THE ROAD WELL-TRAVELED:

Implications of Climate Change for Pavement Infrastructure in Southern Canada

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*cover photos courtesy of Dr. Susan Tighe

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SUMMARY

Relatively little research has been completed to investigate the potential impacts of climate change on pavement infrastructure despite the dependence of Canadian economic and social activity on road transport, and the documented influence of climate and other environmental factors on the deterioration of pavements. A review of pavement management practices and engineering models and approaches used to monitor, assess and predict flexible pavement performance revealed that climate—and thus potentially climate change—is an important consideration in at least three deterioration processes: thermal cracking, frost heave and thaw weakening, and rutting. As with other forms of infrastructure, the fundamental concern related to a changing climate in pavement management is the potential for premature design failure. Current and past designs generally assume a static climate whose variability can be adequately determined from records of weather conditions which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration.

Two sets of case studies were undertaken in order to investigate these generalized impacts of climate change in greater detail. Results for both are contingent on the realization of mid-century changes in climate derived from the CGCM2A2x and HadCM3B21 global climate modeling experiments. These scenarios are moderate compared to those from other models. The first set of case studies examined deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure. The analysis of minimum and maximum in-service pavement temperatures and freezing and thawing indices at 17 Canadian sites suggests that, over the next 50 years, low temperature cracking will become less problematic; structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths; and higher extreme in-service pavement temperatures will raise the potential for rutting.

The second set of case studies involved applying the newly developed Mechanistic-Empirical Pavement Design Guide (MEPDG) to assess the impact of pavement structure, material characteristics, traffic loads, and changes in climate on incremental and terminal pavement deterioration and performance. Evidence from the 6 Canadian sites that were evaluated was not as universal as that revealed through the first set of case studies but nonetheless suggested that rutting (asphalt, base and subbase layers) and cracking (longitudinal and alligator) issues will be exacerbated by climate change with transverse cracking becoming less of a problem. In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life. The effect of climate change was found to be modest, both in absolute terms and relative to variability in pavement structure and baseline traffic loads.

Pavement management systems in Canada are carefully engineered and adaptive. None of the potential impacts of climate change identified through the case studies fall beyond the range of conditions presently experienced in North America. Material and other construction, monitoring, and maintenance technologies exist to manage all of the identified problems and it is highly likely that agencies will make the necessary adjustments and investments (e.g., higher PGs) to preserve the primary paved network. However, the more significant impacts associated with changes in climate may well be realized on the secondary or tertiary networks of provincial and municipal agencies where weak pavement structures coincide with excessive traffic loads.

Results from this study should be thoroughly discussed within the engineering community. Moving from exploratory research that raises awareness of climate change to practical guidance aimed at reducing costs and safeguarding infrastructure will require additional effort and collaboration. To this end, the authors will continue to take advantage of opportunities to present and deliberate findings at meetings of the Transportation Association of Canada, Canadian Technical Asphalt Association, and the Transportation Research Board.

Pavement engineers, with assistance from government and academic climate change experts, should be encouraged to develop a protocol or guide for considering potential climate change in the development and evaluation of future designs and maintenance programs. Such an activity might be initiated through the Transportation Association of Canada or other multi-stakeholder associations and leverage existing activities such as the implementation of MEPDG in Canada and the Canadian Climate Change Scenarios Network (CCSN). Incorporating other climate-related road infrastructure issues, for instance those associated with concrete pavements, surface-treated roads, airfields, bridges and culverts, would also be beneficial.

Environment Canada and other agencies should work with pavement engineers to facilitate greater application of environmental data in the design process and operational management of road networks. At a minimum, long time series of historic climatic and road weather observations—ideally greater than 30 years in the case of climate—should be incorporated into analyses of pavement deterioration and applicability of Seasonal Load Restrictions (SLRs) and Winter Weight Premiums (WWPs) or assignment of performance graded materials.

In terms of future research, more analysis is required to understand the interactive effects among environmental, structural, traffic, maintenance, and construction variables. Additional studies should be conducted to assess the implications of climate variability and change on the more vulnerable elements of the road network, including municipal roads and components of the provincial networks subject to SLRs. In particular, there is a need to further explore the influence of variable sequences of climate events from construction to reconstruction using a combination of simulation (i.e., MEPDG), laboratory material testing, and distress survey data. Where possible, this research should be conducted through partnerships with specific transportation agencies.

1.0 INTRODUCTION

Anthropogenic climate change has been identified by the vast majority of atmospheric scientists and many world leaders as one of the most significant issues facing humanity. Human activities over the past two centuries, chiefly the large-scale combustion of fossil fuel, have raised the concentrations of greenhouse gases and aerosols in the atmosphere to levels that have measurably interfered with the planetary climate system (IPCC, 2001). Numerous efforts to model the impact of past and potential future global trends in emissions of carbon dioxide and other greenhouse gases have all arrived at the same conclusion—global mean temperature has and will continue to increase, perhaps as much as several degrees Celsius, over the next century. Accompanying this warming will be a substantive rise in sea levels and a net increase in global precipitation.

The potential manifestations of global climate change at continental, regional, and local scales, and attendant impacts on ecosystems, society and economy, have been the subject of much study over the past two decades. A very small but growing portion of this literature has identified and examined potential implications for the demand, management, and operation of transportation systems and enabling infrastructure. In Canada, relevant research has been summarized by Irwin and Johnson (1990), Andrey and Snow (1998), Andrey and Mills (2003), and Andrey *et al*. (2004). A synthesis of potential Canadian impacts and sensitivities, conditioned by the amount of research completed and level of certainty in key climate change variables is presented in Table 1. The main conclusion from this research is that the effects of climate change on Canada's transportation system will likely vary by region and mode.

Table 1. Possible implications of climate change for Canadian transportation

CONFIDENCE IN EXPECTED CHANGES IN CLIMATE VARIABLES*	TRANSPORTATION SENSITIVITIES: AMOUNT OF COMPLETED RESEARCH	
	A few studies	*No significant climate change research*
HIGH CONFIDENCE *mean temperature* *sea-level rise*	– East and Gulf coast infrastructure (sea-level rise and storm surge) – Reliable northwest passage through Arctic (ice cover) – Northern infrastructure (permafrost degradation and ice roads)	
MODERATE CONFIDENCE *extreme temperature* *mean precipitation*	– Great Lakes-St. Lawrence shipping	– Winter maintenance costs for surface and air transport – Fuel efficiencies and payloads for motorized transport – Extreme temperature and freeze-thaw related impacts on infrastructure design and maintenance – Construction season length/quality
LOW CONFIDENCE *storm frequency/severity* *extreme local precipitation*	– Landslides/avalanche impacts on mobility and maintenance – Inland urban infrastructure (flooding)	– Health and safety – Mobility – Property damage due to weather-related incidents and severe storms (excluding coastal infrastructure) – Bridges and other structures spanning inland lakes, rivers (flooding) – Transportation demand and competition

Source: Mills and Andrey (2003)

Some northern settlements and coastal regions are expected to face serious challenges associated with changes in temperature and sea level, respectively; while there may be some benefits associated with milder winters in the more populated parts of Canada. All modes are expected to face some new problems, but each may also experience some reduced costs. There is also a growing awareness that public agencies and private industries need to consider adaptive strategies related to design and/or operational practices in response to changing conditions (Andrey *et al*., 2004).

Road infrastructure and operations in southern Canada remain among the least studied of those sensitivities listed in Table 1. The Canadian road system is a valuable resource, both in absolute terms and relative to other transportation modes. Richardson (1996) estimated that the asset value of the system was about $100 billion. In 2002-03, Canadian local, provincial/territorial and federal government agencies invested over $14 billion in roads, roughly 72 percent of investment in all transportation modes (TC, 2003).

Canadian economic and social activities are highly dependent on road surface transportation. By the late 1990s, revenue generated by commercial freight and passenger shipping via trucks and buses exceeded that of all other modes combined (TC, 2003). In 2002, trucks carried 63 percent of the $531 billion worth of goods traded with the United States while automobiles accounted for almost 92 percent of the 188 million domestic trips[1] taken in Canada (TC, 2003). According to the Canadian Vehicle Survey, Canada's 17.3 million light vehicles generated over 500 billion passenger-kilometres worth of travel in 2000 (TC, 2000). The distribution of travel is generally proportional to population, with concentrations in Ontario, Quebec, Alberta and British Columbia.

Many of these benefits are concentrated along the high-volume paved road portion[2] of the Canadian road network, broken down by jurisdiction and class in Table 2. Although high-volume paved roads represent about 15 percent of the 1.4 million kilometre road network, they are responsible for the vast majority of intra-provincial, inter-provincial and Canada-U.S. road movements (TC, 2002; TC, 2003). Traffic is especially concentrated on the 24,000 kilometres that constitute the National Highway System (TC, 2002). The mobility and wealth afforded by the road system is underwritten by substantive costs, including the direct capital and maintenance expenditures alluded to previously. More significant are externalized costs that include roughly 2,900 motor vehicle collision fatalities each year (Andrey, 2000) and a substantial portion of Canadian emissions that contribute to air pollution and global anthropogenic climate change.

Given the considerable asset value of the road system, the dependence of Canadian economic and social activity on road transport, and the documented influence of climate and other environmental factors on the deterioration of pavements (Nix *et al*., 1992; Haas *et al*., 1999) Environment Canada, the University of Waterloo, and the Government of Canada Climate Impacts and Adaptation Program, proposed and supported a research project to examine the impacts of climate change on pavement infrastructure in southern Canada. This project focused on the management of flexible (i.e., asphalt) pavement infrastructure, which is most often encountered on roads and highways, but is also extensively used at airports, and for institutional and private industrial, commercial and residential applications (parking areas, drives, entrances, cycle paths, walkways, etc.). The emphasis in the project is on road infrastructure.

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[1] refers to same-day and overnight trips greater than or equal to 80km from usual place of residence, excluding those to work or school

[2] includes: freeways, primary and secondary highways, arterial roads

Table 2. Canadian road network distribution (2002)

Jurisdiction	Freeway	Primary Highway	Secondary highway/major arterial	Local street/rural road	Total
	Two-lane equivalent km (thousands)				
Newfoundland and Labrador	0.2	1.4	5.4	20.1	**27.1**
Prince Edward Island	0.0	1.3	2.2	2.9	**6.5**
Nova Scotia	1.6	2.8	3.3	40.9	**48.7**
New Brunswick	1.3	1.5	6.2	67.5	**76.6**
Quebec	5.0	10.9	15.1	197.3	**228.3**
Ontario	5.7	10.2	34.2	180.4	**230.6**
Manitoba	0.2	8.2	10.8	85.3	**104.5**
Saskatchewan	0.1	20.5	12.6	216.8	**250.0**
Alberta	1.4	15.5	17.3	171.1	**205.3**
British Columbia	1.3	9.9	5.2	188.5	**204.8**
Yukon Territory	0.0	2.6	0.9	12.5	**16.1**
Northwest Territories	0.0	0.8	1.3	8.1	**10.1**
Nunavut	0.0	0.0	0.0	0.1	**0.1**
Total	**16.9**	**85.8**	**114.6**	**1191.6**	**1408.8**
Percent Share	**1.2**	**6.1**	**8.1**	**84.6**	**100.0**

Source: TC 2003, Table A7-1

This report documents project findings. Section 2 provides a review of literature relevant to understanding the implications of climate change for pavement infrastructure in southern Canada. First, a general review of pavement management practices and approaches in Canada is provided. This is followed by a synthesis of research into weather and climate sensitivities and adjustments and finally an account of completed research into the impacts of climate change. Section 3 of the report documents the approach, methods, data, and findings of impact analyses informed by the literature review and consultations with the engineering community. Results, conclusions and recommendations are discussed and presented in Section 4.

2.0 LITERATURE REVIEW

A literature review was conducted using standard Internet and library research tools supplemented by informal consultations with transportation engineering professionals. The synthesis and assessment of peer-reviewed journal articles and other technical literature was focused around the following themes which are elaborated in subsequent sections:

- pavement management in Canada, including engineering models and approaches used to monitor, assess and predict flexible pavement performance;
- effects of weather and climate on road infrastructure and pavement performance; and
- potential implications of anthropogenic climate change on pavement infrastructure.

2.1 Management of Pavements in Canada

Traditionally, the Canadian road network has been largely funded, constructed, operated and maintained by provincial/territorial transport ministries and local or regional municipal authorities. These agencies accounted for over 96 percent of government expenditure on road transportation in 2002-03, the remainder coming from federal programs. Over the past 20 years, government agencies have devolved many functions to the private sector. Increasingly, the role of government agencies is to establish standards and to manage and assure the quality of work contracted to private consultants and companies for design, construction, operation and maintenance services. In some jurisdictions (e.g., Alberta, Ontario), multi-year contracts are tendered for the operation and maintenance of entire sections of road networks for the duration of their service life. While this shift in organization generates economic efficiencies, it introduces additional "players" into the management of pavements and places a greater emphasis on standards, guidelines and quality assurance. Industry, stakeholder and professional engineering associations (e.g., Transportation Association of Canada, Municipal Engineers Association, AASHTO, etc.) actively participate with government agencies to meet this challenge by developing new standards, tools and technologies to address this emerging need for performance-based management.

Operationally, pavement management exists at the network and project (or section) levels for a given jurisdiction. The primary function at the network level is to acquire and evaluate data for component sections, determine needs and develop priority schedules for construction, maintenance and rehabilitation. As noted in Figure 1, network level decisions are driven by financing, budgets and agency policies (Haas, 1994).

The project or section level is primarily concerned with evaluating in detail those sections identified as requiring attention at the network level. Detailed technical decisions and designs for construction and maintenance activities involve the collection and analysis of site-specific data and are heavily influenced by standards and specifications, budget limits and environmental constraints.

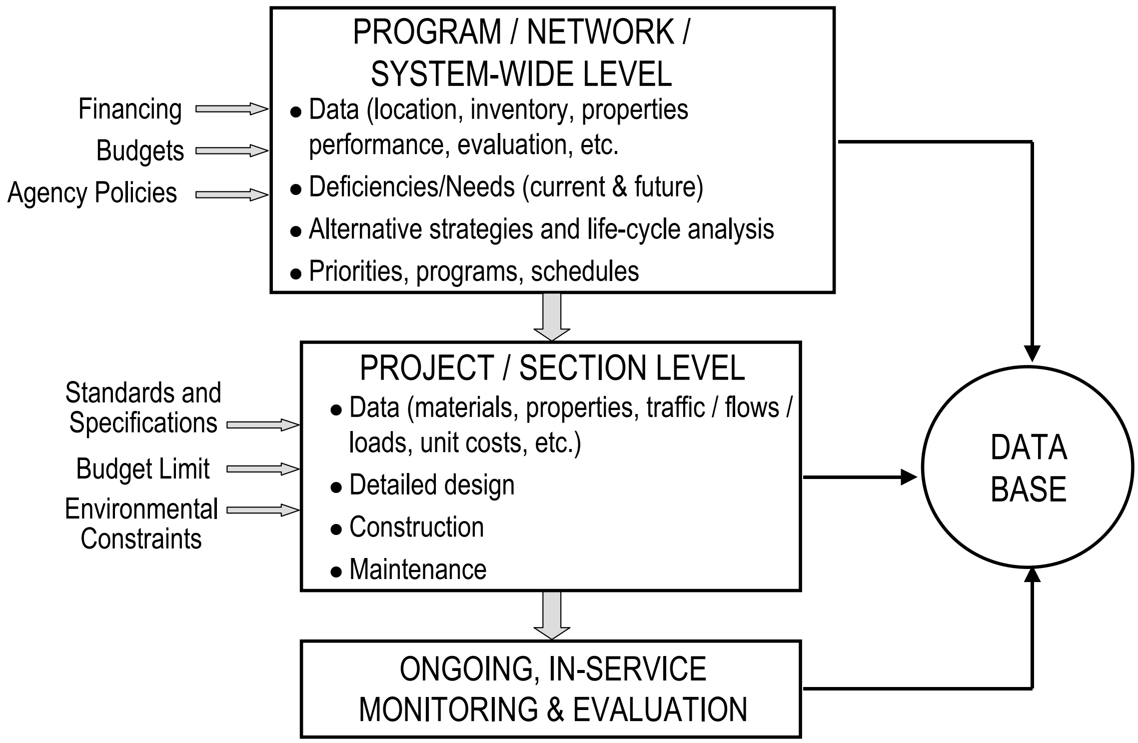


Figure 1. Operating levels for pavement management (Haas, 1997)

Measures of Pavement Performance

Assessing pavement performance involves measuring the ability of a particular section of pavement to meet the assumed needs of users—a comfortable, safe and cost-effective ride with minimal delay. A variety of measures of pavement performance have been identified in the literature, including those related to ride quality, surface distress, structural adequacy, surface friction, surface drainage, and noise as well as several composite indices (Tighe, 2001). These are described in the following sections and then integrated into a network-level life cycle cost effectiveness framework as proposed by Tighe (2001).

