STANDARDS RESEARCH

Climate Change Provisions for CSA S6:25 Canadian Highway Bridge Design Code

Findings and Recommendations

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Executive Summary

The purpose of this project was to research and develop recommendations and guidance on the potential impacts of climate change for integration into the 2025 editions of CSA S6, *Canadian highway bridge design code* (CHBDC) and CSA S6.1, Commentary on CSA S6.

Through the development of new bridge design requirements in this area, CSA Group will help advance the National Research Council of Canada (NRC) mandate to provide Canadians with the essential knowledge, direction, and tools necessary to actively strengthen the climate change resiliency of Canada's infrastructure.

Climate models project that greenhouse gas emissions will increase both global temperatures and the frequency and intensity of extreme weather events throughout many parts of the world. As a northern country, climate change is amplified in Canada compared to other countries. Since 1950, the annual average surface air temperature over Canada's landmass has warmed by 1.7°C, approximately twice the global average. Total annual precipitation across Canada has increased and it is likely that the frequency and severity of extreme weather events, such as heat waves, droughts, extreme winds, extreme precipitation, and floods will also change.

Canada's infrastructure, which includes buildings, bridges, roads, transit, power, water, and wastewater systems, could be at risk if actions are not taken to address expected changes in climate conditions and extremes. Climate change is expected to affect the magnitude and frequency of different weather parameters, such as rainfall, wind, and snow, and their associated climatic loads. This could lead to reduced safety, serviceability, and service life of this infrastructure. The consequences of failure could be significant and may include fatalities, injuries, and illnesses, loss of function and service disruption, high rehabilitation and replacement costs, and significant negative socio-economic impacts.

Highway bridges are critical links in the Canadian transportation network and key components of Canada's core public infrastructure. The design of highway bridges is currently based on historical climatic data that assume climate stationarity. Such assumptions are no longer valid as historical climatic data is no longer a reliable predictor of future climatic conditions and associated loads. Due to changing climate and climate nonstationarity, highway bridges could be vulnerable to a range of climate hazards, which could result in increases in the intensity and frequency of extreme load effects from extreme temperature, precipitation, and wind that, in turn, could reduce their safety, serviceability, post-event function, or durability. To minimize the risk of failure of bridges due to climate change and extreme weather events, new provisions must be developed for the design of highway bridges that enhances their resilience. The consideration of climate change in the design of highway bridges will lead to improved life cycle performance and minimize the risk of failure and the need for costly maintenance, repair, and rehabilitation. The development and implementation of new climate change provisions for the 2025 edition of the CHBDC will lead to more climate-resilient bridges and provide for a more uniform and lower risk of adverse consequences across Canada.

Project Approach

This project entailed a series of key research activities in combination with stakeholder and CSA CHBDC member engagement to identify and study the major risks to bridge infrastructure related to climate change, and to develop recommendations and guidance to reduce the identified risks. The resulting climate change adaptation recommendations have been submitted to CSA's CHBDC Technical Committee and Technical Subcommittees for inclusion in the 2025 Code and Commentary. See Appendix A for a summary of the structure of the CSA S6 committees and subcommittees, as well as a description of the various sections of the CHBDC.

The following tasks and methodology were carried out during this project:

Stakeholder Consultations

Subject matter experts were engaged to evaluate how CHBDC users perceive and experience climate change-related impacts and current climate change adaptation practices. Selected stakeholders participated in an initial interview. Subsequently, three one-day stakeholder workshops were held in Montreal, Toronto, and Vancouver to further discuss risks and necessary adaptation measures, identify existing industry best practices, and to seek input on climate-related issues that codes and standards are not currently addressing and suggestions on the types of climate change adaptation solutions that should be considered. Summary reports from the stakeholder interviews and workshops provided key input for the susequent tasks.

General Recommendations for CSA S6:25 and S6.1:25

General recommendations for climate change adaptation of highway bridges that could be included in CSA S6:25 and CSA S6.1:25 were developed and included the following considerations:

- Potential impacts of climate change on the intensity and frequency of climatic loads on bridge structures;
- Potential impacts of climate change and extreme weather events on the safety, serviceability and durability of bridges;
- Possible climate change adaptation measures to reduce the risk of failure of bridge structures; and
- Ways to effectively integrate and stage climate-enhancing works into highway and bridge renewal plans within existing federal, provincial, territorial, and municipal frameworks.

This task also included the following actions:

- Reviewing the 2019 CSA S6 provisions dealing with climate change and northern issues;
- Assessing the new Environment and Climate Change Canada (ECCC) data, including environmental historical data up to and including 2017 and ice accretion maps, and the implications of the data for bridge design and rehabilitation; and
- Reviewing the Public Infrastructure Engineering Vulnerability Committee (PIEVC) assessments on highway bridges that also deal with climate change and northern issues.

Development of Uniform Risk Approach

This task examined the impact of the regional varying statistics of climatic load factors on the reliability of designed bridges and identified the physical reasons for such variations. Current design for extreme climatic hazards in the CHBDC is based on the concept of “uniform hazard” or an event with geographically uniform probability of exceedance. Climate change is affecting various regions of Canada differently so it is necessary to investigate the impact of climate change (focusing on wind and precipitation) on the reliability of structures in different regions of Canada. There may be instances where the ratio of ultimate load design values to service load design values varies from region to region. To achieve acceptable and uniform levels of risk and reliability throughout the country for loading combinations where climatic loads dominate, new formats for the presentation of the design values of climatic loads, such as wind pressure and ice accretion were explored.

Climate Nonstationarity and Extremes

This task quantified the level of nonstationarity in expected climate conditions through an analysis of recent directly observed climate changes and projections of future change from climate model simulations.

In CSA S6:19, the concept of return periods for climatic loads has been a standard and important tool for bridge design. This is based on the assumption of a stationary climate, with the range of climate variability estimated from historical environmental information. However, an assumption of climate stationarity is not valid in the case of changing climate, leading to trends over time in mean climate conditions and trends over time in the frequency of reoccurrence of extreme climate events. Both effects ultimately lead to non-stationary climatic loads.

Climate conditions that were examined for recent observed and future projected changes are of direct relevance to bridge-relevant climatic loads and associated design life levels. Climate vulnerabilities will vary fundamentally by large-scale geography (e.g., permafrost degradation at high latitudes versus summer heat at low latitudes) and also by small-scale geography (e.g., snow loads at high altitudes and flooding in valley bottoms). To capture this heterogeneity, climate analysis was carried out on a nationwide high-resolution grid to assess the full range of site-specific bridge design vulnerabilities in a unified analysis framework.

This approach was needed to develop methods that integrate knowledge of non-stationary climate in design life levels of climatic loads and associated reliability targets to be met during the design life of the structures. Uncertainty in bridge design (type, location) and site-specific uncertainty in future climate projections were assessed to ensure the outcome accurately reflects the range of potential future design-side and climate-side risks.

Consideration of Localized Extreme Weather Events

This task assessed the need to update the representation of localized extreme weather events in CSA S6:19 to reflect current observational data. The current approach of the CHBDC is to specify loads at specific return periods and then apply time-invariant load factors to convert the loads to ultimate values for bridges. The design for some effects, however, are not “load” based, and require best estimates of weather events to assess bridge geometry, channel clearance, or scour protection. Some extreme weather events are not well represented in historical climatic and environmental data in CSA S6:19 and may also be poorly represented in current meteorological observations.

Climate Change Adaptation Implications on Bridge Design and Materials for Canada’s North

Canada’s North is experiencing the most accelerated change in climate in the country, with a 3.5°C increase in average temperature since the beginning of the 20th century. This, in combination with remoteness, inaccessibility, and aging infrastructure, means that the quality of life in northern communities has been impacted by climate change more than in other parts of the country to date. This task focused on developing the means for bridge designers to specify the composition, properties, and performance of the materials selected for the structure by taking into account the design loads and the expected environmental degradation during the service life of the structure or its elements.

Recommendations for the Implementation of Climate Change Provisions in CSA S6:25 and CSA S6.1:25

The deliverables of the previous six tasks informed the review, assessment, and formulation of recommendations to update existing and introduce new climate change adaptation provisions in CSA S6:25 and CSA S6.1:25, which will be proposed to CSA’s CHBDC Technical Committee.

> "In Canada, both the observed and projected increases in temperature are occurring at a rate that is approximately twice the global average, with even greater warming occurring in Canada's North."

1 Introduction

Climate change is shifting the environmental conditions experienced by Canada's bridge, highway, and transportation infrastructure. There is evidence that these temperature and related climate impacts are primarily due to CO_2 emissions from fossil fuel consumption [1]. Impacts include increases in global air, land, and ocean temperatures, changes to global atmospheric and oceanic circulation patterns, shifting precipitation trends, decreasing ice and snow coverage, and many other effects. Climate change is occurring over the Canadian landmass at an accelerated rate relative to the global average [1] and will continue to do so. In Canada, both the observed and projected increases in temperature are occurring at a rate that is approximately twice the global average, with even greater warming occurring in Canada's North.

These changes will affect the environmental conditions experienced by Canada's buildings and core public infrastructure (B&CPI), including buildings, bridges, roads, transit, water, and wastewater systems. Specific to bridge, highway, and transportation infrastructure, design is currently guided by codes and Standards that are based on historical environmental data. Infrastructure Canada, under the Investing in Canada Plan [2] and in support of the Pan-Canadian Framework on Clean Growth and Climate Change [3], commissioned the Climate-Resilient Buildings and Core Public Infrastructure Initiative (CRBCPI) [4].

This initiative, led by the National Research Council Canada (NRC), has developed foundational guidance for Canada's construction industries to adapt to the increasing demands on infrastructure stemming from climate change. The work undertaken by the NRC will contribute to an infrastructure landscape that is well poised to keep Canadian communities and infrastructure safer from extreme weather and other effects of climate change.

The owners and managers of Canada's B&CPI are looking for productive and cost-effective approaches to the design and rehabilitation of B&CPI that will increase resilience and satisfactory life cycle performance under climate change and extreme weather events. The NRC commissioned Canadian Standards Association (CSA) to lead and support the development of codes, guides, models, and tools for the design and retrofit of transportation structures, to improve their performance against existing and future climate change and extreme weather events, within the mandate of CSA S6, *Canadian highway bridge design code* (CHBDC). These goals will be achieved through partnerships with key collaborators and stakeholders as part of the NRC-led CRBCPI initiative. The delivery model is through evidence-based solutions and collaborative research and development projects in each priority area.

If climate change considerations are incorporated into the planning and design of bridges from the outset, the associated costs are expected to be marginal. The proposed updated and new CHBDC climate change provisions that will be developed during the course of this project will also lead to more robust and resilient bridges, culverts, walls, bridge approaches, and related structures.

Canada's bridge infrastructure is designed based on the CHBDC, which is updated on a 5-year cycle and provides a minimum basis for bridge designs across Canada. The latest update of the CHBDC (CSA S6:19) was published in December 2019 [5][6]. The next edition of the CHBDC (CSA S6:25) will be published in 2025. In addition, CSA S6.1:25, the commentary to the CHBDC, will provide context and background on Code application and guidance on implementation, climate data sources and application, uncertainty, risk frameworks, emerging extreme events, and special considerations for Canada's northern regions.

This report combines the deliverables developed by CSA's project team and submitted individually throughout 2020. The deliverables were provided to CSA's CHBDC committees through working sessions and presentations, including:

- CHBDC Regulatory Authority Committee, who provide guidance and oversight of the CHBDC Technical Committee (TC).
- CHBDC TC, who are responsible for the overall technical content of the CHBDC.
- CHBDC Technical Subcommittees (TSCs), whose members assess, review, and develop the detailed code and commentary technical clauses necessary for bridge design.
- CHBDC Climate Change Working Group, established to assist the TC and the TSCs in reviewing and implementing the climate change recommendations.

This project was undertaken by the following parties:

- CSA Group (prime contractor to the NRC): leads the administration and maintenance of the CHBDC, facilitates the TC and TSC development of technical content, ensures that the CHBDC provisions follow its accredited standards development process, and manages the implementation of the climate change impacts and adaptation for CSA S6:25 and CSA S6.1:25.
- Associated Environmental: subcontracting party, provided climate science-related contributions and project management of the subcontracted activities.
- Associated Engineering Group: bridge engineering technical leaders and primary contributors.
- COWI North America: bridge engineering contributors and reviewers.
- Dr. Han-Ping Hong and collaborators at Western University: primary contributor to the probabilistic framework to implement updated environmental demands into the CHBDC to achieve target reliabilities across Canada. Values and relevant statistics for recent climate-related variables (temperature, wind, snow, ice accretion) were updated first to provide a baseline upon which climate change projections and climate nonstationarity could be included within a uniform risk probabilistic framework.
- Manifest Climate (formerly Mantle314): conducted stakeholder engagement and facilitated cross-country stakeholder workshops.

Fundamental to this project was the ground-breaking work and input by Environment and Climate Change Canada (ECCC) for the NRC on applying climate change projections across Canada to bridge-related impacts [7].

As part of the implementation of this project into CSA S6 and CSA S6.1, CSA established a Climate Change Working Group (CCWG), which comprises subject matter experts to guide CSA's TSC members in reviewing and formulating specific code and commentary content.

1.1 Project Objectives

The key objectives and outcomes of this project are summarized below:

- Conduct cross-country engagement workshops to determine priorities from stakeholders on perceived key climate change impacts that are expected to affect the future design of bridges.
- Adopt guiding principles for capturing climate change impacts on short and medium span highway bridges in Canada, including the adoption of a representative concentration pathway (RCP) scenario and rationale for consideration when developing provisions for CSA S6:25 and CSA S6.1:25.
- Identify specific code and commentary clauses related to climate change that may require updating to improve the climate resilience of Canada's bridges.
- Update selected environmental variable data needed for bridge design, with an emphasis on wind and related load combinations, and on ice accretion effects and combinations.
- Update wind data, observed and projected, including regional statistical variations.
- Provide new wind velocities or pressures, load factors, and load combination factors within a uniform risk approach and related reliabilities across Canada. This includes a probabilistic methodology and adopts a uniform risk approach that captures updated wind statistics, which vary across Canada, longer return period wind events, and climate nonstationarity. It is an extension of the limit states design philosophy and target reliability framework in use in Canada since the 1970s.

Table 1: Summary of Report Content

Task	Objectives and Outcomes
Section 2: Overview of representative concentration pathways (RCPs)	Describes the different RCP greenhouse gas emission scenarios used in climate change modelling and their relevance in determining appropriate risk thresholds for infrastructure design.
Section 3: General recommendations for 2025 edition of CSA S6 and S6.1	Outlines key principles and priorities and provides over-arching recommendations to guide detailed code and commentary updates to CSA S6:25 and CSA S6.1:25.
Section 4: Uniform risk approach for wind demands and updated target reliabilities, load factors, and load combination factors for structural design	Updates relevant wind statistics and provides preliminary findings for Canada's capital cities using projected wind effects considering climate change over a 75-year bridge design life. This framework extends the probabilistic methodology used in Canada for "stationary" wind statistics in recent decades to capture climate nonstationarity while achieving an acceptable target reliability index.
Section 5: Climate nonstationarity and extremes	Describes the concept, importance, and implementation of climate nonstationarity for a recommended RCP for the derivation of updated parameters for CSA S6:25.
Section 6: Consideration of localized extreme weather events	Describes emerging extreme weather events and their potential impacts on transportation infrastructure, and provides recommendations for the CHBDC to address these evolving extreme weather events considering the changing climate.
Section 7: Climate change adaptation implications on bridge design and materials for Canada's North	Describes important impacts of climate change on materials, foundations, and structural design that are unique to Canada's northern regions and provides recommendations to address these effects.

- Provide guidance for events and impacts from local and emerging extreme events. These are not captured in historic data and cannot yet be quantified probabilistically in a limit states design code.
- Provide guidance on unique regional hazards in Canada's North and potential impacts on bridge and transportation structures.
- Provide guidance and resources on CHBDC code and commentary provisions that may be impacted by climate change.

1.2 Report Overview

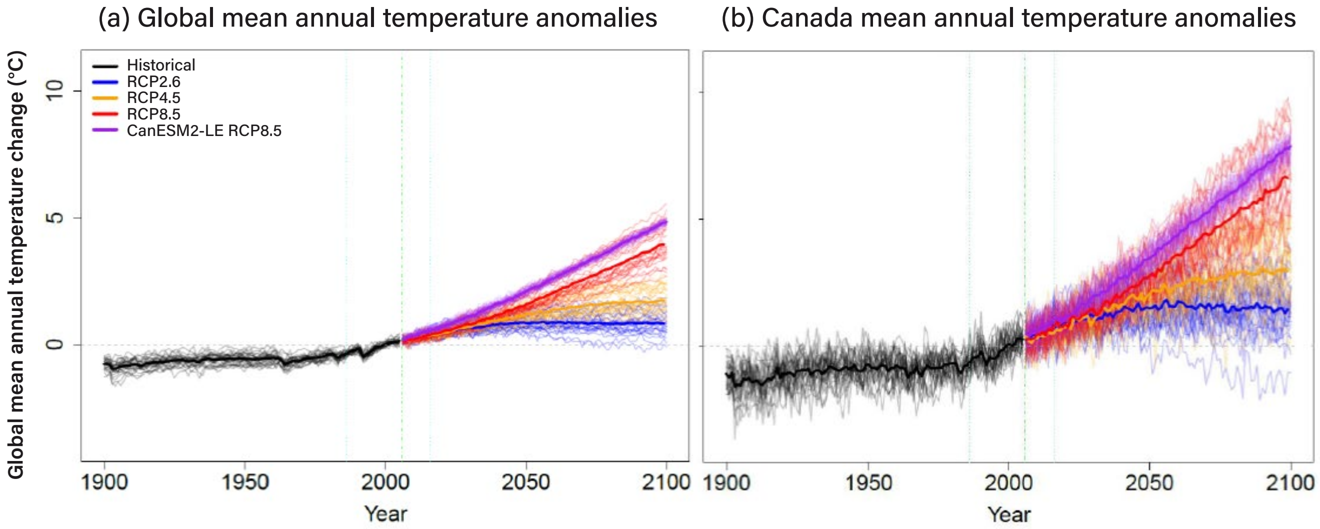
Table 1 provides an outline of how this report is organized.

2 An Overview of Representative Concentration Pathways

To address the potential impacts of future climate change, including uncertainty in future human behaviour, a set of potential "representative" greenhouse gas emissions scenarios are constructed from integrated assessment models (IAMs). These models explore how human development and societal choices interact with and affect the natural world. IAMs include physical laws driving natural systems as well as the changing habits and preferences that drive human society. These scenarios estimate global emissions consistent with a wide set of potential future socio-economic trends. Future greenhouse gas emission projections from IAMs are used as inputs to global climate models, which model the physics of important global climate system components (ocean, atmosphere, land, sea ice, hydrology, biological, and chemical cycles). When run under greenhouse gas emission scenarios such as RCPs, global climate models produce estimates of future changes to key environmental variables, including temperature, precipitation, wind, permafrost, snow, and sea level.

RCPs are future greenhouse gas emission scenarios derived from IAMs and are labelled by the level of extra heat (radiative) forcing that occurs for each scenario by year 2100. For example, RCP 8.5 results in 8.5 watts

Figure 1: Global (a) and Canadian (b) average annual average temperature changes across RCP scenarios. Adapted from [7].



per square meter of extra heating (W/m^2), which is equivalent to Earth receiving energy from a ~10-watt lightbulb at every square meter of atmosphere.

Output from these simulations are a basis for worldwide climate adaptation and resilience efforts, including the present effort to develop and implement climate change provisions for the CHBDC. Figure 1 [7] illustrates the projections for the global and Canadian mean annual temperature increases, with uncertainty bounds, through to 2100 for a range of RCPs.

Each RCP scenario captures a potential 21st century emissions future based on:

- RCP 2.6: a low emissions scenario that assumes near-term, strong emissions reductions and near-complete cessation of greenhouse gas emissions by ~2050. It is considered an unrealistically low emissions and climate change scenario given current global emissions of greenhouse gases and socio-economic trends.
- RCP 4.5: a low-intermediate emissions scenario in which global emissions peak and begin to decline by ~2035.
- RCP 6.0: a high-intermediate emissions scenario in which global emissions peak and begin to decline by ~2060. RCP 4.5 and RCP 6.0 represent more likely scenarios. They project similar temperature and related changes until ~2050, after which they diverge.
- RCP 8.5: a high emissions scenario that combines high population growth with continued fossil fuel use, particularly coal, through to year 2100. It is considered an unrealistically high, pessimistic emissions and climate change scenario, particularly because it reflects implausibly high 21st century coal use. This scenario is thus a top-end scenario without emissions mitigation.

No RCP scenario is associated with a likelihood. Users of RCP-based climate projection data must use either quantitative, probabilistic methods or use risk-based frameworks to apply to design.

Future change will likely be greater than the RCP 2.6 scenario but less than the RCP 8.5 scenario. The use of RCP 2.6 may lead to lower first construction costs but is considered a relatively high-risk decision relative to structural safety for climate impacts on future bridge design. Conversely, using RCP 8.5 for design would be a relatively low-risk decision relative to structural safety but would imply higher first costs. Determining an appropriate risk threshold for infrastructure design includes a risk-based assessment that considers capacity, adaptation, and cost risks associated with different RCP scenarios.

Recommendations for the adoption of RCP scenarios into CSA S6:25 are provided in Section 3 of this report.

Building and bridge design codes used in Canada and internationally in past decades provide environmental quantities for structural design that were derived from observations and an assumption of a stationary climate. The degree of climate variability was assessed from historical environmental information, and both load and resistance factors developed for Canadian structural design codes beginning in the 1970s use these (assumed) stationary data and assumptions [8].

The increasing importance of climate nonstationarity is evident in recent records and in projections of global mean temperature as seen in Figure 1, particularly in the latter part of the 20th century and throughout the 21st century. Local climate trends related to large-scale global changes are being incorporated into both the CHBDC and the National Building Code of Canada 2015 (NBC). For both buildings and bridges required through the 21st century, projections for climate variables must be used.

The use of climate data projections, including statistical nonstationarity in general and specifically for structural design for wind loading, including long return period events, is described in Section 5 of this report.

3 Bridge Impacts and General Recommendations

This section summarizes background and initial general recommendations for consideration in developing climate change provisions for CSA S6:25 and CSA S6.1:25. These initial recommendations served as a basis for the development of quantitative and qualitative recommendations within the project and for ongoing code development work.

3.1 Stakeholder Engagement Workshops

As an early step in the development of initial recommendations, a series of in-person workshops, a virtual workshop, and telephone interviews were held to obtain stakeholder input on concerns, knowledge, and priorities for climate impacts on bridges. Through this process, input was also received on principles, strategies, and possible frameworks for developing climate provisions within CSA S6:25 to respond to these impacts Stakeholders included bridge owners, engineers and infrastructure planners, engineering association and transportation agency representatives, and climate scientists.

Participants were asked to identify and rank their perceptions of top bridge-specific climate impacts. The results are presented in Table 2. This stakeholder input is an important focal point for the CSA S6:25 climate change code development. Inputs from the project team, future guidance from the CSA CCWG, and ultimately from the TC and TSCs will also inform the final changes to the code and commentary.

Table 2: Climate Impacts To Bridge Infrastructure, Ranked

Climate impacts, ranked by workshop participant vote	Points
Hydrology (including flooding, flows, land use, and design flood level)	22
Wind	13
Future uncertainty about climate	13
Scour	11
Temperature change (including freeze-thaw and thermal movement)	8
Ice	7
Combination loads	7
Extreme conditions	7
Coastal flooding (including sea level rise, storm surge, tides, and waves)	5
Permafrost	3
Forest fires	3
Debris loading	3
Level of service depending on importance	3
Riverine (fluvial) flooding (i.e., annual exceedance)	2
Changes in material performance	1

Outcomes from this series of stakeholder engagement workshops emphasized the following key aspects for CHBDC updates:

- Summarize global climate change and relation to Canadian climate change trends.
- Review general climate change impacts to Canadian bridge infrastructure.
- Emphasize impacts identified by stakeholders during project workshops.
- Highlight need for location- and bridge-specific relevant climate change bridge impact assessment.
- Identify and provide climate data and tools for incorporation into the CHBDC.

3.2 General Recommendations

3.2.1 Risks and Projection Uncertainty in Bridge Design

Increased risk to bridge infrastructure due to climate change manifests if: 1) climate change increases the likelihood of bridge-relevant climate hazards over a bridge design lifetime; and 2) notable negative consequences to serviceability, durability, and safety arise as a consequence of these hazards [9]. If the additional climate-related risk exceeds bridge-specific risk thresholds, risk reduction actions [10] can be taken as a part of bridge design or rehabilitation efforts. For example, design values of climatic data that are calibrated to withstand extreme climate events or for uncertain climate-dependent geotechnical conditions already reflect a risk threshold and risk reduction approach. Consideration of climate change represents an extension of these existing principles to encompass future climate conditions. This extension also captures risk arising from uncertainty in future climate resulting from uncertainty in future projections of climate change.

Uncertainty in climate data projections is critical in the derivation and implementation of code provisions and in risk-based decision-making. Bush and Lemmen [1] and Cannon et al. [7] described a tiered approach to uncertainty developed by ECCC that can assist standards developers. They have grouped climatic design variables into three tiers to reflect the confidence in future projections for large regions of Canada. These are based in part on judgments about the body of evidence that is available, including published literature both in Canada and internationally. They are also supplemented by evidence from recent research on Canadian climate model simulations. A detailed description of the following 3 tiers of uncertainty, and which climate variables fall into each tier, is provided in Cannon et al. [7]:

- Tier 1: variables for which there is high or very high confidence in the future projections for a given level of global warming. This confidence relates to an in-depth understanding of the processes involved and a strong body of evidence that deals with the causes of observed changes.
- Tier 2: variables for which there is medium confidence in the future projections for a given level of global warming. It implies that there is some understanding of the processes that lead to future change, which might be supplemented by a body of evidence linking the causes of observed changes at large scales but such evidence would be less extensive and available studies show a lower degree of consistency than for Tier 1 variables. Climate scientists are generally not able to estimate the likelihood of a projected change for variables having medium confidence in future projections. Change factors for these variables are described as more appropriate for cost-benefit analyses or for risk analyses in an exploration of uncertainty associated with infrastructure design.
- Tier 3: variables for which there is low or very low confidence in the future projections for a given level of global warming. These are variables that have not been widely studied in the published literature or for which the processes involved are poorly understood.

General Recommendations for CSA S6:25

- Define and apply the concepts of climate hazard and risk in a consistent manner.
- Define and apply the concept of climate change as a modifying factor to existing and new risks.
- Describe sources of future model uncertainty and their roles in determining future risk changes.

3.2.2 Recommendations for RCP Adoption

Section 2 of this report discussed RCP scenarios and considerations for adopting an RCP to underpin the implementation of climate change adaptation into the CHBDC. The level of climate change risk experienced by Canada's highway bridges and transportation structures depends closely on these future global greenhouse gas emissions and the associated RCP scenarios. These will be the main drivers of global climate change and impacts to bridges. It is important to recognize that long-term projections of greenhouse gas emissions are prone to high uncertainty, given that emission projections rely on forecasts of social, demographic, technological, and economic (socio-economic) factors. The global research and policy community responsible for developing future climate change assessments has adopted a scenario-based approach in part to address this uncertainty.

