliance on foreign oil and the associated pollution risks of moving that oil.

Efforts to control and reduce the introduction of invasive species in the transport sector will make progress, but this emerging concern is likely to continue to be an issue.

Dispersed, auto- and truck-dependent development patterns, often referred to as urban sprawl, can increase costs of providing community services and increase congestion, pollution, and consumption of natural resources. Zoning and land-use patterns that put needed day-to-day services close to each other, and support a range of transportation choices (e.g., communities that encourage less auto dependence, and use of transit, walking, bicycling, and small motorized personal vehicles) will begin to address these concerns, but will take many years to develop.

Table 2. U.S. transportation sector greenhouse gas emissions by gas (Tg CO₂ Eq.) and percent of U.S. total (2002).**⁹

	1990	1995	2000	% of U.S. Total (2000)
Transportation Total	1,530.5	1,655.1	1,879.7	26.80%
Direct Emissions	1,527.7	1,652.4	1,877.0	26.80%
CO ₂	1,471.8	1,579.4	1,789.5	25.60%
CH ₄	4.9	4.8	4.4	0.10%
N ₂ O	50.9	60.4	58.3	0.80%
HFCs	7.9	11.8	24.8	0.40%
Electricity-Related	2.8	2.6	2.8	N.A.

** Estimates are in units of teragrams of carbon dioxide equivalents (Tg CO₂ Eq.), which weight each gas by its Global Warming Potential, or GWP value.

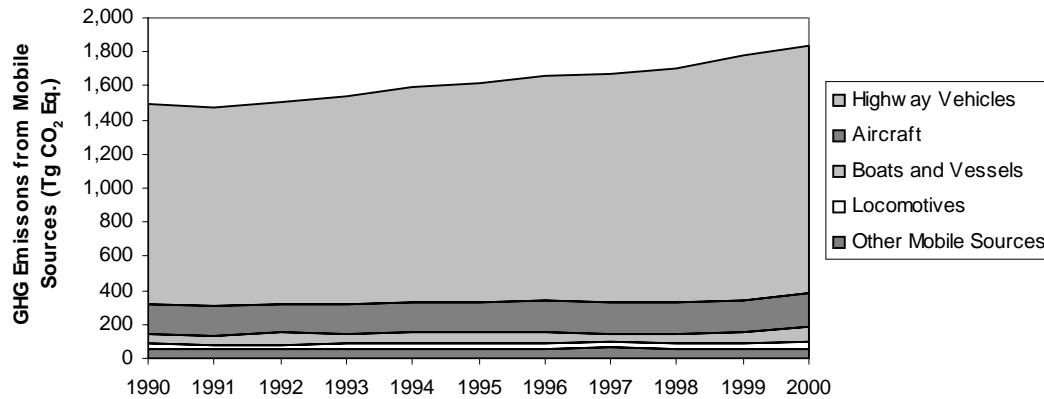


Figure 1. Greenhouse gas emissions from mobile sources by mode (Tg CO₂ Equivalent). Highway vehicles generate the majority of emissions, with aircraft the next largest contributor.¹⁰

In addition, there is growing recognition that transportation planning is not only about transportation, but also about the critical role it plays in all domestic sectors to meet the goals of other social policies. Besides its well defined role in energy policy, trade, and economic development, future planners will more systematically incorporate transportation considerations into their work in the areas of housing, land use, tax policy, health, aging, and homeland security.

Energy Usage

Detailed projections of domestic energy use are available from the Department of Energy only to 2020, as may be seen in Table 3. It projects that transportation energy use will rise from 27 trillion Btu per year to over 39 trillion Btu in 2020, a 44 percent increase. Over the next quarter century, transportation energy growth will continue to be dominated by the burning of gasoline and diesel fuels. There will be no shortage of such fuels, as long as people are willing to pay \$30-35 per barrel for oil or its equivalent, which we willingly did in the past.

New powertrain designs, such as hybrid electric and fuel cells, will become more common. As noted above, these new vehicle designs will be introduced slowly into the fleet, and take more years before their sales volumes

comprise a significant portion of new vehicle sales. Because it will take nearly a decade for such vehicles to capture a significant share of the total U.S. vehicle fleet, their effect on transportation energy use may only begin to make an impact by 2025. Policies such as tax incentives may be employed to accelerate the deployment of electric hybrids and fuel cell vehicles into the fleet.

Globalization

Several references above alluded to the growing globalization phenomenon, as more countries become linked by advanced information technologies, transnational enterprises, integrated financial markets, and growing international goods movement. Globalization will influence much of what we buy in the future. Most changes in transportation will occur outside the United States, requiring new capital for infrastructure investment in developing countries. As globalization spreads, average per-capita income of countries around the world will become closer. International transportation will now require new levels of security to combat terrorism, along with the enforcement of safety codes, environmental standards, and other forms of standardization required to facilitate transborder commerce.

Technology

It is often the case that we see great potential gains in efficiency or functionality from developing technology, but a marked lag in its deployment, so there will be continuing impetus for reducing the time from development to marketplace. Civil use of the Global Positioning System (GPS) will provide the basic infrastructure for a continuing and substantial improvement in the safety and efficiency of our national air, surface, and marine systems. ITS is being widely deployed to improve the mobility and safety of our surface transportation systems. Technologies such as ramp meters, electronic surveillance, signal synchronization and preemption; advanced weather and road condition information; computer-aided dispatch systems; commercial vehicle technologies¹¹; and a host of infrastructure innovations promise to reduce congestion, improve efficiency, and make travel safer. While all of these benefits are expected as we increase the deployment of GPS and ITS, some of these gains will be offset by the expected growth in highway travel by 2025.

Advances in materials will introduce new efficiencies by 2025 at every point of manufacture and construction. Nanotechnology and carbon fiber construction will enable light but very strong automobile and aircraft designs, with commensurate safety and fuel benefits. The same technology will likely spawn a new generation of rigid air ships for both passenger and freight transportation.

The current trend of embedding new technologies into the operations and management of the transportation systems will continue and probably accelerate over the next 25 years, facilitated by the continuing evolution of computers and communication components and networks. This technology will play a

prominent role in enabling sophisticated administration and operations of transportation services in an era of constrained expansion of physical infrastructure. The management of transportation systems will become highly automated and increasingly real-time, to the point where many aspects of it may seem to occur in the absence of human intervention. Real time pricing of transportation facilities will increase efficiency, reduce congestion delays and provide for innovative pricing policies.

Conclusion

Many would rate our transportation system as the best in the world, considering the long trip distances we take for granted, our safety measures in place, the low costs of the delivery of our goods, or the reliability that allows manufacturers to organize production around just-in-time inventory systems. But it is also a system under severe stress in some areas, due to congestion, increasing demands for travel and freight movement, and additional environmental and social requirements. The upward trends in population, and growth in national and international economic activity will exacerbate this, and it may well be that all we can do is maintain the level of service now provided. Technology of all kinds will offer relief, but it is impossible to predict the forms it will take, and how they will transform our society. The transportation system is massive, and its planning, construction and use cycles endure over many decades. It is difficult to project the full extent to which potential climate effects (e.g., more frequent violent storms, flooding) could bring additional stresses. At this juncture, nevertheless, we must initiate the research that will provide a scientific basis for informing our State and local partners, our managers, and our long-range planners, on what future investments would be most cost effective in responding to these effects.

Table 3. *Transportation sector energy use by mode (Trillion Btu).*¹²

	2000	2005	2010	2015	2020	Annual Growth rate 2000-2020
Highway						
Light-Duty Vehicles	14,971	16,743	18,485	20,072	21,367	1.80%
Automobiles	8,641	8,639	8,763	9,065	9,387	0.40%
Light Trucks	6,305	8,079	9,697	10,981	11,953	3.30%
Motorcycles	25	25	25	26	27	0.40%
Commercial Light Trucks (1)	638	686	772	849	914	1.80%
Buses	182	191	200	204	203	0.60%
Transit	87	92	96	97	97	0.60%
Intercity	23	25	26	26	26	0.60%
School	71	75	79	80	80	0.60%
Freight Trucks (2)	4,523	5,212	5,936	6,598	7,099	2.30%
Medium (1000-26000 pounds)	758	805	872	976	1,095	1.90%
Large (> 26000 pounds)	3,766	4,407	5,064	5,621	6,004	2.40%
Non-Highway						
Air (3)	3,113	3,347	3,913	4,571	5,287	2.70%
General Aviation	189	200	226	258	292	2.20%
Domestic Air Carriers	1,812	1,940	2,170	2,426	2,677	2.00%
International Air Carriers	670	731	827	936	1,038	2.20%
Freight Carriers	443	476	689	951	1,280	5.50%
Water (4)	1,713	1,665	1,706	1,756	1,801	0.20%
Freight	1,401	1,342	1,368	1,401	1,430	0.10%
Domestic Shipping	302	321	340	364	383	1.20%
International Shipping	1,099	1,020	1,028	1,037	1,047	-0.20%
Recreational Boats	312	323	338	355	371	0.90%
Rail	585	635	664	691	718	1.00%
Freight	506	547	569	587	605	0.90%
Passenger	79	87	96	105	114	1.90%
Intercity	20	23	25	27	30	1.90%
Transit	44	49	54	59	64	1.80%
Commuter	14	16	17	19	21	1.90%
Lubricants	180	207	222	237	250	1.70%
Pipeline Fuel Natural Gas	792	796	860	950	1,019	1.30%
Military Use	620	701	732	749	758	1.00%
Aviation	509	576	601	616	623	1.00%
Residual Fuel Use	18	20	21	22	22	0.90%
Distillate Fuel Use	93	105	110	112	114	1.00%
Total	27,317	30,182	33,490	36,676	39,416	1.90%

Notes:

(1) Commercial light trucks from 8,500 to 10,000 pounds.

(2) Does not include commercial bus and military use.

(3) Does not include military jet fuel use.

(4) Does not include military residual oil.

Totals may not equal sum of components due to independent rounding.

¹ The Changing Face of Transportation, U.S. Department of Transportation, Bureau of Transportation Statistics, BTS00-007, Washington, D.C.

² Safford, Mark A., Transportation in 2050, John A. Volpe Transportation System Center, Cambridge, MA, unpublished draft, 3/7/02.

³ The Changing Face of Transportation, *ibid*.

⁴ U.S. Bureau of the Census, Census 1999.

⁵ EPA, National Air Quality 2001 Status and Trends, <http://www.epa.gov/air/aqtrnd01/gndozone.html>.

⁶ EPA Fact Sheet:, *EPA's Program for Cleaner Vehicles and Cleaner Gasoline*, (EPA420-F-99-051, December 1999), <http://www.epa.gov/otaq/tr2home.htm>

⁷ EPA, *Nonconformance Penalties for 2004 and later Model Year Emission Standards for Heavy-duty Diesel Engines and Heavy-duty Diesel Vehicles*, August 1, 2002, <http://www.epa.gov/otaq/hd-hwy.htm#regs>.

⁸ National Research Council, *Effectiveness and Impact of Corporate Average Fuel economy (CAFE) Standards*, July 31, 2001.

⁹ U.S. EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990 – 2000, April 15, 2002.

¹⁰ EPA Inventory, *ibid*.

¹¹ Commercial vehicle operations will be enhanced through such services as weigh-in-motion, automated vehicle identification, credential verification from multiple jurisdictions (including border crossings) and on-board and roadside vehicle safety inspection and monitoring. Measures to improve surveillance of potentially dangerous cargos could also improve tracking and dispatching functions for freight carriers generally, resulting in more direct routing and reduction of idling and traffic delays.

¹² U.S. DOE EIA, Annual Energy Outlook 2002, Supplemental Table 33.

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Climate Change and Transportation: Potential Interactions and Impacts

By Brian Mills and Jean Andrey

Introduction

The purpose of this paper is to illustrate several potential interactions between anthropogenic climate change and transportation based on published literature and the opinions of the authors. Although the content is synthesized primarily from Canadian research (Andrey and Mills 2003, Andrey *et al.* 1999), most of the transportation-climate relationships are equally relevant to the American context.

Unfortunately, the available peer-reviewed literature addressing this subject is very limited. For example, the most recent IPCC (Working Group II) synthesis of impacts, adaptation and vulnerability (McCarthy *et al.* 2001) devotes less than one of over 1000 pages to potential transportation-related impacts and sensitivities. Although there is no comprehensive, quantitative assessment of the various transport-sector costs and opportunities associated with the current, let alone changed, climate, there are several qualitative summaries describing the vulnerabilities of transport-related activities to climate variability and change (e.g., Andrey and Mills 2003, Queensland Transport *et al.* n.d., Andrey and Snow 1998, Moreno *et al.* 1995, Lonergan *et al.* 1993, Jackson 1990, IBI Group 1990). In addition, a few quantitative impact

analyses of climate change on selected transportation infrastructure and operations have been published (e.g., Millerd 1996, McCulloch *et al.* 2001). However, the bulk of literature relevant to climate change deals with current weather and climate sensitivities of transport systems.

A general framework to guide discussion is presented in Figure 1. Weather and climate, as represented by several indicators (elements, such as precipitation, temperature, etc.) in Figure 1, contribute to several hazards or sensitivities within the transportation sector (such as landslides, reduced visibility, etc.). The statistics of these variables may be affected by anthropogenic climate change. Weather and climate factors directly affect the planning, design, construction and maintenance of transportation infrastructure in several ways—they also indirectly affect the demand for transportation services. Costs and benefits, measured in terms of safety, mobility, economic efficiency, and externalities, accrue as the operation of transportation facilities and services meets these demands and adjusts to weather and climate hazards. The remainder of the paper explores some of the climate-transportation interactions conceptualized in Figure 1.

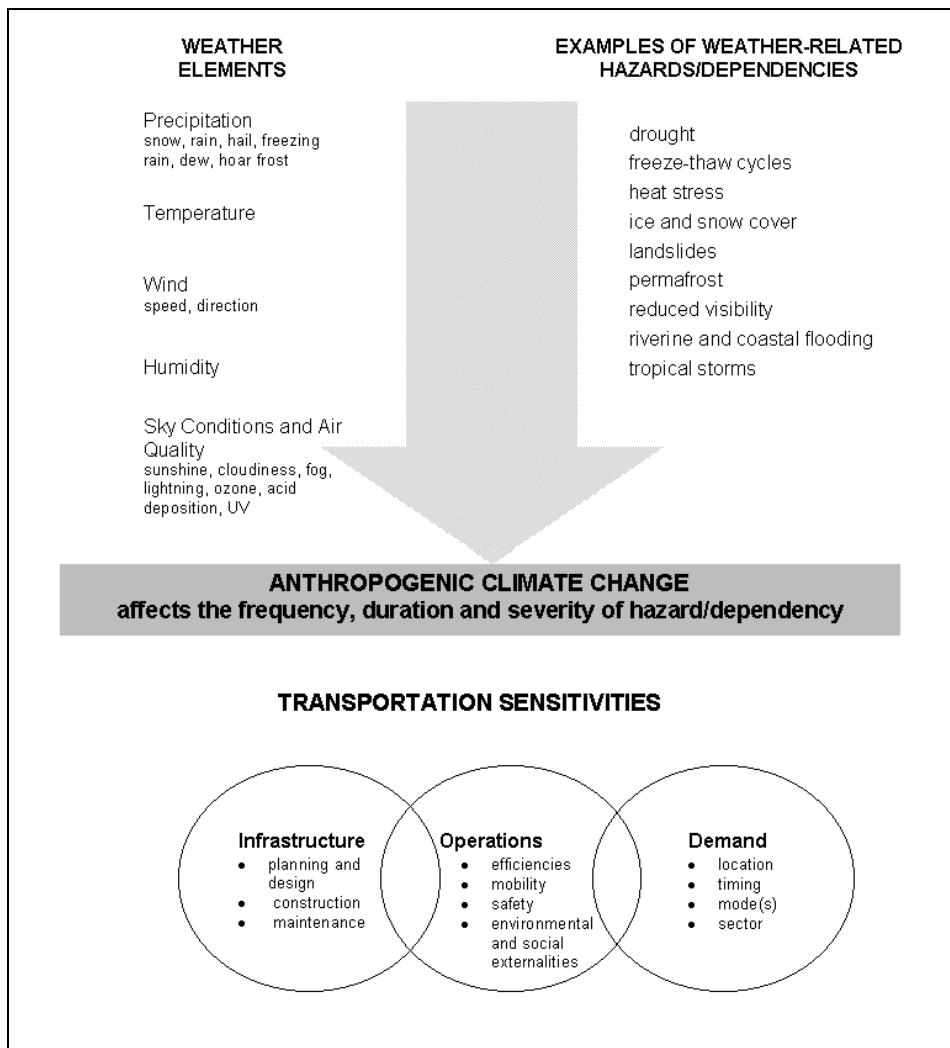


Figure 1. Aspects of transportation that may be sensitive to changes in climate. The diagram conceptualizes how weather elements (precipitation, temperature, etc.) contribute to hazards (landslides, reduced visibility, etc.), which in turn affect transportation infrastructure, operations, and demand.

Infrastructure

Roads, railways, airport runways, shipping terminals, canals, and bridges are examples of the facilities and structures that are required to provide transportation services that enable the movement of passengers and freight. Weather and climate affect the planning, design, construction, maintenance and performance of infrastructure throughout its service life. Infrastructure is built to withstand a wide variety of weather and environmental conditions—the prospect of anthropogenic climate change means that certain assumptions about future

atmospheric conditions may be wrong, possibly resulting in premature deterioration or failure of infrastructure. Current climate modeling research suggests that many transportation-sensitive aspects of climate change will be realized over a long time frame. Fortunately the service life is sufficiently short for many types of transportation infrastructure (i.e., less than 25 years) to facilitate cost-effective replacement using improved designs. In other cases, such as bridges and port facilities, expected changes in climate may occur considerably earlier during the expected service life, possibly forcing expensive reconstruction, retrofit or relocation.

Temperature-Related Sensitivities

Temperature-related sensitivities include extreme heat and cold, freeze-thaw cycles, permafrost degradation and reduced ice cover.

Extreme heat and cold

It is likely that climate change will increase the frequency and severity of hot days while the number of extremely cold days will be reduced across much of North America (Houghton *et al.* 2001). The following pavement impacts might become more common as extreme heat conditions become more severe and frequent:

- pavement softening and traffic-related rutting,
- buckling of pavement (especially older, jointed concrete), and
- flushing or bleeding of asphalt from older or poorly constructed pavements.

This will generally lead to increased maintenance costs wherever pavement thermal tolerances are exceeded—the last issue is also a safety concern. On the positive side, fewer extremely cold days and ‘warmer’ minimum temperature thresholds may reduce thermal cracking of pavement during winter and offset some of the increased summer maintenance costs, at least in Canada and the northern U.S. Buckling of jointed concrete pavement is not a large issue in Canada given its limited use, but may be much more important in parts of the U.S.

Railway track is also subject to buckling from extreme heat—possibly a contributing factor to a July 29, 2002 serious rail incident in Maryland presently under investigation by the Transportation Safety Board (Associated Press 2002). While heat-related impacts may become more frequent, Canadian information suggests that cold temperatures and winter conditions are responsible for a much greater proportion of track, switch, and railcar damage (Andrey and Mills 2003).

Freeze-thaw cycles

Increased frequencies of freeze-thaw cycles have been related to premature deterioration of road and runway pavements, primarily where subgrades are composed of fine-grained, saturated material—conditions that are conducive to frost heaving and thaw weakening (Haas *et al.* 1999). Preliminary research reported in Andrey and Mills (2003) suggests that freeze-thaw cycles, defined using a 0°C (32°F) daily air temperature threshold, may actually become less common under climate change in several cities in southern Canada.

Permafrost degradation

Permafrost degradation and related increases in the active (seasonally unfrozen) permafrost layer may compromise the stability of paved airport runways and all-season road and rail bases in the Canadian (and likely Alaskan) north. Sensitivities are especially high where permafrost temperatures are warmer than -2°C (28°F) and where the ice content of frozen ground is high (Natural Resources Canada 2002).

Reduced ice cover

Another northern issue is the future viability of winter ice roads—a cheaper means of transportation than air for many communities not serviced by all-season roads. Warmer temperatures will reduce both the length of the ice season and thickness/strength of ice, a factor limiting the weight of vehicles (Lonergan *et al.* 1993). These impacts may be offset somewhat by a longer ice-free season that may allow greater use of boats and barges.

Construction season length/quality

Although infrastructure expansion will likely be driven by non-climate factors (economics, population growth, etc.), warmer temperatures could translate into a longer potential construction season and improved cost efficiencies. Extreme heat and unfavourable working conditions for employees and certain types of construction activities may offset such

gains. For example, high temperature, low humidity and high wind are factors that reduce the setting times and strength of concrete (Almusallam 2001).

Sea-level Rise and Storm Surge

Sea-level rise ranging from a global mean of 9–88 cm (approx. 4–35 in) is also a likely outcome of global climate change and will be exacerbated (reduced) where land is naturally subsiding (rebounding) (Houghton *et al.* 2001). Combined with acute storm surges related to tropical (hurricanes) or mid-latitude (e.g., nor'easters) storms, gradual changes in sea level may be expected to damage or render inaccessible low-lying coastal infrastructure including road and railway beds, port and airport facilities, tunnels and underground rail/subway/transit corridors. Detailed studies of vulnerable infrastructure have been completed for the New York City metropolitan region (Klaus *et al.*, n.d.) and parts of Atlantic Canada (McCulloch *et al.* 2001, Martec Ltd. 1987, Stokoe *et al.* 1988). Both regions have experienced damaging coastal flooding over the past decade. The vulnerability is significantly higher in the U.S. than in Canada, owing primarily to much greater levels of investment, including several major airports, along the American East and Gulf coastlines.

Precipitation-related Sensitivities

The impacts of climate change on future precipitation patterns are much less certain than for temperature, due in part to the highly variable nature of precipitation and the inability of global climate models to resolve certain precipitation processes. Increased precipitation may affect the frequency of landslides and slope failures that could damage road and rail infrastructure and force greater levels of maintenance. This is likely to be most problematic in mountainous regions, such as the continental divide (Evans and Clague 1997).

Riverine and urban stormwater flooding may exacerbate impacts related to sea-level rise and may also affect inland regions (road and rail infrastructure within flood plains including bridges, bridge foundations, culverts, etc.). The

1993 summer floods along the Mississippi River provide the most vivid image of this future scenario, although even local urban flooding can cause significant damage to transportation infrastructure (see Changnon 1999).

Precipitation and moisture are also important factors that contribute to the weathering of transportation infrastructure. Premature deterioration of bridges, parking garages and other concrete structures may be magnified where climate change induces more frequent precipitation events, especially in areas (e.g., northeastern U.S. and southeastern Canada) where acid deposition is a problem (Smith *et al.* 1998; Auld 1999).

Transportation Operations

The impact of climate change on transportation system operations extends from current weather-relationships and adjustments that are known to affect safety, mobility, and economic efficiency. Certain externalized environmental issues stemming from transportation operations may also be indirectly influenced by climate change.

Safety

Weather is identified as a contributing factor in approximately 10 train derailments, 10–15 aircraft accidents, over 100 shipping accidents, and tens of thousands of road collisions that occur in Canada each year (Andrey and Mills 2003). In 2000, about 300,000 injury road collisions in the U.S. occurred during rain, snow, sleet or other adverse weather condition (U.S. Department of Transportation 2001). Although a detailed analysis has not been completed, and assuming all other factors remain constant, it is expected that milder winter conditions would improve the safety record for rail, air and ship modes in Canada (Andrey and Mills 2003). In absolute terms, road collisions are by far the most important safety concern. Precipitation generally increases collision risk from 50–100 percent; and research for several Canadian cities reported injury risk increases of about 45 percent (Andrey *et al.* 2001a, 2003). Injury risk was similar for snowfall and rainfall events, relative to normal seasonal driving conditions (Andrey *et*

al. 2003). Should these relative sensitivities remain intact over the next several decades, shifts from snowfall to rainfall as suggested by many climate change modeling studies (Houghton *et al.* 2001) may have minimal impact on casualty rates, contrary to the benefits reported in past studies (IBI Group 1990). Where precipitation events become more frequent, one might expect injury risk to increase.

Mobility

All modes of transportation currently experience weather-related service disruptions, particularly during winter. Commercial passenger flight cancellations and diversions are estimated to cost \$US 40,000 and \$US 150,000 per flight, respectively (Environmental and Societal Impacts Group 1997). Temporarily reduced speeds for rail service during extremely cold conditions and prolonged heat waves, and road or rail closures due to winter storms, flooding, land slides and forest fires are other examples of weather-related impacts on mobility (Andrey and Mills 2003). Associated costs, although variable from year to year, certainly amount to millions of dollars. Any reduction in the intensity or frequency of winter storms or weather extremes would likely translate into a mobility benefit for transportation operators and the public at large.

Another possible benefit of a warmed climate would be the improved potential for navigation, for example in the Beaufort Sea area. A greater extent of open water in the summer, coupled with a longer open-water season and thinner first-year sea ice, may extend the Arctic shipping season (McGillivray *et al.* 1993, Goos and Wall 1994).

Efficiencies

There is general consensus that climate change will result in a reduction of Great Lakes water levels and connecting channel flows (Mortsch *et al.* 2000, National Assessment Synthesis Team 2001). Several investigations of the implications of reduced water levels for shipping activities in the Great Lakes (Lindeberg *et al.* 2000, Millerd

1996, Bergeron 1995, Slivitzky 1993, Marchand *et al.* 1988) have reached similar conclusions—shipping costs for the principal commodities (iron ore, grain, coal, limestone) are likely to increase substantially because of the need to make more trips to transport the same amount of cargo, even considering the prospect of an extended ice-free navigation season. This would present a serious challenge to an industry that is already in decline due to both changing patterns of transport demand and competition from other freight modes. Similar impacts could affect commercial navigation along the Mississippi River system, as supported by observations from recent droughts (Changnon 1989, National Assessment Synthesis Team 2001).

Reduced spending on snow and ice control has been identified as a major benefit of global warming to the transportation sector (IBI Group 1990). Annual winter road maintenance expenditures by government agencies in the U.S. and Canada are approximately \$US 2 billion and \$CDN 1 billion, respectively (The Weather Team 1998, Jones 2003). Less snowfall and days with snow are also likely to result in savings because of some reduction in salt corrosion-related damage to vehicles and steel-reinforced concrete structures (e.g., bridges, parking garages). Empirical relationships between temperature and historic rates of salt use (Andrey *et al.* 2001b, McCabe 1995, Cornford and Thornes 1996) tentatively suggest that a warming of 3–4°C could decrease salt and sand use by between 20 and 70 percent resulting in substantial savings annually. For other modes, considerable benefits will likely be realized for rail companies and airport facilities where snow removal and de-icing are necessary. Reduced sea ice coverage and thickness would lower ice-breaking costs in Atlantic Canada and possibly facilitate the use of Arctic waters as an alternative shipping route to the Panama Canal (Andrey and Mills 2003, Maxwell 1997, McGillivray *et al.* 1993).

The effects of temperature on the fuel efficiency of motorized transport have also been subject to discussion in climate impact assessments (IBI Group 1990, Titus 1992). Surface warming may lead to slight increases in

fuel consumption for aircraft, related to lower engine efficiency, and for road vehicles, related to the increased use of air conditioning and the offsetting impact of reduced use of snow tires and defrosting systems (Andrey and Mills 2003). Higher or more frequent extreme temperatures associated with climate change may, in conjunction with aircraft type (rated cargo and passenger capacity, engine size and efficiency), runway length, destination elevation and location (requirements for additional fuel storage) and other factors, reduce aircraft cargo carrying capacities.

Environmental Externalities

As with the economic and mobility benefits, not all of the costs of operating transportation systems are limited to the transportation sector. Among other things, transportation activities produce air pollution and residual road salt loadings that affect human health and the environment (WGAQOG 1999, Environment Canada and Health Canada 2001). Both of these issues may in turn be indirectly affected by climate change. Benefits may be realized where warmer temperatures, as noted previously, reduce the loadings of road salt, glycols and other de-icing chemicals into the environment. Conversely, transportation-related activities are major sources of NO_x, VOCs, CO, and particulate matter. The surface and upper air conditions (warm temperatures; stagnant anticyclonic air masses) that promote the occurrence of high concentrations of these pollutants may become more frequent and of longer duration under certain climate change scenarios; however, the magnitude and direction of this impact may be highly variable spatially and requires additional research (Patz *et al.* 2000).

Transportation Demand

Very little if any information exists that addresses the possible consequences of climate change for transportation demand. It seems intuitive however to consider the effects of global warming on the sources (location, sector, timing) of specific demands for freight and passenger services and the implications for

various modes of transportation. A few demand adjustments might occur directly in response to climate change impacts on transportation—such as a shift from shipping to rail and truck in the Great Lakes-St. Lawrence region. Other, more important shifts may occur indirectly as a result of adaptation to climate change in other sectors—most notably in natural resource sectors like agriculture, energy, and forestry, and in tourism. For instance, should the spatial pattern of agricultural production change in response to drought or extended growing seasons, it seems reasonable to expect new demands for transportation to arise and others to wane. Similarly for energy, climate change may permit the cheaper development of new fossil fuel resources in the Arctic thus increasing demand for supplies and the bulk shipment of petroleum; increased shipping activity in the Arctic may also generate greater needs for safety-related services and increase the probability of hazardous spills (Maxwell 1997, McGillivray *et al.* 1993). The greatest potential shift, however, will likely result from international commitments to reduce greenhouse gas emissions and associated investment in renewable energy sources. In the extreme case, widespread adoption of renewables and new fuels (e.g., hydrogen) could dramatically transform the transportation sector—creating both new opportunities and challenges.

Conclusions: What We've Learned and What We Need to Know

This paper has provided a sample of possible interactions between aspects of transportation and anthropogenic climate change. Several of these sensitivities are summarized in Figure 2, classified by the amount of research that has been completed, as well as the confidence in expected changes to particular climate variables (as interpreted from IPCC, Houghton *et al.* 2001). The published research provides a general account of several significant vulnerabilities within the transportation sector to climate change—all are based on the assumption that contemporary sensitivities can be extrapolated in a linear fashion into the future. Confidence in sensitivities related to temperature

and sea-level rise is much higher than for precipitation-related impacts, as per Houghton *et al.* (2001). The most significant vulnerabilities that have been studied include: various types of coastal infrastructure that are threatened by sea-level rise and storm surge flooding (U.S. East

and Gulf Coasts, Atlantic Canada); Great Lakes shipping; northern ice roads; and roads and air strips built on permafrost. Unfortunately, relatively little research has been published on the implications of extreme heat—an issue that may be very important for transportation interests in the U.S.

Confidence in Expected Changes in Climate Variables*	Transportation Sensitivities: Amount of Completed Research	
	<i>A few studies</i>	<i>No significant climate change research</i>
HIGH CONFIDENCE <i>Mean temperature</i> <i>Sea-level rise</i>	<ul style="list-style-type: none"> - East and Gulf Coast infrastructure (sea-level rise and storm surge) - Reliable northwest passage through Arctic (ice cover) - Northern infrastructure (permafrost degradation and ice roads) 	
MODERATE CONFIDENCE <i>Extreme temperature</i> <i>Mean precipitation</i>	<ul style="list-style-type: none"> - Great Lakes - St. Lawrence shipping 	<ul style="list-style-type: none"> - Winter maintenance costs for surface and air transport - Fuel efficiencies and payloads for motorized transport - Extreme temperature and freeze-thaw related impacts on infrastructure design and maintenance - Construction season length/quality
LOW CONFIDENCE <i>Storm frequency/severity</i> <i>Extreme local precipitation</i>	<ul style="list-style-type: none"> - Landslide/avalanche impacts on mobility and maintenance - Inland urban infrastructure (flooding) 	<ul style="list-style-type: none"> - Health and safety - Mobility - Property damage due to weather-related incidents and severe storms (excluding coastal infrastructure) - Bridges and other structures spanning inland lakes, rivers (flooding) - Transportation demand and competition

*refers to agreement among global climate models as per IPCC (Houghton *et al.* 2001)

Figure 2. Possible implications of climate change for Canadian and U.S. transportation.

Based strictly on available evidence and compared to the many political, economic and technological factors affecting the evolution of transportation systems—including international agreements to limit greenhouse gas emissions—

the potential impacts of climate change on transportation seem to be largely manageable. This conclusion may be premature given that very little research has been conducted on chronic impacts to pavements or rails; safety; or

the potential benefits of climate change. More generally, insufficient attention has been paid to the dynamic and complex nature of transportation demand, intermodal competition and the implications of these for industry adjustments to climate change impacts.

Thus, many gaps exist in our understanding of climate change impacts, available adaptation strategies, and their various costs. Several recommendations for research are listed below. In addressing these general needs, the emphasis should be placed on developing research projects that focus in-depth on important activities and sensitivities rather than on conducting exhaustive and comprehensive studies of the entire transportation industry.

- Greater attention must be given to road transportation. North Americans are becoming increasingly reliant on road transport, and have invested over \$1 trillion in road infrastructure. Studies should initially focus on estimating the vulnerability of roads to changes in freeze-thaw cycle frequency, extreme heat and cold.
- There is a need to assess the significance of extreme weather events and weather variability in the design, cost, mobility and safety of North American transportation systems. Many of the benefits attributed to potential climate change are based on the assumption that climate variability will remain similar to the present climate. There is a need to test this hypothesis against a variety of measures (cost, mobility, safety, etc.) and for previously unexamined impacts (e.g., potential increased frequency of severe summer weather and effects on aviation).
- A more thorough evaluation of existing adaptive measures and their relative ability to defer infrastructure upgrades, reduce operational costs, and maintain or improve mobility and safety is required.
- Analyses of mitigation (greenhouse gas emissions reduction) options and

adjustments to reduce the impacts of climate change must be integrated so as to identify and work toward a transportation future that is more sustainable from an environmental perspective and more resilient to weather hazards.

- An improved understanding of the implications of climate change for transport demand is needed.
- Since most of the factors (e.g., technology, land use policy, economics) affecting the evolution of transport systems are external to climate, it is important to consider how changes in these factors affect societal vulnerability to climate and climate change.
- The above-mentioned research must be conducted in closer working relationships with transportation stakeholders. Several ‘myths’ surrounding climate change impacts that evolved from ‘arms-length’ investigations and were highlighted in subsequent studies were discounted after consulting managers of transportation activities. Involving stakeholders will also provide the best opportunity for weather and climate-related issues to become acknowledged in legislation, standards and policies.

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Regional Case Studies

Global Climate Change and Transportation Infrastructure: Lessons from the New York Area

By Rae Zimmerman

Background and Introduction

Global climate change (GCC) is now well known, and its impacts are a stark reality. According to the Intergovernmental Panel on Climate Change (IPCC), changes in global climate in the 20th century, whether from human or natural causes, are already reflected in numerous indicators for atmospheric chemistry, weather, biological, physical and economic conditions,¹ and members of the Intergovernmental Panel on Climate Change (IPCC) working groups have rated the probability of those changes as either actually occurring or at least likely to occur.² The estimated impacts of these changes under varying scenarios are in many cases pronounced, and the ability to cope with these impacts varies considerably depending upon the capacity of individuals, groups and institutions to adapt.³

The implications of these changes and their impacts for the planning, design and operation of transportation infrastructure are profound because of the pervasiveness of this infrastructure, its centrality in our everyday lives and culture, its interdependencies with other infrastructure, and its historical location in areas vulnerable to global warming effects. Most importantly, transportation infrastructure plays a critical role in providing emergency response services should some of the potential climate change effects become realized. The manner in which transportation and climate change are interrelated is not only an engineering issue but

involves the climate sciences and social and behavioral sciences as well. Thus, multidimensional, multi-sectoral and multi-disciplinary perspectives and actions are required to address the adverse effects of climate change. Geographical variations also should be taken into account, since global phenomena have local impacts, and spanning these two scales is often difficult. Incorporating a range of geographic scales is critical, however, since actions to prevent, mitigate, or reverse adverse global phenomena are implemented at many levels, especially through local actions, and the success of these attempts is the collective effect of actions at all scales.

This paper addresses two aspects of the relationship between climate change and transportation infrastructure, focusing on the results of studies conducted for the New York area (Rosenzweig and Solecki 2001a).⁴ First, implications of climate change as a factor influencing the current relationships between urban development and transportation management are explored both nationally and regionally for the New York area as a basis for identifying mitigation and adaptation needs and measures. Second, details of flooding and heat-related effects on surface and subsurface transportation-related infrastructure are briefly presented as a basis for lessons these familiar phenomena generate for less obvious climate change and transportation relationships. The paper concludes with observations about the means to manage these outcomes within existing

and expanded institutional frameworks and technologies.

The implications of global climate change for the New York metropolitan region have been addressed in at least two major studies. In 1996, attention to the impacts and prevention of climate change in the New York region were the focus of a 1996 conference and proceedings called *The Baked Apple? Metropolitan New York in the Greenhouse* (Hill 1996). That work included an inventory of the potential infrastructure that might be affected and how it could be affected (Zimmerman 1996: 57-83; New York Observer 1995: 19, 21). In 1999-2001, a consortium based at Columbia University led a stakeholder-based in-depth study of the impacts of climate change in the New York Metro East Coast (MEC) area, its consequences in light of other stressors, and the means available for adaptation. The study was directed by Dr. Cynthia Rosenzweig (NASA Goddard Institute of Space Studies) and Professor William Solecki (Montclair State University) and funded by the National Science Foundation, the U.S. EPA and others. The MEC Regional Assessment was one of 18 study areas of the U.S. Global Change Research Program's National Assessment of the Potential Consequences of Climate Variability and Change for the U.S. (Rosenzweig and Solecki 2001a and 2001b; National Assessment Synthesis Team 2000 at www.usgcrp.gov). One aspect of the MEC Assessment focused on institutional decision-making to manage climate change impacts on infrastructure and land use (Zimmerman and Cusker 2001: 9-1 to 9-25 and A11-A17; Martin 1999).

Development, Transportation and Global Climate Change

Development Patterns and Trends

The environmental impact of our lifestyles reaches far beyond the geographic boundaries of our cities and regions, extending from local to global scales. Concepts that are useful in portraying the role of development in global warming especially through the intermediary of transportation are "ecological footprints," land

consumption ratios, and measures of coastal vulnerability, all of which point to the increasing per capita use of land and other resources to support our lifestyles.

Ecological Footprints. "Ecological Footprints" refer to the amount of land (and other resources) that urban areas use beyond their boundaries to produce food and other services.⁵ Girardet (1995) points out, for example, that cities currently occupy 2% of the land area worldwide, yet consume 75% of the world's resources. In interpreting such observations, one should keep in mind that the flow is two ways - though cities may utilize regional resources, they give back to their regions employment, culture, recreation and other benefits.

Land Consumption Ratios. The amount of land consumed per capita (applicable to rural and suburban areas as well as urban areas) is a common "sprawl" indicator similar to the ecological footprint used to quantify the extent of land used in development. Studies by the U.S. EPA and others use the ratio of urbanized area growth (numerator) to population growth (denominator) (U.S. EPA 2000: 6). Over the past few decades, these ratios have been exceeding 1, indicative of increasing land consumption per capita. For example, according to the U.S. EPA report, the average ratio aggregated for 1950-1990 for the New York metropolitan urbanized area is 4.49 (based on an urban area growth rate of 136.8% and a population growth rate of 30.5%). The New York area ratio has consistently exceeded the national average.

Coastal Vulnerability. The National Oceanic and Atmospheric Administration (NOAA) has used large populations, high densities, and high growth rates in coastal areas as indicators of coastal vulnerability.⁶ These indicators are significant because they reflect potential population exposures to the effects of sea level rise associated with climate change.

Implications for Transportation

Transportation, and in particular, emissions from vehicular transport, is considered a major contributor to greenhouse gases (GHGs). Indicators commonly used to substantiate this include (1) vehicular usage in terms of the extent of travel (e.g., vehicle miles of travel), (2) type and amount of energy used to provide such travel, and (3) environmental effects associated with both extent of travel and energy use (primarily in terms of emissions of greenhouse gases and other gases and particulates).

Vehicle Miles of Travel (VMT).

According to the U.S. Department of Transportation (DOT), VMT is increasing on average nationally, having risen from 1.1 trillion miles in the year 1970 to 2.8 trillion miles during the year 2000, averaging a growth of 3.1% annually over that period, slightly slowing to 2.5% annually from 1990 to 2000.⁷ This is consistent with data that show increasing numbers of licensed drivers and vehicles between 1969 and 1995 (Hu and Young 1999: 11), and in fact, the number of vehicles has increased during those years by 143% while population only increased 32% and the number of households increased 58% nationwide. New York State data indicate that VMT is also increasing within New York State (often in spite of a leveling off of population), and in the New York-New Jersey region. The increased levels of vehicular travel have potential consequences for global climate change since vehicle travel in total generates more emissions in spite of previous gains in fuel economies and engine and end-of-pipe technologies to reduce emissions.

Energy.

Energy Information Administration data for the New York area and elsewhere indicate that transportation consumes a large amount of fossil fuel relative to other activities. Nationally, transportation accounted for 27.9% of total energy consumed in 2001, with the average annual percent change increasing from 1.4% in the period between 1973 and 2000 to 1.9% between 1990 and 2000 in spite of fuel economies (Davis and Diegel 2002: 2-3). In New York State, fossil fuel emissions from transportation continue to

increase as numbers of motor vehicles are expected to rise. The New York State Energy Research and Development Administration (NYSERDA) 1999 Three Year Plan, citing the 1998 New York State Energy Plan, identified the following statewide energy use trends in transportation and associated energy use and air emissions: Although transportation accounts for 30% of energy use in New York State, it contributes 37% to carbon dioxide emissions; energy use for transportation is forecasted to grow 9% by 2015; and "in 20 years, if current trends continue, daily travel in metropolitan areas will increase by 50%" (NYSERDA 1999).

Emissions. Without a change in vehicular emissions, vehicular travel will continue to contribute to the buildup of greenhouse gases because of continued growth in VMT, in spite of fuel economies. By 2000, transportation accounted for about a third of the emissions of carbon dioxide (CO₂), a major greenhouse gas,⁸ contributed by fossil fuels (Davis and Diegel 2002: 3-1). The percentage share of U.S. carbon dioxide emissions from all transportation sectors has increased in absolute terms only by about three percentage points since 1985. However, metric tons of carbon emitted by the transportation sector increased by 33% during that period.⁹ Transportation is expected to be the largest growing CO₂ emitting sector, with growth projected at 47.5% between 1996 and 2020 (U.S. EPA 2000: 31).

National Ambient Air Quality Standard (NAAQS) pollutants are closely associated with global climate change. In 1999, transportation accounted for almost four-fifths of the U.S. emissions of carbon monoxide, over half of the NO_x emissions, and over two fifths of the VOC emissions (Davis and Diegel 2002: 4-3). All of these chemicals are NAAQS pollutants. Although highway vehicles initially dominated the carbon monoxide (CO) emission category (accounting for 88% in 1970), their share has gradually diminished to 50% since the share of CO emissions from off-highway vehicles (primarily used in construction and agriculture) has increased, (Davis and Diegel 2002: 4-3).

Patterns and Trends in Global Climate Change Phenomena in General and in the New York Region

Overall Global Climate Change Trends

Three indicators commonly used to describe global climate change trends are: concentrations of greenhouse gases in the atmosphere, global and regional temperatures, and sea level. Globally, all three of these factors are on the rise (with temporal and geographic variations). Although uncertainties exist in the way the data are interpreted, there is generally little disagreement about these patterns and trends and a growing consensus seems to be emerging that human activity is a significant cause (IPCC 2001a and National Research Council 2002). Moreover, public concern is consistent with these findings. A couple of decades ago, public perceptions had been marked by some skepticism about global climate change, but now the trend is toward growing awareness and concern both of general environmental effects and local vulnerabilities associated with climate change.¹⁰

Patterns and Trends in Potential Global Climate Change Consequences for the New York Area

Transportation not only contributes to climate change, but climate change also has several potential adverse effects on transportation infrastructure. The first effect is related to increased flood elevations or sea level rise and increased frequency and intensity of flooding episodes that can create hazards for transportation located in areas close to sea level. The second is more subtle, and is related to elevations in temperature that, if severe and persistent enough, can result in serious consequences for the materials used in transportation infrastructure.

Increased Flood Elevations. Global climate change-related sea level rise is associated with a number of interrelated factors, namely, increased precipitation, thermal expansion of water, and increased riverine flows

from enhanced snowmelt. In the MEC study (Rosenzweig and Solecki, eds. 2001), estimated temperature and flood elevations over the next century differ according to the global climate models and greenhouse gas emission assumptions used, but all generally point to estimated increases in flood elevations and the return frequency of floods. For the year 2030, for example, across three scenarios (low, medium, high) the predictions for the New York region show that (Rosenzweig and Solecki 2001): increases in annual temperature range from 0.9 to 3.8 degrees F.; days exceeding 90 degrees range from 16 to 32 days; precipitation (annual in inches) ranges from a decline of 0.4 to 2.3 inches, potentially signifying drought conditions; sea level rise ranges from 3.7 to 7.6 inches; and the change in flood elevations ranges from 3.9 inches to 8.3 inches. A key factor is that the flood return frequency is projected to increase over the 21st century (Gornitz 2001). Gornitz, Couch and Hartig (2002: 73) estimate that as a consequence of the change in the flood return frequency, “the likelihood of a 100-year flood could become as frequent as once in 43 years by the 2020s, once in 19 years by the 2050s and once in 4 years by the 2080s, on average, in the most extreme case.” Flooding has many different consequences, but several are particularly relevant to transportation and its infrastructure.

First, transportation systems are traditionally sited in low-lying areas already prone to flooding. Older facilities have not been planned to take into account increased flood frequencies and flood elevations or if they were, the advantages of the location in flat floodplains for ease of operation outweighed the disadvantages of flooding. Changes in these practices cannot easily be applied to the vast amount of infrastructure already in place in such locations (Zimmerman and Cusker 2001: Tables 9-6 and 9-7). New York City alone has over 500 miles of coastline, much of which is transgressed by transportation infrastructure – roadways, rail lines, and ventilation shafts, entrances and exits for tunnels and transit systems, many of which are at elevations at risk of being flooded even by traditional natural hazards (Jacob, Edelblum, and Arnold, J. 2001; U.S. Army Corps of Engineers,

Federal Emergency Management Agency, National Weather Service, New York/New Jersey/Connecticut State Emergency Management 1995). Table 1 below summarizes

the number of such facilities in both the New York and New Jersey portions of the region, many of which are among the most heavily used facilities in the region.¹¹

Table 1. Summary of the extent of transportation infrastructure potentially affected by sea level rise, New York region.

Type of Transportation Infrastructure	Facilities 10 ft. or less above sea level	Facilities 10-12 ft. above sea level
TRANSIT (e.g., track, tunnels, stations, stairways, grates, and vent shafts)		
Amtrak, MetroNorth, Long Island Rail Road	10	4
Subways, PATH system	17	3
SURFACE TRANSPORTATION (roads, bridges, tunnels)	21	9
MARINE	6	-
AIRPORTS	2	2

Notes to Table 1:

- (a) Figures are compiled from Zimmerman and Cusker (2001: Table 9-6, p. 163) from data in USACE (1995).
 (b) Figures are compiled from Zimmerman and Cusker (2001: Table 9-7, p. 164) from data in USACE (1995).

Second, transportation systems provide support for hazardous waste management in the region (Zimmerman and Gerrard 1994), and as such, flooding of transportation infrastructure can become a major environmental and health issue as well as a safety issue if hazardous wastes are released during a flooding episode. This actually occurred during the Midwest floods in 1993, according to U.S. Geological Survey reports (Zimmerman 1994).

Temperature-Related Effects and Transportation Infrastructure. According to the MEC study, temperature increases in the MEC region between 1900 and 2000 are estimated at about 0.2 degrees Fahrenheit per decade, and this rate is expected to increase during the 21st century. Many daily and monthly annual and decade averages as well as temperature extremes and the timing of freezing and thawing cycles have been exceeded in the New York area. For example, a *New York Times* synopsis of temperature variations in 1999 alone in New York City indicates that 1999 had the seventh warmest February, tenth warmest May, hottest July (with a high of 101 degrees on July 5th and 6th), and the seventh warmest November. In addition, two days in December tied for the

record high (Stevens 2000). That record tends to parallel U.S. trends.

According to engineers managing regional infrastructure (Zimmerman 1996: 64), materials used in roadways have a limited range of tolerance to heat, and the stress is exacerbated by the length of time temperatures are elevated and by stress factors, such as vehicle loadings on roadways and bridges during periods of congestion. Bridges can be particularly sensitive to exposure of the road surface to extreme heat. The extent of the risk is, in part, a function of the number of bridges. New York City alone has 2,200 bridges, potentially subject to extra stresses from elevated temperatures depending on the surface materials used. If these consequences are realized, they can, in turn, have economic and social effects, exacerbating already serious congestion problems in urban areas, as indicated by recent studies. According to the Texas Transportation Institute (2001: Appendices), for example, out of a total of sixty-eight areas studied, the New York-New Jersey area ranked 21st in its congestion index, 24th in the cost of congestion per person, and 2nd in the total cost of congestion. The Texas Transportation Institute 2002 (2002) study

indicates that increasing congestion trends are widespread: annual transportation-related delay in 75 urban areas between 1982 and 2000 averaged 62 hours, and this increasing pattern of delay occurred in urban areas of all sizes (however, the extent of delay increases with urban size).

Conclusions

Given the patterns and trends in transportation and its infrastructure in the New York area (regardless of the degree of uncertainty in them), there is little doubt about the potential impact of global climate change effects on public services. As a society, we need to adopt both an adaptive mode, that aims to reduce exposures, as well as a preventive approach that targets sources of global climate change that are within our control, realizing that there is often a fine line between the two strategies.

Adaptation

In light of the more direct and immediate effects of flooding and temperature change and the more indirect, but fundamental effects associated with development patterns, a generic set of examples of adaptation strategies emerge applicable to planning, design, and management practices for both physical transportation facilities and the way transportation services are delivered. These strategies include (Zimmerman and Cusker 2001: 150):

- “Land use and environmental planning and capital programming to ensure the location of new structures and relocation of existing structures outside of impact areas associated with sea-level rise
- Acquiring property to prevent or guide development in hazard areas
- Redesigning structures to avoid impacts, including the removal of traditional flood retaining structures
- Retrofitting existing and redesigning new structures with barriers, higher elevations,

and other forms of protection against water inundation and the extremes associated with heat and wind

- Using operational procedures and controls for infrastructure services and facilities to reduce or avoid population exposure during hazard events”

Other adaptations pertain to changes in the behavior and location of potentially affected populations so they are less vulnerable to the consequences of climate change with respect to transportation (Zimmerman and Cusker 2001: 150):

- “Educating the public about global climate change and adaptations and behaviors, including infrastructure and land usage patterns, that will reduce vulnerability
- Improving communication mechanisms such as warning systems
- Moving people and businesses away from vulnerable areas through incentives, relocations, and in extreme cases, evacuations
- Providing emergency response and disaster assistance for reconstruction”

Prevention

Prevention of the occurrence of some of the adverse climate change effects (as distinct from prevention of the adverse consequences of such effects) might involve, for example, the reduction of greenhouse gas emissions (which was not within the scope of the MEC study). This approach ultimately depends on what is known or believed about the sources of the build-up of greenhouse gases. Vehicular congestion and the development patterns that are often associated with it are likely to be key targets of a preventive approach.

An alteration in modes of transportation or vehicle choice could meet the needs of both adaptation and prevention. For vehicular-based sources of the emissions that influence global

climate change, alternative engine, exhaust, and fuel designs that target energy intensive vehicles are well known that provide reductions in carbon dioxide emissions.¹² However, current cost estimates tend to point unfavorably to their use over currently used petroleum-based technologies, but these estimates do not typically internalize the cost of climate change. The good news is that the cost differentials tend to be narrowing as these technologies become more well-developed. The New York area can also take advantage of some immediate transportation alternatives that reduce automobile usage, such as increasing use of mass transit. The use of public transit has precipitously declined over the past decades, although there are signs of a comeback both nationally according to the American Public Transportation Association (New York Times 2001: A12) and particularly in the New York region (the New York area accounts for about fifteen percent of the trips nationwide by public transit).

A more dramatic approach would be to address the pattern of land development that accompanies population distribution and growth. Population distribution, i.e., the use of land, is a major factor affecting transportation, which in turn affects greenhouse gas emissions. Land is now being used at a faster rate than population is growing at the outskirts of the city, and people tend to be driving longer as a consequence of this. Much of the nation's transportation infrastructure is located along the coast by necessity, either because it is water-dependent, traverses waterbodies, or was historically located there, potentially increasing the consequences of sea level rise. New York City has 578 miles of waterfront, and the region's total is several times that. The population of Long Island, Connecticut and those parts of New York State that abuts Long Island Sound is concentrated along the coastal areas. That population, according to the Census of Population, was, in 1992, by far the densest in the Nation with the six counties of New York State on the Sound or adjacent to it ranking among the top 25 counties in the country with the highest population density (Zimmerman et al. 1999, based on U.S. census data).

Institutional Capacity Building for Adaptation and Prevention

The magnitude and complexity of the role of governmental and quasi-governmental jurisdictions within the 31-county MEC region involved in the global climate change issue is reflected in the very large investment in the built environment within the region and the number and variety of agencies and governments with direct and indirect authority over that investment. Both of these factors potentially provide opportunities for both adaptation and prevention.

First, the level of financial investment, income generated, and estimated assets in the MEC region are enormous. Prior to September 11th, a number of major capital investment projects in transportation were underway or under consideration in the region, such as the Route 9A reconstruction along Manhattan's west side. Since September 11th, estimates for the reconstruction of the transportation system in Lower Manhattan and connecting areas alone have exceeded \$7 billion with over \$4 billion committed by the federal government. Much of this area is either located in or connects to infrastructure at elevations considered vulnerable to sea level rise. Thus, given that considerable modifications of transportation infrastructure are already underway in the form of rehabilitation, accommodating climate change as a design and planning criterion may not produce marginally greater investment needs, depending on how it is accomplished.