Ride Quality

The primary operating characteristic of road pavements is the level of serviceability or ride quality provided to users. Longstanding measures that have been used in North America are the Present Serviceability Index (PSI) and Riding Comfort Index (RCI), which are assessed on scales of 0 to 5 and 0 to 10, respectively (Tighe, 2001; Liu and Herman, 1996). Since these measures are subjective, correlations with summary statistics from objective, repeatable, high-speed profiling measurements are used for regional calibration purposes. One such statistic is the International Roughness Index (IRI), calculated by simulating a standard quarter-car passing over a longitudinal profile and measured in metres of vertical motion per kilometre of road length (Tighe, 2001; Haas, 2001). Paterson (1986) developed the following model, currently used in the South Carolina Pavement Management System, which relates PSI to IRI:

$$PSI = 5 * e^{-0.18\ IRI} \qquad (1)$$

Few studies have compared driver acceptability ratings or satisfaction with ride quality or surface distress indices (Hall, 2001)—and those that have show mixed results. For instance, Shafizadeh and Mannering (2003) observed that IRI values and maintenance thresholds match well to driver acceptability ratings in Washington State. However, based on a series of focus groups and sample surveys in three Midwest states, Giese *et al.* (2001) found that IRI and other pavement condition variables explained less than 5 percent of the variation in driver satisfaction.

Surface Distress

Most road and airport authorities periodically measure and evaluate the surface distress of their pavements. Distresses include ruts, various forms of cracks (longitudinal, transverse, alligator, block), patches, potholes, and ravelling. Many agencies have developed distress survey manuals (e.g., Texas DoT, Chen *et al.*, 2003) that establish protocols for measuring the type, severity, extent and location of the distresses. These should contain a comprehensive description and photograph of each distress type (typically 10-15), severity level (usually slight, moderate and severe), and density or extent (normally 2-5 levels). One of the more comprehensive manuals was developed through the Strategic Highway Research Program (SHRP, 1990).

Surface distress data can be used to establish a maintenance program whereby feasible treatment decisions are defined and prioritized in terms of the specific type, severity and density of distress (or combination of distresses). However, road, airfield, off-road area and other users generally place a low to medium level of importance on this measure, unless severe levels of rutting, pot holes, surface distortions, or cracking are encountered.

For an aggregate picture of paved sections, or the network as a whole, it is common to use a Surface Distress Index measure (SDI), on a scale of 0 to 10 or 0 to 5. Some agencies use a Pavement Condition Index measure (PCI), on a scale of 0 to 100. All of these indices use a "deduct number" approach, where any distresses that appear are deducted (on a weighted basis) from the maximum or perfect scores. As with ride quality indices, efforts have been made to understand the variability in subjective surface distress ratings (Goodman, 2001; Landers *et al.*, 2003) and to relate these indices to more objective standard measures like IRI (e.g., Dewan and Smith, 2002).

Structural Adequacy

Except in extreme cases of pavement collapse, the driving public and most other users are insensitive to changes in structural adequacy. However, structural adequacy measures are critical tools for engineers who manage pavements. The common procedure for evaluating structural adequacy is deflection testing, with the major device of choice being the Falling Weight Deflectometer (FWD) (AASHTO, 1993). While this mechanism is non-destructive to the pavement, FWD deflection data must be interpreted carefully to account for variations in damaged layers, pavement thickness and temperature (Mehta and Roque, 2003).

Deflection data are often used directly in the design of rehabilitation strategies. For evaluation purposes at the section or network level, deflection data can also be transformed into a Structural Adequacy Index (SAI) (Haas, 1994). The transformation works through establishing a maximum tolerable deflection (MTD) for the expected number of equivalent single axle loads (ESALs), and then comparing the measured deflection to the MTD. If they are equal, the SAI of the pavement is 5 (on a 0 to 10 scale). Deductions are assigned where measured deflections are greater than MTD (SAI<5) thus indicating a structurally inadequate pavement. Additions or bonuses are assigned when measured deflections are less than MTD (SAI>5), indicating a structurally adequate pavement. The SAI thus provides an aggregated measure for summarizing the structural status of a section or network. Similar in concept, the structural condition index also provides a relative measure of adequacy (Zhang *et al*., 2003).

Surface Friction, Drainage and Safety

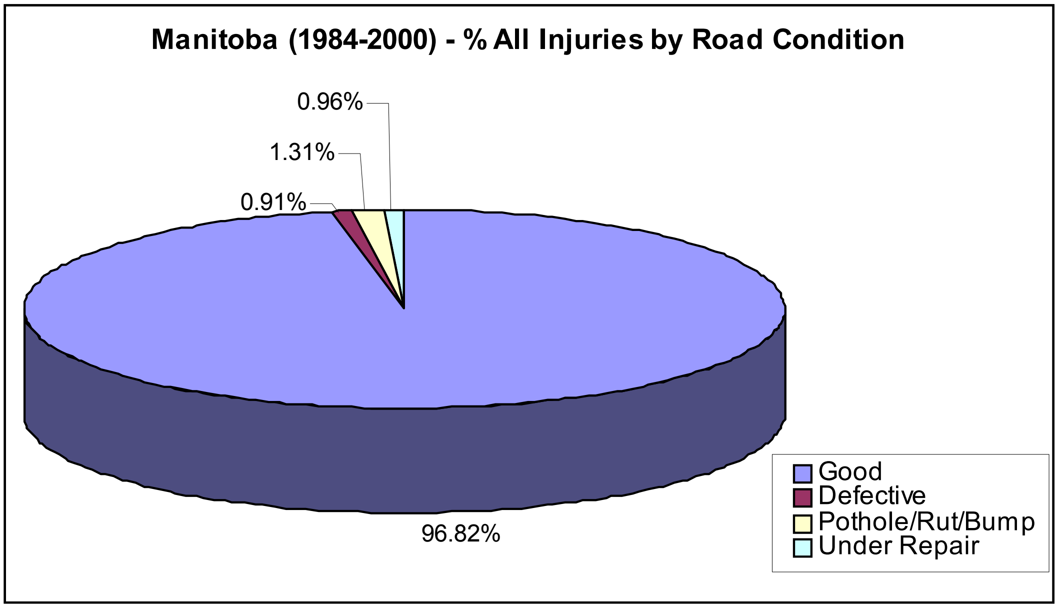
Surface friction is a measure of pavement safety and therefore of high importance to road and airfield users and managers. A function of the macrotexture and microtexture of the pavement, surface friction can be measured by a number of different methods (e.g., ASTM[3], AASHTO[4] and RILEM[5] standards). Over the past decade, efforts have been made to develop an integrated International Friction Index (IFI) (Fülöp *et al*., 2000). While surface friction data is important to pavement managers, particularly as a stand-alone "trigger" for maintenance or rehabilitation, few agencies publish minimum thresholds because of litigation risk. Many do not even collect such data on a network-wide basis. Instead, they identify and evaluate sections that may be more likely to develop low friction factors—as determined by examining accident history, historical skid resistance data, pavement material, road geometry, or reports from maintenance staff or the public (Innes *et al*., 1998).

Effective surface and internal pavement drainage are important to pavement performance and for reducing long-term maintenance costs (Birgisson and Ruth, 2003). While pavement engineers are concerned about both surface and internal drainage, drivers are most sensitive to the former, whether related to rainfall or melting snow. Standing water and visibility-impairing spray from other vehicles are perceived as factors that reduce the quality of the ride and affect safety (e.g., greater risk of dynamic hydroplaning) (Black and Jackson, 2000; Hassan *et al.*, 1998; Andrey *et al.* 2001). Normally, effective drainage is accomplished with sufficient crossfall and adequate slope to a drainage outlet—specific geometric design criteria are generally well-established (e.g., TAC, 1999). In addition, porous or open surface courses have found considerable use in that they can substantially reduce the amount of splash created by vehicles (Ranieri, 2002). While assessments of surface drainage characteristics are conducted as a normal part of post-construction or rehabilitation quality assurance, agencies do not systematically monitor for surface drainage problems over the long-term but rather rely upon reports from staff and the public to identify problem sections.

Surprisingly few studies have demonstrated a strong link between surface road condition and safety (Tighe *et al*., 2000; Andrey *et al*., 2001) let alone defined the independent, confounding or synergistic effects of weather (e.g., road wetness, snowcover, ice, etc.) and non-weather (e.g., pre-existing macrotexture, microtexture, rutting, etc.) elements. This is partly attributable to the fact that primary network roads are maintained to standards above minimum threshold friction levels. For instance, collision data derived from police accident reports for Manitoba imply that more than 96 percent of injuries (and injury collisions) occur on good roads (Figure 2). While there is evidence of an inverse, statistically significant relationship between collision incidence and friction, regression models are limited in their capability to explain wet-weather collision incidence for small spatial and temporal units (Herman, 1984; Xiao *et al.*, 2000, Andrey *et al*., 2001). In addition to friction,

[3] American Society for Testing and Materials (now ASTM International)
[4] American Association of State Highway and Transportation Officials
[5] 'Réunion Internationale des Laboratoires et Experts des Matériaux, Systèmes de Constructions et Ouvrages

researchers have examined the effects of rutting and surface roughness on collisions. Start *et al.* (1998) analyzed rut depth, traffic volume and collision data for rural highways in Wisconsin and reported significant increases in accident rates as average rut depths[6] exceeded 7.6mm. A Jordanian study of rural roads revealed significant positive and negative relationships between IRI levels and multi-vehicle and single-vehicle accident rates, respectively (Al-Masaeid, 1997).



Source: TRAID (Transport Canada)

Figure 2. Manitoba motor vehicle collision injuries reported by road condition (1984-2000)

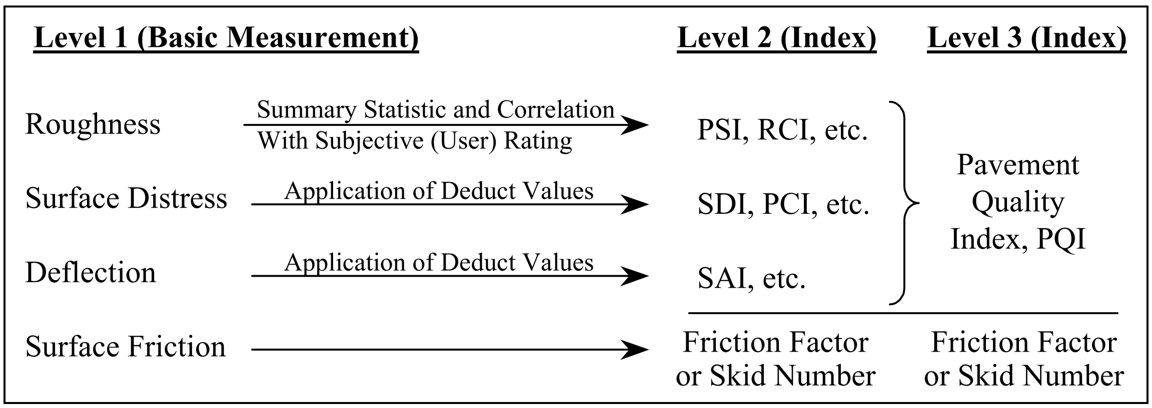
Noise

Noise levels are important to vehicle occupants and to people living or working in buildings and neighbourhoods adjacent to roads (Walton *et al*., 2004; Kaku *et al*., 2004; Ohrstrom, 2004). The degree of noise is a function of vehicle type (including tire qualities), operating speed and acceleration, and characteristics of the road surface (roughness, texture pattern and degree of porosity) (Phillips, 2002). Several methods have been developed to evaluate and predict road noise, including standardized instrumented roadside and tire measurements (e.g., statistical pass-by, Phillips, 2002) and simulation software designed to model noise as a function of vehicle type, traffic flow, pavement characteristics, topography, weather and a range of noise-buffering interventions (e.g., FHWA TNM®, Lee and Rochat, 2002; Berengier and Anfosso-Ledee, 1998). The most commonly used unit of sound measurement is the A-weighted pressure level (dBA) which corresponds to the range of frequencies to which humans are most sensitive (about 1,000 to 10,000 Hz). It is usually expressed as an accumulation of sound energy over the period of interest and normalized to 1 second. Increasingly, new pavement technologies and rehabilitation/maintenance procedures are being developed to control excessive noise (e.g., porous asphalt, Gołebiewski *et al*., 2003).

[6] average rut depth for both directions of 1.8km segments was unit of analysis

A Combined Index to Measure Customer Benefits

Tighe (2001) proposed aggregating data acquired from many of the in-service measurements reviewed previously into a multi-level index to measure benefits to drivers and other customers (Figure 3). The first level consists of direct field measurements, while the second level involves a transformation of these values into a series of indices which are explained in detail by Haas (1994). The final level consists of aggregating all three individual indices into an overall composite, such as Pavement Quality Index (PQI). Due to its significance for safety concerns, surface friction is maintained as a stand-alone measurement. Although information is lost at each level of aggregation, a single composite index serves as an effective tool for communications with senior administrators, elected officials and the public.



Notes: PSI (Pavement Serviceability Index), RCI (Ride Comfort Index), PCI (Pavement Condition Index), SAI (Structural Adequacy Index), PQI (Pavement Quality Index)

Figure 3. Levels of aggregation for measures of customer benefits (Tighe, 2001)

Life Cycle Cost Effectiveness

Measures of pavement performance are important inputs to Life-Cycle Cost Analysis (LCCA). LCCA provides a means to establish the relative cost-effectiveness of flexible pavement maintenance and rehabilitation options at the project and network scales and is thus an important aspect of pavement asset management (Haas *et al*., 1994; Vadakpat *et al*., 2000). General best practices or recommended procedures for conducting LCCA have been published (e.g., FWHA, Wall and Smith, 1998) and other researchers have described complementary or alternative probabilistic and optimization approaches (Tighe, 2001; Ouyang and Madanat, 2004; Abaza, 2002; Li and Madanat, 2002). Recent advances in information technologies are making the entire process of LCCA and pavement management more efficient, cost-effective, standardized and thus operational at the provincial, state and local agency or operator levels (e.g., Tsai and Lai, 2002).

For public transportation agencies, an appropriate way to maximize customer benefits is to maximize life-cycle cost effectiveness of funds expended on the entire pavement network, as summarized by Tighe (2001) in the following four key steps:

1. determining pavement needs,
2. identifying treatment alternatives,
3. calculating life-cycle cost-effectiveness, and
4. optimizing and identifying priority programs.

Step One: Determining Pavement Needs

Pavement needs or deficiencies are determined in terms of one or more of the pavement performance measures introduced in the previous section (i.e., roughness, or some index such as IRI, PSI or RCI; surface distress, or some index such as SDI or PCI; deflection, or some index such as SAI; surface friction; or a combined index, such as PQI) (Tighe, 2001). Specific criteria or thresholds may vary by type and functional class of road, size of the paved road network, and the resources, budget and policies of a particular agency. It has been acknowledged that these measures and associated criteria are designed to reflect rehabilitation rather than preventive maintenance needs (Zimmerman and Peshkin, 2003).

Once criteria are established, performance or deterioration models applicable to both new pavement structures and rehabilitated pavements are required to identify when and where particular sections within the network may require maintenance or rehabilitation (Tighe, 2001). It is generally assumed that pavement performance can be adequately measured in terms of these criteria and that future conditions can be predicted with adequate knowledge of current pavement conditions, pavement thickness, material properties, cumulative traffic load and environmental conditions (Hong and Somo, 2001). Several examples of deterioration models are identified later in this report.

When a pavement section reaches the limit specified (e.g., PSI of 2.0 for collector roads), it becomes a need. However, the needs year is only one of several possible action years—interventions can be made at any point along the deterioration curve (Figure 4) and therefore defer or advance rehabilitation. At the network level, there are many possible combinations of sections, action years and rehabilitation alternatives, and thus a priority analysis is required to determine which combinations represent the best overall value for the available budget (Haas, 2001).