The recommendations for CHBDC updates for climate change adaptation are summarized below:

- Adopt the RCP 6.0 scenario for quantitative and qualitative climate-related highway bridge design provisions, based on the rationale provided in Section 2 of this report and discussed below.
- Maintain the current bridge design life of 75 years as the period of consideration for the calculation of projected design variables. This is unchanged from the current and previous editions of the CHBDC for the safety and durability of bridge structures. The experience of bridge owners and engineers over many decades has demonstrated that this duration provides safe and serviceable bridges, albeit with appropriate maintenance and renewal, and so remains appropriate for bridges.
- Provide guidance in CSA S6.1:25 for using higher scenarios to address cases where bridge owners wish to incorporate greater residual risk reduction or longer bridge design lives beyond the minimum requirements specified in CSA S6:25.

This recommendation differs from the RCP 8.5 adopted for NBC climate change provisions, in part because of different design horizons and the related increase in impacts, variability, and uncertainty, and therefore the greater likelihood of increasingly uneconomic bridge designs or adaptation works. Furthermore, this recommendation is consistent with the philosophy of the CHBDC as a set of minimum standards provisions.

Beyond RCP 6.0 as the CHBDC basis scenario, CSA S6.1:25 should also include guidance on risk-based frameworks for implementing extreme events or environmental variables with lower confidence in the projections, whether from RCP 6 or from RCP 8.5, or for design lives greater than 75 years that is sometimes adopted for major bridges. These implementations would exceed the minimum mandate of the CHBDC.

It is also noted that bridge and transportation infrastructure planning involves engineering decision-making to address uncertainty and to provide for future resiliency. This bridge planning process can include aspects of *adaptive design.* Some features of bridges are effectively "locked in" at first construction, such as bridge deck width or length, span lengths, foundation types, and substructure lateral load capacity (as dictated by stream flow demands). Other aspects may be readily modified in the future for additional climate resiliency, such as adding deck drain inlets, replacing bearing connections for enhanced load path strength, or increasing lateral loads from wind, flooding, or extreme events. Consequently, engineering judgment and design pragmatism will remain important elements of bridge planning and design, and can complement the CHBDC minimum loads inherent in any RCP adopted.

3.2.3 Applying Risk Frameworks to Climate Change Risks for Bridge Infrastructure

The basis for considering climate change risks for CSA S6:25 can reflect established climate change risk protocols and frameworks. The PIEVC Protocol [9] provides a useful starting point for climate risk assessments. It is consistent with the ISO 31000, *Risk management* assessment framework [10]. In the PIEVC Protocol, bridge risks from current climate and weather impacts are first characterized. Subsequently, knowledge of climate change projected to occur over the lifetime of the bridge, developed by global climate model projections and related techniques [7], is leveraged to assess changes to these existing risks (and potential emergence of new risks) over time. The concept of evolving risk and uncertainty arising from climate change is an important component of climate change provisions within CSA S6:25.

> "Bridge infrastructure design or rehabilitation that considers [these] future environmental loads must explicitly include a risk treatment action that reduces future consequences."

General Recommendations for CSA S6:25

- Define resilience and adaptation as methods to reduce risks arising from climate change.
- Include risk-based frameworks as part of the planning and design process, where appropriate, to address uncertainty, data gaps, and mitigation of climate change consequences on transportation structures. Various frameworks exist and are discussed within this report, including the PIEVC Protocol to determine climate change risks to bridge infrastructure, which relies in part on qualitative risk assessment by bridge owners, planners, and engineers and is recommended as a starting point for risk identification.
- Develop a risk or performance-based (objective- or outcome-based) framework for design within the CHBDC.
- Include climate change as a modifying factor to existing and emergent bridge infrastructure risks.
- Develop quantitative and qualitative guidance for bridge design that reflects changing risk from climate change as required.

3.2.4 Climate Change Bridge Adaptation and Resilience

Qualitative and quantitative climate change-based modifications to CSA S6:25 and CSA S6.1:25 will reflect the application of a risk-based framework that includes climate change as a risk modifier. For example, CSA S6:25 will include environmental load factors that quantitatively describe not only present-day loads but also projected future loads. Bridge infrastructure design or rehabilitation that considers these future environmental loads must explicitly include a risk treatment action that reduces future consequences. By integrating climate change projections into this and other commentary aspects, CSA S6:25 will be implementing climate adaptation and resilience steps in line with accepted risk evaluation and risk treatment concepts [10].

As noted in Section 3.1, stakeholder input on potential impacts and priorities was gathered during workshops. Input was also sought on potential strategies for improving climate change adaptation and resilience provisions in general and for their influence on CSA S6:25. An overview of these strategies is presented in Table 3. Stakeholders provided useful insights. The full set of findings from these workshops provided valuable stakeholder-sourced guidance for updates to CSA S6:25 climate change resilience and adaptation provisions.

General Recommendations for CSA S6:25

- Frame climate change-motivated alterations to bridge design or rehabilitation as risk treatment actions.
- Define bridge infrastructure risk treatment as equivalent to climate adaptation that increases bridge resilience.
- Emphasize strategies identified by stakeholders during project workshops.

Table 3: Climate Strategies For Bridge Infrastructure, Ranked

Strategies or approaches, ranked by workshop participant vote	Points
Guidance on sources and application of climate data	19
How to deal with existing structures and rehabilitation, and future service levels	15
Performance-based design for climate change/"criticality" of structure	14
General practice guideline for hydrotechnical assessment and design with respect to climate change (hydraulics)	8
General risk assessments	7
Design life (new) and criticality	7
Commentary on the various places in the CHBDC that deal with a specific issue	7
Clear guidance on target reliability and how to define	6
Level of effort to spend on climate risk assessment	5
Update CHBDC wind loading tables	5
General public acceptance	5
Framework or guidance for special studies	5
Flood hazard assessment guidance	4
Strategic asset management for bridges	4
Improved drainage guidance	3
Watershed analysis	3
Accelerated Bridge Construction (ABC), modular construction, and adaptive capacity/replaceability	2

3.3 Code and Commentary Recommendations

CSA S6:25 will be developed based on modifications to CSA S6:19. Identifying clauses in CSA S6:19 for updating or potential new clauses that incorporate climate change considerations and provide clause-specific general updating recommendations was an important first step. A methodical survey of CSA S6:19 clauses was a core aspect of the overall general recommendations in this report. Additional recommendations will be added in other sections of the CHBDC, including material design (steel, concrete, wood, buried and movable structures, sign structures, and gantries). The results of this code clause survey were tabulated by clause number, title, and for potential impacts on bridges. The recommendations for each clause were based on the general recommendations in the previous sections of this report.

The key bridge-specific issues arising from the workshops, interviews, and the project team's research, and the related recommendations for each are summarized in the following sections.

3.3.1 Hydrology and Hydraulics

This key bridge design issue includes data and information needs, design guidelines and references, rainfall and other updated data, watercourse features or combinations of effects, hydraulic design methodologies, regulations, clearances, vulnerabilities, and risk-based approaches to design.

The CSA S6:19 requirements for hydraulic design are cursory and contained within Section 1 (General) of the CHBDC.

General Recommendations for CSA S6:25

- Include updated environmental data with projections and uncertainty, sources of technical methodologies, data sources for watershed-level assessment and design, intensity-duration-frequency (IDF) curves [11], clearances, channel parameters, and relevant design guidelines, such as the Transportation Association of Canada (TAC) *Guide to bridge hydraulics,* 2nd edition [12], Federal Highway Administration design guidelines [13], and Engineers and Geoscientists BC design guidelines [14] mandated for BC engineers. It is recommended that CSA S6:25 continue to refer to the TAC *Guide to bridge hydraulics* [12] and other references cited above, and that guidance on climate change be included within the body of CSA S6:25 and CSA S6.1:25. CSA S6.1:25 should contain additional technical references to guide risk assessments, finding and using projected precipitation, and other data to assist in design tasks or risk studies for important structures.
- It is further recommended that CSA, the engineering community, ECCC, and others work with the TAC to update the *Guide to bridge hydraulics* to add specific guidance for climate data and application to hydrological and hydraulic design. This would allow the TAC guideline to remain a key and relevant design reference, with specific citation and mandate within CSA S6:25.

3.3.2 Scour

Scour is one of the leading causes of bridge failure and will become increasingly damaging to bridges and culverts in the absence of updated environmental data. It was also one of the highest priority issues identified in this project.

General Recommendations for CSA S6:25

- Update scour calculations for environmental data and watercourse parameters using the methods discussed above for bridge hydraulics.
- Update guidance and requirements for scour for abutments, in particular for high-energy rivers, which may be prone to washout under more frequent and higher flow regional floods or from extreme events. Piers are normally scour-protected while bank-seat abutments (especially without piles) may become prone to failure.
- Update aspects of scour design to reflect climate change impacts and current best practices, as required. Scour methodologies are cited within code and commentary references (e.g., TAC *Guide to bridge hydraulics* [12]).

3.3.3 Wind

Bridge design implications arise from high wind return periods and components affected by either short-term or long-term impacts. Wind load effects, calibration, reliability, and climate-related projections are being advanced quantitatively as part of this project.

Updated tables or maps of environmental variables, including wind, temperature, and ice accretion, will be developed and compiled using the data derived from observations and climate modelling [7]. Code writers should recognize that these variables will change at different locations across Canada, and some values may increase or decrease depending on variables and location. The data will then be used within a purpose-developed probabilistic framework to derive environmental variables and code-specific parameters for CSA S6:25, which will include the following tasks:

i. Outlining and developing the probabilistic method proposed to calibrate the changes to environmental load factors for CHBDC considering the effects of climate change.

ii. Calibrating the required return periods of extreme wind, temperature, and ice accretion loading (referred to as ultimate return periods) based on a uniform reliability approach with a load factor equal to one. This will also account for the spatially varying probabilistic climatic conditions.

iii. Calibrating load factors considering the nonstationary effects due to climate change focused on wind, temperature, and ice accretion, as well as their equivalent ultimate return period values in the CHBDC.

iv. Determining the necessary changes to the companion load factors associated with these environmental actions in the current CHBDC.

Task (i) will inform the CCWG and the TSCs for code and commentary updates. The remaining tasks (ii) through (iv) are quantitative for direct input to CSA S6:25 as load combination factors, companion load factors, tables of environmental variables along with various “ultimate” return periods (as currently included in CSA S6:19 Annex to Section 3, Loads), and code or commentary clauses as required for integration and completeness.

General Recommendations for CSA S6:25

- Adopt RCP 6.0 scenario and maintain the 75-year design life as the basis for the quantitative tasks for wind (as well as for temperature and ice accretion).
- Wind is a Tier 3 variable [7], therefore future uncertainty is high. CSA S6:25 should provide guidance on uncertainty and residual risks for bridge management purposes, including rational risk allocations within alternative delivery projects in which design-build-finance-operated concessionaire teams will have ~30-year operational phases within attendant climate change impact risks during the concession period. These risks also include formal handback condition demonstrations that will likely be impacted by climate change.
- Shorter-term wind load effects on temporary works may increase but are not easily projected with current climate models. Extreme local winds are also expected to increase but cannot be modelled. Some risk-based guidance will be provided for inclusion in the CSA S6.1:25.

3.3.4 Temperature Effects

Temperature change and extreme temperature effects can impact the effective temperature and temperature fluctuations of bridge structures.

General Recommendations for CSA S6:25

- Quantitative environmental data for temperature measures will be updated as part of this project, based on ECCC projections. Temperature ranges for bridge design will then directly reflect climate change effects.
- Perform a review of effective temperatures by superstructure type and region to confirm whether additional (+ or -) temperature increments remain valid for the design temperature ranges.

3.3.5 Ice

Ice effects include ice accretion on the surfaces of structural elements and freshwater ice on rivers, lakes, and other water bodies. Ice accretion on the surfaces of structural elements e.g. cable stays, has been updated as part of this project. Ice strengths used for ice pressure design as a function of ambient temperature and the potential for changes in ice breakup or ice jams also require consideration for CSA S6:25. Quantitative guidance was not included in this project.

General Recommendations for CSA S6:25

- Update Section 3 Loads (Figure A3.1.4) for general icing zones (regions, ice accretion thicknesses, and ranges thereof) across Canada using Cannon et al. 2020 [7].
- Update Section 3 Loads (Clause 3.12.1) to include climate change projections on icing. Because ice effects (thickness, crushing strength) may change with climate change (particularly in the North), allowances for these effects should be made in CSA S6:25. CSA S6:25 should remain relatively conservative on changes to ice loads (i.e., do not rely on temperature increases through 2030 to unduly reduce ice effects).
- Confirm prescriptive ice pressures in Section 3 Loads (Clause 3.12.2.1). While not part of this project, the CHBDC Section 3 Loads TSC may elect to review the design provisions for ice effects more broadly than climate change.

3.3.6 Performance-Based or Risk-Based Design

A performance-based framework provides for differing levels of importance of various issues as a function of transportation route, bridge crossings (watercourses, grade separations), regions and potential impacts on response, recovery, and the potential economic impacts on the transportation infrastructure.

General Recommendations for CSA S6:25

- Similar to the performance-based design framework in CSA S6:19, Section 4 Seismic design, CSA S6:25 should adopt an importance-based framework for life safety and serviceability for bridges and related geotechnical systems. Parameters for a performance-based approach should consider route importance including its expected role in disaster recovery.

- Where risk frameworks are needed to estimate impacts or consequences, include a PIEVC assessment coupled with scenarios and design sensitivity studies (e.g., considering bounds on RCP assumptions). If environmental variables are derived for two return periods (e.g., 50 years for the NBC and 75 years for the CHBDC), then there may be two sets of published data, including projections to interpolate for various design lives, that can be used for climate change adaptation for existing bridges.

3.3.7 Existing Bridges

This was another high priority issue for the stakeholder workshop attendees. Renewal works for existing bridges are typically designed for shorter durations than new bridges. Wind on structures and wind on traffic (operational limits) should receive specific guidance. Short-term and local wind events require guidance for the design of temporary works (e.g., encapsulation for re-coating) or structural modifications during construction.

General Recommendations for CSA S6:25

- Retain the remaining expected life of an existing bridge to guide adoption of a shorter return period than that used for new bridges, and apply risk-based approaches (see CHBDC, Clause 4.12 and Clause C4.12 for risk considerations in current seismic retrofit and rehabilitation of existing bridges).

3.3.8 Combination Events

Design guidance for compound events is considered important, as are quantitative load combinations within CSA S6:25, Section 3 Loads.

General Recommendations for CSA S6:25

- Adopt new ultimate wind pressures with a load factor α_w=1.0, but with α_w <1.0 in combination with other demands (traffic, thermal). Numeric data for the Section 3 loads, developed for this project, should be incorporated into CSA S6:25. Compound events include flood events from watershed changes affected by wildfire and scouring co-associated with seismic events (representative workshop example). Owners and designers in past years have asked for guidance on some compound events, and such guidance should consider both climate-related and non-climate-related demands.

3.3.9 Extreme Events

Design for emerging extreme events was investigated within this project and is discussed in more detail in Section 5 of this report.

General Recommendations for CSA S6:25

- Adopt risk-based frameworks, commencing with the high level PIEVC risk assessment, for extreme events on important bridge projects. Where prescriptive measures appear economic, practical, and reasonable, provide specific code guidance within CSA S6:25 or S6.1:25.
- Provide guidance for localized extreme events, based on this project, including wind microbursts, tornadoes, and regional events such as atmospheric rivers and heat, as well as for combined events (e.g., fire effects plus rain and snow runoff). It is acknowledged that it will be difficult to develop quantitative guidance within the CHBDC at this time. Data to assist in risk assessment and design should be obtained from the ECCC data portal [15]

3.3.10 Coastal Flooding Effects

Design for coastal effects is precluded from the scope of the CHBDC. Bridge owners should retain specialists for related demands.

General Recommendations for CSA S6:25

- Provide references and guidance in CSA S6.1:25 on special studies, so bridge owners and designers have a starting framework from which to work.

3.3.11 Permafrost

Guidance on climate change adaptation and design in Canada's North is a task and deliverable for this project. In the stakeholder workshops, permafrost did not emerge as a high priority item, however, if a workshop been held in one of Canada's northern territories, it is likely that permafrost would have emerged as a top-five issue. Updates to design for permafrost effects should remain a high priority area for CSA S6:25 climate change updates.

General Recommendations for CSA S6:25

- Maintain and update permafrost design provisions within Clause 6.18 (Permafrost) of the CHBDC. If significantly greater design guidance is sought by the Section 6 Foundations and Geotechnical Systems TSC, it should consider:

- Providing enhancements directly within Clause 6.18.
- Expanding permafrost design guidance as an annex within CSA S6:25, Section 6.
- Identifying definitive references that address permafrost design and climate projections and including as a mandatory reference within Clause 6.18. This would be analogous to the reference to the TAC *Guide to bridge hydraulics* [12] within Clause 1.9.
- Reviewing whether the CSA PLUS 4011.1:19, *Design and construction considerations for foundations in permafrost regions* [16], should be adopted.

3.3.12 Bridge/Road Planning as a System

Bridge, culvert, and approach road planning is considered in CSA S6.1:19, Clause 1.9 (Hydraulic design). For road and bridge planning in northern Canada, considering the recent and dramatic impacts of local permafrost melt (lakes, slumping, thermo-karst features) that have been documented, bridge planning should explicitly consider the need for site investigations and the need to avoid unmitigable areas during planning.

General Recommendations for CSA S6:25

- Retain existing commentary as the main source of guidance and add additional commentary and graphics to include climate-related changes and uncertainty to bridge planning.

3.3.13 Additional Issues

Several additional issues arose during the workshops or were raised by CHBDC TC members, resulting in the following list of items that should also be considered:

- Design life uncertainty.
- Climate data sources and proper application to projects.
- Barriers and support accessories: wind and fatigue-related issues due to climate change.
- Excessive precipitation including local short-term and longer-term or regional events. Short-term events are less amenable to downscaling projections for climate change and can affect local deck drainage, for example. Longer-term and regional events can be projected (Tier 2 level of confidence) and guidance within Clause 1.9 (Hydraulic design) and Section 3 (Loads) of the CHBDC will be provided.
- Drought and fire impacts on watershed-level events and related hydraulic design.
- Hydraulic loads on supports or superstructures, and whether prescriptive minimum design forces can be provided.
- Debris loading on bridge structures and piers.
- Soffit clearance is being addressed specifically in Clause 1.9 (Hydraulic design) of the CHBDC. Soffit clearances are also subject to regulatory and legislative environmental requirements both provincially and nationally.
- Loads during construction, including shorter-term wind load effects, the increased likelihood of occurrence, and the relative vulnerability of some bridges during construction, such as balanced cantilever and cable-stayed bridges. This item can be addressed based on observational data using current or five-year code windows rather than on projections for longer-term wind effects.

4 Wind Effects and Ice Accretion

As part of this project, Professor Han-Ping Hong at the University of Western Ontario conducted a comprehensive study to update wind and ice accretion demands on bridges to include recent data and the projected impacts of climate change, and for the projected demands to be used within a uniform risk framework in CSA S6:25. The results are captured in the following reports:

1. *Calibration of design wind load for Canadian highway bridge design code: Preferred design wind load format and effect of thunderstorm winds* [17] provides updated wind data and statistics needed for a uniform risk approach for CSA S6:25.
2. *General considerations of design wind load for CHBDC for non-stationary environmental parameters* [8] discusses how wind data, loads, and load combinations are derived probabilistically within CSA S6:19 and how they should be used in CSA S6:25.

3. *Hazard mapping and reliability-based calibration for Canadian highway bridge design considering the historical climate statistics and climate change effects: Wind and ice accretion* [18] is the final report, which contains load factors and combinations within a uniform risk approach, recommendations, and derived values for wind and ice accretion for inclusion in CSA S6:25.

The results also produced two tables of wind speeds and ice accretion thicknesses:

- Regional wind speeds across Canada for a range of return periods from 10 to 3000 years, using the most recent wind data set to 2016 and projected to 2100 including climate nonstationarity.
- Regional snow loads and ice accretion thicknesses on horizontal and vertical surfaces, also for a range of return periods and considering climate nonstationarity.

4.1 Uniform Risk Approach and Preliminary Findings

The climate change effects on wind and ice accretion included in this report are based on the projections of climate variables developed by Cannon et al. [7] for 0.5°C increments of increasing Canadian mean temperature.

Although regional variations in wind load are reflected in the 50-year return period values, differences in wind load statistics (e.g., mean, standard deviation, coefficient of variation) at locations across Canada introduced regional inconsistencies in reliability (safety indexes). Along with the ability to better address climate change projections and uncertainty, this was part of the rationale for adopting a uniform risk approach.

CSA S6:19 uses a traditional uniform hazard approach in which 50-year return period nominal wind loads are multiplied by a constant load factor of 1.4 for the factored wind demands.

In a uniform risk approach, the load factors for wind and ice accretion are set at 1.0 (instead of 1.4 for wind and 1.3 for ice accretion in CSA S6:19). This reflects that lower annual probabilities of exceedance (higher return periods, such as a 500-year return period) for wind and ice must be used.

In addition, site-specific wind data across Canada, with statistical parameters (including standard deviations and coefficients of variation), required updating using data through to 2018, and was then projected through to 2100 including climate change impacts for the adopted RCP scenario. In parallel, Hong [17] considered extreme wind events associated with synoptic winds (large-scale systems over hundreds of kilometers) and intense thunderstorm winds occurring locally. The events and their statistical parameters were separated to better capture the different events within the uniform risk framework. Together, this approach yields more uniform and acceptable levels of reliability across the country when compared to the current practice, which is based on a uniform hazard approach.

The target reliability index was assessed under conditions of climate nonstationarity because the reliability in such a case is time-varying. This implies that the safety of a bridge design can be acceptable in the early decades of its service but can decrease throughout its service life, even if the degree of nonstationarity remains constant over time. Therefore, selecting and meeting the target reliability is strongly related to climate nonstationarity.

The adoption of a uniform risk approach for wind loadings parallels the current CHBDC approach for seismic hazard. The demands are expressed in terms of probabilities of exceedance within a specified period of time. However, one important difference is that seismic design in CSA S6:19 uses a performance-based design approach that quantifies structural damage and estimates return to service times. These measures are quantified using structural displacement measures correlated to strains and damage seen in large-scale laboratory testing and in actual earthquakes. In the performance-based seismic design framework of the CHBDC, seismic hazard is provided as:

- 2% probability of exceedance in 50 years (generally for public safety under very large earthquakes).
- 10% probability of exceedance in 50 years (generally for rapid return to service under smaller, more frequent earthquakes).
- 5% probability of exceedance in 50 years (for repairability for earthquake intensities between service and safety levels).

> "The safety of a bridge design can be acceptable in the early decades of its service but can decrease throughout its service life, even if the degree of nonstationarity remains constant over time."

The 50-year design period is a legacy value arising from the design life adopted for buildings for which seismic hazard is developed. Despite the longer design life adopted for bridges (75 years), the same probabilities of exceedance for seismic risk are used for design of both buildings and bridges in Canada. The differences in structural performance and design lives are accounted for through different methodologies used in the two standards.

The above probabilities of exceedance are sometimes loosely expressed as "return periods" as follows:

- 2% probability of exceedance in 50 years ~2475-year return period.
- 10% probability of exceedance in 50 years ~475-year return period.
- 5% probability of exceedance in 50 years ~975-year return period.

These are derived from the following expression, which represents the probability that at least one event that exceeds the design limit will occur in a given design life. This is used within CSA S6 to relate probability and return periods of the uniform seismic hazard:

$$R = [1 - (1 - p)\ 1/t\ ]^{-1}, \tag{1}$$

where R = return period, p = probability of exceedance in period t, and t = duration consistent with p (e.g., 1 year for an annual probability of exceedance). Note that dividing the period (t) by the annual probability of exceedance provides an approximation of the return period.

Within CSA S6:19, the use of probabilities of exceedance for seismic hazard is preferred, while return periods are used for the purpose of references to earlier editions, to other codes, or in recognition of common usage among infrastructure stakeholders.

Expressing risk in terms of probabilities is recommended both for seismic hazard and for climate-related variables. This is also preferred in the context of risk-based design, such as for flooding and runoff in a nonstationary climate. The popular use of return period may introduce cognitive biases and incorrect perceptions of risk, particularly for long return period events like seismic hazard. Furthermore, referencing a wind velocity with a return period of 500 years in the context of a changing climate over a 50-year period may reduce credibility or confidence in the design value. Alternatively, referencing a wind load with a probability of exceedance of "10% in 50 years" or "15% in 75 years" may impart a better sense of risk perception in structural design.

Whether new design climate or seismic variables will be expressed in terms of probabilities or return periods will likely be determined during the CSA S6:25 development cycle.

4.2 Findings and Recommendations

This section summarizes Hong's [8][17][18] findings and recommendations related to wind and ice accretion for adoption into CSA S6:25.

The objective for this aspect of the project, to provide an updated reliability-based code re-calibration, was achieved and captured updated historic data as well as climate change projections. Key findings and recommendations related to wind are as follow:

- Target reliability of 3.5 was achieved with a design life of 75 years. Wind pressure projections used were consistent with RCP 6.0.
- Using wind velocity data within up-to-date ECCC databases, the use of α_w=1.0 and a wind pressure of q_{500} (equal to ρv^2_{500}) achieved factored demands that provide the consistent target reliabilities sought across Canada. The projected wind data include the effects of regional variations in wind statistics as well as synoptic (large-scale) and thunderstorm (local) winds.
- A new scale factor, α_{cc} was derived which accounts for the nonstationary, time-dependent projections of climate change impacts on environmental demands. This allows the q_{500} pressures developed during preliminary simulations and the load factor of unity to achieve the target structural reliability ($\beta = 3.5$) from the set of Monte Carlo simulations, including climate change projections. A scale factor was necessary as the results of the Monte Carlo simulations using an a priori estimate of a 500-year return period wind effects alone was unlikely to achieve the target reliability. The primary load combination for safety of a bridge becomes:

$$\alpha_d D + \alpha_{cc} * 1.0\, q_{500} \tag{2}$$

$$\alpha_d D + \alpha_L L + \alpha_{cc} * \alpha_{wL}\, q_{500} \tag{3}$$

- The value of α_{cc} was found to be 1.05.
- The wind loads are to be used with the hourly-mean reference wind pressure, q, and with different return periods for ultimate and service wind effects on bridges or components, and for major bridges beyond the scope of the CHBDC:
- 1000 years for bridge structures with any span 125 m long or longer (for consistency with the current scope cut-off span length for long-span highway bridges in CSA S6).
- 500 years for bridge structures with a maximum span shorter than 125 m, luminaire support structures higher than 16 m, and overhead sign structures.
- 200 years for luminaire and traffic signal support structures 16 m high or shorter, and for barriers.
- 75 years for roadside sign structures where a long-life expectancy is not required or for any of the structures specified in the previous three bullets during construction.