Second, the total number and variety of organizations alone within the 31-county region is remarkable, and the number of entities within those organizations involved in infrastructure functions is even larger, estimated to be about 2000 (Zimmerman and Cusker 2001: 152). An extensive list of these entities for transportation is contained in Zimmerman and Cusker (2001: 203-204). Although these organizations have vast resources, coordination remains a key issue if these resources are to be useful to adapting to and preventing adverse climate change effects associated with transportation. A number of institutional mechanisms in the MEC region

promote some level of integration and coordination among this very large number of entities. However, some forms of integration, for example, between transportation infrastructure and other infrastructure used to support it is often only addressed in an issue-specific or ad hoc manner (Zimmerman 2001). Most of the infrastructure-related entities tend to be highly specialized by function and by area of the region with little integration. For example, at the present time, region-wide planning in general is not the formal role of any governmental agency, though some organizations have undertaken this responsibility such as the Regional Plan Association. Development planning, coastal zone planning, and infrastructure planning, all of which affect transportation, occur within states and localities but by separate public agencies. When these activities are undertaken at a regional scale, they usually occur under the auspices of a state or federal program, and the boundaries of such efforts rarely encompass the entire region. An important aspect of capacity building at the institutional level is directly confronting and addressing public attitudes and behavior toward the uncertainties in global climate change.

In summary, building institutional capacity is the key to the management of both adaptation and prevention of the adverse climate change effects. The IPCC underscored the need for adaptive capacity, and much of the capacity in the transportation sector lies within the institutions responsible for transportation infrastructure from its planning and design through operation and maintenance. It is these organizations, together with public support, that will enable existing transportation investments to reinforce the goals of adapting to and preventing adverse effects of global climate change.

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¹ A summary of these indicators is presented in IPCC 2001c: 5-6. An example of a set of actual changes is the estimated increase over the 20th century in the atmospheric concentrations of a number of greenhouse gases by about 10 to 150 percent (the actual amount depends on which gas it is).

² The IPCC working group authors use the term "likely" where it appears next to an indicator to signify that a given condition has a 66-90% chance of occurring, very likely as a 90-99% chance, and virtually certain as a greater than 99% chance (IPCC 2001c: 5). Only the terms likely and very likely appear in the summary tables on pp. 5-6.

³ The IPCC (2001b, 2001d) reports identify a wide range of impacts with varying degrees of certainty assigned to each.

⁴ Though the emphasis is on the New York area, the results of New York area studies have broader applicability to other areas.

⁵ Although the concept has been applied primarily to urban areas, it applies equally to suburbs and rural areas.

⁶ This concept is usually quantified using county level data as well as in terms of shoreline miles.

⁷ Davis and Diegel 2002 6-8, citing the U.S. DOT, FHWA 2001: Table VM-1, p. V-50 and annual figures.

⁸ Although carbon dioxide's potential for global warming is far exceeded by other greenhouse gases (see Davis and Diegel 2002: 3-3 citing U.S. DOE, EIA 2001: Table 3 and IPCC), carbon dioxide is present in greater quantities and concentrations than these other gases.

⁹ Calculated from Davis and Diegel 2002: 3-5.

¹⁰ For example, McDaniels, Axelrod and Slovic (1995: 581) indicated that the public they surveyed ranked climate change ranked twelfth out of sixty five items, and the actual rank was 2.06 out of 3 on a scale from -3 ("poses no risk") to +3 ("poses great risk").

¹¹ Ten feet is usually used as the threshold for identifying the risk of sea level rise.

¹² See, for example, the comparative matrix provided by Davis and Diegel (2002: 3-9). Some of these alternatives were also explored in Kulash (2002).

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Potential Impacts of Climate Change and Variability on Transportation in the Gulf Coast/Mississippi Delta Region

By Virginia R. Burkett

If the Earth's atmosphere warms within the range projected by the Intergovernmental Panel on Climate Change (IPCC, 2001) during the 21st century, the climate of the northern Gulf of Mexico coastline (hereafter, Gulf Coast) and the Mississippi River Deltaic Plain will likely become warmer, with more frequent or prolonged periods of heavy rainfall and drought. These climatic changes would have significant impacts on water quality, flooding, soil moisture, runoff, and many other environmental factors that affect the transportation sector, either directly or indirectly. Changes in interannual climate variability will also have practical significance to the Gulf Coast transportation sector. Seasonal rainfall and hurricane frequency in the Gulf Coast region have been linked with El Niño and La Niña events, which may become more intense as the Earth's atmosphere warms. The anticipated increase in global average temperature will accelerate sea-level rise, which can lead to increased vulnerability of transportation infrastructure to storm damage and flooding in low-lying coastal zones.

20th Century Climate and Sea Level Trends

Temperature and Precipitation Trends

In the southeastern region, 20th century temperature trends varied between decades, with a warm period during the 1920s-1940s followed by a downward trend through the 1960s. Since the 1970s, however, southeastern temperatures have been increasingly warmer, with 1990s temperatures the highest on record. The average temperature in the Southeast has increased approximately 1 °F since 1970, which was the average annual temperature increase for the entire United States between 1901 and 1998 (Burkett and others, 2001).

The southeastern region of the United States receives more rainfall than any other region, and the region as a whole grew wetter during the 20th

century. Average annual precipitation has increased 20-30% over the past 100 years across Mississippi, Alabama, the Florida panhandle, and parts of Louisiana (Figure 1). The southern tip of Texas and several other areas have slightly decreasing trends in annual precipitation. Much of the increase in precipitation in the Southeast was associated with more intense events (rainfall greater than 2 inches or 5 cm per day). A small percentage of the increased precipitation was associated with moderate rainfall events, which are generally beneficial to agriculture and water supply (Burkett and others, 2001). Analysis of stream flow trends during 1944-93 for the southeastern region of the U.S. showed little change in annual maximum daily discharge but significant increases in annual median and minimum flows in the lower Mississippi Valley (Linns and Slack, 1999).

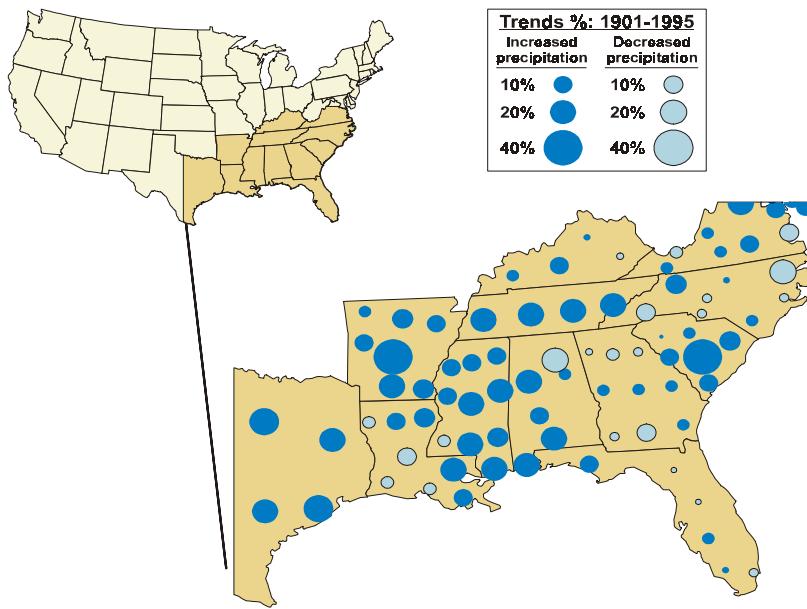


Figure 1. Map of trends in average precipitation in the Southeast (percent change), 1901 - 1995. Source: National Atmospheric and Oceanic Administration, National Climatic Data Center, Asheville, North Carolina, 2000.

Trends in wet and dry spells during the 20th century, as indicated by the Palmer Drought Severity Index (PDSI), are spatially consistent with the Gulf Coast region's increased precipitation trends, showing a strong tendency to more wet spells. The percentage of the southeastern landscape experiencing "severe wetness" (periods in which the PDSI averages more than +3) increased approximately 10% between 1910 and 1997 (Burkett and others, 2001). Average annual summer precipitation decreased and average annual winter precipitation increased in the Gulf Coast region during that period (Melillo et al., 2000).

El Niño/Southern Oscillation Effects on Gulf Coast Climate

The El Niño/Southern Oscillation (ENSO) phenomenon contributes to variations in temperature and precipitation that can affect transportation in the northern Gulf of Mexico coastal zone. ENSO is an oscillation between warm and cold phases of sea-surface-temperature (SST) in the eastern tropical Pacific Ocean with a cycle period of 3 to 7 years. El

Niño events (the warm phase of the ENSO phenomenon) are characterized by 2 to 4 °F (about 1 - 2 °C) cooler average wintertime air temperatures in the Gulf region. During the spring and early summer months, the region returns to near normal temperatures. Gulf Coast states encounter wetter than normal winters (by about 1 - 2 inches per month) during El Niño events. By the spring, the entire eastern seaboard typically shows increased precipitation. In summer, climate impacts of warm events are more localized; for example, drier conditions are typically found in eastern coastal regions, and from north Texas to northern Alabama. El Niño events also create upper atmospheric conditions that tend to inhibit Atlantic tropical storm development, resulting in fewer Gulf Coast hurricanes, while La Niña events have the opposite effect, resulting in more hurricanes (Bove and others, 1998a; Muller and others, 2001). Figure 2 depicts U.S. Gulf of Mexico hurricane landfall trends and the probability of hurricane landfall during El Niño and La Niña years.

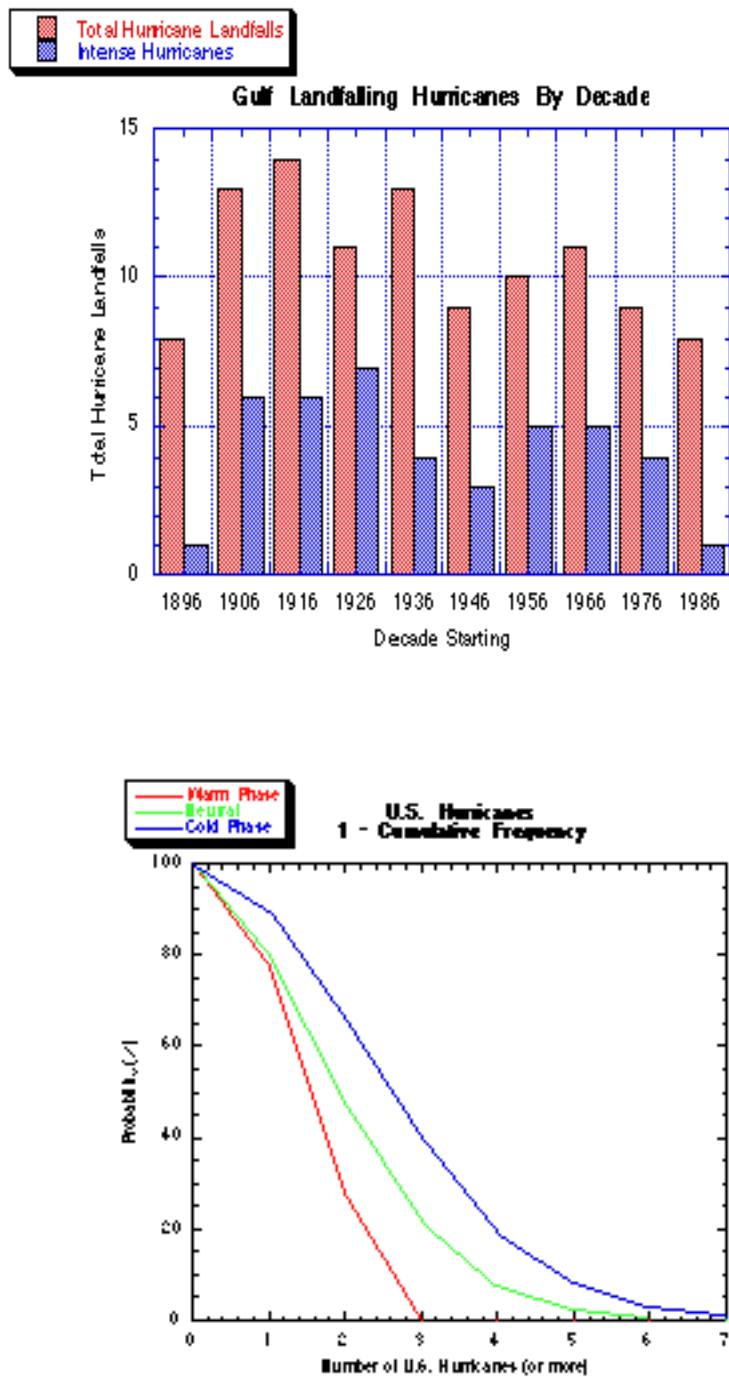


Figure 2. U.S. hurricane landfall trends in the Gulf of Mexico. These charts show the number of U.S. hurricanes making landfall in the Gulf of Mexico by decade for the past 100 years and the probability of the number of hurricane landfalls on the U.S. in a given hurricane season and ENSO phase: warm phase (*El Niño*), neutral, and cool phase (*La Niña*) (modified from Bove et al, 1998 a and b).

During La Niña events (the cold phase of ENSO), the anomalies are sometimes reversed from those associated with warm events, but not everywhere. Wintertime precipitation patterns associated with cold events show increases (1-2 inches or 2.5-5 cm per month) in the band stretching from northern Mississippi to southwestern Pennsylvania. In the spring of a La Niña event, Gulf Coast areas typically have increased precipitation. In summer, the extreme southern U.S. is colder than normal and greater precipitation is evident in the Southeast. Dry to very dry conditions are typically found in parts of Texas and Louisiana during La Niña events (Burkett and others, 2001).

Sea-Level Rise

Global sea level has risen about 400 ft (120 m) as a result of melting of large ice sheets since the last glacial maximum about 20,000 years ago (Fairbanks, 1989). The most rapid rise occurred during the late and post-glacial periods followed by a period of relatively stable sea level during the past 6,000 years (Mimura and Harasawa, 2000). During the past 3000 years, reconstructions of sea level indicate that it rose at an average rate of about 0.004 - 0.008 in/yr (0.1-0.2 mm/yr), but during the 20th century the rate had increased to approximately 0.04-0.08 in/yr (1.0-2.0 mm/yr) or 10-20 centimeters per century (4-8 inches) (Gornitz, 1995; IPCC 1996).

Relative or observed sea level at the ocean/land interface is influenced by local and regional vertical movements of the land surface associated with isostasy (e.g., rebound of the surface after the retreat of ice sheets), tectonic processes (e.g., earthquakes, geosynclinal downwarping, and uplift) and sediment accretion or erosion at the land surface. Although they are mostly natural, these vertical movements can be influenced by human activities such as the extraction of groundwater and hydrocarbons or by the removal and/or redirection of river-borne sediments through the construction of dams and levees. Hence, the local rate of sea-level rise is more important than the global average when evaluating the

vulnerability of transportation infrastructure in a coastal region.

Sea-level rise observed along the U.S. coastline varied between and within coastal regions during the 1900s. However, in general, the U.S. Gulf and South Atlantic coasts (with the exception of Florida) experienced rates of sea-level rise that were significantly greater than those observed on the U.S. Pacific Coast. Relative sea-level rise is greatest along the Louisiana coastline where the land surface of the Mississippi River Deltaic Plain is subsiding (sinking with respect to sea level) as much as 0.25 in/yr (10 mm/yr) due to a combination of natural and human-induced processes. The average rate of sea-level rise in Texas and several segments of the Atlantic shoreline is also double or more the global average. Wetland loss and shoreline erosion are typically higher in regions where relative sea-level rise exceeds the global average.

Projected 21st Century Changes in CO₂, Climate, and Sea-level Rise

Atmospheric CO₂ is higher now than it has been in at least 400,000 years, and the likely scenario over the next 100 years is that it will double or triple over preindustrial levels, and that this increase in CO₂ will be accompanied by an increase in the rate of global warming (IPCC, 1996, 2001). Computer-based general circulation models (GCMs) of the atmosphere and oceans help us understand how elevated CO₂ and other changes in greenhouse gas composition will ultimately affect ecosystems and society. GCMs indicate accelerated warming of the United States over the next hundred years.

Climate change scenarios selected for the United States' "National Assessment" (Melillo and others, 2001) were based on GCM experiments conducted at the United Kingdom's Hadley Centre for Climate Prediction (HadCM2) and the Canadian Climate Centre (CGCM1), hereinafter referred to as the Hadley and the Canadian models, respectively. For the emissions scenario used, these two models are

representative of the higher and lower ends of the range of temperature sensitivity among the “transient” GCMs available at the beginning of the “National Assessment.” Both of these models do a good job of hindcasting 20th century change; they also use a consistent set of realistic, mid-range assumptions about the rate of increase in greenhouse gas emissions during the next 100 years, assuming emissions controls are not implemented. Output from these models should be viewed as a range of two plausible climate futures rather than predictions of what will happen at any particular location. It should also be noted that the current spatial resolution of GCMs is not sufficient to simulate changes in the geographical distribution of storms.

Temperature and Precipitation Scenarios, 2000-2100

Climate models used in the “National Assessment” indicate that the average temperature of the Gulf Coast could increase by 4 to 10 °F during the 21st century. The Hadley model simulates less warming than the Canadian model for the Gulf Coast, and the models do not agree about the direction of future precipitation change. The Hadley model simulates increased rainfall for the Gulf Coast region while the Canadian model simulates declining annual rainfall in this region during the next 100 years. Differences in projections of precipitation change are due mainly to differences in the location of storm tracks simulated by the two models. Both GCMs, however, indicate that the July average heat index increase is very likely to be greatest in the southern states, increasing by 8 to 20 °F above present levels. Both models also simulate declining summer soil moisture in most Gulf Coast counties during the 21st century.

Changes in the Frequency and Intensity of ENSO Events, Tropical Storms, and Hurricanes

Some climate models indicate that the mean climate in the tropical Pacific region will shift toward a state corresponding to present-day El Niño conditions (Timmermann and others, 1999), which could influence seasonal rainfall and decrease hurricane activity in the Gulf

region as described previously. Several ocean-coupled GCMs indicate that the intensity of hurricane rainfall and wave height may increase as the climate warms during the next 100 years (Knutson and others, 1998). However, an analysis by Bove and others (1998) of hurricane intensity in the Gulf Coast region between 1886 and 1995 did not show an increase in hurricane intensity during this historical period. While it is widely acknowledged that El Niño seasons are associated with fewer Gulf of Mexico hurricanes than La Niña seasons, an analysis of less intense tropical storms over the Gulf of Mexico between 1951 and 2000 showed very little difference in the frequency of minor tropical storms during El Niño and La Niña events (Muller and others, 2001).

A recent analysis of Atlantic basin hurricane activity by Goldenberg and others (2001) indicated a five-fold increase in hurricanes affecting the Caribbean when comparing 1995-2000 to the previous 24 years (1971-94). Conversely, Gulf of Mexico hurricane activity decreased from the first half to the second half of the 20th century (Figure 2) (Bove and others, 1998b). It is important to note that hurricanes exhibit multidecadal patterns that appear to be associated with variations in tropical sea-surface temperature patterns and vertical wind shear, and we may be entering a period of high-level hurricane activity in the Atlantic Basin that could persist for 10 - 40 years (Goldenberg and others, 2001).

Acceleration of Sea-level Rise

Sea-level rise is regarded as one of the more certain consequences of increased global temperature, and sea level has been rising gradually over the past 15,000 years. The current average rate of global sea-level rise (1-2 mm/yr) is projected to accelerate two to four-fold over the next one hundred years (IPCC, 2001). The mid-range estimate of global sea-level rise that will occur during the 21st century is 0.48 m (IPCC, 2001).

The Hadley Model simulates a slower rate of sea-level rise than the Canadian model (Figure 3). The relative or apparent rate of sea-level rise during the 21st century in areas will be greater in regions where the land surface is sinking or subsiding. Parts of the city of New Orleans that are presently 7 feet below mean sea level may be 10 or more feet below sea level by 2100, due to a combination of rising sea level and subsidence of the land surface (Figure 4).

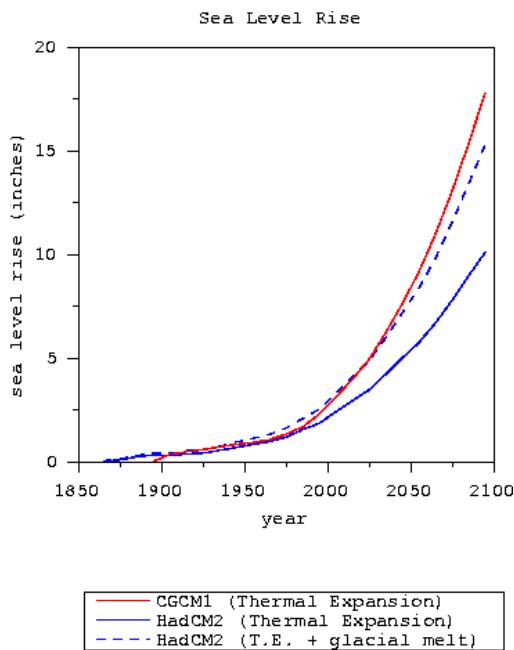


Figure 3. Reconstruction (over the past 100 years) and projections (over the next 100 years) of global sea-level rise from the Hadley Climate Center Model (HadCM2) and the Canadian Center Climate Model (Boesch et al., 2000). This graph illustrates the acceleration of sea level rise in the 21st century as compared to previous periods. Note that the Canadian model (red) does not include sea level rise associated with glacial melt.

Even if storms do not increase in severity, storm surge and its effects will be intensified as sea level rises and natural coastal defenses deteriorate. As sea level rises, islands will tend to “roll over” or move toward the mainland if human activities and changes in storm patterns

do not impact this natural landward migration (Scavia and others, 2002; Twilley and others, 2001).

Louisiana, Florida, and Texas are the top three states in the Nation in terms of annual losses due to hurricanes and floods. Flood damages in Gulf Coast states will increase if sea-level rise accelerates, due to two factors: increased storm surge, and loss of coastal wetlands and barrier islands. Large areas of the Gulf Coastal plain will experience shoreline retreat and coastal land loss if mean sea level increases. Since 1980, losses of coastal forests in parts of Florida, South Carolina, and Louisiana have been attributed to salt water intrusion and/or subsidence. Low-lying Gulf Coast marshes and barrier are considered particularly vulnerable to sea-level rise, but they are all not equally vulnerable. Marshes that are subsiding or have little sediment supply are more vulnerable than those that are accreting material vertically at rates that equal or exceed the rate of sea-level rise. Under the IPCC's mid-range estimate of average global sea-level rise over the next 100 years, the Big Bend area of the Florida Gulf coast will likely undergo extensive losses of salt marsh and coastal forest (Burkett and others, 2001).

Submergence of coastal marshes is expected to be most severe along the shorelines dominated by unconsolidated sediments along the U.S. Gulf and Atlantic coasts. Some coastal marshes and mangrove systems along these coasts are presently accumulating sufficient mineral and/or organic sediment at rates that will compensate for the projected increase in the rate of sea-level rise. In south Louisiana, however, roughly 1 million acres of coastal marsh have been converted to open water since 1940. Natural subsidence and a variety of human activities (drainage projects, dredge and fill, groundwater withdrawals, levee construction on the Mississippi River) have contributed to these losses. If the rate of sea-level rise accelerates, additional marshes and baldcypress swamps are likely to be inundated as the shoreline advances inland (Burkett, 2002) (Figure 5).

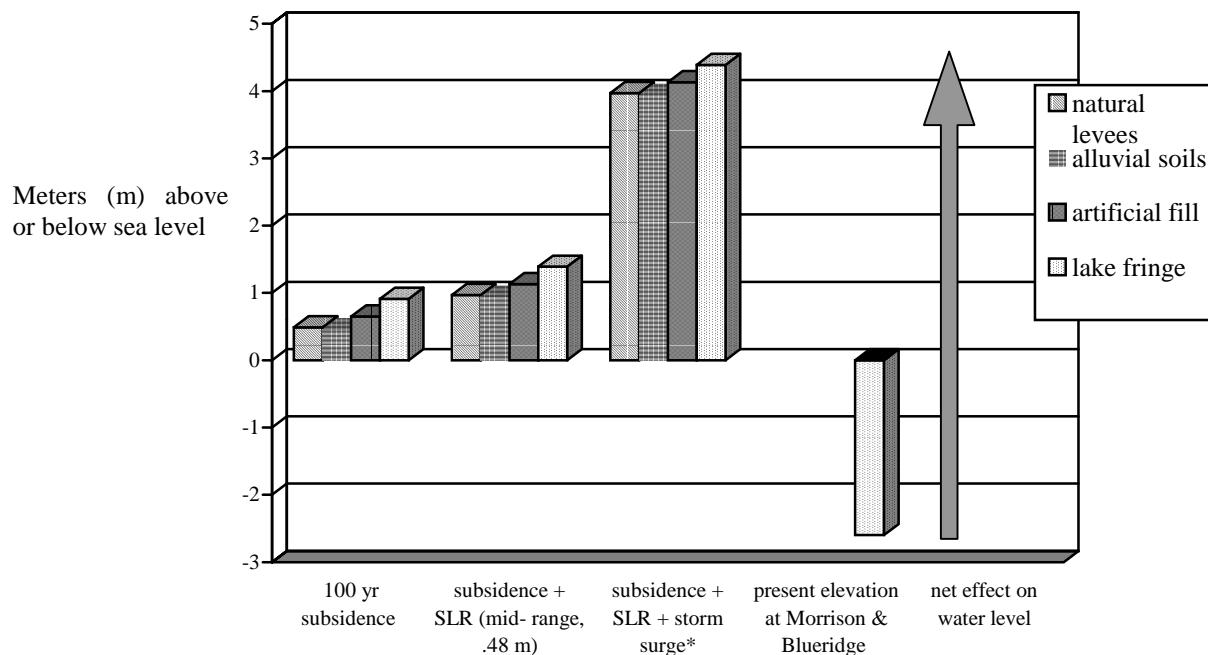


Figure 4. Subsidence and sea level projections for major geologic units in New Orleans and vicinity through 2100. When global sea-level rise, local subsidence, and the present elevation of the land surface are all considered, parts of the city could lie 7 meters below water level during a category 3 hurricane in the year 2100. The arrow on right illustrates this effect for the Morrison Road/Blueridge Court intersection, which is presently about 2.6 m below mean sea level. The arrow represents the cumulative influence of land surface elevation change and sea-level rise on storm surge level (*category 3 hurricane) at this location (from Burkett et al., In Press).

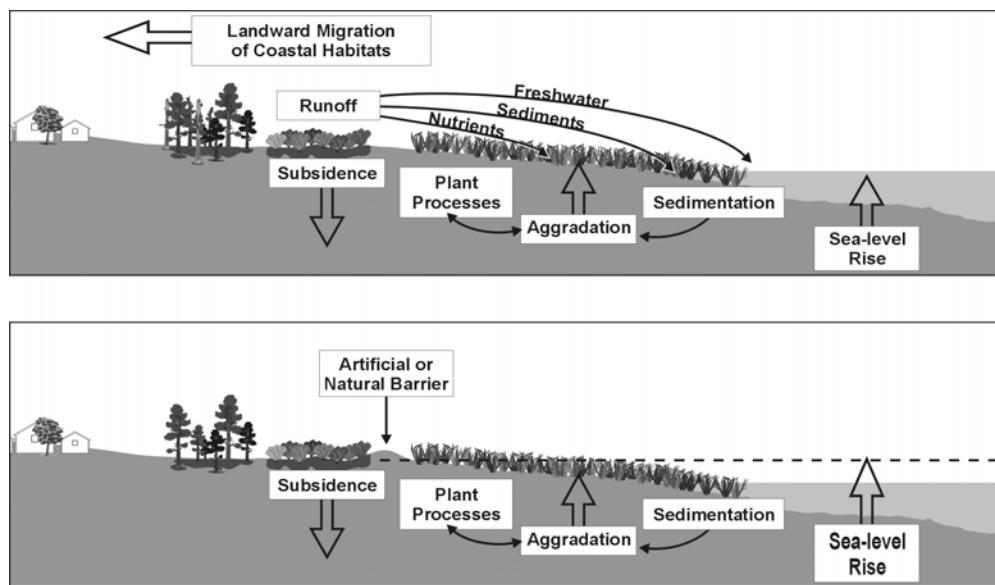


Figure 5. Depiction of processes that affect shoreline retreat as sea level rises (from Burkett, 2002). (a) Due to sea level rise, coastal barriers, shorelines, and wetlands will recede inland. Not all coastal landforms are equally vulnerable to sea level rise. Sedimentation rates, subsidence rates, and the presence of natural or artificial barriers can influence the potential for submergence. (b) Barriers will curtail natural processes such as sedimentation from runoff that maintained the elevation of the land surface. However, they may delay or prevent the submergence of areas landward of the barrier.

Implications for the Gulf Coast Transportation Sector

The changes in temperature, precipitation and sea level that are projected during the 21st century are likely to have numerous implications for the Gulf Coast transportation sector. The six potential impacts on transportation presented below are not intended to be exhaustive, but rather to provide examples that can stimulate ideas and discussion about adaptations within this sector.

Construction Activities

Highway and airport construction activities may be adversely affected by the heat index increase that is anticipated in this region. Effects will vary among age groups. The scheduling of construction and maintenance work, equipment and shelter design, and other modifications for reducing heat stroke could mitigate some effects.

Understanding how El Niño and La Niña events affect rainfall could prove to be very valuable in planning construction work, just as farmers have benefited from using El Niño and La Niña predictions to plan seasonal agricultural activities.

Bridge construction over Gulf Coast streams should consider the fact that the 100-year flood is likely to occur more than once every 100 years, and that flood heights are likely to increase in some watersheds. Bridges and roads can act as dams that increase the potential for flooding if streamflow and/or rainfall increase. Several people have drowned in their vehicles in elevated highway underpasses in Louisiana and Texas Interstate during the past 15 years. Bridge design in virtually all of the Gulf Coast states should consider the fact that rainfall patterns are changing and that peak flows may increase in streams and tidal channels, thereby requiring more erosion prevention and clearance than during the past century.

Soil moisture decline, runoff trends, and increased maximum summer temperature may be a consideration in materials selection and standards. For example, thermal expansion of

materials used in the construction of bridges and roads may become a more important factor in materials testing.

Design for highway construction in coastal counties should consider relative sea-level rise, subsidence, and rainfall trends. For example, culverts should be designed so that increases in tidal levels and peak runoff will not flood property adjacent to highways. Some nations and some states (Maine, Massachusetts, Rhode Island, South Carolina) have passed laws that require development setbacks lines for highways, airports and buildings constructed near shorelines and on barrier islands to accommodate sea-level rise (McLean and others, 2001). The “shelf life” of a coastal highway will generally be shorter than that of an inland highway, and higher costs should be planned to maintain vehicular transportation in the coastal zone.

Port facilities are another class of transportation infrastructure that may be affected by climate change and sea-level rise. Higher sea level will decrease the effectiveness of breakwaters against wave forces, and wharves may need to be raised to avoid inundation. When such effects are anticipated, countermeasures can be implemented to maintain function and stability (McLean and others, 2001).

Freight and Passenger Transport

If the intensity of rainfall continues to increase, runoff and flooding of highways are likely to increase. In low-lying coastal areas and along coastal shorelines, increased storm surge is likely to affect highway access and use. Intense rainfall events in Houston (June 2001) and New Orleans (May 1995) were two of the region’s most costly weather disasters, and in each case major highways were impassable for several days. Elevation of highways and improved drainage of highways, railways, and other transportation facilities may be needed.

Impacts of climate change and sea-level rise on Gulf Coast ports and waterways could be significant, but little work has been conducted to reveal vulnerabilities. Increased dredging may

be required to maintain coastal waterways because siltation in waterways will increase in some areas as natural coastal landforms and man-made levee systems erode. Shipping activity along the Lower Mississippi River could be affected by lowered river stage during a continued drought or by the loss of shipping in other waterways that are affected by climate change (such as the Great Lakes).

Loss of Wetlands

Coastal and interior wetlands in the Gulf Coast states will likely deteriorate as a result of increasing disturbance (fire, storm surge, drought), declining summer soil moisture, and gradual submergence or saltwater intrusion associated with sea-level rise. Wetland loss has two important implications for the transportation sector: (1) mitigation of wetland loss for highway construction may become more difficult and (2) vulnerability of transportation facilities to storm damages will increase as natural coastal defenses deteriorate.

Hurricane Preparedness and Evacuation

Many important hurricane evacuation routes along the Gulf coastal plain are vulnerable to storm surge flooding. Tides were elevated 22.6 feet in one area of Mississippi when Hurricane Camille made landfall in 1969. Sections of Highway 90 and several other evacuation routes were flooded. New Orleans is particularly vulnerable to the loss of life and property during hurricanes since much of the city lies below sea level and there are only two elevated northbound evacuation corridors.

Current evacuation routes are inadequate to evacuate over 1 million people that will need to leave the region in the event of a direct strike of a category 4 or 5 hurricane. Many other Gulf coast cities and small towns are highly vulnerable to loss of life if evacuation capacity is not increased. Design of highways used as major evacuation corridors could be improved to accommodate the reliance on them as evacuation routes (e.g., wider shoulder to accommodate accidents, crossovers on parallel elevated highways).

Oil and Gas Transportation

Storm surge damage and flooding could have important impacts on oil and gas production, transportation, and processing facilities in the Gulf Coast. There are roughly 4,000 production platforms located off the Louisiana/Texas shoreline, accounting for roughly 25% of domestic oil and gas supplies. Storm damage to the network of Gulf Coast pipelines, bulk terminals, and processing plants could be a serious threat to domestic product transportation as well as that of oil imports. Roughly two-thirds of the Nation's imported oil is transported onshore into Texas and Louisiana facilities. Emergency preparedness could decrease the potential impacts of storms and other weather-related disasters on oil and gas transportation. Construction design for these facilities should consider the climate model projections of increased sea level, wave heights, and rainfall.

Water Quality

If summer soil moisture continues to decline in the Gulf Coast region, runoff could be reduced. Summer low flows occur when water quality (particularly dissolved oxygen) of many Southeastern streams and rivers is at its lowest (Meyer, 1992). Reduced dissolved oxygen during summer months can result in fish kills and harmful algal blooms in both coastal and inland waters. Water quality conditions may become critical during more frequent periods of extreme low flow. Water quality problems are most acute in areas of intensive agricultural activity, in coastal areas, and near coastal streams (Burkett and others, 2001). Consideration of these water quality problems in transportation project planning may reduce project obstacles, environmental impacts, and costs.

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The Potential Impacts of Climate Change on Great Lakes Transportation

By Frank H. Quinn

Introduction

The Great Lakes, shown in Figure 1, are one of North America's largest water resource systems with a basin area of about 770,000 km², of which about one third is lake surface. It is one of the most intensively used fresh water systems in the world, serving multiple interests including navigation, hydropower, recreation, water

supply, food supply, and riparian. The outflows from Lakes Superior and Ontario are regulated by regulatory works in the St. Marys and St. Lawrence Rivers respectively. The remainder of the system is naturally regulated. Great Lakes water levels change slowly due to the large lake surface areas and constricted outlet channels which integrate short-term climate fluctuations. There is a likely potential for significant global climate change due to increased greenhouse gas

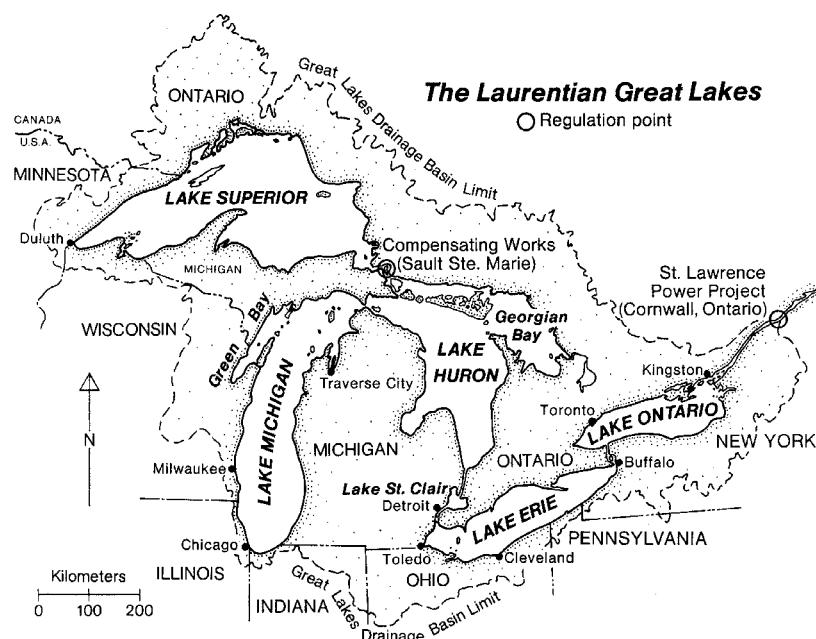


Figure 1. Map of the Great Lakes drainage basin.

concentrations in the atmosphere. The impacts of this change, when translated to the Great Lakes basin, are significant in terms of lake levels and waterborne transportation. The Great Lakes-St. Lawrence water transportation system supports more than 30,000 jobs in the U.S. and Canada with business revenue and personal income from the movement of cargo topping \$3 billion per year (Stead et al., 2000). Because of the relatively small water level variability, about 1.8 meters, shipping interests have become dependent upon a relatively stable lake levels regime, resulting in sensitivity to the water level changes anticipated under climate change. Studies conducted in the U.S. and Canada since the early 1980's show an increased possibility of lake level lowering due to global warming, resulting in major changes to the water resources and lake levels.

The Great Lakes have had two episodes of low water over the past 40 years, in 1963-1966 and 1997-2001, which may provide some guidance in impact assessment. The problem with using them as a true analogue is that they were of limited duration lasting three to four years, and did not represent a long term change. During the last episode, declining water levels in the Great Lakes impacted several major industries in the region. In the year 2000, lake carriers that transport these cargoes were forced into "light loading", carrying 5-8% less goods. Although water levels increased in 2001, they are now the same level as the year 2000. The Lake Carriers Association reported that Dry Bulk Commerce decreased by 6.7 percent in 2001 compared to 2000. A tenfold increase was also noted in the dredging activity during the five year period beginning with 1963 (4,119,000 cubic yards annually) compared with the preceding five years (372,000 cubic yards annually) (Sousounis et al., 2000). Also during the recent episode cruise ships were unable to dock at Saugatuck, MI, a highly desirable stop, because of inadequate water depths in the harbor. Many small picturesque stops may not be available for cruise ships under climate change.

Great Lakes Transportation System

U.S. Fleet. The transportation system comprises bulk cargo carriers, ocean going vessels and smaller cruise ships. Predominant players are the bulk lake carriers with lengths up to 1000 feet. In recent years there have also been two or three small cruise ships running from Montreal or Quebec City with a number of port calls throughout the Great Lakes. Ocean going vessels have plied the Great Lakes since the construction of the St. Lawrence Seaway in the late 1950s. This presentation will concentrate primarily on the lake carriers. The U.S.-Flag Lakes fleet consists of approximately 65 large self-propelled vessels and tug/barge units in the dry- and liquid-bulk trades; another 20 smaller tug/barge units are engaged primarily in moving liquid-bulk products (Lake Carriers Association, 2002). Thirteen of the ships are the 1,000-foot-long super carriers which can routinely carry as much as 70,000 tons of iron ore or coal. In May of 2002 there were 43 dry bulk carriers, three cement carriers, and five tankers in operation (Lake Carriers Association, 2002).

U.S. Cargo. The Great Lakes-St. Lawrence Seaway is a 1270-mile transportation route that handles approximately two billion tons of commercial shipping. Sixty percent of the seaway traffic travels to and from overseas ports such as Europe, the Middle East and Africa. Eighty percent of cargoes shipped each year include iron ore, coal, grain or steel. The following cargo data are from Lake Carriers Association (2002). Iron ore averages nearly 58 million tons each shipping season, twice that of the next largest commodities, stone or coal. The ore is loaded at ports on Lakes Superior and Michigan and delivered to lakefront steel mills, or to transfer facilities where the iron ore is then railed to inland furnaces. The iron ore trade begins out of Escanaba, Michigan, in early March. When the locks at Sault St. Marie, Michigan, open on March 25, loading resumes at the six ore docks on Lake Superior and continues until the federally-mandated closing of the Soo Locks on January 15. Depending on demand for iron ore, shipments will continue from Escanaba until early- or mid-February. Since it has the longest shipping season, the iron

ore trade is the most dependent on icebreaking by the U.S. Coast Guard. Early- and late-season sailing tests the ships' and crews' endurance, but steelmakers must minimize stockpiling costs to remain competitive with foreign suppliers.

Limestone has the most diverse customer base. The steel industry uses "flux-stone" as a purifying agent in the steelmaking process. The flux-stone is either added directly to the blast furnace or mixed in with the iron ore at the mine to produce "fluxed pellets." The construction industry uses "aggregate" as a base for highways, parking lots and sewer systems. The chemical and paper industries also use limestone. When all the applications for limestone are combined, it is estimated that each American uses 8,000 pounds every year. The annual stone float for U.S.-Flag lakers is approximately 23 million tons. The development of fluxed pellets has actually increased the stone trade for U.S.-Flag lakers above pre-recession levels. The Great Lakes region is blessed with an almost inexhaustible supply of limestone and the quarry at Rogers City, Michigan, is the largest in the world. Since stone is somewhat high in moisture content and is often "washed" before loading into vessels, the trade is a bit more weather-sensitive than other cargos. The stone trade generally resumes in early April and finishes by late December.

Coal rounds out the "Big 3" trades for U.S.-Flag lakers. Shipments generally top 20 million tons in a typical navigation season. There are two types of coal hauled on the Lakes: Metallurgical or "met" coal for steel production, and steam coal for power generation. There is another distinction: Eastern and Western coal. Eastern coal is mined in West Virginia, Pennsylvania, Kentucky, Ohio and Illinois and is shipped from Lake Erie and Lake Michigan ports. Western coal is mined in Montana and Wyoming and then railed to Superior, Wisconsin, for loading into vessels. The coal trade begins in late March and generally wraps up by year's end. The coal trade perhaps best exemplifies the benefits of inter-modalism. There is not a single large coal mine anywhere near a U.S. port on the Lakes. American railroads, in other instances fierce competitors

for cargo carried by lakers, deliver the coal to Lakes ports for final shipment by vessel to the customer.

Other cargoes, including cement, salt, grain, sand and various liquid-bulk products in total represent roughly 10 percent of the U.S.-Flag float each year. In many instances, these commodities are "backhaul" cargos, which help keep freight rates as low as possible. Salt cargos top 1 million tons each year. Many Great Lakes communities get the salt they need to keep streets and sidewalks ice-free in U.S.-Flag lakers. Cleveland and Fairport Harbor, Ohio, are the two U.S. salt-loading ports on the Lakes. Roughly 500,000 tons of wheat move between Duluth/Superior and Buffalo each year in U.S.-Flag lakers. Grain is the one trade where "straight-deckers" (non self-unloading ships) are still active. Other commodities carried by U.S.-Flag lakers include sand, gypsum, taconite tailings and coke breeze. The cargo statistics for the last four years are given in Table 1.

There are 15 major international ports and about 50 smaller regional ports on the Great Lakes-St. Lawrence River System. The location of many of these ports is shown in Figure 2.

Climate Impacts

A review of various Great Lakes studies, and their rationale, is given by Quinn (1999). In the late 1980s a major study was undertaken by the United States Environmental Protection Agency to assess the potential effects of global climate change (Environmental Protection Agency, 1989). As part of this effort a detailed assessment of the impacts on Great Lakes water supplies was undertaken using an integrated suite of daily rainfall-runoff models for the 121 basin watersheds and lake evaporation models for each of the lakes (Croley, 1990). This assessment used a pre-selected set of double CO₂ scenarios from the Goddard Institute of Space Sciences (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), and Oregon State University (OSU) general circulation models (GCMs). For the first time, as part of this study, the climate change impacts on each of the lakes and on the water management for

Table 1. U.S.-flag cargo carriage: 2001-1998 navigation seasons (net tons). Source: Lake Carriers' Association: June 2002.

Commodity	2001	2000	1999	1998
Iron Ore, Total	47,277,306	58,519,597	59,086,414	62,800,734
Iron Ore, Direct Shipments	44,182,574	53,242,963	53,182,571	56,988,970
Iron Ore, Transshipments	3,094,732	5,276,634	5,903,843	5,811,764
Coal, Total	21,394,115	21,108,263	21,969,064	21,937,047
Coal, Western	13,350,523	12,878,253	13,471,049	13,515,846
Coal and Coke, Eastern	8,043,592	8,230,010	8,498,015	8,421,201
Limestone and Gypsum	27,334,146	27,933,432	28,392,094	31,618,104
Cement	4,215,357	4,125,542	4,373,812	4,286,049
Salt	876,392	838,017	1,309,894	1,312,157
Sand	625,094	427,070	249,238	234,300
Grain	350,719	351,398	346,814	352,083
Total, All Commodities	102,073,129	113,303,319	115,727,330	122,540,474



Figure 2. Map of Great Lakes-St. Lawrence Seaway ports. Source: <http://www.canadainfolink.ca/glks.htm>.

Lakes Superior and Ontario were determined (Hartmann, 1990). The net basin supply components were used in conjunction with the operational regulation plans and hydraulic routing models of outlet and connecting channel flows to estimate water levels on Lakes Superior, Michigan, Huron, St. Clair, Erie and Ontario. The Lake Superior regulation plan failed under the GFDL scenario and the Lake Ontario regulation plan failed under all scenarios. A large reduction in lake ice cover was also noted (Assel, 1991).

The International Joint Commission (IJC) Water Levels Reference Study (Working Committee 3, 1993) used the methodology developed for the EPA study with GCM scenarios from the Canadian Climate Centre to continue the assessment process. For this assessment the lake regulation models were adjusted to make them more robust to changes in water supplies, while retaining the same basic management framework (Lee et al., 1994). All of the GCM scenarios previously discussed did not include aerosols or the Great Lakes as a physical feature in the GCMs.

During the course of the last 10 years, climate assessments were also developed using historical analogues and climate transpositions, moving climates from the southeast and southwest U.S. to the Great Lakes (Mortsch and Quinn, 1996; Quinn et al., 1997), and stochastic simulations (Lee et al., 1994). These assessments allowed the consideration of changes in variability as well as changes in the extremes and the mean. While the historical analogues show relatively little change to the existing lake level regime, the transpositions show a wide range in impacts depending upon the particular climate used in the transposition.

The U.S. National Assessment¹ is the first Great Lakes study to use GCM scenarios with aerosols. The study uses transient scenarios developed from the recent Canadian Climate Centre model (CGCM1) and the Hadley Center model (HadCM2), the latter of which includes a rudimentary Great Lakes. The two scenarios focus on time slices representing the years 2021-2030 and 2081-2100. This work is progressing also using the basic framework established for the EPA study. This study focuses on the CGCM1 scenario for the 2030 time slice (Lofgren et al., 2002). The impacts for the CGCM1 scenarios are summarized in Table 2. The HadCM2 scenarios gave lake levels very

Table 2. CGCM1 scenarios - Annual mean levels, base and differences (Δ) from the base for various time slices (Lofgren et al., 2002).

Levels	Base (ft)	Δ 2030 (ft)	Δ 2050 (ft)	Δ 2090 (ft)
Superior	601.80	-0.72	-1.02	-1.38
Michigan-Huron	579.23	-2.36	-3.31	-4.52
Erie	571.78	-1.97	-2.72	-3.71
Ontario	245.45	-1.15	-1.74	-3.25

similar or slightly higher than the base case so the impacts on transportation would be the same as the base case. It is my understanding that HadCM3 gives similar results as the CGCM1 model. Good summaries of the hydrologic and lake level impacts of all the various studies are given in Lofgren et al. (2002) and Mortsch and Quinn (1996). *It should be noted that, unlike the seacoasts, the Great Lakes levels fall instead of rise under the influence of climate change.*

Impacts on Transportation

Lake Level Impacts. The Great Lakes transportation system is very sensitive to both changes in economic conditions and to climate change issues such as lower water levels and reduced ice cover. The lower lake levels due to climate change would result in reduced tonnage per trip, because of decreased draft, with the resulting need for additional trips to carry the same volume of cargo. For example, a 1000 foot bulk carrier loses 270 tons of capacity per inch of lost draft. An average ocean going vessel of about 740 feet loses 100 tons of capacity for each inch of lost draft. In addition, the greater number of trips, coupled with the possible increase in the number of vessels in operation, could result in traffic backups at the Soo Locks and perhaps at the Welland Canal. The connecting channels and harbors are dredged to provide a 27 foot project depth.

Sanderson (1987) and Marchand et al.(1988) estimated Great Lakes shipping costs would increase by about 30 percent due to decreased lake levels.

The U.S. Government maintains a 27 foot depth, below low water datum (LWD) for navigation channels in the St. Marys, St. Clair, and Detroit Rivers as well as in Lake St. Clair and the Great Lakes ports. There is basically no impact on navigation in the open lakes because of their great depths, up to 1300 feet. The only problems would be in shoal areas where sufficient depths currently exist but could be problematic under a 1.3-5 feet levels decline. In the connecting channels and harbors, the projected levels declines would be below the project datum much of the time. Table 3 shows the average drop below the low water datum for each lake using the CGCM1 Scenario and the 2030 time slice. Thus by 2030 the average monthly lake level will be below the LWD for Lakes Superior and Michigan-Huron, at the LWD for Lake Erie, and above the LWD for Lake Ontario. This indicates a major loss of government guaranteed capacity for the transportation systems as early as 30 years from now.

Ice Effects. The Great Lakes ice cover is a natural feature of the Great Lakes. Its concentration and duration are a function of

Table 3. CGCM1 scenarios - Monthly mean average levels, ft. (International Great Lakes Datum 1985).

Levels	2030 (ft)	Low Water Datum (ft)	Difference (ft)
Superior	601.08	601.1	-0.02
MI-Huron	576.87	577.5	-0.63
Erie	569.81	569.2	+0.61
Ontario	244.30	243.3	+1.00

climate variability. The ice duration for a 1950 to 1995 base period ranged from 11 to 16 weeks (Lofgren et al., 2002). Under the CGCM1 scenario for 2030 the ice duration is reduced by about 12 to 47 days. Also the percent of ice-free winters will increase by about 2 percent for Lake Superior and 31-61 percent for Lake Erie, depending upon the basin. The ice cover restricts the shipping by blocking the navigation lanes, the ports, and the locks in the system. Historically, generally prior to the 1970s, the Great Lakes navigation season ran from mid-April through mid-November. At the present time the Soo Locks remain open for traffic through January 15 for inter-lake shipping. Intra-lake shipping continues throughout the winter at several locations. The U.S. and Canadian Coast Guard provide ice-breaking support for extended season navigation. The climate change scenarios indicate higher winter temperatures and reduced ice leading to a potentially longer shipping season on the Great Lakes. It is estimated that reduced ice cover will increase the shipping season by one to three months (Sanderson, 1987). This would increase vessel utilization and reduce the need for stockpiling commodities through the winter. It could also have the additional benefit of reduced ice-breaking costs. The extended season due to decreased ice cover could offset some of the costs resulting from lower lake levels.

Lake Regulation. The design and operation of the Lake Superior and Lake Ontario regulation plans will have a direct effect upon the shipping in the Great Lakes-St. Lawrence Seaway. By controlling the outflows from both lakes the regulation affects both upstream and downstream levels. The present Lake Ontario Regulation Plan does not function as designed under most climate change scenarios. The balancing between Lake Ontario and the lower St. Lawrence River, represented by the Port of Montreal, will be particularly important under climate change.

Mitigation. The mitigation required for climate change is the same as that required for extremely low lake levels. The usual form of mitigation for low lake level conditions is to

dredge the harbors to maintain adequate depths for the ships to come in. However, deepening the connecting channels for a greater than 27-foot project depth will require an authorization and appropriation from Congress. Thus the 27-foot project will be the major impediment for navigation under a changed climate. Dredging in the harbors and connecting channels also has serious environmental impacts. Many of the harbors and channels have concentrations of mercury, PCBs, and heavy metals buried in their sediments. This material tends to be resuspended in the water column when disturbed. An environmentally friendly way of removing this material must be undertaken. There will also need to be a system of confined disposal areas designed to handle the dredged material. An associated problem is the geology underlying many of the harbors and connecting channels. The lower Detroit River and the Welland Canal have limestone bottoms, which will necessitate a multi-year effort of blasting the rock to increase the project depths. It should be noted that channel dredging in the connecting channel will have to be compensated for by constructing dikes or control structures in order to prevent additional lowering of the lakes due to increased capacity of the channels. In 1999 Congress provided a broad-range authority to review the feasibility of improving commercial navigation on the Great Lakes/St. Lawrence Seaway navigation system, including locks, dams, harbors, ports, channels, and other related features. The study will report on important factors affecting commercial navigation; such as evolving transportation technologies, inter-modal linkages, characteristics of the Great Lakes fleet and changes affecting demand sectors. The study will identify factors and trends that affect commercial navigation on the Great Lakes/St. Lawrence Seaway and it will project future trends, commodity flows and the external factors that affect them.

Adaptation. There are several things that might be considered in adapting to climate change. The first would be to extend the navigation season, perhaps year-round, to take advantage of the decrease in ice cover. The savings from vessel utilization, reduced

stockpiling and increased trips may offset to some extent the impacts of the lower water levels. Also lake regulation plans should be evaluated as per their navigation-related performance under climate change. New additions to the Great Lakes fleet could be designed taking into account shallower navigation channels. It would however probably be prudent to wait until better estimates of the changed regional climate are available before making this type of economic decision.

The Water Resources Development Act of 1986 (P.L. 99-662) authorized, among other projects, a new large lock at Sault Ste. Marie, Michigan. Non-federal cost sharing for navigation construction projects was required by the law. The proposed new lock would be designed to replace two old and outmoded small locks. This lock design should consider the potential impacts of climate change by perhaps designing a wider and deeper lock than would be warranted under the present climate. It is much easier to design for climate change than to do a retrofit.

Conclusions

Climate change, as currently envisioned, could have a major impact on the Great Lakes-St. Lawrence Seaway transportation system. There are two counteracting impacts, lower water levels leading to reduced draft and increased transits, and reduced ice cover and duration leading to a greatly extended navigation system. The mitigation measures of the past, primarily channel and harbor dredging, are likely to be the first line of defense in the future. This will have to be balanced by strict environmental standards to protect the quality of the Great Lakes water. Prudent planning should include the evaluations of existing regulation plans and the design of the new lock at the Soo Locks. It is also important to update the earlier work on this subject by assessing costs and impacts with the newer climate scenarios and current economic conditions. It is essential that the industry be involved in this assessment relating to the shipping and the port infrastructure, which was not addressed in this paper. It would also be interesting to have the Coast Guard evaluate the

impact of climate change on their Great Lakes activities.

