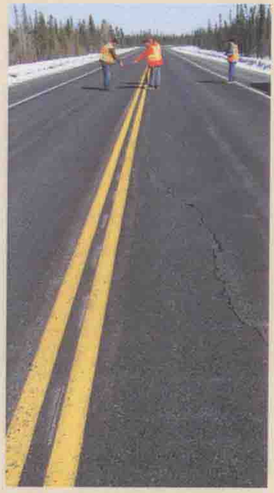
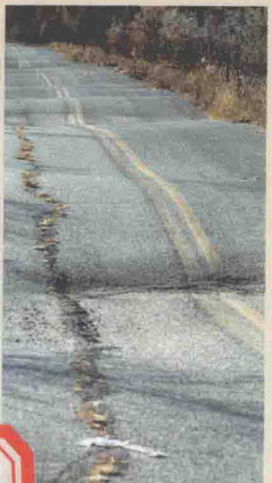
# Climatic Effects on Pavement and Geotechnical Infrastructure



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*Edited by*
Jenny Liu, Ph.D., P.E.; Peng Li, Ph.D.; Xiong Zhang, Ph.D., P.E.; and Baoshan Huang, Ph.D., P.E.

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# CLIMATIC EFFECTS ON PAVEMENT AND GEOTECHNICAL INFRASTRUCTURE

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# Preface

*Climatic Effects on Pavement and Geotechnical Infrastructure* selects 22 papers that represent the latest developments and advances of the impact of various climatic factors, such as freeze and thaw, wet and dry cycle, rainfall, flooding, etc., on designing, building, preserving and maintaining transportation infrastructure.

Many of the selected papers were presented at the International Symposium of Climatic Effects on Pavement and Geotechnical Infrastructure 2013 held in Fairbanks, Alaska, USA from August 4 to 7, 2013. The conference was hosted by the University of Alaska Fairbanks in collaboration with the University of Alaska Anchorage in USA, Tongji University in China, Harbin Institute of Technology in China, Chang'An University in China, International Association of Chinese Infrastructure Professionals (IACIP), the American Society of Civil Engineers (ASCE), and the University of Tennessee, Knoxville in USA.

The papers presented within the *Climatic Effects on Pavement and Geotechnical Infrastructure* Special Technical Publication (STP) are divided into four groups. The first group contains four papers which provide an international perspective on climate change and infrastructure and climate network. The second group of papers contains five papers focused on preservation, maintenance, and operations of pavement and geotechnical infrastructure in correspondence to various climatic conditions. Eight papers are collected in the third group on advancing innovative sustainable materials and design for transportation infrastructure use. Furthermore, five papers on various analysis and evaluation approaches to assess the climatic effects on performance and life of infrastructure are provided.

Two or more reviewers along with the editors evaluated each paper published in this ASCE STP. All published papers are eligible for discussion in the *Journal of Materials in Civil Engineering*, and are eligible for ASCE awards.

We would like to acknowledge the great support from Laura Ciampa and Marvin Oey from the ASCE Construction Institute (CI) that makes it possible for this high quality peer reviewed STP. Most importantly, we would like to thank the peer reviewers who spent their time and efforts in ensuring the exceptional quality of the papers presented within this STP. Without their contributions this publication would not be possible.

# Author List

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*Analysis and Evaluation Approaches*

# Impact of Climate Change on Pavement Performance: Preliminary Lessons Learned through the Infrastructure and Climate Network (ICNet)

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**ABSTRACT:** The Infrastructure and Climate Network (ICNet) was established to develop collaborative networks and platforms needed to integrate the multidisciplinary areas of climate change, pavement design and performance, and economics. Preliminary network activities, described in this paper, have rapidly expanded our knowledge of pavement performance under future climates and provide insights for future research. Specifically, increases in the frequency and/or severity of many types of extreme weather events have already been observed; projected future changes in air temperature, rainfall, sea level rise and hurricanes on pavement performance are significant; and future costs are expected to increase very significantly and non-linearly. Combining these findings, we offer a set of recommendations for future research to address our key research question: *How does climate non-stationarity differentially impact transportation infrastructure design, performance and life span?*