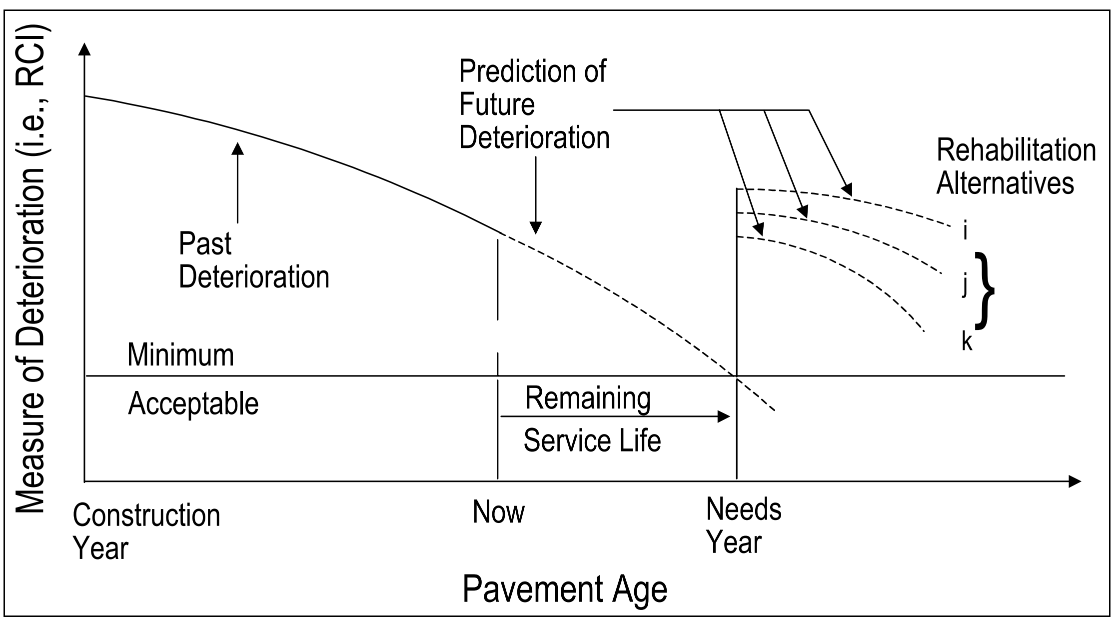


Figure 4. Needs year and possible action years for pavement rehabilitation (Haas, 2001)

Step Two: Identifying Treatment Alternatives

Treatment alternatives for deteriorated pavements include rehabilitation, preventive maintenance (such as chip seals, slurry seals, crack sealing, thin overlays), and corrective maintenance (such as hot- and cold-mix patching). Preventive and corrective actions are usually taken at levels of pavement deterioration considerably above or below the tolerable limits, respectively.

Because the number of practical or feasible treatment alternatives for any particular situation is usually limited, a decision process ranging from simple judgement to a decision tree or expert systems approach is commonly used for screening purposes. Those treatments that are feasible are then considered in the priority analysis (Tighe, 2001).

Step Three: Life-Cycle Cost-Effectiveness Calculations

In order to compare any set of treatment alternatives for a given section and timing combination, a life cycle analysis is required. The following types of costs have been identified and considered in the literature (Tighe, 2001; NCHRP, 2004a):

1. Cost of the actual rehabilitation and maintenance work that occurs within the life cycle, minus the residual value at the end of the life cycle;
2. Vehicle operating costs;
3. User delay costs;
4. Accident costs due to traffic hazards or interruptions associated with the rehabilitation or maintenance; and
5. Environmental damage (e.g., air, water, and noise pollution).

The direct costs of rehabilitation and maintenance are relatively straightforward to calculate as they can be estimated from actual capital, material, equipment and labour expenditures made by agencies. Vehicle operating costs (VOCs) consist of fuel, oil, maintenance, tires, and mileage-related depreciation (Vadakpat *et al*., 2000) and vary with road roughness. For example, Dewan and Smith (2002) estimated IRI from pavement distress data (PCI) to calculate vehicle operating costs for the San Francisco Bay area. Although related to roughness, VOCs are also influenced by differences in vehicle fleets and factors that affect travel demand and thus must be calibrated to specific regions (Tighe, 2001).

User delay costs can be substantial for interruptions on high volume roads—even greater than the cost of the rehabilitation or maintenance project (Haas, 2001). Costs may be broken into three main components: 1) time costs and inconvenience to road users, vehicle occupants and others who detoured or were denied use of the road; 2) extra shipment or inventory-carrying costs; and 3) extra VOCs (Tighe, 2001; Vadakpat *et al*., 2000). Al Assar (2000) described a simplified user delay cost model that can be used to assess various traffic management plans, traffic volumes, and other scenarios. Orders of magnitude differences in costs (US$250-375,000) were demonstrated for a typical 2-lane highway resurfacing project by comparing two traffic control plans and two Annual Daily Traffic (AADT) volumes (5k and 10k vehicles/day).

Accident costs, environmental damage and non-user costs in general are very difficult to reliably quantify in economic terms at scales appropriate for inclusion in pavement LCCA (Vadakpat *et al*., 2000). While undoubtedly real, in the absence of credible estimates, most agencies omit or only qualitatively refer to these costs when performing LCCA (Tighe, 2001).

When comparing various options, most road agencies express costs and benefits on a present worth basis (NCHRP, 2004a) whereby all future costs are discounted back to the present, as follows:

Present Worth of Costs=Future costs x PWF (2)

Where:
PWF= present worth factor = $1/(1+i)^n$
n = number of years to when the cost or benefit is incurred
i = discount rate

For example, if the cost of alternative k at year A is $100,000 per lane-km, A is 3 years from now and i = 5%, then the present worth of cost would be $100,000 x $[1/(1+0.05)^3]$ = $80,600. The relative effectiveness between a rehabilitation treatment and deferred rehabilitation option can be considered as the net area beneath the deterioration curve, as illustrated in Figure 4, multiplied by section length and by traffic volume. It is, therefore, directly proportional to benefits, and can be used as a surrogate. If effectiveness is divided by cost, it can be used as a “cost-effectiveness” measure (Haas, 1994).

Step 4: Optimization and Priority Programs

True optimization would identify the best possible combinations of treatment alternatives for the identified sections and timing over a specified program period and for a specified budget (e.g., Ouyang and Madanat, 2004). Priorities can also be defined using less sophisticated methods, including the simple ranking of sections on a subjective basis. However, this may result in programs that are far from optimal. A particularly convenient method, which is close enough to true optimization for practical purposes, is that of marginal cost-effectiveness (FHWA, 1990). It considers all of the possible combinations and is being used by a substantial number of state, provincial and local agencies.

2.2 Impact of Climate and Weather on Pavement Performance and Deterioration

Weather and climate factors interact with traffic, construction, structural and maintenance characteristics to influence pavement deterioration and performance (Figure 5). Theoretically, it should be possible to discern the relative and interactive effects of these variables; however, in practice this remains a significant research challenge (Haas, 2001). Nevertheless, engineers have developed many empirical and mechanistic-empirical approaches to model pavement performance or underlying deterioration mechanisms as a partial function of these variables. Climate has been identified as an important consideration in three processes: thermal cracking, frost heave and thaw weakening, and rutting.

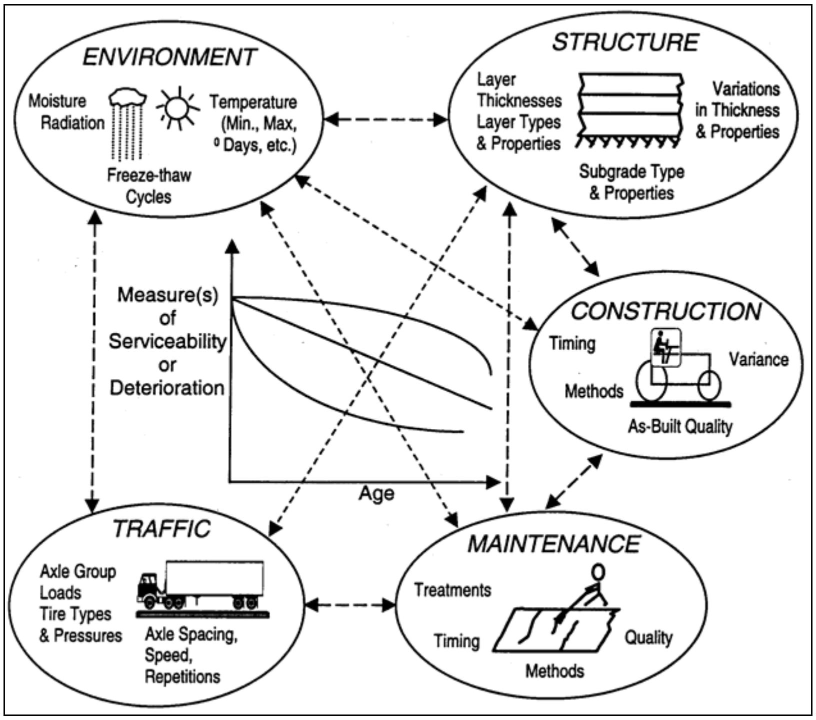


Figure 5. Factors affecting road performance (Haas, 2004)

Thermal Cracking

Thermal cracking is a type of distress that affects the structural (load-carrying capacity) performance of a pavement. There are two main types of thermal cracking. The first type is low-temperature transverse cracking where cracks follow a course approximately at right angles to the pavement centre-line and tend to be regularly spaced along the length of the road (Shenoy, 2002). The second type is thermal fatigue cracking which is triggered by the degradation of pavement material properties due to aging and accumulated residual stresses due to a large number of thermal loading cycles. Extensive cracking leads to reductions in ride quality and facilitates the movement of water, air and fine particles through the pavement structure, thereby accelerating deterioration, further reducing ride quality and increasing maintenance and rehabilitation requirements (Sebaaly *et al*., 2002; Tighe, 2001; Epps, 2000; Shen and Kirkner, 2001; Konrad and Shen, 1997). Cracking is an important component of surface distress indices—in deterioration models it is most often measured in terms of total crack length per unit of road length or area. Field data are often complemented with laboratory tests such as the Thermal Stress Restrained Specimen Test (TSRST) and Indirect Tensile Creep Strength Test (ITCST) (Raad *et al*., 1998).

Thermal cracking is significantly influenced by material homogeneity, ductility of asphalt concrete, frictional constraint on the interface between pavement layers, and the rate of cooling (Shen and Kirkner, 2001). As temperatures cool and pavement contracts, frictional constraint and tensile stress build up until the stress exceeds the tensile strength of the pavement resulting in cracking (Raad *et al.*, 1998; Sebaaly *et al*., 2002). Asphalt thickness, minimum temperature, coefficient of thermal contraction, and temperature susceptibility of the AC have been shown to significantly affect the spacing of cracks (Haas *et al*., 1997; Raad *et al*., 1998). While critical temperature thresholds will vary depending on pavement characteristics, Epps (2000) observed that low temperature cracking generally occurs at temperatures below -7°C, especially when the rate of cooling is rapid, while thermal fatigue cracking most commonly occurs through the accumulation of daily thermal cycles or loads between -7°C and 21°C.

The extreme fracture temperature of a pavement hardened through age may be 10°C warmer than for new asphalt (Konrad and Shen, 1997; Kliewer, 1996). Age-hardening can be exacerbated by extreme maximum pavement temperature. While extreme minimum temperature and thermal load cycle thresholds seem to trigger cracking, some have observed that the maximum temperature reached in pavements during service may be a major factor controlling the ultimate level of age-hardening in the field (Kliewer *et al*., 1996). Higher temperatures potentially lead to premature age-hardening and a more brittle pavement that is more prone to low temperature cracking. Easa *et al*. (1996) caution that aging, penetration and softening point models may not be reliable beyond 8 years of pavement life.

Others note the significance of a related process, micro-cracking, which is largely a function of differing thermal contraction coefficients between the asphalt matrix and aggregate at low temperatures (El Hussein *et al*., 1998). Pavement durability is reduced as hairline cracks deteriorate the asphalt-aggregate interface and lower the fracture toughness of AC. Extensive stripping is possible once moisture gains entry through hairline cracks (Hussein *et al*., 1998; TRB, 2004).

Weather conditions also influence maintenance activities, especially the effectiveness of sealants used to repair cracked pavements. Cold temperatures have been associated with increased frequencies of premature de-bonding and pullout of bituminous crack sealant (Masson *et al*. 1999).

Frost Heave and Thaw Weakening

Frost heave and associated thaw weakening are likely the most important climate-related processes that affect pavement deterioration in Canada. However, there is no up-to-date, comprehensive review[7] of the implications of freeze-thaw cycles and deep-frost penetration for pavement performance—from either a methodological or costing perspective.

Frost heave is the rise in a pavement surface caused by the freezing of pore water and/or the creation of ice lenses in the underlying layers (TAC, 1997). Heaving is mostly an issue for poorly

[7] A study that considers the effects of multiple freeze cycles and deep frost penetration on pavement performance is currently being conducted by Nichols Consulting Engineers, under contract U.S. DTFH61-02-D-00139, using Longterm Pavement Performance (LTPP) data.

constructed primary or secondary roads that have fine-grained subgrades and are located in regions that experience frequent freeze-thaw cycles and high amounts of precipitation (Haas *et al*., 2004; Tighe *et al*., 2001). Low-volume roads in seasonal frost areas[8] are particularly vulnerable (Kestler, 2003). Doré (1995) developed a cracking model for frost conditions that takes into consideration the frost susceptibility of the subgrade soil, freezing index, precipitation, and the total thickness of the structure. He suggested that cracking in frost conditions is a two-phase phenomenon. The first phase is initiation during which pavement resists frost heave induced stresses. The second phase is crack propagation, which begins as soon as the first crack appears. Heaving-related damage is also reflected in surface roughness which can be interpreted from the longitudinal profiles of pavement sections (Fradette *et al*., 2005). Doré (2002) studied the profile wavelengths of 24 Canadian Long Term Pavement Performance (C-LTPP) sites. He observed that longer wavelength distortions (>8m) were common for sections with high fines content and indicative of frost-related subgrade deformation or displacement (Doré, 2002).

Few, if any, road deterioration models incorporate the number of freeze-thaw cycles as an independent variable[9], despite its obvious importance in frost-related action (Haas *et al*., 2004). A notable exception is an analysis of results from the AASHTO road tests (White and Coree, 1990). Many models do make use of a "freezing or frost index", which provides a measure of the air temperature throughout the freezing period. The freezing index, along with soil properties (e.g., porosity, density, saturated permeability, coefficient of uniformity/curvature, hydraulic conductivity, moisture retention), can be used to predict depth of frost penetration (e.g., through the modified Berggren equation, CRRL, 2002), extent of frost cracking (e.g., Joint CSHRP/Quebec Bayesian Application Project, 2000a) and site effects in pavement deterioration models (e.g., Raymond *et al*., 2003). In most applications, the frost index is calculated as an additive value based on seasonal data or longer-term climatic averages:

$$FI = \Sigma\,(0°C - T_d), \qquad (3)$$

where:
FI (frost index);
$T_d<0$;
T_d (mean daily temperature).

Early work showed that there was a logarithmic relationship between the index calculated in this way and depth of frost penetration (e.g., Brown, 1964). Alternatively, Boutonnet *et al.* (2003) and others have calculated the frost index as the difference between the maximum and the minimum of the cumulative degree-C days below zero for a season.

One limitation of the frost index, and other environmental variables derived from climatic data, is that it does not adequately capture the sequencing of weather events (Uzan, 2004). Indeed, it is possible to obtain the same index value when a site experiences one long cold spell as when it experiences several short cold spells (Sherwood and Roe, 1986)—despite the fact that these different weather scenarios have different implications for pavement performance. The treatment of climate data in design (i.e., sampling frequency, averaging) also may have important effects on pavement design life. Zuo *et al*. (2002) showed that pavement life could be overestimated by 50-75 percent if hourly temperatures are aggregated into monthly averages. Thus, additional research is

[8] In Kestler (2003), seasonal frost areas defined as areas that experience an average T <=0°C in any calendar month at least once in 10 years; or where frost penetrates to a depth of 0.3m at least once in 10 years
[9] it is most often handled through regional calibration (Haas et al. 2004)

required to critically assess the relevance of the frost index and other variables to vulnerability assessments and pavement performance practices, and possibly to develop modified/alternative indices.