Additional wind-related findings include:

- Further scrutiny and analysis of tornado wind velocity hazards for Canada is warranted.
- The increase in factored design wind load using updated data and the uniform hazard approach proved to be modest, up to 6% if non-thunderstorm and thunderstorm-recorded winds are analyzed separately. Changes are between -4% and +4% in most cities across Canada for separated wind analyses.
- When non-thunderstorm and thunderstorm-recorded winds are analyzed as a combined dataset, the changes in factored design wind load range between -1% and +4% except for increases of ~6% and 11% for Edmonton and Iqaluit. For Edmonton, the maximum difference becomes 12% if analyzing the thunderstorm and non-thunderstorm winds separately.
- For Fredericton, wind design pressures would decrease by 12% if thunderstorm and non-thunderstorm winds are treated separately. For most Canadian cities, considered changes were within ~4% between CSA S6:19 and CSA S6:25.

Key findings and recommendations related to ice accretion thicknesses include:

- Ice accretion hazard mapping should continue in CSA S6:25 and should be based on a Gumbel distribution fitted using the generalized least-squares method. This was found to be the most appropriate for regions with significant ice accretion in Canada.
- The Chaine model should be used for CSA S6:25. It is the operational scheme used by ECCC [7] and provides a conservative estimate compared to other models.
- The ice accretion load factor is recommended as

$$\alpha_d D + \alpha_{ci} * 1.0\, A_{300} \tag{4}$$

where A_{300} is the ice accretion thickness with a return period for ice accretion of 300 years [17], α_{ci} is a factor derived to account for climate change and for significant regional differences for ice accretion across Canada.

> "Data sets that include projected environmental variables, such as temperature or wind speeds, are necessary to achieve target reliability of the structural design of bridges over the expected service life of a new bridge."

5 Climate Nonstationarity and Extremes

Incorporating climate change in bridge design requires that future changes to environmental effects are taken into consideration.

Data sets that include projected environmental variables, such as temperature or wind speeds, are necessary to achieve target reliability of the structural design of bridges over the expected service life of a new bridge. Bridges designed in the current environment of a changing climate will experience changing levels of safety over the coming decades. This presents a challenge to provide a level of initial reliability such that future safety levels remain acceptable as environmental demands (loads, deformations) evolve.

It is also important to avoid undue conservatism in the initial design to limit unnecessary costs that add little value to infrastructure resilience. These considerations require a statistically-grounded understanding of climate change and an application of changing environmental variables to engineering design.

This section summarizes the uniform risk approach used to include nonstationarity in a probabilistic methodology to achieve a margin of structural capacity over a 75-year bridge design life, and includes:

- A description of stationarity and nonstationarity in climate data sets.
- The adoption of a RCP to underpin climate projections.
- A discussion of climate variability and uncertainty in calibration.
- A description of how nonstationarity is captured in a uniform risk framework for structural design.

5.1 Stationarity and Nonstationarity in Weather and Climate Records

A qualitative understanding of statistical climate change concepts, particularly of stationarity, nonstationarity, measures of variability and change, and their relation to the concept of signal-to-noise, is an important aspect of composing climate change provisions. This section provides a review of these concepts in the context of climate change.

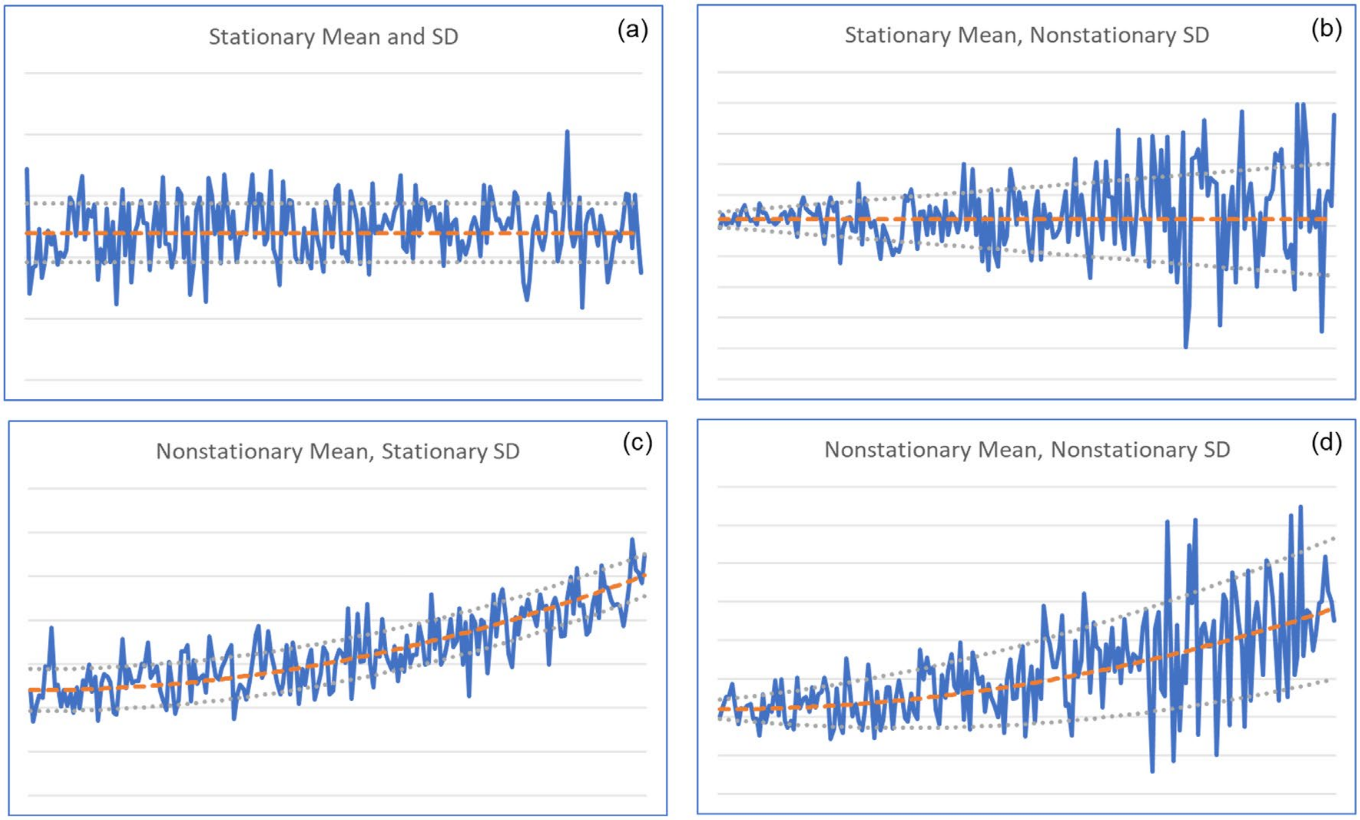
A stationary time series is a collection of data for which statistical properties do not vary with time. In other words, a data series is considered stationary if statistical properties from one subset of the data taken over one time period are indistinguishable from a similar subset of data taken from any other time period, as shown in Figure 2a. Stationary time series in the natural world typically include "noise" or oscillations around a constant mean value. To be considered stationary, the statistical properties of this noise also cannot change over time.

A nonstationary time series is a collection of data that displays time-dependent statistical properties. A nonstationary example is shown in Figure 2b, where the variability increases over time but the mean value does not change. Figure 2c provides an example where the mean increases over time but there is no change in variability, capturing an underlying trend in the data. Figure 2d provides an example in which the mean and the variability both increase over time.

Estimates of weather and climate are often defined in terms of climate parameter time series for a given location or region (e.g., nationally for Canada as seen in Figure 1). Because of this, the concepts of time series stationarity and nonstationarity are important in communicating climate change in statistical terms.

In the absence of climate change caused by any external climate forcing, time series of weather and climate parameters would be statistically stationary, after adjusting for regular daily/seasonal cycles and sampling over a sufficiently long period (e.g., World Meteorological Organization 30-year Climatological Standard Normals, [19]). A time series of precipitation in a stationary climate, for example, would display unchanging long-term average seasonal/annual total mean accumulation, regardless of which normal climate period the mean was calculated over. However, because short-term weather conditions naturally oscillate around mean average climate conditions, this stationary climate would also be characterized by the presence of anomalous noise, including reoccurring extreme events, such as anomalously high annual daily maximum precipitation, for a given year. To be considered stationary, the long-term statistical probability of occurrence of such events would not change with time. Graphically, this means that any

Figure 2: Representative examples of stationary and nonstationary time series. Stationary mean and standard deviation (SD) (a); stationary mean with nonstationary SD (b); nonstationary mean with stationary SD (c); nonstationary mean with nonstationary SD (d).



distribution function of any climate parameter would look functionally identical, regardless of which subset of the time series was used to develop the distribution.

In contrast, a nonstationary climate is one that, due to significant external climate forcing, exhibits persistent time-dependence to one or more statistics or to one or more climate parameters. A nonstationary climate demonstrates a persistent, statistically measurable signal of change that is strong enough to emerge from the noise of natural climate oscillations. Casting climate change in terms of signal and noise highlights that the process for detecting climate change is closely related to general engineering processes for detecting signals within noisy electrical, geotechnical, or ambient vibration time series.

A common measure of a nonstationary climate is the presence of time-dependent changes to average/mean climate parameters, determined by the calculation of mean conditions for different periods within the climate parameter time series. Detection of climate nonstationarity in this way can be strongly impacted by the signal-to-noise ratio of individual climate parameter time series records. For example, global, annual-scale time series of mean near-surface air temperature typically demonstrate low year-to-year variability (noise), such that the signal of climate change emerges clearly. Conversely, local, daily-scale temperature time series are typically much noisier, such that the signal of climate change can be more difficult to detect.

Nonstationarity related to climate change can also be reflected in persistent changes to statistics representing extreme weather and climate events. These statistics are typically much more important for engineering design thresholds. The detection of a climate change signal in extreme events is also impacted by natural noise in the time series. This is usually a greater challenge with extreme event time series and reflects lower confidence in projections of changes to such events in the future [7]. This has driven the development of techniques for improving statistical characterizations of extreme events (and changes to these statistics). These techniques include extreme value distribution fitting (e.g., using Gumbel and generalized extreme value distributions) to estimate the magnitude of very low probability climate events and the application of large ensembles of climate and weather models to effectively multiply the sample size available for statistical analysis. For context, both techniques are applied to reliability modelling for the CHBDC and within this project.

Finally, independent from long-term trends to mean and extreme conditions, climate nonstationarity may also be reflected by changes in variability, such as increases in standard deviation or coefficients of variation. In addition to general temperature increases, which shift the entire distribution of temperatures upwards, the occurrence of warm and cold conditions relative to the time-dependent mean will also increase, broadening the width of temperature distributions with time. In general, climate change is, and will increasingly be, reflected in nonstationarity across multiple statistics of weather climate and weather time series.

5.2 Incorporating Climate Nonstationarity in Calibration of Target Reliability

5.2.1 Probabilistic Framework Used in the CHBDC

As a foundational aspect of capturing nonstationary data within a reliability-based design approach, an overview of the key assumptions in the probabilistic methods and stationary environmental data is provided in this section. These methods have been used for Canadian structural design codes and standards for almost five decades. They have been adopted in this project and are also used to resolve discrepancies in the current reliability levels for wind at different sites across Canada using an updated set of measured environmental data through to 2016. A detailed discussion is available in [8].

A reliability index of β, based on probabilistic models, means, and coefficients of variations of structural capacity and demand, can be established for a given limit state function (load combination). If the structural capacity and demand can be assumed to follow a log-normal distribution, the reliability index, β_{RE}, can be estimated by considering the ratio of the capacity to the demand. A reliability index of β_C is defined as the mean to the standard deviation of the limit state function. In general, the relation between the failure probability, P_f, and β can be established by using the normal cumulative probability distribution function or its inverse.

For calibration in identifying the required factored structural design capacities and design load demands, a target reliability index for a specified design working life, β_T (or a corresponding tolerable failure probability, P_{Tf}), needs to be selected. The essence of the design calibration is then to develop factored design values of variables involved in the considered limit state function such that the calculated reliability index of the designed structures equals, on average, the target reliability index. Limit state functions considering environmental loads, as either principal loads or as companion loads (load factors and load combinations in CHBDC), are developed in this way.

The load factors for the climatic parameters included in CSA S6:19 are based on two concepts: (1) a uniform climate and related environmental variables, and (2) environmental variables having relatively large exceedance probabilities. For example, the annual probability of exceedance adopted to evaluate nominal wind velocity pressure was a 50-year return period value. The annual exceedance probability was selected independently of the sites. The wind load factor was derived as $\alpha_w = 1.4$ (the CHBDC provides tables of nominal design wind pressure for locations across Canada). The use of a load factor greater than one and the 50-year return period environmental variables produce a factored design load corresponding to the desired low exceedance probability.

However, the exceedance probability will vary from site to site if the coefficient of variation of the climatological element varies regionally [20][21]. This is the case for wind in Canada, therefore the use of a uniform climate hazard (at 1/50 annual probability of exceedance) approach leads to inconsistent reliabilities for structures at different sites across the country. Hong described an approach with a lower probability of exceedance [22].

Hong showed that using a nominal wind velocity pressure for a 500-year return period value, a wind load factor of $\alpha_w = 1.0$, and a scale factor for climate change of 1.0 (i.e., for a stationary climate case) is adequate to generate the required reliability index for 14 cities across Canada. This derived table of environmental variables provided insight into the degree of importance of the spatial differences in the coefficient of variation of wind across Canada. It also provided a baseline against which this project's results, including climate change for the adopted RCP scenario, could be compared. Furthermore, this allows future CHBDC changes to be separated when arising from the probabilistic methods, the 2016 baseline data, and future updated climate projections.

5.2.2 Incorporating Nonstationary Climate Data Projections

Hong has extended and refined a probabilistic model to capture nonstationary climate data. The model exploits projected increases in mean global temperature derived by ECCC [7]. Developing a scale factor to capture climate change effects can provide consistent structural safety, considering the expected time-varying frequency and intensity of certain extreme weather events such as rainstorms, flooding, freezing rain, and other hazards that contribute to the damage or failure of bridges. The time-varying, increasing temperature trend is expected to affect the statistical and extreme environmental parameters that need to be used for structural design, including wind, ice accretion, and other variables.

Climate modelling and projections are a computationally intensive process. A recent study by [7] provided reports on the percentage of changes for a given temperature increment, which can be applied to the RCP scenario through a formalized mapping procedure. With statistics and probabilistic models of the environmental parameters based on historical data, this data and mapping can be used to define nonstationary extreme environmental parameters, such as wind velocity, ice accretion, and precipitation. Relationships between environmental variables and temperature changes were also developed and extrapolated to the future for a given RCP scenario. Hong (2020) [8] adopted the following expression of these statistics:

$$s(t) = s_H + \Delta_s(t, RCP), \qquad (5)$$

where s(t) is a given statistic at time t in the future, sH is the historical value of the statistic, and Δ_s(t,RCP) is the change in the statistic at a time t for a given RCP scenario.

With these statistics defined for any time in the future, a probabilistic model can be defined for each environmental variable. For example, an annual maximum wind velocity can readily be described using a Gumbel-distributed random variable. More specifically, for any given year of the considered design life, an extreme value distribution of wind speed conditioned on that given year, $G(v|\text{mean}_i, \text{COV}_i)$, is determined, where mean_i and COV_i denote the mean and coefficient of variation of the given year, *i*. The distribution parameter of the wind speed can then be calculated directly from these two statistics. For the reliability analysis, a sequence of annual maximum wind velocity for each year within the design life can then be simulated and used for the reliability analysis.

Hong proposed that the same design load format described above for stationary data be adapted for a nonstationary extreme climatological variable by deriving an additional factor accounting for nonstationarity. This scale factor for climate change is denoted as α_{cc}. For the case of wind load, this may be expressed as:

$$\alpha_w \alpha_{cc} q_{500}, \tag{6}$$

where α_w is the wind load factor equal to 1.0, α_{cc} accounts for the nonstationary climate change effects and could be time-dependent. The task becomes calibrating the required α_{cc} to achieve the targeted reliability index. Hong carried out the reliability calculations using Monte Carlo simulations for the required limit state functions.

For the calibration of α_{cc} for the nonstationarity datasets, the reliability achieved in the Monte Carlo simulations was tested against one of two criteria:

1. Determine the minimum annual reliability index achieved for each year in the design life and compare that to the target minimum annual reliability, or
2. Determine the reliability index for the entire design life and compare that to the selected target reliability index for that entire design life.

In both cases, the year when the structure is put into service and each subsequent year through the design life would be modelled. By using the time-varying statistical measures, the adopted probabilistic model for wind velocity, the calculated reliabilities on either an annual or full design life, and a comparison to the annual or full design life target reliabilities, two sets of α_{cc} would be determined for different sites and RCPs. The two sets of α_{cc} would be assessed and one would be recommended as the best for meeting target reliability for the design wind load, including climate change effects.

The probabilistic methodology established in this project may need to be refined or re-applied with new measured data for future editions of the CHBDC to continue to achieve bridge designs with targeted levels of structural safety. In addition, for bridges of different importance categories that target a design life longer than the 75-year window adopted for Canada's typical highway bridges, the design variables may also require nominal increases to achieve owner and designer objectives.

This methodology may also affect bridge components that are locked in during initial construction (i.e., those that are difficult to strengthen or retrofit in the future). Examples could include span lengths and foundation types. As part of the design process, it may sometimes be more pragmatic to meet longer-term and uncertain climate-related design goals through adaptive design during the bridge planning and concept design phases. Adaptive design allows for future practical modifications to bridges, rather than designing and constructing excessively conservative and expensive measures for future climate-related risks with higher levels of uncertainty.

6 Localized Climate Extreme Events

Climate change is currently shifting weather and climate conditions in ways that negatively impact Canadian highway bridge infrastructure. Of particular concern are climate change-driven increases in the magnitude or frequency of extreme weather events, to which bridge infrastructure is exposed and vulnerable. These types of events increase material risk to infrastructure.

The previous sections of this report focus on the implications of climate change to relatively "well-characterized" physical bridge impacts, including wind pressures, temperatures, and ice accretion. This section extends the discussion and provides insight into more intermittent extreme climate impacts.

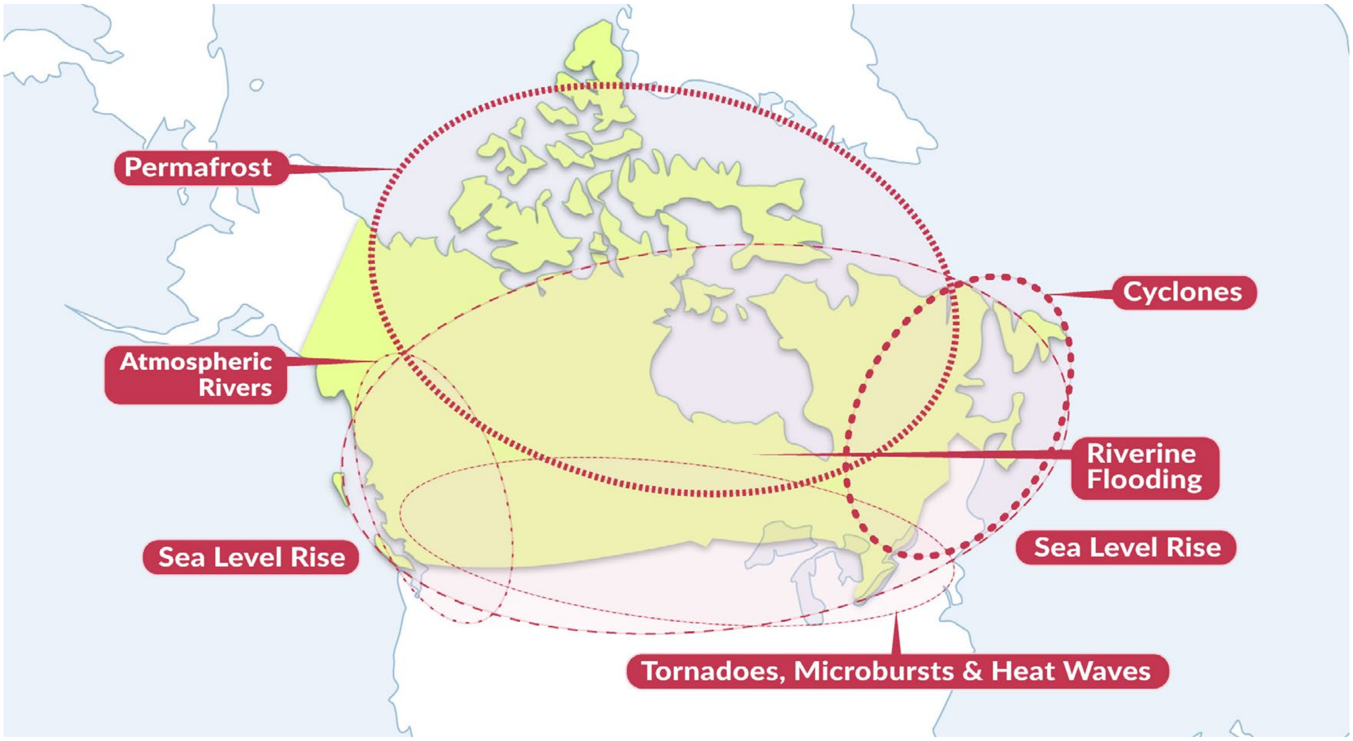
6.1 Climate Change-Driven Impacts on Extreme Climate Events in Canada

Several categories of extreme climate events are explicitly represented in CSA S6:19 and the implications of changes to the magnitude and frequency of these events due to climate change will be added to CSA S6:25. For example, Section 1 (General) should add or revise content related to climate change impacts on bridge infrastructure due to flooding, Section 3 (Loads) should revise content on design loads that incorporate climate change considerations, and Section 6 (Foundations and geotechnical systems) should enhance its current guidance related to permafrost loss and its impacts on bridge infrastructure.

CSA S6:19 is silent on bridge infrastructure vulnerability to certain categories of potentially consequential extreme events that occur or are emerging at various locations throughout Canada (Figure 3). This section examines potential changes to extreme events that may present new or heightened material risks to Canadian highway bridge infrastructure, and includes:

- A survey of potentially impactful extreme events. In each case, available knowledge on their historical occurrence is reviewed, with an emphasis on impacts to bridge infrastructure.
- A discussion of potential future trends. Typically, future projections for the extreme events reviewed here are scarce or subject to uncertainty. In these cases, the uncertainty is noted to provide context around the inclusion of treatment of potential impacts in CSA S6:25 and CSA S6.1:25.
- For each event, potential implications to bridge infrastructure and recommendations for CSA S6:25 are developed.

Figure 3: A schematic of extreme events in Canada. All regions of Canada having bridge infrastructure experience multiple extreme events.



- Where appropriate, recommendations are provided around possible methods for inclusion into S6:25 and CSA S6.1:25. In some cases these recommendations are specific, in others they describe general methodologies that may be undertaken to approach uncertain climate changes to extreme events.

6.1.1 Tropical and Extra-Tropical Cyclones

6.1.1.1 Historical Occurrence

Tropical and extra-tropical cyclones are large, powerful storms that are driven by the evaporation of seawater and develop over oceans due to warm surface waters. Warmer oceanic conditions lead to increases in the maximum strength of tropical cyclones. Hurricanes and typhoons are both forms of cyclones with different naming terminologies used in the Atlantic, Pacific, and Indian oceans. Extra-tropical cyclones are tropical cyclones that have reached latitudes typical of Canadian coastlines. By this stage, they have typically begun to interact with mid-latitude atmospheric conditions, which causes shifts in storm character (e.g., elongation, loss of clear hurricane eye). Nonetheless, storms experiencing this extra-tropical transition can still generate damaging winds, waves, and precipitation.

Tropical cyclones are entirely linked to warm ocean conditions, leading to a concentration of tropical cyclone development in particularly warm regions of Earth's oceans. Historically, Canada has remained well outside of strong tropical cyclone regions due to colder coastal ocean temperatures, so their impacts on Canadian bridge infrastructure have been infrequent. However, cyclones have periodically occurred as hurricanes (on the Atlantic coast) or less frequently as typhoons (on the Pacific coast), with demonstrably high consequences for highway bridge infrastructure. Tropical cyclones and significant tropical storms reaching Canadian coastlines are typically remnants of much stronger tropical systems originating from low latitudes (Figure 4). These storms are distinct from other prominent maritime weather events, such as atmospheric rivers on the Pacific coast, and North Atlantic-sourced storms on the Atlantic coast. There are prominent examples of landfalling Canadian cyclones causing extensive damage (Figures 5 and 6), including the following examples:

- Hurricane Hazel (Atlantic Coast; 1954; 81 deaths)
- Typhoon Freda (Pacific Coast; 1962)
- Hurricane Juan (Atlantic Coast; 2003; 8 deaths)
- Hurricane Igor (Atlantic Coast; 2010; 1 death)

Figure 4: Trajectory of all historical hurricanes tracking within 100 km of Newfoundland while retaining hurricane strength. Source: US National Oceanic and Atmospheric Administration.

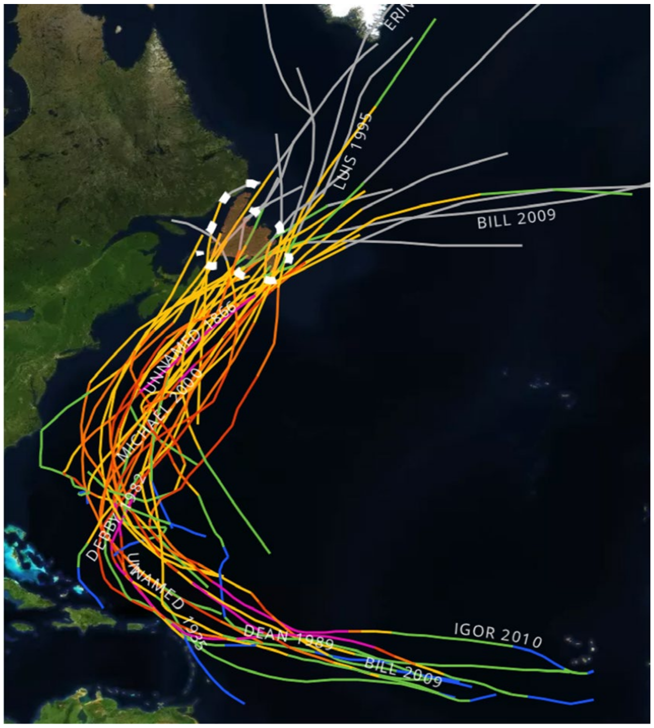


Figure 5: Bridge damage due to Hurricane Hazel, 1954
Source: Martin Taylor, https://creativecommons.org/licenses/by-sa/3.0/deed.en

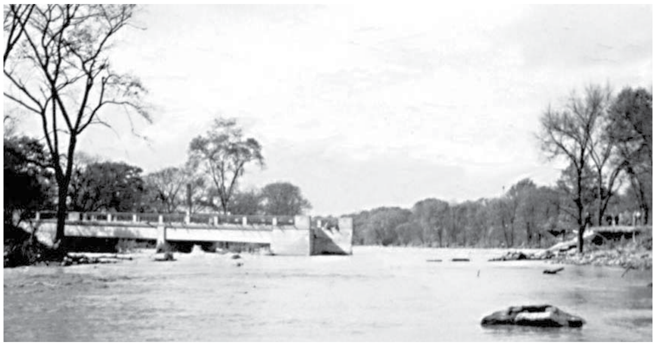


Figure 6: Highway damage resulting from Hurricane Igor, 2010. Source: Environment Canada.