## INTRODUCTION

The nation's infrastructure is becoming increasingly vulnerable to damage from changing weather patterns resulting from global climate change. Observations, models, and even paleohydrologic studies identify the potential for changes in climate characteristics that directly impact infrastructure design. Observed and projected future changes in infrastructure-relevant climate characteristics include the average, variability, and extreme values of temperature, solar radiation, snow and rainfall, freeze-thaw cycles, groundwater levels, and streamflow. Increases in sea level and changes in the intensity of tropical storms and hurricanes carry additional implications for coastal infrastructure.

Pavements constitute the most widely used part of the nation's infrastructure for the transportation of people and goods. Changing climate can impact the properties of the pavement layers, making them susceptible to accelerated damage under traffic loading, reducing their serviceable life span, and increasing maintenance costs, all of which would have a major negative impact on the nation's economy. An increase in pavement temperature as a result of rising air temperature, reduction in subgrade and hot mix asphalt (HMA) modulus due to high rainfall (saturation), and flooding due to rise in sea water level (in coastal areas) and stronger hurricanes are all factors that should be considered to design and construct pavements that will perform under non-stationary future climate conditions.

We argue that the key to constructing resilient pavements is accounting for the fact that climate can no longer be assumed to be a stationary process – in other words, that the past is no longer a reliable guide to the future. Instead of relying solely on historic datasets and single-valued design parameters, engineering methods must be able to accommodate changing parameters and a range of projected climate futures to ensure that pavements are designed to withstand the conditions that are likely to occur over their lifetime.

There are many challenges to incorporating information from climate projections into the existing pavement design methodologies and also more generally into the knowledge community supporting long-range infrastructure decisions. The Infrastructure and Climate Network (ICNet), a network of engineers and scientists, was formed to integrate climate science and engineering research for sustainable transportation infrastructure in New England and is funded by a U.S. National Science Foundation (NSF) research grant from the RCN-SEES program (CBET-1231326). ICNet uses joint knowledge-building approaches which are appropriate for complex problems and have slowly permeated into the planning and policy communities as well as a few large-scale institutions like the U.S. Army Corps of Engineers (http://www.sharedvisionplanning.us/).

ICNet's goal is to integrate climate change and adaptation research into infrastructure engineering by addressing the problem as a network of researchers and practitioners, rather than as individual investigators. ICNet members are identifying, prioritizing and developing climate impact information and resources needed to make decisions about building bridges and roads today that will last longer and cost less to maintain under the uncertain conditions of tomorrow. A distinctive part of our strategy is to build community and develop resources to support knowledge-sharing and prioritization among ICNet researchers and to link that knowledge to the community of user institutions. This is being done through interactive workshops with researchers and stakeholders, webinars, and a knowledge commons that is readily accessible (theicnet.org). ICNet is an open community that encourages participation in network activities and the development of new collaborations among researchers and practitioners in New England. This paper presents outcomes from ICNet's early exploration process in which the research and practitioner communities jointly collaborated to identify relevant climate information, to use that information to identify research needs and to explore the impact of future climate on pavement performance at multiple scales.

## CLIMATE CHANGE AND SEA LEVEL RISE

Climate defines the range of conditions (both "normal" and extreme)—in terms of temperature, precipitation, humidity, etc.—experienced over multiple decades. The notion of climate stationarity assumes that average conditions do not change over time and that climate variability remains within a quantifiable range. This assumption has allowed engineers to design infrastructure that are reliable to an acceptable level of failure risk. However, both the validity and utility of this assumption has been called into question (Milly et al., 2008; Lins and Cohn, 2011). Climate is already changing, here in North America and around the world (USGCRP, 2009) and decades of research has demonstrated that extreme events are more sensitive to climate change than average events; in fact, "a changing climate … can result in unprecedented extreme weather and climate events" (IPCC, 2012). Despite large increases in heavy precipitation events, it has been difficult to tease out the influence of climate change on flooding, given the complex nature of watershed processes, natural climate variability and anthropogenic factors such as land use change, urbanization and flow regulation (i.e., Shaw and Riha, 2011; Smith et al., 2011). However, the observed and projected impacts of climate change on temperature extremes are direct and clear: the number of cold days and cold extremes is decreasing, while the frequency, magnitude and duration of heat waves and heat extremes are increasing.