There is growing evidence that a large proportion of frost-related damage occurs during the thawing period. Many empirical and mechanistic-empirical models have been developed to predict the strength of pavements and constituent layers—all invariably demonstrate that minimum pavement strength, usually measured in terms of resilient moduli based on FWD data, corresponds with spring thawing and heightened water content of the unbound layers (Samson and Fréchette, 1995; Simonsen *et al*. 1997; Jong *et al*. 1998; Watson and Rajapakse, 2000; Birgisson *et al*., 2000; Marshall *et al*., 2001; Heydinger, 2003; Uzan, 2004; Haas *et al*., 2004). Conversely, the strongest pavement conditions are realized when the pavement structure is completely frozen and relatively free of moisture. Precipitation (total accumulation and event frequency) has been shown to be important for damage because it affects water availability (e.g., CSHRP/Quebec roughness models (2000) were found to be sensitive to precipitation amount).

Several jurisdictions currently use a "thawing index" to predict the penetration of thaw and the onset of thaw weakening as a basis for SLRs and WWPs (e.g., C-SHRP, 2000; Manitoba Transportation and Government Services, 2004; Minnesota DOT, 2004; Clayton *et al.*, 2006, Montufar *et al.*, 2006; Huen *et al.*, 2006). Others recommend a mechanistic approach based on in-situ measurements (Montufar and Clayton, 2002). The implications of not posting SLRs or removing WWPs are significant—Minnesota research suggests that being one week late in posting SLRs or one week late in removing WWPs could shorten pavement life by 4-12 percent (Montufar and Clayton, 2002).

Thawing indices are a relatively recent management tool and tend to be region-specific. There is a need to critically assess their usefulness in pavement performance and to develop a rigorous approach for regional calibration and comparison. For Manitoba conditions, Watson and Rajapakse (2000) related resilient moduli of the asphalt concrete, base and subbase layers to air and pavement temperature. Once thawing commenced, a summation of hourly temperature values above 0°C produced a suitable index—the inclusion of below-zero temperatures resulted in very poor correlations with resilient moduli. They concluded that the strength of pavement varies considerably when temperatures are below 0°C (5000 times stronger at -20°C relative to 0°C) and only weakens slightly as temperature increases beyond freezing. The most critical period of weakest pavement conditions was found to occur when the asphalt temperature exceeds 0°C and the unbound (base) layers are melting—a condition that developed in the case study after the thawing index reached 823°C•h (Watson and Rajapakse, 2000).

Several studies have attempted to develop empirical relationships between environmental variables and pavement performance measures. Hong and Somo (2001) examined data from Brampton, Ontario and showed that mean RCI was significantly affected by uncertainties in subgrade modulus and the actions of traffic and environment. Insufficient consideration of these uncertainties could lead to unrealistic estimates for timing of appropriate maintenance or rehabilitation actions.

Rutting

Rutting is a distortion occurring in the wheel paths of an asphalt concrete (AC) pavement (TAC, 1997). It results from densification and permanent deformation under the load, combined with displacement of pavement materials, and affects the "functional" performance (i.e., ride quality and safety) of a pavement (NCHRP, 2004). It has also been used as a primary indicator of the structural performance of pavement (Archilla and Madanet, 2001). In deterioration models (e.g., NCHRP, 2002a, 2002b; NBDOT, 1995, Ramia *et al*., 1995; Collop *et al*., 1992), rutting is normally expressed as a depression depth relative to the plane of the pavement surface.

Rutting may be caused by several factors, including unstable asphalt mixes resulting from high temperatures, high asphalt content, or low binder viscosity (MTO, 1989; Archilla and Madanat, 2001). Rutting is a common form of distress where heavy traffic loads coincide with high in-service temperatures (Nikolaides, 2000; Uzan, 2004). As asphalt temperatures increase, the stiffness of the AC decreases making it more prone to deformation under wheel loads (Marshall *et al*., 2001; Prozzi and Madanat, 2003). The effect of temperature on pavement strength (AC moduli) exhibits hysteretic qualities—it varies depending on whether the profile is cooling (lower layers remain relatively soft) or heating (lower layers remain relatively stiff) (Park *et al*., 2001). Rutting may also initiate within base and subbase layers underlying the asphalt and serve as the primary form of distortion when thaw-weakened pavements, as described in the previous section, are subjected to heavy loads.

As suggested earlier, the timing and sequence of environmental conditions may play a significant role in determining long-term deterioration patterns. For example, Mishalani and Kumar (2005) observed that both warmer and colder temperatures during the first few years after initial construction positively impacted long-term rutting due to the less hardened pavement in the early stages of its life. Moreover, the sensitivity of rutting to design grows with increasing early warm temperature and decreasing early cold temperature, while the sensitivity to material quality decreases. These results imply that for a constant long-term average temperature, the higher year-to-year variation in temperature, the more likely that the adoption of a higher design level would be more beneficial.

2.3 Potential Impacts of Climate Change on Pavements

Members of the research team have spent considerable time reviewing the issue of climate change and potential impacts on transportation in Canada (Andrey and Snow 1998, Andrey *et al*. 1999, Andrey *et al*., 2004, Mills and Andrey 2003). This work suggests that relatively little or no research has been conducted linking climate change to the future state of Canadian road and pavement infrastructure despite the substantial asset value of the road system, the dependence of Canadian economic and social activity on road transport, and the documented influence of climate and other environmental factors on the deterioration of pavements (e.g., see previous section; Nix *et al*. 1992, Haas *et al*. 1999).

Building on the findings and recommendations of the research noted above and other sector scoping studies (e.g., Irwin, 1988; Moreno 1995), much of the attention regarding possible climate change impacts on Canadian roads has focused on infrastructure underlain by sensitive permafrost (e.g., Beaulac *et al*., 2006; Arenson *et al*., 2006; Ciro and Alfaro, 2006; Wright *et al*., 2002; Smith *et al*., 2001; Brennan *et al*., 2001). Regional analyses of varying levels of sophistication on the impacts of temperature changes for seasonal (snow/ice) roads and seasonal load restrictions on paved highways have also been initiated (e.g., Hinzman *et al*., 2005; Instanes *et al*., 2005; Clayton *et al*., 2006; Montufar and McGregor, 2006). Haas *et al*. (2004) provide an overview of these and other climate change-related issues for the maintenance and lifecycle costs of paved and other road infrastructure. While many factors affect the onset, rate, nature and impacts of pavement deterioration (summarized in Figure 5), it is still possible to isolate climate-related influences as generally shown in Table 3.

Table 3. Factor Effects on Road Deterioration and Costs: Paved Roads (Haas *et al*., 2004)

Factor	Remarks	Maintenance Costs	Life-Cycle Costs
Increased freeze-thaw cycles	Increased rate of deterioration and shortened service life, particularly in areas of fine grained (frost susceptible) soils	Higher	Higher
Increased flooding and wash-out	More frequent replacement	Higher	Higher
Increased slope failures	More frequent repairs	Higher	Higher
Thermal degradation	a. Existing discontinuous perma-frost zone will be reduced	Little change	Little change
	b. Existing continuous perma-frost zone will be reduced (part will become discontinuous)	Higher	Higher
Precipitation increase	More skidding accidents and accelerated moisture damage to pavement	Higher	Higher
Precipitation decrease	Less of above	Lower	Lower
Icing increase	More accidents	Little change	Little change
Icing decrease	Less accidents	Little change	Little change

Haas *et al*. (2004) state that the major climate change-related factor affecting road deterioration and in turn costs, is freeze-thaw cycles associated with changes in temperature. It is well recognized that a high number of freeze-thaw cycles can accelerate road deterioration (He *et al*., 1997). This is particularly the case where a frost susceptible subgrade and a high amount of precipitation exist, as shown in results presented in Figure 6 from a study by Tighe *et al*. (2001). The study initiated through the Canadian Strategic Highway Research Program Long Term Pavement Performance experiment (C-LTPP) examined multiple pavement sections of various thicknesses in 24 provincial sites. Performance trends, in terms of roughness progression[10] and associated trigger levels for repair/rehabilitation, were examined in terms of several factors, including climatic zone. Should conditions under climate change trend from a dry, high freeze environment (e.g., typical of northern Alberta) to a wet, low freeze environment (e.g., typical of southern Ontario) then more rapid pavement deterioration might be expected assuming no counter-measures are taken.

[10] Roughness profile measurements are transformed into a summary statistic, International Roughness Index (IRI) using a quarter car simulation and appropriate filters (TAC 1997).

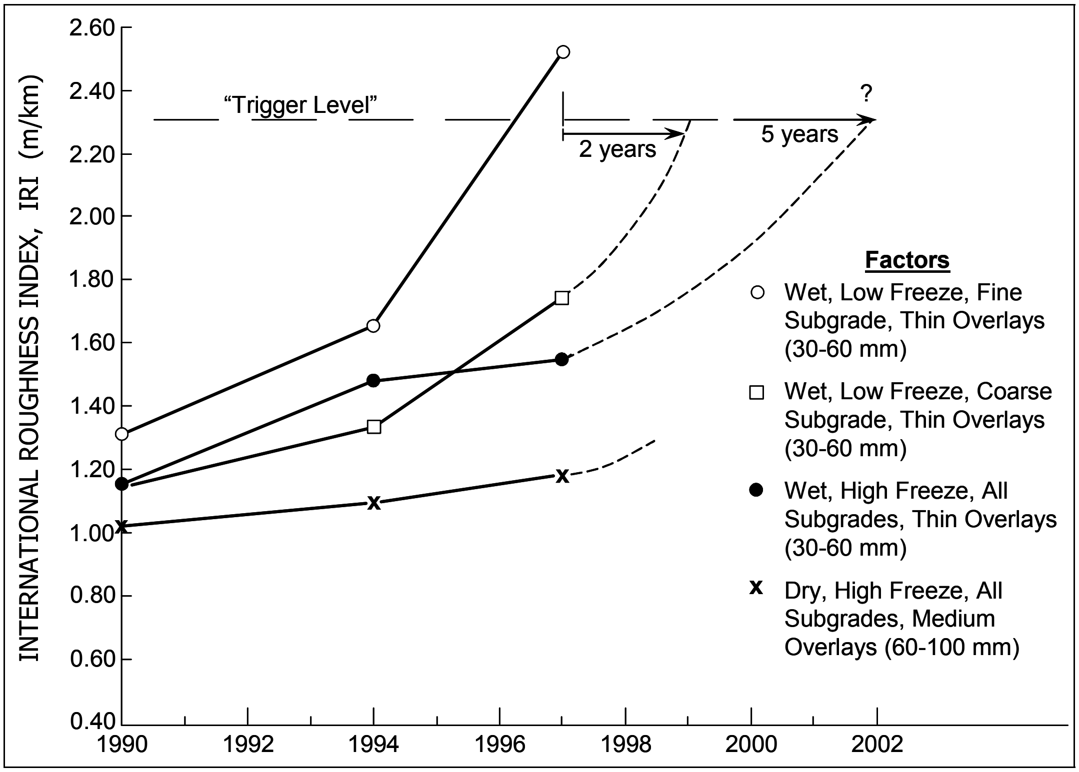


Figure 6. Roughness progression comparisons from Canadian strategic highway research program, Long Term Pavement Performance (C-LTPP) experiment (Tighe *et al.*, 2001)

The only substantive national assessment of the impact of climate change on road infrastructure uncovered during this project was completed for Australia (Austroads, 2004). Austroads, an association of Australian and New Zealand road transport and traffic authorities, and several research partners, used climate change scenarios developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Atmospheric Research to assess the direct temperature and moisture impacts on pavement deterioration and associated costs. These scenarios were also applied to examine impacts associated with increased groundwater salinity and the indirect effects of climate change on the location of future population growth and related changes in the demands for road transportation. Riverine and coastal flooding issues were acknowledged but not thoroughly treated in the formal analysis.

Climate change impacts on pavement deterioration were determined by Austroads (2004) at network and section levels. At the network level, the AARB Transport Research Pavement Life Cycle Cost model (PLCC) was used to predict pavement roughness as a function of average annual maintenance expenditure, pavement age, cumulative Equivalent Axle Loads (ESAs) and an index of moisture (Thornthwaite Index). Pavement roughness was then used to estimate life cycle maintenance and rehabilitation costs for road agencies and road user costs (travel time, VOCs). The model incorporates treatment strategies that, within roughness and budget constraints, minimize the present value costs. Analyses were conducted over a 60-year period for 60 different section types across the country. The Highway Development and Management 4 (HDM4) model was used to analyze impacts in greater detail for sample pavement sections in each Australian state and territory. HDM4 required much greater data needs as its algorithm includes functions to predict pavement roughness and strength plus many of the individual deterioration mechanisms (e.g., cracking, potholing, rutting, ravelling, etc.) discussed previously.

The Austroads (2004) analysis revealed that the direct impacts of climate change on future road infrastructure maintenance and rehabilitation costs will be marginal, whether in the Northern Territory, where a warmer and much wetter climate can be expected, or elsewhere where the warmth may be accompanied by much drier conditions. Indirect impacts of climate change, through changes in traffic, lead to greater absolute road user costs in some states. However, it must be noted that future population growth was assigned to different regions subjectively using changes in future comfort index (i.e., changing climate drives migration which then influences traffic loads).

3.0 IMPACT OF CLIMATE VARIABILITY AND CHANGE ON CANADIAN PAVEMENT PERFORMANCE: CASE STUDIES

General methods for assessing the potential impacts of climate change on various aspects of society, economy and environment have been developed over the past two decades, largely based on approaches rooted in applied climatology or the hazards and risk assessment literature (Kates, 1985; Burton *et al*., 1993; Bruce *et al.*, 2001). The leading international source of guidance on climate change impact assessment is the Intergovernmental Panel on Climate Change (IPCC), an organization that is responsible for periodic reviews of the scientific literature on aspects of climate change science, impacts and adaptation assessment, and emissions mitigation (IPCC, 2001, 2007). Carter *et al*. (1994) and IPCC-TGCIA (1999) propose several generic steps in a framework to guide climate impacts and adaptations assessment: 1) problem definition, 2) selection of method, 3) testing of method, 4) selection of scenarios, 5) assessment of biophysical and socio-economic impacts, 6) assessment of autonomous adjustments, 7) evaluation of adaptation strategies. While this study implicitly focuses on steps 1 through 5, important adaptation issues are introduced in the discussion, conclusion and recommendation sections (Sections 3.3., 4.1., 4.2).

The review of pavement design and management practices and engineering models and approaches used to monitor, assess and predict flexible pavement performance revealed that climate—and thus potentially climate change—is an important consideration in at least three deterioration processes: thermal cracking, frost heave and thaw weakening, and rutting. Two sets of case studies were undertaken in this research to investigate these generalized impacts of climate change in greater detail. The first involved examining deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure. The second set of case studies were conducted using the Mechanistic-Empirical Pavement Design Guide (MEPDG) and software, a new tool developed through the Unites States NCHRP/AASHTO. A description of each set of studies, including underlying methods, data requirements, and results is provided below.

3.1 Analysis of Deterioration-relevant Climate Indicators

Three deterioration-relevant climate indicators were chosen to illustrate the potential effects of climate change on an aspect of each of the processes outlined in the previous section:

- extreme minimum daily temperature;
- 7-day average maximum daily temperature; and
- freezing and thawing indices.

The first two are important indicators of climatic conditions conducive to thermal cracking and rutting, respectively, and are applied in the selection of appropriate asphalt binders. Freezing and thawing indices are useful indicators of frost/thaw depths and thus pavement strength; they are particularly important in managing traffic loads.

Analysis of Climate Change Impacts

The analysis of potential climate change impacts consisted of several steps that are outlined in Figure 7 beginning with the identification of 17 Canadian study sites (Table 4). The primary criteria for selection were location (southern Canada), proximity to test sections in the Long Term Pavement Performance (LTPP) program (more relevant for the MEPDG analyses), and availability of daily records of temperature[11]. Most of the selected sites are airport locations. Collectively the Census Metropolitan Areas (CMAs) or Census Agglomerations (CAs) represented by the sites include over 53 percent of the Canadian population and encompass a wide range of the environmental conditions experienced in southern Canada. Baseline time series of daily minimum, maximum and mean temperature data for the period 1951-2001 were obtained from the Environment Canada climate archive for each of the sites listed in Table 4.