Existing datasets for wind velocities and for precipitation measured in Canada capture these events. There is no distinction made in the datasets between wind speeds or rainfall associated with extra-tropical cyclones and other storm events typical of Canadian latitudes. Therefore, for the design of bridges for wind pressures or precipitation, these events have been captured in the environmental design data published for bridge design. Changes in winds or precipitation arising from climate change trends and from extreme events should be considered in CSA S6:25.

6.1.1.2 Climate Change Tools

Climate change impacts on tropical cyclone characteristics are primarily assessed in the context of tropical regions, where risks and damages from these storms are most prevalent. Present understanding of climate change impacts on tropical cyclones [23] suggests an increase of approximately 5% in maximum cyclone wind speeds, associated with a general increase in storm intensity, counteracted by a decrease in storm frequency and speed (i.e., the rate of drift of the cyclone centre, with implications for persistent storm impacts at a given location). In general, this implies that tropical cyclones will not become more frequent. Instead, they will become more intense and slow-moving.

The understanding of climate change impacts on mid-latitude cyclones that impact Canadian maritime locations is currently poor, and is the focus of ongoing climate science and meteorological research. However, there is some emerging evidence of trends based on numerical cyclone simulations. For example, Michaelis et al. [24] identified a significant:

- Increase in the fraction of tropical cyclones undergoing a transition to severe extra-tropical cyclones at Canadian latitudes;
- Northward transition in the tropical-to-extra-tropical transition zone; and
- Strengthening of extra-tropical cyclone intensity (67% increase in maximum 6-hourly rain rate and 22% increase in near-surface wind speed).

This implies that cyclones making landfall on Canadian coastlines will increase in frequency and intensity, which in turn implies an increased risk of these discrete, damaging events to coastal and near-coastal Canadian Atlantic ocean highway bridge infrastructure.

6.1.1.3 Implications for Bridge Infrastructure

Tropical and extra-tropical cyclone impacts on Canadian highway bridge infrastructure are limited in the current climate state to Southern Atlantic and Pacific Canadian coastal transportation. Climate change-driven shifts to landfalling cyclone characteristics in these regions may include:

- More intense and long-lasting event-specific rainfall events, leading to intensified watercourse flows and impacts on bridge channels, approach embankments, piers, and local bridge deck flooding. Design and construction for flood flows, lateral forces and scour on bridges, and for increased flow risk on culverts can be mitigated through bridge and route planning and design.
- Greater soil destabilization and potential for landslides and flood-induced debris flows impacting bridge substructures and superstructures.
- Higher storm surge pressures on low-lying coastal and ocean harbour or channel crossing bridges.
- For evolving or extreme winds, increased pressure and loads on bridges and on traffic traversing the crossings.
- Partially mitigated impacts of extreme events through updated design for hydraulics and wind.

Despite their consequence to highway bridge infrastructure, rainfall and flood events due to infrequent cyclones are unlikely to be robustly integrated into current design loads for coastal bridge infrastructure. Their rarity and hence poor representation in statistical rainfall and flood statistical distributions are also not well reflected in design-relevant probabilities of exceedance.

6.1.1.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following recommendations address key issues related to climate change and tropical and extra-tropical cyclones for inclusion within CSA S6:25 and CSA S6.1:25:

- Treat planning and designing for these extreme events as risk mitigation measures rather than mandatory foundation or clearance design requirements. In regions and at sites where these events may occur, building resilience in design (e.g., use of piles rather than spread footings) should be considered early in the bridge siting and conceptual design.
- Identify in CSA S6.1:25 that these events are considered beyond the scope of normal design practice and include latent risks to owners or concessionaires that are difficult to quantify. In the absence of project-specific guidance on risk ownership (i.e., in alternative delivery projects and especially those with operating concessions), these risks may be most appropriately borne by the owners.
- Include guidance for CSA S6:25 and CSA S6.1:25 to perform site-specific hydrology and hydrotechnical analyses, and commentary additions for atmospheric river impacts (and for other extreme precipitation events) to be included for infrastructure in regions of the country prone to atmospheric river landfall. Modelling should be appropriate to the crossing and be able to model extreme event scenarios. Similar analyses can be avoided or tuned to other extreme precipitation scenarios elsewhere in Canada.
- Add a requirement to consider hazards and impacts of extreme events in the bridge planning and crossing site selection and evaluation. For example, the 2013 Calgary flood event was a rare event[1] that bridge design may not have fully considered [25]. Bridge damage was localized (i.e., one permanent rail bridge damaged by scour) and one bridge under construction had temporary works severely damaged by streamflow pressures.
- Provide design consideration guidance for extreme events to recognize the likelihood of increased flood resilience associated with design updates including climate change projections, and potentially the adoption of lower probability (i.e., longer return period) events for life safety. Also consider the benefits of other prescriptive measures to mitigate consequences (e.g., freeboard) or regulatory changes in consideration of extreme events.
- Avoid undue prescriptive increases in bridge soffit clearances for extreme events. An exception may be increased clearance for ice flows/breakup or ice in combination with extreme backwater effects in rare events. Updated climate data and the incorporation of climate change projections may lead to increased clearance requirements. For extreme events, ultimate failure modes (bridge collapse) should be considered in planning and design unless an owner wishes enhanced resilience. Related damage may be acceptable provided the crossing can be restored to service. Route and crossing importance to short- and long-term response and recovery should be considered (i.e., importance classification of crossings or routes, as in Section 4 Seismic Design, for a performance-based design framework).
- Include extreme event scenarios as sensitivity studies to identify the implications on bridge planning. This would apply in particular for precipitation and potential flooding. If flow volumes, velocities, and watercourse elevations are not unduly affected, recognize (provide guidance) that design for life safety for flooding using appropriate exceedance probabilities (or return periods) and climate projections may produce the resilience necessary to manage extreme events without unacceptable or irreparable damage.
- Consider the risks and impacts of scour from extreme events and their related increase in flows. Some prescriptive guidance in CSA S6.1:25 on scour mitigation as part of design should receive additional attention to guide resilience for these events.

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[1] The 2013 Calgary flood event was the fourth flood of this magnitude since the 1890's.

- Recommend strengthened guidance in CSA S6.1:25 for increased foundation resilience, in particular for erodible soils (e.g., adopt piles rather than aprons or deepened footings where appropriate). Extreme flows have the potential to significantly impact channel morphology (shape and changes) and scour depths. With scour being cited as one of the leading causes of bridge failure in North America, this hazard should be considered in conceptual bridge planning through design.
- Provide guidance in CSA S6.1:25 on deck drainage under these extreme scenarios (i.e., that enhanced bridge deck drainage may not be required for safety or life safety, as traffic usage during such events would be slow and cautious such that transient deck flooding would often be acceptable).
- Confirm the extent to which current precipitation design parameters from cyclone landfalls are captured in datasets used for highway bridges. This is important so the design or planning treatments for extreme events can be separated from design for life safety and damage from recorded and projected precipitation (or wind) parameters.
- Recommend that monitoring of emerging scientific reports related to climate change-driven shifts to extra-tropical cyclone frequency, duration, and translation speed be carried out by CSA's TSCs. This literature is expected to grow significantly in the coming years.

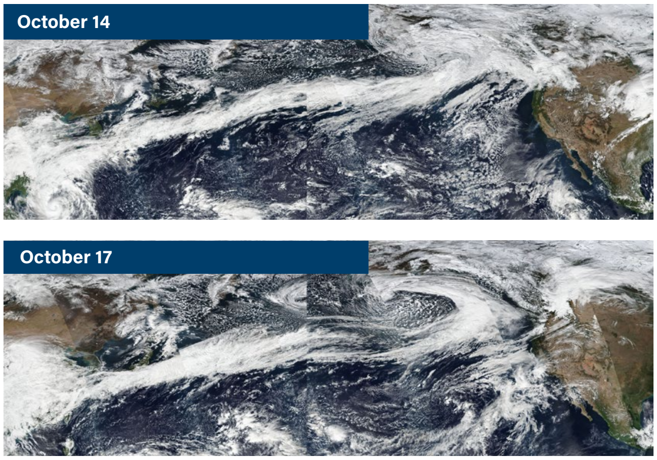
6.1.2 Atmospheric Rivers

6.1.2.1 Historical Occurrence

Atmospheric rivers (ARs) are discrete atmospheric events that rapidly transport large amounts of water over short periods of time from tropical ocean to mid-latitude coastal locations (Figure 7). Due to prevalent large-scale atmospheric circulation patterns, AR impacts on Canadian highway bridge infrastructure are typically focused on the Canadian Pacific coast and originate in the tropical and subtropical Pacific. Landfalling ARs are less common in Atlantic Canada because regional Atlantic circulation patterns do not typically create the right conditions.

ARs tend to bring both extremely wet and warm conditions, so they are often colloquially called "Pineapple Express" events on the Pacific coast [26].

Figure 7: Pacific Ocean atmospheric rivers, occurring in October 2017. Source: NASA Earth Observatory.



Between 1979 and 2012, an average of 20 AR events per year affected coastal British Columbia, delivering 20% to 25% of coastal annual precipitation. Each event typically involves short (hours to days), high-intensity precipitation, focused on a relatively narrow stretch (50–100 km) of coastline. Given their relatively common annual occurrence, it is likely that the impact of ARs is accounted for in the statistics used to derive precipitation-based environmental loads. However, the impact of rare compound events in which ARs combine with remnants of tropical cyclones, or contribute to rain-on-snow events, or remain in place for significant periods of time (or arrive in the same location in sequences) are likely not accounted for. This is evidenced by historical compound AR events that resulted in catastrophic highway bridge structure collapse and consequent loss of life due to substantial exceedance of design parameters.

6.1.2.2 Climate Change Trends

ARs are expected to substantially increase in frequency and intensity in the future on the Canadian West Coast. An analysis by the Pacific Climate Impacts Consortium, using the high emission RCP 8.5 climate change scenario, predicts that the number of days the Canadian Pacific coast experiences AR conditions will double [26]. This is consistent with a more recent global assessment [27], which found similar increases globally, and tied these increases to wider, longer duration, and more intense individual AR events.

6.1.2.3 Implications for Bridge Infrastructure

Increased occurrence of ARs on the Pacific coast of Canada will increase the probability of extreme wet weather conditions. This impact is largely captured by current relevant climate assessments (e.g., [1] [7], which rely on global climate model simulations that capture the broad nature of ARs [27]. However, increased AR occurrence will also increase the chance of compounding events, in which ARs combine with other factors in a multiplicative manner that can cause bridge infrastructure damage. For example, as ARs are often associated with warm conditions, they can cause sudden and severe flooding from simultaneous snow melt and rain-on-snow conditions. Such events are not captured in pure precipitation statistics. Key implications for bridge infrastructure related to changes in ARs and AR-enhanced compound events include:

- More intense and longer lasting event-specific rainfall events, leading to intensified bridge approach and deck flooding.
- Greater soil destabilization, landslides, and flood-induced debris flows impacting bridge structures and abutments.
- Higher probability of damaging compound events in which ARs play a multiplicative role leading to damaging bridge infrastructure impacts.
- ARs may also lead to similar bridge impacts and design implications as those described in Section 6.1.1 for extra-tropical cyclones.

Figure 8: Bridge washed out from atmospheric river in Merritt, BC, 2021. Source: Province of British Columbia.

6.1.2.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following general recommendations address key issues related to climate change and ARs for inclusion within CSA S6:25 and CSA S6.1:25. Recommendations provided in Section 6.1.1.4 of this report regarding precipitation and flood impact for extra-tropical cyclones would be addressed similarly for AR hazards and impacts.

- Confirm the extent to which current precipitation design parameters for ARs are captured in datasets used for highway bridges. As discussed for cyclones, this will aid in design or planning treatments for extreme events so that extreme event impacts can be separated from design for life safety and damage from recorded and projected precipitation (or wind) parameters.
- Include guidance in CSA S6.1:25 for performing site-specific hydrotechnical analyses and commentary additions for AR impacts on infrastructure in regions prone to AR landfall. This guidance will have similarities to that provided for precipitation from landfall cyclones, with both cases to be considered appropriately on a regional basis.
- Continue to monitor emerging scientific reports related to climate change-driven shifts to AR characteristics and their potentially increasing role in extreme high flows.

6.1.3 Tornadoes

6.1.3.1 Historical Occurrence

Tornadoes are well-known meteorological phenomena that occur in continental interiors, particularly in the interior of North America. Tornadoes are typically summer events that are generated by the collision of warm and cool air masses, and are often also associated with high (non-tornado) winds, thunderstorms, and intense hail and rainfall events. Tornadoes form through well-studied (but not fully understood) atmospheric dynamic processes associated with convective (heat-driven) storms.

Historically, observed tornado occurrence in Canada has focused on the southern Prairies, and in southern Ontario and Quebec (Figure 9). In recent years, damaging tornadoes have been increasingly observed in western Canada, southern Ontario and Quebec. These areas represent the northern extent of the broader North American area that is tornado-prone. Canada experiences the second-most tornadoes on a per-country basis (5% of global total). Canadian tornado activity, which peaks in July, has the following annual impact:

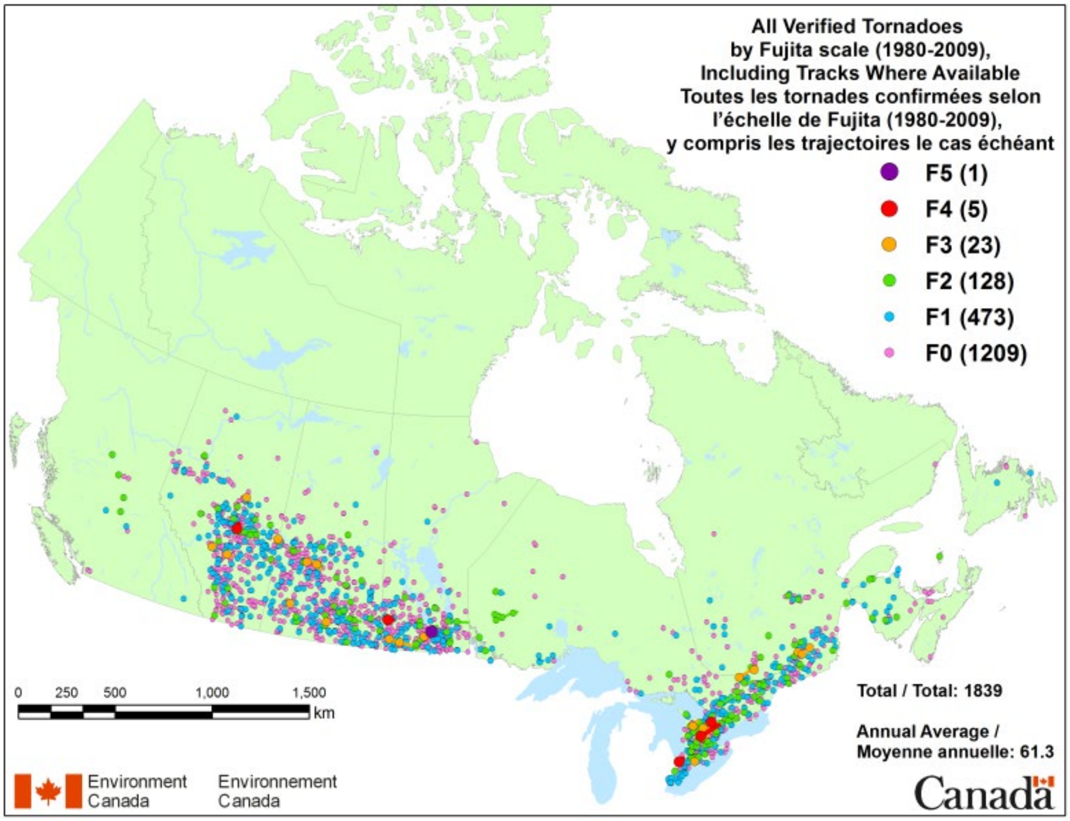
- Approximately five F2 to F5 (Fujita scale) verified and damaging tornadoes per year (data from 1980–2006, Canadian National Tornado Database);
- Approximately $18M in damages per year, skewed heavily toward small numbers of catastrophic events;
- Approximately 33 days per year with one or more tornadoes occurring nationally; and
- Approximately 18 tornadoes per year in Saskatchewan, the province with the highest tornado occurrence.

Quantifying tornado probability at a given point in Canada has not been achieved to date, and remains challenging because:

- Many tornadoes and related storm systems go unrecorded as they occur in sparsely populated regions; and
- Tornadoes are relatively rare, localized, short-lived weather phenomena, which also renders them difficult to record.

To circumvent these challenges, proxies for tornado occurrence can be developed, such as lightning flash density, which is statistically correlated to the occurrence of tornadoes. Estimates of population density relative to tornado observations can also be used to estimate the occurrence of unobserved tornado events. These methods result in pointwise

Figure 9: Tornado occurrence in Canada. Source: Environment and Climate Change Canada.



approximate probability estimates for tornadoes across Canada (e.g., [28]). These estimates, which are based on standard tornado footprints, path lengths, and occurrence frequencies, reach a maximum of $3x10^{-5}$/year in southern Ontario and the southern Prairies (i.e., an effective tornado return period of ~33,000 years at a given point). They diminish to $2x10^{-6}$/year (i.e., an effective return period of 2,000,000 years) before reaching near zero in most of northern Canada.

6.1.3.2 Climate Change Trends

Climate change-related trends for tornadoes are associated with low confidence, largely because existing climate models and downscaling tools are incapable of directly resolving individual tornado events. In addition, extreme value statistics of present-day tornadoes are difficult to robustly constrain, making changes to these statistics even more challenging to quantify.

Because of these challenges, estimates of climate change-regulated shifts to tornado frequency and magnitude are often based on trends in broader meteorological conditions associated with tornado genesis. Unfortunately, assessing changes to these conditions due to climate change is also challenging. As a result, current climate assessments [28] [29] do not make definitive climate change-based projections of shifts to tornado frequency and intensity, even for the continental United States where the state of science is most advanced.

Resulting from this lack of knowledge, a best estimate of future tornado occurrences is arguably present-day probabilities (e.g., [30]).

6.1.3.3 Implications for Bridge Infrastructure

Maximum present-day estimated tornado occurrence probabilities are low at Canadian point locations characteristic of individual bridge infrastructure. A hypothetical doubling of these probabilities still results in low values. There is also a very low probability that highway bridge infrastructure exists at a given Canadian point location. This leads to a low probability of a tornado occurring in the same location as a given highway bridge infrastructure unit over its lifetime.

Finally, modern and expected future highway bridges in Canada are primarily built using materials and techniques that would be relatively impervious to tornado impacts in the unlikely chance of a direct tornado impact. Bridges at higher risk for severe damage or failure from tornadoes include pedestrian bridges, flexible cable-supported bridges (in particular having relatively short spans, low damping, and low mass), and bridges under construction (e.g., balanced cantilevers, lightly braced girders during span erection, signs and sign gantries, lighting or hi-mast lighting, or tolling infrastructure).

Tornado implications for most Canadian highway bridge infrastructure design are deemed low for present-day and future tornadoes because of these considerations, specifically:

- Low joint probability of tornadoes impacting discrete bridge infrastructure;
- Uncertain climate change impacts; and
- Naturally tornado-resilient modern bridge infrastructure design and materials, with exceptions listed or similar to those above.

6.1.3.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following general recommendations address key issues related to climate change and tornadoes for inclusion within CSA S6:25 and CSA S6.1:25.

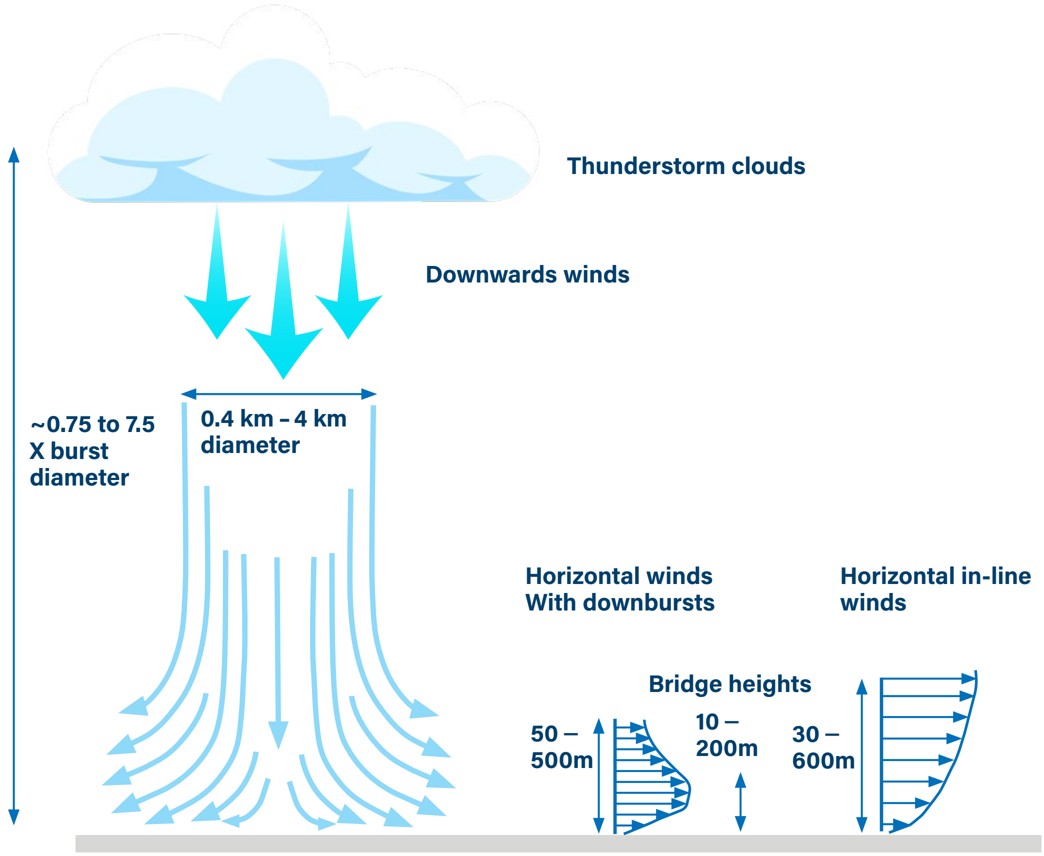
- Address tornado impacts or climate change implications for tornado impacts in CSA S6.1:25 rather than in CSA S6:25.
- Provide guidance for lightweight structures that may be at risk, such as pedestrian bridges or certain cable structures for lateral stiffening, tie-down, or overturning. If simple prescriptive details are believed to be effective, such as tie-down or overturning prevention, such provisions may be prescribed in the CHBDC.
- Include commentary related to tornado hazards, impacts, and mitigation measures for bridge appendages and gantries falling under CHBDC in CSA S6.1:25. Address life safety aspects rather than serviceability design aspects.

- Include guidance on the apparent increase in tornadoes across Canada beyond the traditional regions for structures that may be sensitive to tornado impacts.
- Conceptual through detailed design of structures should not rely on estimates of joint probabilities of occurrence of a tornado at a given bridge site. Data are sparse, and therefore probabilities have high uncertainty or may be lacking. However, consequences may be high and may be readily mitigated if tornado impacts are considered and mitigation measures are included (deterministically) as part of the design process.
- Monitor Canadian tornado research, as well as research into climate change impacts on Canadian tornadoes. This research is likely to evolve rapidly.

6.1.4 Microbursts

Microbursts (or downbursts) are localized, strong, short-lived downdrafts that are closely associated with (largely) summertime convective storm events. As these storms are also potentially associated with tornadoes, damage from microbursts are often incorrectly attributed to tornadoes (and vice versa). However, microburst winds have different characteristics than tornadoes, and thus may require different mitigation approaches in the case of highway bridge infrastructure. While damaging tornado wind pressures primarily act in the horizontal, microburst wind pressures have a strong vertical (downward) component at the microburst core, which then translates to horizontal pressure as the microburst core is deflected by the ground (Figure 10). Note that

Figure 10: Microburst flow, including comparison to typical boundary-layer wind vertical profiles relative to bridge heights. Adapted with permission from Sengupta et al. [31]



in Figure 10, the scale of the considered microburst is large; however, observations of tree destruction in forests in the Lower Mainland region of British Columbia suggest that the scale of some microbursts may also be smaller and more localized, potentially affecting individual bridges.

6.1.4.1 Historical Occurrence

Microbursts in Canada occur in close conjunction with summer convective storm events. As a result, the distribution of microburst probability is likely qualitatively similar to that for tornadoes. As with tornadoes, quantitative estimates of spatial patterns of downburst likelihood are difficult to determine given the small spatial scale and short duration of convective storm-specific microburst events, which likely largely excludes them from standard meteorological and climatological wind records, as well as design wind data that are derived from this information.

6.1.4.2 Climate Change Trends

Climate change-related trends for microbursts were not seen during this task development, likely due to the complex, small-scale nature of microburst processes, which preclude them from all but the highest resolution emerging modelling frameworks (e.g., [32]) that could potentially be used for future scenarios.

Because of the challenge associated with microbursts and climate change projections, emerging estimates of shifts in microburst frequency may be based on trends for broader meteorological conditions associated with microburst precursor conditions. Assessing changes to these conditions due to climate change is challenging. As a result, a best estimate of future microburst probability is arguably present-day, empirically-sourced, site-specific probabilities, until microburst probability assessments similar to tornado-based assessments [30] become available.

6.1.4.3 Implications for Bridge Infrastructure

Microbursts may have the most impact during bridge construction, particularly during stages where superstructures have reduced capacity (e.g., balance cantilever construction). Smaller, lighter, or flexible bridges and transportation structures would also be at risk of significant damage or collapse during these extreme events. Strong and highly focused microburst winds, including potentially significant vertical wind components, could be highly damaging. However, the probability of a microburst event impacting under construction infrastructure is likely low, and it is unclear how this joint probability might evolve under climate change. Because of these considerations, risks to standing Canadian highway bridge infrastructure are deemed low for present-day and future microbursts; however, consideration of mitigation measures as part of risk assessments during construction merit consideration by bridge owners.

6.1.4.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following recommendations address key issues related to climate change and microbursts for inclusion within CSA S6:25 and CSA S6.1:25:

- Include guidance in CSA S6.1:25 for design consideration for microburst impacts and related climate change implications for microburst impacts, with a view to including owners in bridge site-specific design requirements. While such events and related impacts may have low joint probabilities, the impacts include risk to life (safety) during bridge construction, and mitigation methods may be straightforward and cost-effective if considered early.
- Provide commentary in CSA S6.1:25 regarding hazards, risks, and mitigation measures to guide owners or concessionaires to consider design implications.
- Continue monitoring Canadian microburst research, as well as research into climate change impacts on Canadian microbursts. This research may improve prior to revision of CSA S6:25 and CSA S6.1:25.