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¹The National Assessment of the Potential Consequences Of Climate Variability and Change (<http://www.gcrio.org/NationalAssessment/>) is a major effort to understand what climate change means for the U.S. Its purpose is to synthesize, evaluate, and report on what we presently know about the potential consequences of climate variability and change for the U.S. in the 21st century. Projections of climate change from the Hadley Centre (HadCM2) and the Canadian Centre for Climate Modeling and Analysis (CGCM1) served as primary resources for this assessment.

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Climate Change and the Potential Implications for California's Transportation System

By Pierre duVair, Douglas Wickizer, and Mary Jean Burer

Abstract

Increased frequency and intensity of storm activity combined with sea level rise is expected to worsen problems of beach erosion and cliff under-cutting. This is a serious issue for coastal road and rail systems, as well as California's system of levees. Warmer winter temperatures will lead to more precipitation falling as rain rather than snow. Increased runoff during the winter and spring months will increase the risk of flooding and landslides. Events such as the Mill Creek landslide along Highway 50 in January 1997 may become more common. Other potential climate impacts on the transportation sector in California are discussed in this paper, which concludes with a review of existing and potential climate change mitigation strategies for California's transportation sector.

Introduction

California's economy, including foreign and domestic trade, relies heavily upon its transportation infrastructure. The state's important role in the world economy makes its transport systems vital to people inside and outside its borders. "In 2000, shipments by land, sea, and air through California ports totaled \$392 billion – an increase of nearly \$100 billion since 1996."¹ Throughout the decade of the 1990s, California's transportation sector felt the destructive power that extreme climate events can yield. Its roads, highways, and railroads were closed due to landslides triggered by heavy rains. Low elevation roadways were flooded and washed out in places. A prolonged heat wave made freeways buckle to the forces of climate. California's transportation system will certainly face further challenges due to extreme weather

events and other climate-related factors that are sure to yield important economic, environmental and social impacts.

Transportation accounts for nearly 60% of all anthropogenic carbon dioxide emissions from the combustion of fossil fuels in California. Although California's industrial sector consumes more energy, transportation accounts for more carbon dioxide emissions because of its near complete reliance on petroleum. While efforts to improve transportation system efficiency and reduce toxic and other emissions that impair public health have been positive, transportation-generated greenhouse gas emissions continue to grow. The California Regional Assessment report (see footnote #2) provides a vast amount of information on climate variability and the potential impacts to some of California's unique ecological, social, and economic systems.

California's population is projected to grow by 12 million people over the next 20 years, reaching 45 million. Increasing population coupled with growing numbers of vehicles, a continuing decline in average new vehicle fuel economy, and predicted increases in total vehicle miles of travel, pose substantial challenges within the state's transportation sector. Decisions made today regarding land use, technology investment, and transportation policies and practices will determine the extent to which travelers and freight movement impact and are impacted by California's climate in both the near and distant future. Efforts to prepare the transportation sector for both the anticipated and unanticipated effects of climate change will require collaboration among federal, state, regional and local agencies. California communities will need to become more involved and better educated about the possible consequences of maintaining the status quo in regards to emissions of greenhouse gases. Furthermore, climate change will require more investment in research, a commitment to alternative transportation technologies, reduced dependence on petroleum, and more effective land use and energy decision-making.

In this paper we first examine a set of climate-related implications for California's rural, coastal, and urban transportation

infrastructure. This first section also notes potential air quality impacts related to climate change. In the second part of the paper we provide a review of some current and potential state greenhouse gas mitigation activities within the transportation sector - looking towards a less greenhouse gas intensive economy in the future.

Climate-Related Implications for Rural and Mountain Roadways

Much of California's landscape is vulnerable to flooding, landslides, or both and, importantly, both become more likely when precipitation levels are high, storms are frequent, and above-normal precipitation continues for several years. In higher elevation watersheds where surface water is stored as snow, flooding can result from unusually warm winter storms, a fast warming of the air, or early springtime melting of the snow. At all elevations landslides and slope failures are partly the result of precipitation and geology and partly the result of land-use practices that allow or encourage building of structures in risky areas. Mountain watersheds frequently generate floods during the spring snowmelt season. The 1997 flooding in the Central Valley was triggered by a warm, mid-winter storm. This storm caused an enormous amount of immediate damage, but it also brought future risks associated with the damage it caused to California's extensive levee system.



Figure 1. Photo of a roadcut failure. Cut banks on rural roads are often very close to vertical. These banks are more prone to failure as warmer more intense winter storms increase proportion of rain versus snow. Access to rural locations will be lost more frequently and roadway maintenance costs will rise.

Just as water supply infrastructure, crop choices, and electricity production choices have been developed with expectations regarding seasonal runoff patterns from mountain watersheds, California's transportation infrastructure has been developed based on typical temperature and precipitation regimes. Authors of the California Regional Assessment reviewed projections from two general circulation models – the Canadian and the Hadley models. Results from these models suggest that even modest precipitation changes expected to result from climate change can have proportionally large impacts on water runoff in California. As one might expect, these climate models predict that as average temperatures rise (especially winter and nocturnal) precipitation tends to fall more as rain than as snow. Most of this rainfall turns into runoff immediately. Increased runoff during the winter and spring months will increase the risk of flooding and landslides, both in the mountains and throughout most watersheds. Many rural roadways are especially at risk due to the increased chance of flooding in the winter and spring months.

Accessibility via the rural road system is a key concern to California's rural economy. The California transportation roadway system is at best a complex arrangement of private and local, state and federal government roads and highways. For the wildlands and forested areas in California portions of these intertwined yet independent road systems are extremely important. Increased water flows as a result of winter rainstorms will lead to both a greater number and greater severity of erosion events and consequent damage to roadways. These events in turn lead to additional restrictions in transportation system capacity. However, less snow on roads may also result in increased winter season accessibility. Nonetheless, it is expected that private landowners face more frequent loss of access to part or all of their property with increased climate variability.

Small parcel residential landowners may lose ingress and egress from their residences, with corresponding impacts to any agricultural practices such as livestock or orchards. For larger landowners (e.g., greater than 40 acres),

potential impacts depend upon the types of land uses selected by the individual landowner. High intensity storms can easily result in high flows destroying watercourse crossings on rural roadways, thus eliminating access to properties. Flooding from such storms can also impact lower lands with a different set of human impacts. One can also anticipate damage to domestic water supply facilities and equipment relied upon by landowners with resultant impacts varying significantly across landowners. Inability to access properties will preclude all management practices such as tree harvesting, tree planting, vegetation thinning, and watershed maintenance activities.

Implications of Climate Change Related to Forest Road Accessibility²

Road access in California's forested lands is important for timber management, recreational activities, fire protection, and tree stand improvement practices. The state as a landowner faces the same potential climate-related problems as that of the private landowner only on a similar or larger scale. For example, the inability to access a state forest will not only impact the harvesting of trees, but also preclude measures to prevent fires and minimize sedimentation of watersheds. In fact, perhaps the most worrisome impacts are related to the increased risk of forest fires due to both warm and cold season implications of climate change. For example, the expected increased length of dry seasons could make fires more frequent in the summer. Subsequently, the effect on transportation of this phenomenon may be the closing of roads due to smoke and fire danger.

Some of the cold season implications of climate change such as increased flooding may also result in an inability to access the state's forests for prolonged periods of time. This has the potential to increase risks of large damaging fires by preventing vegetation management and resulting in increased fuel loads. One of the most significant short-term impacts will be reduced capability to respond to emergency situations.



Figure 2. Photo of a levee breach in the Sutter Bypass. A warm winter storm in January 1997 caused this breach. A temporary bladder seen at left in the photo was used to protect the repair and prevent additional flooding from rising water levels in the bypass.

Beyond the private, county and state maintained roads, there are the U.S. Forest Service, Bureau of Land Management, National Parks, Bureau of Indian Affairs and other federal land management agencies that own and maintain thousands of miles of forest and wildland development roads. While not intended to meet the transportation needs of the public at large, these roads are used to facilitate access to the national forests and other federal land ownership. In most areas, they are open to the public and are a key part of the transportation system for many rural counties. New roads are added each year in relation to land acquisition or projects such as timber sales. Roads are also decommissioned where the net financial and environmental costs would be lower if the roads were removed instead of improved. The national forests of the Sierra Nevada are estimated to contain approximately 24,500 miles of forest development roads.

The dominant use of these roads has changed from support of timber harvesting to recreational use by the public. While the U.S. Forest Service does not maintain many of the roads to the quality standards of most public roads, maintenance is required on road surfaces and drainages, bridges, and culverts. In the past decade, the backlog of undone or deferred maintenance has grown. This maintenance represents a multi-million dollar burden on the national forest system. An increase in intensity of storms will only result in additional backlog of maintenance and further reductions in access to these lands. The potential impacts to federal lands are the same as for state and private lands, only with the possibility for losing much larger areas of lands to wildfire or greater impacts on the quality of watersheds within the state.

A range of adaptation strategies related to fire hazards have been suggested and include: implementing pre-fire management (including limiting development in high fire hazard areas), prescribed burning, clearing brush from buildings, mapping fire behavior, increasing fire resistance of roofing, improving emergency access and increasing public education and information.

The California Department of Forestry and Fire Protection (CDP) and the US Forest Service conduct land cover mapping and monitoring to enhance fire protection and natural resource management on public and private lands in California (this program uses Landsat Thematic Mapper satellite imagery to map land cover types and derive land cover changes across all types of ownership). Fire-prevention methods include those suggested above. These measures make a great deal of sense both as a way of dealing with current stresses and as a hedge against future climatic changes.

The California Board of Forestry and CDF supported state Senate Bill 1075 (Rogers, 1987) related to minimum statewide standards for defensible space in State Responsibility Areas (SRA). This legislation was motivated by the limited response of local governments to the wildland fire protection problem over the previous 20 years. This comprehensive wildland

fire safety legislation required the California Board of Forestry to establish minimum fire safety requirements that applied to SRAs. These requirements covered topics such as emergency access and water supplies, address and street signs, and fuel modification related to new construction and development.

Climate-Related Implications for Coastal Roads and Railroads

In low-elevation coastal watersheds, flooding is most common when a wet winter results in frequent storm events. Numerous coastal mountain watersheds in northern California have rivers that flow over their banks once or twice every ten years. The Russian River exceeded flood stage (39 feet) six times between 1900 and 1950 and eight times between 1950 and 1990. In 1995 and 1997, Russian River floods created large economic losses that were amplified by the presence of many housing developments within the 10-year flood plain. Similar flood events occur in southern California coastal watersheds during severe precipitation events.



Figure 3. Photo of inundated flood plain and bridge across Freshwater Creek in Humboldt County in January 2000. Increases in the intensity of storms will lead to more frequent isolations of populations with associated health and safety risks.

Coastal erosion is another important climate-related impact in California caused by sea level rise and increased storm activity. Cliff under-cutting is a serious issue for coastal road, pipeline, and railroad systems. Stormy, turbulent seas and intense precipitation events can cause

extreme erosion over time along the coast. Coastal erosion is already a significant problem in California. Further erosion due to climate change and rising sea levels will worsen already narrow or stressed coastal shorelines. Coastal roads and railroads are likely to be more vulnerable as a result of increased climate variability. Highway 1 already experiences frequent mudslides and high waves during mild winter storms, as well as washouts every year. Certain roadways could be closed permanently if there are significant increases in erosion, landslides or roadway undercutting. Coastal railroads have had similar problems during heavy storms, often resulting in the shutting down of passenger and freight traffic for days.

Adaptation is possible but likely at significant cost to society. Some roads near the coast may have to be moved or protected from additional exposure to the ocean. Regarding land use planning in specific regions, the Coastal Land Use group participating in the California Regional Assessment Workshop in March of 1998 provided a tiered response strategy. This group considered impacts and stresses from climate changes in three categories: the existing built environment, the natural environment, and future coastal development. They suggested establishing priorities in addressing impacts to the built environment:

- Defend with engineered fortifications assets of high strategic value such as airports, ports, and delta levees (for water supply security).
- Relocate (or engineer alternative solutions) vital assets to higher ground.
- For less strategic aspects of the built environment (housing on coastal bluffs), simply retreat and let nature take its course.³

This group and others have clearly recognized the need to consider potential risks associated with new coastal developments from future climate change and variability. Local and state land use decision-making in the coastal zone should be informed by careful consideration of climate-related factors such as

rising sea levels, increased frequency and intensity of storm events, rising average temperatures, and greater levels of climate variability.

One additional climate impact to California's roadways is the potential for softening and buckling of some pavements as extreme temperatures rise and the duration of the warm season increases. Finally, one can expect increasing temperatures to lower engine efficiencies on trucks in the summer months, leading to additional air pollution and fuel costs. At a minimum, we believe adaptive actions should involve preparing for higher costs of maintaining existing transportation infrastructure, the building of new - more climate-friendly - infrastructure, and progress towards a less carbon-intensive transportation system. Coordination between federal, state, and local transportation planners must bring a new focus upon ways to improve transportation energy efficiency.

Climate-Related Implications for Air, Sea, Railroad, Truck and Pipeline Transport Throughout California

California has several airports very close to sea level where maintenance of levees or embankment fortifications may become more difficult and costly with future climate changes. Rising sea level and higher winter water flows in the Sacramento River-Delta Region are likely to cause a variety of significant problems including: disruptions to sections of railroads, pipelines, and roadways within the coastal region, effects on the transport of water from north to south, and problems with shipping into and out of the ports of Stockton and Sacramento (e.g., more difficult to maintain channels depths). Climate changes may bring a lowering of water density in the Bay (due to warmer waters and greater volume of fresh water in some seasons), which would lead to ships riding lower in the water, and potentially affect navigation in the shallower channels.

The California Regional Assessment states: "Many coastal airports are vulnerable to

flooding. Built on wetlands back when they were called swamps, many of these facilities, such as the San Francisco, Oakland, and Santa Barbara airports, are about 10 feet above current average sea level. Extreme high tides, coupled with flood conditions, can reach close to the existing levels. A recent tidal flux in the San Francisco Bay area closed Highway 101 north of the city due to eight-foot tides, two feet above what had been expected. With an additional meter of sea level, a number of critical facilities would be highly vulnerable. In the future, sea level rise, storm surges, and high tides could conspire to inundate runways. Harbors may suffer wave damage, additional siltation from storm runoff, and other navigation and safety problems. Jetties and seawalls may have to be raised and strengthened to protect harbors, which support commercial shipping, recreation, tourism, and many other economic sectors."⁴

Transportation via car or truck for commercial or industrial purposes may also be increasingly hampered by storms, flooding, the washing out of coastal, rural and mountain roads, landslides, and road damages due to climatic changes. Environmental Defense notes in its report "Hot Prospects" the impacts of inland flooding due to heavy rains during the 1997-1998 El Nino event. Some impacts included the repeated washing out of major highways and smaller roads during much of January and February, completely isolating some rural communities at that time, extensive mudslides and inland flooding, the destruction of 1,000 feet of the levee constructed along the Santa Maria River flooding hundreds of acres of agriculture lands in Ventura County, the undermining of the Union Pacific railroad trestle by the surging flow of the Ventura River, and a damaged rail bridge in San Clemente.⁵ Thirty-five California counties were declared federal disaster areas, the event took 17 lives and caused the state \$550 million in total losses and damages.⁶

When considering climate change impacts to inland river transportation, California can learn from experiences in the mid-western states. In 1988, the Mississippi River flows began to decline because of drought and reached record

lows during May that ended up continuing throughout the summer. By early July, Mississippi River traffic was reduced by one-fifth. Like the Mississippi River navigation system, many California rivers have control mechanisms which can be operated to maintain water levels and safeguard navigation during much of the year. But in 1988, even carefully timed water releases could not prevent low water levels on the Mississippi River brought about by drought that year. With increased risk of drought in California, such issues are of high concern. At one point in 1988, nearly 4,000 barges were stranded in Memphis, Tennessee. The economic costs of reduced access to inland water transport can mount very quickly, as alternative modes are typically less efficient and more costly.⁷

Potential adaptation actions for transport via rivers might include: 1) additional dredging in shallow areas; 2) limiting the number and weight of barges; 3) releasing more water from upstream sources (recognizing that this can interfere with other water uses such as hydropower generation, ecological resources, agriculture, municipal, industrial, and recreational); and 4) finding alternate navigation routes or modes of transportation.⁸

Climate-Related Implications for Air Quality

Another climate-related transportation impact results from higher temperatures increasing the formation of ground level ozone and particulate matter, making it more difficult to meet the health-based air quality standards for these pollutants. This expected outcome makes transportation planning even more challenging. Ground-level ozone has been shown to aggravate existing respiratory illnesses such as asthma, reduced lung function, and induced inflammation of the respiratory system. Ambient ozone also reduces agricultural crop yields and impairs ecosystem health. Warmer average and extreme temperatures will lead to increased use of air conditioners, resulting in additional air pollution from power plant and vehicle operation. Therefore, we expect that climate change and variability will impact California's

transportation sector, air quality, and potentially the health of many of its residents.

Environmental Defense identifies some adaptation strategies in *"Hot Prospects: The Potential Impacts of Global Warming on Los Angeles and the Southland."*⁹ The authors suggest: increasing public health education and warnings of risks, improving health-care for low-income groups, planting more trees, establishing parks, and increasing reflective surfaces to cool the urban environment. The report also recommends the maintenance of aggressive air emission controls.

Additional Background on California's Transportation Sector

Transportation-related greenhouse gas emissions are inextricably tied to energy use; a disconcerting point when one examines projections of California's transportation fuel consumption. Motor vehicle fuel consumption and attendant greenhouse gas emissions are projected to grow in California as a result of the increasing number of vehicles and vehicle miles traveled (VMT). VMT is expected to increase twice as fast as the population growth rate. Compounding the problem is the fact that average on-road fuel economy of new vehicles is eroding, primarily due to greater share of the personal vehicle market for light-duty trucks and sport utility vehicles. In addition, hotter days and a longer warm season will increase air conditioner use in cars, reducing their efficiency and miles traveled per gallon. Engines also tend to function less efficiently in hot weather, largely because the density of air entering the engine decreases.

In 2001, California drivers used an estimated 17.1 billion gallons of motor fuel with an estimated cost of over \$25 billion, while traveling some 307 billion miles -- a 15 percent increase since 1990. If current growth trends continue, fuel use and related CO₂ emissions in the state would increase approximately 40 percent over the next 20 years. This trend has significant economic and environmental implications. Such trends could mean an additional \$10 billion in the cost of fueling

California's transportation system alone. Considering that over 50% of petroleum supplies in California are imported and that 98% of transportation is dependent upon petroleum, expenditures on transportation fuel will affect the state's economy and its balance of payments. Efforts to reduce greenhouse gas emissions and make transportation more energy efficient and less petroleum dependent will provide important economic, environmental and security benefits.

Activities to Mitigate Transportation Emissions and Prepare for the Future

The California Air Resources Board (CARB) conducts research on air emissions and is now mandated to adopt standards for greenhouse gas emissions from motor vehicles as described in AB 1493 (Pavley, 2002). The CARB evaluates vehicle system performance and emissions to promote development and use of clean fuel sources and advanced vehicle technologies. The California Energy Commission (CEC) and CARB are evaluating a range of strategies to reduce the state's dependence on petroleum. The CEC sponsors research and analysis of emerging transportation technologies and fuels, including studies of an in-state biomass-to-ethanol industry and ways to improve efficiencies of tires. The California Department of Transportation researches, demonstrates and implements energy efficiency and conservation measures, provides system operations and congestion improvements, and promotes smart transportation, livable communities, and effective fleet management. The Department of General Services (DGS) is working with CARB and CEC on ways to reduce energy consumption of the state's vehicle fleet by 10%. The DGS vehicle purchase policy requires state agencies to purchase Ultra Low Emission (ULEV) or Super Ultra Low Emission certified light duty gasoline vehicles, and requires commercial car rental companies under contract to the state to have alternative-fueled vehicles (AFVs) and ULEVs available to renters.

Building upon current state efforts, the outline below provides a framework for expanded and new initiatives, including incentives, tools and information to advance a clean and energy

efficient transportation system that significantly reduces greenhouse gas emissions. It emphasizes actions that require collaboration and coordination to achieve the objectives of such an expanded initiative.

A potential framework might include the following major components:

1. Mainstream Energy Efficiency and Conservation Measures

Currently the statewide and regional transportation planning and project development programs require no energy and conservation element and analysis. The extent of transportation energy related activities at the state, local and regional levels is limited and disjointed with at times offsetting activities. This effort provides a strategic shift to focus on transportation energy and ensure that energy efficiency measures and analysis are systematically integrated into transportation plans, programs, projects, and investment decisions.

2. Vehicle and Fleet Efficiency

This program promotes and establishes a comprehensive plan with specific targets for improving vehicle and fleet efficiency beyond the current project-by-project approach to fleet greening.

3. Policy, Legislative, and Institutional Support

About 68 percent of advanced technology sales in the transportation sector are a result of federal and state mandates for fuel-economy standards, emission programs, technology implementation programs, or energy policy regulations. Similarly, air quality improvements and reductions in tail pipe emissions are in most part produced by air quality conformity rules and related mandates. Therefore, mandates on tail pipe greenhouse gas emissions may require similar rules to drive technology to the optimum level of greenhouse gas emission rate.

4. Improve Data Collection and Analysis

This program will enhance technical knowledge and capabilities of transportation planners and engineers and generate transportation related climate change and greenhouse gas emission statistics for transportation communities and policy makers.

5. Transportation Demand/Supply Management and Land Use Planning

This program would develop a comprehensive demand management and supply management program to optimize operational efficiency of the transportation system.

6. Increase Transit and High-Efficiency Mode Shares

Increasing transit share, use of alternative modes and intermodal connectivity is one of the most effective non-regulatory strategies to improve air quality and reduce energy consumption and greenhouse gas emissions.

7. Enhanced Education and Performance Standards

This program would provide information and support to the legislature and to policy makers to advance global warming related issues and funding sources. The intent is to explain greenhouse gas emissions in language that the public can readily understand, and explain immediate benefits and costs in terms of economic and strategic security and cost of transportation. Research proposed in the state includes developing an aggregate agent-based model of the California economy that includes representations of large-scale climate change impacts.

8. Financing Strategies to Support Proposed Activities

Information and support to legislature and policy makers on financial strategies is needed to advance global warming related issues.

9. Increase Freight Transport Efficiencies

Freight is responsible for a notable portion of energy use and carbon emission in transportation. Since cost reduction is a dominant factor in freight shipping, and energy use in the freight industry is driven by cutting costs and increasing speed, a mix of improvements in engine and vehicle design and in management and operations would be desirable.

10. Interagency Coordination and Cooperation

This framework for a clean and energy efficient transportation initiative can only be advanced through joint efforts and close coordination among state, federal and regional agencies, non-profit organizations and the private sector. Many of the proposed programs already exist in basic form at varying levels of implementation. Many of the strategies listed have been successfully demonstrated in California and elsewhere; however, their level of success is often constrained by lack of sufficient resources and effective coordination or comprehensive planning. Many of the initiatives pursued for decreasing emissions may also change how California adapts to climate change. For instance, a greater reliance on public transit in order to lower emissions will make climate impacts to transit infrastructure more important than they would be otherwise. Increased land-use planning and transit-oriented development that reduces emissions could also influence future travel patterns in ways that minimize the impacts of a changing climate.

Potential Benefits and Expected Results of Taking Actions

In addition to reducing greenhouse gas emissions from the transportation sector, a more sustainable transportation system will foster other short-term benefits including improved air quality, more efficient use of transportation resources, increased use of bio-fuels, reduced dependency on imported fossil fuels, greater energy security; improved mobility and travel options, and create more energy efficient and livable communities.

A clean and energy efficient transportation initiative can be cost-effective, flexible, equitable and good for the economy. Technology industries will benefit from improved markets for advanced transportation and communication systems both domestically and internationally, along with potential

improvements in the safety and security of transportation facilities, vehicles and the supporting infrastructure.

¹ *The Potential Consequences of Climate Variability and Change for California. The California Regional Assessment*. A report of the California Regional Assessment Group for the U.S. Global Change Research Program. Draft Final Report, June 2002, p. 27.

² This section is based, in part, on the draft Forest and Range Assessment 2002, in preparation by the California Department of Forestry and Fire Protection, Fire and Resource Assessment Program (FRAP).

³ Wilkinson, Robert, and Theresa Rounds. 1998. *Potential Impacts of Climate Change and Variability for the California Region. California Regional Workshop Report*. Report to the U.S. Global Change Research Program National Assessment, p.45.

⁴ *The Potential Consequences of Climate Variability and Change for California. The California Regional Assessment*. A report of the California Regional Assessment Group for the U.S. Global Change Research Program. Draft Final Report, June 2002, p. 4-3-8.

⁵ Environmental Defense. 2001. *Hot Prospects: The Potential Impacts of Global Warming on Los Angeles and the Southland*. Washington, DC.

⁶ National Climatic Data Center. 1998. California flooding and Florida tornadoes. National Climatic Data Center, <http://www.ncdc.noaa.gov/ol/reports/febstorm/february98storms.html>.

⁷ W. Riebsame, S. Changnon, Jr., and T. Karl, *Drought and Natural Resource Management In the United States: Impacts and Implications of the 1987-89 Drought* (Boulder, CO: Westview Press, pp. 43-112).

⁸ U.S. Congress, Office of Technology Assessment. 1993. *Preparing for an Uncertain Climate--Volume I*, OTA-O-567. Washington, DC: U.S. Government Printing Office.

⁹ Environmental Defense. 2001. *Hot Prospects: The Potential Impacts of Global Warming on Los Angeles and the Southland*. Washington, DC.

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Does Sea Level Rise Matter to Transportation Along the Atlantic Coast?

By Jim Titus

Introduction

A steady barrage of studies and news reports about global warming has ensured that virtually all transportation planners realize that the transportation sector of the U.S. economy is an important cause of increasing concentrations of greenhouse gases. Less attention has been paid, however, to the effects of global warming on transportation—and virtually no attention has been paid to the ways by which our transportation infrastructure may impair our ability to adapt to the consequences of global warming.

The focus on causes of global warming may be appropriate. The effects on climate of greenhouse gas emissions are not fully evident until roughly 50-100 years after they are released into the atmosphere, so it is generally understood that we have to reduce emissions now to mitigate the problem by 2050-2100.¹ Although the lead-time for roads and airports can be substantial, it is not 50-100 years; so why should a transportation planner worry about the consequences of global warming?

Several plausible answers come to mind: First, because we have been releasing greenhouse gases for over a hundred years, the effects of past emissions are becoming more and more evident. For example, the sea is already rising,^a so transportation activities that are sensitive to small rises in sea level already have

to deal with the consequences. Second, some aspects of our infrastructure have long enough lifetimes to justify a consideration of long-term environmental changes like sea level rise. Finally, and perhaps most important: Transportation routes can channel development patterns for centuries, and thus, the ability of coastal regions to adapt to climate change during the next century and beyond may be helped or hindered by the decisions that transportation officials make today.

The fact that climate change may affect the outcome of today's decisions does not, however, prove that those impacts are important enough to consider today. Ultimately, it's a question of magnitude. The data show that the transportation sector contributes about 27 percent of U.S. greenhouse gas emissions,² so DOT clearly needs to think about emissions. But no one has assessed the extent to which today's decisions leave our transportation infrastructure vulnerable to climate change.

This paper is part of a DOT process to motivate adaptation to climate change in the U.S. transportation sector. In this paper, I lay out the implications that seem important enough to think about, both as a first step toward a comprehensive assessment of how the transportation sector can adapt to sea level rise, and hopefully, to motivate some decision makers to recognize those cases where they need not await such an assessment before beginning to take appropriate measures.

^a Global warming appears to be responsible for about 1 mm/yr of the current rate of sea level rise.

Some Background Facts

Other discussion papers and presentations explain what scientists know about the causes and effects of global warming, and projections of future sea level rise. To recap: Sea level is already rising along the U.S. coast; see Figure 1. IPCC estimates that global sea level will rise 9 to 88 cm during the 21st century.³ Because of regional subsidence, the rise will be 15-25 cm greater in parts of the mid-Atlantic, and 5-15 cm greater elsewhere along

the Atlantic Coast. Considering the effects both subsidence and greenhouse gases, sea level is most likely to rise by about 2 feet along most of the Atlantic Coast. There is a 1-percent chance of a 4-foot rise, and a 95% chance that the sea will rise more rapidly in the next century than in the last century.⁴

Rising sea level inundates low areas, erodes beaches and wetlands, increases flooding from storm surges and rainstorms, and enables saltwater to advance upstream. All of these

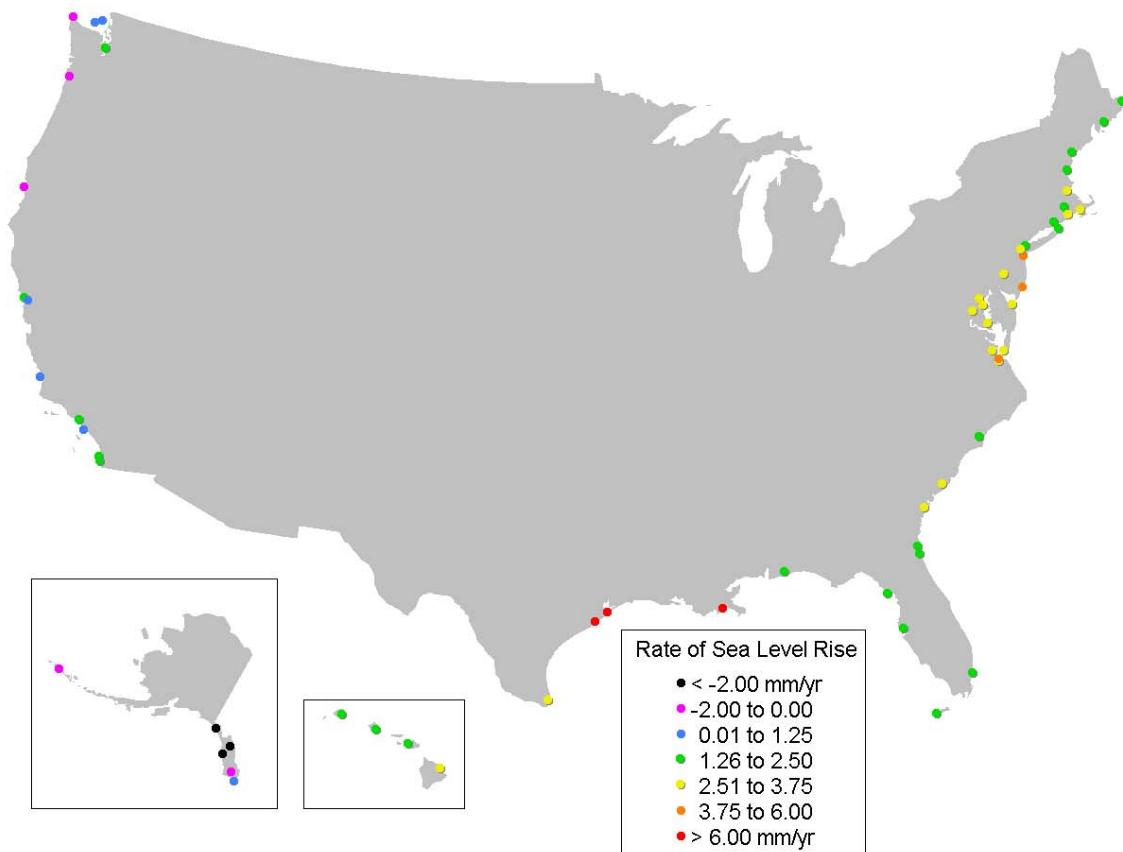


Figure 1. Sea level trends along the U.S. coast, 1900-2000. This map shows all sites with at least 50 years of data. The greatest sea level rise is shown in Louisiana (at the Mississippi delta), in Texas (near Galveston), and along the mid-Atlantic coast. The estimates are based on a linear regression of sea level on time, using data collected by the National Ocean Service and provided to the Permanent Service for Mean Sea Level in the United Kingdom.

effects can have impacts on transportation. Figure 2 shows the approximately 60,000 square kilometers of land along the U.S. Atlantic and Gulf Coasts that lies below the 5-ft (NGVD^b) contour, which is roughly within 2-3 feet above the ebb and flow of the tides.^c Louisiana, Florida, Texas, and North Carolina account for more than 80 percent of the lowest land.^d Outside of those four states, the largest vulnerable populated region is the land along the Eastern Shore of Chesapeake Bay stretching from Dorchester County, Maryland to Accomac County, Virginia. Most of the U.S. Pacific Coast is on relatively high ground, although there are some low areas along San Francisco Bay. In addition to these lands, erosion can threaten relatively high ground within a few hundred feet of a tidal shore.

Global warming also increases flooding in the coastal zone. Storm surges from hurricanes and northeasters^d will build upon a higher base, and hence reach farther inland. Moreover, higher sea level slows the rate at which areas drain, so rainstorms will also tend to cause greater flooding in coastal areas. Furthermore, because a warmer atmosphere can hold more water vapor, rainstorms are getting more intense, which may further increase flooding. In addition to flooding and lands loss, sea level rise enables saltwater to advance farther upstream.^e

The actual effect of sea level rise depends on what people do in response to the direct physical responses. There are three fundamental response pathways: hold back the sea with dikes and other structures; hold back the sea by

^b The National Geodetic Vertical Datum of 1929 is used as the reference elevation for most topographic maps, although it is gradually being replaced. Along the East Coast, mean ocean sea level is about 8 inches above NGVD, largely because of sea level rise since 1929. Back barrier bays tend to have a mean tide level of about 1 ft. NGVD.

^c The ocean tide range tends to be about 5-6 feet; in the estuaries along barrier islands the range is much less, while some harbors have much greater tide ranges. The surge from a 100 year storm is close to 20 feet in parts of Florida, but more on the order of 8-10 feet in the Mid-Atlantic and 5 feet in many estuaries.

^d A number of reports on the EPA Sea Level Rise Reports web page examine the issue of increased flooding and saltwater intrusion. Go to www.epa.gov/globalwarming/sealevelrise.

^e A number of reports on the EPA Sea Level Rise Reports web page examine the issue of increased flooding and saltwater intrusion. Go to www.epa.gov/globalwarming/sealevelrise.

elevating the land surfaces and other structures, and allow nature to take its course and accommodate as necessary. As a general proposition, holding back the sea with dikes and other structures results in a large-scale elimination of wetlands, beaches, mudflats, and other coastal habitat; but the environmental consequences may be minor in areas where this habitat has already been destroyed. Elevating land surfaces maintains the status quo and generally preserves the narrow fringing wetlands and beaches; whether there is a large-scale loss of vegetated wetlands depends on whether the effort to elevated land surfaces extends to those areas. Retreat usually has the least environmental impact, because human activities are not squeezing intertidal ecosystems between the rising water and the coastal development;^f but it can have the greatest impact on communities whose residents have to move. As we discuss below, transportation considerations may often affect which path society takes in its response to rising sea level.

Direct Effects of Sea Level Rise on Transportation

Navigation

Sea level rise makes water deeper, which enables deeper draft vessels to navigate a particular channel. This effect, however, is fairly small compared with the draft of most vessels. Saltwater advancing upstream can alter the point at which flocculation leads to sedimentation and the creation of shoals. Similarly, the clearance under bridges decreases. In a few cases where clearances are extremely tight, this effect could limit the ability of boats to pass underneath a bridge, particularly in the case of very small boats slowly passing underneath very small bridges, where the clearance may be less than a foot. Larger vessels are less likely to be impeded, because most bridges over key shipping lanes are either drawbridges or have very high spans. (A few low bridges have been deliberately located to

^f A number of reports on the EPA Sea Level Rise Reports web page provide estimates of the impact of holding back the sea on wetlands and beaches.



Figure 2. Map of lands close to sea level along the U.S. Atlantic and Gulf Coasts. Although the results nominally are in meters, the 1.5 meter contour is primarily based on the 5-ft NGVD contour from USGS topographic maps. Source: Titus and Richman (2001).⁶

prevent large ships from passing farther upstream.^{g)}

Port facilities are on the water's edge, and therefore potentially vulnerable to sea level rise. Docks, jetties, and other facilities are deliberately set at an optimal elevation relative to the water level and therefore a rise in sea level leaves them at a suboptimal elevation. However, these facilities tend to be rebuilt

relatively frequently compared with the time it takes for a substantial rise in sea level.⁷

Sea level rise can also have important indirect effects on navigation, which we discuss below.

Aviation

Sea level rise is not likely to be a serious problem for a mode of transportation that is miles above the sea. Still, coastal cities such as Boston, New York, and Washington tend to have airports built along tidal waters, sometimes on filled areas. Therefore, their runways are

^g An example of a low bridge that prevents large ships from proceeding farther upstream would be the bridges over the Mississippi River in Baton Rouge.

vulnerable to flooding. A dike already protects New York's LaGuardia airport, but other airports might experience increased flooding as the sea rises, or have to take protective measures.⁸ Changes in storms could also affect airports—but no one knows the direction of the likely change.

Rail and Tunnels

Railroads often cut across marsh areas in the coastal zone. In the case of some smaller short-line railroads, tracks are so low that they are often flooded, and the beds may be vulnerable to sinking from compaction of marsh peat. Thus, as the sea rises, some tracks will be more vulnerable to flooding.

Tunnels may also become more vulnerable, both because the risk of their entrances and vents flooding will be greater, and because the hydraulic pressure on the tunnel walls increases as water tables rise.

The New York Metro Area rail and subway system appears to be particularly vulnerable. A number of East Coast railroads have been in their current locations for 150 years, during which time the sea has risen 1.5-2 feet. Many tracks, signals, and stations are low enough to be flooded during severe storms. Many subway entrances are in the 100-year floodplain, and are occasionally flooded by northeasters.⁹

Roads

The most important impact of sea level rise on transportation concerns roads. In many low-lying communities, roads are lower than the surrounding lands, so that land can drain into the streets. As a result, the streets are the first to flood. In some barrier island communities, the lowest bayside streets are already flooded during spring high tides. As the sea rises, this flooding will become more and more frequent. Most roads are not flooded by the tides, and have some type of drainage system to convey water away during rainstorms. As sea level rises, these drainage systems become less effective, causing more flooding—and increased rainfall

intensity will further increase the severity and frequency of flooding there.

Whether street flooding is a serious problem or a minor nuisance depends on a variety of factors. In recreational areas during the summer, a flooded street is often a source of entertainment for people who came to that community to be on the water.^{10,h} During cold weather or severe storms, however, some of these roads may be critical evacuation routes. Increased flooding increases evacuation times, which either increases the risk to life or requires emergency officials to require evacuation sooner, including for storms where it later becomes evident that evacuation was unnecessary.

Some roads are threatened by erosion. In some cases, the loss of a road parallel to the shore may remove the only road access to a particular area.

Transportation Adaptive Responses to Sea Level Rise

When one attempts to describe the impact of sea level rise on transportation without describing the adaptive response, one is generally implicitly assuming that the community does nothing about sea level rise, that is, that it is simply allowing nature to take its course. But that is only one of many possible options, and in developed areas where most transportation occurs, it is probably the least likely option. That does not mean, however, that sea level rise has no impact on transportation—but it is very different than the impact from passively allowing the situation to deteriorate. Moreover, transportation considerations may often play an

^h See *Bergen Record*, "Rise in sea level likely to increase N.J. floods," Wednesday, September 04, 2002 (by Alex Nussbaum). "Two days a month... Barnegat Bay creeps over the sea wall at the end of 28th Street in Ship Bottom... Like clockwork, water backs up through storm drains and trickles down the dead-end street that runs between a half-dozen summer homes. Local kids grab their inner tubes and float down the block. Carried by the tide, a few confused crabs wander the pavement. Some days, it's a full-fledged creek. Others, it's merely a puddle around the storm grates.... Laurence Delorme said he has to tie his garbage cans down to keep them from floating off during these tides. 'It gives me beachfront property twice a month,' jokes Delorme, 33. 'The kids splash in it.'"

important role in the actual response to sea level rise. Let us consider the three fundamental pathways, in turn.

Elevate Land and Structures

Roads

Many developed barrier islands and other low lying communities will probably respond to sea level rise by bringing in fill to elevate the land.ⁱ If the streets are elevated by the amount that the sea rises, flooding will be the same as it is today. In some cases, this may be less expensive than keeping streets at the current elevation. When streets are repaved, it is often necessary to remove the old pavement down to the roadbed, and haul away that material. Simply repaving on top of the existing road saves a step, at least for slow residential streets. On the other hand, high-speed roads may require additional fill and reconstruction of the roadbed.

An important advantage of simply elevating the land is that the location of the roads do not have to be changed. Moreover, many types of drainage systems will continue to work properly, because the head gradient between street level and the sea remains the same. An important exception may be the underground runoff storage systems found in some communities, such as Atlantic City. Those tanks are currently above sea level and hence can gravity drain; if the sea rises and the tanks are below sea level, they would need to be retrofitted with check valves, and perhaps even pumps. Eventually, of course, a higher street would allow for higher tanks; but elevating the streets may be advisable as a near-term measure, whereas reconstruction of the tanks may not be necessary for many decades.

Another advantage of elevating lands is that transportation planners do not have to anticipate long-term sea level rise; they simply need to keep up with the rise as it occurs. When roads become flooded, they can be elevated; but it is probably not necessary to design most roads for future conditions because roads can generally be repaved to a higher elevation as flooding gets worse, as part of the ordinary program of repaving. And there may be problems from making a street too high relative to the surrounding lands.

However, some advance notice may be necessary in those communities that rely on the streets to drain the land. For example, Ocean City, Maryland requires lots to have at least a 2 percent grade so that all property can drain into the street, to prevent standing water and the resulting breeding habitat for mosquitoes. If the town elevated the streets a foot, some streets would drain into people's yards, which would essentially contravene the town's policy. Therefore, as the sea rises, the town tolerates increased flooding in the few streets that are low enough to frequently flood. For all practical purposes, the lowest lot on the block dictates the street elevations for all. Therefore, the town may have to give people some notice that in the future they need to elevate their lots—eventually, low lots can not be a reason to not elevate the street; instead, an elevated street must trigger the requirement to elevate the lot.

The situation in Ship Bottom, Long Beach Island, New Jersey also illustrates the need to look into the future. One of the key thoroughfares is flooded by spring tides as long as there has been at least modest rainfall and hence inflow into the estuaries. The county spent tens of thousands of dollars to retrofit a street drain with a check valve, which prevents the street drain from backing up into the street (unlike numerous side streets to the south). However, during several months of the year, spring tide (about 1.5 feet above mean tide level) overtops the surrounding land and floods the streets anyway (see Figure 3). Confused crabs are often seen walking down the street as the tide recedes. Elevating the street will eventually be necessary—forcing the homeowners to

ⁱ Eight New Jersey towns on barrier islands have signed agreements with EPA pledging to prepare for the consequences of rising sea level. All of those agreements stated that the particular towns find the dike and retreat options as unacceptable, and hence the communities' only viable option is to gradually elevate land and structures. For an analysis of Long Beach Island, see "Greenhouse Effect, Sea Level Rise, and Barrier Islands: Case Study of Long Beach Island, New Jersey", *Coastal Management*, 18:65-90 (1990).



Figure 3. Photo of flooded street in Ship Bottom, New Jersey. This area tends to be flooded during spring high tides except for drought years, when nearby Barnegat Bay is lower than usual. The author took this photo on Labor Day 2002 during a neap tide with a northeaster whose 25kt winds from the East had elevated the ocean levels by approximately one foot.

elevate their yards or be flooded by rainwater. Local governments must ask themselves whether retrofitting a drainage system with a checkvalve is a wise use of limited funds if the rising sea will require the street to be elevated anyway; by contrast, the checkvalve is almost certainly a useful first step in an area that must eventually be diked.

Of course, if areas are going to be elevated, then the roads may have to accommodate increased dump truck traffic.

Air, Rail, Shipping, Tunnels

Just as roads can be elevated, so can runways and railroad beds. New bridges and tunnels can be built higher than would otherwise be the case. For example, recognizing the logic of anticipating sea level rise, the designers of the new causeway to Prince Edward Island made it one meter higher than it would otherwise have been. But existing structures will remain at current elevations. Therefore, even communities that are elevated may have increased seepage into tunnels and reduced clearance under bridges.

Navigation in tidal waters will be automatically elevated by the amount of sea level rise, but one has a choice with canals. If water levels are elevated by the amount of sea level rise, canal drainage will remain the same, although bridge clearance will reduce.

Protect with Dikes

If a community will be protected with a dike, the roadways do not need to be elevated, but otherwise, planners have a great deal more to be concerned about, because the response cannot be purely incremental as with elevating the land surface. If a dike will eventually be constructed, it's important to make sure that there is a road parallel to the shore fairly close to the shore, preferably seaward of all construction. Such a road could be the location of the eventual dike system, which may include not only a dike but also a drainage canal and road for dike construction and maintenance. Without such a roadway, the public authority will have to purchase shorefront lands for the dike, and perhaps demolish waterfront homes.

Once land is protected by a dike, the problem of street flooding from tidal and storm surges will be abated. However, rainwater flooding can become worse because the barriers that keep the sea out also keep rainwater in. Even before the dike is built, road engineers need to consider its eventual construction. For example, street drains in some areas are only rebuilt about every 100 years. If a dike is likely to be built in the next 100 years with streets kept at current elevations, the eventuality of check valves, pumping stations, and increased underground storage may imply a different optimal configuration for the drain pipes, especially if a large number of outfalls would be replaced by a smaller number of pumping stations, or if the pumping stations would be located somewhere different from existing outfalls. Because the best way to rebuild a drainage system depends on whether the land will be elevated or protected by dikes, municipal engineering departments need to know whether—and preferably when—the city will elevate the land surfaces or protect with dikes.

Ideally, the leaders of a community will decide with appropriate input whether—and how—to hold back the sea and transportation planners can act accordingly. Because most communities have not yet made those decisions, however, the decisionmaking may flow in the opposite direction: Road planners do what they do, with or without a consideration of sea level rise, and decades later the status quo that the transportation infrastructure created will be a primary determinant of the community's ultimate decision. Even if the retreat option is preferred, the existence of an important road along—and close to—the shore may make holding back the sea the only realistic option. Even if a dike would have been less expensive than elevating the land, the absence of a shore-parallel road may make land acquisition costs too costly or politically impossible. Therefore, if a community does not have a long-term sea level rise plan, anyone planning infrastructure with a long lifetime becomes—by default—the sea level rise planner who must either make an assumption about whether and how the sea will be held back, or ignore the situation and design the system as if the sea was not rising.

Highway reconstruction may also dictate responses to sea level rise if there is no plan. As the sea rises, roads through undeveloped low areas tend to become dikes unless there is an explicit decision to convert it to a causeway. The roadway may have been originally elevated to prevent flooding; but as the sea rises and shores retreat, tidal waters reach the road—and the road blocks the flow of water, acting as a dike. Later, communities may build upon this initial de facto dike and create a complete dike system. Alternatively, the road authority may install culverts under the roadway, or make occasional breaks in the dike with bridges, to allow water to flow around the road, essentially converting the road to a causeway.

Air, Rail, and Tunnels

Dikes can reduce the effective length of a runway. Assuming a typical descent angle of 3 degrees and that the runway stretches all the way to the dike, a one foot rise in sea level effectively shortens the runway by 20 feet. This

is not too serious for a typical 10,000-foot runway.

Dikes along with effective pumping systems can largely solve the existing and projected vulnerability of low-lying railroads within the urban areas that are protected. Increased hydraulic head may be a problem for tunnels in areas where the water table continues to rise with the sea; but an effective drainage system would keep the water table from rising.

How Inclusive is the Dike?

Perhaps the most serious problem with the dike option is the fact that because it is not incremental, one must decide which areas are within the dikes and which areas are outside of the dikes, and such decisions may be continually revisited. New highways might logically avoid low areas that are not going to be protected with dikes. But that may be a moving target.

A key question regarding dikes is whether to dike the coast as it is today, or to follow the Dutch approach of shortening the coast. The basic idea behind shortening the coast is that it may be safer and much less expensive to build a large dike across the mouth of a bay, than to build smaller dikes along all the shores of the bay and its tidal rivers and creeks. Because existing ports would now be inside the dike, either ships would have to pass through locks, or new deepwater ports would be built outside the dike. Such an approach seems unlikely in the United States, both because of the environmental consequences and our nation's general preference for small, uncoordinated infrastructure projects over large, coordinated efforts.

Nevertheless, the basic principal of coast shortening will probably be applied in a number of areas. First, in areas with finger canals for recreational boaters, it would be impractical to dike all shores. Dikes around the entire communities with locks at the main stem of the canal would be more feasible, assuming that the communities are not elevated with fill. Second, storm surge barriers such as the Thames River Barrier have the effect of shortening the

coastline during storm surges, but they generally stay open and hence need not interfere with navigation. Finally, large-scale water projects have some similarities with coast-shortening dikes. In the Everglades and Dismal Swamps, one must choose between elevating the canal waters by the amount of sea level rise, or keeping canals at current elevations.

The sea will rise for the foreseeable future—perhaps even more rapidly during future centuries than the 21st century. In theory, we might elevate low lands forever as the sea rises. Holding back the sea, however, may become progressively more difficult. At first, tide gates and check valves allow water to drain at low tide; later, communities would need pumps. As the sea continues to rise, a community would have to pump more and more water due to greater infiltration, and the water would have to be pumped to higher locations. The dikes would probably have to be elevated by more than the sea level rise, because the impact of a dike failure would be far greater if the sea was 10 feet above Main Street than if it was only 2 feet above the town. This concern may be an issue for Louisiana, where the eroding shores are bringing the Gulf of Mexico closer every year to New Orleans, which is already below sea level. But for the Atlantic Coast, these are issues for future generations.

Retreat and Accommodation

Just as a dike can avert many impacts of sea level rise on transportation, so a retreat strategy can be very similar to the direct effect of ignoring the issue and addressing the consequences. In some areas that are destined to be abandoned^j, it may not make sense to make additional investments in transportation so as to prevent the consequences of sea level rise. Some of the roads to Delaware Bay in Cumberland County, New Jersey, are very rough, and there is little reason to fix them because much of the coastal zone of that county is being returned to nature. Roads along the

^j Several communities have used EPA funding to develop maps illustrating which areas will be protected and which will be abandoned.

retreating shores of the undeveloped Outer Banks are washed out during storms and rebuilt inland; roads along developed areas are also washed out in storms, but rebuilt and maintained—and given minimal protection such as a few dump truck loads of sand to act as a sacrificial dune for the next moderate storm.

Although lightly developed areas may retreat without advance planning, a retreat policy requires a substantial degree of planning in more densely developed areas. With no dikes planned and the land surfaces not being elevated, street flooding gets worse and worse; but that flooding can be mitigated by increasing the size of ditches and other maintenance that is probably worthwhile even in an area that will be given up to the sea. Ironically, it may be particularly important to elevate highways as evacuation routes, because such areas will become more and more vulnerable, and will probably remain inhabited until a catastrophic storm destroys most structures.

Just as shore-parallel roads are important for areas that will be diked, areas that will retreat need roads that are not shore-parallel. If someone's only access is a shore-parallel road, then as soon as one part of the road is washed out, she loses access even if her property is a long way from being lost. Put another way, shore-parallel roads tend to thwart a retreat policy, even if it would otherwise be desirable.

Although a retreating ocean shore requires oceanfront roads to be abandoned or relocated inland, the submergence of lands along an estuary does not necessarily mean the road will be abandoned. As an extreme example, consider US-64 and US-264, which connect the Outer Banks to the population centers of North Carolina. As Figure 4 shows, a large portion of the Albemarle-Pamlico Peninsula is low enough to be submerged with a significant rise in sea level. But the Outer Banks will continue to be viable and popular beach resorts, as far as we know, and less vulnerable to complete inundation than the peninsula. Therefore, those coastal planners who have thought about the issue expect that a small number of communities on the peninsula will be protected, the Outer

Banks will survive, and people will continue to drive there. Figure 5 illustrates the thinking of these planners, which implies that US-64 and 264 will become a combination of causeway-style bridges, filled causeways, and isthmuses with the highway and some development on either side, connecting the various small towns with the mainland, each other, and the Outer Banks. This map is just one possibility: perhaps one of the highways will instead determine the location of a dike. But currently, retreat is taking place and there is a universal consensus in the state that US 64 and 264 will continue to exist. Many developed barrier islands are connected to the mainland with roads that pass through low-lying marsh that may become open water in the future.

The retreat policy will have only minor impacts on navigation on the East Coast, which fortunately does not have the problems facing Louisiana, where solving land loss will probably require a reconfiguration of shipping lanes. To be sure, retreating barrier islands are difficult to reconcile with inlet stabilization projects, both politically and geologically. Hence Oregon Inlet, along North Carolina's retreating Outer Banks, still has not been stabilized. In most cases, however, the areas where the inlets have a lot of boat traffic have populated barrier islands where retreat is unlikely; while retreating barrier islands are found in areas with relatively little boat traffic.

Figure 6 shows these various options being put into effect in North Carolina. Figures 6a and 6b demonstrate retreat and accommodation in Kitty Hawk and Elizabeth City. Figure 6c shows a dike-protected community, while Figure 6d pictures homes being elevated.