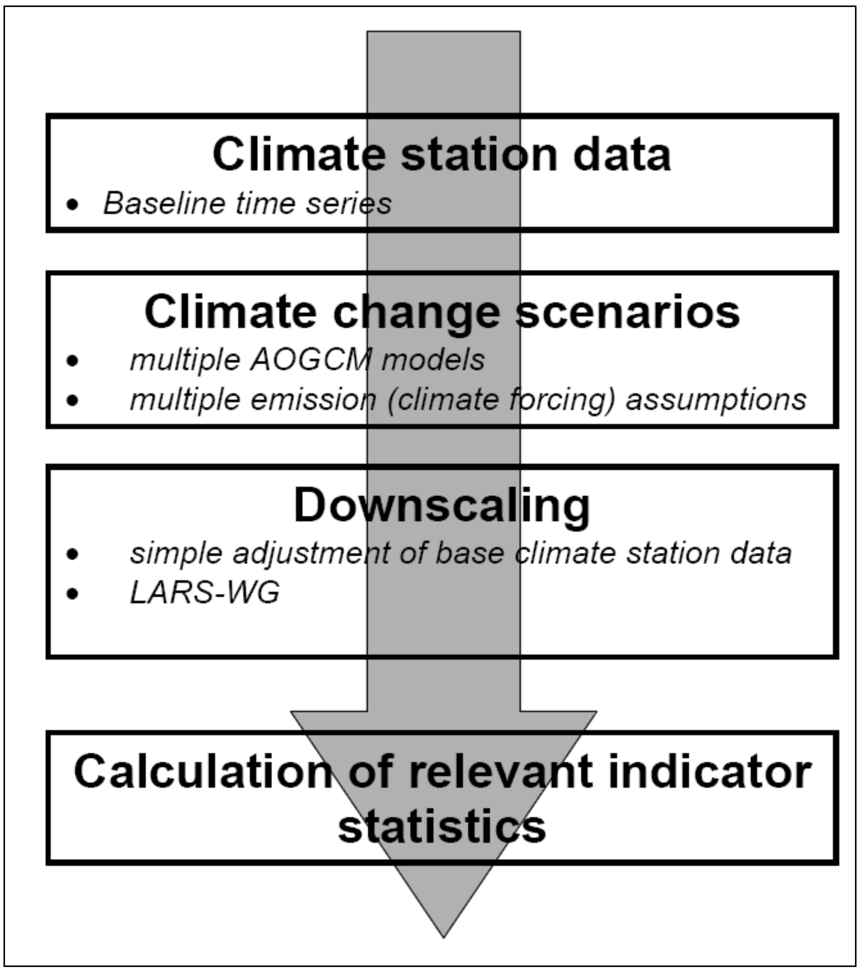


Figure 7. Steps in the analysis of climate change impacts

[11] Additional stations in Ontario were analyzed for use in other research projects.

Table 4. Case study site locations and characteristics

City (MSC Observing Station reference)	Latitude	Longitude	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Vancouver (1108447)	49.2	123.1	4.3	10.1	1199.0
Kelowna (1123970)	49.9	119.4	429.5	7.7	380.5
Calgary (3031093)	51.0	114.0	1084.1	4.1	412.6
Edmonton (3012205)	53.5	113.5	723.3	2.4	482.7
Regina (4016560)	50.5	104.6	577.3	2.8	388.1
Winnipeg (5023222)	50.0	97.2	238.7	2.6	513.7
Thunder Bay (6048261)	48.4	89.3	199.0	2.5	711.6
North Bay (6085700)	46.4	78.4	370.3	3.8	1007.7
Muskoka (6115525)	44.9	79.3	281.9	4.9	1098.6
Windsor (6139525)	42.3	82.9	189.6	9.4	918.3
Toronto (6158733)	43.7	79.6	173.4	7.5	792.7
Ottawa (6106000)	45.3	75.7	114.0	6.0	943.5
Montreal (7025250)	45.5	73.6	35.7	6.2	978.9
Quebec (7016294)	46.8	71.2	74.4	4.0	1207.7
Fredericton (8101500)	46.0	66.7	20.7	5.3	1143.3
Halifax (8202250)	44.6	63.6	145.4	6.3	1452.2
St. John's (8403506)	47.6	52.7	140.5	4.7	1513.7

*from 1971-2000 climate normals (Environment Canada http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html)

Climate Change Scenarios

Coupled general circulation models of the atmosphere and ocean (AOGCMs) are the only credible tools presently available to quantitatively estimate the transient global climate response to scenarios of future greenhouse gases, sulphate aerosols and other elements that affect climate forcing (IPCC-TGCIA, 1999). While the scientific community is quite confident that anthropogenic activities will lead to significant warming of global air temperature and a general increase in precipitation over the next century, there remains considerable uncertainty concerning potential climatic changes at local and regional scales and at specific points in time (Houghton *et al*., 2001). It is therefore recommended that scenarios from multiple AOGCM experiments (different models and assumptions concerning future emission patterns) be considered in analyses of climate impacts.

After considering available resources, required levels of effort, and choices made in recent comparable climate impact assessments, two climate change scenarios were adopted for analysis in the current study: one based on the A2x[12] emission experiment from the Canadian Centre for Climate Modelling and Analysis Coupled Global Climate Model 2 (CGCM2A2x), the other from the B21 experiment run through the Hadley Climate Model 3 (HadCM3B21). More information

[12] the CGCM2 A2x scenario is actually an ensemble or average of three separate A2 experiments for which the model was initialized differently. Similarly, the HadCM3 B21 scenario is the first experiment in its B2 series.

concerning the basis of the emission scenarios, which are grouped into four families (A1, A2, B1, B2) having similar demographic, societal, political, economic and technological assumptions over the next century, is provided in IPCC (2000). The specifications of the CGCM2 and HadCM3 climate models, and performance in relation to other internationally recognized models, are also well-documented elsewhere (Flato *et al*., 2000; Flato and Boer, 2001; Gordon *et al*., 2000; CMIP, 2001).

Raw scenario surface temperature (minimum, maximum, mean) and precipitation (total) data for each model and experiment were obtained through the Canadian Climate Scenarios Network (CCSN, 2005). Monthly data were available for baseline (1961-1990) and three future 30-year temporal windows centred on the 2020s, 2050s, and 2080s. Given that the average design life of pavement infrastructure is about 20-30 years, only the 2050s scenarios were examined in the current study. The data consisted of output for climate model grid cells, each of which spans 2.5 (HadCM3) to 3.75 (CGCM2) degrees latitude and 3.75 (both models) degrees longitude (i.e., over 100,000 km^2). Each site in Table 4 was assigned to the model grid cell in which it was located, except when the cell was designated as 'water' in the model specifications; in these cases, the nearest 'land' cell was used. Scatterplots of potential changes in annual and seasonal mean temperature and precipitation were prepared to indicate the position or severity of the CGCM2A2x and HadCM3B21 experiment results relative to other AOGCM scenarios for each site. Examples of annual scatterplots for the most northern (Edmonton) and southern (Windsor) study sites are provided in Figures 8-9. In general the CGCM2A2x and HadCM3B21 scenarios are average and conservative, respectively, when compared to other AOGCMs and experiments. Tables of the monthly values for the CGCM2Ax and HadCM3B21 that were used for each site are provided in Appendix A.

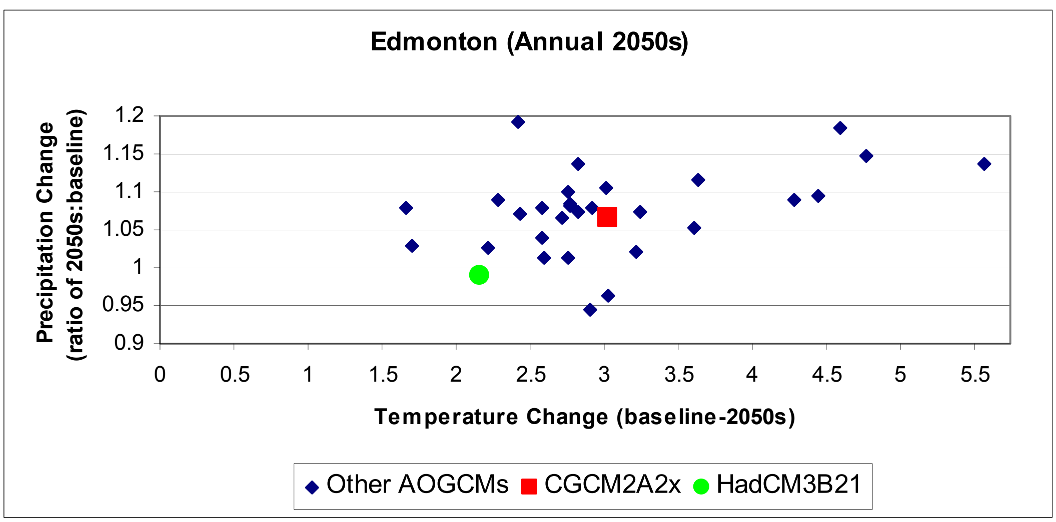


Figure 8. Scatterplot of potential changes in mean annual temperature and precipitation (Edmonton case study)

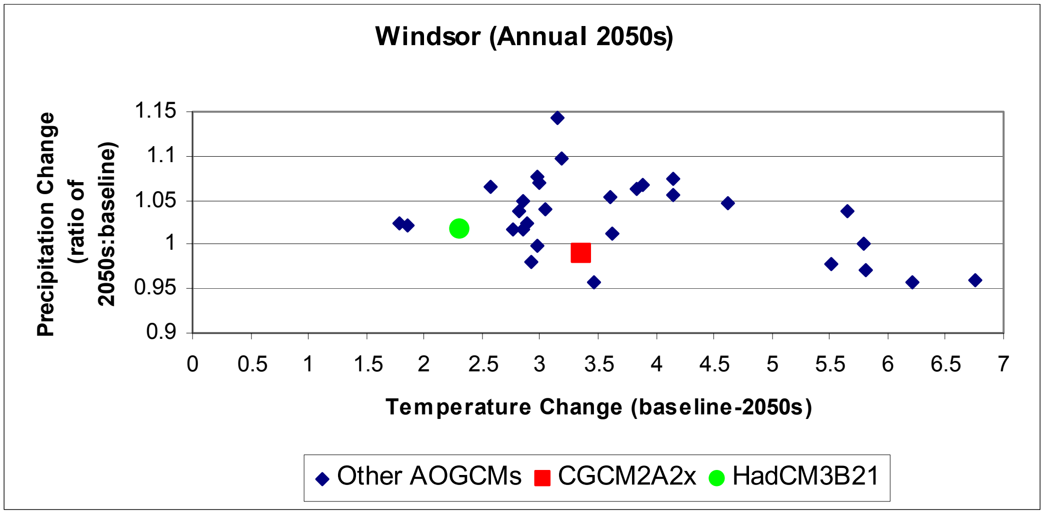


Figure 9. Scatterplot of potential changes in mean annual temperature and precipitation (Windsor case study)

Downscaling

As noted, the spatial resolution of AOGCM output is very coarse such that daily or monthly time series of variables are generally not suitable for direct input into climate impact analyses. Instead, the output is normally downscaled to match the scale at which the impact exposure unit is modeled (e.g., a point on a road network, hydrologic basin, city, etc.). Barrow *et al*. (2004) describe several downscaling techniques ranging in sophistication from simply adjusting historic time series by an average change factor derived from output for a particular AOGCM cell (e.g., increase mean January temperature by 4°C or precipitation by 15 percent) to developing a high resolution dynamic regional climate model nested within a coarser AOGCM (e.g., Goyette *et al*. 2001). Statistical weather generators (e.g., Semenov *et al.*, 1998; Wilks and Wilby, 1999; Wilby *et al*., 2002) fall between these extremes, both in terms of sophistication and ease-of-use, and were the tools chosen in the current study.

LARS-WG, a stochastic weather generator developed and described in detail by Semenov *et al*. (1998), was used to produce 3 random, synthetic, 50-year daily time series for the baseline and each climate change scenario. LARS-WG was first parameterized for each site using the 1951-2000 daily temperature and precipitation data obtained from Environment Canada. LARS-WG preserves the basic statistics of the original data in simulating a synthetic series; thus it allows the user to examine a degree of random variability in the baseline. LARS-WG allows the user to insert monthly factors (i.e., changes in mean and standard deviations of temperature, mean precipitation) that are applied to the baseline parameters of a particular site and thus incorporated into the simulation of future daily time series. As with the baseline, 3 separate 50-year simulations of future daily data were completed for each site and scenario (CGCM2A2x, HadCM3B21). These data were then used to generate time series and calculate basic summary statistics for each of the deterioration-relevant climate indicators permitting comparison between baseline and changed climate states. The calculation methods and results are discussed in the next section.

Performance Grade Asphalt Cement Selection

Extreme minimum daily temperature and 7-day average maximum daily temperature indicators are used to assist in the selection of performance grade (PG) asphalt binders or asphalt cements (PGAC) (USFHWA, 2002; OHMPA, 1999) that have been appropriately rated using extensive laboratory material testing. A suitable PGAC will minimize thermal cracking under cold temperatures while simultaneously minimizing traffic-induced rutting under hot temperatures. A reliability factor, most often 98 percent over the design life of the pavement structure, is associated with each PGAC and is determined as part of the calculations for each design. Grades are assigned in 6°C increments for both minimum and maximum pavement temperatures as illustrated in Table 5.

Table 5. Example performance grade asphalt binders/cements (USFHWA, 2002; OHMPA, 1999)

Extreme Minimum Pavement Temperature (°C)	7-day Maximum Pavement Temperature (°C) 40	46	52	58	64	70
-40	PG 40-40	PG 46-40	PG 52-40	PG 58-40	PG 64-40	PG 70-40
-34	PG 40-34	PG 46-34	PG 52-34	PG 58-34	PG 64-34	PG 70-34
-28	PG 40-28	PG 46-28	PG 52-28	PG 58-28	PG 64-28	PG 70-28
-22	PG 40-22	PG 46-22	PG 52-22	PG 58-22	PG 64-22	PG 70-22
-16	PG 40-16	PG 46-16	PG 52-16	PG 58-16	PG 64-16	PG 70-16
-10	PG 40-10	PG 46-10	PG 52-10	PG 58-10	PG 64-10	PG 70-16

For example, a PG 58-28 asphalt cement meets a minimum daily surface pavement temperature requirement of -28°C, and an average 7-day maximum temperature of 58°C, with 98 percent reliability over its design life (Haas *et al*., 2004). The minimum PG threshold refers to surface pavement temperatures while the maximum PG threshold refers to a temperature within the pavement, normally about 20mm from the surface (OHMPA, 1999). In practice, maximum temperature PG thresholds are adjusted upward one or more increments to account for traffic and load considerations (e.g., sections of Highway 401 in southern Ontario that are subject to stopped or slow moving heavy truck traffic) (USFHWA, 2002; OHMPA, 1999).

While continuous 50-year records of air temperature data are available throughout North America, similarly extensive datasets for pavement temperature are not as common or reliable. Several empirical formulae relating air and pavement temperatures have been developed through the Superpave and Long Term Pavement Performance (LTPP) programs to assist engineers in the design and binder selection process. The most recent equations cited by the USFHWA (2002) are described below:

For maximum pavement temperature:

$$T_{pmax} = 54.3254.32+0.78T_{airmax}-0.0025Lat^2-15.14\log_{10}(H+25)+z(9+0.61\sigma_{Tairmax}{}^2)^{0.5} \quad (4)$$

where:

T_{pmax} = maximum pavement temperature at depth, °C
T_{airmax} = average annual extreme 7-day mean maximum daily air temperature, °C
Lat = latitude of location, decimal degrees
H = depth from surface, mm
z = z-score for appropriate level of reliability assuming standard normal distribution (z=2.055, 98% reliability)
$\sigma_{Tairmax}$ = standard deviation of annual extreme 7-day mean maximum daily air temperature, °C

For minimum pavement temperature:

$$T_{pmin} = -1.56+0.72T_{airmin}-0.004Lat^2+6.26\log_{10}(H+25)-z(4.4+0.52\sigma_{Tairmin}{}^2)^{0.5} \quad (5)$$

where:

T_{pmin} = minimum pavement temperature at depth, °C
T_{airmin} = average annual extreme minimum daily air temperature, °C
Lat = latitude of location, decimal degrees
H = depth from surface, mm
z = z-score for appropriate level of reliability assuming standard normal distribution (z=2.055, 98% reliability)
$\sigma_{Tairmin}$ = standard deviation of annual extreme minimum daily air temperature, °C

While more sophisticated heat-balance and finite-difference models have been developed to determine temperatures throughout the pavement structure (e.g., Yavuzturk *et al*., 2005), the Superpave formulae are more commonly used in practice and are based on LTPP climate and pavement data from over 30 North American sites. Nevertheless, for comparison the authors also applied two additional formulae derived from 3 years of Road Weather Information System (RWIS) pavement and air temperature data from 3 sites in Ontario (MTO, 2006). These RWIS stations better capture the latitudes of the Canadian sites examined in the current study. The data are plotted in Figures 10-11 and the best fit (approximate r-squared values of 0.97) second-order, polynomial equations are noted below for each relationship.

