

**ESTIMATING ENVIRONMENTAL LOAD DEMANDS CONSIDERING
WEATHER EXTREMES TO ENHANCE RESILIENCY OF OKLAHOMA
BRIDGES**

**Quarterly Progress Report
For the period ending June 30, 2025**

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1. Background and Introduction

Bridges are critical components of transportation infrastructure facilitating uninterrupted flow of goods and services within communities. However, the growing occurrence and intensity of natural hazards and extreme weather events are escalating the vulnerabilities of bridge infrastructure. In recent years, Oklahoma has faced an increasing frequency of extreme weather events, including tornadoes, rising temperatures, and flash floods. These threats pose significant challenges for bridge design and maintenance leading to safety and functionality concerns.

Increased frequency and severity of extreme weather events due to anthropogenic change in weather patterns poses a major threat to Oklahoma's bridge infrastructures that are already in vulnerable condition. In recent years, significant progress has been made in predicting future weather conditions through the development of advanced weather models. Also, the availability of high-quality data has rapidly expanded our knowledge and ability to predict performance of infrastructure under future weather conditions.

The proposed study aims to use these developments, specifically latest weather models and data to estimate environmental load demands for Oklahoma bridges that can be readily implemented by ODOT and other entities. The predicted environmental loads will be compared with the design load obtained using historical climate data. A risk analysis will be conducted to quantify the effect of future weather conditions on bridge performance and service life.

2. Problem Statement

Changes in weather patterns have drawn significant attention as their effects have become increasingly evident in recent decades. Increase in atmospheric and ocean temperatures, shifts in precipitation patterns and sea-level rise have reached unprecedented levels. The growing frequency, intensity and duration of natural hazards and extreme events, such as floods, hurricanes, and heat waves are the consequences of these changes in weather patterns. According to the National Centers for Environmental Information (NCEI), between 2017 and 2021, the United States experienced 89 "Billion-Dollar" extreme weather events that resulted in more than \$765 billion in losses and 4,555 fatalities. Oklahoma has been experiencing a wide range of extreme weather events due to its location in the central U.S., where diverse climatic influences converge. The state is particularly known for its high frequency and intensity of tornadoes. In addition, Oklahoma faces intense heat waves, droughts, flash floods, and ice storms. Also, results from different climate models indicate significant changes in Oklahoma weather patterns in future.

For example, Dixon et al. (2020) used statistically downscaled climate model output from multiple individual ensemble members of three Coupled Model Intercomparison Project Phase 5 (CMIP5) to show a range of future temperature and precipitation conditions for Oklahoma by mid- and late-century. Annual-average temperatures are projected to increase 2 to 6°F across Oklahoma by mid-century and up to 24 more days per year of high temperatures greater than 100°F than seen in the historic period (Dixon et al. 2020). The annual 1-day and 5-day maximum rainfall totals are projected to increase by 0.25-inch to 0.5-inch, particularly in eastern Oklahoma. An increase of 5-20% in the 1-in-100-year rainfall threshold is expected by mid-century for the Oklahoma City metro, with higher changes in southern and eastern Oklahoma Dixon et al. (2020). These changes in weather patterns can be devastating for the bridge infrastructure and the community it serves.

The state and federal agencies are searching for ways to integrate the consideration of risks associated with the changing weather patterns and extreme events into its planning, operations, policies, and management to promote resilience. It is widely recognized that incorporating mitigation strategies during the design and construction phases is more cost-effective than responding to the impacts after an event has occurred.

Traditionally, bridge design standards rely on extrapolating stationary historical weather data to predict future environmental loads, disregarding the potential impacts of changes in weather patterns and extreme events. Statistical analyses are performed on these historical datasets to derive design values for various environmental factors, such as wind speeds, temperatures, precipitation, rainfall intensity, and snow-related effects. The likelihood of these design events occurring is expressed as $1/n$, where n represents the return period (Saad et al., 2024).

Other studies suggested that the statistical distribution of loads used for determining design parameters is changing due to the ongoing anthropogenic changes in weather patterns and potentially placing bridges outside their built operating conditions (Steenbergen et al., 2009; Geurts & Bentum, 2010). Despite the known variance of historical climate, these natural hazards and extreme weather events will cause a shift in the mean and “fattening” of the tails of the distributions of weather variables (i.e., more intense and frequent extremes), many of which will lie outside of the range observed in the historical record. This increase in non-stationary weather conditions will result in poor performance and reduced service lives for bridges designed using historical data.