Assessment Options

This cursory examination shows that sea level rise can have important impacts on roads, and that how we plan our roads can have an important impact on how coastal communities deal with sea level rise. The serious impacts of sea level rise on shipping appear to be limited to Louisiana, where a multiagency process is already underway to develop a long-term plan of

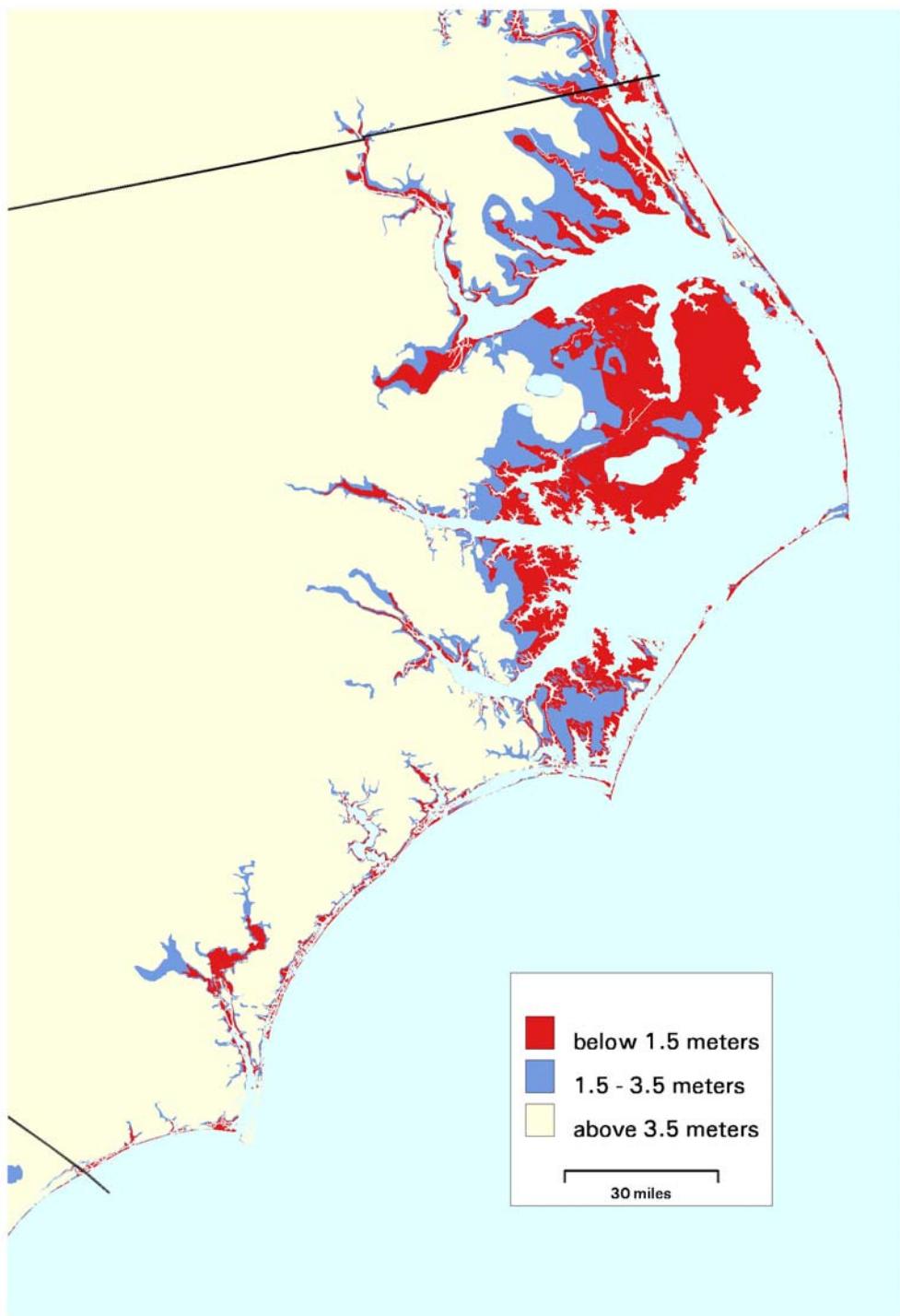


Figure 4. Map of lands close to sea level in North Carolina. Source: Titus and Richman. (2001).

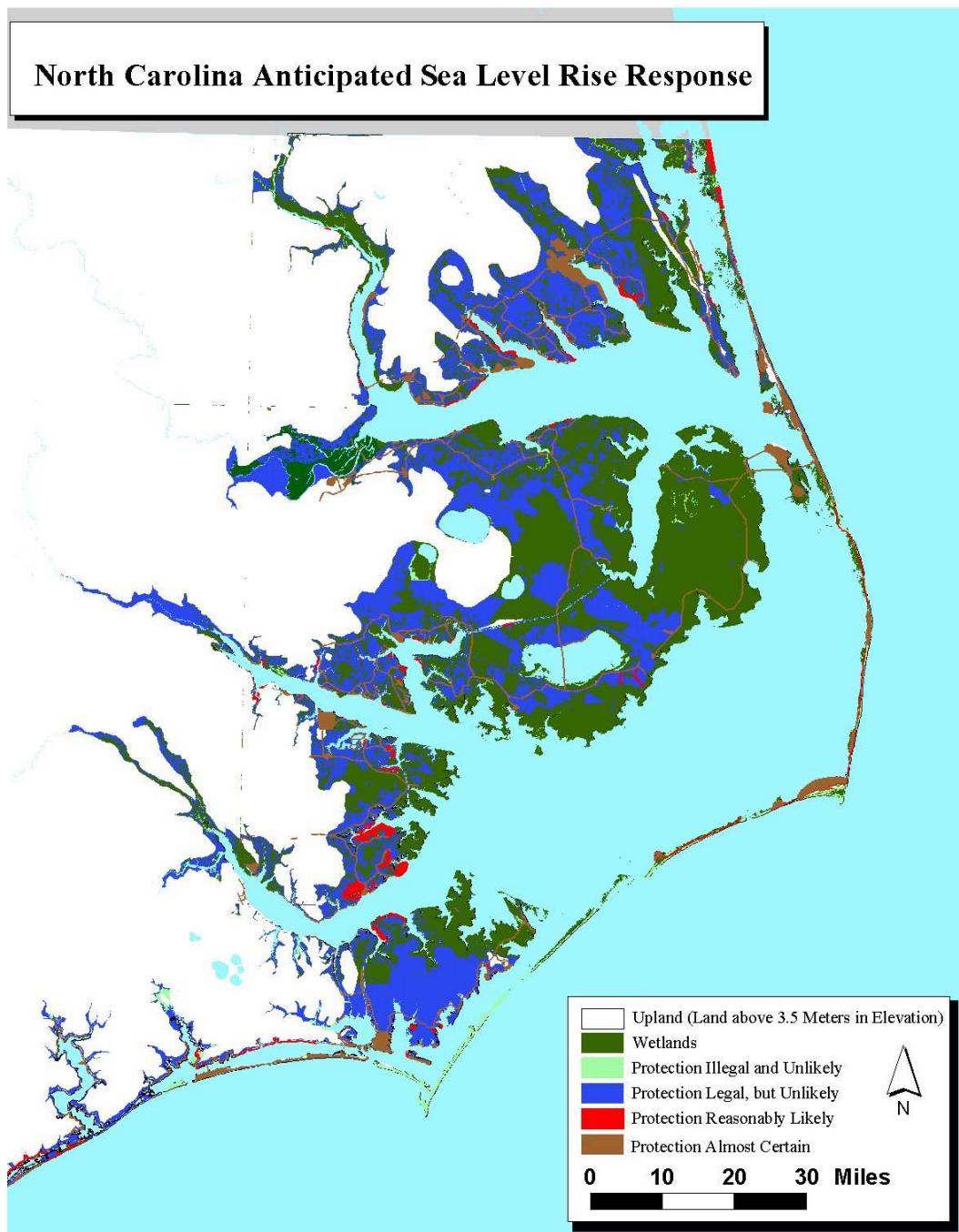


Figure 5. Draft maps illustrating the areas where North Carolina state coastal planners expect people to hold back the sea. Areas depicted in brown are almost certain to be protected with beach nourishment, fill, or some form of structure. Areas in blue represent privately owned land that the state planners do not expect to be protected. Areas in red represent land that probably will be protected, but where protection is less likely than the areas in brown. For example, along the barrier islands north of Corolla, the Coastal Barrier Resources Act prohibits federal assistance. Although property values may be sufficient to justify beach nourishment to hold back the sea, the absence of federal funding makes such projects less likely than in similar areas that are eligible for federal funding. These maps are being revised to reflect the local expertise of county governments, who generally expect more areas to be protected. Source: Walter Clark, North Carolina Seagrant.



(a)



(b)



(c)



(d)

Figure 6. Photos of four ways to respond to sea level rise in North Carolina. (a) Retreat along the Southern portion of Kitty Hawk: houses on stilts being abandoned to the sea; (b) Accommodating the higher water levels in Elizabeth City: a house on stilts is still occupied in this inlet; (c) A dike protects the Gum Neck agricultural community in Tyrrell County; and (d) Every home in sight is being elevated along this road in Carteret County. All photos taken the week of Columbus Day, 2002.

action. The implications for railroads and airports seem to be more limited, but potentially very amenable to long-term planning for sea level rise because of the relatively small number of decisionmakers, compared with roads.

Unfortunately, the impacts of sea level rise on transportation have not been quantified. Some types of guidance probably do not need quantitative assessments to prove meritorious; but a complete absence of quantitative evidence makes it difficult to be sure that the impacts of sea level rise on transportation are serious at a national scale. Therefore, an obvious next step would be to conduct a few relatively targeted assessments just to quantify the scope of the problem, including:

1. A GIS assessment to quantify roadmiles, miles traveled, railroad miles, and railfreight under various definitions of vulnerable area (e.g., within one meter above the ebb and

flow of the tides, within one meter of the 10-year flood, within the area that might either be inundated or eroded as the sea rises).

2. Overlay through areas within 1-meter above the ebb and flow of the tides (or where that form of elevation data does not yet exist, below the 5 and 10-ft contour) and the coastal floodplain.
3. Overlay areas where planners expect people to hold back the sea, and areas that planners expect to be abandoned.
4. Identify the roads in the coastal zone that are currently flooded by tides.
5. Initiate a stakeholder outreach program with coastal highway departments to determine what kind of help they need from DOT to factor sea level rise into their planning.

¹ Intergovernmental Panel on Climate Change. 2001. "Climate Change 2001: The Scientific Basis". Cambridge and New York: Cambridge University Press.

² U.S. Environmental Protection Agency. 2002. *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. Washington, D.C. U.S. Environmental Protection Agency: EPA 430-R-02-003

³ Intergovernmental Panel on Climate Change. 2001. "Climate Change 2001: The Scientific Basis". Cambridge and New York: Cambridge University Press.

⁴ EPA. 1995. "The Probability of Sea Level Rise," www.epa.gov/globalwarming/sealevelrise.

⁵ Titus, J.G. and C Richman. 2001. "Maps of Lands Vulnerable to Sea Level Rise: Modeled Elevations along the U.S. Atlantic and Gulf Coasts." *Climate Research*, CR 18:205-228.

⁶ Titus, J.G. and C Richman. 2001. "Maps of Lands Vulnerable to Sea Level Rise: Modeled Elevations along the U.S. Atlantic and Gulf Coasts." *Climate Research*, CR 18:205-228.

⁷ National Academy of Engineering, Marine Board. 1987. *Responding to Changes in Sea Level*. Washington, D.C.: National Academy Press.

⁸ Jacob, K.H., N. Edelblum, and J. Arnold. 2000. "Risk Increase to Infrastructure due to Sea Level Rise." In *Climate Change and a Global City: An Assessment of the Metropolitan East Coast Region*. Washington, D.C.: United States Global Change Research Program.

⁹ Jacob et al. supra note 10 at 17-30.

¹⁰ Nussbaum, Alex. *Bergen Record*, "Rise in sea level likely to increase N.J. floods," Wednesday, September 04, 2002.

Jim Titus, J.D., directs EPA's Sea Level Rise project, whose continuing mission is to accelerate the process by which the U.S. coastal zone prepares for the long-term consequences of rising sea level.

Impacts of Climate Change on Transportation Infrastructure in Alaska

By Orson P. Smith and George Levasseur

Introduction

The economy of Alaska is extraordinarily dependent on the efficiency of its limited transportation infrastructure for mineral exports, fisheries, and tourism. Gravel airstrips, many built on permafrost, tenuously uphold the standard of living of the hundreds of Alaskan communities without road connections. Global warming is projected to bring more erratic winter weather, increasing the frequency of freeze-thaw cycles. As this occurs, Alaskan roads, railways, and airport runways will suffer attendant problems and maintenance costs are likely to increase (Figures 1, 2, and 3). This paper is intended to open discussion of these and other potential impacts of global warming in Alaska.

Changes to Permafrost

Warming and thawing permafrost foundations are the most serious of climate change consequences to land and air transportation services in the 49th state. Extensive evidence exists of permafrost warming and thawing in Alaska over the past several decades (Osterkamp and Romanovsky 1999). Maximum thaw settlement occurs with ice-rich fine-grained frozen ground that is unfortunately common across much of the State. Figure 4 shows the extent of permafrost in Alaska, color-coded by ice content (see Brown et. al. 1997 for detailed explanation of color codes and markings). Figure 5 illustrates the distribution of public infrastructure built on permafrost.



Figure 1. Photo of settlement and cracks on an Alaskan roadway due to warming of the permafrost foundation.



Figure 2. Photo of Richardson Highway bridge across One Mile Creek in Alaska's interior.



Figure 3. Photo of channel and bridge repairs after a flash flood at One Mile Creek.

The Case of One Mile Creek

Alaska's mountain roads are beginning to feel the effects of receding glaciers and melting permafrost. One Mile Creek crosses Alaska's Richardson Highway in the State's interior near the Alaska Range (Figure 2). The stream is approximately 2.25 miles in length, with headwaters in an ice field at an elevation of about 5,200 feet. The gradient is very steep down to an elevation of approximately 1,800 feet, just upstream of the Richardson Highway bridge. The Alaska Department of Transportation and Public Facilities (ADOT&PF) has spent increasing time and money in recent years to remove alluvial gravel from the stream channel beneath the bridge. Gravel can cover the roadway in less than 24 hours. An ordinary rainfall or even just a spell of warm weather starts the ice melting and the gravel moving. An increased supply of sediment in the drainage basin is deemed to be due to receding glacial ice cover and melting permafrost. The increase in sediment transport to the bridge may also be due to increasingly frequent and intense rainstorms.

On July 11, 2000 a flood washed out the One Mile Creek bridge (Figure 3). The closure of the Richardson Highway lasted 2 days and ADOT&PF spent over \$100,000 to make repairs. Since 2000, after each rainstorm maintenance crews remove rock from the bridge

channel to a depth of 9 to 12 ft (see Figures 2 and 3). One Mile Creek flooded 6 times in 2001. Each event required a week's work to clear debris and as much as 10,000 cubic yards of gravel from under the bridge.

Melting permafrost on the south side of the Alaska range has also caused several landslides elsewhere, closing roads and isolating rural residents. According to ADOT&PF officials, increased stream sediment loads over the last decade from retreating glaciers and melting permafrost have also led several of Alaska's interior rivers to change channels, resulting in more highway dike and levee projects.

Views of Alaskans

Historical warming appears to be maximum in North America between 50 and 70° north latitude, as indicated in Figure 6. Evidence of this and other global warming trends has been discussed in Alaska at several meetings in recent years, with a view toward impacts on public and commercial infrastructure. A series of January "Science-to-Engineering" workshops, co-sponsored by federal, State, and commercial interests, including the U.S. Arctic Research Commission, have taken place at the University of Alaska Anchorage (UAA) since 1998. The January 2000 workshop was titled "The

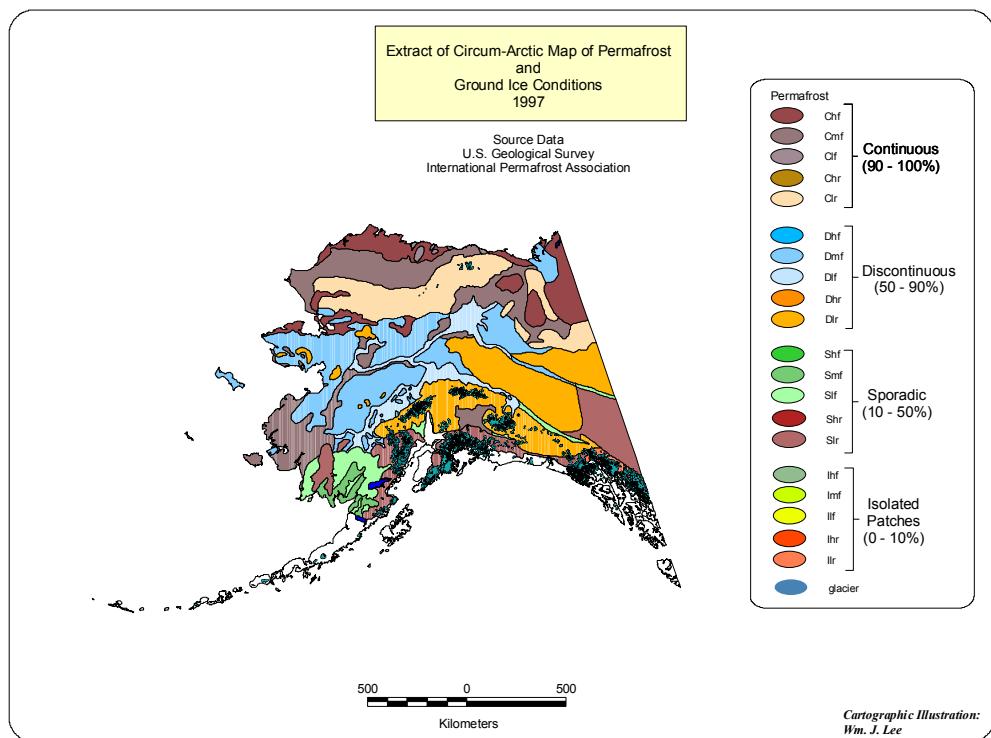


Figure 4. Map showing extent of permafrost in Alaska. Permafrost can be found to varying extents in most parts of Alaska. Source: Brown et al 1997.

Warming World: Effects on Alaska Infrastructure" (Smith and Johnson 2000). This workshop attracted over 100 researchers, practicing engineers, educators, and leaders of public agencies and commercial businesses with Alaska interests. Attendees agreed that roads, airports, and critical infrastructure in Alaska would be adversely affected by long-term warming.

Experienced engineers pointed out at the January 2000 UAA workshop that tested solutions are available, given warning of changes, reliable local information, and funding. Arctic engineers are accustomed to dealing with warming, since the structures they build tend to cause warming of frozen foundations. New works can be located over gravelly thaw-stable permafrost to avoid the worst consequences, but expensive investigations are required for optimum site selection. Widely used Alaskan

engineering references on climate and ground conditions are outdated, some based on measurements from the 1950s. Project site measurements reveal current conditions, but don't foretell the future unless they are part of a monitoring sequence. Environmental monitoring and global warming research were supported by a consensus of workshop attendees. Public works agencies that fund projects only for the duration of design and construction, such as the Alaska Department of Transportation and Public Facilities (ADOT&PF) and the U.S. Army Corps of Engineers, should leave in place means for monitoring infrastructure status. ADOT&PF has subsequently increased its efforts to monitor existing roadway foundations (ADOT&PF 2002).

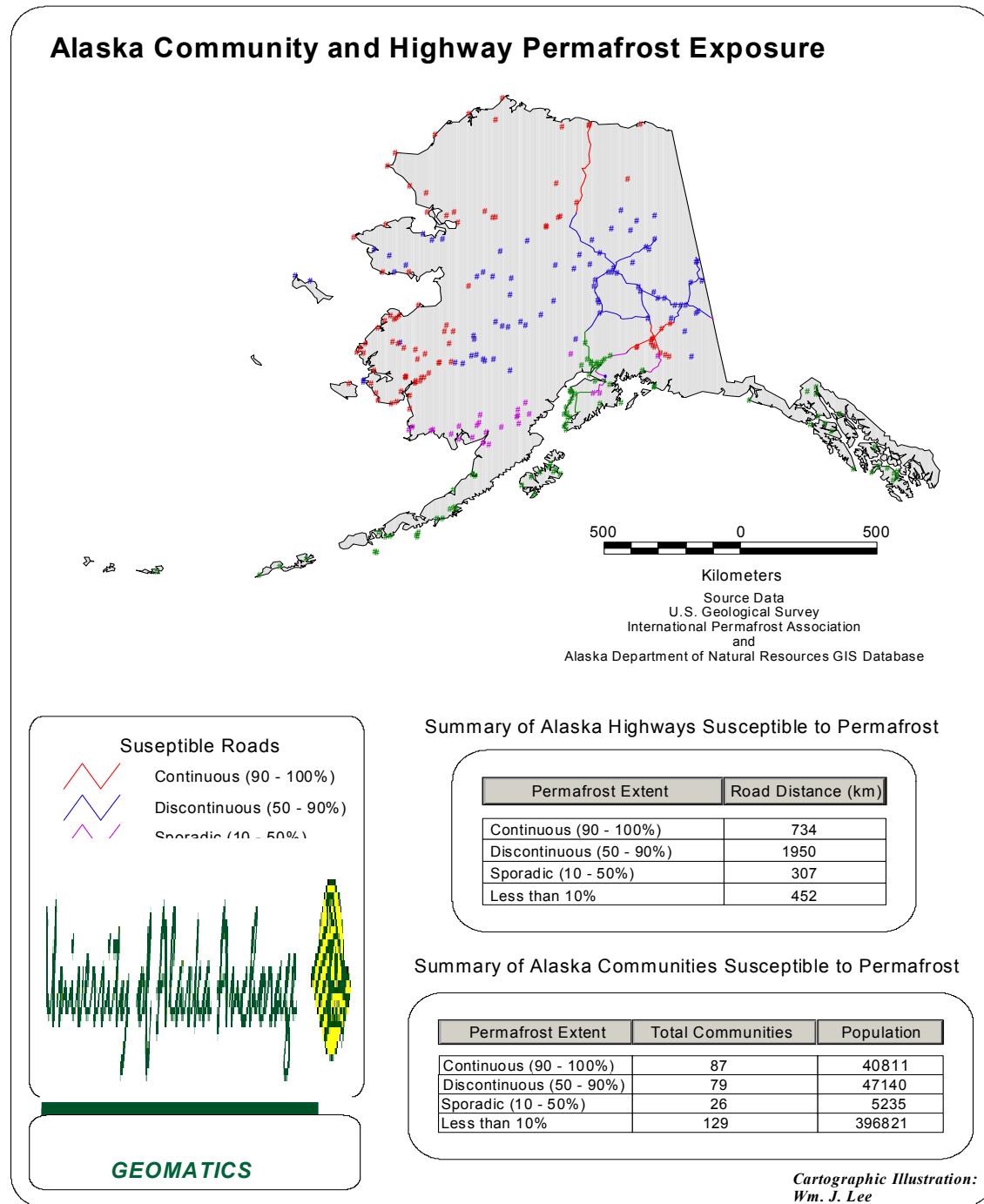


Figure 5. Map of Alaska infrastructure on permafrost foundations.

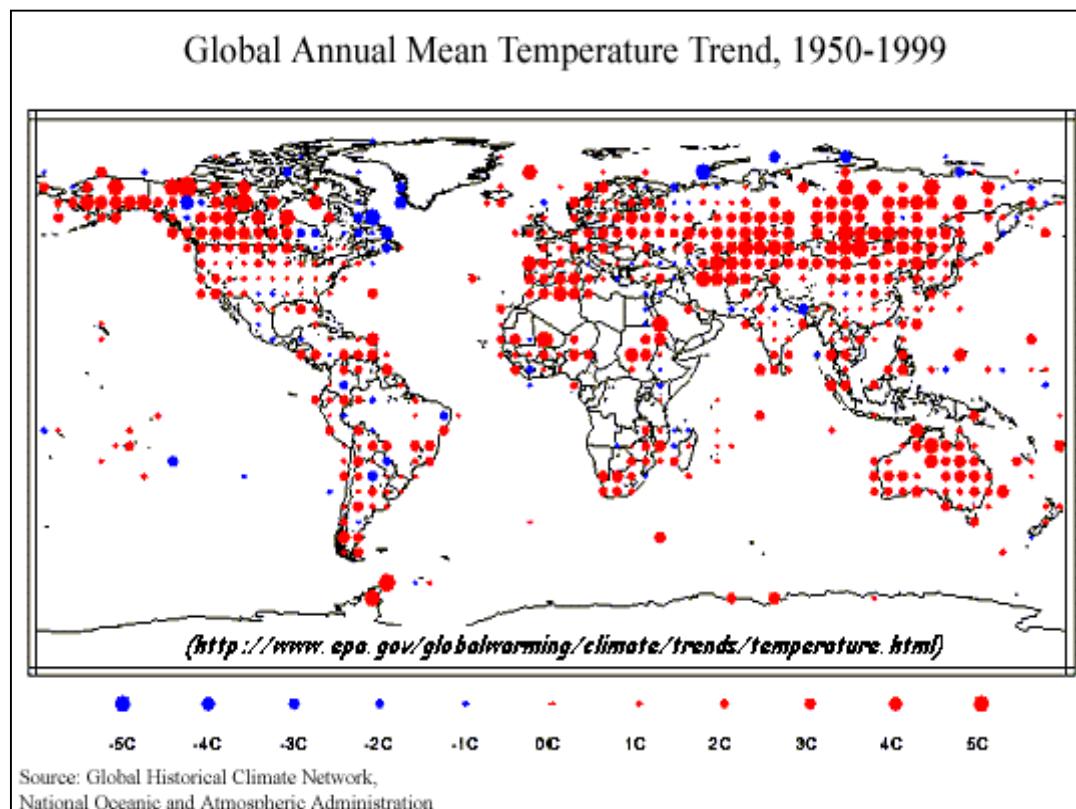


Figure 6. Map of annual mean temperature trends worldwide, 1950-1999. Historical temperature trends show the most warming in Canada and Alaska.

A January 2001 workshop at UAA focused on “Cold Regions Port and Coastal Engineering,” with discussions of science and engineering needs related to coastal problems and engineering solutions. The following excerpt from the workshop report (Smith and Johnson 2001) summarizes conclusions regarding permafrost shorelines:

“...Wise decisions must be made with regard to the life of new infrastructure in the face of erosion threats. Bluff shoreline retreat rates of up to 5 meters or more per year are common in Arctic Alaska, Canada, and Russia, due to thawing of permafrost. The International Permafrost Association

has proposed a circum-Arctic coastal monitoring system to quantify coastal erosion, as part of an international Arctic Coastal Dynamics initiative. Remote sensing is of great utility in this regard, both for the extent and nature of erosion trends and associated sea waves, currents, water levels, and for ice conditions. Satellite-borne sensors include RADARSAT, AVHRR and SSM-I, from which processed data is available from the University of Alaska Fairbanks and the National Weather Service. Regular monitoring of survey profiles across the shore at selected representative sites is important ground truth and provides the best information for site-specific studies and

erosion control designs. Globally, Arctic coastal erosion seems to average about 1 - 2 meters a year, according to recent regional analyses. Local residents can be trained and equipped to accomplish valuable objective measurements of coastal change..."

The U.S. Senate Appropriations Committee convened a hearing in Fairbanks, Alaska on 29 May 2001 with focus on climate change research needs. Testimony of Orson Smith (2001), University of Alaska Anchorage, included the following remarks:

"...Permafrost coasts are especially vulnerable to erosive processes as ice beneath the seabed and shoreline melts from contact with warmer air and water. Thaw subsidence at the shore allows even more wave energy to reach these unconsolidated erodible materials. Alaska's permafrost coasts along the Beaufort and Chukchi Seas are most vulnerable to thaw subsidence and subsequent wave-induced erosion..."

...Thawing permafrost and freeze-thaw cycle changes in the active layer of soils across Alaska may bring adverse impacts to existing foundations of all types. New foundations can be designed to accommodate these changes, if site conditions are known and predictions are accurate...

...Climate change began some time ago and problems of warming permafrost and other environmental changes have occurred throughout the careers of cold regions engineers in practice today. Their fears for northern infrastructure relate to lack of site information and reliable prediction of future change..."

Native Alaskan Concerns. Caleb Pungowiyi, President of the Robert Aqqaluk Sr. Memorial Trust and a respected spokesman on native Alaskan issues, also testified at the May 2001 hearing. His testimony included the following statements (Pungawiyi 2001):

"...More wind causes wave action and wave action along with rising waters causes erosion. In the past 20 years we have lost much land to beach and shore erosion. Many subsistence camps have lost land to erosion, especially in areas like Cape Espenberg and Cape Krusenstern. As you mentioned the other day, Senator, some of the communities like Shishmaref [see Figure 7] and Kivalina will have no choice but to relocate..."

...Most people take change too lightly and do not think that people are being affected directly. It is not the severe events, such as hurricanes, floods, drought, and unseasonable snowfall that are major effects from climate change, but small changes that will or are having dramatic effects...



Figure 7. Photo of coastal erosion leaving buildings at the edge of the sea at Shishmaref, Alaska.

...We need to document and record the economic and other effects of the warming on the coastal residents of Western and Northern Alaska..."

International Interests

International efforts are also bringing attention to bear on climate change impacts to Alaska infrastructure. The Arctic Council, a forum of the eight Arctic national governments (Canada, Denmark/Greenland, Finland, Iceland, Norway, Russia, Sweden, and the U.S.) is sponsoring an assessment of the consequences of climate change in the Arctic region. The Arctic Climate Impact Assessment (ACIA 2001) project is under the purview of the Arctic Council and the non-governmental International Arctic Science Committee (IASC). The ACIA Secretariat is located at the International Arctic Research Center at the University of Alaska Fairbanks. The U.S. National Science Foundation and National Oceanic and Atmospheric Administration provide funding for the Secretariat. ACIA will focus on projections for the years 2020, 2050, and 2080, applying an intermediate scenario of global warming from climate model projections investigated by the Intergovernmental Panel on Climate Change (Leggett et al 1992 and IPCC 2000). Chapter 15 of the ACIA report is titled "Infrastructure: Buildings, Support Systems, and Industrial Facilities" and will include a summary of anticipated impacts in Alaska. The report will also propose research, education, and other measures in response to climate change impacts.

Coastal Erosion

Alaska is bounded by over 50,000 km of diverse Arctic and sub-Arctic coastline, most of which is uninhabited. Over 90% of its population lives within 20 km of the coast, however, so coastal development is critical to the economy and social well being of nearly all Alaskans. Fisheries and oil and gas developments are concentrated along the coast. Markets for minerals and other resources from the hinterland are constrained by export through widely

scattered seaports. Tourism aboard cruise ships is growing rapidly.

Alaska's coastal zone includes a broad range of temperate, sub-Arctic, and Arctic characteristics. Coastal dynamics of the northern half of the State are affected directly or indirectly by the presence of permafrost (Figure 4). Sea level rise and thaw subsidence of permafrost shores are projected to exacerbate problems of increased wave energy at the coast from extended periods of broad ice-free fetches. More energetic waves would be generated by more frequent and intense storms that may accompany global warming.

The southern half of the State has coastal characteristics complicated by erodible glacial deposits and high tides. Cook Inlet, in south-central Alaska, has a 10-m tidal range at its northern extreme and an eroding shoreline of glacially deposited bluffs (Figure 8, Smith et al 2001). Freezing of brackish water at the northern end and ice deposition on broad tidal flats create huge blocks of "beach ice" that carry coarse sediments for distances over 100 km (Figure 9, Smith 2000). These sediment-laden ice blocks are most dangerous of all Cook Inlet ice to ships in winter. The complex dynamics of bluff erosion and ice-borne sediment transport will become even more difficult to forecast with sea level rise and a more erratic storm climate.

The history of coastal erosion studies in Alaska is one of isolated site-specific efforts aimed at design of erosion control works. Erosion control measures in place are mostly small expedient works that run the gamut of low-cost alternatives. Exceptions to this rule occur where protection of critical transportation justifies larger investments of State and federal funds. Erosion problems at rural locations, such as Kivalina and Shishmaref (Figure 7), are not associated with the same scale of tangible economic loss.

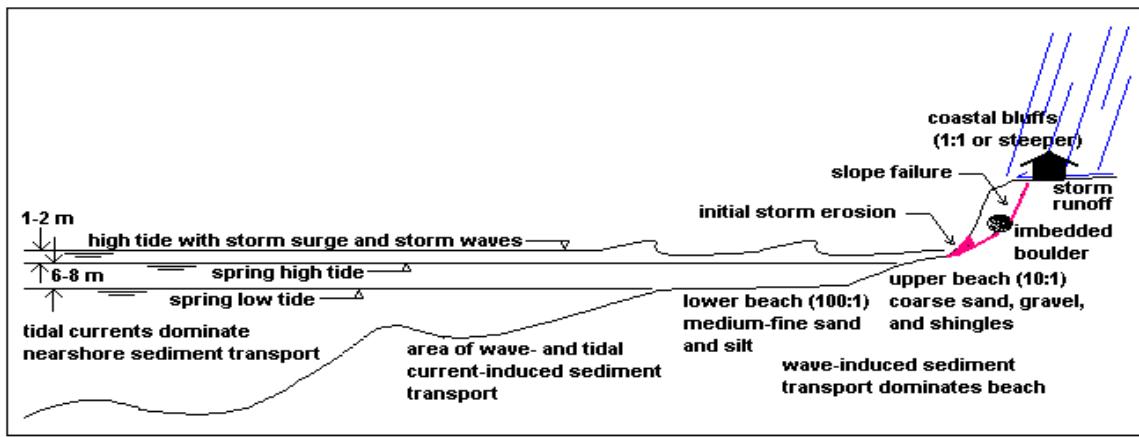


Figure 8. Diagram of bluff erosion of glacial deposits in macro-tidal Cook Inlet in southcentral Alaska. Storm waves initially undercut steep coastal bluffs. Combined with storm runoff, this triggers slope failure and erodes the coast farther inland.

Through the Alaska Department of Transportation and Public Facilities, the State government relies a great deal on technical resources of the federal government, primarily the U.S. Army Corps of Engineers, to investigate coastal erosion concerns and to design erosion control measures. Other State agencies, such as the Department of Natural Resources, generally only involve themselves in erosion control problems from a regulatory versus a problem-solving perspective. The net effect is that severe constraints on federal appropriations for coastal erosion also apply to the State government and large-scale trends of coastal change in Alaska are poorly understood.



Figure 9. Photo of beach ice on a beach in upper Cook Inlet. Beach ice in macro-tidal zones of Alaska is a significant agent of sediment transport and hazard to navigation.

Marine Transportation Considerations

Ocean Navigation. Continuing trends of lesser ice extent and thickness (Smith and Lee 2001) will provide an opportunity for export of natural resources and other waterborne commerce over new northern shipping routes. Prospects for increased international trade through Alaskan waters via the Northern Sea Route along the Russia's northern coast will improve if Arctic Ocean ice conditions continue to become less severe. Few ice-breaking cargo ships exist with a capacity to make the distance advantage of the Northern Sea Route more profitable than use of larger ships through the Panama and Suez Canals or southern cape routes (Smith 1995). Ice-capable commercial cargo vessels specifically suited for Alaskan coastwise service have not been built. Marine transportation remains critical to Alaska's economy; so, early attention to these opportunities will save time and money getting valuable products to market.

River Transportation. Global warming is also changing Alaska's rivers as transportation routes, water sources, and habitats. Projected precipitation increases will induce higher stream flows and more flooding. Associated improvement of bridges and culverts may prove

to be a particularly expensive impact of global warming. Erosion of thawing permafrost banks will accelerate with increased inundation, threatening hard-won infrastructure of rural Alaska river communities, such as Bethel and Noatak. River ice breakup may continue to occur earlier and be more difficult to predict in terms of ice jam flooding risks. Prediction and prevention of ice jam flooding in Alaska warrant further study. Conditions for commercial river navigation may improve for transport of minerals and bulk exports to tidewater. Since no State or federal agency is presently responsible for either charting or marking river channels, this prospect will be difficult to quantify. A program to survey river navigation routes would provide a baseline from which to monitor change and evaluate improvements for waterborne commerce.

Design Criteria Development

Scientific research findings are only occasionally tailored to fit the practice of engineers in design criteria development and structural computations. Conventional historical extrapolations now appear to be incomplete bases for predicting future permafrost characteristics during a projected accelerating global warming trend. A non-linear trend and

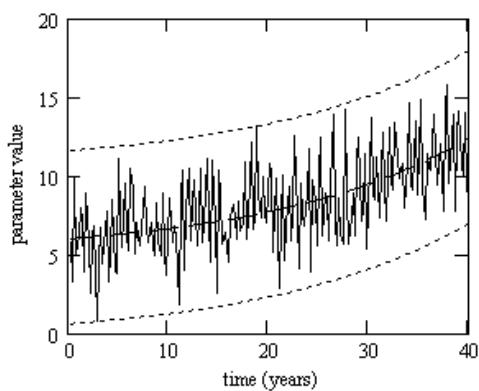


Figure 10. Chart showing a hypothetical accelerated increase in the time series of a naturally variable parameter. Although the value of the parameter varies up and down considerably in the short run, in the long run the parameter trends upwards at an increasing rate.

maxima and minima bounds for a naturally variable parameter are shown in Figure 10 as dashed lines. Linear extrapolation of any portion of this hypothetical time series will underestimate future means and extremes (Smith 2002).

Decisions regarding new infrastructure on permafrost foundations are likely to be wiser if they consider accelerated warming, as predicted by global circulation models (GCM's), weighted by associated probabilities (Vinson and Bae, 2002). Design criteria that make use of projections of GCM's will better predict the full range of possible permafrost thawing rates and other climate change effects on infrastructure. A rational approach to development of design criteria using GCM results should be more affordable than applying an arbitrarily large factor of safety to conventional design criteria. Adaptation of conventional statistical analyses of trends and of extremes to apply GCM projections of accelerated change is a challenging topic for research and development. Once available, engineers may develop rational design criteria for future conditions with global warming.

Data Access. Data application doesn't automatically follow expansion of the archives. Storage and accessibility of engineering site data are improving, but more old data can be saved and new data must be measured. The World Wide Web provides means for quick access to modern GIS-based atlases of linked environmental databases, complete with common engineering computations. One such effort is the Alaska Engineering Design Information System (AEDIS), now in its first stage of development at the U.S. Army Cold Regions Research and Engineering Laboratory in cooperation with the University of Alaska. The AEDIS program will provide online information to replace outdated printed atlases of engineering information, but needs additional resources to achieve its goals.

Conclusions and Recommendations

Environmental monitoring, though universally favored by researchers, is difficult to fund by infrastructure agencies whose budgets revolve around construction projects. A comprehensive monitoring program is warranted. Instituting a “one percent for monitoring” federal funding policy for large public works projects could finance a consolidated monitoring, data analysis, and dissemination program well within the confidence bounds of construction cost estimates and contract bids.

Alaska is the U.S. Arctic, where projected effects of global warming are most pronounced in the entire nation. The State will probably undergo expansive development in the 21st century as the world turns to the north for natural resources. Applied research and development of engineering methods to account for climate change are best tested in Alaska where the signal of global warming is strong and new applications will be economically and strategically crucial to America.

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Orson Smith received a B.S. in Mechanical Engineering in 1971 from the University of Kentucky, a graduate Diploma in Coastal Engineering and Port Planning in 1979 from the International Institute of Hydraulic and Environmental Engineering in Delft, the Netherlands, an M.S. in Civil Engineering in 1986 from Mississippi State University and a Ph.D. in Physical Oceanography in 1989 from North Carolina State University. He is a registered Professional Civil Engineer in the State of Alaska. Orson accumulated 20 years' experience with the U.S. Army Corps of Engineers as a Project Manager of dredging, hydrographic surveying, port, harbor, coastal erosion control, flood control, and other civil works projects, primarily in Alaska, but extending to coastal areas of the lower 48 and a number of overseas locations. He presently teaches undergraduate and graduate civil engineering courses and is Arctic Engineering Program Chair at the University of Alaska Anchorage, School of Engineering. Orson is now involved in several research projects related to sea ice, ice navigation, shoreline resources, and climate change in Alaska.

George Levasseur is a graduate of the University of Minnesota. He began his career with the Alaska DOT in 1974 and manages the maintenance and operations efforts for much of Southcentral Alaska. This area contains the geography in Alaska most affected by the warming trend. His greatest challenges are dealing with the melting permafrost on the highway and airport system and handling the bridge problems associated with the increase water flows and bedload deposition.

System Impacts

Surface Transportation Safety and Operations: The Impacts of Weather within the Context of Climate Change

By Paul Pisano, Lynette Goodwin, and Andrew Stern

Introduction

Surface transportation is the dominant method of moving people and commerce in the United States. Services supporting surface transportation require usable infrastructure and effective systems. Primary highway operational goals—safety, mobility and productivity—are affected by environmental conditions. Weather acts through visibility impairments, precipitation, high winds, temperature extremes, and lightning to affect driver capabilities, vehicle maneuverability, pavement friction, and roadway infrastructure.

The Road Weather Management Program of the Federal Highway Administration (FHWA) has documented operational practices of traffic, maintenance, and emergency managers employed under various weather threats and the weather information needs of travelers. This paper examines weather impacts on roadways, operational practices of transportation managers and road users, and the weather parameters with the greatest effects on roadways. Finally, a discussion of how possible climate change may affect these parameters during the next century is presented.

Overview of Surface Transportation Safety and Operations

Weather impacts roadway safety through exposure to environmental hazards and increased crash risk, either from impacts of a

weather event or from the event's effect on the pavement. Each year 10 percent of passenger vehicle crashes occur in rain, snow, or sleet and approximately 13 percent of commercial vehicle (i.e., large truck) crashes happen in rain, snow, sleet, hail, or fog. Roughly 16 percent of commercial vehicle crashes occur on wet, snow-covered, slushy, or icy pavement each year. The combination of adverse weather and poor pavement conditions contributes to 18 percent of fatal crashes and 22 percent of injury crashes annually (National Center for Statistics and Analysis, 2001).

All U.S. residents are exposed to some form of weather-related hazards. Nearly 70 percent of the population and 74 percent of the nation's roads are located in snowy regions. Over 50 percent of U.S. residents have a five percent or greater chance of being affected by a hurricane in any given year. Most hurricane fatalities are related to inland flooding after landfall. Nearly 60 percent of deaths during Hurricane Floyd in 1999 were associated with drowning in vehicles from fresh water inundation and associated flooding.

Weather affects mobility by reducing traffic speed and volume, increasing travel time delay, and decreasing roadway capacity (i.e., maximum rate at which vehicles can travel). An Iowa State University study concluded that winter storms reduce average freeway speed by roughly 16 percent and traffic volume by 29 percent. Studies sponsored by the FHWA have found that weather accounts for roughly 12 percent of

travel time delay in two metropolitan areas. A nationwide study conducted for FHWA estimated that 23 percent of delay and 11 percent of capacity reductions resulted from fog, snow and ice in 1999. These weather events were the most prevalent causes of non-recurrent traffic congestion.

Weather events impact transportation system productivity by increasing operating and maintenance costs and by disrupting access to roadway networks. Nearly 39 percent of road operating costs can be attributed to winter maintenance annually. Each year, state and local agencies spend over 2.3 billion dollars on snow and ice control operations and an estimated five billion dollars to repair roadway infrastructure damaged by snow and ice.

Review of Operational Practices

Transportation managers utilize three types of operational practices to mitigate environmental impacts on roadways: advisory, control, and treatment strategies. These mitigation strategies are employed in response to various weather threats including fog, rain, snow, ice, high winds, flooding, tornadoes, hurricanes, and avalanches. Advisory strategies provide information on prevailing and predicted conditions to both managers and motorists to influence operational decisions. Control strategies alter the state of roadway devices (e.g., traffic signals, ramp gates) to regulate roadway capacity and permit or restrict traffic flow. Treatment strategies supply resources to roads (e.g., spreading sand or salt) to minimize or eliminate weather impacts.

Transportation managers use environmental and traffic data to make decisions about system operation and resource deployment. Weather threat information is typically gathered through surveillance systems that detect and transmit data from roadways to central systems accessed by managers. Environmental sensor stations (ESS) are deployed along roads across the country to observe atmospheric, pavement, subsurface, water level, and slope stability conditions. Environmental data may be integrated into road weather information systems

(RWIS), advanced traffic management systems (ATMS), emergency management systems (EMS), and advanced traveler information systems (ATIS) as depicted in Figure 1. Vehicle detectors and closed circuit television (CCTV) cameras are components of ATMS used to monitor traffic conditions. By integrating accurate, timely road weather data into decision-making processes, transportation managers can effectively counter weather-related problems and disseminate relevant, credible information that allows travelers to avoid unsafe conditions or cope with weather effects.

Operational Practices of Maintenance Managers

Maintenance managers obtain surveillance and predictive information to assess the nature and magnitude of an environmental threat. These information resources help managers make decisions about staffing levels, road treatment strategies, the timing of maintenance activities (e.g., crack sealing operations in summer months), and resource management (i.e., personnel, equipment, and materials).

Winter road maintenance involves removing snow and ice through mobile techniques or fixed systems. Snow and ice treatment strategies

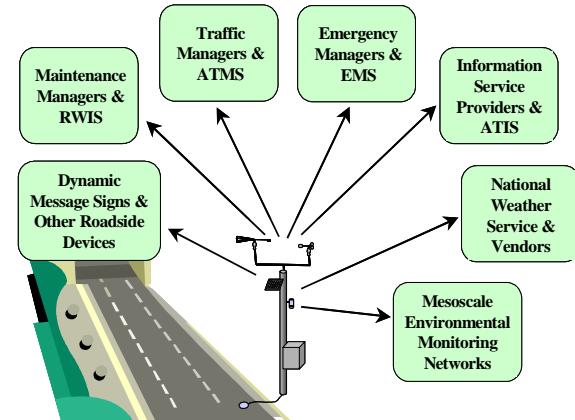


Figure 1. ESS operational applications, showing the many users of ESS data.

include plowing snow, spreading abrasives (e.g., sand) to improve vehicle traction, and dispensing anti-icing/deicing chemicals (e.g., salt, magnesium chloride, potassium acetate) to lower the pavement freezing point. In regions with heavy snowfall, maintenance managers may erect snow fences adjacent to roads to reduce blowing and drifting snow.

Another mitigation strategy involves use of slope sensors and avalanche forecasts to minimize landslide and avalanche risks. When a slope becomes unstable due to snow accumulation or soil saturation, roads in the slide path may be closed to allow the controlled release of an avalanche or landslide. After snow, mud and debris are cleared and damaged infrastructure is repaired the affected route can be reopened to traffic.

In mountainous areas, super-cooled fog can persist in valleys for weeks. To improve roadway visibility and reduce crash risk, managers can employ a fog dispersal treatment strategy. Small amounts of liquid carbon dioxide are sprayed behind maintenance vehicles to encourage precipitation of water droplets in the fog. This strategy includes the application of anti-icing chemicals as fog is dispersed to prevent the precipitate from freezing on road surfaces.

Maintenance vehicle management practices involve treatment planning, real-time operations monitoring, and post-storm analysis. Managers may consult decision support systems to plan the most efficient treatment routes, select treatment chemicals, and dispatch crews. Truck-mounted sensor systems facilitate surveillance of road conditions and tracking of vehicle status (e.g., truck speed, plow position, material application rate) with automated vehicle location, global positioning system, and geographical information system technologies.

Table 1 lists several advisory, control and treatment strategies exploited by maintenance managers and the resulting effects on roadway safety and operations. These strategies improve safety by reducing crash frequency and minimizing risks to field personnel and

motorists. Increased visibility distance and roadway capacity enhance mobility. Productivity is improved by preventing vehicles from interfering with winter road maintenance and by minimizing road maintenance costs.

Operational Practices of Emergency Managers

Emergency managers obtain current and predicted weather information through RWIS, water level monitoring systems, the federal government (e.g. the National Hurricane Center), private companies, the media, and various decision support systems. Decision support systems may present weather data integrated with population data, topographic data, and road and bridge locations, as well as traffic flow data. In response to flooding, tornadoes, hurricanes, wild fires or hazardous material incidents, emergency managers can evacuate vulnerable residents, close threatened roadways and bridges, operate outflow devices to lower water levels, and disseminating information to the public. Many emergency management practices require coordination with traffic and maintenance managers.

Evacuation management begins with an advisory strategy. Emergency managers gather weather observations and forecasts to identify hazards, their associated threatened areas, and select a response or mitigation strategy. Managers may use several control strategies to manage traffic on designated evacuation routes. These strategies include opening shoulder lanes to traffic, contraflow operations to reverse traffic flow in selected freeway lanes, and modified traffic signal timing on arterial routes.

Emergency managers deploy environmental sensors (e.g., rain gauges) to monitor precipitation and water level conditions. Surveillance data are used to identify areas that may be significantly impacted by heavy rainfall. To prevent or alleviate flooding it may be necessary to activate outflow devices to control the release of water.

Table 1. Operational practices of maintenance managers.

Mitigation Strategies		Safety & Operational Effects
Advisory	<p>Surveillance/Prediction</p> <ul style="list-style-type: none"> atmosphere (temperature, precipitation, visibility, wind) pavement temperature/condition subsurface temperature/condition water level & flooding slope stability (i.e., avalanche/landslide onset) 	<ul style="list-style-type: none"> assess nature/magnitude of threat (e.g., impaired paving, lane obstruction, loss of vehicle stability) determine threatened areas/routes select appropriate treatment strategy mobilize personnel (e.g., prepare/load vehicles) determine risks to field personnel (e.g., hypothermia) determine risks to roadway infrastructure (e.g., pavement buckling, lane submersion)
Treatment	<p>Winter Road Maintenance</p> <ul style="list-style-type: none"> conventional snow/ice control (e.g., plow snow, spread sand) apply anti-icing/deicing chemicals erect snow fence 	<ul style="list-style-type: none"> improve visibility (safety) reduce crash risk (safety) improve vehicle traction (mobility) increase roadway capacity (mobility) minimize treatment costs (productivity)
Control & Treatment	<p>Avalanche/Landslide Control</p> <ul style="list-style-type: none"> road closure release avalanche/landslide clear roadway & repair damaged infrastructure 	<ul style="list-style-type: none"> minimize risks to public (safety) minimize risks to field personnel (safety) reduce length of road closure (mobility)
Treatment	<p>Fog Dispersal</p> <ul style="list-style-type: none"> spray carbon dioxide into super-cooled fog apply anti-icing/deicing chemicals 	<ul style="list-style-type: none"> reduce crash risk (safety) increase visibility distance (mobility)
Advisory	<p>Maintenance Vehicle Management</p> <ul style="list-style-type: none"> route planning automated vehicle location vehicle system status (e.g., plow blade up) treatment monitoring (e.g., application rate) post-storm analysis (e.g., plow passes per route) 	<ul style="list-style-type: none"> minimize treatment costs (productivity) minimize maintenance costs (productivity)

Some emergency management practices and effects on roadway safety and operations are shown in Table 2. Control strategies increase roadway mobility by reducing travel time delay or by maintaining adequate roadway capacity to

ensure public safety. Emergency managers must disseminate evacuation orders, road closure and flood information to minimize exposure to hazards.

Table 2. Operational practices of emergency managers.

Mitigation Strategies		Safety & Operational Effects
Advisory	<p>Surveillance/Prediction</p> <ul style="list-style-type: none"> atmosphere (storm track, precipitation, wind) water level & flooding traffic volume (e.g., route-specific, state-to-state) travel time 	<ul style="list-style-type: none"> assess nature/magnitude of threat (e.g., hurricane storm surge, hail size, wind speed) determine threatened areas/routes select appropriate response strategy mobilize personnel (e.g., preposition equipment) determine risks to roadway infrastructure (e.g., lane submersion, loss of communications) eliminate field measurements (productivity)
Control	<p>Evacuation Management</p> <ul style="list-style-type: none"> determine evacuation type/timing (e.g., voluntary, mandatory, phased) open shoulder lanes contraflow (e.g., reverse freeway lanes) modify traffic signal timing 	<ul style="list-style-type: none"> minimize risks to public (safety) minimize risks to field personnel (safety) increase roadway capacity (mobility) minimize travel time delay (mobility)
Control	<p>Flood Control</p> <ul style="list-style-type: none"> operate outflow devices to induce drainage 	<ul style="list-style-type: none"> minimize risks to public (safety) minimize risks to field personnel (safety)
Advisory	<p>Disseminate Road Weather Information (e.g., storm track, threatened routes, access restrictions)</p>	<ul style="list-style-type: none"> minimize risks to public (safety) minimize risks to field personnel (safety)

Operational Practices of Traffic Managers

Roadway conditions are monitored from traffic management centers (TMCs). Most traffic managers access weather forecasts from the commercial sector including the media. Customized weather forecasts are also utilized in many TMCs and weather data are integrated with control software in some TMCs. Based upon weather surveillance or prediction data, managers execute control strategies to manage traffic flow and advisory strategies to disseminate road weather information.

Traffic signal timing plans may be altered in adverse weather conditions to accommodate slower travel speeds on “wet”, “slushy”, “snowy”, or “icy” roads. Traffic managers may modify incident detection software algorithms for “sunny”, “rainy”, “snowy”, “dry pavement”

or “wet pavement” conditions to identify traffic flow disruptions on freeways.

Another control strategy utilized by traffic managers is speed management. Speed limits are changed based upon the safe travel speed for prevailing visibility, pavement, and traffic conditions. Managers notify drivers of reduced speed limits via dynamic message signs (DMS) or variable speed limit (VSL) signs.

When travel conditions are unsafe due to low visibility conditions, lane obstructions, excessive snow accumulation or flooding, managers may restrict access to entire road segments, specified lanes, bridges, all vehicles, vehicles without required equipment (e.g., tire chains), or designated vehicle types (e.g., tractor-trailers). Dynamic message signs and lane use signs are typically used to inform motorists of travel restrictions.

When visibility is reduced by fog or wind-blown dust, managers may guide vehicles by illuminating pavement lights embedded in road surfaces or bridge decks to delineate travel lanes. Traffic and emergency managers also cooperate to guide vehicle platoons in low visibility conditions. Patrol vehicles with flashing lights may be used to group traffic into platoons. Patrols, at the front and the rear of a platoon, lead traffic through affected areas at a safe pace.

Traffic management practices and associated effects are shown in Table 3. Advisory and control strategies improve safety by reducing traffic speeds and crash risk, and enhance mobility by delineating travel lanes and minimizing delay.

Operational Practices of Travelers or Road Users

Transportation managers disseminate road weather information to all road users to

Table 3. Operational practices of traffic managers.