6.1.5 Sea Level Rise, Storm Surge, and Tsunamis

Historically, average long-term sea level has been treated as a constant, on top of which storm waves, storm surges, and tsunamis can cause coastal flooding that is further exacerbated by high tides. Such flooding has the potential to cause increased impacts on coastal Canadian infrastructure, including bridges. In this context, long-term increases in mean sea level is a gradual (chronic) signal. The actual impacts of sea level rise are and will be felt first in the form of more frequent and severe extreme coastal flooding. This is captured by a schematic describing contributions to coastal water levels, as used to establish coastal flood construction levels (Figure 11).

6.1.5.1 Historical Occurrence

Storms cause coastal flooding through a combination of atmospheric low pressure and high wave effects. The former reduces pressure on the local ocean surface, causing a local increase in water height, while the latter results from strong and sustained storm winds over extended fetches of water.

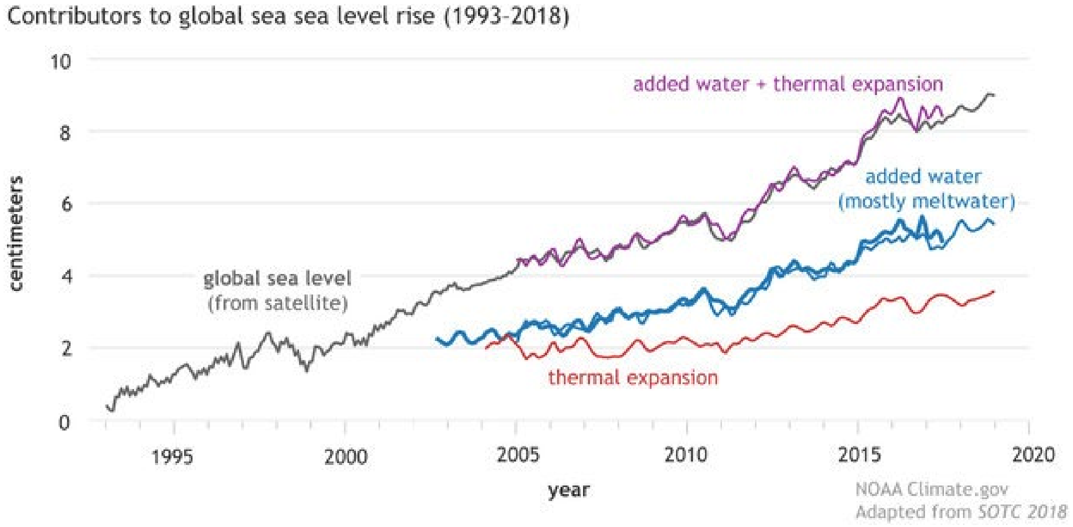
Sub-sea earthquakes or landslides cause sudden displacements of the sea floor, generating full-column tsunami waves that, when impacting shallow coastlines, can become extremely high and damaging. While ocean tsunamis are not directly related to climate change, the hydraulic pressures and debris effects on bridges over rivers and estuaries can be similar to storm surge effects.

Both forms of coastal flooding have impacted Canadian coastlines in the past, including coastlines hosting highway bridge infrastructure:

- Repeated and increasing storm surge impacts to low-lying Atlantic and Pacific communities and transportation and other infrastructure.
- Port Alberni tsunami (1964): an earthquake in Alaska resulted in a 3 m wave in the Port Alberni inlet, causing extensive damage.
- St. Lawrence tsunami (1929): an offshore Atlantic earthquake caused a tsunami of up to 7 m height to impact the Burin Peninsula, with significant loss of life.

Damage to coastal road and railway bridges from storm surge or tsunamis have also occurred in the past two decades in the southwestern United States, around the Indian Ocean following the Banda Aceh earthquake in 2004, and the great Sendai earthquake in Japan in 2011. Canadian engineers visited damage sites following both events and reported on tsunami impacts [33].

Figure 11: Observed global mean sea level rise, including contributing factors. Source: NOAA Climate.gov.



NOAA Climate.gov
Adapted from *SOTC 2018*

The engineering literature contains numerous papers on hydrodynamic and debris effects on buildings and bridges [34] and on other storm surge effects [35] [36]. Tsunami hazards and impacts on railway bridges, including lessons learned that are relevant to coastal road bridges, are contained in American Railway Engineering and Maintenance-of-Way Association (AREMA) publications and conference proceedings (e.g., [37]). Meyer [35] reported that one relatively common impact on bridges was uplift pressures that could lift superstructures from their bearings, in some cases flipping them over and severing the crossing completely. Tsunami hazard exists on both coasts, with this hazard increasing with increasing sea level.

6.1.5.2 Climate Change Trends

Global average eustatic sea levels are rising because of thermal expansion due to warming waters and melting and increased discharge of glaciers and the large Greenland and Antarctic ice sheets [28].

This trend is expected to continue, and potentially accelerate, with the rate of sea level rise highly dependent on global future emission scenarios. Regional relative sea level changes differ from global average changes due to:

- Regional climate change-driven oceanographic effects, as climate change shifts regional ocean circulation patterns, and water mass densities;
- Vertical land motion due to regional tectonic settings and past ice sheet loading.

Because of these impacts, Canadian projected relative sea level trends for the remainder of the 21st century vary widely around the country's coastlines. Consistently amplified relative sea level increases, exceeding 70 cm under current best estimates are expected along the Atlantic coastlines due to a combination of rising seas and lowering land elevations in response to Last Glacial Maximum residual loading effects [38]. High rates of projected relative sea level rise are also found in regions of the West Coast, most notably in the highly populated Lower Mainland region of British Columbia. Lower but still notable levels of sea level rise are projected to occur along other Canadian coastlines, including the remainder of the British Columbia coastline, and much of the coastline of Quebec and Newfoundland. Relative sea level increases in these regions will increase both the severity and frequency of coastal flooding impacts from storms and earthquakes, including impacts on coastal highway bridge infrastructure.

Conversely, despite global average eustatic sea level increases, local relative sea level is expected to drop in other Canadian locations (particularly northern regions). This will occur as land uplift rates outpace regional sea level rise trends in response to continued rebound from past ice sheet loading. Potential impacts of storm surges and tsunamis in these regions will be commensurately reduced.

6.1.5.3 Implications for Bridge Infrastructure

Sea level rise will increase coastal flooding frequency due to the combination of higher background sea levels, high tides, and storm surge, with individual bridge hazards and vulnerability depending on the local bridge design, siting, topography, and geotechnical conditions. For hazards and impacts arising from these conditions, hydraulic, geotechnical, and scour design in CSA S6 have the potential to mitigate risks of this emerging extreme hazard. However, the impacts from sea level rise, storm surge, and tsunamis may intensify and may affect planned or existing bridge sites for which these hazards would not have been considered.

- Coastal flood impacts to low-lying/sea-side Canadian bridge infrastructure will increase in:
  - Severity;
  - Frequency; and
  - Persistence.
- New highway bridge infrastructure will begin to experience coastal flooding impacts as average sea levels rise and coastal flood fronts are able to penetrate farther into low-lying near-coastal regions.
- Bridges over estuaries may experience higher flows, upstream and downstream, from related storm surge events. These may also occur in combination from compounding increased river flows due to related intense inland precipitation.

- Uplift pressures on superstructures, strong enough to lift superstructures off of bearings, have been observed in bridges following Hurricane Katrina in 2005 [35].
- Surge-related scour effects around piers and embankments are likely, as evidenced by tsunami-related scour observed for railway infrastructure.
- Soil conditions around bridge infrastructure may also be affected by extreme flow conditions.
- Channel or bank degradation may occur, with the risk of approach washout as described for other hydraulic extreme events.
- Water and potential debris pressures on superstructures are likely to occur.

6.1.5.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following recommendations address key issues related to climate change and sea level rise, storm surge, and tsunamis for inclusion within CSA S6:25 and CSA S6.1:25:

- Confirm the extent to which coastal flooding is integrated into climate variable data for national highway bridge design standards.
- Provide commentary recommending screening to highway bridge infrastructure that may be vulnerable to storm-based and tsunami-based coastal flooding within design life, based on sea level rise projections.
- As discussed for other extreme and emerging events discussed herein, recommend using a scenario-based risk approach to these hazards and impacts as part of a risk-based evaluation of options, over and above normal bridge design for code-mandated demands.
- Add commentary guidance for consideration of bridge-relevant hydrotechnical analyses and commentary for coastal flooding impacts for infrastructure in regions of Canada prone to coastal flooding.
- Provide commentary guidance and possibly prescriptive code clauses on water and potential debris pressures on superstructures during these extreme events. These impacts are described for substructures as part of bridge hydraulic design to CSA S6:25 (and TAC), but similar effects on superstructures may also occur and should be considered as an extreme event scenario.
- Update Clause 1.9 (Hydraulic design) to identify scour risk impacts as emerging events at coastal or estuary crossing site. Similar considerations should be made as part of planning and design for embankment and bridge retaining walls, culverts, and larger buried culverts or soil structures.

6.1.6 Riverine Flooding

Scour and structural damage from riverine floods is a leading risk for Canadian highway bridge infrastructure [36]. In the Canadian context, riverine flooding occurs due to a range of driving factors. One major cause of flooding that impacts highway bridge infrastructure is extreme spring freshets, as inland snowmelt swells river and lake systems (Figures 12 and 13).

Extreme freshet conditions are typically related to a combination of an abnormally high snowpack (e.g., high precipitation) from the previous winter, the timing of springtime warm spells, and the potential for these coinciding with springtime rainfall. Increasingly, these may be exacerbated by changed runoff conditions caused by forest fires (i.e., the loss of tree cover and fire impacts on surface soil properties). Within larger, or downstream of, combined watersheds, widespread and intense rains over days or weeks, including rain-on-snow events, can also lead to unprecedented or extreme flood events. Compound extreme events can occur when combinations of these conditions occur together. This may not be captured in the normal datasets for precipitation and stream flow. Nonetheless, the impacts of compounding can be addressed as part of a modelling and scenario assessment during bridge conceptual design.

6.1.6.1 Historical Occurrence

The 2013 floods in Alberta, at the time the costliest disaster in Canadian history, in which the majority of inspected bridges incurred some damage (Figure 12), was a prominent example where flooding was primarily caused by an extended, widespread compound rain-on-snow event. Bridge damage and failure, including road, rail, and pedestrian bridges, occurred in many communities along the Bow and Elbow rivers and affected both completed bridges and the St. Patrick's Island Pedestrian Bridge (now the George C. King bridge) in Calgary, which was under construction at the time.

Figure 12: Bridge damage in response to 2013 Alberta freshet flooding. Source: Alberta Government.

Figure 13: Ottawa River flooding, 2019. Source: Hydro Ottawa/Twitter.

Flooding can also occur because of ice jams, as disintegrating river ice is swept downstream during spring freshet and is subsequently trapped by constrictions in the watercourse. Such constrictions are often caused directly by the first cost economics of shortening bridge crossings using embankments, or by berms during construction. Ice jams account for up to one-third of all flood events in Canada [39].

Flooding can also arise due to short duration, localized rainfall events (e.g., associated with intense convective thunderstorms, which are also related to tornado occurrence). Such events can cause immediate, localized flooding. Major highway bridges over larger watercourses that drain substantial watersheds are typically less susceptible to such events, as localized storms are smaller in scale than the watershed, resulting in a dampening of the storm signal in water levels. Conversely, small highway bridge infrastructure can be vulnerable to such events.

Finally, flooding can also occur due to broader-scale extreme events, such as cyclones (Section 6.1.1) and ARs (Section 6.1.2). Highway bridge infrastructure spanning rivers that drain both small and large watersheds are susceptible to flooding from broader-scale events due to their larger size. However, such events are typically concentrated along Canada's coasts, due to their marine influence.

6.1.6.2 Climate Change Trends

The impact of climate change on flood condition trends will continue to influence Canada's highway bridge infrastructure, and these impacts will vary substantially by region and flood mechanism.

Changes to freshet flood magnitude will be influenced by overlapping changes to prior end-of-winter (antecedent) snowpack magnitude, spring temperature shifts, and spring precipitation extremes, as well as changes to the compound occurrence of these conditions over any given spring season. Projected snowpack changes vary substantially by Canadian geography. Southern regions are typically expected to experience less seasonal snow accumulation on average, due to warmer temperatures that cause precipitation to fall as rain, which then drains instead of accumulating (Figure 14). However, in northern regions, increased winter precipitation that still falls as snow may largely cancel and potentially overcompensate for shoulder-season transitions from snow to rain. Increasing rain events at higher elevations where snow persists, such as the Canadian Rockies, will substantially increase the likelihood of flood-inducing rain-on-snow events, while rain-on-snow events at lower elevations will decrease due to loss of snow [40]. Highway bridge-relevant watershed response to changing freshet conditions will be highly dependent on local conditions, including hypsometry, ground cover, and river cross-section geometry near highway bridge infrastructure.

Climate change impacts on ice jam floods are also highly dependent on location-specific climate-regulated river ice characteristics, breakup patterns, and trends in seasonal weather and climate conditions [39]. The dominance of particular trends over others must therefore be assessed on a case-by-case basis in relation to the influence on ice jam occurrence and flooding. For example, locations that experience a near-total loss of river ice due to warming conditions will also experience a decrease in ice jams. Conversely, locations with increased springtime flows from heightened rain-on-snow events, in the continued presence of substantial river ice, could experience an increase in ice jams.

Climate change-driven shifts in localized flood magnitudes and frequencies will likely reflect an increase directly related to projected future increases in short-term, extreme precipitation events across the Canadian landscape (Figures 14 and 15). These changes, which are distinct and largely independent of changes in conditions responsible for freshet-based flooding, will drive an increase in flood impacts, particularly on highway bridge infrastructure spanning small-watershed river crossings.

Changes to riverine flood conditions related to climate change-driven shifts to cyclones and ARs impacting highway bridge infrastructure are discussed in Sections 6.1.1 and 6.1.2, respectively.

6.1.6.3 Implications for Bridge Infrastructure

Riverine flood impacts on Canadian highway bridge infrastructure will be highly location-dependent, with increasing impacts in some locations and decreasing impacts elsewhere. In some locations, such as those in which upstream watersheds are likely to experience more future rain-on-snow events, riverine flood risks to bridge infrastructure will increase. These increased impacts will include increased scour, superstructure overtopping, debris and ice loads, and other related riverine flood risks. In other locations, including those in which upstream watershed rain-on-snow events are likely to decrease and that are not impacted by short duration flooding or coastal-focused storm events, flood risks may stay relatively constant or even decrease.

Impacts of riverine flood extreme events on bridges, culverts, approach embankments, and buried structures will be similar to those discussed in Sections 6.1.1 and 6.1.2. The hazards, impacts on bridge infrastructure, and conceptual through detailed design approaches are also similar. Hydraulic design will be as outlined in CSA S6:25 and as described in detail in

Figure 14: Shift in annual maximum 24-hour precipitation events, by recurrence time, under RCP8.5 emissions scenario [1]

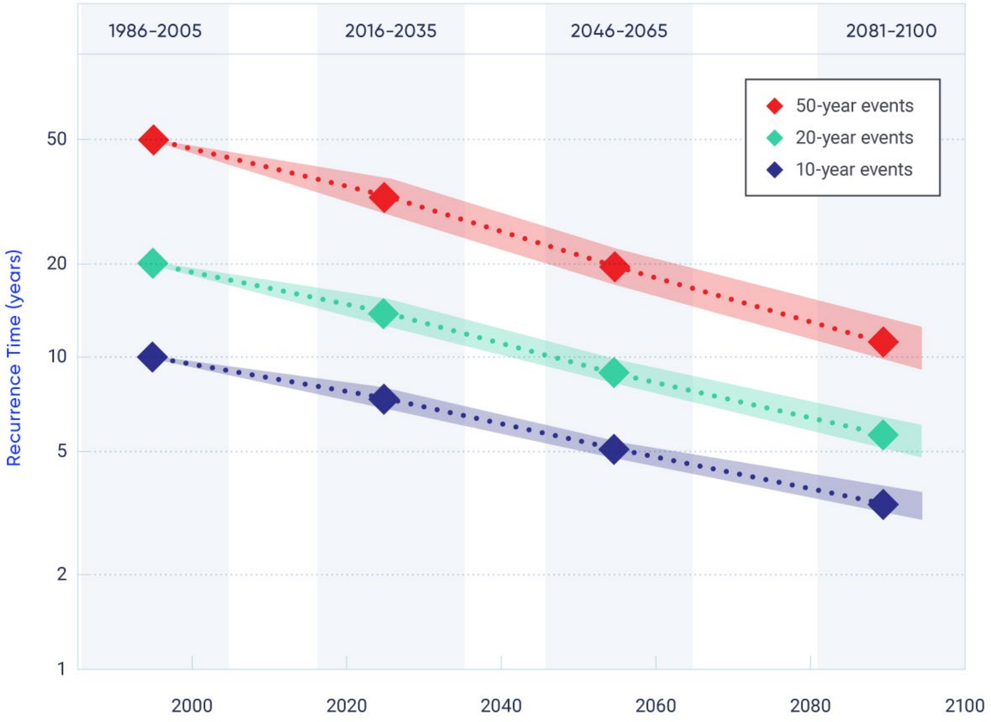
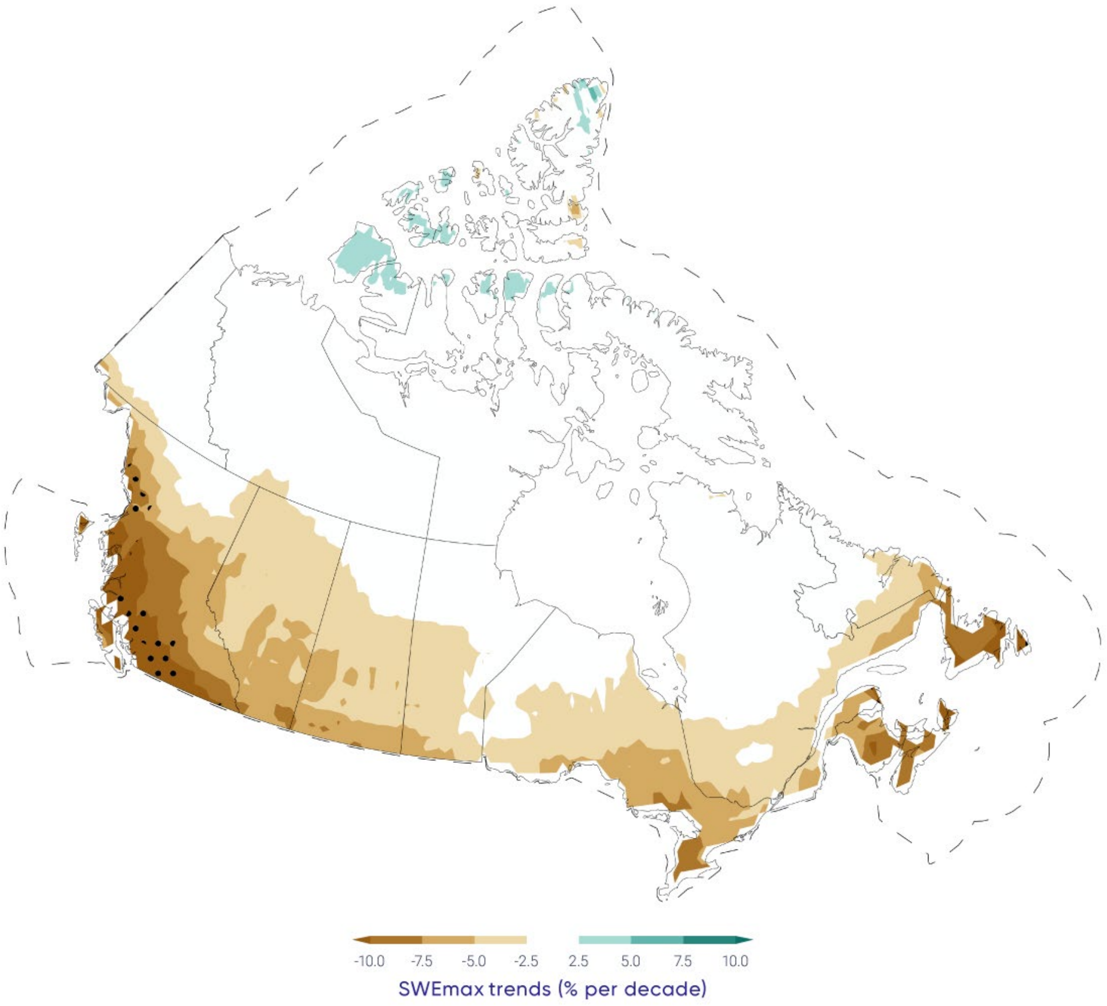


Figure 15: Projected trends in maximum snow water equivalent (%/decade), 2020-2050, under RCP 8.5 emissions scenario [7]



the *TAC Guide to bridge hydraulics* [12], AASHTO [41], FHWA [13]. Extreme events, including as compound events or scenarios, should be treated as sensitivity tests early in the basic bridge planning, conceptual, and detailed design.

6.1.6.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following recommendations address key issues related to climate change and riverine flooding for inclusion within CSA S6:25 and CSA S6.1:25:

- Plan and design for extreme riverine flooding within a risk mitigation framework rather than through mandatory foundation or clearance design requirements. One potential risk framework will be provided and considers route and bridge importance, governing flooding event types, watershed impacts, channel, and bridge conditions. At sites where these events may occur, building resilience into design (e.g., use of piles rather than spread footings) should be considered early in the bridge siting and conceptual design.
- Include commentary that states these events are beyond the scope of normal design practice and imply latent risks to owners or concessionaires (alternative delivery) that are difficult to quantify and hence to flow through contractually. In the absence of project-specific guidance on risk ownership in alternative delivery projects, and especially those with operating concessions, these risks are more appropriately borne by the owner.

- Provide guidance in the commentary that highway bridge-relevant riverine flood climate change impacts, including extreme event scenarios, should be developed on a case-by-case basis using the risk-based scenario framework discussed elsewhere. The application of codes, standards, and guidelines for flooding, especially with the adoption of projections related to climate change, should be expected to provide a high level of resilience against damaging floods. In addition, for important bridges and routes, the potential impacts of extreme or compound events can be considered as scenarios in both the hydrological and hydraulic modelling.
- Provide guidance on a standard procedure for assessing riverine climate change flood risk, for example:
    - On a case-by-case basis for river-crossing highway bridge infrastructure, determine which type of riverine flooding is expected to be most impactful for hydraulic design.
    - Based on flood type assessment, identify appropriate and relevant climate change information, if it exists. For example, do not base climate change flood assessments for systems dominated by freshet or ice jam floods on projected IDF curve information.
    - If relevant climate change information does not exist, determine which type of flood impact modelling is most appropriate to understand changes to relevant flood type.
- Apply climate change flood information arising from extreme events to highway bridge design based on bridge importance. Climate change impacts may be considered by one of the following methods, in consultation with the owner and qualified engineers, scientists, or other professionals. As noted, extreme events by definition are not amenable to prescriptive or historical design methods from observational data. However, good bridge and hydrotechnical engineering along with appropriate applied climate science for projections of environmental variables can produce highly resilient bridge designs capable of withstanding extreme events without catastrophic consequence. Significant restoration works to restore traffic or effective channel flow should be recognized as an acceptable risk for most bridges in such cases.
    - Prescriptive measures such as accepted provincial, federal, or agency design guidelines that recognize the hazards, risks, and impacts on bridges, walls, culverts, river training works, or approaches.
    - Lessons or knowledge from past projects with similar characteristics.
    - Downscaling of climate modelling for inputs to watershed modelling. Risk scenarios can guide the selection of models and modelling assumptions.
    - Hydrological modelling using projected data for the scenarios considered.
    - Hydraulic modelling of the channels crossed for flood elevations, velocities, and local channel and substructure effects.
    - Scour assessments based on results and on soil properties at the site.
- Adopt risk-based methods for consideration of ice pressures, flows, backwater, and ice levels.This can also be done using scenarios, some of which may combine with riverine flooding.

6.1.7 Additional Extreme Events

In Sections 6.1.1 through 6.1.6 of this report, selected extreme events with the potential to impact Canadian highway bridge infrastructure were reviewed in the context of changing extreme event magnitude or frequency due to climate change. The emergence or strengthening of other forms of extreme events, beyond those reviewed, may also occur. This section briefly describes some additional extreme events for consideration.

6.1.7.1 Heat Waves

Climate change may increase the magnitude, persistence, and severity of heat waves in Canada. Heat waves are defined as the current 95th percentile of summer temperatures [7]. Bridge infrastructure vulnerability to heat waves may be less pronounced than in more southern or tropical latitudes, where absolute heat levels may promote greater corrosion of concrete and steel [42] or lead to heat-related material deformation or buckling in the case of dirt/debris-clogged expansion joints [43]. Bridge performance under extreme heat events is well established from performance observations in the United States, Middle East, and tropical regions. In general, heat effects are believed to be manageable, with less consequence to life safety impacts than indicated in some of the literature [43]. Extreme temperatures, in combination with "frozen" expansion bearings, will likely cause increased restraint forces within superstructures, bearings, shear keys, piers, and abutments. These are expected to lead to serviceability performance issues rather than life safety concerns. One cautionary note relates to the I-35W bridge collapse in Minneapolis in 2007, in which one theory of collapse causation was that it was due to an instantaneous release of internal strains from a seized expansion bearing [44]. This theory differs from the National Transportation Safety Board report [45] on the collapse. While extreme heat-induced strains were not implicated, the idea that seized bearings and thermally-induced strains may have an impact on bridge safety should be considered in extreme heat risk assessments.

Extreme heat may also increase thermal gradients through superstructures. For new bridges, the use of reinforcing steel in decks or girders is already recommended in CSA S6, and modern superstructures are likely to possess the ability to redistribute these gradient effects, therefore these strains may cause serviceability issues rather than impact safety. Older bridges with less superstructure rebar, and potentially with less shear capacity and brittle behaviour, should be identified for assessment for extreme heat within CHBDC Sections 15 (Rehabilitation and repair) and 16 (Fibre-reinforced structures). Extreme heat and thermal gradients may also lead to increased deformations in movable bridges and may cause misalignment of guides or other components that could impede bridge opening, closing, or service.

6.1.7.2 Polar Vortex

Recent persistent extreme meteorological conditions, particularly during winter, have been attributed to possible changes in the behaviour of the polar vortex, a persistent feature of Earth's atmospheric circulation characterized by counter-clockwise rotation. The edge of this vortex, which can vary in space and time, is represented by the jet stream, which tends to divide warmer low-latitude conditions and colder polar conditions. Drifting in the vortex edge can cause migration of cold polar conditions southwards or migration of warm mid-latitude conditions northwards. It has been postulated that climate change can cause increased drifting of the polar vortex boundary, which would result in more persistent variable weather conditions for regions that tend to straddle this boundary, like Canada. For Canadian highway bridges, one implication of polar vortex changes may be extended periods of anomalous weather, such as cold Arctic air outbreaks or persistently warm summer conditions. While the absolute temperatures may not be impacted, the duration for which these temperatures are experienced may lengthen, with potential impacts to expansion and contraction deformations as bridge infrastructure components thermally equilibrate to individual anomalous events. However, this is likely to be a service condition rather than one of life safety, even for extreme conditions related to these changes.