In recent years, several studies have been conducted to evaluate the risk of extreme weather events on bridges. For example, according to Nasr et al. (2019) the increase in global temperature due to changes in weather patterns can have major impacts on bridges as it can create stresses of the same magnitude as traffic loads. Palu and Mahmoud (2019) reported that most of the main load carrying girders in bridges could potentially reach their ultimate capacity when subjected to service loads coupled with extra thermal stresses caused by changes in weather patterns.

Khelifa et al. (2013) assessed the probability of bridge failure due to scour based on data from the 2009 U.S. National Bridge Inventory. The analysis showed a range of potential bridge failures and the corresponding economic losses across the United States that could be caused by changes in weather patterns. Guest et al. (2010) found that the lifespan of reinforced concrete bridge decks may be reduced due to heightened exposure to environmental factors.

Ghosn (2010) investigated wind load effects on bridge reliability, developing a failure model that demonstrated a decline in reliability as wind speeds increased. Additionally, Bastidas-Arteaga et al. (2014) reported that the increase in temperature could accelerate structural failure and significantly reduce service life of bridges. In another study, Saad et al. (2024) developed a methodology to evaluate the effect of changes in thermal loads in concrete box girders. The results show that the changes in weather patterns could lead to a significant increase in the magnitude of thermal loads on bridges. These findings indicate that the shift in weather patterns is introducing unforeseen environmental load demands on structures, compromising safety and functionality.

Therefore, it is essential for bridge design standards to be updated to accommodate the evolving demands imposed by changes in weather patterns and extreme weather events. Several challenges must be addressed to achieve this goal, including a lack of expertise among bridge engineers in assessing changes in weather patterns, the unavailability of high-resolution future climate data necessary for such evaluations, the complexity of selecting from numerous climate models and

scenarios, and the absence of critical climate variables required for comprehensive analysis. The proposed study will address the eminent challenges and estimate environmental load demands for Oklahoma bridges including consideration of changing weather patterns and weather extremes, and “what if” scenarios.

The proposed study will address two US DOT Strategic Goals, namely “Climate and Sustainability” and “Economic Strength and Global Competitiveness.” Improving durability of bridge infrastructure is a major focus of IBT/ABC-UTC and the proposed study directly addresses that need. Also, this study aligns with the vision of Southern Plains Transportation Center (SPTC), a regional UTC serving Southern US including Oklahoma.

3. Objectives and Research Approach

The overall approach of this project is to evaluate the effect of changes in weather patterns and extreme weather events on the environmental load demand related to temperature and wind speed for bridges in Oklahoma. The use of advanced climatic models to predict future changes in weather patterns and estimate environmental load demand will be explored.

The primary objectives of this research are:

- To understand Global Climate Models (GCMs) and select the most relevant model(s) for predicting future weather patterns in Oklahoma. The selected model(s) will be used for prediction of future weather patterns and estimation of environmental load demands.
- To calculate bridge design loads using historical climate data obtained from Oklahoma Mesonet and other sources and compare with GCMs outputs.
- To conduct a risk analysis to evaluate the impact of weather variables, namely temperatures, precipitation and wind on Oklahoma bridges.
- To develop recommendations to incorporate changes in weather patterns and extreme events in bridge design.
- To conduct impactful workshops and webinars focused on this topic.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Document Current Practices.

Working closely with ODOT and through literature review, the team will document the current practices on bridge design. This will include bridge design strategies, consideration of the type of extreme events and likelihood in the bridge design, and bridge risk assessment process. The models and data used by ODOT for determining the bridge design loads or return periods of extreme events will be documented. Also, the risk assessment models used for evaluating the vulnerabilities of bridges to different extreme events will be examined.

Description of work performed up to this period: A literature review is being conducted for Task 1 focusing on the AASHTO LRFD Bridge Design Specifications, particularly the guidelines related to scour, stream migration, and extreme hydraulic events, such as the 500-year scour check flood. It also incorporated scientific literature addressing the impacts of changing weather patterns, specifically variations in precipitation, temperature, and wind on bridge vulnerability. Finally, a

review of methodologies for integrating historical and projected climate data using NASA's NEX-GDDP-CMIP6 datasets was performed. The review also included the consideration of local data on historical flood events and environmental hazards in Oklahoma to support site-specific vulnerability assessments.