New England has already experienced increases in annual and seasonal temperatures and changes to hydrologic processes (for information and publications, see www.climatechoices.org/northeast). These changes are expected to accelerate into the future as human emissions of carbon dioxide and other heat-trapping gases continue to rise. For example, an average summer in New England could feel like a summer below the Mason-Dixon line by mid- to late century. For coastal areas, rising sea level is one of the most certain and potentially devastating impacts of climate change. Globally, the ocean is expanding and rising as an estimated 93% of the excess heat trapped within the Earth's climate system by human emissions is being absorbed by the ocean (Levitus et al., 2012). Atmospheric warming is accelerating glacial ice melt and the increased ocean heat content is destabilizing ice sheet margins in Antarctica and Greenland (Joughin et al., 2012). Kemp et al. (2011) suggested that the increase in sea level since the 19$^{th}$ century along the eastern Seaboard represents the steepest century-scale increase in sea level over the past two millennia. Sallenger et al. (2012) identified the Northeast U.S. coastline as a SLR "hot spot", with SLR rates 3-4 times faster than the global rate. Add to that a potential two- to seven-fold increase in extreme "Katrina-magnitude" storm surge events along the U.S eastern and Gulf coast (Grinstead et al., 2013) and the likelihood of future damage to infrastructure increases dramatically.

## RESILIENT PAVEMENT DESIGN IN A CHANGING CLIMATE

It is evident that pavements are at increasing and critical risk from climate-driven stressors; anticipated changes could alter the frequency, duration, and severity of road failures as well as the time and cost of reconstructing the pavement systems. ICNet members conducted a detailed review of pavement systems in New England to better understand potential impacts of climate change on pavement design and maintenance in the future and to identify limitations in the sector's knowledge. ICNet's findings indicate that pavements face failure from a combination of temperature and water impacts. Higher temperatures will decrease the stiffness of the asphalt concrete pavement, increasing susceptibility to rutting, while more freeze thaw cycles would increase the damage from frost heaves and potentially increase thermal fatigue cracking. Increased precipitation, flooding events, and/or SLR will increase the moisture content of the granular (soil) sub layers under the pavement surface. The increase could be permanent (in case of higher groundwater tables) or temporary (longer drainage times). Coastal roadways, especially local and secondary roads, will be flooded more frequently as the limit of high tide moves landward and storm surge and wave effects reach farther inland than in the past. Higher moisture contents weaken the pavement base and subgrade; this can lead to increased cracking or rutting of the pavement surface due to loss of underlying support, hastening failure of the entire pavement structure. Flooding can also lead to sudden catastrophic failure (washout) if the event is sufficiently large. Impacts from temperature and water ultimately will require new pavement designs, roadway elevation or re-routing in order to accommodate expected changes.

Better understanding of these potential modes and consequences of failure is critical to the evaluation of options with regard to infrastructure (Transportation Research Board, 2009). ICNet members have conducted some initial research activities to quantify changes in pavement failure modes under future climates in New England. The sections below briefly describe research and results from two pilot studies that evaluated local-scale pavement design and pavement system dynamics. Challenges and opportunities for future research are presented in each section.