6.2 General Recommendations

6.2.1 Assessing Impacts and Risks from Changing Climate Extremes

Understanding the changing impacts of extreme climate events and providing guidance to reduce the risk of these events as part of bridge design will sometimes involve the application of risk assessment methodologies. General risk assessment approaches such as ISO 31000, *Risk management – Guidelines* [10], are amenable to extension to consider changing likelihoods, consequences, and risk scenarios resulting from climate change. This extension of risk assessment methods to the case of changing likelihoods and consequences is also reflected in the PIEVC Protocol [9] and in ISO 14091:2021, *Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment* [46]. These methodologies typically follow a common set of general steps for transportation infrastructure:

- Identify the component or system elements (e.g., abutments, bridge deck, watercourse).
- Identify stakeholders and subject matter specialists (e.g., bridge owners, designers, operators).
- For each element, identify exposure and vulnerability to impactful extreme weather and climate events.
- Identify compound and/or indirect vulnerabilities (e.g., to serviceability, emergency access, weather event response and recovery, life safety).

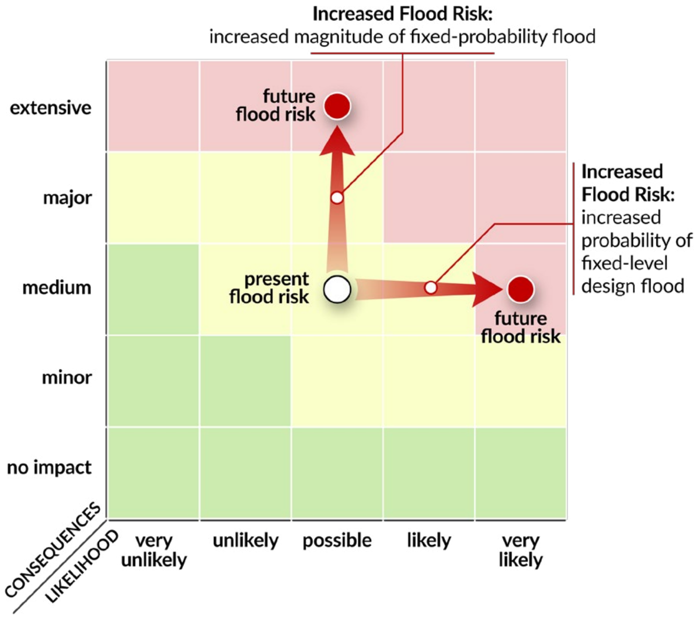
- For identified vulnerabilities, identify consequences if weather events occur.
- For these vulnerabilities, assess changes to weather and climate event likelihoods and consequences due to climate change over the infrastructure lifetime. This can be done for each climate parameter within a series of discrete time windows from the present into the future using appropriate climate model data or data from impact models using climate input model data. Climate change impacts to likelihood can be based on changing chances of exceedance for a fixed-level impact. Climate change impacts to consequence can be based on changing impacts for a fixed-level chance of exceedance (Figure 16).
- Based on time-dependent risk profiles for each, determine an acceptable design basis for the system or each element. This design basis may relate to present-day conditions (if the risk is highest during the present-day) or future conditions (if the risk is higher in the future).

Of these steps, the last two are the most significant diversions from the general ISO 31000 approach because these steps involve repeated applications of the general risk assessment procedure to determine time-dependent risk profiles.

Risk assessments inherently integrate uncertainty into the process. For example, annual exceedance probabilities address the uncertainty of a particular extreme event occurrence in any given year. Uncertainties around changing climate risks may be integrated similarly, if sufficient information permits a statistical analysis (e.g., across large ensembles of climate model simulations). Conversely, risk assessment procedures also exist for more qualitative treatments of climate uncertainty, such as scenario, what-if, storyline, and no-regrets approaches, which provide important context, including bounding boxes on likely levels of future impacts to highway bridge infrastructure. In this context of changes to local extreme events, statistics will be inadequate so qualitative treatments of uncertainty should be used.

At the planning and conceptual design stage, risks that are currently present or may emerge during the bridge lifetime that exceed risk thresholds can potentially be addressed with adaptation measures during design.

Figure 16: Schematic flood risk assessment for a bridge that includes a climate change risk profile change*.



In this hypothetical example, climate change is projected, through climate and hydrologic modelling, to produce more frequent returns of floods of a given design flood magnitude (i.e., 1-in-100 year, or 0.01 annual exceedance probability floods) or, equivalently, high magnitudes or a given flood return period/annual exceedance probability. This change can be reflected in a shift to a higher risk category via a shift along the likelihood axis (purple, horizontal axis), or a shift along the consequence axis (blue, vertical axis). In either case, higher future risk suggests risk mitigation action may be necessary in present-day design, to avoid future exceedance of acceptable risk thresholds.

Maximum acceptable risk levels are used as a basis for risk reduction planning. In some cases, the risk may peak near-term, with reduced risk over time. In others, the maximum risk is experienced in the future. In these cases, adaptation measures can be designed and constructed that are over-compensated for today's climate but appropriately designed for future climate. For example, increased scour protection may be added through the addition of bridge piles, in anticipation of increased flow conditions due to climate change-induced cyclone or atmospheric river intensity and frequency, as discussed previously. In all cases, consideration should be given to the trade-off between risk and cost. In some cases (Figure 17), bridge infrastructure criticality and potential impacts to the functional design life is high and judged to be worth the cost of designing for worst-case climate scenarios.

In other cases (it may be that the criticality or risks to the functional design life of the bridge infrastructure are low enough that the heightened risk due to climate change is acceptable in return for reduced first cost.

Guidance on risk frameworks within CSA S6.1:25 is recommended, with the adoption of consistent climate change risk assessment framing and terminology as an integrated aspect of evolving climate change risks.

Figure 17: Deh Cho Bridge, example of a bridge that required identification and mitigation actions due to high criticality and design life. Source: Associated Engineering

6.2.2 Route and Bridge Risk Classification

The complexity, level of detail, and level of effort allocated to risk assessments depends on the importance of the crossing or route and the changing likelihoods of impactful extreme climate events. These aspects may apply to new bridges or to the assessment of existing important bridges for which renewal works are foreseen. Renewal works may be undertaken to extend the functionality and service life or in combination with other extreme event risk mitigation, such as earthquake/seismic retrofit strategies.

To guide decision-making on bridge planning for extreme local events, CSA S6:25 may include a route and bridge classification framework for which bridge importance, minimum service life, guidance on acceptable risks to hazards and impacts, bridge replacement cost, and regional and site potential for extreme event scenarios are developed. This could be analogous to the performance-based framework contained in Section 4 (Seismic design) of the CHBDC, as illustrated in Table 4.

The parameters considered for seismic design include the importance of the crossing, probability of an earthquake intensity being exceeded, return to service times for different probabilities, and related damage levels that correlate to the return to service times. In the case of seismic hazard, there are two thresholds of performance and risk of the hazard occurring. The risk is defined probabilistically. Extreme event scenarios will need to be similarly postulated by owners and subject matter experts to reflect, for example, watershed size and the potential for various weather events, such as extreme flooding or unprecedented ice jam events, tornadoes, forest fires, impacts of fire on runoff, or combinations thereof.

Table 4: Minimum Performance Levels for Seismic Design of Bridges [5]

Seismic ground motion probability of exceedance in 50 years (return period)	Lifeline bridges		Major-route bridges		Other bridges	
	Service	Damage	Service	Damage	Service	Damage
10% (475 years)	—	—	Immediate	Minimal	Service limited	Repairable
5% (975 years)	Immediate	Minimal	—	—	—	—
2% (2475 years)	Service Limited	Repairable	Service disruption	Extensive	Life safety	Probable replacement

For local weather-related extreme events, parameters to consider might include route importance to post-event recovery, hazards and impacts on the bridge or site (e.g., river channel migration), design and construction impacts and initial costs, ability to adapt in the future (i.e., retrofit if climate change leads to changes in impacts), and benefits versus costs.

Guidance is recommended on a consistent use of a climate analogs approach within CSA S6.1:25 as a viable method for developing risk mitigation strategies for climate change.

6.2.3 Climate Analogs Approach to Determine Emergent Event Risk Treatment and Adaptation Options

The climate analogs approach identifies locations that currently exhibit conditions similar to those expected in the future for locations of existing or planned Canadian highway bridge infrastructure. Identification of these analog locations allows for experience gained from existing bridge designs to be considered in the design of new bridges to reduce future vulnerability to expected climate impacts. The use of climate analogs in new Canadian highway bridge infrastructure design could be a useful aspect of CSA S6:25.

The methodology for identifying climate analogs is generally conducted as follows, and requires some climate science expertise at the individual project level:

- Carry out a general climate change risk assessment procedure for a bridge at given location, A.
- For climate conditions associated with priority project-specific climate risks:
  - Identify future frequencies and magnitudes of these conditions;
  - Identify present-day bridge infrastructure at B locations where these conditions presently exist; and
  - Investigate present-day bridge design characteristics at the B locations as potentially adaptable for design at location A to ensure resiliency to expected future climate change.

Guidance is recommended on a consistent use of a climate analogs approach within CSA S6.1:25 as a viable method for developing climate change risk mitigation strategies.

6.2.4 Project-Specific Climate Change Impact Modelling

Project-specific climate change impact modelling refers to site and infrastructure-specific assessments necessary to inform design parameters that are not codifiable in terms of national-scale design parameters or even regionally-specific design parameters. Such modelling cannot be feasibly performed on a broad scale for all potential nationwide bridge infrastructure sites, despite their importance in bridge infrastructure design.

Identifying site- and bridge-specific impact modelling requires careful, methodical thought to avoid undue or ineffective design or bridge construction cost.

In the context of bridge design, impact modelling describes the methodologies employed at site scales to understand site-specific, design-specific conditions. It will vary from simple to complex, the latter of which applies to larger highway bridge design efforts. The impact of climate change on design can be assessed by inputting future weather and climate conditions into relevant impact models to develop not only present-day design impacts but also future design impacts. Such approaches are an important part of detailed risk assessments (see Section 6.2.1). They are related by their use of future climate and weather data and information from climate models and climate downscaling methods as inputs to site-specific models or analyses. These models will also relate to the climate change projections including nonstationarity as described in Section 5 of this report.

Examples of climate change inclusion on impact modelling within bridge design include:

- Flood, scour, and erosion assessments: Develop projected future high flow conditions by incorporating projected future temperature and precipitation extreme frequencies/magnitudes to site-specific hydrology (watershed-scale) and hydraulic (project-scale) models:
  - **Impact model:** Hydraulic or hydrology model;
  - **Future climate input to impact model:** Projected future spring flood-relevant climate conditions (e.g., winter snowfall, spring warming).

- Permafrost assessments: Develop projected geotechnical conditions associated with permafrost changes by incorporating future temperature and precipitation trends to site-specific geotechnical models:
    - **Impact model:** Permafrost geotechnical models on foundation capacities, embankment stability;
    - **Future climate input to impact model:** Projected future average temperature and precipitation conditions.
- Infrastructure flooding assessments: Develop projected local rainfall and localized inundation conditions by incorporating projected future convective storm, atmospheric river, and/or cyclone conditions into infrastructure drainage modelling:
    - **Impact model:** Deck drainage model;
    - **Future climate input to impact model:** Projected future deck inundation-relevant extreme precipitation magnitudes and frequencies.

Adoption of consistent climate change impact modelling framing and terminology is recommended for discussions involving detailed climate change impact analysis.

7 Implications on Bridge Design and Materials in Canada's North

This section addresses climate change risks specific to northern Canada's highway bridge infrastructure and discusses recommendations for northern-focused adaptation responses. It includes the following topics:

a. Description of northern Canada's highway bridge infrastructure;

b. Discussion of climate change in northern Canada;

c. Discussion of climate change impacts, vulnerabilities, and risks to northern Canada's highway bridge infrastructure; and

d. Discussion of design and material-based adaptation strategies to reduce climate change risks to northern Canada's highway bridge infrastructure.

Bridge and culvert design considerations in northern regions generally include rapidly rising temperatures, loss of permafrost and potential impacts on bridge-related infrastructure and the environmental system, low sun angles relative to the horizon and unique forms of construction including piles deriving structural capacity from ad-freezing to the ground.

7.1 Knowledge of Northern Climate and Climate Change

Many climate statistics can be determined from weather records [1], including statistical measures of mean, median, accumulated, and extreme climate and weather conditions. However, measurements in Canada's northern regions are sparse compared to data from the rest of Canada. Local traditional knowledge can sometimes be useful in identifying trends and historic conditions.

7.1.1 Measuring Northern Climate Change

Direct measurements of weather and climate that form the basis for environmental design parameters within the CHBDC are captured primarily via meteorological (weather) stations. These stations, when operated for long continuous periods, can provide assessments of key bridge-relevant weather and climate variables including:

- Temperature
- Precipitation (rain and snow)
- Wind speed and direction
- Humidity
- Radiation

In recent decades, remotely sensed satellite data have also augmented in situ meteorological station measurements to provide a fuller picture of Arctic Canadian conditions.

Additional weather and climate-related variables can be assessed in a variety of ways for the purposes of bridge infrastructure design. Hydrologic stations can estimate streamflow in Arctic rivers; ground temperature sensors can monitor site-specific permafrost conditions, and snow gauge measurements can track snow accumulation and melt. Remotely sensed information is increasingly being used to monitor for environmental change. For example, permafrost conditions near existing or planned bridge infrastructure can be estimated from satellite altimeter, radar, and laser measurements, and sea ice conditions relevant to any coastal bridge and highway infrastructure can be effectively tracked via satellite imagery.

Taking stock of weather and climate in Canada's North is challenging due to a paucity of in situ weather measurements compared to southern regions of the country. This makes regional assessments of northern climate and climate change more difficult. In this context, leveraging local traditional knowledge of past conditions can be a useful way to supplement limited community or project-specific meteorological and environmental observations to understand local weather and climate baselines relevant to northern bridge design.

7.1.2 Historical Northern Climate Change

Extreme weather and climate define Canada's North. For example, typical (climatological) temperatures are colder by season than anywhere else in the country, particularly winter average and extreme temperatures. The Canadian North also ranks among the driest regions in the country with respect to precipitation and interior northern regions experience the largest continentality (i.e., swings between maximum summer and minimum winter temperatures) of any Canadian region.

These weather and climate conditions form the baseline for ongoing climate change that is occurring at a higher rate than any other Canadian region [1] [16]:

- **Temperature:** The rate of temperature change in Canada's North (2.3°C between 1948 and 2016) is approximately three times higher than the global average and roughly 40% higher than the Canadian average, with most warming occurring since the 1970s and during winter (4.3°C between 1948 and 2016) [16].
- **Precipitation:** The sum of rain and snow has increased disproportionately in the North relative to the rest of Canada, with an estimated average increase of 33% between 1948 and 2012, up to 54% in the winter over the same period [1].

Temperature and precipitation changes in Canada's North are related to a range of secondary climate change impacts that directly affect northern Canadian highway bridge infrastructure, including:

- **Permafrost change:** Permafrost is warming, with the greatest increases in the high Arctic (e.g., 0.9°C per decade in the northern Mackenzie Valley), and thermokarst areas (regions characterized by thawing permafrost, leading to surface subsidence and water ponding) are expanding.
- **Snow cover change:** Fall and spring warming is shortening the winter snow-covered period, while increased winter precipitation as snow is causing more total snow accumulation during mid-winter.
- **Arctic river hydrology change:** Spring snowmelt-driven freshet floods are occurring earlier in the year and changes to freshet flood magnitude are changing, although with complex regional signals.
- **Coastal change:** Arctic coastal sea ice is decreasing in thickness and seasonal duration, leaving Arctic coasts more exposed to open water conditions. Arctic sea level rise is mitigated, and in many places reversed, by vertical ground uplift resulting from previous glaciations.

7.1.3 Northern Climate Modelling

Assessing future climate change in Canada's North is a complex topic that requires an understanding of the full global climate system. This global perspective is necessary because climate change in Canada's North is dependent on changes to local climate conditions and signals of change transported to Canada's North by broader atmospheric and oceanic circulation patterns from the Arctic, Atlantic and Pacific Oceans, and more southern latitudes.

For this reason, simulations of future 21st century climate change performed by global climate models that include all key aspects of the global climate system are important starting points from which to develop future climate change projections in Canada's North. In combination with local weather and climate observations and after translation into metrics and measures relevant for bridge infrastructure risks, this information forms the basis for understanding adaptation implications on bridge design and materials for Canada's North.

7.1.3.1 Global Climate Modelling and Application to Canada's North

Global climate models are complex computer programs that include all important global climate system components (i.e., ocean, atmosphere, land, sea ice, hydrology, and biological and chemical cycles). When run with simulated future greenhouse gas emissions, global climate models produce estimates of future change for climate parameters that are also observed historically. Coordinated climate model simulations are typically carried out for a set of future scenarios to understand the full range of potential future climate trends.

Future RCP-based climate projections from many different climate models, and from multiple runs from the same climate models, are often downscaled and bias-corrected before being used in engineering design. Downscaling refers to the combination of global climate model data with local information (e.g., topography, microclimate conditions, or known regional climate anomalies) to produce higher resolution climate information. Bias corrections are also often applied to calibrate global climate model information to local conditions. Despite bias correction, uncertainty can persist in projections of northern Canadian future climate, due to:

- Large natural Arctic climate variability and accelerated rates of historical and future change;
- Uncertainty in future global carbon emissions (e.g., RCP scenarios);
- Differences in Arctic Canada climate projections from different climate models; and
- Lack of observational data for use in downscaling and bias correction.

7.1.4 Future Northern Climate Change

Climate change in Canada's North will be consistent with observed trends to date, and with the emergence of new trends from the noise of natural Arctic climate variability. These trends, which are strongly dependent on emission scenarios, will have direct implications for highway bridge infrastructure design and include [1]:

- **Substantial warming:** Arctic warming will continue to occur at rates higher than the global and Canada-wide averages. Under the RCP 2.6 to 8.5 scenarios, by the end of the century, the Arctic is expected to warm by 2.1°C to 7.8°C in total, relative to the 1986 to 2005 period.
- **Permafrost loss:** Arctic warming will hasten ongoing permafrost loss, with the areas of deep, continuous, and non-continuous permafrost across all permafrost thermal categories expected to decrease (e.g., a 16%–20% loss of deep permafrost by 2090 relative to the 1990s). Permafrost loss may also be exacerbated by increased Arctic vegetation growth, precipitation, and wildfire frequency.
- **Increased precipitation across seasons:** Annual precipitation as rain plus snow will continue to increase across seasons by 8% to 33% under the RCP 2.6 to 8.5 scenarios relative to the 1986 to 2005 periods. Most precipitation increases will occur in winter, falling as snow. However, in spring and fall, more precipitation will fall as rain, shortening the overall snow cover period.
- **Shifting Arctic river hydrology:** Substantial region-specific changes to Arctic river hydrologic characteristics are expected, including earlier spring freshet floods, greater annual average flow due to increased annual precipitation, and potentially warmer summer river temperatures.
- **Coastal erosion and flooding:** Permafrost degradation, increased coastal wave action from sea ice loss, and increased Arctic Ocean storminess, combined with regional increases to relative sea level, will likely increase ongoing rates of Arctic coastal erosion and coastline regression.
- **Increased forest fire frequency:** Warmer summer conditions will drive increases in wildfires, particularly in forested regions in the southwestern Canadian Arctic [47].

Potential consequences of these climate impacts on bridge infrastructure in Canada's North are described in Section 7.2.

> "Bridge infrastructure in Canada's North is vulnerable to present-day environmental impacts and risks arising from weather, climate, and climate-related geophysical conditions, as well as future new impacts and risks."

7.2 Climate Impacts, Vulnerabilities, and Risks to Northern Highway Bridge Infrastructure

7.2.1 Climate Change Impacts, Vulnerabilities, and Risks

Bridge infrastructure in Canada's North is designed in consideration of local weather, climate, and climate-linked geophysical conditions. Risk to northern bridge infrastructure exists if:

- These conditions result in impacts that have an appreciable likelihood of occurring over a bridge design lifetime, and
- Notable negative consequences to serviceability, durability, and safety arise from vulnerability to these impacts.

Climate change will cause changes to weather, climate, and climate-related geophysical conditions, which will:

- Change the likelihood and severity of existing weather, climate, and climate-related geophysical impacts on bridges; and
- Potentially introduce new and novel location-specific impacts and risks.

Practically, this means that environmental load factors and design configurations must be updated to reflect not only present-day conditions in Canada's North but also future conditions.

If the risk from present or future conditions exceeds northern bridge infrastructure-specific risk thresholds, risk reduction actions should be considered as part of design or rehabilitation efforts. Specification of environmental load factors developed in response to projected future northern weather and climate events, and design specifications configured against uncertain geotechnical conditions, directly reflect a risk threshold and risk reduction approach applied to northern bridge design.

7.2.2 Climate Change Risks to Northern Bridge Infrastructure

Bridge infrastructure in Canada's North is vulnerable to present-day environmental impacts and risks arising from weather, climate, and climate-related geophysical conditions, as well as future new impacts and risks. However, amplified climate change in the North will result in greater impacts on bridge infrastructure than in southern latitudes, with some impacts on northern bridge infrastructure being entirely absent in the south.

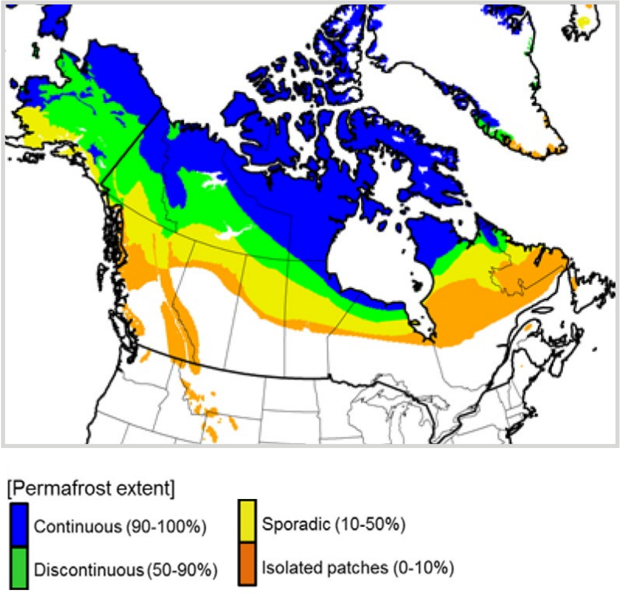
This section describes the climate change impacts specific to northern Canada highway bridge infrastructure, including recommendations for CSA S6:25. The impacts and risks are based on ranked input obtained during a series of nationwide stakeholder engagement workshops carried out as part of this project. Each impact or risk was screened to identify potentially amplified or unique northern considerations in order to facilitate northern-tailored recommendations for CSA S6:25 and CSA S6.1:25.

7.2.3 Permafrost

7.2.3.1 General Overview

Permafrost is a layer of soil that remains at or below 0°C continuously for more than two years [7]. Typically, permafrost is overlaid by an "active layer" that experiences a freeze-thaw cycle over the course of a year. In 2019, permafrost existed for about 40% of Canada's land area and was present in continuous or discontinuous (10%–50% coverage) form over much of Canada's North (Figure 18) [1], including in many regions where highway bridge infrastructure currently exists or is likely to be developed. Permafrost conditions are very tightly linked to average air temperatures. Warm permafrost (i.e., in regions with annual average air temperatures between -2°C and 0°C) is prevalent in southern areas of the North, whereas thicker, cold permafrost (i.e., in regions with annual average air temperatures below -4°C) is more prevalent further north. In addition to ambient air temperatures, permafrost thickness depends on geothermal heat flux, local biological and geotechnical conditions (vegetation and soil types), surface and subsurface hydrology, including proximal river and flood plain hydrology, and snow accumulation and drifting.

Figure 18: National distribution of permafrost conditions in Canada [7].

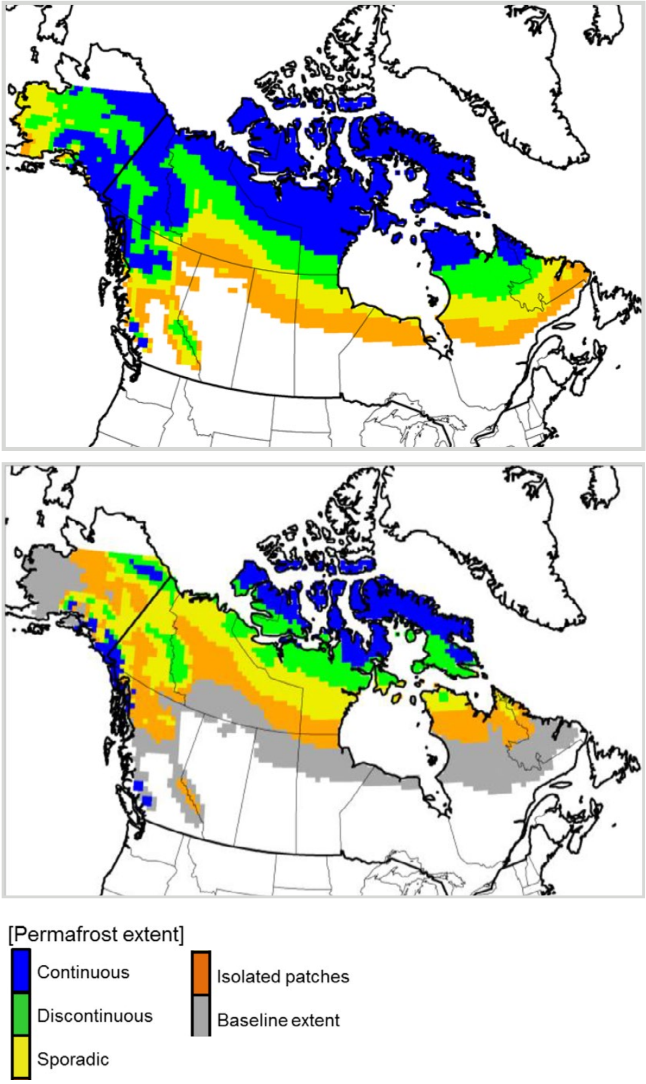


Local and regional permafrost studies often involve targeted data acquisition, because it is difficult to accurately assess permafrost conditions (temperature, depth, and active layer thickness) using remotely sensed data products. In regions of discontinuous permafrost, basic presence or absence assessments are undertaken to determine if permafrost exists in proposed or existing bridge infrastructure sites. Given permafrost presence, characterizing ground-ice conditions at a site can involve drilling to recover samples of permafrost monitoring via in situ instrumentation, and sample recovery via drilling for geotechnical testing and assessment of ice content, rock or soil type, and soil plasticity. These characteristics are important for defining current permafrost creep in response to expected loading from bridge infrastructure (e.g., pilings, footings) and creating the geotechnical conditions baseline that will evolve under climate warming. Additional permafrost characteristics can be estimated from soil and surficial geology maps, aerial photography, high-resolution satellite imagery, and LiDAR imagery analysis.