A review of design methodologies and integration of risk, reliability, and climate data in design, is provided in the following section:

AASHTO LRFD Bridge Design Specifications (AASHTO 2024), general overview:

- Section 3 (Loads and Load Factors) of the 10th Edition expanded the LRFD approach to include Extreme Event Limit States (EELS), addressing hazards like floods, high winds, and seismic activity. Designers should identify climate-related loads (e.g., increased precipitation, temperature) and verify adequacy under EELS criteria. For Oklahoma State, this may include hydrologic extreme events (e.g. intense storms, flash flooding) and velocity changes due to warmer climates.
- Service Life & Durability Design: despite a typical 75-year design life and according to the incidence of many elements, this design period can be intended to exceed 100 years when considering environmental degradation.
- Reference from Coastal & Flood Guidance Supplements: AASHTO guides on coastal storms, hydrology, and extreme precipitation can provide valuable methodologies transferable to inland flooding scenarios, like the ones present in Oklahoma State.
- Factors in Hydrologic and Hydraulic Updates: AASHTO guides encourage the integration of updated IDF (intensity-duration-frequency) curves, flood risk data, and Federal Highway Administration (FHWA) Hydraulic Design to assess climate-driven changes in hydrology. It would be ideal for Oklahoma to consider new IDF curves that reflect recent trends in extreme precipitation events.
- Adopt Risk-Targeted Design and Standardization: The 10th edition standardizes methods across agencies, encouraging use of Representative Concentration Pathways (RCPs) and risk-based thresholds. Aligning with Oklahoma Department of Transportation (ODOT) to achieve consistent climate vulnerability assessments.
- The detail on Materials design strategies should also be considered for increasing corrosion, freeze-thaw, and alkali-silica reactions due to changes in precipitation and temperature patterns.

Site Characterization and Foundation Profile:

Current review of geotechnical investigation standards, soil-structure interaction, and site-specific risk, includes:

- AASHTO LRFD Sections 10 & 11 (Foundations and Abutments)
- ODOT Geotechnical Engineering Manual (2021)
- FHWA NHI-16-072 – Soils and Foundations Reference Manual (2015)

These documents focus on soil, rock classification and groundwater considerations, which are fundamental for bridge design. Most guidelines and standards recommend borehole spacing ranges

to obtain accurate information of the soil profile. Nevertheless, there is not a rule-of-thumb for borehole spacing and most engineers decide the number of boreholes and their depths based on experience, technical recommendations, cost and time. Table 1 lists some recommendations for borehole spacing regularly used in the United States.

Table 1 Borehole spacing recommendations according to different guidelines and standards (Federal Highway Administration (FHWA) 2016; American Concrete Institute (ACI) 2018; AASHTO 2020).

Standard	Borehole Spacing Recommendation	Observations
FHWA	30–60 m (for highways), 15–30 m (for critical conditions)	Closer spacing for deep foundations. It depends on the type of structure.
AASHTO	6–30 m	Denser in variable soil
ACI 336.3R	3–6 times the pile diameter	Depends on soil homogeneity

Foundation Design (Substructure)

The current review of design procedures for deep and shallow foundations exposed to hydrological and temperature stress includes the following standards:

- AASHTO LRFD Section 10.7 (Pile Foundations)
- FHWA GEC 12 – Design and Construction of Driven Pile Foundations

Saturated conditions are considered during the determination of pile capacity. Unsaturated conditions are usually neglected, since suction effects usually cause an increment on effective soil stress. Corrosion of materials due to increased humidity or the presence of chemical changes could also be considered. The fluctuation of water levels due to changes in weather patterns may trigger differential settlement risks under climate-induced soil changes.

Some general design considerations to reduce the vulnerability of the bridge foundation system due to scour and hydraulic loads are as follows:

- Set high deck elevations (i.e., bridge finished grades) according to the given site conditions to reduce the risk of inundation by floods. Bridges subjected to inundation should provide an overtopping of roadway approach and minimize the superstructure area subjected to hydraulic loads and the collection of ice, debris, and drifts.
- Relief bridges, guide banks, dikes, and other river training devices should be used to reduce turbulence and hydraulic forces acting at the bridge abutments.
- For continuous-span bridge designs with anchored superstructures, recommendations are similar: provide proper drainage to resist hydraulic, ice, and debris forces; minimize and streamline piers, aligning with flow and placing abutments/pier foundations away from unstable channels. Anticipate channel shifts and consider debris racks for sites that are far from the streamline.

- HEC-18 (FHWA, 2012) provides additional detailed guidance on pier and abutment location, alignment, and shape within and near the channel.

Design frequencies: Table 2 displays the recommended scour design and flood frequencies according to the selected hydraulic design flood events. The scour design and check floods have higher return periods since they should account for greater uncertainty and greater foundation vulnerability if extreme conditions are given.

Table 2 Hydraulic Design Flood Frequencies, and Corresponding Scour Design and Check Flood Frequencies (FHWA 2012).