### Pilot Study 1: Local Scale Evaluation of Climate Change Impacts on Pavements

The impact of a changing climate on pavement performance has been investigated by a few researchers in the past (Mills et al. 2009) and most recently, ICNet members presented a methodology to assess the impact of future climate change on pavement deterioration (Meagher et al. 2012). Instead of relying on historic observations, they conducted a mechanistic-empirical analysis of pavement structures (designed for four sites across New England) with projected future temperatures, and evaluated their effects on the rutting and cracking performance of the pavements. The effect on the rutting potential of the asphalt concrete layer was found to be significant. The authors demonstrated and proposed the use of high-resolution future climate projections to create modified hourly climatic inputs for the mechanistic empirical pavement design guide/software (MEPDG/S). For example, Meagher et al. used the North American Regional Climate Change Assessment Program's (NARCCAP) products to provide modeled output for two periods, 1971-2000 and 2041-2070, at a spatial resolution of 50 km, based on the SRES (Special Report on Emissions Scenarios) A2 mid-high emissions scenario. Because there often is a bias between model output and the required MEPDG site information, a cumulative distribution function transformation method was used to adjust the NARCCAP temperature data to site-specific data for use in the MEPDG. The importance of this probabilistic transformation was underscored by the shift in historical and future temperature forecasts once the observed statistical characteristics were matched. This method is fundamentally different from a recent study completed by Truax et al. (2011) for the state of Mississippi which also evaluated the impact of climate on pavement performance using the MEPDG. Truax et al. used decadal output from a single regional climate model (RegCM2) for the 1990s and 2040s to calculate the change in precipitation and temperature due to climate change. This 'delta' was then applied to the historic MEPDG climate files to create future climate files. While both approaches are reasonable, their differences make comparisons across studies difficult.

Even if the climate projections are consistent across studies, challenges will still arise from how to best use that information. For example, the MEPDG/S requires climate projections at an hourly time resolution that are not readily available from either global or regional climate models, so Meagher et al. applied average values to each of the corresponding three-hour intervals. However, the use of averages reduces the extreme temperatures that are critical to predicting rutting and thermal cracking. Also, one must consider that different climate variables have different degrees of uncertainty associated with them: lower uncertainty for projected temperature changes, higher for precipitation, sunshine, relative humidity, and a great deal higher for wind speed and direction. MEPDG/S requires forecasted modifications to all variables to completely assess net impacts of climate change and the decoupling of the interactions among the variables could change predictions of future pavement performance.

## Pilot Study 2: A Systems Dynamics Approach for Evaluating Climate Change Impacts on Pavements

The effect of climate change on the entire life cycle of pavements (and pavement systems) including maintenance costs may be best evaluated through a systems dynamics approach. Systems dynamics modeling has the ability to link elements across disciplines (such as climate science and civil engineering), to model the interdependencies, and to utilize feedback loops (causal loops) to identify non-linear trends in responses, if any, which may appear only at a later period. A system dynamics model linking climatic changes to pavement maintenance and costs was developed by members of the ICNet group (Mallick et al., 2014). The effects of climate change which are considered include increases in average annual rainfall, maximum air temperature, hurricane frequency and SLR. These parameters will affect the pavement systems by increasing the pavement temperature and number of months during which the subgrade is saturated. Pavement state variables were linked to stiffness (represented through modulus) of the HMA and subgrade. The life of the pavement is represented by rutting evaluated using the MEPDG to illustrate the framework.

The model was run for a time span of 100 years for two cases, with and without climate change. The average pavement life decreased from 16 (without climate change) to 4 years (with climate change) as a result of reduced effective subgrade and HMA modulus due to climate change. The maintenance costs increased after 20 years for both cases; a linear increase was observed when climate change was not considered whereas consideration of climate change resulted in a non-linear increase.

At the end of 100 years, the cost of maintenance considering climate change increased 160%, as compared to the less than 60% increase without the impact of climate change. The study recommends that, for making long-term predictions and optimizing pavement performance for expected changes, engineers must integrate available climate, pavement and economic (as well as environmental) data in a systems dynamics approach. There is a critical need for accurate and reliable data regarding climate changes, particularly those that will have significant effects on pavement performance.