		Mitigation Strategies	Safety & Operational Effects
Advisory	Surveillance/Prediction	<ul style="list-style-type: none"> atmosphere (temperature, precipitation, visibility, wind) pavement temperature/condition subsurface temperature/condition water level & flooding traffic volume traffic speed 	<ul style="list-style-type: none"> assess nature/magnitude of threat (e.g., low visibility, loss of vehicle traction) determine threatened areas/routes
Control	Weather-Related Signal Timing (i.e., modify green time, modify cycle length)		<ul style="list-style-type: none"> reduce speed (safety) reduce crash risk (safety) prevent traffic congestion (mobility)
Control	Weather-Related Incident Detection (i.e., modify detection algorithms)		<ul style="list-style-type: none"> minimize incident response time (safety) reduce risk of secondary incidents (safety) minimize delay (mobility)
Control	Speed Management <ul style="list-style-type: none"> determine safe speed reduce speed limit 		<ul style="list-style-type: none"> reduce speed & speed variance (safety) reduce crash risk (safety)
Control	Access Restriction (on threatened routes) <ul style="list-style-type: none"> road/bridge/ramp closure tire controls (e.g., tire chains, snow tires) lane use controls designated vehicle types (e.g., trucks) 		<ul style="list-style-type: none"> reduce crash risk (safety) minimize risks to public (safety) minimize risks to field personnel (safety) minimize delay due to treatment (mobility) minimize treatment costs (productivity)
Control	Vehicle Guidance (in low visibility conditions) <ul style="list-style-type: none"> illuminate pavement lights lead convoys at safe speed with patrol vehicles 		<ul style="list-style-type: none"> delineate travel lanes (mobility) reduce crash risk (safety)
Advisory	Disseminate Road Weather Information (e.g., access restrictions, safe speed) <ul style="list-style-type: none"> roadway warning systems interactive telephone systems web sites 		<ul style="list-style-type: none"> reduce speed & speed variance (safety) reduce crash risk (safety) minimize risks to public (safety) promote uniform traffic flow (mobility)

influence their travel decisions. Different types of travelers, or road users, have varying information needs. In the event of a road closure recreational travelers may need alternate route information, while commuters familiar with their route may not. Passenger vehicle drivers are interested in road surface conditions and commercial vehicle operators need information about road restrictions due to subsurface freeze/thaw conditions. Road weather information allows travelers to make decisions about travel mode, departure time, route selection, vehicle type and equipment, and driving behavior.

Road weather warnings and regulations may be furnished via roadway warning systems, telephone systems, web sites, and other broadcast media. Roadway warning systems—which are typically controlled by traffic managers—utilize highway advisory radio transmitters, DMS, VSL signs, and flashing beacons atop static signs to alert motorists to hazards. Interactive telephone systems allow motorists to access road weather information before a trip and while en-route. Many state departments of transportation (DOTs) provide general road condition data through toll-free telephone numbers and via 511, the national traveler information telephone number, which was allocated by the Federal Communications Commission in 2001. Travelers may also access tailored road weather information provided by private vendors. For example, drivers in Minnesota, Montana, North Dakota, and South Dakota can dial #7233 (or #SAFE™) to obtain route-specific road condition reports and six-hour weather forecasts extending 60 miles (or one hour) in their direction of travel. Many state DOTs also provide textual and graphical road weather information on Internet web sites. Mitigation strategies employed by travelers to improve safety are listed in Table 4.

Weather Parameters Affecting Safety and Operations

Weather is complex and dynamic. It affects operations and planning for all surface transportation modes. While great strides have

been made in improving short and long range forecasting, there is still a significant gap between the state-of-the-art and what is needed to provide a full suite of accurate, high-resolution meteorological guidance to roadway operators and users.

Looking into the future, transportation professionals will be able to utilize new technologies for decision support. However, they must also be able to adapt to potential changes in global climate. This section will rank and discuss those weather parameters that most affect the safety and operations of roadways and how climate change may affect the parameters.

It is apparent in the previous section that there are many weather parameters that affect highway safety and operations. A previous effort to describe all the parameters was completed on behalf of the Office of the Federal Coordinator for Meteorology. This was done as part of a broader effort to capture the weather information needs for the entire surface transportation community. Since it is not feasible to examine all these parameters in the context of climate change, only those weather parameters that have significant affects on maintenance management, emergency management, traffic management, and road users are identified and prioritized below. Weather parameter rankings are based on experience and observations of each discipline, rather than extensive analysis. Ranking criteria include area of influence (i.e., portion of the country that is affected by the weather condition), frequency of occurrence (i.e., seasonal or year-round effects), impact on roadway operations, and ease of mitigation. Table 5 provides a listing of weather parameter rankings for each operational area. The sections that follow briefly describe how each parameter affects roadway operations and safety, and the potential impacts from climate change.

Table 4. Operational practices of travelers or road users.

Mitigation Strategies		Safety & Operational Effects
Advisory	Access Road Weather Information <ul style="list-style-type: none"> • warnings/regulations via roadway devices • tailored road weather data via telephone • road weather data posted on web site 	<ul style="list-style-type: none"> • determine mode, route & departure time • select vehicle type & equipment
Control	Make Travel Decisions <ul style="list-style-type: none"> • defer trip • prepare vehicle • drive slower • increase following distance 	<ul style="list-style-type: none"> • reduce speed (safety) • reduce crash risk (safety)

Table 5. Weather parameters that most affect roadway safety and operations.

Rank	Maintenance Management	Emergency Management	Traffic Management	Road User/Traveler
1	Ice	Severe Storms	Snow/Ice	Snow/Ice
2	Snow	Tropical Cyclones	Severe Storms	Low Visibility
3	Road Temperature	Winter Storms	Tropical Cyclones	Severe Storms
4	Severe Storms	Wind (Dispersion Info)	Low Visibility	Wind (Vehicle Stability)

Potential Climate Change

This paper is not a vehicle to discuss the validity, magnitude nor duration of projected climate change. Rather, the discussion will take one viewpoint and apply these hypotheses to each weather parameter listed in Table 5. The Environmental Protection Agency (EPA), citing studies performed by the National Academy of Sciences, has indicated that a buildup of greenhouse gases in the Earth's atmosphere has hastened a global trend of rising surface temperatures. Using the United Kingdom's Hadley Centre climate model, the EPA has written reports on the impacts of potential climate change during the twenty-first century for each state. Table 6 contains a compilation of potential climate change projections with respect to both air temperature and precipitation.

The seasonal projected temperature changes for each state by the year 2100 are listed in the temperature columns. From these data, the following projections can be made:

- Average U.S. air temperatures are projected to increase by 3.5 degrees (Fahrenheit) in the spring, by 3.7 degrees in the summer, and by 4.0 degrees in both the fall and winter.
- The greatest temperature rise is forecast to occur over Alaska during the winter with an average increase of 10 degrees.
- During the summer season, the area with the smallest projected temperature rise extends from the Midwest to the southern mid Atlantic coast. The areas with the largest projected rise are New England and the western states.
- During the winter season, the area with the smallest projected temperature increase extends over the Deep South and Gulf coast states. The area with the largest projected rise (outside of Alaska) is along and west of the continental divide.

Precipitation models also forecast a general increase during this century across the nation. However, unlike temperature, there are a few locations that are actually projected to have a net decrease in precipitation amounts. These areas are centered over the intermountain region and the desert southwest during the summer season. Additional precipitation related estimates include:

- The average amount of precipitation across the country is projected to rise by 10.7 percent in spring, by 14.1 percent in summer, by 16.2 percent during fall and by 19.0 percent during winter.
- Precipitation projections for Hawaii could not be determined due to uncertainties associated with

Table 6. Composite of projected climate change by the year 2100.*

Source: U.S. Environmental Protection Agency (2002), Global Warming – State Impacts.

State	Temperature				Precipitation				State	Temperature				Precipitation			
	Sp	Su	Fa	W	Sp	Su	F	W		Sp	Su	F	W	Sp	Su	F	W
AL	3	2	4	2	10	15	15	0	MT	4	4	5	5	10	10	10	30
AK	5	5	5	10	10	10	5	5	NE	3	3	4	4	10	10	10	15
AZ	4	5	4	5	20	-10	30	60	NV	4	6	4	6	15	-10	30	40
AR	3	2	3	2	15	25	15	0	NH	4	5	5	5	0	10	10	40
CA	3	5	3	5	30	0	30	40	NJ	4	5	5	4	10	20	20	30
CO	4	6	4	6	10	0	10	40	NM	3	5	4	5	15	-5	5	30
CT	4	4	4	4	10	20	20	40	NY	4	5	5	4	10	20	20	30
DE	3	4	4	4	15	30	15	40	NC	3	2	3	2	15	20	20	15
FL	4	4	4	3	0	0	0	0	ND	4	3	4	4	5	10	15	25
GA	3	2	4	3	10	30	30	10	OH	3	3	4	3	15	25	20	15
HI	3	3	4	3	████████████████				OK	2	3	3	4	20	20	5	0
ID	4	5	4	5	10	0	10	20	OR	4	5	4	5	5	-5	15	15
IL	3	2	4	3	10	50	30	10	PA	5	3	3	5	10	20	50	20
IN	3	2	4	3	10	30	20	10	RI	4	5	5	4	10	10	15	25
IA	3	2	4	4	10	20	15	10	SC	4	2	4	2	15	20	20	10
KS	2	3	4	4	15	15	15	0	SD	3	3	4	4	10	10	10	20
KY	3	2	4	3	20	30	20	0	TN	3	2	4	3	20	30	20	5
LA	3	3	4	2	0	10	10	0	TX	3	4	4	4	10	10	10	-15
ME	3	5	3	5	0	10	10	30	UT	4	6	4	6	10	-10	30	40
MD	3	4	4	4	10	20	10	30	VT	4	5	5	5	0	10	10	30
MA	4	5	5	4	10	10	15	40	VA	3	3	4	3	20	20	20	20
MI	4	4	4	4	10	20	10	10	WA	4	5	4	5	0	0	0	10
MN	4	3	4	4	0	15	15	15	WV	3	3	4	3	20	25	20	20
MS	3	2	4	2	10	15	15	0	WI	4	3	4	4	0	20	20	20
MO	3	2	3	3	15	40	15	0	WY	4	5	4	6	10	-5	10	30

*Temperature values under are in whole degrees Fahrenheit. Precipitation values represent percentage change from the present climatological norm. Decreases in precipitation are shown in lightly shaded cells. Unknown values are shown in darkly shaded cells.

Pacific Ocean currents and phenomena such as El Nino.

- Florida is the only state to have a projection of no change in precipitation amount in any season.
- Winter precipitation amounts are forecast to increase (by over 30 percent) along the eastern seaboard due to the potential for more frequent nor'easters.

Maintenance Management

The weather parameters with the greatest affects on maintenance management are ice, snow, road temperature, and severe storms. The following sections describe how these parameters affect road maintenance, and how the potential climate

change scenario presented in the previous section could impact management practices in the future.

Ice Impacts on Maintenance Management

The occurrence of ice on the pavement is one of the most hazardous conditions for all road managers and users. Ice can form directly on roadway surfaces (e.g., black ice or frost), or can fall as precipitation in the form of freezing rain, freezing drizzle or sleet. While the former can occur anywhere outside of the more tropical climates (e.g., south Florida), the map in Figure 1 shows that freezing precipitation occurs with the highest frequency over the central and upper plains, extending east to New England and south over the mid-Atlantic region in the lee of the Appalachian Mountains. High frequencies can also be seen over portions of the Northwest.

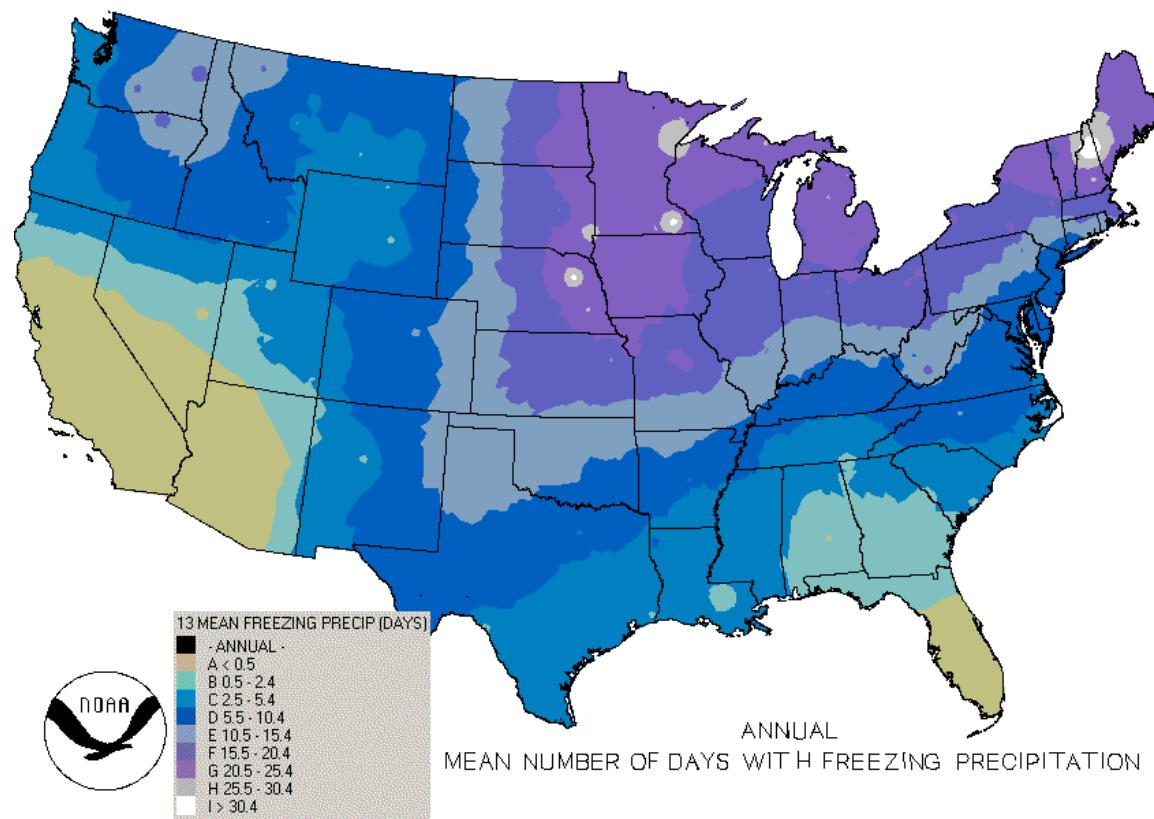


Figure 1. Annual mean number of days with freezing precipitation observed.

Source: National Climatic Data Center, 2000.

With respect to maintenance management, there are many hazards to roadway safety and operations associated with surface icing. Icing causes a loss of pavement friction, which can reduce maintenance vehicle stability and maneuverability, as well as increased winter road maintenance costs. There is also the potential for lane obstruction and infrastructure damage due to ice accretion on pavement, tree limbs, power lines, and communication equipment. Elevated bridges, ramps, and roads out of direct sunlight are at the greatest risk for icy surface conditions.

Climate change projections indicate that in general both winter temperatures and precipitation could increase over the next century. However, that does not necessarily translate into less ice. Moderation in atmospheric temperature could allow precipitation, which would otherwise fall as snow, to become freezing rain or sleet. This is a consequence of relatively warm moisture falling through colder air masses close to the surface.

This could increase the frequency, duration, and amount of ice that occurs particularly from the mid-Atlantic piedmont north to New England and west into the midwestern states. This would require that road maintenance agencies in these regions budget for increased maintenance activities and utilize more effective techniques, such as proactive treatment, to handle potentially treacherous conditions.

Snow Impacts on Maintenance Management

Snow occurs with greater frequency than ice and can cover a larger area in an individual storm. In general, the snow threat region only covers about two-thirds of the nation. Figure 2 shows the mean number of days per year that snowfall accumulates to one inch or more. This graphic clearly delineates those regions of the continental United States that are affected by snowy conditions. The frequency of snowfall is very low over the entire southern tier of states, portions of the southwest, and much of the west coast. Snow reduces maintenance vehicle maneuverability, increases winter road treatment costs, and increases the potential for avalanches.

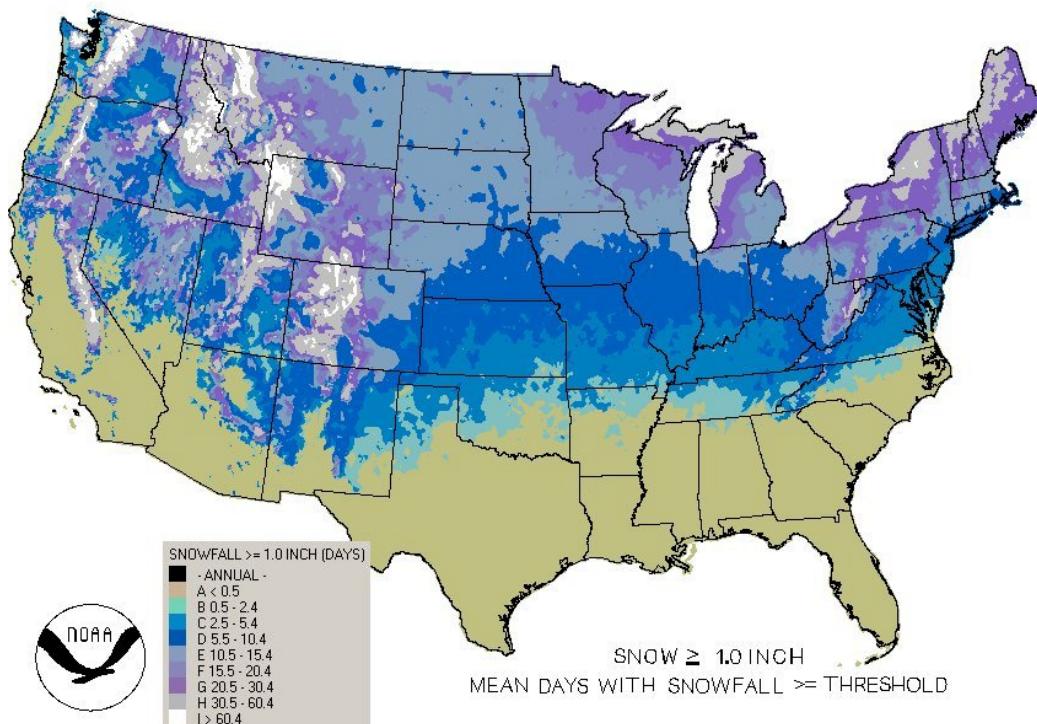


Figure 2. Mean number of days with snowfall of one inch or greater.

Source: National Climatic Data Center, 2000.

Long-term climate projections indicate that mean winter temperatures will increase more than in any other season. On average, this could reduce the areal extent and duration of snow impacting the country's roads. It is possible that the southern fringes of snowy regions shown in Figure 2 will retreat northward. Warmer ocean temperatures could also provide for more mixed precipitation along the urban corridor from Washington, D.C. into New England. However, the frequency and intensity of nor'easters may increase and affect interior portions of the mid-Atlantic region into interior New England providing the potential for more disruptions from snow. Under this scenario, maintenance managers may have to increase budgets for snow removal in these areas. However, regions ranging from the Carolinas west across the Tennessee Valley into the central plains may see a reduction in winter maintenance costs.

Road Temperature Impacts on Maintenance Management

Road surface temperatures play a significant role in determining the effectiveness of winter treatment strategies and resulting pavement conditions. Dark pavement can efficiently absorb daytime solar radiation, potentially storing heat overnight or for the beginning of a precipitation event. However, if pavement temperature falls below freezing in the presence of precipitation or surface moisture, ice can form and pavement friction will be reduced affecting maintenance vehicle operations. In addition, pavement temperature can affect the bonding of ice to road surfaces, which can make treatment more difficult and more costly.

An estimation of rising cold season temperatures would act to reduce the total number of days with freezing temperatures, particularly along the coastal plain along the Gulf and Southeast coasts. However, the temperature rise could create more frequent freeze/thaw cycles in areas that currently experience freezing over longer durations. This could cause infrastructure damage in the form of buckling, heaving or water main breaks, as well as an increase in the number of frost or black ice events.

Severe Storm Impacts on Maintenance Management

Severe convective storms, or thunderstorms, can occur at any time of the year, over the majority of the country, with the highest likelihood of occurrence in the Southeast and the Great Plains, as shown in Figure 3. They typically have a short duration, are somewhat limited in areal coverage, and usually occur during warmer months. Though rare, thunderstorms can occur in winter. Thunderstorms can produce a plethora of dangerous conditions ranging from torrential rains, low visibility, lightning, damaging winds, hail, and on rare occasions a tornado or even blinding snow. These conditions can cause infrastructure damage (e.g., lane submersion, debris on roads) and reduce the productivity of road maintenance crews (e.g., impaired paving).

The “thunderstorm season” typically extends from April through the summer and tapers off in November. A trend of overall warming could extend this season at both ends. Additionally, there could be an increase in storm intensity due to warmer daytime temperatures and higher atmospheric moisture content. This trend could lead to more disruptions of road maintenance activities and necessitate more frequent repair of damaged infrastructure decreasing productivity.

Emergency Management

Severe storms, tropical cyclones, winter storms and high winds are the weather parameters with the greatest effects on emergency management. The following sections detail how emergency management activities are impacted by these phenomena.

Severe Storms Impacts on Emergency Management

Severe storms can produce a number of adverse conditions year round. Torrential rains can induce roadway flooding. High winds and tornadoes can produce swaths of devastation toppling trees and bringing down power lines. Large hail can damage property and lightning can affect power grids and start fires. Severe

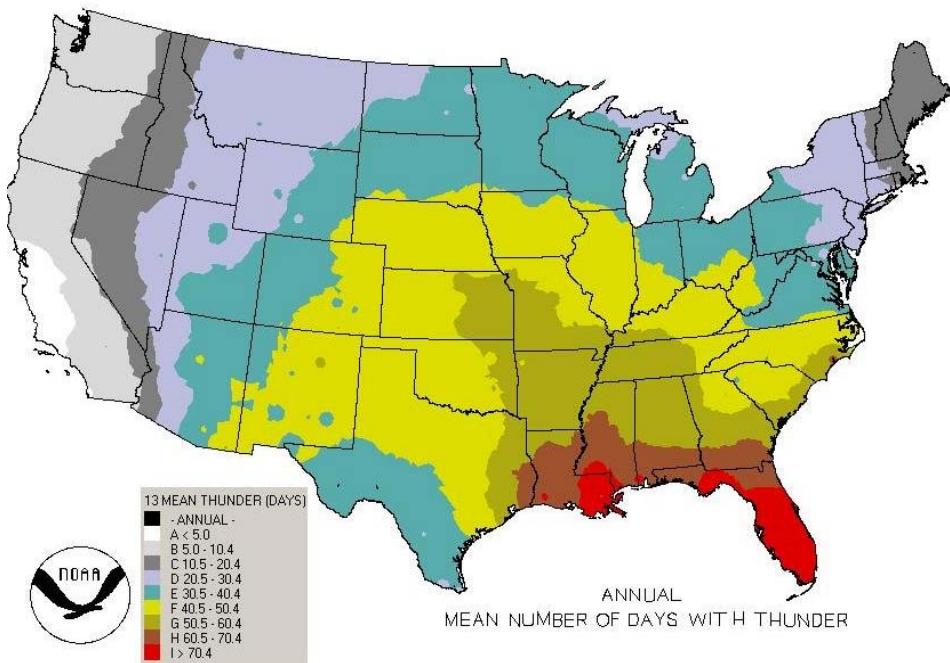


Figure 3. Annual mean number of days with thunder observed.
Source: National Climatic Data Center, 2000.

storms have the highest rank for emergency management due to their frequency of occurrence and high risks of roadway infrastructure damage.

Severe convective storms occur primarily during spring and fall seasons in the months of April and May and the months of September and October when air masses are under the greatest transition. Projected warming could extend these seasons earlier in the spring and later in the fall (e.g., March through May and September through November). The frequency and intensity of these storms may also increase due to warmer temperatures and increased atmospheric moisture. This trend could shift the focus of some emergency managers toward activities aimed at handling warm season storms and resulting flooding.

Tropical Cyclone Impacts on Emergency Management

As coastal populations grow, the likelihood that a land falling hurricane will have devastating effects increases. Hurricanes produce coastal

storm surge and high winds that can undermine or submerge roads and damage communications infrastructure. Tornadoes embedded within a hurricane can also produce areas of total devastation. While weak tropical systems can produce significant floods, major structural damage is usually limited to relatively rare, major hurricanes (i.e., Category 3 or higher).

Hurricanes can affect a large area and have significant impacts on emergency management operations, both before and after a landfall. Hurricane track, precipitation, and wind speed forecasts factor into management decisions to issue evacuation orders and manage traffic on evacuation routes. The map in Figure 4.4 shows the chance (based on climatology) that a tropical storm or hurricane will affect some portion of the eastern U.S. during the hurricane season (June through November). Based on these statistics, both Miami and Cape Hatteras are at the highest risk for being affected by a tropical cyclone, at 48 percent. South Florida is at the highest risk of being struck by a major hurricane, at four percent annually.

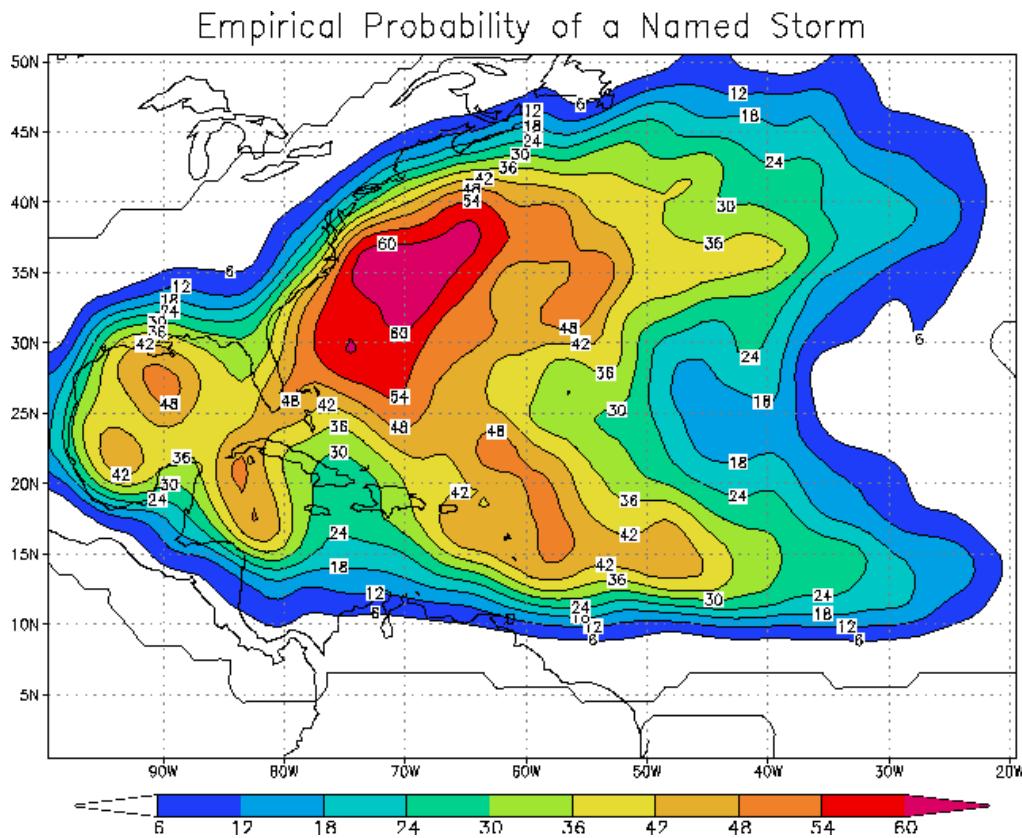


Figure 4. Probability that a named storm (tropical storm or hurricane) will affect any location during the hurricane season. Numbers on the chart represent the probability at that location. Source: Atlantic Oceanographic and Meteorological Laboratory (2002).

According to the United Nation's Intergovernmental Panel on Climate Change, "[i]ncreasing amounts of anthropogenic greenhouse gases may result in increased tropical sea surface temperatures ... which could lead to more frequent and intense hurricanes, typhoons and severe tropical cyclones." Other experts, such as Houghton et al. 1996 and Henderson-Sellers et al. 1998, have noted that sea surface temperatures are only one part of the equation necessary for the development of tropical systems and that there is little reason to believe that global warming will significantly alter the characteristics of future storms. They summarize that:

- There is little evidence to suggest that there will be major changes in *where* tropical cyclones form or occur.

- There may be little significant change to the total *number* of tropical cyclones.
- The *peak intensity* (wind speed) of tropical cyclones may increase by five to 10 percent.

Increasing population densities combined with limited new construction of evacuation routes will significantly increase demand and congestion on roadways. Consequently, with a projection of the same or slightly stronger tropical cyclones, emergency managers will need to continue to expend resources on pre-storm evacuation planning and post-storm repair or cleanup activities.

Winter Storm Impacts on Emergency Management

Large winter storms, such as the blizzard of 1993 (i.e., the “Storm of the Century”), can cause widespread disruption to surface transportation systems. During this blizzard, roadway networks were shut down for days, impeding emergency response across a large portion of the country east of the Mississippi River. Major winter storms and blizzards can produce significant snow accumulation, blowing snow, reduced visibility, and dangerously low wind chill temperatures. The effects of long-term warming may slightly shift the track of future storms poleward. However, the frequency of winter storms and nor’easters may increase as the warmer subtropical atmosphere and Gulf Stream provide energy for storm initiation and growth. The net result is that emergency managers from the Rockies east to the mid-Atlantic coast may need to expend more resources preparing to handle disruptions caused by a higher frequency of these storms.

Wind Impacts on Emergency Management

Winds can disperse hazardous atmospheric pollutants, which pose risks to public safety. Emergency managers can utilize dispersion forecasts to predict where a plume of particulates will flow, and how pollutants will be diluted in the air. These forecasts can be used to predict the potential impact of nuclear or biological chemical releases. Output from dispersion models can be used to identify and delineate evacuation areas, warn communities at risk, and provide information on the level of protection required for response personnel involved in containment or cleanup activities. A gradual warming trend would promote the development of thunderstorms that could contain strong, gusty winds during a longer period of the year. These storms could complicate the prediction of plume trajectories and consequently make evacuation decision-making more difficult.

Traffic Management

Traffic management is affected most significantly by winter weather, severe storms, tropical cyclones, and low visibility. The following sections describe how these weather parameters impact operational practices.

Snow and Ice Impacts on Traffic Management

Wintry weather of any type can produce hazardous roadway conditions and can be a major impediment to effective traffic management. Snow, freezing rain, freezing drizzle and sleet can greatly increase crash risk. Even non-precipitation events such as black ice or roadway frost can greatly reduce vehicle traction and maneuverability. Traffic managers may employ control strategies (e.g., road, bridge, and ramp closures) in an attempt to mitigate some of these conditions. However, the result of wintry precipitation on roadways yields reduced roadway capacity and increased travel time delays.

As stated in earlier sections, there may be a net increase in freezing precipitation over certain parts of the country due to projected atmospheric warming. This may impact portions of the urban corridor in the northeast. An increase in the frequency of winter storms over the nation’s mid section and east coast may also increase snowfall amounts. Traffic managers of the future would have to plan for the impacts of these possibilities.

On the other hand, a possible trend of warming may reduce the frequency of occurrence of wintry conditions from the Carolinas west across the Tennessee Valley and into the southern plains. In these localities, traffic managers would have to deal with a population that is not accustomed to driving in snow and ice. Traffic managers in these situations may need to restrict roadway access more often to minimize crash frequency.

Severe Storm Impacts on Traffic Management

Rain of any intensity can reduce pavement friction, decrease roadway capacity, and increase crash risk. On roads that have not had recent precipitation, light rain can mix with pavement contaminants (e.g., motor oil) decreasing pavement friction further. Vehicles entering areas of heavy rain can hydroplane or encounter slow or stopped traffic. Heavy rain can produce very low visibility, lane submersion, flooded underpasses, and damage to roadbeds. Hail and gusty winds, which can blow trees and power lines down, may also render roads impassable. Lightning can cause disruptions to power, communications, and control systems (e.g., traffic signal system, ramp gates).

An estimate of warming and the contrast in temperatures between warmer ocean waters and relatively cool land temperatures could lead to the formation of more thunderstorms that reach severe intensity, and extend the thunderstorm season. In order to prevent frequent congestion and delays, managers may need to utilize weather-related traffic signal timing and disseminate road weather information more frequently.

Tropical Cyclone Impacts on Traffic Management

Tropical cyclones can be a major challenge for traffic managers, who must coordinate with emergency managers to control cross-jurisdictional evacuation traffic before a hurricane and coordinate with maintenance managers to identify damaged infrastructure and detour traffic in the aftermath. To increase roadway capacity and traffic flow away from vulnerable areas, contraflow operations may be used on major freeway routes to guide vehicles out of designated evacuation areas quickly and efficiently, and the timing of traffic signals along major arterial corridors may be changed. After the storm, lanes may be submerged under water or obstructed by debris and there may be damage to roads, bridges, and other infrastructure. Traffic managers must also provide advisories and detour information to threatened populations. Projected warming could lead to the formation of the same or

slightly more intense tropical cyclones in the future.

Low Visibility Impacts on Traffic Management

In low visibility conditions traffic managers disseminate advisories and regulations (e.g., “fog ahead reduce speed”) to travelers to promote more uniform traffic flow, reduce traffic speeds, and reduce crash risk. In extremely low visibility, traffic managers may close roads and bridges or coordinate with emergency managers to guide traffic through foggy areas.

Road Users or Travelers

Travel decisions of road users are impacted primarily by wintry precipitation, low visibility, severe storms, and high winds. The effects of these weather parameters are discussed below.

Snow and Ice Impacts on Road Users

The occurrence of wintry precipitation can cause reduced road friction, loss of vehicle maneuverability, travel delays, and increased crash risk on roadways. In the presence of snow or ice, road users make travel decisions such as selecting vehicle type, installing special vehicle equipment (e.g., tire chains), and increasing following distance.

Future warming may reduce the amount and frequency of snow across central portions of the country and decrease the occurrence of ice frequency across portions of the Deep South. In addition, warmer atmospheric temperatures may cause mountain snows to occur at higher elevations. In some areas, the risk of snowstorms and nor'easters could increase due to greater temperature differences between the land and ocean. Portions of the interior mid-Atlantic region into New England may see more icing with an increase in coastal storms.

Road temperature also becomes important to commercial vehicle operators if their trucks exceed weight limitations imposed due to freeze/thaw cycles beneath roadbeds. This is most common for tractor-trailers that traverse

the northern tier of the nation or travel in Alaska. In these regions, long periods of subsurface freezing or permafrost allow heavy vehicles to travel without damaging the underlying surface. However, during subsurface thawing road access to over-weight trucks may be restricted. A projection of warming could increase the number of freeze/thaw cycles across the northern tier and in Alaska for periods of the winter.

Low Visibility Impacts on Road Users

Reductions in visibility distance can produce variations in travel speed, which greatly increase the risk of chain-reaction crashes. Without information about the safe travel speed, each driver makes his or her own judgment, contributing to significant speed differences.

An estimate of future warming would probably not have much effect on fog formation in areas that typically experience reduced visibility. There may be a reduction in fog along the Atlantic and Gulf coasts due to the warmer water temperatures. However, the increased moisture content of the atmosphere may contribute to visibility restrictions elsewhere. Also, there is a possibility that warming could increase the frequency and intensity of heavy precipitation or wind blown dust, which could also impact visibility distance.

Severe Storm Impacts on Road Users

One of the greatest threats to public safety is driving a vehicle through moving water of unknown depth. Each year, many fatalities are attributed to floods from heavy rain, which can occur from localized storms to major cyclones. Prolonged heavy rain can produce flooding in underpasses and inundate entire road sections. Heavy rain in mountainous terrain may cause a sudden rise of water in small streams and creeks (known as flash flooding) that can overflow onto roads. The possibility of landslides, which can obstruct roadways, also increases during these torrents. Potential warming could increase the frequency of heavy rain as warm moist air surges north from the Gulf of Mexico and Atlantic Ocean.

Wind Impacts on Road Users

Strong winds can play a major role in vehicle operation. The buffeting of vehicles may decrease their stability and control, particularly in high-profile vehicles. In addition, high winds blowing across exposed roadways, elevated expressways or bridges may prevent these vehicles from crossing. Strong winds can blow snow or dust reducing visibility, and reduce fuel economy if blowing opposite the direction of travel. Finally, motorists have to avoid lane obstructions due to wind-blown debris. Estimated warming probably would not have a significant effect on wind patterns. Those areas that typically experience high-sustained winds (such as in the lee of the Rockies or across the central plains) would likely continue to experience them.

Conclusion

There is much speculation about how climate change will affect the weather over the nation. This paper used one scenario from the Environmental Protection Agency as a base to project how possible climate changes could impact surface transportation across the United States during the next century.

With a trend toward warming global temperatures, transportation managers may have to develop and implement mitigation strategies to deal with weather hazards. The following list summarizes some of the highlights of potential climate change:

- A gradually warming atmosphere may increase the frequency of ice (i.e., freezing rain and sleet) over portions of the Midwest and Northeast as precipitation, heated by warmer ocean temperatures, falls through cold air masses at the surface. This change may have significant effects on mitigation strategies used by maintenance managers, traffic managers, and road users.

- This same warming atmosphere may produce less snow over portions of the Southeast, the Tennessee Valley and the lower plains. However, the greater difference between land and water temperatures may lead to more winter cyclones that could bring periods of heavy snow, particularly to central and eastern portions of the nation. These changing snow patterns may produce problems in the south as transportation managers and motorists may be less familiar with safe and efficient operations under these conditions. Maintenance and traffic managers across northern climes may have to deal with a higher frequency of winter storms or nor'easters.
- Warming temperatures may change freeze/thaw cycles beneath roadways. This may induce infrastructure damage such as heaving or buckling. In areas where permafrost has been the norm, there may be periods where a thaw may necessitate access restrictions for truck traffic.
- The warming atmosphere may lead to a longer and more intense thunderstorm season. Transportation managers and road users will have to cope with the plethora of conditions that can occur with severe storms such as flooding rains, gusty winds, lightning and hail.
- Tropical cyclones may become slightly more intense with projections that the seasonal storm frequency may stay the same. With coastal populations increasing at a very fast rate, and limited new construction of evacuation routes, traffic and emergency managers will have to plan for better control strategies to manage evacuation traffic.

Today, the impacts of adverse weather on the roadway system are well recognized, and transportation agencies have successfully implemented advanced systems and strategies to

respond to them. As the climate changes, there will be a need to continue this trend, modifying their operations to include the appropriate level of advisory, control and treatment strategies to limit the weather impacts on roadway safety and operations.

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Potential Impacts of Climate Change on Freight Transport

By Harry Caldwell, Kate H. Quinn, Jacob Meunier, John Suhrbier, and Lance Grenzeback

Introduction

This paper presents the results of a preliminary scan of potential impacts that global climate change may have on the movement of freight, examining implications for the physical facilities and infrastructure and also the patterns or demand for the shipment of freight. Climate change scenarios used by the National Assessment Synthesis Team in preparing its *Climate Change Impacts on the United States* report suggest that during the course of the 21st century the temperature on Earth is likely to warm in the range of three to 10 degrees Fahrenheit. As a result, evaporation will increase, ice melt and precipitation will intensify, sea levels will rise, and weather patterns are expected to become more variable.

In the United States, as in other countries, these kinds of effects resulting from climate change could have important impacts on the movement of freight by all modes: road, rail, air, and water. While some of the effects of global warming on freight transport are likely to be positive, such as fewer delays and crashes attributable to snow and ice in wintertime, others are likely to be negative, such as more frequent flood and storm damage to long-established port facilities. Mitigation can be accomplished by far-sighted planning and steady, long-term investments.

After a brief overview of the current state of the nation's freight transport system, this paper summarizes likely impacts on freight transport

that could result from climate change-related environmental changes that are projected to occur over the next 100 years.

Freight Movement in the United States

The United States freight transport system comprises a vast network of roads, airports, railroads, waterways, terminals, ports, and pipelines. This network includes 161,000 miles on the National Highway System, 46,000 miles of Interstate Highways, 3.8 million miles of other roads, 800 major airports, 170,000 miles of freight railroads, 26,000 miles of navigable waterways, 10,000 commercial waterway terminals, and 1.4 million miles of oil and gas pipelines. Many of these facilities, especially intermodal ports, are sited in low-lying coastal areas, reflecting the historical importance of water access to the movement of freight. In the future, however, their location may prove as much a liability as an asset, since many global climate change models forecast an increase in flood frequencies and elevations.

To describe the movement of goods over the transportation network, several sources and types of freight data are available. One such source is the TRANSEARCH® database, which includes all domestic moves by truck, rail, air, and water, and is linked to a set of commodity-specific forecasts. Based on this source:¹

- The nation's freight system moved 14 billion tons of domestic freight valued at \$11 trillion over 4.5 trillion ton-miles in the

year 2000. Figure 1 shows the share of tons, ton-miles, and revenue dollars for each mode.

- Trucks moved 78 percent of the nation's domestic freight tonnage, generated 60 percent of its ton-mileage, and accounted for 88 percent of its dollar value, the highest percentage in each category. Trucks moved 11 billion tons valued at \$9.5 trillion over 2.6 trillion ton-miles in 2000.
- Rail moved 16 percent of total domestic freight tonnage, second to truck. Rail moves tended to be longer in distance than truck moves and therefore accounted for a proportionately higher share (28 percent) of ton-miles. Rail moves also tended to involve lower-value commodities than truck, so rail represented a proportionately lower share (six percent) of total domestic freight

value. Rail moved two billion tons valued at \$600 billion over 1.2 trillion ton-miles in 2000.

- Air represented a negligible share of tonnage and ton-miles, but a disproportionately high share of value, five percent. Airfreight tends to be very light and valuable.
- Water (e.g., river barges and coastal and lake steamers) moved six percent of tonnage, 15 percent of ton-miles, and one percent of value. These figures cover only domestic waterborne tonnage. Like rail, water moves tended to be longer in distance and lower in value than truck moves. Domestic shipping moved one billion tons valued at \$138 billion over 540 billion ton-miles in 1998.

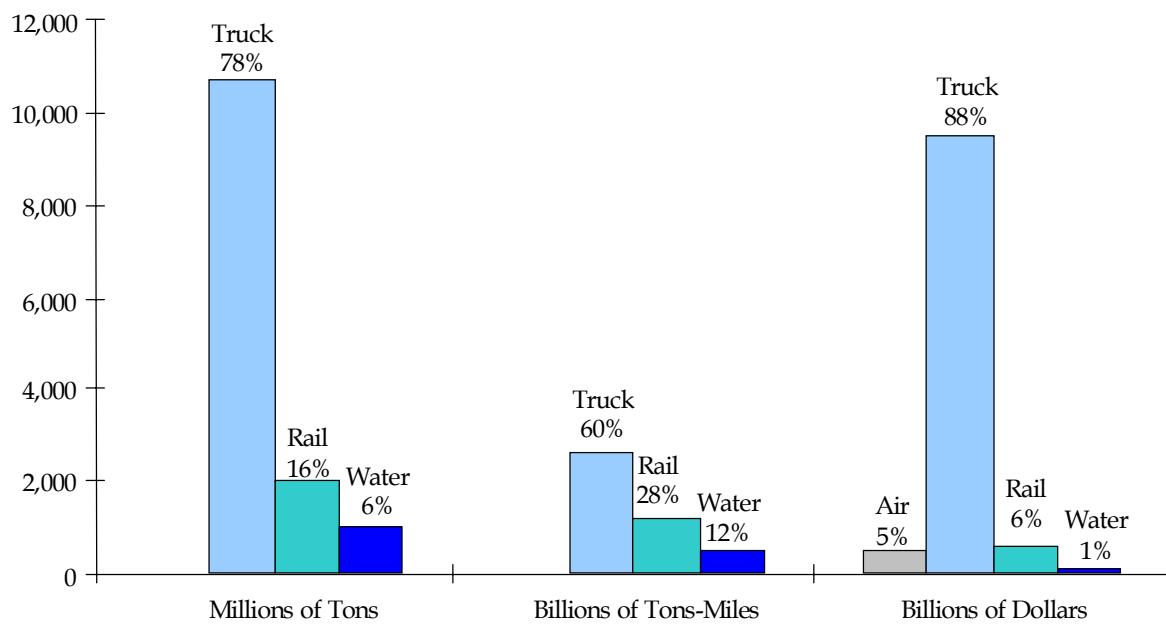


Figure 1. U.S. domestic freight movement, year 2000. Source: Reebie Associates' TRANSEARCH and U.S. DOT Freight Analysis Framework Project, unpublished data.

A useful source for data pertaining to international waterborne commerce is the U.S. Army Corps of Engineers (USACE) Navigation Data Center which compiles statistics on freight moved on United States waters. According to the USACE, in 1999 foreign waterborne commerce (imports and exports) totaled 1.3 billion tons valued at \$631 billion. While comparable statistics for foreign airborne cargo shipments are not readily available, the Bureau of Transportation Statistics Reports that 13 of the top 50 foreign trade freight gateways by value of shipments were airports, with a combined value of \$426 billion.

Each of the four freight modes offers certain advantages and disadvantages in terms of cost, speed, reliability, visibility, and security, with shippers buying freight services that best fit their specific shipping needs. Figure 2 shows the spectrum of freight transport services with the

approximate cost per pound and key service characteristics. For example, package and express shippers favor air and truck because these modes offer the fastest and most reliable door-to-door service for lightweight shipments. The cost is high, but customers are willing to pay for the high quality of the service. In contrast, shippers of bulk commodities like coal, grain, and petroleum prefer to use water or rail. These modes offer less speed and reliability, but provide transportation at a far lower unit cost, which makes these commodities affordable across the nation. Figure 3 compares average trip length by mode. Average trips are longest for air at 1,070 miles, followed by rail (617 miles), water (511 miles), and truck (247 miles). Figure 4 compares average value of cargo by mode, showing the very high value of air cargo compared to freight shipped by other modes. Cargo shipped by air is valued at almost \$61,000 per ton, compared to \$890 per ton for truck, \$304 per ton for rail, and \$131 per ton for water.

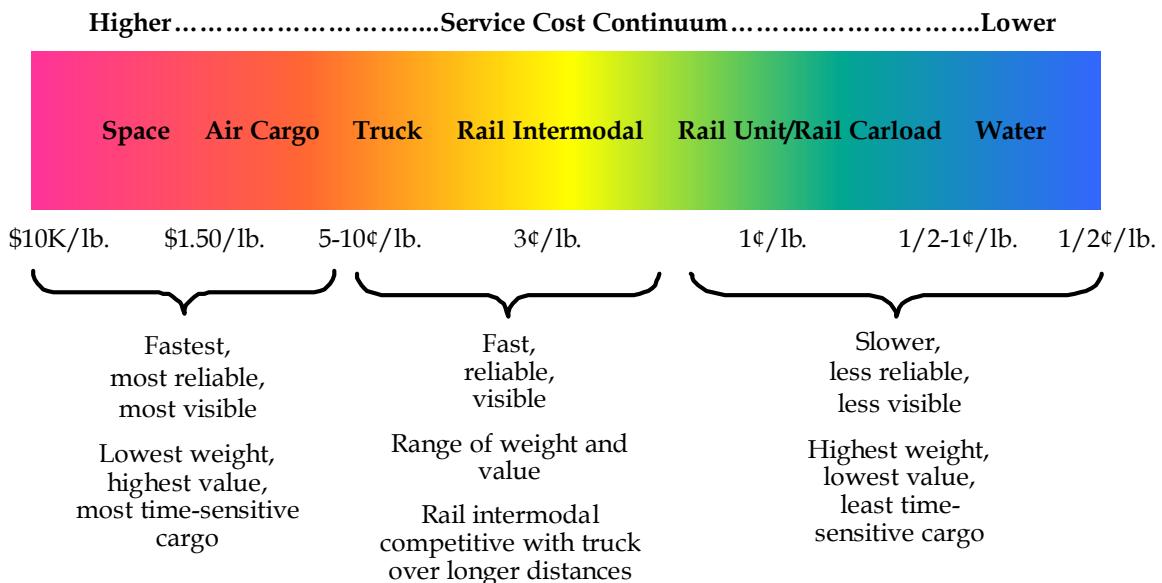


Figure 2. Freight transportation “service spectrum.”

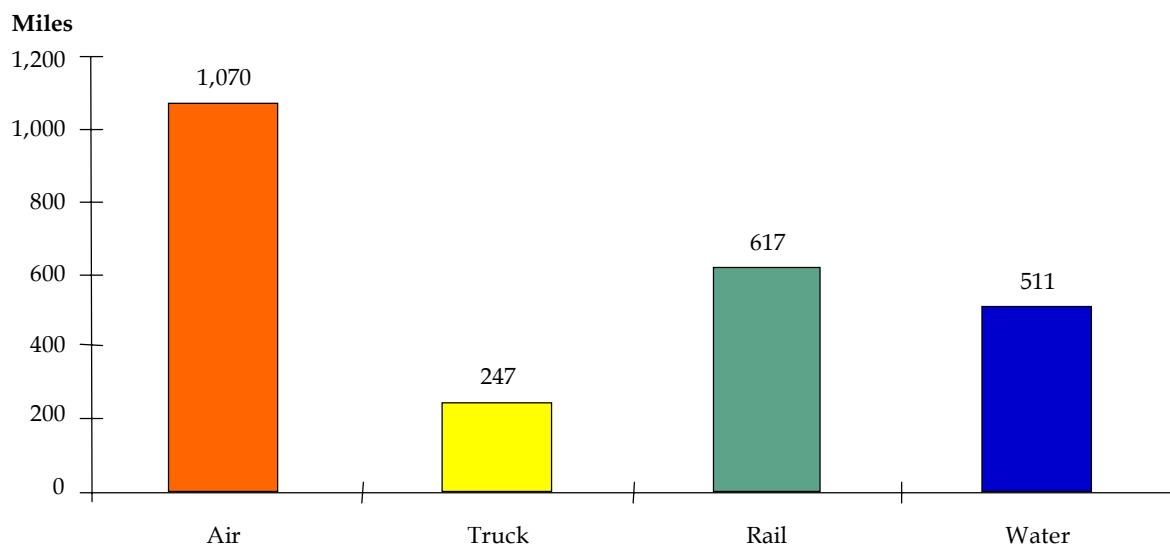


Figure 3. Average length of trip by mode in miles, year 2000. Source: Reebie Associates' TRANSEARCH and U.S. DOT Freight Analysis Framework Project, unpublished data.

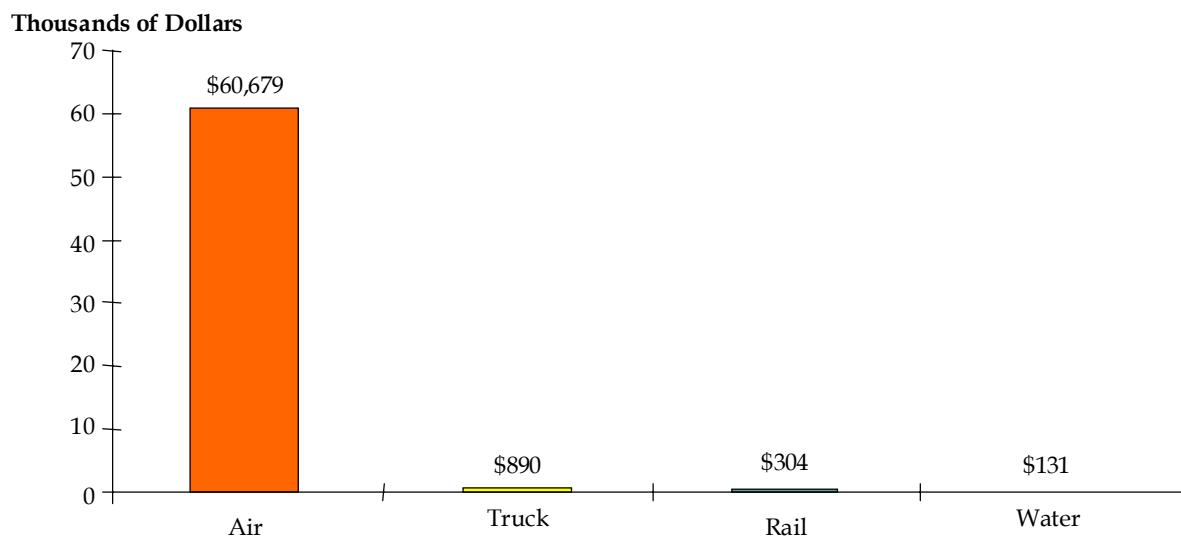


Figure 4. Average value per ton of cargo, year 2000. Source: Reebie Associates' TRANSEARCH and U.S. DOT Freight Analysis Framework Project, unpublished data.

In examining the potential impacts of climate change on freight transport, it also is useful to examine the growth in freight movements over time. Freight always has been an important underlying driver of the economy. This continues to be the case today, especially with the increasing globalization of national economies.

Demand for freight transport in the United States has grown rapidly in recent years. Over the past four decades, domestic freight movements by air, rail, road, and water have increased nearly two and a half times, reaching a record 3.8 billion ton-miles in 1999 (Figure 5). Over the same period, the combined (real) dollar value of inbound and outbound freight flows crossing United States land and sea borders has increased tenfold (Figure 6). If one takes a truly

long-term perspective on imports and exports, the increases become even more impressive. Between 1860 and 2000, the real dollar value of inbound and outbound commodities – excluding those moving by air – increased 136 times (Figure 7).

This growth is projected to continue into the future. Based on the U.S. DOT's Freight Analysis Framework, the value of cargo handled by the United States transportation system is projected to reach \$30 trillion per year by 2020. Air and truck modes will experience the fastest increases. Domestic air cargo tonnage is projected to nearly triple. Trucks are expected to move over 75 percent more tons in 2020, and to capture a somewhat larger share of total tonnage. International trade is estimated to grow faster than domestic trade, presenting particular challenges to United States ports and border gateways.