Hydraulic Design Flood Frequency (QD)	Scour Design Flood Frequency (QS)	Scour Check Flood Frequency (QC)
Q10	Q25	Q50
Q25	Q50	Q100
Q50	Q100	Q200
Q100	Q200	Q500

Task 2 – Predict Weather using Climate Models.

In this study, multiple GCMs that provide regional weather projections for Oklahoma will be used for future weather predictions considering changing weather patterns and extreme events. GCMs are physics-based and computationally expensive, solving numerous nonlinear scientific equations in both space and time to simulate the Earth physical climate system. Initially, these models are presented with boundary conditions i.e., values for different forcings for the Earth climate system, such as solar irradiance, atmospheric concentrations of greenhouse gases, surface type and temperature, and volcanic activity. Earth is then divided into grid points and several equations from physics, fluid mechanics, and chemistry are then solved numerically per grid point and iterated in time. For future weather simulations, these models are run with different scenarios known as Shared Socioeconomic Pathways (SSPs) representing different potential futures.

For the purpose of this study, the models from NEX-GDDP will be used for predicting future climatic conditions in Oklahoma (NEX-GDDP-CMIP6; Thrasher et al. 2002). The model archive contains over 35 different climate models from the CMIP6 archive which would be ideal for assessment of regional weather patterns across Oklahoma. The archive contains most of the necessary environmental variables needed for bridge design. Also, multiple scenarios are available, covering a wide range (e.g., from low (SSP125) to high (SSP585) emissions) for comparison. The research team will choose at least 10 GCMs from the archive to predict future weather patterns in Oklahoma. Statistical analysis will be performed to calculate the return period of extreme weather events for different GCMs with different scenarios. Also, the mean or median values of the return periods from the models will be determined based on statistical distributions. Currently, Dr. Zaman, a C-PI of this study, and his team are working on a project funded by ODOT to upgrade the weather data and models used for pavement design in Oklahoma (Li, Zaman and Furtado, 2023). The proposed study benefits from the climatic models evaluated in that study and helpful to completing this task successfully.

Description of work performed up to this period: The team is currently working on downloading future climate data from NASA's NEX-GDDP-CMIP6 platform, including variables such as maximum temperature, minimum temperature, and precipitation. In parallel, Oklahoma Mesonet data is being retrieved for specific stations across the state to support site-specific validation. Bias correction will be performed for these climate variables. Additionally, a thorough review of climate scenarios and GCM models, as outlined in the initial project report, will be conducted to determine the most appropriate data sources and temporal coverage for analysis. Table 3 shows some Global Climate Models characteristics under different SSP scenarios, evaluating a possible suitability for bridge design in Oklahoma, considering: emission levels, model strengths, and relevance to certain climates, some other sources are in current review.

Table 3 Some Particularities of GCM Models and SSP Scenarios for bridge design assessment (NASA, 2025).

N	GCM Model	SSP Scenario	Emission Level	Description	Applicability to Bridge Design in OK	Applicability Rating (0–5)	Source
1	GFDL-ESM4	SSP585	High	Developed by NOAA (USA); strong simulation of warming and precipitation extremes	High-risk scenario assessment	5	Dunne et al. (2020)
2	MPI-ESM1-2-HR	SSP370	Med-High	Developed by Max Planck Institute (Germany); high-resolution and strong atmospheric dynamics	Wind load and flood hazard analysis	5	Mauritsen et al. (2019)
3	CNRM-CM6-1	SSP245	Medium	Developed by Météo-France/CERFACS (France); reliable precipitation and temperature trends	General infrastructure and lifespan design	4	Voldoire et al. (2019)
4	MRI-ESM2-0	SSP245	Medium	Developed by Japan Meteorological Agency; emphasizes precipitation extremes	Precipitation frequency and storm events	4	Yukimoto et al. (2019)
5	UKESM1-0-LL	SSP370	Med-High	Developed by UK Met Office (United Kingdom); high climate sensitivity	Captures future heat extremes	4	Sellar et al. (2019)
6	BCC-CSM2-MR	SSP585	High	Developed by Beijing Climate Center (China); balances radiation and surface fluxes	Surface stress and thermal boundary loads	4	Wu et al. (2019)
7	IPSL-CM6A-LR	SSP126	Low	Developed by Institut Pierre-Simon Laplace (France); conservative emissions path	Testing resilient, low-stress designs	3	Boucher et al. (2020)

Task 3- Compare GCMs prediction with Historical Climate Data.