The data requirements and challenges for the systems approach differed greatly from that of the site-specific MEPDG study. In order to capture the overall system performance and ultimately maintenance cost increases, empirical relationships are more appropriate to link climate data to pavement state and performance than a complex physical model (e.g., MEPDG's mechanistic approach). However, the empirical relationships are derived from a database of results that are generated from mechanistic-empirical analyses. The reduction in model complexity allows the systems model to broadly evaluate the relative contribution from many climate forces that potentially cause deterioration and to deploy sensitivity analyses.

Even when targeting simplified methods, developing estimates of subgrade saturation and inundation frequency is a nontrivial process. There is no direct method to translate precipitation to subgrade saturation. Mallick et al. used a simple one-dimensional water balance model to predict the change in the number of times the soil could be expected to be at or close to saturation. While this approach can account for the arrival of rain events, it requires additional subgrade soil properties to be specified. Inundation frequency presented the greatest challenge because it is a function of both SLR and hurricanes. While reasonable estimates of SLR are available, the impact of SLR is sensitive to the road location. Inundation frequency due to hurricanes is difficult to quantify because there is no consistent dataset that links hurricane arrivals and intensity to roadway inundation and only recently have climate modelers been able to provide some estimate of future hurricane frequencies.

Pavement temperatures are more readily determined and provide an opportunity to examine the uncertainty among model output of future temperatures. The maximum pavement temperature was determined empirically from the maximum air temperatures model (LTTP model). The LTTP approach could readily be used to develop ranges of future maximum pavement temperatures if an ensemble of climate models were used to determine future maximum air temperatures. Temperature changes are readily determined using the delta method (differencing current and future climate variables) available. The primary difficulty is determining which models and scenarios are appropriate for the study region. Mallick et al. used only one climate model output for their estimates of temperatures in their initial systems analysis. Extending beyond a single model adds to the complexity and points to the need for a suite of climate models with output that is readily composited into pavement relevant variables.

## CONCLUSIONS

The future can never be predicted with certainty. What is certain, however, is that climate is changing. Most existing pavement design and management practices use historic climate records and do not include our current understanding of future variability in sea and river water levels, storm frequency and intensity, and temperature means and extremes when predicting the response and remaining service life of roads. Pavement and other infrastructure design based on specifications from historical climate average conditions and extremes is no longer valid today, and will certainly not be valid in the future as temperatures increase, precipitation patterns change, and sea level rises. Transportation agencies should adjust or adapt to the challenges posed by changing climate and use scenarios of possible future climates to find adaptation strategies that function reasonably well over all climate conditions (so-called robust solutions), employ adaptive management adjusting to impacts as they occur, or most likely, a combination of these.

Incorporating climate projections and other information on a changing climate into pavement design standards, however, is complicated. The information produced by one field of research (i.e, climate science) is not necessarily the information most directly useful to another field of research (i.e., engineering design). Approaches that build regional knowledge and improved collaboration between climate scientists and transportation engineers such as ICNet are critical so that engineers understand the uncertainties and limitations of future climate projections and climate scientists can generate the best possible model output for end users. There is a need to use system dynamics approach to integrate the multidisciplinary topics of climate change, pavement design and performance, and economics to determine the key factors and responses, and the nature of responses. The goal should be the assessment and prioritization of risks of climate change and their economic consequences and determination through simulation, of innovative, sustainable, cost-effective and practical approaches to meet the demands of the changing climates. This approach is necessary to make sure that appropriate materials and methods are developed and that the optimal combination (for road construction) is utilized in the future, for long term positive outcomes. The work should be carried out under two main subject areas – risk assessment (which determines the risk to pavement performance and the transportation network), economic assessment (to determine the cost of damage) and risk management (which involves the evaluation of innovative materials and techniques for cost-benefit data). ICNet participants, who include transportation planners, designers and researchers, will be instrumental in highlighting the long-term implications of such impacts as well as helping to promote research that will lead to more permanent solutions.

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