For maximum pavement temperature:

$$T_{pmax} = 3.0305+0.007T_{airmax}{}^2+1.1715T_{airmax} \quad (6)$$

where:

T_{pmax} = maximum pavement temperature (~20mm depth), °C
T_{airmax} = 7-day mean maximum daily air temperature, °C

For minimum pavement temperature:

$$T_{pmin} = 2.0722+0.0051T_{airmin}{}^2+1.0453T_{airmin} \quad (7)$$

where:

T_{pmin} = minimum pavement surface temperature, °C
T_{airmin} = minimum daily air temperature, °C

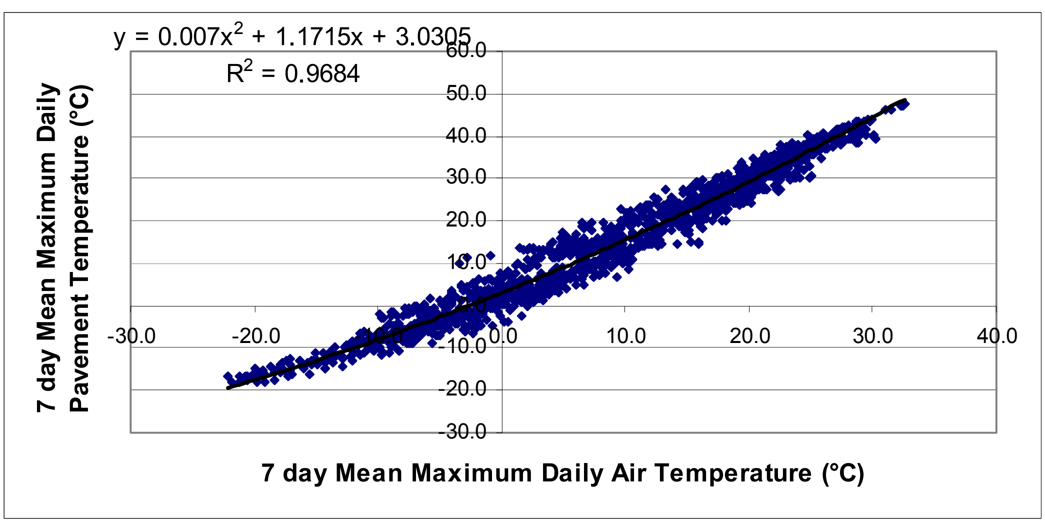


Figure 10. Relationship between 7-day mean maximum daily air and pavement temperatures

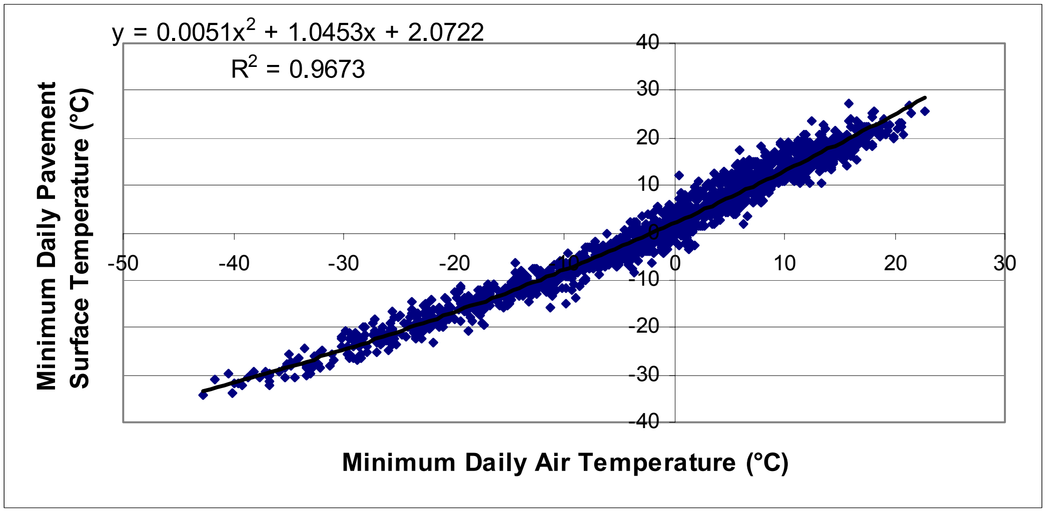
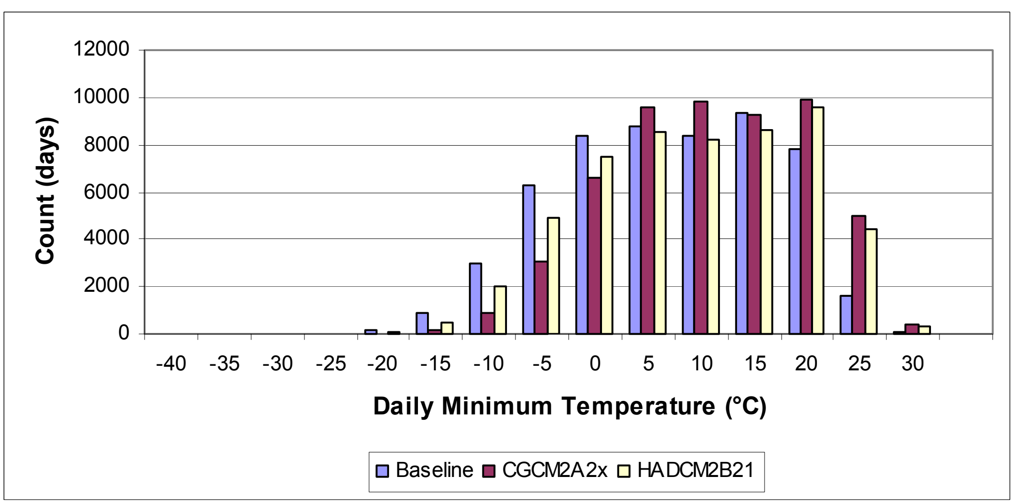


Figure 11. Relationship between minimum daily air and pavement surface temperatures

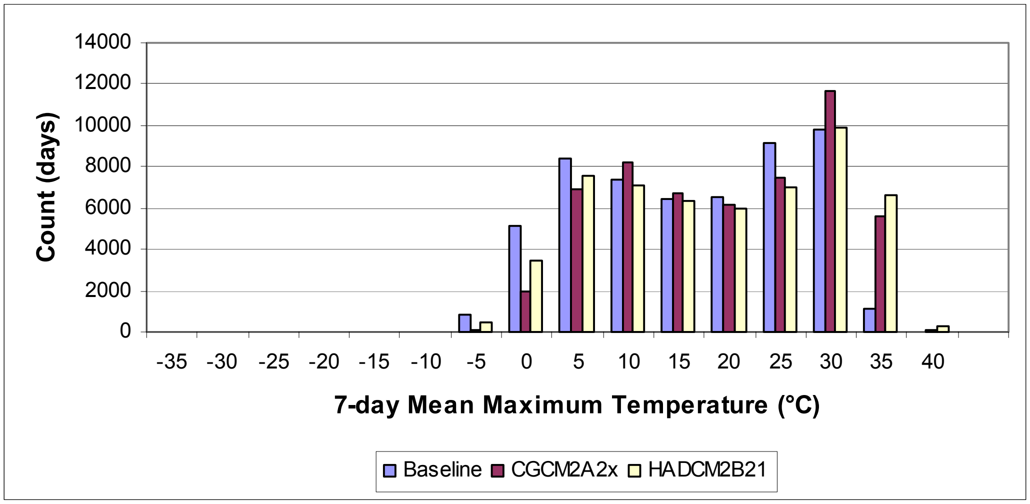
Performance Grade Analysis Results

Daily minimum and 7-day mean maximum temperatures are expected to increase with climate change at all of the sites examined. In general, the CGCM2A2x scenarios yield the greater changes in both minimum and 7-day mean maximum temperature variables. For example, Figures 12-13 show the distribution of all daily minimum and 7-day mean maximum temperatures for the Windsor site under baseline and future climate conditions. Every day in each of the 3, 50-year simulations for the baseline, CGCM2A2x, and HadCM3B21 scenarios is represented in Figures 12-13. Comparable results for all sites are included in Appendix B. From this daily data, time series of the minimum temperature and the highest 7-day mean maximum temperature observed in each year of the simulation are extracted for the calculation of performance grades. These variables are referred to as the *annual extreme minimum daily temperature* and *annual extreme 7-day mean maximum temperature* throughout this report. Minimum, maximum, and quartile statistics of these variables for the Windsor site are presented in Figures 14-15.



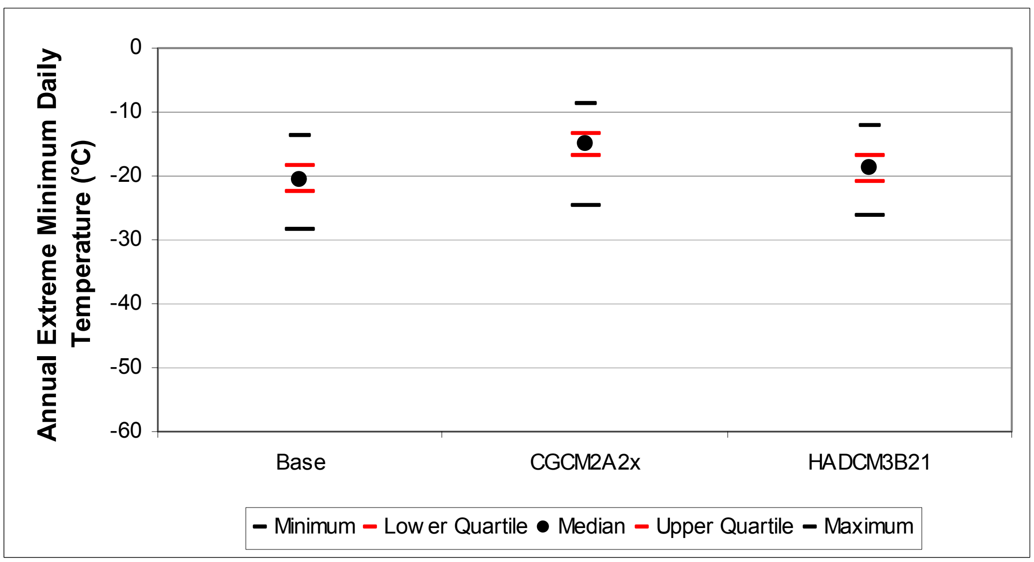
Notes: 1) based on 3, 50-year synthetic series (54750 days)
2) x-axis labels refer to upper limit (i.e., 0 category includes values greater than -5 and less than or equal to 0)

Figure 12. Daily minimum air temperature statistics for Windsor site under baseline and future scenarios



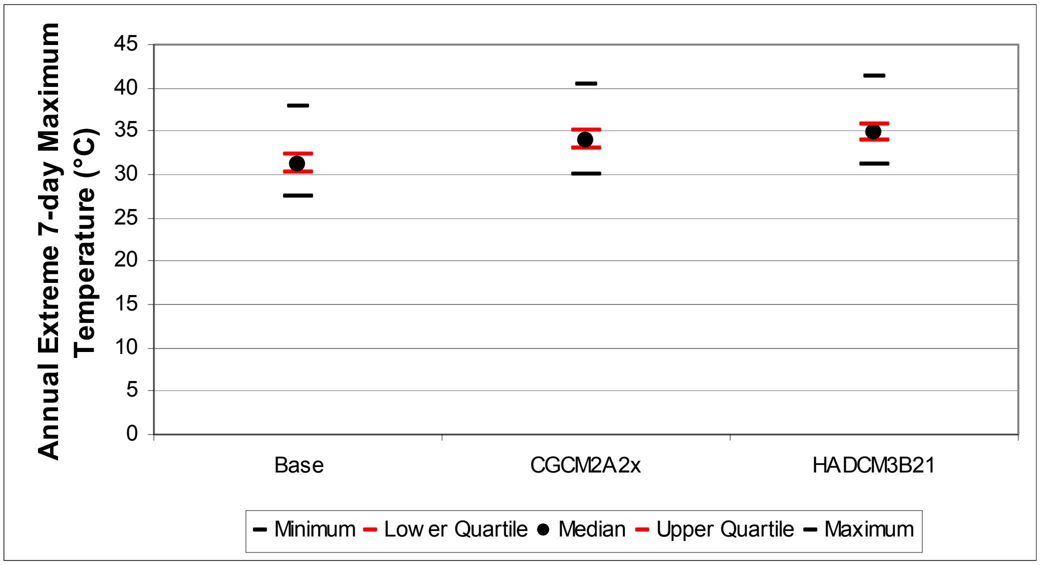
Notes: 1) based on 3, 50-year synthetic series (54750 days)
2) x-axis labels refer to upper limit (i.e., 0 category includes values greater than -5 and less than or equal to 0)

Figure 13. Seven-day mean daily maximum air temperature statistics for Windsor site under baseline and future scenarios



Notes: based on 3, 50-year synthetic series (150 values)

Figure 14. Annual extreme minimum daily air temperature statistics for Windsor site under baseline and future scenarios



Notes: based on 3, 50-year synthetic series (150 values)

Figure 15. Annual extreme 7-day mean maximum air temperature statistics for Windsor site under baseline and future scenarios

The annual extreme minimum daily temperature and annual extreme 7-day mean maximum temperature data for Windsor and the other sites were then applied to the Superpave and RWIS-based pavement temperature formulae to estimate PG ratings. As presented in equations 4 and 5, the Superpave formulae require average and standard deviation values for each variable in order to calculate a PG temperature at 98 percent reliability (assuming a normal distribution). For the RWIS-based equations, the PG temperature at 98 percent reliability was estimated by applying the 98th percentile for each temperature variable in the formulae. Results for the minimum PG temperature threshold are presented in Figure 16-17. Baseline low temperature thresholds determined using the Superpave algorithm ranged from -16°C (Vancouver) to -46°C (Edmonton). Relative to the baseline, no change in PG rating occurred at any of the sites under the HadCM3B21 scenario while 7 of 17 sites warmed up by one category under the CGCM2A2x scenario.

Baseline thresholds estimated using the Ontario RWIS-based algorithm were similar to those derived from the Superpave formula—the one exception was the Edmonton site where, with a value of -46°C, the Superpave baseline was one increment lower (colder). As with the Superpave PG rating, the HadCM3B21 results indicate no change relative to the RWIS-based baseline while PG ratings for 7 of 17 sites increased by one increment under the CGCM2A2x scenario. The specific sites that changed were not completely identical under the two algorithms, with Edmonton and Kelowna only changing under the Superpave and RWIS-based approaches, respectively.