Relevant historical climatic data (i.e., temperature, precipitation and wind speed) from the Oklahoma Mesonet and other nearby weather stations will be obtained. The research team plans to selectively co-locate the future weather predictions from GCMs with Oklahoma Mesonet sites. The historical weather data from Oklahoma Mesonet sites will be analyzed to calculate the return period of weather extremes and compare with GCMs predictions.

Description of work performed up to this period: This task was not pursued during the reporting period. Progress will be reported in the next report.

Task 4 – Conduct Risk Assessment of Bridges Considering Future Weather Conditions:

In this study, a risk assessment of bridge infrastructure subjected to predicted future weather conditions will be conducted using methodologies proposed in the literature. For example, the method proposed by Chang et al. (2020) using Risk Priority Number (RPN) could be used for this purpose. Using this method, the risk of bridge failure due to rise in temperature and wind speed will be quantified by including three aspects: occurrence, severity, and significance. Occurrence quantifies the likelihood of an extreme weather event occurring during the lifetime of the bridge. Future weather predictions using GCMs will be used for this purpose. Severity defines the probability of a bridge to experience damage or failure. Significance, a factor on a 1–10 scale, represents the importance of the bridge to the agency in the network. The Risk Priority Number (RPN) parameter combines these three aspects and is defined as a comparative metric that identifies the bridge at higher risk.

For the purpose of risk assessment, selective bridges commonly used in Oklahoma will be considered. The selection of these bridges will be based on the recommendations of the ODOT personnel and the vulnerability to extreme weather events. The level of risk of bridge infrastructure failure due to an extreme weather event will be calculated by considering what-if scenario analyses for high-, medium-, and low-risk impact. The risk assessment matrices for each environmental scenario and potential causes of failure will be identified. The results will be used to calculate the RPN value for each bridge.

Description of work performed up to this period: This task was not pursued during the reporting period. Progress will be reported in the next report.

Task 5 – Provide Recommendations for Updating Bridge Design Codes and Standards

The findings of this study will be used to recommend changes in the bridge design codes and standards. Also, the authors will prepare guidelines to perform weather data analysis using advanced models like GCMs. Also, the process of estimating design load or return period from future weather scenarios will be documented. The consideration of future natural hazards and extreme weather events will be important to ensure long-term durability of bridge infrastructure.

Description of work performed up to this period: This task was not pursued during the reporting period. Progress will be reported in the next report.

Task 6 – Organize Workforce and Webinar:

One workshop and one webinar will be organized as part of this task. The goal is to share the findings of this project and increase awareness of the incorporation of changing weather patterns and extremes events in bridge design. Assistance of the Southern Plains Transportation Center (SPTC) & IBT/ABC-UTC will be sought to make these events successful.

Description of work performed up to this period: This task was not pursued during the reporting period. Progress will be reported in the next report.

Task 7 – Submit Quarterly Progress Reports and Final Report:

Quarterly progress reports will be submitted to IBT/ABC-UTC. A final report documenting all the data, data analysis, and suggested improvements in bridge design will be submitted to IBT/ABC-UTC.

Description of work performed up to this period: The quarterly progress report for the period ending June 30, 2025 is being submitted.

5. Expected Results and Specific Deliverables

- High-resolution climate projections (tasmax, tasmin, precipitation) downscaled for Oklahoma, including historical (1950–1997) and future (2015–2100, SSP245) periods.
- Integrated dataset combining observational Mesonet data and GCM projections, aligned temporally and spatially.
- Identification of changes in weather patterns hotspots for extreme rainfall, heatwaves, and wind events affecting infrastructure.
- Quantitative estimates of future loading conditions on bridges due to climate extremes.
- Evaluation of structural demand for bridge models under changing climate conditions, particularly for scour-prone foundations.
- Updated design recommendations for long-term bridge resilience considering significant return period for flood events and temperature/wind extremes.

6. Schedule

Progress of tasks in this project is shown in Tables 4 and 5.

Table 4 Activity Completion Chart

Items	% Completed
Task 1: Document Current Practices	60%
Task 2: Predict Weather using Climate Models	30%
Task 3: Compare GCMs prediction with Historical Climate Data	0%
Task 4: Conduct Risk Assessment of Bridges Considering Future Weather Conditions	0%
Task 5: Provide Recommendations for Updating Bridge Design Codes and Standards	0%
Task 6: Organize Workforce and Webinar	0%
Task 7: Submit Quarterly Progress Reports and Final Report	10%

Table 5 Gant Chart for the Project

TASKS	2025												2026		
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Task 1															
Task 2															
Task 3															
Task 4															
Task 5															
Task 6															
Task 7															
Work performed															
Work to be performed															

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