7.2.3.2 Climate Change Impacts

Recent changes in northern Canada's permafrost provide important context for expected future trends. Trends in permafrost temperature provide one direct measure of change. In the Northern Hemisphere, measurements taken between 2007 and 2016 reported an increase in continuous and discontinuous permafrost region temperatures of 0.39 ± 0.15°C and 0.20 ± 0.10°C, respectively [1], with decreased warming in discontinuous permafrost regions partly due to extra heat melting permafrost rather than warming it [16]. Canada-specific estimates of permafrost temperature changes are limited to locations where long-term in situ temperatures have been recorded. Warming of 0.2°C/decade has been observed in the southern Mackenzie Valley in British Columbia and in the Yukon Territory. In the northern Mackenzie Valley, permafrost changes of up to 0.2°C/decade have been observed [1]. Since 2000, high Arctic permafrost temperatures have increased at higher rates, ranging from 0.7°C/decade to more than 1.0°C/decade depending on location and depth [1].

Figure 19: Present day (left) and future (right) permafrost extent under 3°C warming, based on relations between air temperature and permafrost extent [7].



Evidence of changing permafrost conditions that are potentially relevant to highway bridge infrastructure design is based on landscape-level observations of thermokarst landscapes that are undergoing permafrost loss. Air photo or satellite imagery indicates an increase in thermokarst features across many regions of the North and regional differences in permafrost change due to local conditions. Differential thaw–settlement results in irregular, poorly drained ground surfaces [16] and overall ground subsidence as ice in soil pore space melts and drains into regional hydrologic systems. Permafrost change is not just driven by direct temperature forcing. Regional and local changes have also been linked to increases in northern precipitation, wildfire events, and coastal increases in wave action and ocean warming, potentially exacerbated by sea level rise [1]. In addition to natural drivers, permafrost is strongly impacted by human activity, including the development of engineered highways, bridges, and other infrastructure in permafrost-hosting soils.

Climate change will continue to drive extensive changes to permafrost conditions in Canada's North (Figure 19). Based on empirical relationships between air temperature and permafrost extent, future near-surface permafrost area over Canada is expected to decrease by about 16% per 1°C of global temperature increase, with higher confidence in the direction of change, but lower confidence in the change magnitude [7]. Considering the range of potential RCP emission scenarios, the area of near-surface (within 3 m of the surface) permafrost could be reduced by 37% to 81% Arctic-wide by the end of the 21st century [28]. Permafrost loss and its impact on highway bridge infrastructure will be most apparent in southern regions of Canada's North currently exhibiting warm permafrost conditions.

Other climate change-related effects beyond temperature change will regulate warming-driven permafrost loss, which may require consideration as part of geotechnical permafrost modelling for northern highway bridge infrastructure design. For example, intensification of Arctic rainfall can augment thaw slumping, and expansion of tundra shrub growth can increase mid-winter snow accumulation and resulting insulation (warming) of underlying soils. Damage to vegetation and the organic soil layer due to wildfires, which are projected to occur more frequently under a warming climate, can increase active layer thickness and permafrost degradation. Increasing hydrologic peak flows near highway bridges and approaches over flood plains can influence flood plain permafrost thermal conditions. Finally, vegetation clearing and surface disturbance due to human activity and infrastructure construction can also lead to ground warming and thawing and enhance the effects of changing air temperatures on permafrost environments [1].

Permafrost is highly spatially dependent, with significantly different permafrost environments potentially existing within meters of each other. Therefore, assessments of permafrost extent during northern Canadian highway bridge infrastructure design require local assessments on a per-project basis. Uncertainty in local scale responses must also be assessed on a per-project basis as this response is a function of local permafrost vulnerability, which is regulated by local soil, hydrology, and human disturbance characteristics [16]. Finally, uncertainty in the full magnitude of permafrost loss at any point is strongly dependent on future global emission (RCP) scenarios [7].

7.2.3.3 Implications for Highway Bridge Infrastructure

Permafrost changes have several direct implications for highway bridge infrastructure:

- **Increased creep deformation of frozen soil subject to bridge infrastructure loading:** Warming (but still-frozen) ice and soil matrices will exhibit higher creep deformation rates due to the temperature dependence of ice deformation, as higher temperatures result in higher creep rates for a given loading.
- **Intensified loss of infrastructure structural support during deepening of summer active layer:** Warming of active layer depth will deepen the surface layer, which then cannot be relied on during summer months to support piled bridge foundations. Decreased soil moisture and increased drainage will also impact the support provided by the soil as permafrost degrades [48]. Bridge pile capacity that relies on adfreeze of piles to permafrost will lose strength, and may settle, or piles may heave relative to the adjacent ground. Groundwater salinity changes may also impact this bond [49].
- **Loss of highway bridge infrastructure support due to total permafrost column loss:** Full loss of permafrost columns adjacent to load-bearing bridge infrastructure, walls, and approach embankments can reduce structural integrity [16]. Full-column loss could arise from:
    - Gradual in situ loss due to diffusion of atmospheric thermal energy to depth;
    - Migration of thermokarst loss fronts (e.g., by feedback-reinforced riverbank slope slumping); or
    - Loss due to thermal energy delivered by hydrologic surface or subsurface flow regimes [50].
- **Differential structural settlement rates:** Differential settlement across bridge supports could occur as local conditions (e.g., soil layers, ice melting, or hydrologic conditions) and cause differing behaviours to similar levels of climate change forcing [16]. Similar impacts on approach embankments can affect bridge access and future maintenance. Settlements or other surficial ground deformations across large culverts, at culvert inlets or outlets, buried structures (portal frame/tunnels), and on retaining wall foundations and soil pressures can also lead to loss of soil-structure interaction necessary for stability, and potentially to culvert or structure collapse.
- **Deformations or stiffness changes of integral abutments:** Abutment wall flexibility in embankments may change with freeze-thaw cycles. Increased maintenance rather than life safety conditions may arise.
- **Culvert inlets and headwalls:** Ground deformations have changed inlet and outlet elevations of culverts. It is notable that additional depth allowances in past practice have not always been effective.
- **Debris impact from regional slope instability:** Regional permafrost loss in sloped terrain will lead to widespread slope instability, which could cause landslides or debris flows to impinge on bridge infrastructure.

7.2.3.4 Recommendations for CSA S6:25 and CSA S6.1:25

Development of CHBDC changes stemming from climate change impacts on permafrost has been undertaken as a specialized task by subject matter experts with the CHBDC Section 6 Foundations and Geotechnical Systems TSC. The following recommendations address key issues in addition to those contained within the current Section 6 (Foundations and geotechnical systems) related to permafrost:

- **Route planning and alignment:** Route planning will be important to CSA S6:25 recommendations as follows:
    - As part of route planning, broad-based geotechnical and geophysical surveys should be emphasized.
    - Recommendations should refer to all-weather roads/highways in the North for resource development and community connectivity, as distinct from geotechnical planning for roads within communities.

- **Culverts and buried structures:** Continued liaison between the CHBDC Section 7 (Buried structures) and Section 5 (Methods of analysis) TSCs is recommended regarding permafrost change impacts on culvert durability (e.g., headwalls, settlement, invert elevations) and related wall design.
- **Permafrost regions:** Both Clause 1.9 (Hydraulic design) and Section 6 (Foundations and geotechnical systems) of the CHBDC should indicate the need for coordination between hydrotechnical assessments, including the effects of increased precipitation and the resulting impacts on permafrost conditions.
- **Embankment settlements:** While embankments are not strictly within the CHBDC's scope, guidance in the commentary may assist bridge owners and designers for embankment-bridge interface zones. Whether designing for total, differential, short-term (during construction or during a handover period from contractor to owner), or longer-term (warranty period or new baseline), guidance from the CHBDC Section 6 Foundations and Geotechnical Systems TSC would be useful. Geotechnical/foundation manuals or other documents will also require updating but are outside the scope of this project.

Due to the continuing use of design-build or public-private-partner (P3) contracts, guidance on possible design aspects for handback criteria for certain time-dependent aspects of permafrost change is needed. Examples include embankment settlements and differential settlements during the handback period. While this is beyond the scope of the CHBDC, commentary and guidance should be provided at least for bridge/embankment interfaces.

7.2.4 Hydrology

7.2.4.1 General Overview

Hydrologic systems describe the movement of water through all components of a physical environment. Typically, this movement is described as a water cycle that includes precipitation, plant and microbial transpiration, surface water evaporation, groundwater, and surface water. Surface water flow typically occurs in streams, and the streamflow is generated from precipitation runoff, snowmelt and glacier melt, groundwater, and other sources such as permafrost melt. Northern Canadian highway bridges and culverts are frequently in close contact with one or more of these hydrologic system components while crossing northern Canadian rivers or lakes. Some have substructures embedded within substrates hosting groundwater and permafrost or culverts may be buried within these strata.

The flow regime of a stream describes the major contributors of water to the stream and the timing associated with these contributions and the low flow periods. Common flow regimes in northern Canada are pluvial (rain-dominated), nival (snowmelt-dominated), pluvial-nival (significant rainfall and snowmelt components), and glacial (glacier melt-dominated). The topography and hydroclimate of northern watershed basins are the primary controls of its flow regime, which in turn determine typical peak flow timing and characteristics (i.e., floods) and other hydrologic characteristics at waterway-crossing highway bridge sites. Floods can derive from spring freshet melt, ice jamming, and, for small watersheds, individual severe rainstorms.

Figure 20: Nisutlin Bay Bridge, Yukon Territory. Reproduced with permission from Associated Engineering.

Streamflow is typically measured at hydrometric stations, where discrete water level measurements are related to continuous discharge measurements to generate continuous stream level records. The Water Survey of Canada operates a network of such hydrometric stations throughout Canada, but the distribution of these hydrometric stations is particularly sparse in Canada's North. Many hydrometric stations are telemetry-enabled, such that near real-time stream flows are available. These data should be interpreted carefully, especially in the presence of potential ice jamming or fully frozen conditions [39]. Hydrologic flood monitoring and forecasting are typically managed by provincial or territorial agencies. However, due to hydrologic complexity and meteorological forecasting challenges, these flood assessments often struggle to predict the precise flood timing and magnitude at specific locations.

7.2.4.2 Climate Change Impacts

Climate-driven changes in hydrology are closely linked to precipitation amount and phase (i.e., rain or snow), with potentially large impacts on northern Canadian streamflows and associated highway bridge infrastructure. Arctic fall, winter, and spring rainfall events are more frequent and are projected to increase in the future. There is a high likelihood that extreme short duration precipitation events will increase [1], although the magnitude of the increase of the extreme events is uncertain.

Projected impacts on the hydrologic flow regimes of northern rivers are closely tied to changing precipitation trends. A shift from snowmelt toward rainfall dominated flow regimes is expected, and spring freshet flood magnitude may decrease in areas of degraded permafrost [48]. This shift, together with increasing extreme rainfall intensity and duration, is likely to lead to more frequent, rapid rain floods and peak streamflows [51] [52]. Ice jams linked to breakup or winter floods may increase or decrease in severity at individual highway bridge infrastructure sites, as these jams depend on basin-specific characteristics, precipitation, and the preceding local weather [51]. While peak flows can lead to bank erosion, streambed scour (particularly around bridge supports), and bridge deck overtopping, flood inundation of ground underlain by permafrost can increase local active layer depth and thickness by more than 1 m [50], with possible impacts on bridge structural integrity.

Despite the projected climate change trends in northern hydrology outlined above, the response in an individual basin will vary widely, even considering consistent climatic drivers [53]. Basin-specific changes depend on basin topography, physiography, local weather events, and other local factors. As a result, design flood magnitudes at a given northern location are difficult to predict without assessments that account for interactions between precipitation shifts, snowpack, and snowmelt changes [51]. Changes to watershed characteristics arising from boreal fires, geomorphological changes, thermokarst, or soil properties may also occur. One consequence of ongoing change is that standard flood frequency or design flood determinations will require periodic updating to ensure continued validity.

7.2.4.3 Implications for Highway Bridge Infrastructure

Hydrologic changes, particularly peak flow magnitude and flood frequency, have several substantial implications for northern bridges and transportation infrastructure:

- **Scour and bank erosion:** In basins where peak flows of a given probability will increase, particularly in response to increased winter precipitation and rainfall-induced snowmelt, higher peak flows will increase scour around bridge footings and pilings and erode the banks supporting bridge abutments and bridge approach infrastructure. Similarly, increasing occurrence of design floods of a given magnitude will cause more frequent stream flows capable of generating damaging scour and erosion events.
- **Overtopping:** In basins where peak flow magnitude increases, especially if a peak flow coincides with ice breakup-induced ice jam, bridge deck overtopping can occur and cause bridge damage.
- **Permafrost active layer thickness:** Winter rain and rain-induced snowmelt floods, as well as earlier spring freshets, can lead to localized permafrost thawing around bridge abutment infrastructure. This will extend the effective local permafrost melt season and related local active layer thickness in summer.
- **Watershed characteristics from warming:** Coupled with changes in precipitation amounts in mix (rain vs. rain/snow) and extreme events (fire), changes to watershed characteristics can significantly increase uncertainty in IDF curves, particularly in the North.

7.2.4.4 Recommendations for CSA S6:25 and CSA S6.1.25

The following recommendations address key issues related to hydrology and climate change in Canada's North:

- A framework for a risk-based approach related to climate change is needed in CSA S6:25 or CSA S6.1:25. This is particularly important for impacts from warming in the North.

- Provide guidance in CSA S6.1:25 to bridge owners, engineers, and scientists on RCP scenario (See Section 3) precipitation data sources, warming projections and modelling, and addressing uncertainty and risk. Updates to the TAC *Guide to bridge hydraulics* [12] for climate change are needed, including for northern impacts. While this is beyond the scope of this project, it represents one of the more important opportunities to improve the design of highway bridges for climate change, including in the Canada's North.
- Scour design is also addressed in the TAC *Guide to bridge hydraulics* [12] and should also be updated for changes in streamflow, ice properties, and ice flow impacts.
- For conceptual design of culverts, their sizing, inlet and outlet treatment, open versus closed bottom culverts, and ground settlements related to runoff, soil changes from permafrost melt, or scour should be updated in CHBDC Section 1 (General) and Section 7 (Buried structures), as well as in the TAC *Guide to bridge hydraulics* [12].
- Clause-specific updates for northern impacts related to hydrology, hydraulics, ice, and scour should be included where practicable and where updates to the *TAC Guide to bridge hydraulics* [12] are not expected to address.

7.2.5 Air Temperature

7.2.5.1 General Overview

Air temperature is measured at meteorological stations, which provide temperature data at the local scale. Because meteorological stations are sparse in the North compared to the rest of Canada, regional analyses of air temperature use gridded climate reanalysis data products. These products use a combination of models and observations to estimate climatic variables, typically at daily to sub-daily resolution over large regions at moderate spatial resolution. Climate reanalysis data products do not provide real-time estimates of air temperature; rather, they provide a best estimate of historical temperatures at good spatial and temporal resolution.

Measurement of and changes to air temperature in Canada's North were summarized in Section 7.1. Overall, greater warming has occurred during the winter, leading to a greater change in the annual daily minimum air temperature than the annual daily maximum air temperature.

7.2.5.2 Climate Change Impacts

Projected changes in the extreme temperatures indicate that winter minimum temperatures will likely increase more than summer maximum temperatures, resulting in a shifted but smaller extreme temperature range [1]. While there will be natural climatic variability that impacts the annual minimum and maximum temperatures in any given year, annual extreme temperatures will experience warming trends [1] [54].

Changes in air temperature directly and indirectly impact other components of the natural environment, such as permafrost, precipitation falling as rain or snow, snowmelt timing, hydrology, and forest fires. This relationship is important when considering how these natural processes will change in the future.

7.2.5.3 Implications for Highway Bridge Infrastructure

Changes to average daily temperatures and extreme annual temperatures have several significant implications for materials used in the construction of highway bridges. Some impacts can affect safety or crossing integrity, such as warming and melting of permafrost and the effects on embankment or foundation stability, or similar impacts on walls, culverts, or larger buried structures. Another impact of warming on materials relates to component service life. Even with the projected warming, temperatures in the North will typically remain lower than in the rest of Canada, and in most cases, the current provisions in CSA S6:19 adequately address service life, corrosion rates of steel, diffusion rates of chlorides in concrete, and construction methods and material quality. Notwithstanding, risks and impacts of warming and adaptation recommendations for consideration for CSA S6:25 are described below:

- **Increased average daily temperatures:** Warming in Canada's Arctic is increasing at a faster rate than in other regions of the country. The rate of warming is more than double the rate of global mean warming, and roughly double the warming rate in southern Canada. This will impact the materials used in bridges within the 75-year design life of bridges in the CHBDC.

- **Steel corrosion:** For steel components, whether structural steel in girders and piles or corrugated and galvanized steel in culverts, warming and humidity will nominally increase the rate of corrosion. Historical rates of corrosion in northern Canada are significantly lower than in warmer and more humid regions of Canada. However, recent research predicts that an increase of 3°C could increase the corrosion rate of weathering steel by 16%, and by 32% if there is a 5% increase in relative humidity [55].
- **Other steel property impacts:** With increased mean temperature, the frequency of extreme cold temperatures in the North will decrease, as will the risk of brittle steel fracture. Notch-tough specifications for steels used in the North may become less stringent, although this potential benefit is not certain and may not warrant changes to current material and bridge specifications for northern bridges.
- **Buried steel culverts:** Corrosion rates of buried steel culverts, which are typically galvanized, may increase with warming and may also be affected by changes in soil or groundwater properties related to permafrost melt, runoff changes, increased number of freeze-thaw cycles, or other reasons. CSA S6:19 and related material provisions for corrugated steel culverts are likely adequate for northern applications unless soil and water chemistry are affected by these processes.
- **Corrosion of reinforced concrete elements:** With northern warming, bridge owners may increase their use of road salts, which become effective at temperatures above -15°C. This issue is likely more relevant in southern areas of Canada's North. Two related impacts may be increased chloride ion concentrations and increased rates of diffusion of the ions into deck cover concrete and to the top reinforcing layer. These impacts are currently covered in CSA S6:19 and CSA A23.1:19, and the measures therein are likely adequate to deal with deck or other concrete element service life in the North. Bridge owner design and material specifications are beyond the scope of the CHBDC, but may warrant updating for these impacts. For example, if covers to top bar are specified to be less than what the CHBDC recommends for bridge decks, the CSA S6:25 provisions may become more appropriate to ensure adequate service life.
- **Decreased range of extreme annual minimum and maximum temperatures:** Extreme minimum and maximum temperatures are expected to shift upwards in northern Canada. Although the joint/bearing movements associated with the maximum temperature are expected to increase, the total movement range experienced by the joints and bearings may decrease due to differences in winter and summer warming magnitudes, as winter minimum temperatures in the North increase at a rate greater than maximum summer temperatures. As a result, bridge owners and designers will need to consider both initial (at construction) and final (end of bridge service life) joint/bearing movements due to thermal joint and bearing movements.
- **Joints and bearings:** It is relatively common in bridge infrastructure to see premature wear, deterioration, or malfunction (e.g., sticking) of bearings and joints. As a result, joints and bearings, including shear keys or other internal or purpose-designed guides, may become increasingly important in northern regions. Guidance to this effect, including case histories from the literature or as owners may provide, would be beneficial within CSA S6, Section 2 (Durability and sustainability) and Section 11 (Joints and bearings).
- **Elastomeric bearings:** The trend to warming or to less frequent extreme cold may allow for increased use of natural rubber bearings, including the use of rubber bearings in seismic isolation applications. However, cold temperatures lead to crystallization of rubber bearings, which is detrimental to the performance of elastomeric seismic isolation bearings and may limit their use in some locations. Expensive extreme cold weather testing is currently specified, which adds cost. This may remain appropriate for the foreseeable future, but the impacts of northern warming in higher seismic zones (i.e., Yukon Territory) should be reviewed for CSA S6, Section 4 (Seismic design) and Section 11 (Joints and bearings), and for bridge owner requirements.
- **Changes in differential heating:** Due to the prolonged low angle of solar radiation in the North, bridge and culvert infrastructure is prone to differential heating during spring, summer, and fall, as direct incoming shortwave radiation during clear-sky days shines more predominantly on southern aspects and below deck level components of the infrastructure.

"The bridge construction temperature should be selected to suit the typical local conditions at the anticipated time of construction."

This radiation is one component of the overall radiative balance that controls material temperature-dependent behaviour such as expansion and contraction. Climate change will likely cause changes to cloudiness in Canada's North, although projections of changes to cloudiness are not currently available. Cloudiness changes will decrease the amount of differential heating, as more energy is supplied to infrastructure components via other energy balance terms (i.e., turbulent and sensible heat). Thus, changes in cloudiness may have implications on the amount of differential warming that northern highway bridges experience. This topic should be re-evaluated in the future as northern cloud cover projections emerge.

- **Bridge construction temperature:** The bridge construction temperature should be selected to suit the typical local conditions at the anticipated time of construction. In the North, the specified default value of 15°C in CSA S6:19 is likely too high. While an appropriate construction temperature value should be selected corresponding to the expected time of construction, increasing northern temperatures will reduce the deviation from the CSA S6 default value.

7.2.5.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following general recommendations address key issues related to air temperature and climate change in Canada's North:

- Address the current relatively low rate of corrosion in northern areas due to lower ambient temperatures in Section 2 (Durability and sustainability). The discussion should include expected higher increases in corrosion rates due to the higher projected ambient temperature increases for northern regions.
- Discuss the potential for increased use of road salts in northern regions with increasing ambient temperatures in Section 2 (Durability and sustainability). Use of salt becomes effective at temperatures above -15°C, therefore this issue is likely more relevant in the southern areas of Canada's North. This may be an adaptive design issue (future modifications, other than potential concrete classes or covers).
- Rising maximum and minimum daily mean temperatures in northern regions will require the provision of maximum and minimum temperature data at the time of design and for the expected end of the bridge service life. Provide figures for the present and for 75 years in the future. If not reasonably linear, advice on interpolations between the time periods should also be provided.
- Describe the requirements for considering structural thermal effects at both the beginning and end of bridge design life in Clause 3.9.4 (Temperature effects). In addition, specify the requirements for movements of joints and bearings in Section 11 (Joints and bearings), and consider thermal effects at the beginning and end of the bridge design life, unless components are expected or designed to be reset during the service life.

- Discuss the potential thermal effects of the sun being at a low angle for prolonged periods of time in the North in Clause 3.9.4 (Temperature effects). This may have significant impacts on bridge girders and substructures, as well on culvert interiors relative to more southerly regions.
- Discuss the selection of a more appropriate construction temperature for northern regions in Clause 3.9.4.2, (Effective construction temperature).
- Add provisions in Section 6 (Foundations and geotechnical systems) on potential impacts of foundation material properties arising from permafrost melt or potential soil or water chemistry changes arising from northern warming.
- Consider adding warming impacts on elastomeric bearings in Section 11 (Joints and bearings) for bearing material selection and for testing of both prototype and production bearings.
- Consider future warming in the North Section 15 (Rehabilitation and repair), as described above, which may affect rehabilitation design decisions and requirements. Impacts and recommendations herein should be reviewed by the TSC responsible for this section to capture the impacts on bridge service life and renewal design in the North.

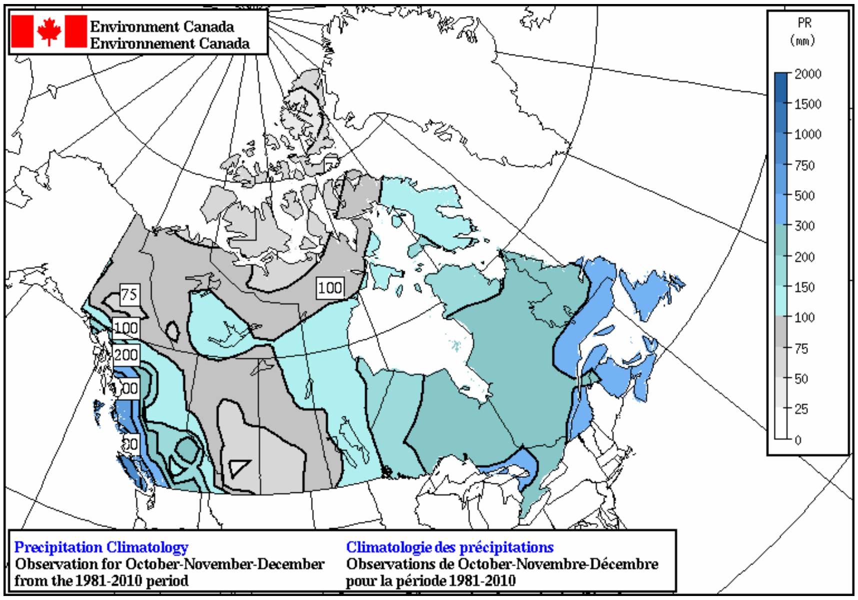
7.2.6 Precipitation

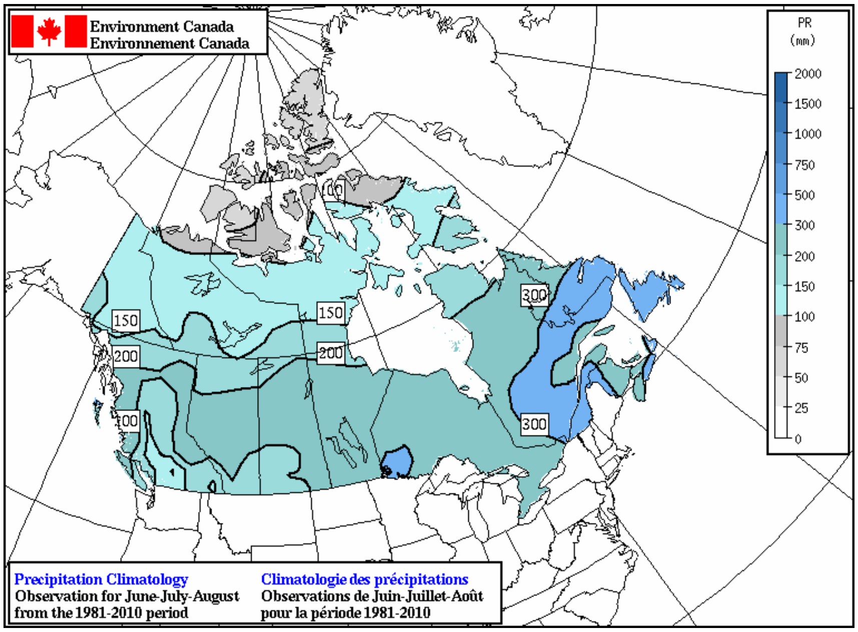
7.2.6.1 General Overview

Precipitation occurs as rain, snow, and hail, when water vapour in the atmosphere condenses and falls to the surface. Air temperatures in the lower atmosphere and near the surface are the primary factors that determine whether precipitation reaches the surface in solid or liquid form. In northern Canada, precipitation is dominated by snowfall in winter, spring, and fall, and experiences significant snowfall in summer [56]. Nonetheless, a sizeable portion of summer precipitation occurs as rainfall, and sporadic winter rainfall occurs as well, particularly in southern regions of Canada's North.

The amount of precipitation that falls over a period at any point is strongly influenced by large-scale atmospheric circulation patterns and moisture carrying ability, regional topography, and environmental conditions. Due to these factors, Canada's North exhibits some of the consistently driest (low precipitation) average conditions in the country (Figure 21). At the same time, northern precipitation tends to exhibit high relative variability around low average total amounts (e.g., high coefficient of variation).