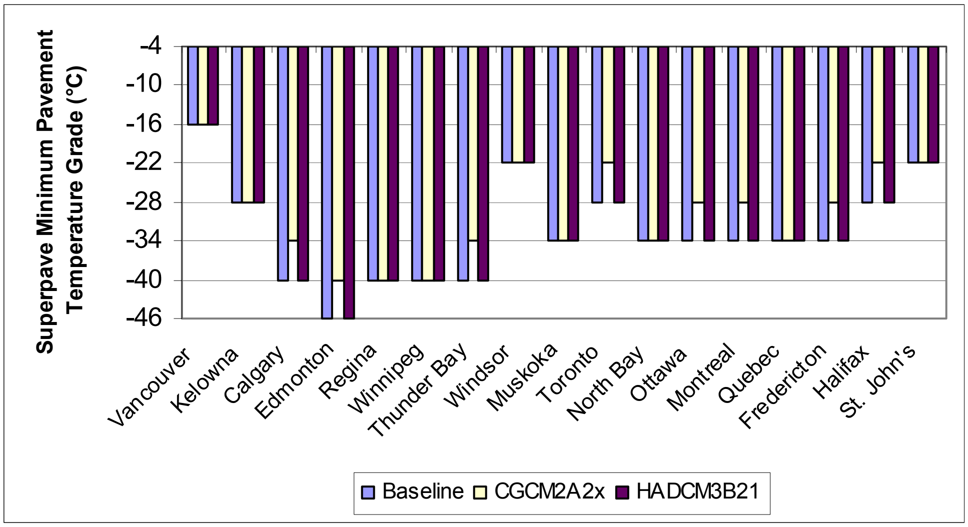


Figure 16. Low PG rating thresholds estimated using the Superpave algorithm under baseline and future scenarios for all sites

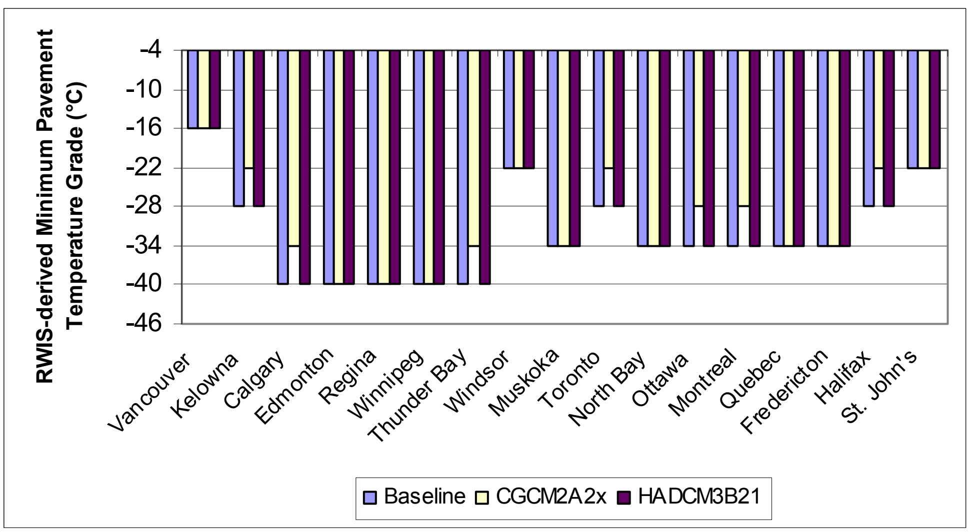


Figure 17. Low PG rating thresholds estimated using the RWIS-based algorithm under baseline and future scenarios for all sites

Results for the maximum PG temperature threshold are presented in Figure 18-19. Baseline high temperature thresholds determined using the Superpave algorithm were either 52°C (Vancouver, Calgary, Edmonton, North Bay, Halifax, St. John's) or 58°C (Kelowna, Regina, Winnipeg, Thunder Bay, Windsor, Muskoka, Toronto, Ottawa, Montreal, Fredericton). The upper limit of this range expanded to 64°C (Kelowna, Windsor) after results from the climate change scenarios were considered. PG ratings for 6 of 17 sites increased by one category under the HadCM3B21 scenario relative to the baseline; ratings for four of these sites also increased by one increment under the CGCM2A2x scenario.

Baseline thresholds estimated using the Ontario RWIS-based algorithm ranged from 46°C (Vancouver, North Bay, Halifax, St. John's) to 58°C (Kelowna, Regina, Windsor). Results were one category lower than those derived from the Superpave formula for 12 sites and identical for the remaining 5 locations. The climate change scenarios produced thresholds ranging from 46°C (Vancouver) to 70°C (Kelowna). PG ratings at 13 sites increased by at least one increment under the HadCM3B21 climate change scenario (Kelowna increased by two categories) and eleven of these sites also increased by one increment under the CGCM2A2x scenario. The higher PG estimates under the RWIS-based formula are likely a product of the limited range of data upon which the equation was derived. As shown in Figure 7, the highest 7-day mean maximum air temperature considered in the 3-year dataset is less than 35°C which is much lower than the 98th percentile values that were analysed in the baseline and climate change scenarios. This issue is not apparent for the extreme minimum equation as the RWIS data captured the full range of values in the baseline and climate change scenarios. Regardless, the differences illustrate the importance of using long time series of data whenever possible when developing empirical relationships.

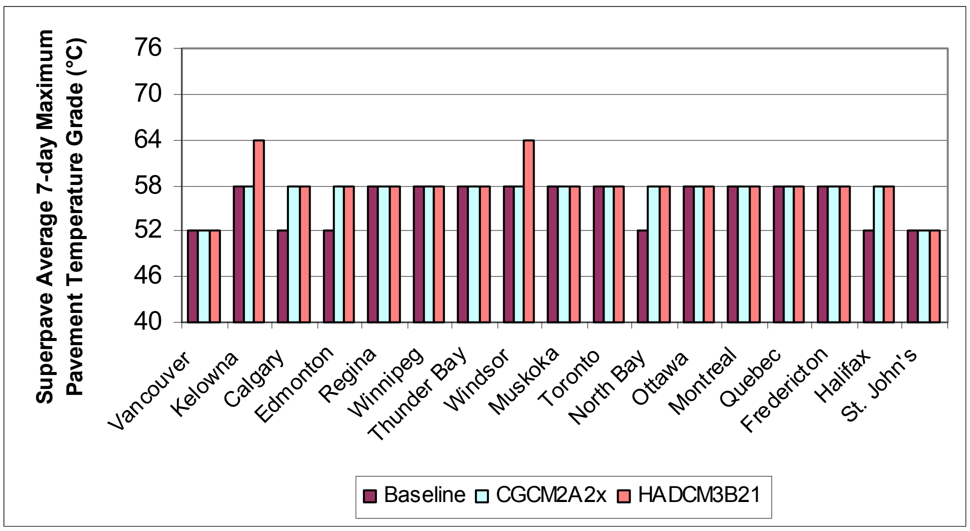


Figure 18. High PG rating thresholds estimated using the Superpave algorithm under baseline and future scenarios for all sites

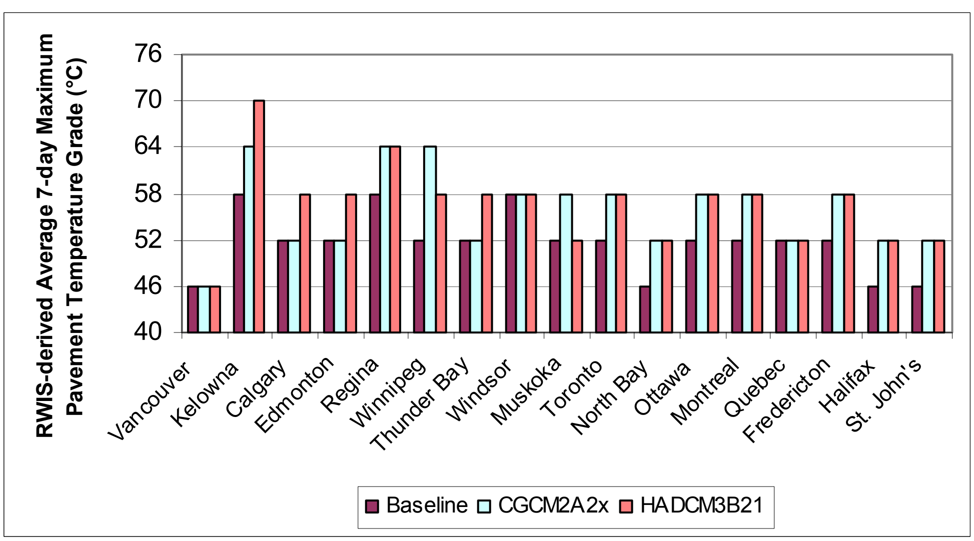


Figure 19. High PG rating thresholds estimated using the RWIS-based algorithm under baseline and future scenarios for all sites

A complete summary of results from the PG analysis is presented in Table 6. Detailed results for each site are provided in Appendix B.

Table 6. PG analysis summary of Superpave- and RWIS-based results

	Superpave-based Performance Grade Estimates			Ontario RWIS-based Performance Grade Estimates		
Site	**Baseline**	**CGCM2A2x**	**HadCM3B21**	**Baseline**	**CGCM2A2x**	**HadCM3B21**
Vancouver	PG 52-16	PG 52-16	PG 52-16	PG 46-16	PG 46-16	PG 46-16
Kelowna	PG 58-28	PG 58-28	PG 64-28	PG 58-28	PG 64-22	PG 70-28
Calgary	PG 52-40	PG 58-34	PG 58-40	PG 52-40	PG 52-34	PG 58-40
Edmonton	PG 52-46	PG 58-40	PG 58-46	PG 52-40	PG 52-40	PG 58-40
Regina	PG 58-40	PG 58-40	PG 58-40	PG 58-40	PG 64-40	PG 64-40
Winnipeg	PG 58-40	PG 58-40	PG 58-40	PG 52-40	PG 64-40	PG 58-40
Thunder Bay	PG 58-40	PG 58-34	PG 58-40	PG 52-40	PG 52-34	PG 58-40
North Bay	PG 52-34	PG 58-34	PG 58-34	PG 46-34	PG 52-34	PG 52-34
Muskoka	PG 58-34	PG 58-34	PG 58-34	PG 52-34	PG 58-34	PG 52-34
Windsor	PG 58-22	PG 58-22	PG 64-22	PG 58-22	PG 58-22	PG 58-22
Toronto	PG 58-28	PG 58-22	PG 58-28	PG 52-28	PG 58-22	PG 58-28
Ottawa	PG 58-34	PG 58-28	PG 58-34	PG 52-34	PG 58-28	PG 58-34
Montreal	PG 58-34	PG 58-28	PG 58-34	PG 52-34	PG 58-28	PG 58-34
Quebec	PG 58-34	PG 58-34	PG 58-34	PG 52-34	PG 52-34	PG 52-34
Fredericton	PG 58-34	PG 58-28	PG 58-34	PG 52-34	PG 58-34	PG 58-34
Halifax	PG 52-28	PG 58-22	PG 58-28	PG 46-28	PG 52-22	PG 52-28
St. John’s	PG 52-22	PG 52-22	PG 52-22	PG 46-22	PG 52-22	PG 52-22

Freezing and Thawing Indices

As noted previously, freezing and thawing indices are used to establish Winter Weight Premiums (WWPs) and Spring Load Restrictions (SLRs) and to empirically model the depth of frost within the pavement structure, a key determinant of its strength or structural adequacy. Assumptions used in the calculation of the Freezing Index (FI) and Thawing Index (TI) chosen for the study are summarized in Table 7.

For the purposes of this case study, an FI threshold of 156 degree days for WWP was drawn from research performed by Minnesota DoT (2004). FI calculations commence each season (October 1-May 31) following the first day that mean daily temperature falls below 0°C. Degrees below (above) zero are added (subtracted) each day and accumulated until the threshold is reached and sustained for 7 days, a surrogate for frost penetration to a sufficient depth (~40cm) to increase pavement strength and justify extra loads on roads subject to SLRs.

Thawing index (TI) calculations were based on a modified Minnesota approach as applied in recent work by Leong *et al.* (2005) and adjusted slightly by the authors. More specifically, once a site reached the critical freezing index noted previously, a daily thawing index (degree day count) was calculated for those days when the mean daily air temperature exceeded a reference value (-2°C). This value approximately corresponds to a temperature of 0°C at the base of the asphalt layer (i.e., to account for pavement response to radiation even though air temperatures are below 0°C). SLRs are assumed to be required in order to mitigate pavement damage when the cumulative daily TI reaches and sustains a critical value (13 degree days). To ensure that the thaw is prolonged sufficiently to affect the structure, additional criteria—attainment of at least 30 degree-days within seven days and an average TI of 21.5 degree-days—were applied to establish the recommended SLR date.

It should be noted that the specific thresholds or constants used in calculating freezing and thawing indices vary by jurisdiction and/or practice. Complementary studies are being completed by the authors in order to explore the implications of these, using sensitivity analysis. More specifically, the following decision points are being explored:

- Should the freezing index be adjusted for winter thaws?
- How much freezing is required to change the moduli of the pavement?
- When there is enough freezing, at what temperature should the thawing index calculation be initiated?
- How should low temperatures be treated after the thawing index calculation has been initiated?
- How should the first possible date for thaw-related damage be determined?
- When should SLRs/WWPs be implemented and monitored to minimize pavement damage?

The results of this work, as applied to two sites—Edmonton International Airport and Toronto Pearson International Airport for the months of September through April, from 1971 to 2000—will be reported in a Master's thesis in Geography at the University of Waterloo (Parm, 2007). A separate study, initiated by the University of Waterloo in partnership with the Ministry of Transportation of Ontario, is also examining these issues within the context of utilizing Road Weather Information Systems (RWIS) to control load restrictions on gravel and surface treated highways (Huen *et al*., 2006).

Table 7. Freeze and thaw analysis calculation assumptions adopted in the analysis

VARIABLE	CONDITION
Freezing Index (FI) Calculations	
Season begins/ends	October 1/May 31
Reference Temperature	0°C
FI threshold (day 1)	≥156
FI threshold (day 2-7 mean)	≥156
Thawing Index Calculations	
Season begins/ends	October 1/May 31
Reference Temperature	-2°C
TI threshold (day 1)	≥13
TI threshold (day 2-7 minimum)	≥13
TI threshold (day 2-7 maximum)	≥30
TI threshold (day 2-7 mean)	≥21.5

Freeze-Thaw Indicator Results

The freeze-thaw analysis consisted of comparing the timing of critical FI and critical TI and the length of the 'freeze' season—taken to be the sum of days between FI and TI—for baseline and climate change scenarios. Results for the Winnipeg case study site are shown in Figures 20-21 for illustration while similar accounts for the remaining sites are profiled in Appendix B. Median values are reported for the timing of critical FI and TI while both median and mean statistics are used to interpret changes in freeze season length.

Days to critical freeze and thaw thresholds, counted from October 1, are plotted in Figure 20 for each of the 150 seasons contained within the baseline, CGCM2A2x, and HadCM3B21 time series. On average at the Winnipeg site, critical freeze index values were reached within 61, 66, and 68 days for the baseline, CGCM2A2x, and HadCM321 scenarios, respectively. The slight delay of about one week in median freeze-up under climate change relative to the baseline was accompanied by a reduction in the median length of time for thawing to occur. Critical thawing index was achieved within 187, 172, and 182 days for the baseline, CGCM2A2x, and HadCM321 scenarios, respectively. Figure 21 summarizes the distribution of freeze season lengths calculated for the Winnipeg site. Although the baseline time series contained the year with the shortest freeze season duration, the average season length dropped from a baseline of 122 to 101 days under the CGCM2A2x scenario.

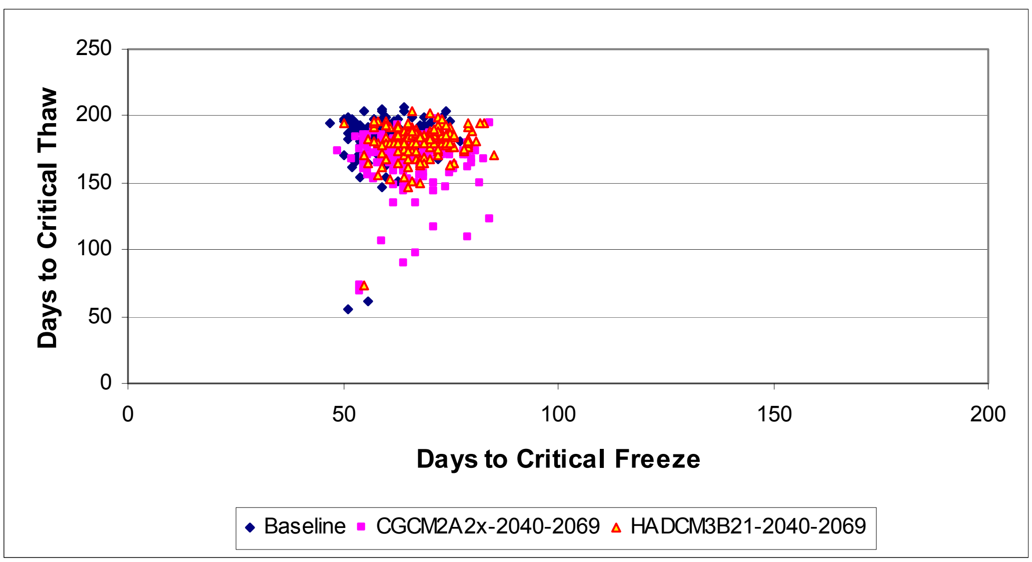


Figure 20. Days (from October 1) to reach critical freeze and thaw indices at the Winnipeg site under baseline and future scenarios

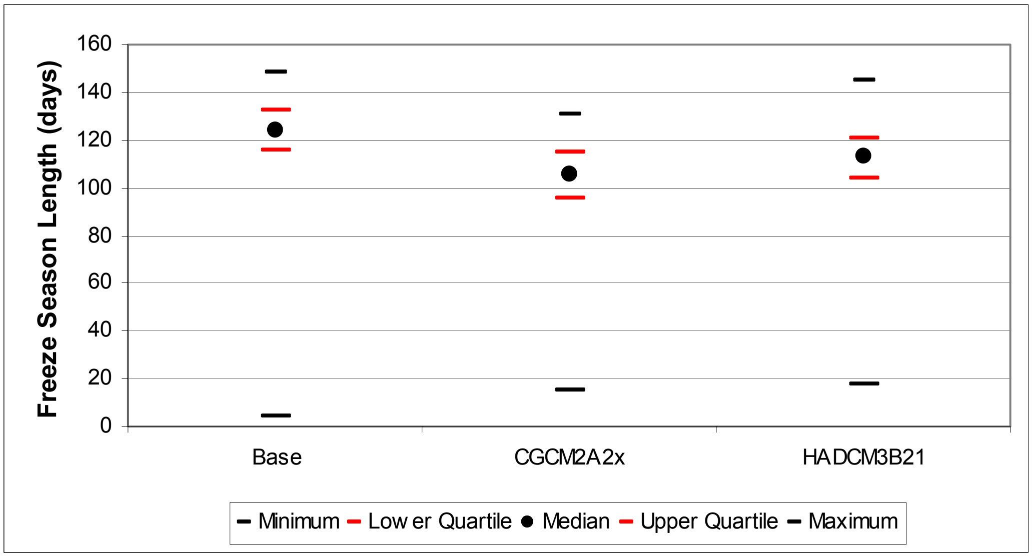


Figure 21. Freeze season length at the Winnipeg site under baseline and future scenarios.