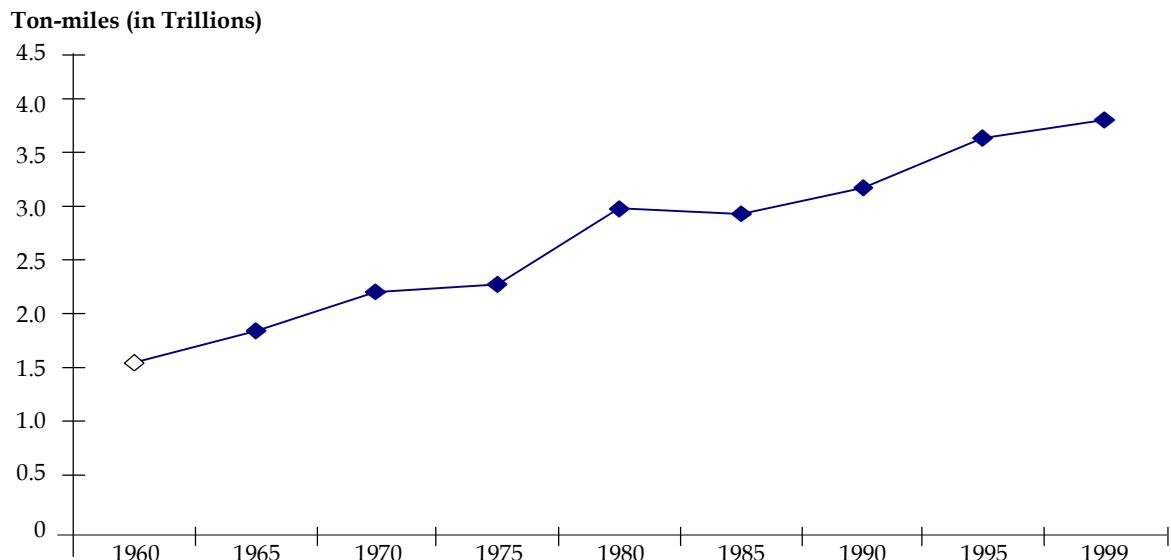


Figure 5. Domestic freight movement, 1960-1995. Source: Bureau of Transportation Statistics, National Transportation Statistics 2001 (Washington, D.C.: U.S. Department of Transportation, 2002).

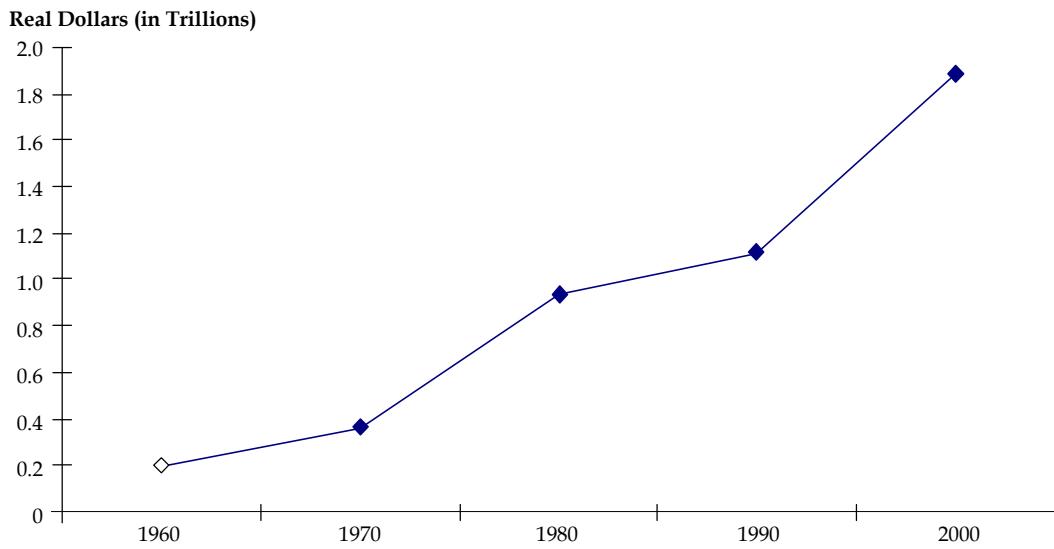


Figure 6. Merchandise imports and exports (combined), 1960-2000. Source: U.S. Bureau of the Census, selected Statistical Abstracts of the United States, 1971-2001.

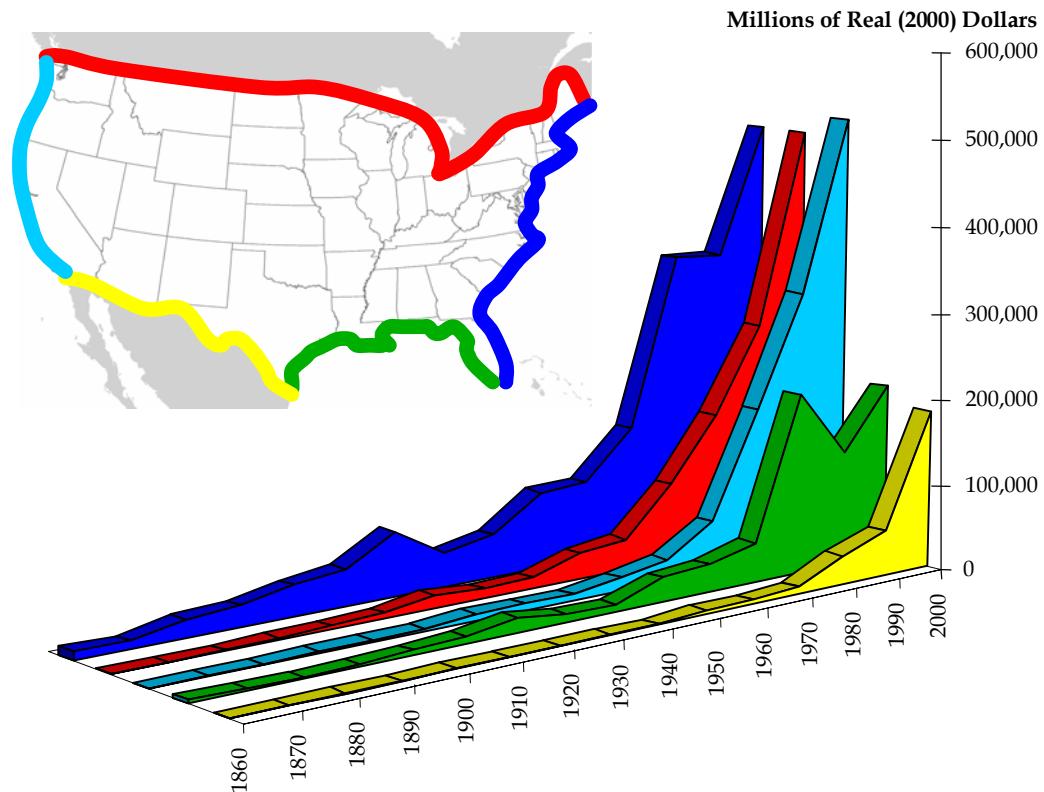


Figure 7. Growth in value of imports and exports from 1860 to 2000 by U.S. coast and border regions. U.S. Bureau of the Census, Historical Statistics of the United States, Colonial Times to 1970, Series U 264-2 U.S. Bureau of the Census, Statistical Abstracts of the United States, 1971 – 2001.

A Changing Climate

Developing an understanding of the impacts of climate change on freight transport first requires an understanding of how different regions within the country may be affected by long-term changes in climate. While estimates vary, a general consensus has emerged within the scientific community that temperatures worldwide could rise by three to 10 degrees Fahrenheit by the year 2100. This would constitute a rapid acceleration of the warming trend that began in the twentieth century. Indeed, a nine degree increase over the next 100 years would be roughly equal to the increase since the peak of the last ice age 18,000 years ago.

Generally speaking, regions that now experience the coldest temperatures, such as Alaska, will see the greatest warming. Higher temperatures will cause evaporation rates to increase as well, which is likely to reduce soil moisture during the warm season in many parts of North America.

Continuing a trend already observed in the late twentieth century, weather patterns are projected to become *more variable* as a result of global warming. In some areas, overall precipitation is projected to increase, although not enough to offset the increase in evaporation. Across the United States, precipitation is likely to occur in heavy, extreme events (downpours and snowstorms). Winter snowfall and periods of extreme cold are very likely to decrease, while the frequency of very wet and very dry conditions is likely to increase.

Sea levels, which are already rising at a rate of one foot per century along the mid-Atlantic and Gulf coasts due to polar ice melt and thermal expansion, are very likely to rise one to three feet by 2100. However, most models project that the water level of the Great Lakes is likely to *fall* three to six feet due to increased summertime evaporation. This would constitute a net loss of about 15 percent of the Great Lakes' water supply.

Floods and forest fires are likely to become more frequent and severe. Crop and forest productivity (especially hardwood) will probably increase in some areas, but the increases may not persist through the century if temperatures rise too high or too quickly. Changes in the distribution of plant species are also likely, affecting crop and forest diversity and productivity.

Impacts on Transport

The impacts of global warming on freight transport are likely to result in changes in the origins from which freight is shipped and also affect the design, safety, operations, and maintenance of the physical infrastructure used to move freight, with water and temperature the main agents of change.

Physical Infrastructure – Water-Related Impacts

A greater number of extreme weather events – hurricanes, snow storms, ice storms, floods, etc. – will increase damage to infrastructure used for the movement of freight. Each year, state and local transportation agencies spend an estimated five billion dollars repairing roads, bridges, and other infrastructure damaged by snow and ice.

The most serious and costly water-related impacts of climate change are likely to be coastal flooding that would result from increased flood frequencies and flood elevations. The risk of damage to low-lying port facilities, locks, airports, roads, rail lines, tunnels, pipelines, ventilation shafts, and power lines is particularly great because of the large number of freight facilities – international gateways in particular – that are concentrated on the Atlantic, Pacific, and Gulf Coasts and along inland waterways (Figure 8).

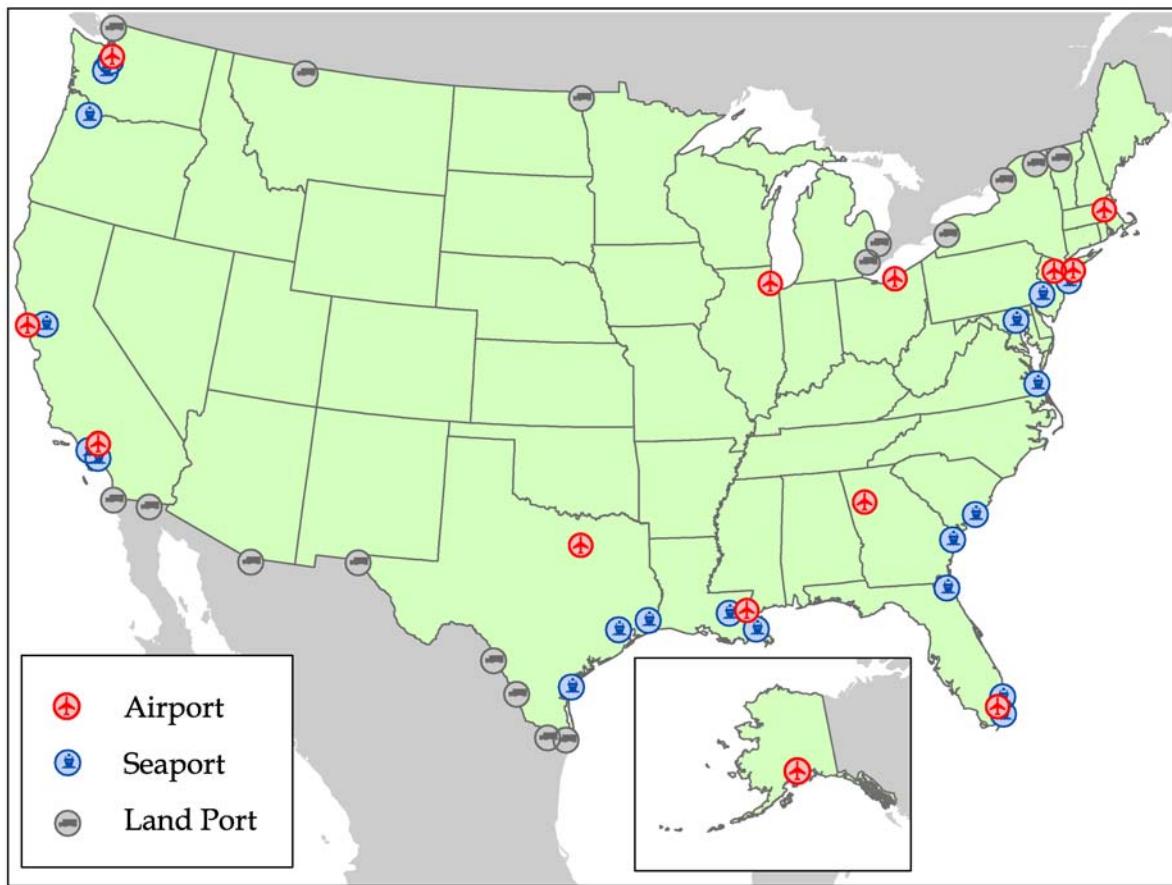


Figure 8. Map of top United States foreign trade freight gateways by value of shipments (Year 1998). Source: Bureau of Transportation Statistics, National Transportation Statistics 2000 (Washington, D.C.: U.S. Department of Transportation, 2001), 66-67.

The transport infrastructure of low-lying port cities, such as New York, Boston, Charleston, Miami, New Orleans, Texas City, San Jose, and Long Beach, could be particularly at risk. For example, New York's La Guardia Airport, which is less than seven feet above sea level, already maintains a dike and pumps for floodwaters. Newark International and John F. Kennedy International Airports are about 10 feet above sea level. In 2000, JFK was the country's largest foreign trade gateway measured by value. Building higher retaining walls around flood-prone airports is generally not a viable option, as these would interfere with aircraft takeoff and landing.

At least four New York tunnels – the Lincoln, the Holland, the Queens Midtown, and the Brooklyn Battery (the longest continuous underwater vehicular tunnel in North America) – are also potentially subject to flooding, depending on the extent of sea level rise and storm surges. Several key freight rail facilities in New York City are also vulnerable to the effects of rising sea levels and storm surges, including the Greenville Yard, the Harlem River Yard, the Oak Island Yard, and the Express Rail Terminal. In all, New York City has nearly 600 miles of waterfront, nearly all of which could face flood and storm damage.

Transportation facilities on the Gulf Coast are already prone to storm surges and flooding. On an annual basis, Louisiana, Florida, and Texas are the top three states in the nation in terms of the damage they suffer due to hurricanes and floods. Given the large number of facilities on the Gulf Coast dedicated to oil and gas production, distribution, and processing, the impact of climate change on United States energy supply could be dramatic. Two-thirds of the nation's imported oil shipments enter through facilities in Texas and Louisiana. These

same two states produce one-quarter of the nation's domestic oil and gas supplies from 4,000 offshore production platforms.

Inland freight facilities are also at risk (Figure 9). River flooding, rainstorms, and snowstorms are likely to affect key roadways, rail lines, and intermodal terminals. Chicago, the nation's largest rail hub, is projected to suffer more frequent extreme weather events, although the effects of these may be mitigated by milder winter weather.

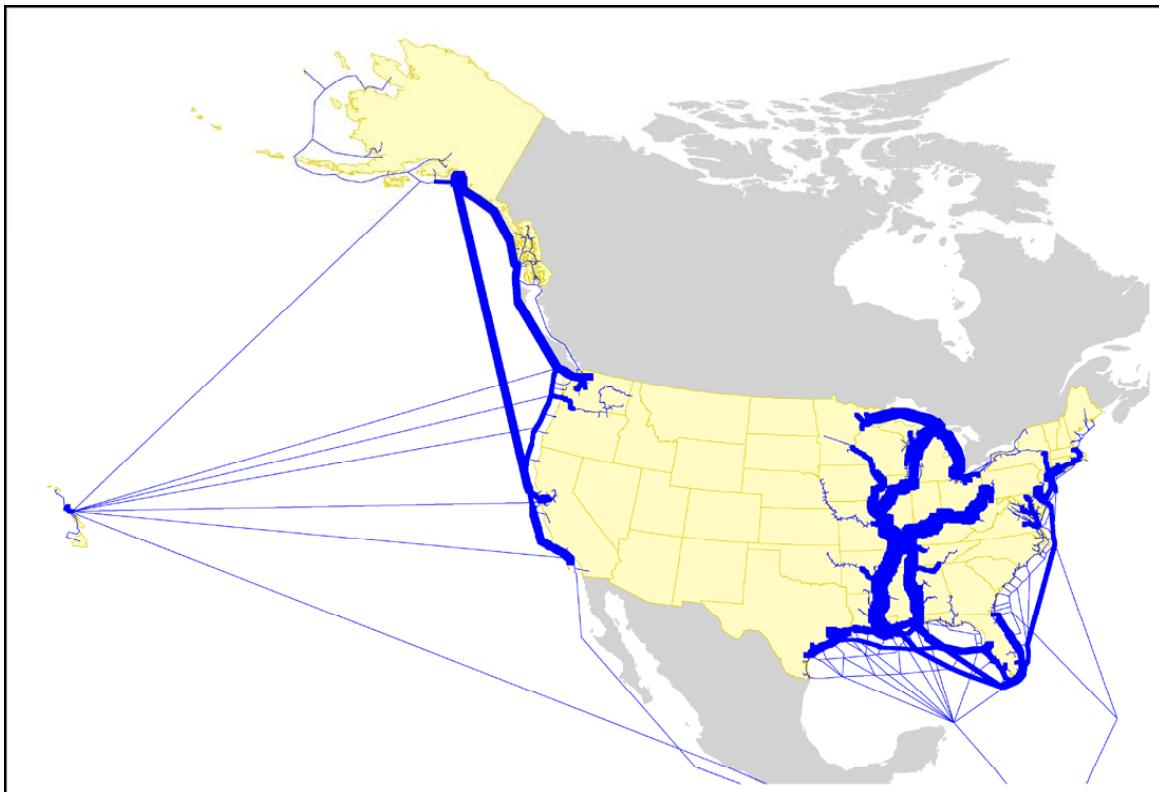


Figure 9. Map of inland and coastal water-freight flows, year 2000. Source: Reebie Associates' TRANSEARCH and U.S. DOT Freight Analysis Framework Project, unpublished data.

The impact of climate change on the Great Lakes and St. Lawrence Seaway could be particularly dramatic. On the one hand, milder winters could lengthen the ice-free shipping season by several weeks, increasing vessel utilization and reducing the costs of ice-breaking. On the other hand, falling water levels on the lakes will decrease water depths, necessitating shallower draft vessels, and therefore less tonnage capacity per trip. Per inch of lost draft, a 740-foot ocean going vessel loses 100 tons of capacity, and a 1,000-foot bulk carrier loses 270 tons of capacity. By some estimates, Great Lakes shipping costs could increase by 30 percent due to decreased water levels resulting from climate change. Past instances of low water levels on the Great Lakes hint at the seriousness of the problem. Most recently, in 2000, low water levels forced carriers into "light loading," reducing their cargo tonnage by five to eight percent.

Harbor and channel dredging, the usual means of mitigating the effects of low water levels, will not be easy in the Great Lakes; deepening channels below the 27-foot project depth will require an authorization and appropriation from Congress. It will also have serious environmental impacts, because in some areas lakebed sediment is contaminated with mercury, PCBs, and heavy metals that if disturbed will become suspended in the water. In others areas, rocky bottoms will require blasting. On the St. Lawrence Seaway, the problem of decreasing draft will be no less acute, especially if the level of the Great Lakes falls as the level of the Atlantic rises. The decreasing disparity between water levels in the Great Lakes and the ocean would cause the flow of water through the seaway to diminish, and with it its ability to "self-scour." If lake levels fall as much as some predictions suggest, a modal shift from water to rail or truck would be likely. While this might be good news for road and rail haulers, the maintenance costs on highways and rails would likely increase, given the heavier and bulkier loads traditionally carried by barge.

Rising ocean levels and declining flows could also pose problems on the Mississippi

River system, which handles a large percentage of the country's bulk commodities, such as grain and coal. The result would be more water diversions and salt intrusion, and possibly the disappearance of much of the Mississippi Delta. This would necessitate a new shipping outlet to the Gulf. Droughts and floods would also disrupt traffic on the Mississippi. In 1988, low water levels prevented the movement of 800 barges in the river for several months. In 1993 and 1997, flooding again disrupted barge traffic and prevented ships from reaching the port of New Orleans for several days.

Global climate change is likely to require reengineered freight facilities that are better able to withstand storm surges and flooding. For example, stronger, higher, corrosion- and scour-resistant bridges will be needed in areas subject to storm surges and salt water contamination. Lift-on/lift-off port facilities may replace roll-on/roll-off port facilities in harbors that experience unusually large tidal variations. Protective structures and water removal systems will be needed for road and rail tunnels subject to flooding. Global warming also could necessitate changes in the *location* where new infrastructure is built. For example, if the origin of farm and forest product shipments shifts as their optimum growing regions change, demand for new roads and rail lines would also shift.

Physical Infrastructure – Temperature-Related Impacts

The temperature-related impacts of global climate change are also likely to be significant. At northern latitudes, permafrost degradation is a major concern. In Alaska, melting permafrost is already causing entire stands of trees to list at odd angles, a phenomenon that Alaskans have dubbed "drunken trees." The softening ground is causing pavement and tarmac to buckle, disrupting some freight movements moved by road, rail, and air. Because frozen pavements are less susceptible to damage by trucks, they are legally allowed to carry 10 percent heavier loads. Warmer winters will reduce the time this exception is permitted. The impact will be felt most acutely in Alaska, which relies heavily on

the structural integrity of frozen roads and has a freight rail network less than 500 miles long.

In contrast, ocean borne freight moving at far northern latitudes may benefit from rising temperatures. Perhaps as early as 2015, the Northwest Passage may be sufficiently free of ice during the summer months to allow container ships and oil tankers to take the Arctic route rather than the Panama Canal, saving nearly 5,000 nautical miles of travel. For vessels that are too wide to fit through the Panama Canal, the lure of the Northwest Passage will prove even stronger.

At lower latitudes warmer temperatures are also likely to have important consequences for freight movement. While warmer winters could reduce the need for salting and plowing, thus increasing pavement life, impact of wider temperature swings and more frequent freeze/thaw cycles, which are likely to cause buckling and heaving of pavement, rail lines, and pipelines, will be far greater. Very warm temperatures (above 90 or 100 degrees Fahrenheit) can cause "sun kinks" in rail lines and "blowups" along cement pavement expansion joints. In the summer of 2002, for example, a passenger train derailment outside Washington, D.C. that injured 100 people was blamed on heat-stressed rails, which expanded to the point that pressure forced them out of alignment. It is common for sun kinks to suddenly appear ahead of a train, leaving engineers with no time to stop. As a precautionary measure, CSX, the owner of the track, imposed temporary speed restrictions on the line. Such restrictions could become more common if summertime temperatures frequently climb into the 90s, increasing the risk of track distortion.

Global climate change is likely to increase demand for reengineered freight facilities that are better able to withstand heat. For example, deliberately heating rails to more than 100 degrees before they are installed, a common practice in Florida, makes them less susceptible to distortion. New roadway construction techniques and materials could also be used to prevent pavement blowup.

Safety, Operations, and Maintenance

Climate change is likely to affect freight-related safety, operations, and maintenance in a number of ways. More frequent icing and extreme weather events could significantly reduce safety while increasing delays and maintenance costs. Today, approximately 16 percent of commercial vehicle crashes occur on wet or frozen pavement. Snow and ice control accounts for 39 percent of road operating costs, costing state and local agencies over \$2.3 billion annually. In 1999, fog, snow, and ice were the most frequent causes of non-recurring traffic congestion, accounting for nearly one-quarter of all delays in 1999. If precipitation in the form of ice rather than snow becomes more common, maintenance costs could rise. More frequent freeze/thaw cycles could similarly drive up the cost of operations and maintenance.

Warmer summer weather will also have important implications for safety, operations, and maintenance. First, it will make the need to refrigerate perishable goods all the more critical. Second, it will reduce engine combustion efficiency. This will place a particular burden on air carriers because aircraft will require longer runways or lighter loads. Third, on extremely hot days it will preclude certain maintenance efforts that require prolonged outdoor exposure.

If there is a general push to reduce carbon dioxide emissions, the fuel efficiency of heavy- and light-duty trucks could come under closer scrutiny. This could affect both long-distance haulers and urban delivery companies. Cargo planes and other aircraft could also be subject to tighter environmental regulation; at high altitudes, aircraft emissions have a greater impact on ozone levels than emissions on the ground.

Water operations are likely to become more expensive and less reliable. Not only will an increase in extreme weather events create more frequent disruptions in service, it will cause sediment shifts in channels, increasing requirements for dredging. Rising sea levels will reduce bridge clearances and the

effectiveness of roll-on/roll-off port facilities at high tide. "RO-RO" facilities, such as those at the ports of New York/New Jersey, Baltimore, and Jacksonville, are used primarily for loading and unloading shipments of automobiles, farm equipment, and military equipment.

Finally, the timing and demand for freight services is likely to shift as a result of global climate change. For example, coal shipments may decline as cleaner forms of energy are substituted. This would have serious consequences for the freight railroads, which carry virtually all of the coal mined in the U.S.. Coal accounts for 41 percent of tonnage moved by rail and about one-quarter of the revenues of Class I railroads. Heating oil and liquid natural gas shipments might also decline as winter heating needs lessen. In contrast, agricultural shipments are likely to rise as longer growing seasons make multiple harvests in a single year more common. Timber shipments (particularly hardwood) may also rise. The spatial pattern of agricultural production is also likely to change, causing demand for freight transportation in some regions of the United States to increase and in other regions to decline.

Conclusion

This preliminary scan suggests that the impacts of climate change on the transport of freight could be quite significant, influencing both shipping patterns and the facilities used to move this freight. Intermodal freight facilities and shipping routes located in coastal areas are particularly vulnerable. However, pavement design and maintenance requirements could change in any part of the country that is subject to an increase in the number of freezing and thaw cycles.

Rising temperatures are likely to change the mix of maintenance costs. In existing snow-belt states, precipitation may fall less frequently as snow and more frequently as sleet or freezing rain. In Sun Belt states, excessive summertime heat could have an effect on maintenance activities. Rising sea levels and an increase in extreme weather events could reduce reliability and threaten transport facilities in low-lying

areas. Indeed, all modes of freight transport – road, rail, air, and water – are vulnerable to the effects of global climate change. If industries continue to move in the direction of just-in-time production and distribution, the economic consequences of disruptions in the transportation system become more acute.

An important question is how the transportation community responds to these potential changes. Based on the results of this initial scan, more intensive and focused freight transportation research is merited to better understand both the magnitude and the distribution of climate change impacts. At the same time and while still acknowledging the uncertainty in transportation-specific impacts that currently exists, selective initial policy and design changes can be made immediately. The knowledge and technology necessary for the freight sector to adapt to climate changes already is available. Moreover, given the time frame of the projected changes, adaptation strategies can be incorporated into normal life-cycle replacement plans. New or expanded intermodal freight facilities can be located in areas that are less vulnerable to the anticipated effects of climate change. Similarly, a bridge slated for replacement but also facing the possible threat of increased ocean storm surges could be rebuilt on the same location but several feet higher and of stronger materials. Alternatively, the possibility could be investigated of building on higher ground a few hundred yards inland, thereby diverting the road away from the coast.

In summary, it is not too early to begin incorporating the effects of climate change projections into freight planning. With foresight, the nation's freight transport network can continue to provide safe, reliable service regardless of what transformations are in store.

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¹The data and forecasts reported were prepared for Cambridge Systematics, Inc., for use in the 2002 *AASHTO Freight Rail Bottom-Line Report*, by Reebie Associates using Reebie's TRANSEARCH® database and the DRI/WEFA/Global Insights economic forecasts.

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Weather and Aviation: How Does Weather Affect the Safety and Operations of Airports and Aviation, and How Does FAA Work to Manage Weather-related Effects?

By Gloria Kulesa

Weather Impacts On Aviation

Introduction

According to FAA statistics, weather is the cause of approximately 70 percent of the delays in the National Airspace System (NAS). Figure 1 illustrates that while weather delays declined with overall NAS delays after September 11th, 2001, delays have since returned to near-record levels.

In addition, weather continues to play a significant role in a number of aviation accidents and incidents. While National Transportation Safety Board (NTSB) reports most commonly find human error to be the direct accident cause, weather is a primary contributing factor in 23 percent of all aviation accidents. The total weather impact is an estimated national cost of \$3 billion for accident damage and injuries, delays, and unexpected operating costs.

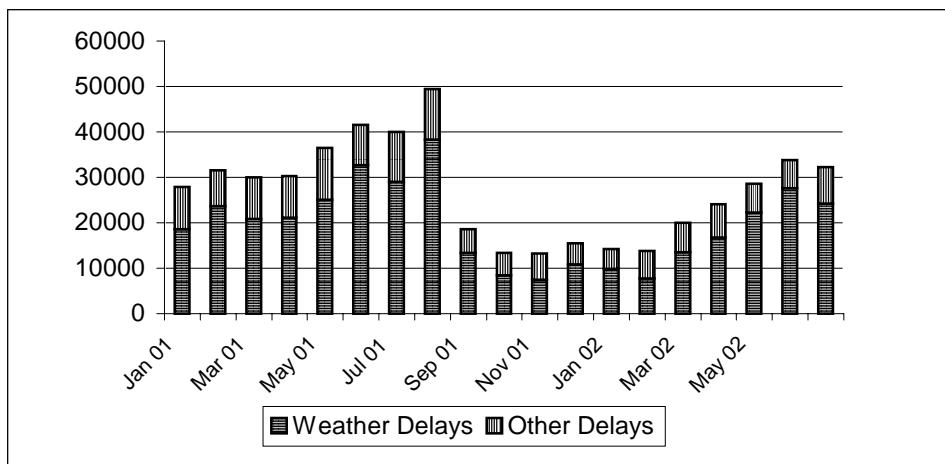


Figure 1. Delay hours in the National Airspace System for January 2001 to July 2002. Delay hours peaked at 50,000 hours per month in August 2001, declined to less than 15,000 per month for the months following September 11, but exceeded 30,000 per month in the summer of 2002. Weather delays comprise the majority of delays in all seasons.

Thunderstorms and Other Convective Weather. Hazards associated with convective weather include thunderstorms with severe turbulence, intense up- and downdrafts, lightning, hail, heavy precipitation, icing, wind shear, microbursts, strong low-level winds, and tornadoes. According to National Aviation Safety Data Analysis Center (NASDAC) analysis, between 1989 and early 1997, thunderstorms were listed as a contributing factor in 2-4 percent of weather-related accidents, depending on the category of aircraft involved. Precipitation was listed as a factor in 6 percent of commercial air carrier accidents, roughly 10 percent of general aviation accidents, and nearly 19 percent of commuter/air taxi accidents. American Airlines has estimated that 55 percent of turbulence incidents are caused by convective weather.

In addition to safety, convective weather poses a problem for the efficient operation of the NAS. Thunderstorms and related phenomena can close airports, degrade airport capacities for acceptance and departure, and hinder or stop ground operations. Convective hazards en route lead to rerouting and diversions that result in excess operating costs and lost passenger time. Lightning and hail damage can remove aircraft from operations and result in both lost revenues and excess maintenance costs. In Figure 1, the vast majority of the warm season delays are due to convective weather.

In-Flight Icing. In the period 1989-early 1997, the NTSB indicated that in-flight icing was a contributing or causal factor in approximately 11 percent of all weather-related accidents among general aviation aircraft. Icing was cited in roughly 6 percent of all weather-related accidents among air taxi/commuter and agricultural aircraft. The percentage was 3 percent for commercial air carrier accidents. The 1994 crash of an ATR-72 near Roselawn, Indiana, which claimed 68 lives, took place during icing conditions.

In-flight icing is not only dangerous, but also has a major impact on the efficiency of flight operations. Rerouting and delays of commercial carriers, especially regional carriers and commuter airlines, to avoid icing conditions lead to late arrivals and result in a ripple effect throughout the NAS. Diversions en route cause additional fuel and other costs for all classes of aircraft.

Icing poses a danger to aircraft in several ways:

- Structural icing on wings and control surfaces increases aircraft weight, degrades lift, generates false instrument readings, and compromises control of the aircraft. See Figure 2.
- Mechanical icing in carburetors, engine air intakes, and fuel cells impairs engine performance, leading to reduction of power.

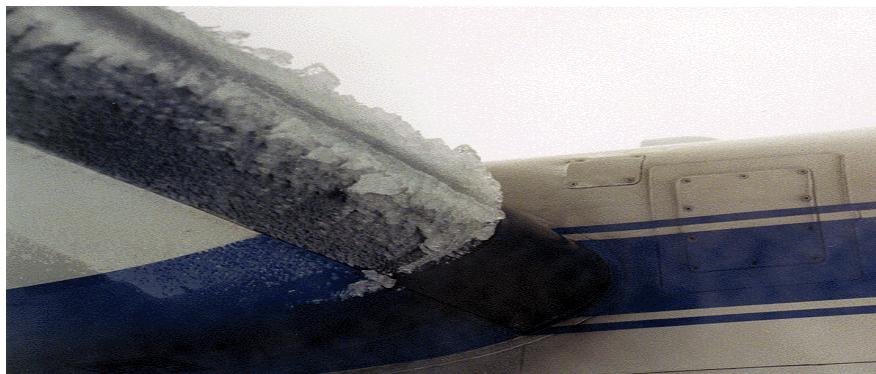


Figure 2. Photo of structural icing on an aircraft's wing.

Small aircraft routinely operate at altitudes where temperatures and clouds are most favorable for ice formation, making these aircraft vulnerable to icing for long periods of time. Larger aircraft are at risk primarily during ascent from and descent into terminal areas.

Turbulence. Non-convective turbulence is a major aviation hazard. All aircraft are vulnerable to turbulent motions. Non-convective turbulence can be present at any altitude and in a wide range of weather conditions, often occurring in relatively clear skies as clear-air turbulence. Any aircraft entering turbulent conditions is vulnerable to damage; smaller aircraft (both fixed- and rotary-wing) are susceptible at lower levels of turbulent intensity than are large aircraft. See Figure 3.

The effects of turbulence range from a jostling of the aircraft that is mildly discomforting for passengers and crews to sudden accelerations that can result in serious

injury and temporary loss of aircraft control. Recently an air carrier en route from Japan to the U.S. encountered turbulence which caused the death of a passenger.

Clear-air turbulence is not only dangerous, it also has a major impact on the efficiency of flight operations due to rerouting and delays of aircraft.

Ceiling and Visibility. Low ceiling and reduced visibility are safety hazards for all types of aviation. The NASDAC study of NTSB statistics indicated that ceiling and visibility were cited as contributing factors in 24 percent of all general aviation accidents between 1989 and early 1997. They were also cited as contributing factors in 37 percent of commuter/air taxi accidents during the same period. Low ceiling and poor visibility accidents occur when pilots who are not properly rated or are flying an aircraft not equipped with the necessary instrumentation encounter such conditions, resulting in loss of control, or controlled flight into terrain.



Figure 3. Photo of an aircraft missing an engine which had been torn off by turbulence.

The NTSB statistics also imply that air carriers have the expertise, procedures, and equipment necessary to fly safely in reduced visibility conditions. Low ceiling and poor visibility were cited as contributing factors in less than 2 percent of the commercial air carrier (Part 121) accidents between 1989 and early 1997.

In 1991, the University of Illinois used simulated weather conditions to test twenty Visual Flight Rule (VFR) rated pilots. When deprived of visual contact, each pilot experienced loss of control. On average, it took approximately 178 seconds giving each pilot less than 3 minutes to live after entering a cloud.

Low ceiling and poor visibility are not just a safety issue. They can also severely degrade the efficiency of commercial and military aviation. Reduced ceiling and/or visibility can severely reduce the capacity of an airport and lead to airborne or ground delays that result in diversions, cancellations, missed connections, and extra operational costs. See Figure 4.



Figure 4. Photo from an aircraft on approach to San Francisco International Airport. Two parallel runways can be seen. Pilots of aircraft on parallel approaches must be able to see each other.

Ground De-Icing. Aircraft on the ground during periods of freezing or frozen precipitation and other icing conditions are susceptible to the buildup of ice on control surfaces, instrument orifices, propellers, and engine inlets and interiors. Aircraft that are moving along taxiway

and runway surfaces in slush or standing water at near-freezing conditions are also susceptible to surface contamination, even after precipitation has stopped. Even a very small amount of ice on a wing surface can increase drag and reduce airplane lift by 25 percent. This type of ice accumulation has been a cause or a factor in 10 commercial aircraft takeoff accidents between 1978 and 1997. Ice blockage of airspeed or altitude measurement instrumentation can cause loss of control or navigation errors.

Ice and snow also have an impact on terminal operations. Boarding gates, taxiways, and runways may become unusable. Airport operational capacities may be sharply reduced. See Figure 5.



Figure 5. Photo of an aircraft being de-iced on the ground.

Volcanic Ash. Volcanic ash is pulverized rock. It is composed largely of materials with a melting temperature below the operating temperature of a jet engine at cruise altitude. Volcanic ash in the atmosphere is usually accompanied by gaseous solutions of sulphur dioxide and chlorine. The combination of the pulverized rock and acidic gases can significantly affect the performance of jet engines at cruise altitudes. Ash clouds are often invisible, particularly at night.

To put this problem in perspective, the ash from the Mount Pinatubo eruption in 1991 circled the globe within a matter of days and affected a multitude of air traffic routes. Consequently, aircraft that traversed this thin

layer of ash required more maintenance. Statistics show that there are 575 active volcanoes globally which normally contribute to 50 eruptions, resulting in 50-75 "danger days" per year. Volcanic ash exceeds 30,000 feet on active air routes 25-30 days per year. There have been over 100 damaging encounters to aircraft in the last 20 years costing more than \$250M in damages.

Within the United States, a particular area of concern is along the Aleutian Islands and the Alaskan Peninsula. The density of active volcanoes in this area, lying as it does adjacent to the heavily-traveled North Pacific Air Traffic Routes, makes the ash threat especially acute. The generally westerly flow of winds in the region means that ash can be transported easily into airspace over the Canadian and U.S. Pacific Northwest regions. Ash from volcanoes on the Kamchatka Peninsula of Russia also poses a threat because it tends to drift into the heavily traveled North Pacific airways, which are within U.S. Flight Information Regions.

AWRP Mitigation Initiatives

The FAA Aviation Weather Research Program (AWRP) has as a goal to relieve weather impacts on NAS safety, capacity, and efficiency. To work towards this goal, the program conducts applied research organized around ten meteorological product development teams

(PDTs). The primary laboratories performing AWRP research include: the National Center for Atmospheric Research (NCAR), Massachusetts Institute of Technology/Lincoln Laboratory, National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory and National Severe Storms Laboratory, Naval Research Laboratory, and the National Weather Service's - Aviation Weather and Environmental Modeling Centers.

Convective Weather Product Development Team

On September 27, 2001, the AWRP participated in a landmark event when one of its weather research products, the National Convective Weather Forecast (NCWF) transitioned from an "experimental" stage, to an operational National Weather Service (NWS) product, approved for use by both meteorologists and end users. The NCWF is designed specifically to minimize delays caused by convection as it provides locations of significant convection one hour in the future, with updates every 5 minutes. A goal of the Convective Weather PDT is to eventually develop forecasts of convective weather out to six hours. The team also developed a 1-hour Terminal Convective Weather Forecast (TCWF) product which is being tested at the Dallas-Ft. Worth, Memphis, Orlando, and New York airports. See Figure 6. This product provides more than an extrapolated position of storms; it

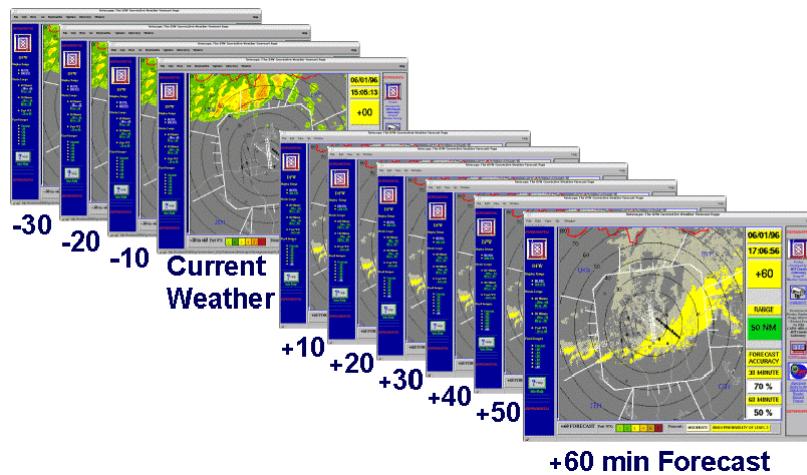


Figure 6. Succession of screenshots from the Terminal Convective Weather Forecast (TCWF), showing forecast convective weather for a local area.

also includes the effects of growth and decay. The Regional Convective Weather Forecast (RCWF) includes a 2-hour prediction, and it is being tested in the Northeast U.S.

In-Flight Icing Product Development Team

To address the in-flight icing problem, the AWRP has developed a Current Icing Potential (CIP) product (shown in Figure 7). The first generation CIP became an operational NWS product on March 27, 2002. As improvements to CIP are being made, a related product, the Forecast Icing Potential (FIP), which provides a forecast of icing conditions, is being developed. FIP is presently approved by the FAA and the NWS for experimental use. These products enable users to better anticipate where icing hazards are going to occur, and will allow air traffic controllers to make more informed decisions when assigning altitudes to aircraft.

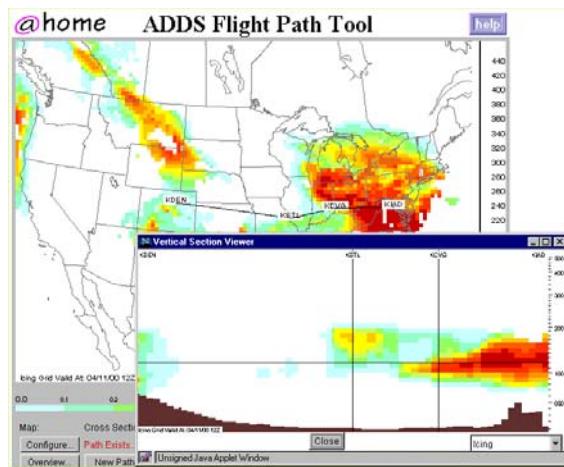


Figure 7. Screenshot of the Current Icing Potential (CIP) product, showing icing potential for a sample flightpath from Denver to Washington, DC. Hazard areas are shown both as an overlay on a map of the United States and as a vertical cross-section.

Turbulence Product Development Team

The mission of the turbulence PDT is to produce timelier and more accurate analyses and forecasts of turbulence, and develop user-friendly turbulence products. An algorithm designed to forecast turbulence models jet stream, mountain induced turbulence, and

convective induced turbulence. From this diagnostic data, and the addition of in-situ and remotely sensed data, an Integrated Turbulence Forecast Algorithm (ITFA) was produced and is now being used experimentally (see Figure 8).

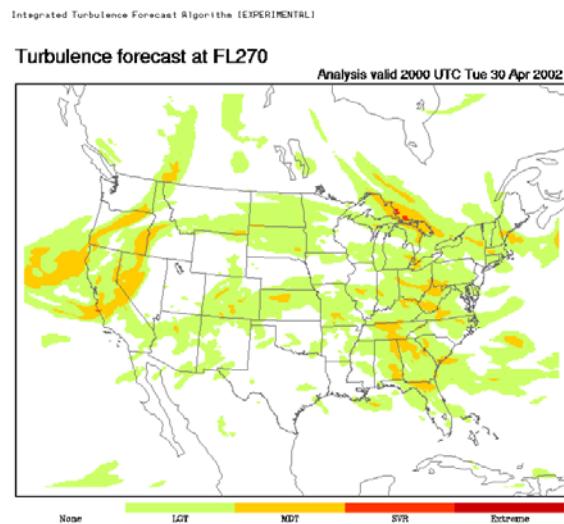


Figure 8. Screenshot of the output from the Integrated Turbulence Forecast Algorithm, showing forecast turbulence overlaid on a map of the United States.

Terminal Ceiling and Visibility Product Development Team

San Francisco International Airport is adversely affected by low clouds and poor visibility due to its location along the coast. During periods of poor weather, aircraft are assigned to holding patterns, or are prevented from taking off en route to San Francisco until the weather clears. The Terminal Ceiling and Visibility PDT is developing a 1-6 hour forecast of the time when simultaneous parallel approaches can be resumed so that the aircraft arrival rate at San Francisco matches the acceptance rate. This would allow additional aircraft to arrive at the terminal as extra capacity becomes available. An automated algorithm for predicting the time when the airport could increase its capacity is undergoing evaluation.

National Ceiling and Visibility Product Development Team

Since low ceilings and visibilities impact all airports to some degree, the AWRP began a national ceiling and visibility research program in March 2001. The primary beneficiaries of this PDT's work are expected to be operators of general aviation, who are often involved in "controlled flight into terrain" accidents. A preliminary version of such a product is shown in Figure 9.

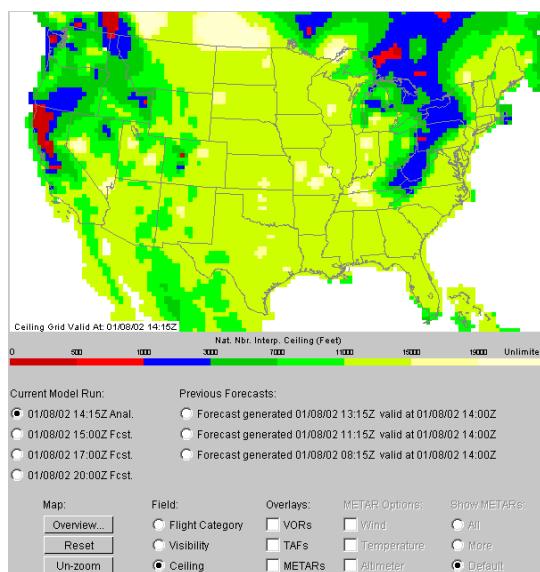


Figure 9. Screenshot of preliminary National Ceiling and Visibility product, showing current ceilings overlaid onto a map of the United States.

Winter Weather Research Product Development Team

The FAA's Winter Weather PDT began supporting ground deicing research in 1991. The research resulted in development of an integrated display system that depicts accurate, real time determinations of snowfall rate, temperature, humidity, wind speed and direction, called the "Weather Support to Deicing Decision Making" (WSDDM) system (Figure 10). The sources of weather data used by WSDDM include Doppler radars, surface weather stations, and snow gauges located near the airport, which accurately measure the amount of water in the snow. Research indicates that the icing hazard for aircraft directly corresponds to the amount of water in the snow. Additionally, WSDDM's accuracy is enhanced by using current and site specific weather information that results in a more accurate decision making tool for a particular airport. The system requires little meteorological knowledge and minimal training to operate, and enables decision makers to obtain valuable information in seconds. A new snowgauge has recently been developed which is smaller than the traditional snowgauge and requires very little maintenance. This new "hotplate" snowgauge determines the liquid water equivalent of precipitation by measuring the amount of electrical current required to maintain the top and bottom sides of a horizontal plate at the

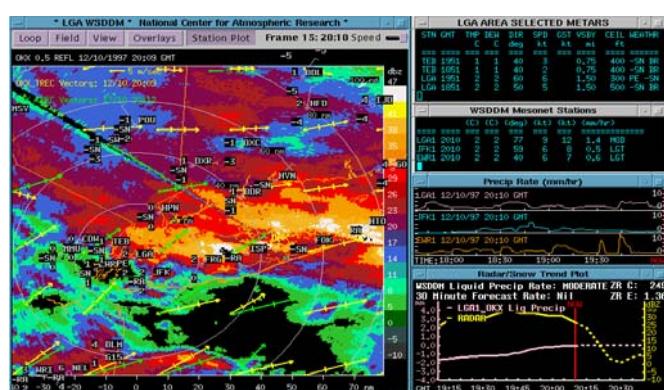


Figure 10. Screenshot of the Weather Support to De-Icing Decision Making (WSDDM) display, showing sample data for the LaGuardia airport area.

same temperature. The Winter Weather PDT is also involved in the “Northeast Corridor” project and has started to investigate the formation of winter fog by deploying numerous fog sensors at Rutgers Airport.

Oceanic Weather Product Development Team

At present, aircrews for long-range oceanic flights receive a general weather briefing before departure, including a summary of flight level winds and expected en route weather conditions. While the current weather products do provide valuable information for strategic planning, the information is already hours old by the time the aircraft depart and only the most general weather updates are provided during the flight.

The Oceanic Weather PDT was established to conduct applied research leading to the phased introduction of advanced weather products for oceanic areas including convection, turbulence, in-flight icing, high resolution winds, and volcanic ash dispersion. The observation of weather phenomena over the ocean is more difficult than over the continental United States due to the relative scarcity of weather data. Within the convective weather domain, research is being done on a diagnosis, nowcast and a forecast out to 6 hours. The first product that has recently entered the testing phase is the “Cloud Top Height” product.

The Cloud Top Height product, which is available on a cockpit printer or graphic display system, portrays areas along the aircraft’s flight path where cloud tops are expected to be between 30,000 to 40,000 feet. Another graphical designation shows clouds with tops above 40,000 feet (Figure 11).

Support Product Development Teams

The three PDTs discussed below do not address individual weather phenomena directly, but rather provide capabilities needed by the direct impact PDTs.

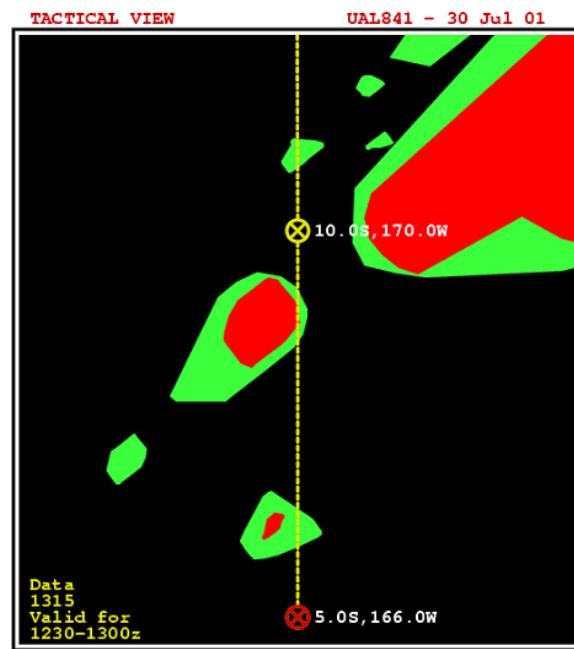


Figure 11. Screenshot from the Oceanic Weather Cloud Top Height product.

Aviation Forecasts and Quality Assessment Product Development Team. This PDT produced and maintains the Aviation Digital Data Service (ADDS). ADDS is a tool which is available on the Internet and which allows pilots, airline dispatchers, and other users easy access to weather data. An important component of ADDS, the “Flight Path Tool”, is a relatively new innovation which employs user-friendly graphics to display vertical cross-sections of turbulence, icing, thunderstorms, and other aviation weather hazards for specific flight altitudes and flight paths selected by the user. By allowing pilots and dispatchers to have easy access to forecast weather conditions, ADDS facilitates flight planning and minimizes the time required to change the route of flight when required. The convective weather, in-flight icing, and turbulence products mentioned above have been incorporated into the ADDS web site. ADDS is a winner of the Government Technology Leadership Award. See a sample ADDS screen in Figure 12.

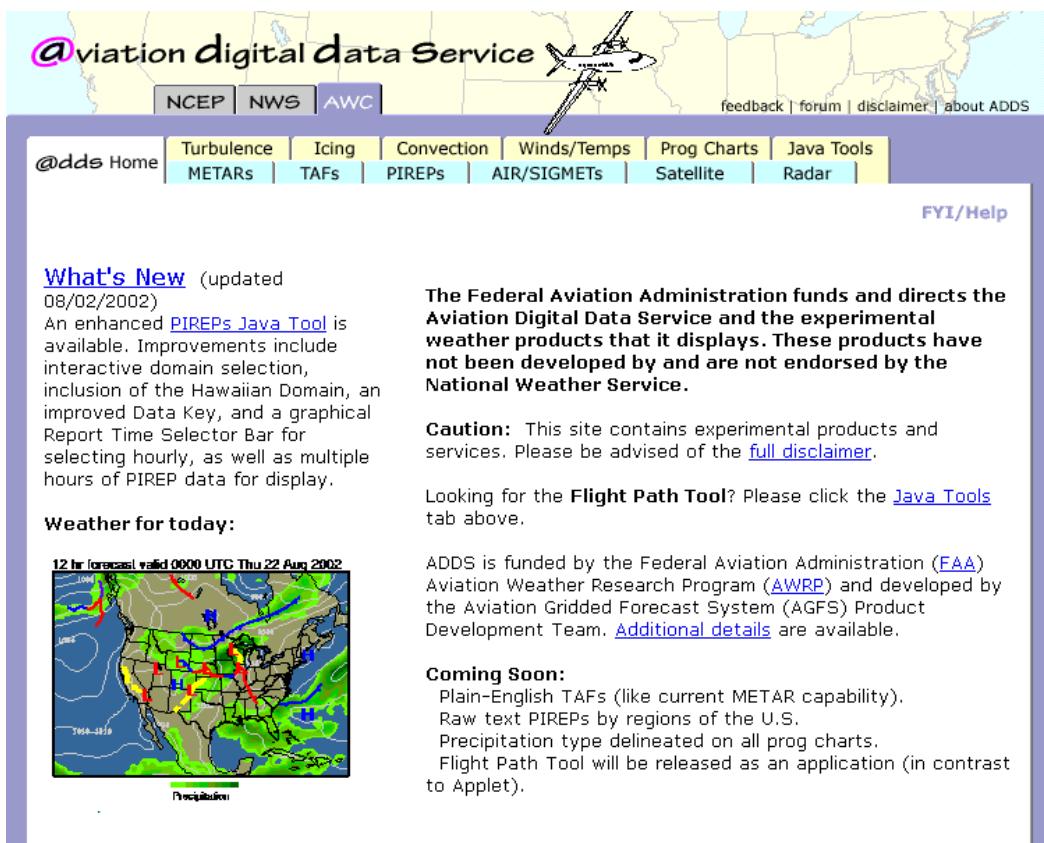


Figure 12. Screenshot of the Aviation Digital Data Service (ADDs) web page.