Figure 21: Winter (top) and summer (bottom) average 1981-2010 climatological precipitation. Note that driest conditions occur in the North. Source: Environment and Climate Change Canada.





Precipitation can be measured both directly and indirectly. Meteorological stations with rain gauges measure the amount of precipitation collected by the gauge and can report hourly rainfall amounts and intensities. "Snow pillows" are a type of meteorological station that measure snowfall depth and snow density. Some meteorological stations have precipitation gauges that measure total precipitation (the sum of snow and rain). These direct methods provide accurate and robust measurements of local precipitation where available.

7.2.6.2 Climate Change Impacts

Because warmer air can hold more water vapour and thus produce more precipitation, winter and summer precipitation are both expected to increase in northern Canada, with greater relative increases in the winter. In both seasons, the fraction of precipitation that falls as rain is projected to increase substantially [1] [7].

Despite the shift from snow to rain in northern Canada, the increase in total precipitation will result in a net increase in winter snowfall amounts and maximum annual snow accumulation [57] in lieu of continued dominance of temperatures below freezing. There is relatively high confidence in the magnitude of the increase in precipitation but continued uncertainty in its local spatial distribution.

The magnitude and frequency of short duration intense rainfall events are also projected to increase in the North. These rainfall events are projected to occur both in summer and winter as intense, convective precipitation [48] and these events may contribute to storm-related flood risks. The magnitudes of the 10-year, 20-year, and 50-year rainfall events in Canada are projected to increase by up to 11% by 2050 and up to 30% by 2100 [1]. The increase in frequency is projected for all of Canada because local projections have substantial uncertainty [7].

7.2.6.3 Implications for Highway Bridge Infrastructure

Projected precipitation changes through the end of the century have several potential implications for highway bridge infrastructure:

- **Increased snow clearing operations:** High relative increases in northern winter precipitation will result in disproportionately large relative increases in snowfall on northern bridge decks and adjacent approaches. This will require increases to snow clearing operations over bridge decks and approaches relative to other Canadian regions. It will also result in greater degradation of these infrastructure components due to abrasion from plows and possible use of salt in response to increased snow clearing.

- **Increased summer localized precipitation:** Increased summer short duration, high-intensity precipitation events may produce localized flooding in low-lying areas and poorly drained bridge decks. This will impact bridge deck drainage design, although short duration events that only have temporary impacts on truck or vehicle passage may not warrant increased expenditures. Many northern bridges have reduced shoulder widths due to low traffic volumes, which can make it more difficult to meet the bridge deck drainage criteria.

7.2.6.4 Recommendations for CSA S6:25 and CSA S6.1:25

The following general recommendations address key issues related to precipitation changes and climate change in Canada's North:

- Include recommendations in Section 1 (General) for maintaining shoulder widths for snow storage and bridge deck drainage. Shoulder widths are frequently minimized on northern bridges due to low traffic volumes and budget limitations. Shoulder widths on some bridges could also be increased for local snowmobile passage and safety.
- Enhance provisions of Section 1 (General) to allow greater (wider) intrusion of deck water into travelled lanes, where lower traffic volumes and hand safety implications may be lower.
- Provide guidance regarding local bio-treatment (environmental impacts including on wetlands and permafrost implications).
- Provide guidance on recommendations for bridge deck drainage design, capture, and treatment that are appropriate for northern regions, and adaptive design or risk acceptance.

7.2.7 Wind

7.2.7.1 General Overview

Wind occurs when there are atmospheric pressure gradients caused by ever-evolving regional weather circulation dynamics. Near-surface wind speed, which is most pertinent to northern highway bridge infrastructure, is influenced by regional and local topography and microclimatic effects, local surface roughness, and for large infrastructure such as major highway bridges, infrastructure-sourced alterations to local wind flow. Horizontal wind pressures are typically higher than vertical wind pressures. However, convective storm activity can introduce strong downdrafts, which can damage elevated or under construction bridge infrastructure. High surface wind speeds in northern Canada are associated with severe storms, which can occur on local to regional scales.

Wind is measured at meteorological stations, airports, and weather balloons. Wind speed observations are sparse across northern Canada, which presents a challenge for spatially comprehensive wind assessments, because direct wind measurements are representative of a limited spatial range. Gridded climate reanalysis products provide estimates of wind speed across large spatial extents but are not available in real-time and are also limited in spatial resolution. Few studies have examined trends in surface winds or their distribution across Canada. Wan [58] reported that northern Canada is generally windier than southern regions of the country. ECCC's Wind Atlas reports mean wind speeds 30 m above the surface as higher in the Nunavut and Yukon Territories than the rest of Canada during fall and winter [1]. Wan [58] also reported long-term mean wind speeds above 20 km/h across northern Canada in all seasons.

The presence of wind against a structure induces positive pressure or suction. Simultaneous rain and wind pressures are referred to as driving rain wind pressure (DRWP), with potential impacts discussed in the following section.

7.2.7.2 Climate Change Impacts

It is difficult to project the future occurrence of extreme wind events as current global circulation models and regional circulation models cannot resolve the small-scale storm events that generate extreme wind loads [7]. Projections of the 10-year and 50-year return level design wind pressure indicate minimal increases (< 3%) in northern Canada, but these projections are subject to significant uncertainty. The projected increase in 5-year return level design DRWP is greater in northern Canada (22%) relative to the rest of Canada (9%) under a 3°C global warming scenario. High uncertainty is associated with changes in extreme wind events and related pressures.

7.2.7.3 Implications for Highway Bridge Infrastructure

Projected wind changes may increase driving rain wind pressures. This would have implications for highway bridge infrastructure in the form of:

- Increased damage to bridge structures from water infiltration;
- Increased wind-induced oscillation and pressure or suction on bridge superstructure, supports, and fixtures.

7.2.7.4 Recommendations for CSA S6:25 and CSA S6.1:25

Special recommendations were not developed at this time for wind loading on northern bridge infrastructure.

7.2.8 Ice

7.2.8.1 General Overview

Ice, or its formation, occurs in several ways that are relevant to Canada's northern highway bridge infrastructure.

Ice accretion occurs when freezing rain falls onto exposed surfaces. Freezing rain occurs when precipitation is formed and falls as rain but encounters surface air temperatures between -10°C and 0°C [59]. The resulting ice can accrete on horizontal, vertical, or radial surfaces like bridge decks or suspension cables. Freezing precipitation is observed at some meteorological stations, but the distribution of stations across Canada's North is sparse. Climate models and climate data reanalyses provide estimates of the historical occurrence of freezing precipitation and its accumulation at moderate spatial resolution. The models estimate fewer than 10 days of freezing precipitation annually in northern Canada, with 20-year return levels of less than 12 mm [59].

The daily freezing and thawing of water on the surface or in the near-surface is referred to as a freeze-thaw cycle. It occurs when the daily minimum and maximum air temperatures cross 0°C. Freeze-thaw cycles can enlarge existing cracks due to the expansion of water as it freezes. Freeze-thaw cycles are more rapid and have shallower impacts than the active layer processes described in Section 7.2.3. In colder weather areas, potholes are created as water seeps through cracks in asphalt and freezes [60]. The expansion of asphalt potholes through freeze-thaw cycles is greatest during late winter and early spring [61].

River ice forms on many rivers in northern latitudes during winter. An estimated 60% of northern rivers experience some degree of ice effects [62]. River ice is particularly relevant to highway bridge infrastructure when the river ice undergoes spring breakup, during which ice jams can form. Ice jams are often initiated by increased streamflow and river ice interaction with bridge piers and abutments [63]. Ice breakup and ice jam occurrence is impacted by air temperature, precipitation events, and changing streamflows [64]. Due to the multiple climatic variables influencing ice jam occurrence, it is difficult to predict when they will occur. Ice jam occurrence can sometimes be indicated by hydrometric observations, but they are often recorded as personal observations.

7.2.8.2 Climate Change Impacts

The atmospheric conditions required to produce freezing rain are projected to become more frequent in northern Canada. Total precipitation, precipitation intensity, and wind speed are also projected to increase in northern Canada [59]. As a result, freezing precipitation and ice accretion are projected to increase across Canada's North[7] [59] .

Ice accretion increases are tied to air temperature increases, and a scenario of 3°C warming is expected to increase extreme ice loads by up to 100% in the Yukon and Northwest Territories. Significant increases in the 50-year extreme ice loads are also projected with 1°C and 2°C warming scenarios. However, ice load projection magnitudes are made with low confidence because of the complexity of modelling ice accretion events [7].

Freeze-thaw cycles are projected to decrease across the entire Canadian North. Annual freeze-thaw cycles are projected to decrease by 10 to 20 in southern Yukon Territory, and 5 to 10 fewer annual freeze-thaw cycles in the rest of the Yukon and the other territories [65]. The decreased number of cycles is strongly linked to surface air temperatures and is expected to continue as air temperatures continue to warm.

Minimal research has been done on the historical change in ice jam frequency and magnitude or its projected change in relation to climate change. Ice jam formation is impacted by air temperature, precipitation, wind, and other weather conditions [64]. Ice jam response to these climate variables is not consistent. Air temperature in northern Canada is projected to increase, shortening the river ice season and decreasing the likelihood of ice jam occurrence. However, precipitation in northern Canada is also projected to increase, especially in winter, which may increase ice jam frequency [64]. There is significant uncertainty in how ice jam frequency and magnitude will respond to climate change in northern Canada.

7.2.8.3 Implications for Highway Bridge Infrastructure

Projected climate change impacts on ice accretion and design ice loads, freeze-thaw cycles, and river ice-jams have several possible implications for northern highway bridge infrastructure:

- **Increased ice accretion:** Projected increases in freezing precipitation will result in increased ice accretion on all exposed surfaces of northern bridges and adjacent approaches, which will lead to increased ice loads and increased hazards from falling ice. Bridge infrastructure may require more frequent ice removal operations from bridge decks and from elevated structures.
- **Reduced freeze-thaw cycles:** Freeze-thaw cycles are projected to decrease across the North. This may reduce the amount of maintenance needed to repair potholes and road surfaces.
- **River ice-jams:** Ice jam formation can stress and damage bridge piers and abutments and can damage bridge superstructure if there is substantial accumulation. Ice jams also cause abrasion and vibrational effects on bridge structures. The uncertainty associated with changes to ice jam frequency and magnitude due to climate change will require more careful consideration and research.

7.2.8.4 Recommendations for CSA S6 and CSA S6.1

The following general recommendations address key issues related to ice:

- Update Clause 1.9, (Hydraulic design) and the TAC Guide to bridge hydraulics for northern river hydrology and hydraulics and for related design changes for northern river ice conditions.
- Include guidance on extreme event risk assessments for bridge design related to the impacts of increased northern temperatures, including changes in ice loads, frequency, and levels of ice jams [39,] [50] [52] [53] [62] [63] [64].
- As part of conceptual planning, provide guidance in Section 1 (General) to consider ice jam formation in planning on bridge lengths, and in particular, when extending embankments or abutments into the watercourse or when considering pier locations within the watercourse.

7.2.9 Forest Fires

7.2.9.1 General Overview

In northern Canada, the boreal forest is prone to high-intensity, large-scale wildfires. Northern Canadian forests receive relatively little to no aggressive wildfire suppression, which can lead to larger areas burning than in southern forests [66]. While Canada's North has the lowest number of fires, they are large. For example, the Northwest Territories had 6,696 fires between 1980 and 1999, which burned 13.7 million hectares. In comparison, British Columbia had 49,291 fires that burned 1.3 million hectares over the same period [67]. The Yukon Territory has the lowest historical fire occurrence rate, but also has larger than average burned area per fire [67]. Forest fire rates in central and northern British Columbia have met and exceeded past records for square kilometers burned, with four of the largest six fires occurring in 2014 and 2017 [68]. These signify an increased fire risk in Canada's North related to warming.

7.2.9.2 Climate Change Impacts

The fire frequency and intensity in a region can evolve under a changing climate [69]. Projected increases in air temperature contribute to increased frequency of burn conditions. Projected decreases in permafrost extent will reduce soil moisture [48], increase the burnable area, and produce difficult-to-suppress peatland fires [70]. Projected increases in

> "In northern Canada, the boreal forest is prone to high-intensity, large-scale wildfires."

summer precipitation may have a moderating effect, although no studies have investigated this interaction. Some regions of boreal forests in northern Canada are projected to double the proportion of days with conditions that could produce unmanageable fires [47].

7.2.9.3 Implications for Highway Bridge Infrastructure

Projected general increases in fire frequency and severity in northern Canada may not have severe implications for northern highway bridge infrastructure, despite notably increased fire activity. Unmanageable wildfires may cause access limitations to northern highway bridges, but this impact would not be limited to bridge infrastructure and would be difficult to mitigate using bridge infrastructure design options. Wildfires impact overland water runoff and hydrology, which can affect bridge geometry (spans, clearances), foundations (scour), as well as culvert and buried structure design.

Concrete and steel bridges are not impacted by forest fires or wildfires unless there are substantial quantities of combustible materials beneath or immediately adjacent to the bridge. Timber bridges or timber bridge components (e.g., exposed timber piles or cribbing, timber bridge decks or railings) are susceptible to fires, including bridge approach structures (e.g., guard rails installed on wooden posts).

Given the relatively small number of wooden bridges in the territories, there may be little core infrastructure-specific vulnerability to wildfires. Within northern regions of the provinces, however, such as rural municipalities, a significant proportion of bridges include timber crossings. Timber decks, trestle supports (bents and piers), glulam girders, and other timber components of roadway bridges, ties of railway bridges, and culverts or roadways (barriers, delineators, abutment walls) all include risk of damage and need for repair following forest fires.

British Columbia introduced legislation in 2009 [71] that requires consideration of timber as a construction material in new buildings and structures. The BC Ministry of Transportation and Infrastructure applies the legislation's material selection criterion to bridges. The use of engineered timber is also evolving, adding to the potential use of large timbers in bridges. Glulam bridges are common in British Columbia on resource roads and cross-laminated timber may also see greater use throughout British Columbia and in Canada's northern regions.

Timber truss and trestle bridges have been used across North America for highway and railway bridges, and potentially also in northern regions. Some of these timber highway bridges remain in use, and a number of timber trestle railway bridges also remain in service. However, these bridges are prone to damage and collapse should fire occur. Historically, timber in bridges was treated with creosote, which is highly flammable and increases the risk of damage or loss from fire.

The existence of timber bridges and the limited use of timber in new bridges, combine to create a modest risk of extensive damage from fires in Canada's North.

However, trestle, truss, and glulam bridges have been lost to fires, including some to forest fires, so the risk of damage to timber bridges and timber components should be recognized in bridge planning and conceptual design.

7.2.9.4 Recommendations for CSA S6 and CSA S6.1

The following general recommendations address key issues related to forest fires:

- When assessing a timber bridge as a structural option, consideration should be given to the presence of combustible materials at the bridge site, availability and effectiveness of wildfire control measures, and availability of alternative routes. This would include timber bents, superstructures, decks, ballast walls, barriers, or bridge delineators.
- With consideration of environmental (especially riparian) impacts, consideration should be given to clearing fuel load in the immediate vicinity of a bridge that may be at risk of forest fires. This is similar to practices and recommendations for fire prevention in interface areas for buildings and forests.
- Provide guidance in Section 9 (Wood structures) on the risk of forest fire impacts to timber in new or existing bridges. Trestle, truss, and glulam bridges have been lost to fire, and acknowledgement of these risks in the context of extreme or increased fires in Canada's North should be included in CSA S6.1:25.

7.3 Conclusions and General Recomendations

7.3.1 Conclusions

This section of the report identified potential impacts on highway bridge infrastructure in Canada's North that could arise due to northern-specific or northern-focused climate change trends. It was developed to support updates to CSA S6:25 and is intended to be used as a reference document by the CHBDC TSCs for developing CSA S6:25 and CSA S6.1:25.

Amplified northern climate change trends will be superimposed against likely increases in the development of northern highway infrastructure as northern Canada's population and transportation development accelerates. Northern highway bridge infrastructure will thus experience compound pressures due to increased environmental impacts and increased usage. The description of specific climate change impacts outlined in Section 3 of this report should not be taken as an exhaustive list of all potential impacts. Instead, they should be considered as the subset of the Canadian bridge infrastructure climate change impacts that may require special attention in the northern context.

Future climate change in Canada's North will typically be characterized by larger magnitudes of change, for both average conditions and highway bridge infrastructure-relevant extreme conditions. At the same time, projections of northern climate change will likely exhibit larger absolute uncertainty with respect to the specific magnitude of change. This larger uncertainty is directly linked to:

- Large natural variability in northern climate;
- Large signal of change;
- Fewer observational constraints on climate downscaling and bias correction efforts; and
- Less northern-focused climate research.

7.3.2 General Recommendations

- Emphasize in CSA S6.1:25 that the magnitude of climate change in Canada's North will continue to outpace national and global average rates of change.
- Undertake northern-focused highway bridge infrastructure design-specific investigations to better understand northern bridge impacts in CSA S6.1:25. Investigations should at a minimum target northern-specific impacts listed in Section 3 and Section 7 of the commentary, as well as other potential site-specific impacts. It is likely that the details of such investigations are beyond the scope of CSA S6.1:25 to fully delineate, so general recommendations around northern-specific investigations may suffice. Many of these recommendations may formalize practices that are already in place in the northern context, but do not yet consider the impact of a changing climate. Examples of such investigations should include:
    - Assessment of northern-specific permafrost and hydrologic flow changes proximal to northern watercourses and flood plains crossed by planned highway bridge infrastructure;

    - Assessment of precipitation extreme changes in locations of planned highway bridge infrastructure; and
    - Assessment of freeze-thaw cycle changes in locations of planned highway bridge infrastructure.
- Include site-specific climate risk assessments in CSA S6.1:25. Risk assessments should be guided by local known climate impacts and should screen for potential risks from northern-specific impacts identified in Section 3 of the commentary, at a minimum. National-scale guidance on highway bridge infrastructure resilience may not be applicable to northern contexts, meaning that local expert judgment, appropriately applied and documented, will be important.
- Develop northern location-specific risk profiles that identify changing risk levels in response to climate change. Such profiles may indicate decreasing risk over time (for example, to freeze-thaw intensity), and in such cases, building to present-day conditions is appropriate.
- As part of route selection planning, including for bridge or large culvert watercourse crossings, note that some northern routes involve long distances between population or industry centres and viable alternative routes are limited or nonexistent. While this creates a situation where higher levels of reliability in bridge performance is desirable, wider economic realities or route resilience also need to be considered. Long roadways with limited traffic volumes can create conditions where economics favour narrower bridges without significant loss of user safety. Justifying the benefits of longer or wider bridges to deal with future issues such as permafrost change, increased river flows, and long-term durability can be a challenge. Providing guidance in CSA S6.1:25 relating to adaptive design or increased crossing capacity or resilience for bridge infrastructure and routes against potential impacts from climate change-induced warming in Canada's North is recommended.

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Appendix A – Overview of CSA S6:19 Committees and CHBDC Sections

In Canada, the legal mandate for establishing design and construction requirements for highways, including highway bridges, lies with provincial and territorial governments. All provinces and territories, except Manitoba, have mandated CSA S6, Canadian highway bridge design code (CHBDC) for use under their jurisdictions. Among the benefits associated with undertaking the development of the CHBDC is the opportunity to establish consistent safety and reliability levels for highway bridges across Canada. Adoption of a single code makes it easier for the consulting and producer industries to respond to calls for proposals and eliminates the need for familiarity with the details of several codes. The adoption of a single code also supports the implementation of a national highway transportation system with agreed minimum standards and demands for bridges on interprovincial highways, thereby encouraging consistency of vehicle weights across jurisdictions and supporting the objective of more cost-effective transportation of goods.

The CHBDC is developed by taking into account the different regulatory structures and standards of Canada's provinces and territories. Overall priorities and objectives are established by the CHBDC Regulatory Authority Committee (RAC), which also monitors the progress of the CHBDC development. In accordance with CSA procedural requirements, responsibility for the technical content of the CHBDC is assigned to the Technical Committee (TC), as are decisions on how to deal with the priorities and objectives identified by the RAC. Because of the breadth and complexity of the CHBDC, Technical Subcommittees (TSC) have also been established to oversee each Section of the CHBDC.

The CHBDC comprises the following 17 sections:

Section 1 (General) specifies general requirements for applying the CHBDC and includes definitions and a reference publications clause applicable throughout the CHBDC. It also specifies geometric requirements, based in part on the Transportation Association of Canada's *Geometric design guide for Canadian roads* [72], and hydraulic design requirements, based in part on the Transportation Association of Canada's *Guide to bridge hydraulics* [12]. There are also general provisions covering durability, economics, environmental considerations, aesthetics, safety, maintenance, and maintenance inspection access.

Section 2 (Durability and sustainability) specifies requirements for durability and sustainability that need to be considered during the design process of bridges, culverts, and other structures located in transportation corridors. The durability requirements are based on principles applicable to service life design that consider the environmental exposure conditions, the deterioration mechanisms, the protective measures, and detailing requirements needed to meet the projected service life of structural components. The concept of sustainability considerations alerts owners and designers to undertake design and decision-making practices that will help to achieve the context-specific balance of social, environmental, and economic values, and the impacts associated with the investment in building new or rehabilitating existing bridges and other transportation structures included in the scope of the CHBDC. Similarly, local climate change and exposure conditions are brought to the attention of designers and owners.

Section 3 (Loads) specifies loading requirements for the design of new bridges, including requirements for permanent loads, live loads (including special trucks), and special loads (excluding seismic loads). The CL-625 kN truck load model and corresponding lane load model are specified as the minima for interprovincial transportation and are based on current Canadian legal loads. Selected environmental design loadings are specified for wind, temperature, and ice accretion along with design provisions for these and other environmental loadings. Section 3 does not specify limits on the span lengths for application of the truck and lane loads. Accordingly, long-span requirements have been developed and appear in Section 3 and elsewhere in the CHBDC.

Section 4 (Seismic design) specifies seismic design requirements for new bridges and evaluation and rehabilitation requirements for existing bridges. Performance-based design (PBD) has been maintained using updated values for damage states in ductile substructures and seismically isolated structures. Force-based design (FBD) is still permitted for a refined set of special cases. Capacity design is required for ductile structures using PBD and FBD. PBD and recommended minimum performance targets are provided for the evaluation and rehabilitation of existing bridges. FBD approaches for existing bridges are discouraged, while guidance on displacement-based methods is provided.

Section 5 (Methods of analysis) specifies requirements for analyzing bridge superstructures. Additional guidance related to longitudinally connected beams and integral abutment bridges are provided. This section presents methods for the simplified analysis of longitudinally connected concrete box-beam bridges, curved steel girder bridges, and steel or aluminum pony-truss bridges. Requirements and guidance for the refined method of analysis are included as are methods for the design of deck slab cantilever overhang. A simplified method of analysis is provided for determining the factored flexural resistance of steel-reinforced concrete barrier to transverse traffic barrier load.

Section 6 (Foundations and geotechnical systems) adopts a risk-based approach to the design of foundations and geotechnical systems (including bridge approach embankments and retaining systems). The risk-based design approach uses a resistance factor, which captures our uncertainty in the ground and in our performance predictions, combined with a consequence factor, which adjusts target reliabilities depending on the severity of failure consequences (i.e., depending on the importance of the supported structure), to produce designs that properly account for the level of site understanding and failure consequences.

Section 7 (Buried structures) deals with structures whose design and performance are heavily influenced by soil-structure interaction. The conduit wall of these buried structures can be fabricated from metal, steel or aluminum, or concrete. This section provides for a wide variety of structure shapes from low profile metal boxes or three-sided concrete boxes to large span metal or concrete arches. It specifies the use of refined methods of analysis for design, the requirements for determining the properties and dimensions of the engineered soil and non-soil components, and addresses construction requirements, geotechnical requirements, and foundation design requirements.

Section 8 (Concrete structures) covers reinforced, fully prestressed, and partially prestressed concrete components, including deck slabs, made of normal-density, semi-low-density, and high-density concrete of a strength varying from 30 to 80 MPa. Compression field theory is used for proportioning for shear and for torsion combined with flexure. The latest edition of the CHBDC includes an informative annex with design provisions for tension softening and tension hardening fibre-reinforced concrete, including ultra-high performance concrete.

Section 9 (Wood structures) applies to structural wood components and their connections. This section specifies properties for materials and fastenings that are consistent with CSA O86, *Engineering design in wood.*

Section 10 (Steel structures) specifies the requirements for the design of structural steel bridges and highway accessory supports, including requirements for structural steel components, such as tension and compression members, composite and non-composite straight and horizontally curved girders of I-shape or box shape and their connections. It also covers trusses and arch type bridges.

Section 11 (Joints and bearings) specifies the minimum requirements for the design of deck joints and bearings. The provisions for the design of elastomeric bearings are consistent with approaches used in other North American and international standards and codes. Alternative sliding materials (as an alternative to polytetrafluoroethylene) comprised of ultra-high molecular weight polyethylene and a testing protocol for such materials are also presented.

Section 12 (Barriers and highway accessory supports) specifies the requirements for the design of permanent bridge barriers and highway accessory supports. It includes provisions to define the extent of the “zone of intrusion” behind barriers and for the design of noise barriers, and provisions for designing highway accessory supports at the serviceability and fatigue limit states.

Section 13 (Movable bridges) specifies requirements for the design, construction, and operation of conventional movable bridges (bascule, swing, and vertical lift). Although the structural design aspects are based on the limit states design approach, the mechanical systems design procedures follow the working stress principle used in North American industry. This section provides special load combinations and load factors specific to movable bridges.

Section 14 (Evaluation) includes provisions concerning the three-level evaluation system, evaluation of deck slabs, detailed evaluation from bridge testing, and load posting of bridges. An optional probability-based mean load method that uses site-specific load and resistance information for more accurate evaluation is also provided.

Section 15 (Rehabilitation and repair) specifies minimum design requirements for the rehabilitation of bridges, with particular emphasis on condition assessment, remaining service life and rehabilitation design life. This section also provides guidance on the selection of loads and load factors for rehabilitation that is based on the intended use of the bridge following rehabilitation.

Section 16 (Fibre-reinforced structures) specifies design requirements for structural components containing high-modulus fibre-reinforced polymers. The high-modulus fibres (aramid, carbon, and glass) are employed in fibre-reinforced polymers (FRPs), which are used for internal reinforcement as replacements for steel bars and tendons or as external reinforcement for retrofit. This section also covers concrete beams, slabs, columns, concrete deck slabs, barrier walls, and stressed wood decks using FRP, and includes design provisions for glass-fibre-reinforced polymers to be used as primary reinforcement and as tendons in concrete. An informative annex is included to provide guidelines for glass FRP composite bridges.

Section 17 (Aluminum structures) specifies the requirements for the design, fabrication, and erection of aluminum highway bridges. Where permitted in Section 12, this section may also be applied to highway accessory structures.

CSA S6.1, Commentary on CSA S6, Canadian Highway Bridge Design Code, provides rationale statements and explanatory material for many of the clauses in CSA S6.

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.