Model Development and Enhancement Product Development Team. The cornerstone of modern weather forecasts is numerical weather prediction. It is so critical to most of the weather PDTs that a special, separate PDT was created solely for this purpose. The Model Development and Enhancement PDT has produced a special aviation-oriented model called the Rapid Update Cycle (RUC). RUC is now an operational NWS product which runs once per hour. The latest version of RUC became operational on April 17, 2002. This PDT is also involved with the NWS Eta model and the futuristic Weather Research and Forecasting (WRF) Model now being created in the broader weather modeling community.

NEXRAD Enhancements Product Development Team. All weather prediction begins with knowing the present state of the atmosphere. Radar is a very important way of obtaining this knowledge, and the FAA has for

years participated with the NWS and the Department of Defense in developing the present national weather radar system. AWRP operates a special PDT for improving the radar needed by the FAA or by the other PDTs.

AWRP Benefits Studies

The following benefits analysis information was obtained from benefits studies that were conducted by MCR Federal Inc. The results of the studies and the dates of the reports are provided below:

Current Icing Potential (CIP) Safety Benefits Analysis Case Studies (Aug. 10, 2001): A potential safety benefit of \$30M annually is estimated for general aviation, air taxi, and commuter in-flight icing accidents.

Ceiling and Visibility (C&V) at San Francisco, Marine Stratus Forecast Benefits Estimate (July 18, 2002): A marine stratus forecast can potentially provide a benefit of \$5.45M annually in arrival and departure delay savings.

Terminal Convective Weather Forecast (TCWF) Benefits Analysis at DFW and Orlando Airports (June 2, 2000): The total benefit point estimates are \$18.4M for DFW and \$6.0M for Orlando, annually.

Terminal Convective Weather Forecast (TCWF) Benefits Analysis at New York Airports (Kennedy, LaGuardia and Newark) (Nov. 21, 2000): The total benefit point estimate is \$80M annually for the New York airports.

Terminal Convective Weather Forecast (TCWF) Benefits Analysis (national) estimated for a national system deployed at Integrated Terminal Weather System installed airports (Feb. 12, 2001): The estimated total benefit is \$524M annually.

Weather Support to Deicing Decision Making (WSDDM) Benefits Analysis Update (Oct. 2, 2000): Annual benefits of \$12.7M for Kennedy, LaGuardia and Newark Airports combined.

Climate Change Research

AWRP has no mission and no program for climate change research. However, several projects undertaken by AWRP for aviation purposes have applications for climate change

research. The most significant of these is a project jointly funded by AWRP and the NOAA Office of Global Programs (OGP). The project is referred to as the Water Vapor Sensing System (WVSS). Until now, global measurements of water vapor in the atmosphere consisted of surface observations and of soundings taken by instrument carried aloft by balloons twice per day. WVSS uses commercial aircraft as data gathering platforms. AWRP-produced sensors are flown on commercial carriers (30 UPS aircraft presently for test purposes), and the readings from the sensors are downlinked to the ground every few minutes in flight. The result is that measurements of water vapor, which is the single most important greenhouse gas, are being increased by a factor in the hundreds.

In addition to WVSS, AWRP has produced a climatology of in-flight icing conditions over the US, and has also collected new, high-quality data on turbulence, radar-measured parameters, and air chemistry. Any of these could be useful to those studying various aspects of climate change.

More Information

An overview of AWRP products can be found on the AWRP web page at <http://www.faa.gov/aua/awr/>.

Live AWRP products are available on the ADDS web page at <http://adds.aviationweather.gov/>.

Gloria Kulesa is the Team Leader for the FAA's Aviation Weather Research Program.

Potential Impacts of Climate Change on Railroads

By Michael A. Rossetti

The purpose of this paper is to identify and evaluate the effects associated with the potential impacts of climate change on railroad operators. It describes weather and climate factors affecting railroads along different time scales. It recommends the development of partnerships among governmental, industry, academia, and the research community in the study of the potential impacts of climate variability and change on transportation systems.

Railroads and their Physical Operating Environments

Throughout their existence, railroad operators have faced difficult environmental conditions that expose tracks, facilities, trains, and crews to an array of severe weather situations. Operating in sometimes remote and wilderness locations, railroad companies must deal with thunderstorms, tornadoes, flash floods and river floods, rock and mud slides, avalanches, desert heat, extreme cold, high crosswinds, snow and ice storms, limited visibility, lightning, and tropical cyclones (see Box 1).

The certainty and severity of some of these events often requires specific actions such as train rerouting or halts with little advance warning. Still other events are amenable to planning and strategies with longer lead times, but sometimes with more uncertainty. Terrorist threats have now placed urgent emphasis on the security of hazardous materials shipped by rail, with the intentional release and dispersion of such materials then potentially affected by existing meteorological conditions, and perhaps even climate anomalies.

Implications of Climate Change

Climate models suggest a future warming of 0.2 - 0.3°C per decade.¹ Sea levels are expected to rise at a rate of 4 to 10 cm per decade. Ancillary effects include changes in regional distributions of rainfall and soil moisture, and possibly more frequent and more intense storm systems. In recent years, the complexities of climate change and predictions of climate model outputs have introduced an additional measure of uncertainty for railroad operators. Weather events, climate oscillations, and climate trends hence affect railroad safety, including fatalities, injuries, and property damage. Through their interactions with maintenance, planning, operating efficiency, scheduling, and demand for freight and passenger services, weather and climate may also affect a firm's balance sheet, and cash flow, capital investment decisions, and even competitive stance within the industry.

Box 1. How weather affects railroad operations.

Weather is a major influence on many aspects of the transportation system: particularly safety, mobility, accessibility, economic efficiency, and infrastructure. While the nature and extent of this influence may vary between modes, all modes are affected. Railroads are no exception, and in fact suffer from a variety of atmospheric and environmental factors, many of which are unique to this particular mode and deserving of special focus by the transportation and meteorological communities.

Weather adversely affects railroad safety, efficiency, and property in many ways. Intermodal crossing points, such as grade crossings and waterway/railroad trestle intersections are vulnerable, as are remote stretches far removed from observational networks. Railroads may also be subject to sudden weather-induced mode shifts, such as occurred during the East Coast blizzard of January 1996.

Precipitation and fog lead to decreased visibility of signals to locomotive engineers. Flash floods can lead to washout of tracks and consequent derailment. Seasonal floods from rivers may make some track segments impassable. Warping of tracks due to uneven thermal expansion in the summer, or buildup of snow and ice on the tracks in the winter, can lead to decreased speeds and derailment. Extreme cold causes brittle track and track separation. Since railroad locomotives and cars are high-profile vehicles, high-speed crosswinds can influence their stability.

Weather can lead to serious delays on the railroads and resulting loss of economic efficiency, as had happened during the Midwestern floods of 1993. Damage to tracks due to weather, besides being a safety hazard as mentioned earlier, also has serious economic consequences. Additionally, weather induced delays contribute to inefficient fuel use and reduced air quality.

These impacts represent the potential benefits in saved lives and saved resources from enhanced weather information to support railroad decision-making. Two reasons why we have unique opportunities to apply better weather information are 1) major gains on the weather side. Advances in meteorological science and technology have led to the development of advanced weather sensing capabilities (such as NEXRAD and weather satellites). They have also led to improved forecasting capabilities through major advances in our understanding of atmospheric behavior (for example, of the physics of storms), and in computational power. Forecasting technology today has the capability to provide fine-grid weather information, near or at the required spatial (~1km) and temporal (~30 minutes) resolution for railroad decision making. 2) Gains on the transportation side that facilitate the use of enhanced weather information. One example is Positive Train Control (PTC) technology, which some analysts suggest is part of the intelligent transportation system (ITS). Established in 1991, the ITS embodies a unified set of electronics, communications, hardware, and software. It also includes “intelligent vehicles” driver assistance and control systems and represents a collection of mostly existing technologies arrayed to produce benefits to surface modes.

Railroads can be both a consumer and producer of atmospheric and environmental data. Onboard sensors may one day prove useful as a data source for meteorological models and forecast decisions. Similarly, stationary sensors mounted in wayside bungalows and along track right-of-ways may provide meteorologists and railroad traffic managers with valuable, multipurpose observations from remote locations.

Railroad operations and infrastructure adapt or respond to short term weather conditions as well as longer-term climate conditions. Longer-term effects include cyclical or transient climate changes within a normally expected climatology. Longer-term effects also include secular changes that require a more permanent response. Figure 1 depicts some of these

comparative interactions and how the railroad industry and emergency response industry may respond. The planning and decision making functions in railroads have time horizons that vary according to the hypothetical forecast accuracy and lead time required for a given weather event. Compared to emergency managers, railroad personnel have generally less

need for real-time information, but greater requirements for long-range guidance.

Cyclical and Secular Changes in Climate

Fluctuations in local, regional, and national climate regimes occur at intervals ranging from periodic to irregular. Some of these processes, such as volcanic activity and the El Niño southern oscillation (ENSO), are better understood than are others, but most have some direct or indirect implications for transportation and railroads (see Table 1). Some are naturally occurring conditions, while others are forcing mechanisms, such as a change in solar radiation or the atmospheric accumulation of greenhouse gases (GHG).

Climate models offer predictions about the future chemistry of the atmosphere, about the response of the oceans, and potential effects on broadly defined land areas. They also predict potential large-scale atmospheric and hydrologic regimes within which day-to-day weather events occur. There are two general types of climate prediction work: seasonal to interannual (e.g. El Niño and other types of oscillations), and decadal to century (global warming studies/secular trends).

Because short-term weather events are affected by the same processes that climate changes may alter, it may be possible to use seasonal or interannual oscillations, or long-term secular trends, to adjust forecasts for weather events. Intrinsic skill levels for weather forecasts have generally improved over the past two decades, thus input from climate knowledge may help local forecasters at the margin, particularly in situations where short-term models disagree on things such as storm tracks and intensity, or the likelihood of severe convection. Given that, climate models provide some lead information about tendencies toward:

- Changes in sea surface temperatures and major currents (polar ice cap melt)
- Changes in ocean salinity levels (from above)

- Changes in regional rainfall patterns that result in regional droughts or excessive precipitation.
- Warmer winters
- Increased cloudiness
- Decreased snowfall
- Increased storminess (overall higher amounts of heat energy can be converted into storminess, or transferred to the oceans)
- Rising sea levels (when combined with more intense storms, this will allow battering waves to produce coastal erosion and destruction of infrastructure)

Evidence of a Climate Change

Although the reliability of regional scale climate and weather predictions is still low, and the degree to which climate variability may increase remains uncertain, potentially serious changes have been identified. These changes include increases in some regions in the frequency and intensity of extreme weather events such as high temperature waves, droughts, floods, and storm tides. Climate change and its associated effects (e.g., temperature, sea level, precipitation, and water levels) could jeopardize portions of the railroad system.

The vulnerability of the railroad system to climate change arises mainly from the susceptibility to sudden unforeseen changes in weather or climate patterns and from potential increases in the intensity and frequency of extreme weather events. Analysis of the potential effects of climate change and variability on railroad systems must also distinguish between their potential effects on railroad infrastructure and on railroad system operations. Railroad infrastructure includes all physical capital infrastructure elements for both freight and passengers. Railroad operations include all recurring activities related to the movements of goods and people.

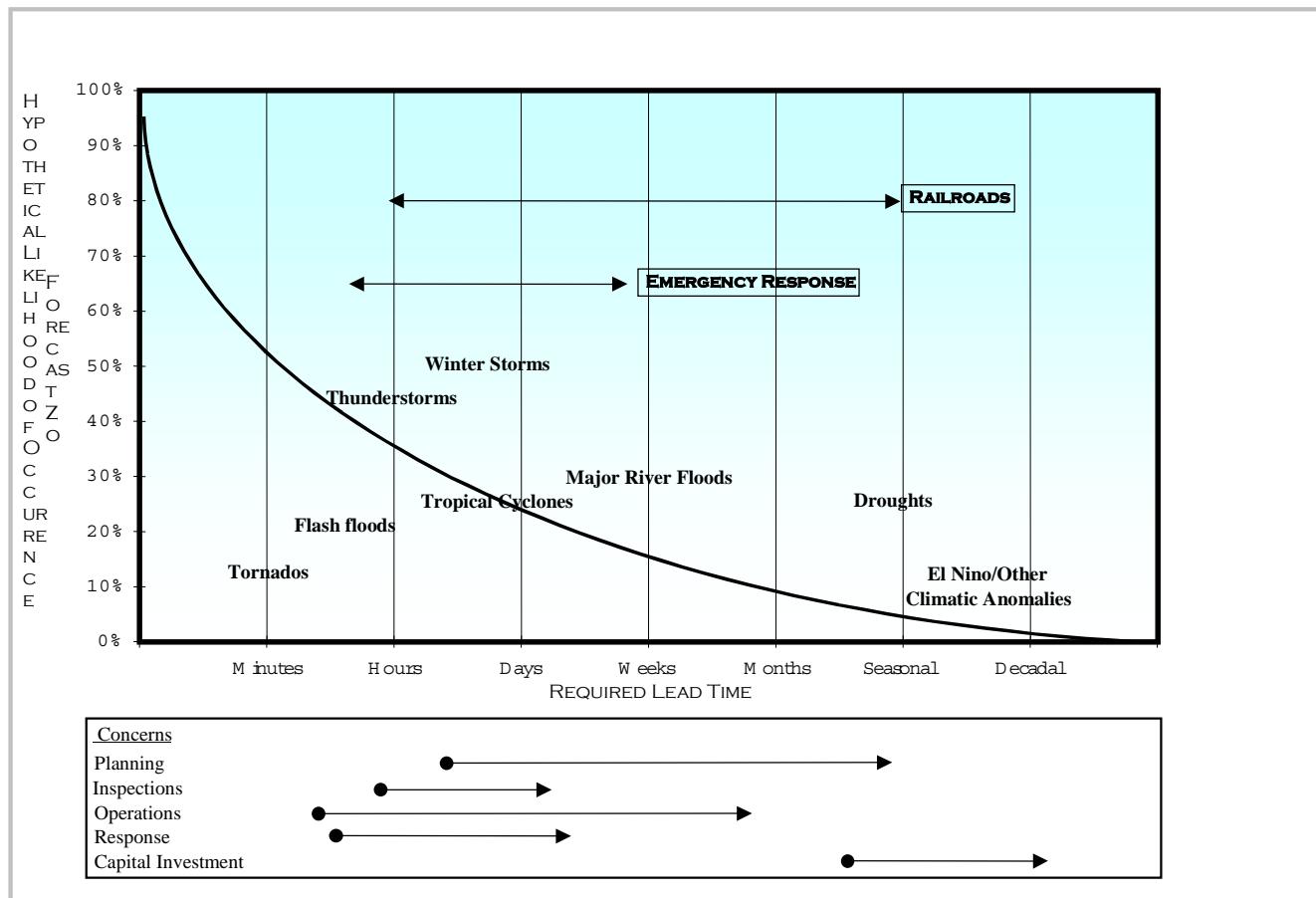


Figure 1. Weather and climate events, hypothetical forecast likelihood and lead times required by railroads and emergency response.

Railroad Systems and Climate and Weather

In order to begin to investigate relationships between weather and climatic data and railroad operations, the FRA Accident/Incident database² was consulted, and data were downloaded for analysis. It is important to begin to identify, collect, and analyze data of potential use in

establishing interrelationships between climate and weather events and railroad operations. In addition to FRA and industry information sources, such data could potentially include local, regional, and national climate and weather averages and events, as well as short term and localized weather information (see Box 2 for a

Table 1. Climate indices and transportation impacts.

Climate Influence	Description	Periodicity	Sample Effect on Climate	Sample Impacts on Transportation
El Niño Southern Oscillation (ENSO)	Long term changes in sea surface temperatures in the Pacific Ocean. Dominant southern jet stream results in warmer conditions, and heavy precipitation in the western U.S.	1-3 years	<u>Warm phase</u> : flooding, storm tracks, violent weather, fewer Atlantic hurricanes <u>Cold phase</u> : regional droughts, more Atlantic hurricanes	Pacific coastal infrastructure exposed to stronger storms, heavy precipitation, high winds and waves. Heavy snows in Sierras and Rockies.
North Atlantic Oscillation (NAO)	Long-term pressure changes over the Atlantic	Broad band spectrum with no significant dominant periodicity	<u>Positive phase</u> : milder, wetter, east coast winters <u>Negative phase</u> : colder, snowier winters in eastern states	More frequent episodes of difficult travel conditions. Colder temperatures may result in price increases for fuels.
Pacific Decadal Oscillation (PDO)	A cycle of long term variability of sea surface temperatures in the North Pacific	23-30 years	<u>Warm phase</u> : warmer, drier winters in northern states-wetter and cooler in the south <u>Cold phase</u> : colder, snowier condition in the eastern U.S., warmer in the west and Alaska	Cold phase makes transportation more difficult in northern areas.
Arctic Oscillation (AO)	Changes in pressure patterns of polar vortex	Broad band spectrum with no significant dominant periodicity	<u>Positive phase</u> : milder U.S. winters <u>Negative phase</u> : Colder winters	More frequent winter travel conditions
Pacific-North American Teleconnection (PNA)	A strong trough and ridge pattern over the North Pacific and North America	4 years	Warmer conditions in western U.S, more polar outbreaks and storms in east	Similar to negative AO
Madden Julio Oscillation (MJO)	Intra-annual fluctuation that explains weather variations in the tropics.	30-60 days	Low-frequency variations in the tropics produce weak eastward/poleward moving waves	Large-scale changes in tropical convection from MJO affect jet streams over North Pacific and South Pacific – modulations in jet can cause blocking patterns in North America
Global warming from greenhouse gases: carbon dioxide, black carbon, and methane	Combustion of fossil fuels results in higher levels of carbon dioxide, methane, black carbon, and particulates	Secular trend	Rising sea levels, warmer and wetter conditions, more frequent and intense storms	Coastal infrastructure at risk (ports, airports, roads, rail)
Volcanic activity	Large ejection of particles into upper atmosphere	n/a	Reduced sunlight causes cooling	Air traffic affected by volcanic ash, more winter-like conditions

preliminary agenda for research and data analysis).

Methodology

By examination of a ten-year period of FRA safety data (1993-2002 partial), approximately 5,700 records were available. Through the

application of screening criteria, the fields listed below were considered to be a reasonable portrayal of weather related data. It should be noted that weather data are not as comprehensive as would be desirable, and there is reason to believe those weather-related accidents and incidents are probably under-represented in the records. For example, frozen

air lines are a chronic problem in cold weather operations, but there is no code available to approximate this activity. The same problem exists for brittle or broken tracks caused by extreme cold.

Train Accident Cause Codes Possibly Weather Related

- T001 Roadbed settled or soft
- T002 Washout/rain/slide/flood/snow/ice damage to track
- T109 Track alignment irregular (buckled/sun kink)
- M101 Snow, ice, mud, gravel, coal, etc. on track
- M102 Extreme environmental condition - TORNADO
- M103 Extreme environmental condition - FLOOD
- M104 Extreme environmental condition - DENSE FOG
- M105 Extreme environmental condition - EXTREME WIND VELOCITY
- M199 Other extreme environmental conditions (provide detailed description in narrative)
- M305 Highway user unawareness due to environmental factors (angle of sun, etc.)
- M306 Highway user inability to stop due to extreme weather conditions (dense fog, ice or snow packed road etc.)

In addition to the causal data fields above, all accident records were downloaded that were reported as having snow, sleet, rain or dense fog present at the time of the event. This yielded a total of 795 usable records out of the original 5,700. Code T001, while not directly weather-related, was included to capture all possible soft roadbed activity arising from excess soil moisture or heavy rains. Code T002 directly

captures this activity, but only if there is an observed consequence, i.e., a washout, mudslide, etc. Code T109 directly captures sun kinks, a perennial problem for trains operated in hot, sunny regions of the country. Table 2 shows some preliminary tallies of the T-type codes:

Considering the problems posed by flash floods and slides, it is surprising to see how few accidents are associated with T002, as well as the lack of any seasonality from years with known flood events. Only 18 such incidents were reported in the 10-year period. Sun kinks (T109) present slightly better, with an average of about 7 incidents per year, and with some weak seasonality apparent in 1994 and 1999.

Table 3 shows a similar tally for accidents where environmental conditions were listed as the primary cause. Extreme winds were most frequently reported as an environmental cause, although the total of 26 incidents over ten years again seems on the low side. Track obstructions – snow, ice, mud, rock – appeared 22 times as the primary cause. Only four tornadoes and four floods were reported during the period.

Table 4 looks at the specific weather factors reported present at the time of the accident, though not reported as a cause of the accident. There is probably some classification error present when accident forms are filled out, and perhaps there is a bias against citing weather as a primary cause. The presence of these weather conditions – snow, sleet, rain, and dense fog – may act to increase overall risk in a given situation regardless of causality. Considering the usual confusion involved in identifying sleet, it could probably be eliminated as a data field. Freezing rain may prove a more useful attribute. Fog seems underreported, especially in view of the many remote locations through which railroads operate.

Table 2. Reported cause of accident/incident was track, roadbed, or structures.

Year	T001 Roadbed settled or soft	T002 Washout/rain/slide/flood/ snow/ice damage to track	T099 Other roadbed defects (Provide detailed description in narrative)	T109 Track alignment irregular (buckled/ sunkink)
1993	6	3	0	8
1994	8	4	0	10
1995	4	0	0	9
1996	3	0	0	6
1997	3	2	0	2
1998	4	3	0	6
1999	5	2	0	13
2000	6	2	0	7
2001	4	1	1	6
2002	3	1	0	0
Totals	46	18	1	67

Box 2. An agenda for further research and analysis to investigate climate and railroads.

Climate variability and change assessments and scenarios

- 1) *Analysis of the climatic record.* Develop an understanding of the influence of natural processes and human activities – including railroads – on climate variability and change. Establish basis to understand the relationship between railroad activities and the climate system. Define hypothesis under which DOT and FRA operate in the climate change arena.
- 2) *Analysis of climate change assessments and forecast scenarios.* Develop an understanding of the projected changes in climate and weather patterns at the local, regional, and national levels, and study the relationship between – and effects of – climate change on weather. This includes review of models and reports from the USGCRP and others.

Impacts of climate change on the railroad system

- 1) *Identification of critical climate and weather parameters.* Identify and analyze climate and weather parameters that affect railroad operations and infrastructure (e.g., visibility, precipitation).
- 2) *Scaling of data on the interaction between railroad and weather.* Scale weather data to the temporal and spatial resolutions required to develop relationships at the level of climate change data.
- 3) *Analysis of climate change effects on railroad operations.* Identify relationship between climate and weather parameters and railroad operations. Analyze safety, mobility, accessibility – and the resulting economic – implications of climate change under forecasted scenarios.
- 4) *Analysis of climate change effects on railroad infrastructure.* Identify vulnerable railroad infrastructure elements (e.g., coastal and low-lying areas), survivability (e.g., life-cycle degradation due to corrosion and water flow effects) of infrastructure elements, and construction implications (e.g., evacuation infrastructure and infrastructure replacement) of climate variability and change.

Table 3. Reported cause of accident/incident was an environmental condition.

Year	M101 Snow, ice, mud, gravel, coal, etc. on track	M102 Tornado	M103 Flood	M104 Dense fog	M105 Extreme winds	M199 Other extreme environmental condition	M305 Highway user unawareness due to environmental factors (angle of sun, etc.)	M306 Highway user inability to stop due to extreme weather conditions (dense fog, ice or snow packed road etc.)
1993	2	1	1	0	1	0	0	0
1994	1	0	1	0	1	2	0	0
1995	2	2	0	0	2	1	0	0
1996	2	0	1	0	4	1	0	0
1997	2	0	1	0	2	1	0	0
1998	1	0	0	0	4	2	0	1
1999	3	0	0	0	3	1	0	0
2000	3	0	0	0	4	0	0	0
2001	5	1	0	0	2	0	0	1
2002	1	0	0	0	3	0	0	0
Totals	22	4	4	0	26	8	0	2

Table 4. Weather conditions reported at time of accident/incident.

Year	6 Snow	5 Sleet	4 Fog	3 Rain
1993	16	1	11	38
1994	14	3	10	41
1995	12	2	8	54
1996	13	2	4	41
1997	12	0	5	38
1998	5	1	8	43
1999	12	1	9	33
2000	26	3	11	63
2001	16	0	14	51
2002	5	3	1	9
Totals	131	16	81	411

Figure 2 looks at the data according to month. As might be expected, weather-related accidents reach their peak in the December to January time frame, with a secondary peak in April, likely coinciding with the problems of spring floods, soft roadbeds and the like.

The final graph (Figure 3) shows weather related accidents distributed by state. Generally, the number of accidents conforms to state distributions of track mileage or similar indicators of volume. Out of the top 5 states, however, Arkansas and Washington are slight exceptions to this rule. The rough terrain crossing Washington State probably accounts for some of this activity, as there are frequent days of heavy snow, rain, and fog, all requiring navigation through steep grades.

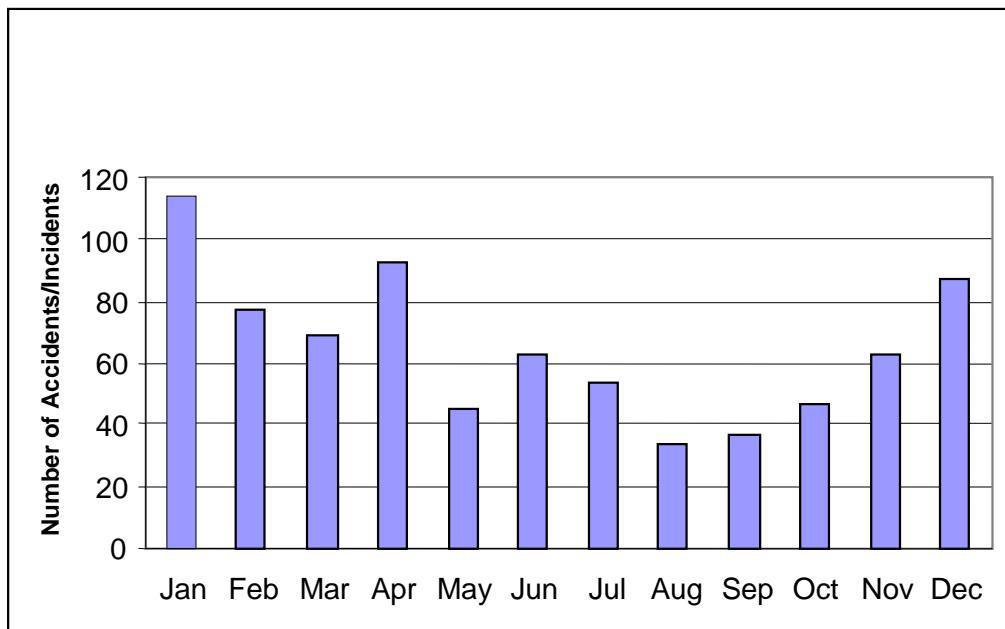


Figure 2. Weather-related railroad accidents/incidents, by month of occurrence, 1993-2002.

Weather Hazards that Could Be Affected by Fluctuations or Changes in Climate

Floods and Flash Floods

The nature of the problem is both meteorological (understanding the location, duration, and quantity of rainfall in the atmosphere) and hydrological (understanding soil absorption, runoff, how the water will behave after it hits the ground). Despite technology modernization, advances in modeling, and increases in computer power, quantitative precipitation forecast (QPF) skill levels remain low. Adding a climate dimension to model output may impart a more valuable forecast for the public, government, emergency management field, and businesses with exposures to such events. Problems posed by high waters from flash floods, river floods, persistent heavy rains, and hurricanes have historically been one of the most prominent weather-related concerns facing the railroad industry, as well as the nation as a whole. Some climate models predict increased precipitation in specific regions. This, along with faster melting of mountain snow and seasonally high spring

water levels, may significantly impact railroad operations in the next century.

Among weather events, floods annually produce some of the largest amounts of economic damage and fatalities. The Midwestern river floods of 1993 devastated railways, with over 4,000 miles of track either flooded or idled and over \$200 million in estimated losses. A flash flood that weakened an existing wooden trestle led to the 1997 Kingman, Arizona derailment of an Amtrak passenger train that injured 183 and produced damages of \$7.2 million. The Kingman incident generated a special FRA safety advisory, concerning the use by railroads of official weather watches and warnings.

Rockslide and Avalanche Hazards

Aside from possible increases in the number of floods, hurricanes, tornadoes, and other violent storms, climatic fluctuations that produce increased precipitation and greater temperature swings are likely to trigger more earth, rock, and snow slides in mountain areas. Because of the mitigation efforts that the railroad industry has

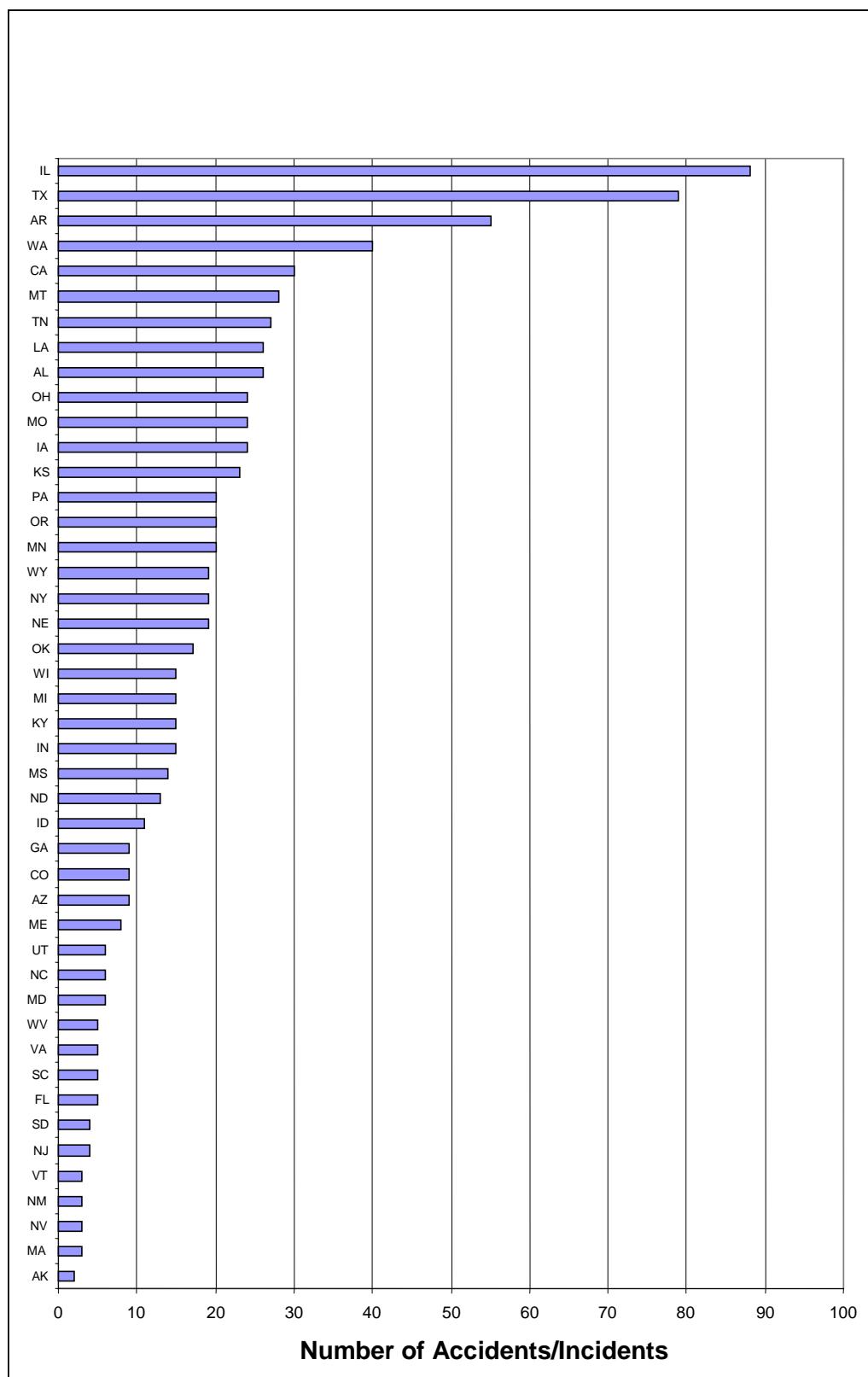


Figure 3. Weather-related railroad accidents/incidents by state, 1993-2002.

taken, serious accidents, injuries, and fatalities due to these natural hazards are relatively few, but they still result in a considerable number of disruptions and delays. As with any surface transportation, slides can threaten the safety of railroad operations, but slide mitigation planning and implementation for railroads must consider the following characteristics of railroad operations and of the U. S. railroad network. First, warnings must allow for trains to safely stop in advance of a hazard. For heavy freight trains or faster passenger trains on descending grades, stopping distances are often between one and two miles. Second, trains cannot steer around even the smallest slides or obstructions. And third, especially in the western U. S., there are relatively few alternative railroad routes, and the detour distances for accessing these may be hundreds of miles long.

Avalanches pose a seasonal threat to railroad operations in the western U.S. Avalanche zones occur in four areas: the intermountain zone of the northern Rockies, the coastal zone of the Sierra Nevada and Cascades, the continental zone of Utah, Colorado, Wyoming and New Mexico (Mock and Birkeland 2000)³. The authors found relationships between two types of climate processes and subsequent avalanche activity – the Pacific-North American (PNA) teleconnection pattern, and the Pacific decadal oscillation (PDO). These findings emphasize the connections between application of long-term climate records and current forecasts.

Temperature Extremes

When exposed to the summer sun, railroad tracks occasionally develop heat kinks that may in turn create a hazardous condition for oncoming traffic. Track misalignments caused by sun kinks have often been identified as a cause of train derailments with the potential for injuries, fatalities, property damage, and toxic release of hazardous materials. In addition to the direct effect of solar radiation, railroad tracks may also be exposed to uneven thermal expansion when shade covers nearby sections, thereby posing the risk of warp and misalignment to freight traffic. A similar condition may occur in winter, when extreme

cold results in brittle track, thus increasing the risk of breakage. Cold temperatures are also the cause of frozen air lines, when moisture present in the distal part of the line cannot be dislodged by heat from the locomotive.

Thunderstorms and Tornadoes

Exposed to weather in nearly all directions in parts of the Midwest and western U.S., train operators are often direct, in-line targets of large-scale convection and supercells that generate tornadoes. The FRA database reports four tornadoes causing accidents during the 1993-2002 period, but the actual effects are likely much higher when slow orders or halts are dispatched to train conductors, thus impeding efficiency and cost-effectiveness. Similarly, thunderstorm activity may harm rail operations through various means, including lightning strikes to switching equipment, flash floods of poor drainage areas, and high winds associated with microbursts and squall lines. Although a separate meteorological phenomenon, intense crosswinds that often set-up in the front range of the Rocky Mountains may disrupt, halt, or even force the rerouting of downwind rail traffic.

Tropical Cyclones

Landfalling hurricanes along the Gulf and Atlantic seaboards adversely affect transportation interests and sometimes inflict heavy damage to the infrastructure and assets of the system. Railroads often sustain damage from flooding, washouts, storm surges, and debris flows associated with the passage of these storms. Many notable examples appear in historical records.

The effects of Hurricane Floyd on inland North Carolina showed the importance of pre-existing soil moisture as a critical indicator of flood potential in areas previously saturated by heavy rains. Unable to absorb typical 10+ inch rainfalls produced by landfalling storms, such areas are especially vulnerable to rapid rises in local streams and rivers. Flood amplification is a real concern. Rain runoffs quickly undermine structures such as dams, railroad beds, bridges, and buildings. Outputs of land-surface models

help by providing risk estimates of land surface temperatures, soil moisture, and surface wetness, where wetness depends on precipitation and soil texture. Land surface temperatures fall during the passage of a hurricane. This decrease in temperature also then decreases evaporation levels.

Winter Storms

Across the eastern seaboard, the intermountain states and northern tier of the U.S., severe winter storms sometimes disrupt the entire transportation system. Railroad operations degrade in such conditions, due to lowered visibility, icing, snowdrifts, and cold temperatures. Railroad segments dependent on overhead electrical catenaries may fare especially poorly since their exposure tends to allow ice build-up. Winter storms also adversely affect rail in an indirect way – by preventing producers of goods from shipping to intermodal terminals or delivering goods to rail sidings, freight traffic becomes backlogged and trains may not run at full economic efficiency.

Rising Sea Levels

Although slight rises in ocean levels have now been observed, the increase is likely not yet high enough to force changes in coastal rail infrastructure or capital planning decisions. The future effects of storm tides and wave battering from large storms may amplify the risks posed by changes in sea levels.

It is probably still not too early for railroads to begin thinking about vulnerabilities in the location of rail infrastructure. Consideration should be given to limiting construction in highly vulnerable areas (e.g., floodplains, coastal areas). The industry may also want to begin thinking about infrastructure design, framing specifications determined by a new set of (uncertain) environmental constraints (e.g., number of 100-year storms the element is expected to face and survive). Another related concern is the adequacy of existing insurance policies against natural disasters and extreme weather events, and the likelihood that premiums – for bridges, tunnels, vehicles, and

other structures – will begin rising in line with the higher risks posed by global warming and rising sea levels.

Conclusions and Recommendations

This report has reviewed the possible linkages between railroad operations, weather, and climate change. Where pertinent, the predictions of climate change models were connected with specific weather events encountered by railroad operators, with the objective of speculating on how these might increase or decrease in frequency or intensity under a long period of climate change. The report considered the effects of climate change on all aspects of railroad operations, from traffic management, to safety, to capital investment in new infrastructure. It also offered speculation on the effects of climate fluctuations (interseasonal and interannual) on railroads, as distinct from the secular changes anticipated by global warming.

As a preliminary approach to looking at these possible relationships, an analysis was performed on 10 years of FRA railroad accident data, specifically examining any data items that might shed light on these emerging issues. In setting up this approach, a proposed agenda for future research and analysis was set forth, outlining areas where efforts may be most fruitful. To re-emphasize some of those points and to investigate others, the following recommendations are made:

- Advance the understanding of the interrelationship between railroad systems and climate and weather, by developing baseline data and a framework on how climate and weather conditions currently affect railroad operations, infrastructure, and planning.
- Synthesize the findings of climate change assessments and future scenarios of climate and weather changes at both the national and regional level. Emphasize the understanding of those projected changes that are expected to most affect railroads (based on the previous analysis of baseline sensitivity).

- Develop probabilistic analyses of the occurrence of forecasted events and changes.
- Analyze the potential impacts of climate change on the railroad system. Spatial and temporal coupling of baseline and climate change assessments and future scenarios data would be used to establish relationships between climate change and railroad systems.
- Identify the safety, economic, mobility, and accessibility implications of climate change.
- Identify the railroad infrastructure elements and railroad operations most at risk under scenarios of widespread or large scale climate change.
- Develop strategies to address the potential implications of climate change impacts on the railroad sector, including mitigation efforts, adaptation of railroad system operations and infrastructure, and railroad planning under uncertainty to minimize the effects of future climate change.
- Assess the effectiveness of strategies to address climate change impacts on the railroad sector.

Institutional Strategy

- *The Department of Transportation (DOT) and Federal Railroad Administration (FRA) should develop a public-private partnership program for the design and conduct of research on the potential impacts of climate change on transportation systems.*

This research can be most effectively undertaken through a collaborative effort that builds on the expertise, resources, and common interests of DOT and other agencies. Collaborative technical work by the DOT, the railroad industry, and other research organizations could build on both existing departmental expertise in relevant areas (e.g., radar meteorology, climate analysis) and also take advantage of departmental participation in related activities. These elements should be pursued through an overall private-public partnership on the potential impacts of climate change on railroads.

¹ “Climate Change Projections from the Hadley Centre.” <http://www.met-office.gov.uk/research/hadleycentre/models/modldata.html>.

² Federal Railroad Administration, Office of Safety Analysis. <http://safetydata.fra.dot.gov/officeofsafety/>.

³ Mock, Cary J. and Karl W. Birkeland. 2000. Snow avalanche climatology of the western United States Mountain Ranges. *Bulletin of the American Meteorological Society*. 81, 2367-2392.

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Environment and Planning

Climate Change and Air Quality

By Anne Grambsch

Introduction

Air pollution is a major concern in the U.S.: it can threaten human health, damage ecosystems, cause haze and reduce well-being. At the same time, the Earth's climate system has the potential to both affect, and be affected by, air pollution. The first section of this paper is intended to provide background on the current status and trends of air pollutant emissions and concentrations, with a focus on mobile sources. The next section briefly describes historical and ongoing programs to reduce mobile source emissions. The third section discusses the potential interactions between climate, climate change and air quality. The last section details a few key research needs to further our understanding of these interactions.

Current Status and Trends¹

Over the past 30 years, there have been substantial reductions in air pollutant emissions and concentrations despite large increases in total U.S. population, vehicle miles traveled (VMT), energy consumption, and gross domestic product (GDP). Since 1970 total U.S. population increased 36%, VMT increased 143%, energy consumption increased 45% and GDP increased 158% while aggregate criteria air pollutant emissions decreased 29% (see Figure 1). Changes in individual pollutants range from a 98% decrease in lead (Pb) emissions to a 20% increase in nitrogen oxides (NO_x) emissions.

To protect public health and welfare, EPA has established National Ambient Air Quality Standards (NAAQS), for six criteria pollutants: carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM), and sulfur dioxide (SO_2). EPA tracks trends of these pollutants in terms of both ambient air concentrations, using actual measurements of pollutant concentrations at monitoring sites, and emissions, which are based on monitored readings and engineering calculations. Table 1 shows that air quality, based on concentrations of criteria air pollutants, has improved nationally over the last 20 years. Total emissions, with the exception of nitrogen oxides, have also declined.

These improvements are a result of effective implementation of clean air laws and regulations, as well as improvements in the efficiency of industrial technologies. Despite great progress in air quality improvement, the ambient air quality in many areas still falls short of the NAAQS. In 2000, approximately 121 million people lived in counties with air quality that did not meet EPA's health-based standards for at least one criteria air pollutant. Nonetheless, the declining trends in the emissions and monitored concentrations of several criteria pollutants provide strong evidence that air quality in the U.S. has significantly improved over the past 30 years.

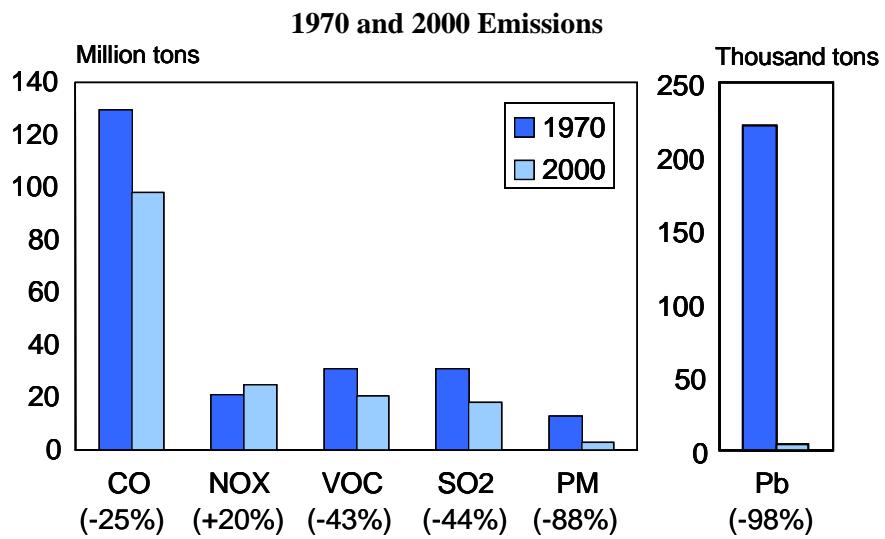


Figure 1. The chart compares 1970 and 2000 air pollutant emissions. Emissions decreased for CO, VOC, SO₂, PM, and Pb. Only NO_x emissions increased in that period. Source: USEPA, 2001b.

Table 1. Percent change in air quality and emissions: 1980-1999. Source: USEPA, 2001a.

Pollutant	Percent Change in Air Quality (Pollutant Concentrations)		Percent Change in Emissions	
	1980-1999	1990-1999	1980-1999	1990-1999
Nitrogen Dioxide	-25	-10	+4	+5
Ozone/VOC*				
■ 1-hour	-20	-4	-31	-14
■ 8-hour	-12	No Change		
Sulfur Dioxide	-50	-36	-27	-20
Particulate Matter ₁₀ **	---	-18	---	-15
Particulate Matter _{2.5} **	Trend data not available		---	-17
Carbon Monoxide	-57	-36	-21	-2
Lead	-94	-60	-94	-16

* Ozone and many particles are not emitted directly into the air. They are formed after directly emitted gases, such as volatile organic compounds (VOCs), react chemically to form them.

** Includes only directly emitted particles.

Note: Negative numbers indicate improvements in air quality or reductions in emissions. Positive numbers show where emissions have increased.

Note: Air quality concentrations do not always track nationwide emissions. For example, most monitors are located in urban areas so air quality is most likely to track changes in urban air emissions rather than in total emissions. In this case, the 20-year decline in ambient NO₂ levels closely tracks the 19-percent reduction in emissions from gasoline-powered vehicles over the same time period. In addition, nitrogen chemistry in the atmosphere is nonlinear and, therefore, a change in NO_x emissions may not have a proportional change in ambient concentrations of NO₂. The relationship between emissions and ambient air quality levels is dependent on a number of factors such as concentrations of compounds, which react with NO_x emissions (e.g., free radicals and VOCs), as well as the form and concentration of various nitrogen compounds in the area being monitored.

Mobile Sources

Air pollution in the United States comes from many types of engines, industries, and commercial operations. These include: stationary sources, such as factories, power plants, and smelters; smaller sources, such as dry cleaners and degreasing operations; mobile sources; and natural sources, such as windblown dust and wildfires. The focus of this paper is on mobile sources, which pollute the air through combustion processes and fuel evaporation. In addition, travel on roads results in “fugitive dust” emissions (dust generated from road travel is called fugitive because it does not enter the atmosphere in a confined flow stream). These emissions contribute to air pollution nationwide and are the primary cause of air pollution in many urban areas.

Mobile sources refer to a wide variety of vehicles, engines, and equipment that move, or can be moved, from place to place. On-road (or highway) sources include vehicles used on roads for transportation of passengers or freight (e.g., cars, trucks and buses). Non-road (or off-road) sources include vehicles, engines, and equipment used for construction, agriculture, transportation, recreation, and many other purposes (e.g., dirt bikes, snowmobiles, tractors, marine engines, aircraft, locomotives). Within these two broad categories, size, weight, use, and horsepower further distinguish on-road and non-road sources.

Mobile sources make up a significant portion of emissions of four air pollutants: CO, NO_x, volatile organic compounds (VOCs), and PM. These are described in more detail below. Mobile sources also produce several other important air pollutants, such as air toxics and greenhouse gases.

Carbon Monoxide

Transportation accounted for 77% of the nation’s total CO emissions in 1999. Despite a 57% increase in vehicle miles traveled (VMT), emissions from on-road vehicles decreased 56% during the past 20 years as a result of automotive emissions control programs. However,

emissions from all transportation sources have decreased only 23% over the same period, primarily due to a 42% increase in off-road emissions, which has offset the gains realized in reductions of on-road vehicle emissions.

Table 2. 1999 carbon monoxide emissions (in thousand short tons).

Total emissions	97,441
Transportation	75,151
On-road	49,989
Non-road	25,162

Nitrogen Oxides

Nitrogen oxides (NO_x) play a major role in the formation of ozone in the atmosphere through a complex series of reactions with volatile organic compounds (VOCs). Anthropogenic emissions of NO_x account for a large majority of all nitrogen inputs to the environment. The major sources of anthropogenic NO_x emissions are high-temperature combustion processes, such as those occurring in automobiles and power plants. Transportation accounted for 56% of U.S. NO_x emissions in 1999. Emissions from transportation sources increased 16% overall for the period 1980 to 1999. While on-road emissions were virtually unchanged from 1980 levels, emissions from non-road sources increased 56%.

Table 3. 1999 nitrogen oxide emissions (in thousand short tons).

Total emissions	25,393
Transportation	14,105
On-road	8,590
Non-road	5,515

Over the past 10 years (1990-1999), NO_x emissions for both light duty gasoline vehicles and light duty gasoline trucks peaked in 1994 and then began a steady decrease (8% and 24% respectively) through 1999, for an overall increase of 19%. The decrease after 1994 can be attributed primarily to the implementation of the Tier 1 emission standards, which lowered NO_x emissions from new cars and light duty trucks. In contrast, NO_x emissions from heavy duty vehicles, both gasoline and diesel, increased significantly from 1990 to 1999 (50% for gasoline and 61% for diesel). A portion of this increase is due to the increase in VMT for these categories (104% for heavy duty gasoline vehicles and 99% for heavy duty diesel trucks). Emissions from off-road vehicles, particularly diesel-fueled vehicles, increased steadily over the last 10 years (15% increase).

Ozone/VOC

Ground-level ozone continues to be a pollution problem throughout many areas of the United States. Ozone is not emitted directly into the air but is formed by the reaction of VOCs and NOx in the presence of heat and sunlight. Ground-level ozone forms readily in the atmosphere, usually during hot summer weather. A variety of sources, including motor vehicles, emit VOCs. Nationally, transportation sources accounted for 47% of anthropogenic VOC emissions in 1999.

Table 4. 1999 volatile organic compound emissions (in thousand short tons).

Total emissions	18,145
Transportation	8,529
On-road	5,297
Non-road	3,232

VOC emissions from transportation decreased 24% over the past 20 years. On-road emissions decreased 41% from 1980 to 1999 but were partially offset by the 40% increase in non-road emissions. Recent control measures to reduce transportation sector emissions include regulations to lower fuel volatility and to reduce NOx and VOC emissions from tailpipes. The effectiveness of these control measures is reflected in a decrease in VOC emissions from highway vehicles. VOC emissions from highway vehicles declined 18% since 1990, while highway vehicle NOx emissions have increased 19 % over the same period.

Particulate Matter

Particulate matter (PM) is the general term used for a mixture of solid particles and liquid droplets found in the air. The chemical composition and physical properties of these particles vary widely. Particles less than or equal to 2.5 micrometers in diameter, or PM_{2.5}, are known as "fine" particles. Those larger than 2.5 micrometers but less than or equal to 10 micrometers are known as "coarse" particles. PM₁₀ refers to all particles less than or equal to 10 micrometers in diameter. Fine particles result from fuel combustion (from motor vehicles, power generation, industrial processes), residential fireplaces and wood stoves. Fine particles also can be formed in the atmosphere from gases such as sulfur dioxide, nitrogen oxides, and volatile organic compounds. Coarse particles are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, crushing and grinding operations, and windblown dust.

Table 5. 1999 particulate matter (in thousand short tons).

	PM ₁₀
Total emissions	23,679
Non-traditionally inventoried, Total	20,634
- Unpaved roads	9,360
- Paved roads	2,728
- Misc./natural	8,546
Traditionally inventoried, total	3,045
- Transportation	753
- On-road	295
- Non-road	458

In 1999, transportation accounted for 25% of direct PM₁₀ emissions (coarse particles) from traditionally inventoried sources such as fuel combustion, industrial processes, and transportation). However, these traditionally inventoried sources made up only a small share, about 13%, of total direct PM₁₀ emissions. For direct PM_{2.5} emissions (fine particles) transportation accounted for about 28% of traditionally inventoried sources, which in turn made up 34% of all PM_{2.5} emissions nationwide. While miscellaneous and natural sources actually account for a large percentage of the total direct PM₁₀ and PM_{2.5} emissions nationwide, they can be relatively difficult to quantify compared to the traditionally inventoried sources.

Other Emissions

Lead. Twenty-five years ago, automotive sources were the major contributor of lead emissions to the atmosphere. The large reduction in ambient concentrations and emissions from 1980 to 1990 can be largely attributed to the phasing out of leaded gasoline for automobiles. Overall, lead emissions decreased 94% between 1980 and 1999. The 4% increase in lead emissions from 1998 –1999 is largely

attributable to increased use of aviation gasoline. Aviation gasoline is not regulated for lead content and can use significant amounts of lead to comply with octane requirements for aviation fuel.

Air Toxics. Hazardous air pollutants (HAPS), commonly referred to as air toxics, are pollutants known to cause, or suspected of causing, cancer or other serious human health effects or ecosystem damage. EPA is required to reduce air emissions of 188 air toxics listed in the Clean Air Act. The National Toxics Inventory 1996 emission estimates for the 188 HAPS totaled 4.6 million tons, with on-road sources accounting for 30% and non-road sources accounting for 20% of the total. Based on the data in the National Toxics Inventory, estimates of nationwide air toxics emissions have dropped approximately 23% between the baseline period (1990—1993) and 1996. Mobile sources contribute a large share (i.e., more than 40%) of emissions for several air toxics including benzene, 1,3-butadiene, acetaldehyde, acrolein, formaldehyde, and diesel particulate matter. EPA has identified 21 Mobile Source Air Toxics (MSATs), including several VOCs, as well as diesel particulate matter plus diesel emission organic gases (DPM+DEOG).

Greenhouse Gases. Transportation accounted for 1,877 teragrams of CO₂ equivalent² (Tg CO₂ Eq) in 2000, or about 27% of total U.S. greenhouse gas emissions (USEPA, 2002). Focusing on CO₂ emissions from fossil fuel combustion (excluding international bunker fuels³) the transportation sector accounted for the largest share – approximately 32% – of CO₂ emissions. Petroleum-based products supplied almost all of the energy consumed in transportation activities, with nearly two-thirds related to gasoline consumption in automobiles and other highway vehicles. Other fuel uses, especially diesel fuel for freight trucks and jet fuel for aircraft, accounted for the remainder. Carbon dioxide emissions from fossil fuel combustion for transportation increased by 22% from 1990 to 2000 to 1,792 Tg CO₂ Eq. The growth in transportation sector emissions has been relatively steady, including a 3.5% single year increase in 2000.

Mobile Source Pollution Control Programs

Starting in the early 1970s, EPA set national standards that considerably reduced emissions of CO and other pollutants from motor vehicles. Today's cars, for example, typically emit 70 to 90% less pollution over their lifetimes than their 1970 counterparts (USEPA, 1994). Under the

Clean Air Act and subsequent Amendments in 1977 and 1990, tailpipe standards for cars were set and later tightened, emission standards for diesel-powered trucks and buses were adopted, and Inspection and Maintenance (I/M) programs were established and subsequently expanded to include more areas and allow for more stringent tests (see Table 6).

Table 6. Milestones in motor vehicle emissions controls.

1970	New Clean Air Act sets auto emissions standards.	1990	Clean Air Act Amendments set new tailpipe standards.
1974	EPA sets fuel economy standards.	1992	Oxyfuel introduced in cities with high CO levels.
1975	First catalytic converters are used for hydrocarbons and CO. First use of unleaded gas in catalyst equipped cars.	1993	Limits set on sulfur content of diesel fuel.
1981	3-way catalysts with on-board computers and O ₂ sensors appear.	1994	Phase-in of new vehicle standards and technologies begins.
1983	I/M programs are established in 64 cities.	1995	On-board diagnostic systems in 1996 model year cars. Phase I Federal Reformulated Gasoline sales begin in worst ozone nonattainment areas.
1989	Fuel volatility limits are set for RVP.	1998	Sales of 1999 model year California emissions equipped vehicles begin in the Northeast.

The 1990 Amendments to the Clean Air Act also introduced several new approaches to reducing motor vehicle-related air pollution. Fuel is considered along with vehicle technology as a potential source of emission reductions. And more attention is focused on reducing the growth in vehicle travel. The new provisions include:

- **Emphasis on Fuels:** The Clean Air Act mandates that improved gasoline formulations be sold in some polluted cities to reduce emissions of ozone-forming hydrocarbons and air toxics. Other programs set low vehicle emission standards to stimulate the introduction of even cleaner cars and fuels. EPA also regulates the vapor pressure of all gasoline during the summer months.

EPA has regulated highway diesel fuel quality since 1993 and most recently established low sulfur requirements in diesel fuel starting in 2006.

- **Non-road Engines:** The 1990 Clean Air Act requires EPA to consider emissions from off-highway vehicles as well as from highway vehicles such as cars and trucks.
- **Clean Transportation Alternatives:** The law requires the smoggiest cities to limit growth in vehicle travel by encouraging alternatives to solo driving.

Potential Effects of Climate Change on Air Quality

The atmospheric sciences community recognizes that climate and air quality are linked through atmospheric chemical, radiative, and dynamic processes at multiple scales (NRC, 2001). The results of a limited number of studies of the relationship between weather and ozone concentrations, the effects of temperature on atmospheric chemistry, and the sensitivity of emissions to weather and land use suggest that climate change could adversely affect air quality. However, the community's understanding of the many climate-air quality links is still very limited.

Ozone. An association between tropospheric ozone (O_3) concentrations and temperature has been demonstrated from measurements in outdoor smog chambers and from measurements in ambient air (USEPA, 1996). Chamber studies found a linear relationship between maximum O_3 and temperature (Kelly and Gunst, 1990). Numerous ambient studies done over more than a decade have reported that episodes of high temperatures characterize seasonally high O_3 years (see USEPA, 1996; NRC, 1991 for a summary of these studies). In general, an increase in atmospheric temperature accelerates photochemical reaction rates in the atmosphere and increases the rate at which tropospheric O_3 and other oxidants (e.g., hydroxyl radicals) are produced. However, O_3 levels do not always increase with an increase in temperature (e.g., when the ratio of VOCs to NO_x is low).

Ozone is expected to be influenced by wind speed because lower wind speeds should lead to reduced ventilation and the potential for greater buildup of O_3 and its precursors. Abnormally high temperatures are frequently associated with high barometric pressure, stagnant circulation, and suppressed vertical mixing resulting from subsidence (Mukammal et al., 1982), all of which may contribute to elevated O_3 levels. Increases in water vapor increase the potential for O_3 formation (Penner et al., 1989), as do frequent or intense high-pressure systems.

Climate change could reduce O_3 concentrations, however, by modifying factors that govern O_3 -producing reactions (Smith and Tirpak, 1989; NRC, 1991); for example, a more vigorous hydrologic cycle could lead to an increase in cloudy days. More cloud cover, especially in the morning hours, could diminish reaction rates and thus lower O_3 formation.

Changes in meteorology are also likely to affect biogenic emission rates and evaporative emissions, in addition to altering rates of atmospheric chemical reactions and transport processes (see NRC 1991, EPA 1996). In particular, high temperatures cause increased VOC evaporative emissions when people fuel and run motor vehicles. The seasonal variation in natural emissions of VOCs and NO suggests that warmer temperatures are associated with increased natural emissions. For example, an increase of 10°C can cause over a 2-fold increase in both VOC and NO biogenic emissions (USEPA, 2000).

Higher outdoor temperatures will reduce the demand for heating services during winter and increase the demand for cooling services during summer. To the extent that these services are provided by fossil fuel combustion, emissions of associated pollutants, such as CO, NO_x , and VOCs will change. However, the overall net effect on future emissions, after taking into account future emissions controls, is unclear.

Sulfur Dioxide and Nitrogen Oxides. SO_2 and NO_x oxidize in the atmosphere to form sulfuric acid and nitric acid, respectively. These acids can be deposited to the earth's surface in "dry" form as gases or aerosols or "wet" as acid rain. Wet deposition is determined by the amount, duration, and location of precipitation and changes in the total acid levels, which are in turn determined by atmospheric chemistry and precipitation patterns (Martin, 1989; Smith and Tirpak, 1989). Although regional patterns of acid deposition are uncertain, many of the factors that affect O_3 formation also influence acid deposition (Penner et al., 1989; Smith and Tirpak, 1989). Higher temperatures accelerate the oxidation rates of SO_2 and NO_x to sulfuric

and nitric acids, increasing the potential for acid deposition.

If climate change results in a more vigorous hydrologic cycle and increased cloud cover, this may reduce rates of transformation from SO₂ to acidic materials, thus reducing the potential for acid deposition. Changes in circulation and precipitation patterns will affect transport of acidic materials, which in turn will determine the geographic location of acid deposition (Penner et al., 1989; Martin, 1989). Local, regional, and national air quality levels, therefore, will be partially determined by changes in circulation and precipitation patterns (Martin, 1989; Smith and Tirpak, 1989).

Particulate Matter. Secondary particles are formed from gases through chemical reactions in the atmosphere involving atmospheric oxygen and water vapor; reactive species such as ozone; radicals such as the hydroxyl and nitrate radicals; and pollutants such as SO₂, NO_x, and organic gases from natural and anthropogenic sources. In addition to these factors, secondary aerosol formation depends on atmospheric conditions, including solar radiation and relative humidity. As a result, the same meteorological processes that are noted above may affect fine particulate concentrations. In addition, natural particulate emissions (e.g., from wildfires and soil erosion) can also be affected by weather patterns such as droughts.

Atmospheric particles also play an important role in altering the amount of solar radiation transmitted through the Earth's atmosphere (i.e., radiative forcing). Particles, especially those containing sulfate, exert a direct effect by scattering incoming solar radiation back to space, thus providing a cooling effect. However, black carbon in particles absorbs solar radiation and consequently warms the atmosphere. The IPCC Third Assessment Report (IPCC, 2001) provides estimates of the net direct effect of aerosols on radiative forcing, but notes that there is much less confidence in these estimates relative to estimates for greenhouse gases.

Particles also exert an indirect effect on climate by affecting the size and number of

cloud droplets. As a result of these processes, clouds reflect more solar radiation back to space. These effects have been observed (e.g., cloud droplets in polluted areas tend to be smaller than those formed in clean areas). However, the magnitude of the overall indirect effects of aerosols on climate is very uncertain (IPCC, 2001).

Modeling Studies of Climate Change and Air Quality. Of the few modeling studies of regions in the U.S. that have quantified the effects of climate change on ambient concentrations, most have examined the impact of increased temperature on O₃ formation. Although these studies reveal O₃ concentrations increase as temperature rises, the estimated magnitude of the effect varies considerably. However, several of these studies relied on assumptions or held constant key variables such as emission levels, mixing heights, and cloudiness. As a result, these studies demonstrate the sensitivity of atmospheric air pollutants to changes in specific meteorological variables but cannot be viewed as projections of future changes in air quality. For example, these studies have not addressed such issues as changes in the frequency of stagnation episodes associated with high levels of observed ozone, future levels of emissions (important for non-linear processes), or changes in synoptic weather conditions.

In a preliminary study, Gery et al. (1987) examined the effects of increased temperature and decreased stratospheric O₃ on tropospheric O₃ formation in 15 separate combinations of city and meteorological episodes. The temperature effect (holding stratospheric O₃ constant) was found to increase ground-level O₃ by about 2-4% for a 2°C increase and by about 5-10% for a 5°C increase (p. 76). Morris et al. (1989) examined the effects of a uniform 4°C temperature increase and an attendant increase in water vapor concentration (assuming a constant relative humidity) on daily tropospheric O₃ concentrations. The model results indicated that changes in the highest daily O₃ concentrations could range from a decrease of -2.4% to an increase of 20%. A further study (Morris et. al., 1991) examined a broader range

of reactivity conditions and used locally specific, model-predicted temperature changes corresponding to a doubled CO₂ experiment. The impact of temperature on biogenic hydrocarbon emissions was included. The study estimated the changes in VOC emission controls that would be needed to attain the O₃ NAAQS in each city. In all cases the needed controls increased approximately in proportion to the local increases in temperature.

In the most recent of these studies (Morris et. al., 1995), a 4°C temperature perturbation was imposed uniformly on a region encompassing the Northeastern United States. The response of evaporative hydrocarbon emissions from motor vehicles to the temperature increase was also included in the analysis. The model simulations showed that under global warming conditions the concentrations of O₃ increased throughout the region. Incremental increases in O₃ concentration associated with the 4°C temperature increase ranged from about 28 parts per billion (ppb) (compared to 145 ppb O₃ without the 4°C increase) to 8 ppb (compared to about 27 ppb).

Hales (1988) used a storm-cloud model (PLUVIUS-2) to examine the impacts of a temperature increase on the production of acidic materials. The model results indicated that sulfate (SO₄) production increased by about 2.5 times for a 10°C increase in temperature. Gery et al. (1987) also show that a temperature increase would speed the formation of H₂O₂, increasing the conversion of SO₂ to sulfuric acid.

Conclusions

Changes in weather that may accompany climate change may affect atmospheric concentrations of air pollutants. Of particular concern are potential changes in O₃ and particulate matter concentrations. These pollutants cause a range of health and other effects, and air quality standards for these pollutants were exceeded in many areas. Ozone and secondary particulate matter are formed in the atmosphere and thus are influenced by prevailing meteorological

conditions. In addition, they are known to have important effects on the climate system. These linkages are complex and involve nonlinear processes. Because many parameters can change (e.g., emissions, climate variables, ultraviolet levels) more or less simultaneously, predicting future changes in air quality is a challenging task.

However, there is a great deal that is unknown with respect to climate change and air quality. There remains a basic need to conduct process studies to develop a better understanding of key relationships (e.g., sensitivity of biogenic emissions to changes in temperature). More fundamentally, better emission inventories and observational datasets are needed to analyze specific atmospheric processes. Ultimately, improving our understanding of interactions between climate change and air quality will require the ability to couple regional-scale air quality/climate models with global-scale climate and chemistry under a range of socioeconomic, emissions, and climate scenarios.

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¹ Estimates cited here are from various EPA reports, including the National Air Pollutant Emission Trends: 1900-1998 (USEPA, 2000), National Air Quality and Emissions Trends Report: 1999 (USEPA, 2001a) and Latest Findings on National Air Quality: 2000 Status and Trends (USEPA, 2001b). Electronic versions of these reports can be found at www.epa.gov/airtrends.

² Estimates are presented in units of teragrams of carbon dioxide equivalents (Tg CO₂ Eq), which weight each gas by its Global Warming Potential (GWP) value.

³ International bunker fuels refer to fuels used by ships or aircraft for international transport activities. In accordance with greenhouse gas emission guidelines, emissions resulting from the combustion of international bunker fuels are reported separately and not included in national emissions totals. The Parties to the United Nations Framework Convention on Climate Change have yet to decide on a methodology for allocating these emissions between countries.

The views expressed in this paper are those of the author and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

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Potential Climate Impacts on Land Use

By Paul Marx

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has released its third assessment report on potential regional impacts of climate change in the U.S.¹ This report indicates that the effects of changes in regional weather will not be uniform from place to place. Some regions will receive more moisture than historic averages, others less. Temperatures are projected to shift significantly, resulting in permanent alteration of ecosystems. Will these changes be sudden or gradual, benign or harmful, mild or catastrophic? There is no single or simple answer to these questions. However, we do surmise that the projected changes in the global climate, which in turn will mean changes in national and regional weather patterns, may have substantial effects on our transportation system. How might these effects demonstrate themselves? The effects on transportation depend to a great extent on how we use the land for various purposes.

This paper will look at broad ranges of effects that might result from climatic change with regard to three types of land use activity – agriculture, industry and commerce, and residence. Then, it will describe a range of transportation scenarios that might result from changes in land use that are prompted by a significant climate change. For every scenario and reaction to a scenario described in this paper, there are likely to be many alternatives that could lead to large or small changes in individual or societal behavior. The intent behind this paper is not to forecast or predict specific economic or sociological behavior. Rather, the intention is to present possible

alternatives in a way that spurs discussion. Because weather by itself is extremely unlikely to instigate changes in human behavior, we must examine factors that derive from variations in climate and extrapolate these effects on daily behavior. For example, does a gradual evolution from dry plains to desert imply concentration or dispersion of residences? The answer may depend upon whether the vision of a Buckminster Fuller (Geodesic domes) or a Texas rancher leads the particular community. At root, the adaptation to any climatic shift depends upon the sum of individual economic decisions by all of the members of the affected community.

Significant climate changes, in this context, are not the most extreme events that are commonly thought of as emblematic of global climate change – such as dramatic sea-level changes or expansions of deserts. Rather, this paper will focus on fairly subtle changes in regional climates – changes that can easily result from periodic anomalies in weather patterns regardless of their fundamental cause, but that may also be recognized as symptomatic of major changes in underlying weather patterns in coming years. Again, the intention is not to address the best case or worst case – circumstances where opinions are easily formed and defended – but to stay within the range where the future remains the most intractable, or “foggy.” The best debates must occur when any participant can reasonably discuss both “pro” and “con” in a single conversation.

Agriculture

The United States faces two broadly-based changes in its weather that would affect agriculture. One is quantity and timing of rainfall (Figure 1). The other is temperature. (Rising CO₂ concentration itself will also affect agriculture, and not necessarily in the same way as related climate effects.)² Not only do both factors affect agriculture, but the IPCC report indicates that they will not change uniformly, or in tandem. Some regions of the U.S. will experience greater temperature change than others, and some will experience greater variability in rainfall and snow levels. These factors in turn affect a great range of variables that influence agricultural productivity, including seed germination rates, presence or absence of beneficial and harmful insects, effectiveness of soil treatments (lime, pesticides, fungicides, etc.) and more; together these influences will affect productivity and the type of agriculture that is extant in particular regions. What might be the transportation impacts of a gradual but significant shift in rainfall and temperature over a multi-state part of the country?

One fairly benign scenario has been described (given its more extreme outcome, a desert type scenario is addressed later), in which the Northern Midwest of the U.S. experiences a modest increase in temperature, along with a rise in annual rainfall. Assuming that this is not accompanied by severe weather anomalies (which often damage crops), one might expect a gradual shift in the form of agriculture. More days of sunshine, warmer temperatures, and earlier growing seasons in the states of Missouri, Illinois, Iowa and Kansas might change their agriculture from machine-based (wheat, corn, soybeans) to more labor-intensive crops such as leafy greens, tomatoes, legumes, and fruits.³ That is, assuming that the change in rainfall does not result in higher erosion levels and a net decrease in agricultural productivity.

Taking this scenario further, changing agriculture to more labor-intensive crops would have far-reaching effects on the region. Rather than a few, highly-paid farm hands driving

combines to harvest thousands of acres at a time, many more farm hands would be required to plant, care for, and then harvest the crops. It would require a significant increase in local populations, either on a migratory or permanent basis. Field sizes would be smaller, and crops more diverse, to minimize pest and fungus migration. Field workers would need vehicles to move between their homes and growing areas. The surrounding communities would have to grow to accommodate additional residents, probably in some combination of permanent and transient housing. All of these changes would require additional road and automotive infrastructure. Unless extraordinary measures were taken, the added travel demand would most likely be met through the use of personal automobiles. Would the agricultural shift result in a net increase in automotive and farm-based internal combustion engine use, or would it produce a population shift from one region to the other?

This is not the only effect, however. More damageable crops must be packaged by hand, (rather than being aggregated by conveyor, for example) and are usually shipped in refrigerated containers. What would be the effect on railroads of no longer carrying significant quantities of grain? Could railroads substitute vegetables for unit trains of grain?⁴ Would trucking have to increase to service the new agricultural areas? How would that affect carbon emissions, or the distribution of automotive emissions on a regional scale? How would agricultural prices be affected by changes in shipping cost? Who would bear the burden of such costs? How would the relative competitive positions of the U.S. and Canada change with regard to agriculture? How would NAFTA adjust to a large shift in agricultural outputs among its partners? At what point would climate effects be addressed in bilateral or multi-lateral trade talks?

Commerce/Industry

Approximately 70 percent of the U.S. electrical capacity is provided from coal. Another 20 percent or so is provided by nuclear power. The rest is provided by a combination of hydro,

wind, solar, biomass, and other sources. However, some areas are particularly dependent on hydropower – particularly in the Northwest and Northeast. In some instances, this has led large users of electricity, such as aluminum manufacturers, to locate near such power sources. Two scenarios analyzed in the IPCC Synthesis Report indicate opposite outcomes for the Pacific Northwest. In one scenario, annual runoff declines by 50 to 150 mm. In the other, annual water runoff increases by more than 150 mm. Either case causes potentially severe disruption.

In the reduced runoff scenario, the cost of hydropower rises, particularly during times of water shortage. As the shortages become more frequent and persistent, the plant must purchase more power than it provides to the grid. Businesses no longer have access to lower-cost electric power. If this lasts more than a year or two, these businesses will have an economic incentive to move to where power is less expensive. This could be to the U.S. Eastern states, or to Canada.

In the increased runoff scenario, there is not much improvement. While there is more water, temperatures are also higher, so less of the water falls as snow – to be melted gradually in the spring. Rather, there are heavier rains causing greater levels of erosion and increasing maintenance and operating costs of hydropower basins. The incidences of excessive rainfall may be followed by extended periods of inadequate rainfall, and higher temperatures, leading to increased evaporation rates and increases in electricity used for air conditioning. This would raise both the cost of producing electric power and the price due to higher demand. What would be the effects of such changes on the transportation system?

One would expect the higher electric power cost to raise the cost of some manufactured products, but would the cost increase be sufficient to alter demand for the final product? We would have to analyze widely differing industries, from canned beverages (soft drinks and beer) to automobile parts. What about the cost of electric power from other sources? Could

the higher cost or reduced availability of hydroelectric power provide an opportunity for another fuel type? This would require analysis of the competitive advantages of other fuels such as coal, oil, and natural gas. Unfortunately, in the short term, since coal already provides 70 percent of electric power generation, it would be likely to provide a similar proportion of any increase in demand for electricity, thus contributing to additional quantities of CO₂ emissions.

The effects of the preceding scenarios on the transportation system are difficult to project. They depend on the price sensitivity of consumers with regard to specific goods, as well as the net effects of the manufacturers' cost increase. If the cost can be passed on to consumers, the businesses may remain in place. If the power cost can be mitigated through competitive products produced elsewhere, then businesses that depend on the higher-cost electricity may need to move in order to protect their market shares. This would cause medium-term disruption in the local economies as they adjusted to a new business model.

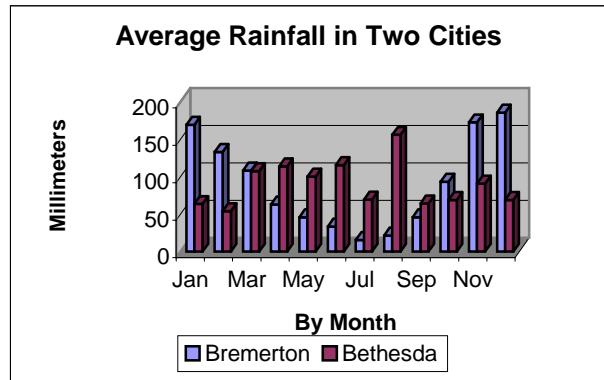


Figure 1. This chart shows average monthly rainfall in two areas on opposite coasts of the U.S. with nearly identical annual rainfall. Yet, their monthly rainfall patterns are significantly different. Bremerton receives very little rainfall in summer, while Bethesda's is spread more evenly throughout the year. Source: NCDC Cooperative Stations, 1919–1995.

Residence

This is the most difficult area of human activity to assess in terms of climate change. Our society is in flux, gradually urbanizing as more of our agriculture becomes either machine-oriented or dependent on migrant labor. Even where our population is gravitating to cities in search of employment, this often means “suburbanization” rather than urbanization. That is, new urban immigrants will often reside where housing prices are lower – in the suburbs – rather than in towns where the cost of housing is significantly higher. At what point is it more expensive to live outside of town than in town? At the same time, our society is aging. “Empty nesters” who have raised their children and are now approaching retirement age have sufficient wealth and income to afford an urban lifestyle. Thus, many American towns are seeing a resurgence in their downtown cores. Houston, long known as a center of auto-oriented culture, is building a light rail system through its downtown, to accommodate the highest rate of resident immigration in the U.S. for the last two years.

So what does climate change mean to residential land uses? Taking the two basic scenarios of excessive rainfall and insufficient

rainfall as points of departure, the effects depend on location. In Central and North Texas, temperatures are likely to rise and rainfall decline. This may result in the elimination of forest habitat and evolution of a desert habitat. The transportation effects of such a change could be significant, and may be disruptive unless the infrastructure is modified to accommodate the necessary uses. With a significant decline in rainfall would come reduced water levels in the aquifers needed to support continued habitation. The two alternatives cited previously would come into play. Residences might coalesce around a center, at the extreme reaching a futuristic Geodesic Dome form to minimize per capita consumption of water and other essentials for life. Or, residences might spread out, following the traditional pattern that has evolved since the initial European settlement of the Southwest.

In the near to medium term it is hard to imagine entire communities of Geodesic Domes springing up in the desert. Thus, this scenario would most likely result in low-density communities, heavily dependent upon individual automobiles for transportation. Local shops and businesses would depend upon trucking more than trains for their freight needs. Vehicle miles



Figure 2. Photo of the Colorado River in Mexico. The extensive use of its waters for agriculture and urban water supplies throughout the Southwest reduce it to a trickling stream by the time it reaches the sea. Photo source: Los Alamos National Laboratory.

of travel would increase on a per capita basis. At what point would a sustainable, ecological equilibrium be reached?

Let us take a more problematic scenario. Rainfall and snowfall feeding the Colorado River are projected to decline in an erratic pattern. The river already provides a limited but vital resource to California and northern Mexico. Some argue that the Colorado River is not adequately priced even now to reflect its essentiality to the Southern California economy, and that Mexico is being short-changed as a result. What happens if the flow is reduced, or severely disrupted, by weather anomalies? The cost of living rises, States are forced to renegotiate long-standing agreements, and farm products that depend upon irrigation rise in cost.⁵ Not only do costs rise for California, but for the rest of the nation as well. For how long are people willing to pay the higher price to live in Los Angeles or Orange County? Part of these cost increases will come from higher repair costs for the infrastructure, as roads, railroads and bridges are damaged by more frequent (and more severe) floods.

One potential effect would be to depress real estate prices as the cost of living increased. Rates of in-migration would fall, lowering demand for housing, and rates of out-migration might increase, as people sought new situations with a better mix of wages and cost of living. If this process continued long enough, businesses would follow the workforce to areas with greater

stability of resources, particularly water, such as the Pacific Northwest and Western Canada.

If the water supply disruption in the Pacific Southwest continued long enough, the region would be forced to adjust to a new environment. Water rationing would be common. New investments would be reviewed on the basis of their probable demand for water. If conditions became severe enough, entire communities would be re-designed in a more compact form. More space and resource-efficient designs for residences and businesses would proliferate, and the levels of resource use per person might decline. In such a scenario, personal trips by automobile would be viewed as excessively resource-intensive. Living near where one worked, or near public transportation, would confer significant economic benefits.⁶

These changes in personal behavior would be encouraged by the municipality, within a sustainability strategy. Such a strategy might include the design of special transportation infrastructure, engineered to withstand both excesses of heat and flash flooding, which might occur with increasing frequency.

An Excessive Rainfall Scenario

The Pacific Northwest has been mentioned as a possible haven from the disruptions in water supply that may affect the Southwest. Already, places such as Portland, Oregon and Seattle, Washington have seen dramatic increases in

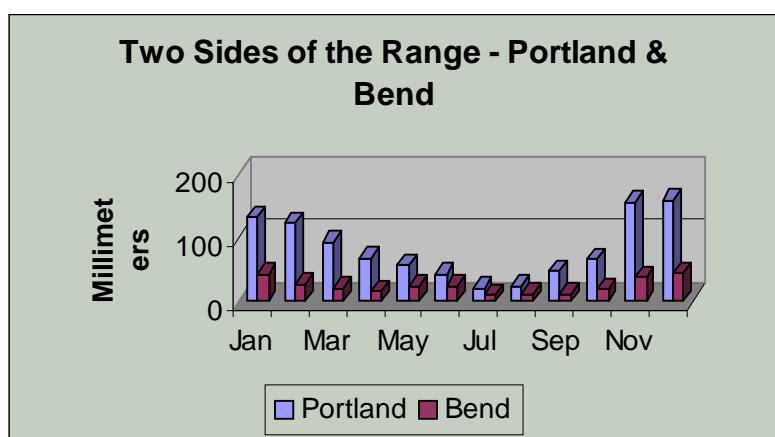


Figure 3. Average monthly rainfall in Portland and Bend, Oregon. Bend, on the east side of the Cascades, is significantly drier than Portland, so that even a 50 mm change in rainfall is an extreme change for Bend, while Portland might absorb it with only moderate disruption. Source: NCDC Cooperative Stations – 1919 to 1995.

in housing cost from the increased demand. This has occurred through an entire cycle of boom and bust in the raw materials processing and transportation sectors. But even this region of the United States is not immune from climate variation.

A likely weather scenario that may result from global climate change is a modest increase in temperature and concurrent increase in rainfall in the Pacific Northwest. How could this be bad? The region is already famous for its persistent rainfall, particularly along the coast. However, the rainfall is fairly light. Many communities depend upon fresh water runoff for municipal water supplies. Aquifer recharge occurs through a combination of spring runoff of winter snows and very gradual seepage from rainfall. Even a modest increase in average temperature could shorten the accumulation time of winter snows, or disrupt the pattern or frequency of snowfall. The same circumstances that are cited above with regard to the water-dependent industries of the Pacific Northwest would also affect residential land uses.

The gentle rainfall of the Northwest has ample time to filter through the ground. Current temperatures allow significant snowfall to remain high in the mountains, to melt gradually as spring approaches. One-time disruptions in these patterns have proven highly disruptive on both sides of the mountains. On the densely populated coastal region, streams have flooded and fish spawning areas have been disrupted. Water quality has been reduced by flooding, which introduces pollutants from the soil surface, requiring more complex (expensive) filtration and treatment. On the agricultural side of the mountains, a boom and bust cycle is initiated, where disruptive floods are followed by periods of inadequate moisture, and thus lower crop yields (Figure 2).

Communities in the Pacific Northwest are beginning to adapt their infrastructure to these circumstances, however, and this may point the way toward a more broadly-based approach to infrastructure nationwide. Through "Green Building Standards" the town of Portland rewards businesses for innovative design and

construction of their facilities. For example, tax credits are offered for businesses that grow grass on their roofs, or that design parking facilities with water-filtering swales rather than hard concrete channels. How do these modifications in infrastructure design make any difference?

The surface of the Northwest coast is not very permeable - it requires gentle and persistent rain to function as a water collector. Most transportation infrastructure is even less permeable. Thus, any pollutant that can be transported by air will eventually fall to the ground or on a building or parking lot and be carried to storm drains. From there these pollutants make their way into the municipal water supply, where they have to be filtered and processed before the water can be used. But, if the buildings have permeable earth roofs, with grass or other vegetation growing on them, then pollutants are filtered out from rainfall before it reaches the ground, mitigating the pollutants' effects on the water supply. Such a technology could be applied to transportation infrastructure generally.

The Dutch government, recognizing that one of Holland's primary agricultural activities, greenhouses, presents an even less permeable surface than roads, has mandated that greenhouses be surrounded by filtration canals. This prevents any airborne pollutants from reaching nearby streams or rivers. In Germany, bicycle and pedestrian trails are being built from interlocking, permeable construction blocks. These are angled away from storm drain systems, to ensure that rainfall is filtered and channeled toward parkland and other surfaces that help to recharge aquifers. In the U.S., roadway materials have been developed for safety reasons, to wick away rainwater and assure cars and trucks of continued traction even in heavy rainfall. Now these materials are also being used for environmental reasons, to prevent the intrusion of particulates and other airborne pollutants from invading streams and rivers. How would a national plan be developed to identify the locations where this technology is most necessary today? Would initiating such adaptive mechanisms actually allow a community to mitigate the negative effects of

climate change sufficiently to remain viable over time?

Conclusion

This paper was written to provide a broad overview of potential effects of climate variation on basic human activities, remaining silent on the possibility that those very activities may be contributing to the self-same climate variations through greenhouse gas emissions. The scenarios presented should be viewed as notional, rather than predictive. The reader is encouraged to view the potential adaptations presented as a limited subset of options, developed to force a transportation infrastructure impact if possible. However, while transportation is involved in most human activities, it is not the only issue in most instances. The intent behind this paper was to address that subset of possible impacts that would relate to transportation and its infrastructure, in an effort to identify whether, and how, the infrastructure might have to be modified.

All of the modifications to infrastructure mentioned in this paper have a cost. However, that cost has to be balanced against the benefit provided by the modification. In the case of changing land uses, the benefit may be

significant. The modifications being made to buildings in downtown Portland may help to mitigate long-term effects of a changing climate *at the same time as they help to mitigate pollution that results from human activities*. By having a robust infrastructure, able to help recharge the local aquifer and preserve the purity of runoff water supplies, Portland preserves its ability to cope with excessive rainfall and to mitigate some negative effects on its local ecology. By reducing the human infrastructure impact on otherwise disruptive weather effects, Portland is actually helping to mitigate some of the most severe effects of modified rainfall or snowfall patterns that may be caused by global climate changes.

The question is whether such measures are sufficient as an adaptation strategy. Individual techniques will not work everywhere, but their root philosophy - working with the local environment - may help to formulate similar strategies for a wide variety of environments, from Arctic to Desert. In the end, it may be that the solutions developed to mitigate the effects of severe weather events on our Nation's transportation infrastructure are also those that reduce the climate effects of our patterns of land use and life activities. Solutions developed to adapt to climate change may help us to mitigate our effects on our climate. The final question is, "will it be enough, soon enough?"

¹ "Climate Change 2001: Synthesis Report" Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2001

² Higher CO₂ concentrations are linked to global climate effects, but the relative effect on specific crops depends on other supporting circumstances. While higher CO₂ levels may result in higher-yielding crops, *ceteris paribus*, concurrent high heat and low moisture rates may interfere with germination or fruiting in unpredictable ways, thus supporting rapid growth, for example, with little or no fruit.

³ Actually, the soil there is probably much too heavy to allow such a transition. The scenario is proposed in order to arrive at a structural shift in type of agriculture, to see its potential effect on transportation.

⁴ In fact, recent advertisements by the Freight Railroad Association indicate that trucking is the railroads' fastest growing market segment. Trains are carrying an increasing share of trailers on long distances, for distribution near their points of destination. At what point does this market repositioning require additions of rail track to serve the new markets, and at what cost?

⁵ Recent news commentary (MSNBC, Dan McFadden, October 10, 1999) implies that the positions of the States regarding Colorado River agreements are so intractable that the U.S. Government may have to initiate some change in these relationships via negotiations with Mexico.

⁶ In the soon to be published TCRP H-21 study "Combating Global Warming Through Sustainable Surface Transportation Policy" the Center for Neighborhood Policy indicates that the more dense urban environment uses far less energy per transportation use than surrounding suburban and rural areas. The lower energy use (and resulting carbon emissions) is directly linked to the presence of public transportation. GIS analysis shows that the higher-efficiency pattern of land use follows commuter rail lines to the suburbs.

Mr. Marx is a Senior Economist with the Federal Transit Administration, working on transit finance, land use and transportation, and climate change. He holds an MBA from George Washington and an M.S. from the U.S. Naval War College. Mr. Marx was a German Marshall Fund Environmental Fellow in 1999, and a European Commission Expert Evaluator in 2000.

Water Quality and Ecosystems

By Erika S. Mortenson and Fred G. Bank

General Environmental Responsibilities of the Federal Highway Administration

The mission of the Federal Highway Administration (FHWA) is to continually improve the quality of our Nation's highway system and intermodal connections. As one of its strategic goals, the FHWA includes the need to carry out its mission in a manner that protects and enhances the natural environment and communities affected by transportation. This goal requires that principles of environmental stewardship be incorporated in all of the FHWA's policies, procedures, and decisions. Therefore in concert with the State transportation agencies, the FHWA must responsibly consider and evaluate all aspects of the environment throughout the highway planning, design, and development processes. The FHWA also must provide training and technical assistance to its State and Federal partners to help minimize the potential adverse environmental impacts of Federal-aid and Federal Lands projects. Training and other assistance enhances FHWA's ability to implement ecosystem and habitat conservation, and showcase existing exemplary initiatives.

The possibility for global climate change draws the attention of organizations whose responsibilities not only shape current activities, but also respond to projected future trends concerning the status of the environment. Although the existence, magnitude, direction and potential affects of global climate change are in constant debate, the FHWA should consider and develop contingencies for possible

effects of climate change on surface transportation systems and the surrounding environment.

Therefore, this paper generally examines transportation responsibilities and outcomes in light of changes in climatic conditions that could occur based on possible trends in global warming. The paper specifically addresses trends that may influence how FHWA and its partners fulfill responsibilities to protect water quality and ecosystem integrity relative to the nation's highway program. Its purpose is to stimulate thought on these potentially important issues by pointing out possible consequences of warming trends on these resources. The paper does not draw conclusions on the likelihood of such consequences nor attempt to estimate their severity.

Transportation Development – The Federal Partnership with the States

Area-wide transportation planning is a pivotal strategy in the cooperative approach for financing needed improvements in the nation's transportation infrastructure. The approach is a federal-aid program wherein State and local governments finance needed transportation improvements with the use of Federal funds made available from taxes collected primarily through the sale of gasoline. Under this funding arrangement, the State Departments of Transportation (DOTs) and the Metropolitan Planning Organizations, must plan highway and transit improvements through the use of an integrated process that results in long-term programs of projects needed to support the current and future movement of people and

goods. These programs address needs over several frames of reference. Although mobility improvements are the focus, the planning process also includes participation by the public and private sectors in order to support other quality of life objectives. The process incorporates a variety of elements, including environmental protection and enhancement coupled with accessibility to, and equity in, the provision of transportation services. Collectively, these and other elements of the planning process can fit together as a Federal-State partnership to help meet a variety of local needs and national priorities.

FHWA's Environmental Obligations and Commitments

Transportation agencies and planning organizations acting through the Federal-State partnership, must comply with numerous Federal and State environmental statutes, implementing regulations, and Executive Orders. The most significant of these in terms of both time and money expended to address potential effects of transportation projects on water quality and ecosystems are the National Environmental Policy Act of 1969 (NEPA), the Clean Water Act of 1977 [in particular Sections 404 (permits for the discharge of dredged and fill material), 402 (Stormwater permits for Phase I & Phase II), 401, and 303 (TMDLs)], Coastal Zone Act Reauthorization Amendments (CZARA) of 1990, Executive Order 11990: Protection of Wetlands, and the Endangered Species Act of 1973.

Actual costs for implementing programs and strategies to avoid, minimize, and mitigate potential impacts to water quality, wetlands, and endangered species are difficult to distinguish and measure. Current baseline examples are necessary if DOTs are to plan for changes in time and costs that may be needed for compliance and environmental stewardship in a future with an uncertain and changing climate. Lack of available data makes the planning for future outcomes problematic. There could be scenarios where resource commitments must increase as transportation programs adjust to more numerous and varied effects of climate.

Conversely, the importance of environmental features may diminish over time due to climate changes, thereby reducing the relative effects of transportation on the environment and lowering current expenditures for impact mitigation. Given projected warming trends, conclusions of how continued compliance may change expenditures in the future are discussed in the sections that follow.

Stormwater Programs and the Clean Water Act

The Clean Water Act is addressed by individual DOTs through the implementation of Best Management Practices for the mitigation of potential water quality impacts from roadway stormwater runoff, construction activities, maintenance and other highway-related activities. The costs of these measures can be expressed through various means – permit application requirements, construction of detention ponds, design, monitoring and maintenance programs, and other requirements.

The most common contaminants in highway runoff are heavy metals, inorganic salts, aromatic hydrocarbons, and suspended solids. The major sources of these pollutants are vehicles, maintenance activities, and wet and dry atmospheric deposition. Vehicles are both a direct source of pollutants and an indirect source. Vehicles contribute directly to the pollutant load through normal operation, corrosion, tire wear, leakage of lubricants and fuels, cargo spills, and accidents. They indirectly contribute pollutants by picking up solid materials, which they later deposit on the road through precipitation wash-off, the scouring action of wind, and gravity. Highway maintenance activities, such as sanding, deicing and the application of herbicides also contribute materials to the runoff pollutant loadings from highways. Atmospheric fallout, or dustfall, accumulates on paved surfaces during dry periods and can contribute significantly to the runoff mix during wet periods. Dry and wet deposition can be characterized by a variety of substances most often reflecting land use sources adjacent to the highway.

Roadways and highways are designed to quickly convey stormwater away from the travel path of vehicles. This is done for safety reasons and also to ensure that the physical integrity of the road surface is maintained. These impervious surfaces affect the potential concentration of pollutants by intercepting and diverting the stormwater flow. Retention and detention basins, among other management practices, can be highly effective means for controlling pollutant release to the environment and have been used extensively for many years.

But by far, the most prevalent highway drainage design has been unintentionally treating stormwater runoff effectively since the time of the first paved roads. These are the common features of vegetated swales and ditches along roadsides. Simple measures such as these collect runoff pollutants directly from the pavement, trapping them through soil adsorption and filtering through the vegetation. These simple drainage features can be very effective when considering only physical mechanisms to remove pollutants from stormwater, but they also provide important chemical and biological abatement as well.

Where vegetated drainage features are not practicable, such as urban and suburban areas with curb and gutter draining into storm sewer systems, highway runoff may have adverse effects if no specifically designed measures are taken for the removal of excessive contaminants before the runoff reaches receiving waters. In these cases, adverse effects of highway runoff water quality can be minimized through structural and non-structural best management practices or through a combination of both.

Structural best management practices consist of infiltration technologies, detention, retention, filtering systems, low impact development features, and in limited applications, porous pavements. Structural best management practices operate by physically trapping runoff until contaminants settle out or are filtered through underlying soils or other artificial media. They work through the process of gravity settling of constituents, or through the infiltration of soluble nutrients through soil or

filters, or through constructed biological and chemical processes.

Non-structural best management practices deal mainly with source controls, such as low impact development land use planning and management (which also use structural methods), street sweeping, or improved maintenance programs. These methods help reduce the initial concentration and accumulation of contaminants in the stormwater runoff. Non-structural controls can reduce the need for generally more costly structural controls.

Climate Changes and Highway-related Stormwater Quality

Water quality is a direct result of the chemical inputs received from air and the surrounding land and the biogeochemical processes that transform those inputs. Direct chemical contributions come from point source discharges, such as from sewage treatment plants. Indirect contributions come from atmospheric deposition and surface waters that flow in watersheds through vegetation, soils, and aquifers, each of which contributes to water chemistry. Global climate changes have the potential to significantly alter stormwater runoff quality and quantity by changing water temperature, flows, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants.

Climatic changes leading to higher intensity storms may increase flows from highway facilities over and above what is now calculated during the design of typical drainage systems. This may mean increasing erosion of receiving stream channels, leading to higher sediment, chemical, and nutrient loads. On the other hand, lower flows associated with drought conditions could reduce dissolved oxygen concentrations, reduce the dilution of pollutants, increase zones with higher water temperatures, and increase flushing times.

Increased rates of oxygen depletion in already eutrophied waters in U.S. may occur if global warming trends continue as some predict.

Warming could increase the rate of biological production and decomposition by increasing the rates of metabolism, the duration of the growing season, and the volume of waters that are biologically active. Increased water temperatures enhance the toxicity of metals in aquatic ecosystems and increased lengths of biological activity could lead to increased accumulation of toxics in organisms. If changes in terrestrial ecosystems occur because of warming, nutrient cycling rates and the delivery of nutrients to surface waters may be altered. Nitrification rates in soils are temperature dependent and in some regions, mean annual nitrate concentrations in streams are highly correlated with average annual air temperature. Extended droughts in some regions may increase the risk of acidification of streams due to the oxidation of pools of organic sulfur in soils.

The net effect on water quality for rivers, lakes and groundwater in the future depends in part on how climate conditions might change. This may require that DOTs expend greater funds to adjust stormwater drainage designs to compensate for the potential of additional adverse impacts.

Wetlands

There is an overall national policy for Federal agencies to protect and enhance the nation's wetlands. The policy is to reverse the trend in habitat loss by achieving a net gain in wetland acreage resulting from Federal actions. Provisions of the Clean Water Act support it, most specifically by the Section 404 program that regulates the discharge of fill material into waters, including wetlands. In 1994, FHWA issued an agency Environmental Policy Statement. Among the commitments made by the FHWA in the statement was a call for the protection and enhancement of all natural resources, including wetlands. In subsequent strategic plans and performance agreements, the FHWA established an agency policy of no-net-loss of wetlands impacted on a program-wide basis for Federal-aid highway projects.

In 1996, the FHWA revised its no-net-loss policy upward to a net gain goal. The agency's 1996 performance plan and all subsequent plans indicated this change by establishing a performance measure for wetland acreage replacement ratio of 1.5:1. The current FHWA Performance Plan states that the agency will: "*On a program-wide basis, replace at least an average of 1.5 acres of wetlands for every 1 acre directly affected by Federal-aid highway projects where impacts are unavoidable*" The FHWA achieves its wetland conservation and enhancement goal by working with the DOTs to encourage the use of the flexibility under authorizing legislation to finance wetland mitigation and restoration projects.

As a measure of performance under the FHWA's net gain policy, the agency gathers annual wetland loss and gain under the Federal-aid highway program nationwide. Data gathering from the State DOTs began in fiscal year 1996. Data collected over the last 6 years indicate that nationwide, the Federal-aid highway program has achieved a 130 percent gain in wetland acreage (2.3:1 gain/loss ratio). In terms of acres, the Federal-aid highway program produced a total reported net gain of more than 16, 958 acres of wetlands nationwide 1996-2001.

Once a DOT has clearly established the need for a highway that will require the taking of wetlands (after exploring avoidance alternatives), the DOT must develop plans to mitigate for wetland losses. The FHWA has developed a tool to collect and analyze wetland mitigation information from each of the DOTs. The estimate for average cost per acre of compensatory wetland mitigation is approximately \$35,000, nationwide. This figure was \$16,000 per acre in 1995. This results in an estimated cost from 1996-1999 for the entire federally funded highway program of approximately 50-80 million dollars per year for replacement wetlands (in pre-1995 dollars). Comparing these figures with the average total national obligation of Federal funds from categories that could be used for wetland mitigation during those years of about \$11

billion, the cost of mitigation is approximately 0.7% of the total annual expenditure.

Likely climate change impacts on wetlands can be expected because changes in temperature and precipitation can alter wetland hydrology, biogeochemistry, plant species composition, and biomass accumulation. Because of the fragmentation impacts resulting from past human activities, wetland plants often cannot migrate in response to temperature and water-level changes and hence are vulnerable to complete elimination. Existing roads, as well as future road projects may inhibit migration rates in a changing climate and therefore require an increase in the number of acres that must be mitigated, thus leading to higher cost to the highway program.

Small shifts in the balance between precipitation and evapotranspiration can alter the groundwater level and affect groundwater discharge and streamflows, which may significantly reduce the size of wetlands and changes in wetland types. Loss of remnant plant and animal species from alpine wetlands seems likely since there is little opportunity to migrate. Mid-continent wetlands that depend on precipitation as a primary water source may be especially vulnerable to climate variation and change. Some climate scenarios for the Northern Great Plains region suggest that increased temperatures over the next 50 years could result in a 40% or more reduction in the number of prairie potholes and a resulting decline in waterfowl populations.

Although wetland species are sensitive to changes in seasonality of precipitation, there are some practical options for protecting wetlands as a whole from changes in precipitation and other factors, such as rising sea level. Future wetland mitigation may require greater emphasis on linking fragmented ecosystems to provide plant and animal migration routes. It could also mean development in coastal and estuarine areas would have to be rethought to maintain viable wetland resources because sea level rise would tend to “re-establish” wetlands further inland. All these potential occurrences could have dramatic effects on how transportation systems

are planned and implemented, particularly the costs associated with the mitigation of impacts to a wetland resource otherwise threatened or redefined by climate changes.

Endangered Species and Ecosystems in General

The Federal Highway Administration and State Highway Agencies have broad responsibility for ensuring the planning, construction and operation of an environmentally sound, effective, and safe national transportation system. These responsibilities encompass almost all ecosystems where any human development has occurred. Transportation projects often have important direct and indirect impacts on natural ecosystems, and connect adjacent or distant ecosystems through travel corridors and right-of-way management practices. Highways affect ecosystems by altering and replacing existing biological communities, by creating barriers between different habitats, by introducing new species and activities, by providing new access for socio-economic development and construction, by altering drainage patterns, and by changing the basic geochemistry of a region (for example, water and air quality). Many of these impacts are long-term, even those which we often consider to be temporary. An example is erosion and sedimentation. While the source of erosion might be temporary, the effects of the sediment are long lasting once it has entered the aquatic system. Other impacts, such as those generated by access, can be both long term and progressive, depending on local land use and development planning.

Whenever a proposed transportation improvement has the potential to affect a species listed, or proposed to be listed as either Threatened or Endangered under the Endangered Species Act of 1973, certain actions are required. This may involve studies to determine the actual presence of such species in the project area, and consultation with the agencies having jurisdiction over the species, either the U.S. Fish and Wildlife Service or the National Marine Fisheries Service. The result of these actions may mean project modification and special

measures to remove the potential for impact to the species.

There are currently 1,261 species listed as either endangered or threatened on the Threatened and Endangered Species List in the U.S. The FHWA tracks the cost of Endangered Species involvement on Federal-aid highway projects on a yearly basis. The most recent data indicate that in 1998, \$6,933,700 was spent on items such as land acquisition, habitat enhancement, and monitoring.

Previous assessments have established a wide range of possible direct effects, including changes in lake and stream temperatures, lake levels, mixing regimes, water residence times, water clarity, thermocline depth and productivity, invasions of exotic species, fire frequency, permafrost melting, altered nutrient exchanges, food web structure, and more. These impacts could lead to a wide range of serious adverse impacts on ecosystems, with changes in vegetation patterns, possible extinction of endemic fish species already close to their thermal limits, declining area of wetlands precipitating reductions in waterfowl populations, concerns about stream health, and major habitat loss.

In the southeastern U.S., for example, the projected impacts of higher temperature are: reduction in habitat for cool-water species, such as brook trout and many aquatic insects, which are near the southern extent of their ranges; greater summer drying of wetland soils resulting

in greater fire threat; and the northward expansion of subtropical species, some of which are nuisance exotics. Indirect effects mediated through food web interactions are also likely in an altered climate.

Species have differing environmental needs in their ecosystems. A change that can be devastating to one species is likely to encourage the expansion of another to fill that niche in the system. Extreme conditions such as floods, droughts and fire are critical to sustaining certain ecosystems, and changes in the frequency of these events are likely. The natural ecosystems of the Arctic, Great Lakes, Great Basin, Southeast, and prairie potholes of the Great Plains appear highly vulnerable to the projected changes in climate.

The health and dynamics of ecosystems are fundamentally dependent on a wide range of climate-sensitive factors, including the timing of water availability, overall water quantity, quality, and temperature. A changing climate may intensify current threats to ecosystems and species in peril in many ways, such as by accelerating the spread of exotic species and further fragmenting populations. The number of species that are currently listed as threatened or endangered is likely to increase in the future due in part to climate changes. Therefore in the future, there will likely be an increase in money and time spent researching, consulting on, and implementing compensatory measures for endangered species potentially impacted by transportation projects.

Ms. Mortenson is an ecologist and Environmental Coordinator with the New York Division office of the Federal Highway Administration. She manages and provides oversight of the agency's environmental responsibilities, as they relate to delivery of the Federal-aid highway program in New York State. Topics under her oversight responsibilities include the assessment and mitigation of highway impacts to water quality, streams, wildlife habitat, wetlands, and other natural resources. She holds a Bachelor of Science degree in biology from Coastal Carolina University and a Master of Science degree in biology from New Mexico State University.

Mr. Bank has been an ecologist with the Federal Highway Administration since 1975. His work focus is the technical application of his discipline related to the environment and highway system development in

the United States. This includes responsibilities for developing policies and managing agency activities on water quality, wetlands, sediment and erosion control, highway stormwater runoff, streams and watersheds, wildlife habitat impacts, ecosystems, cumulative and secondary impacts, and environmental research. He holds both Bachelor and Master of Science degrees in Range Science from the University of California, Davis.

Part III: Appendices

DOT Center for Climate Change and Environmental Forecasting
Federal Research Partnership
DOT – EPA – DOE – USGCRP

Workshop re: Potential Impacts of Climate Change on Transportation

AGENDA

Date: October 1-2, 2002

Location: Brookings Institution

Workshop Objective: *To gain input and perspectives on priority research topics related to the potential impacts of climate variability and change on transportation – through dialogue with transportation professionals, regional and national stakeholders, and experts in climate change and assessment*

OCTOBER 1, 2002

7:30 **Coffee, continental breakfast, and check-in**

8:30 **Welcome / Introductions (Stein Room)**

DOT Center for Climate Change & Environmental Forecasting

The Importance of Research on Climate Change and Transportation

Mr. Emil Frankel
Assistant Secretary for Transportation Policy, DOT

Dr. James Mahoney
Assistant Secretary of Commerce
Director, Climate Change Science Program Office
U.S. Department of Commerce

Workshop Purpose and Agenda Review

Workshop Facilitator: Mr. Douglas Brookman, Public Solutions

8:45 **Creating a Shared Context (Stein Room)**

All

9:45 **Panel A – Overview of Trends (Stein Room)**

Moderator: Mr. Joel M. Szabat, OST
Deputy Asst. Secretary for Transportation Policy, DOT

How has climate changed in the U.S., and how is it projected to change?

Dr. David R. Easterling
Principal Scientist
NOAA National Climatic Data Center

What lies ahead for transportation?

Dr. Martin Wachs
Director, Institute of Transportation Studies
University of California, Berkeley

How do climate change and transportation intersect?
What do we know, and what don't we know?

Mr. Brian Mills
Adaptation & Impacts Research Group
Meteorological Service of Canada
Environment Canada

Q&A

10:45 **Break**11:00 **Panel B – Assessing the Impacts of Climate Change and Variability on Transportation**
(Stein Room)

Examples of how climate change and transportation concerns may intersect - looking at specific regions, transportation networks, and climate impacts.

Moderator: Mr. James Shrouds, Director, FHWA Office of Natural Environment

Dr. Rae Zimmerman
Institute for Civil Infrastructure Systems
Robert F. Wagner Graduate School of Public Service
New York University

Mr. John Gambel
Senior Technical Advisor
Federal Emergency Management Administration

Dr. Virginia Burkett
Chief, Forest Ecology Branch
USGS National Wetlands Research Center

Q&A12:00 **Discussion** (Stein Room)

What are the key concerns regarding climate changes for transportation?

All
Distribute topics raised to breakout groups

12:30 **Lunch / Table Talk** (Zilkha Lounge)

Informal conversation with climate change and transportation experts

- What are the latest trends and important findings?
- What are the 1-2 things we could do to advance research through cross-agency collaboration?

Coordinator: Dr. Michael MacCracken, Senior Scientist, USGCRP

Table 1: Climate change – Dr. David Easterling, NOAA (Saul Room)

Table 2: Assessment – Dr. Michael MacCracken, USGCRP (January Room)

Table 3: Impacts – Mr. Brian Mills, Meteorological Service of Canada (Kresge Room)

Table 4: Transportation issues and trends – Dr. Donald R. Trilling, DOT; Dr. Martin Wachs, U.C. Berkeley (Kresge Room)

1:30 **Brief Table Talk Reports** (Stein Room)

Ways to Enhance Collaboration

All

2:00 **Break Out Sessions****Concurrent Groups****KEY ISSUES**

- What are the potentially most significant problems to be addressed?

- Coastal Areas – Rail and Road (Stein)
- Coastal Areas – Marine (Kresge)
- Interior Regions – Rail and Road (Stein)
- Great Lakes and Rivers – Marine, Rail and Road (Kresge)
- National – Aviation (January)
- National – Transportation Systems (Saul)

3:15 **Break**

3:30 **Break Out Sessions** (continued) Concurrent groups continue

KEY RESEARCH

- For each of these priority areas, what specific research needs to be initiated?
- Who should initiate this research?
- What are the opportunities for partnering?

4:30 **Reconvene. Day 1 Wrap – Up** (Stein) All

What did you find that was interesting or surprising in discussing these problem areas?

Preview of Day 2

5:15 **Adjourn**

5:30 **Reception at Brookings Institution** (*Brief session with facilitator and breakout session leaders*)
(Zilkha Lounge)

OCTOBER 2, 2002

8:00 **Coffee, continental breakfast**

8:30 **Brief Reflections from Yesterday...** (Stein) All

9:00 **Report-Backs / Q& A / Discussion** (Stein)
(10 minutes per Group) Session Leaders

10:30 **Break**

10:45 **Discussion – Where Do We Go From Here?** (Stein) All

How do we assure these priority research areas are undertaken?

Action Items/ Next Steps

12:00 **Closing Comments** (Stein) Mr. Joel M. Szabat

Adjourn

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