The relative results for Winnipeg are similar to those analyzed for the other sites. In principle, warmer (or warming) climates are associated with greater lengths of time until critical FI is achieved and shorter periods until critical TI conditions are met. The median number of days to attain critical FI and TI are presented for all sites in Figures 22-23. With exception of Vancouver, where freeze thresholds were never satisfied in any of the baseline or future scenarios, the baseline median duration until freeze ranged from 58 days (Edmonton) to 116 days (St. John's). The corresponding baseline median number of days until thaw ranged from 131 (Kelowna) to 187 (Winnipeg).

Under the climate change scenarios studied, the number of days required to achieve critical FI and TI substantially increased and decreased, respectively. Assuming that CGCM2A2x conditions prevail, Kelowna, Windsor, Toronto and St. John's join Vancouver in the subset of sites where over 50 percent of all seasons fail to reach critical FI (and therefore TI); elsewhere the median duration before reaching critical FI increases from 4 days (North Bay) to 27 days (Halifax) while critical TI is achieved 10 days (Thunder Bay) to 31 days (Muskoka) earlier. Critical FI is reached under the HadCM3B21 scenario in at least 50 percent of seasons at all sites (except Vancouver). Under this scenario, median values for most sites increase by about 1-2 weeks relative to the baseline, except for Kelowna, Toronto, Windsor, Halifax and St. John's, where the median increased by up to 28 days. Critical TI is reached earlier in the season under the HadCM3B21 scenario at all sites except Kelowna, with median values ranging from 2 (Regina) to 14.5 (Halifax) less than the baseline. Median values increased at Kelowna by 3 days.

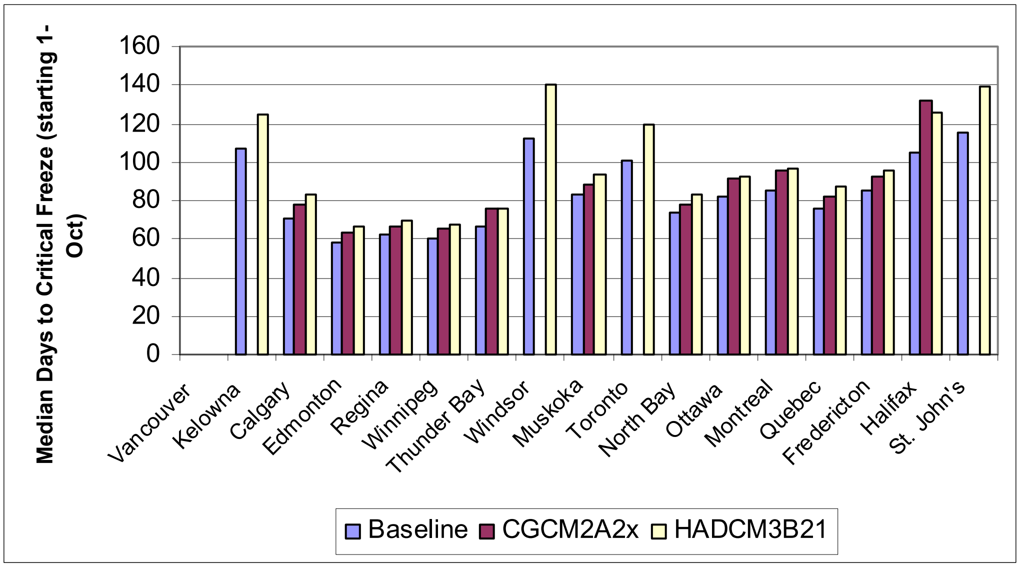


Figure 22. Median number of days required to reach the critical freeze index for all sites under baseline and future climate scenarios.

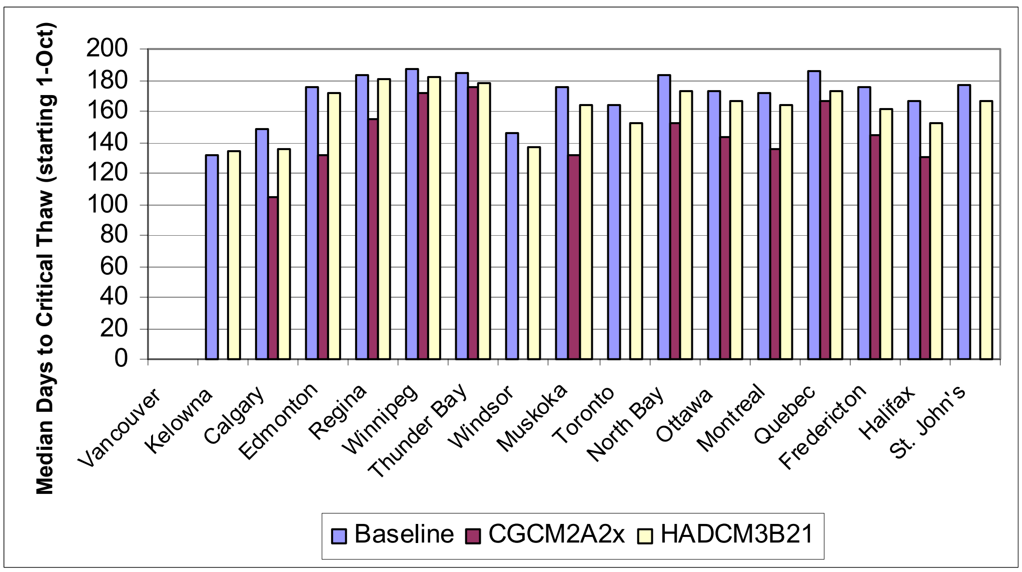


Figure 23. Median number of days required to reach the critical thaw index for all sites under baseline and future climate scenarios.

Combining the FI and TI results allows examination of changes in the duration of the freeze season. Mean and standard deviation freeze season lengths for all of the study sites are presented in Figures 24-25. Baseline mean values ranged from 0 days in Vancouver to 122 days in Winnipeg. Vancouver, Kelowna and Windsor were the only sites that experienced ‘freeze-free’ seasons under baseline conditions (Figure 26). Baseline standard deviations were similar for most sites (generally 15-20 days) except for Vancouver (no freeze seasons therefore no variability) and Calgary and Edmonton where the influence of periodic winter chinook conditions likely introduces greater variability.

The mean duration of the freeze season dropped substantially under the climate change scenarios examined, from roughly 8 percent at Winnipeg (HadCM3B21) to 98 percent at the St. John’s and Windsor sites (CGCM2A2x). The CGCM2A2x scenario consistently produced greater reductions in season length than the HadCM3B21 scenario. At least one in three seasons might be ‘freeze-free’ under the CGCM2A2x at the Vancouver, Kelowna, Toronto, Halifax and St. John’s sites while rare (~1 in 100) occurrences might also occur in Calgary, Muskoka and Ottawa. As expected, where the mean season length remained relatively long under the climate change scenarios (i.e., > 50 days), the standard deviation increased relative to the baseline. At sites where the mean season length was less than 50 days, the standard deviation under climate change was reduced relative to the baseline.

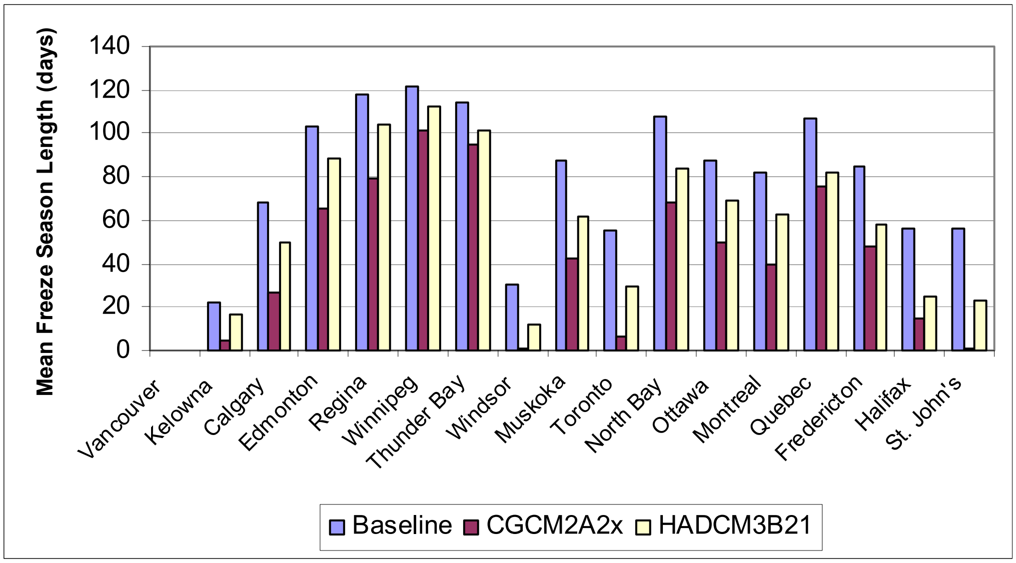


Figure 24. Mean freeze season length for all sites under baseline and future climate scenarios.

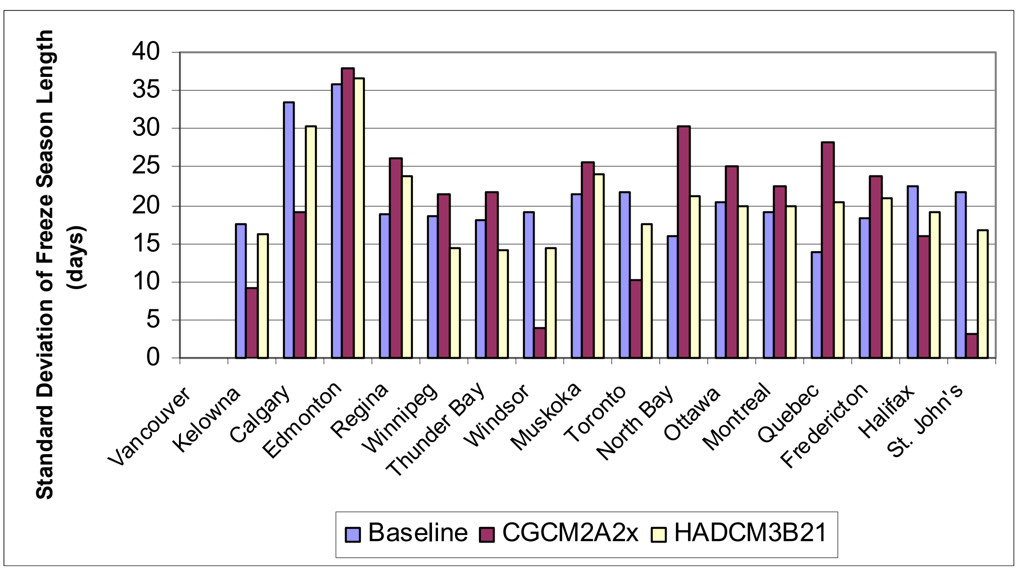


Figure 25. Standard deviation of freeze season length for all sites under baseline and future climate scenarios.

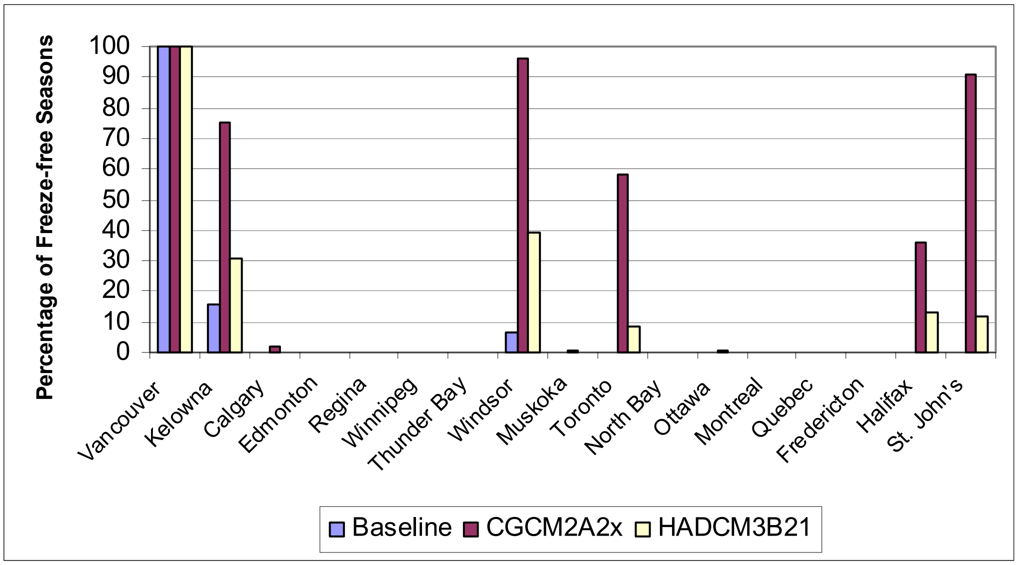


Figure 26. Occurrence of 'freeze-free' seasons for all sites under baseline and future climate scenarios.

3.2 Mechanistic-Empirical Pavement Design Guide (MEPDG) Application

The analysis of deterioration-relevant climate indicators revealed important implications that may result from climate change. However, the analysis was conducted independent of adjustments in several factors important in determining future patterns of deterioration, including other environmental variables (e.g., moisture) and those related to pavement structure, traffic, construction, and maintenance. The next set of case studies were designed to begin probing how the combination of such factors might affect the deterioration and performance of pavement sections over time as measured in terms of International Roughness Index (IRI), cracking (both load- and environment-related), and permanent deformation or rutting. The United States NCHRP/AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) and software were used to conduct the case studies, in part because of the interest in applying MEPDG in Canada. The Transportation Association of Canada has established a pooled fund study, with representation from all provincial departments of transportation as well as several large Canadian municipalities, in order to adapt the MEPDG for Canadian conditions.

Methods and Data

MEPDG is being developed to assist engineers in making decisions about asphalt and concrete pavement design and rehabilitations based on the application of state-of-the-practice mechanistic-empirical principles (NCHRP, 2004b). It allows the user to test various assumptions or scenarios concerning the variables noted above. In doing so, it provides output concerning the progression of pavement deterioration and performance and the adequacy of various pavement designs. The primary inputs required to run MEPDG include:

- general site and project information (e.g., design type, design life, construction and opening dates);
- analysis parameters (e.g., initial and terminal IRI, various forms of cracking, permanent deformation), critical values, and reliability (used to account for error in predictions of various distresses);
- traffic assumptions (e.g., lane alignment, baseline volume and future growth and distribution of truck traffic);
- pavement structure (e.g., specification of layer thicknesses and material properties); and
- climate (e.g., station location and elevation, groundwater table level, hourly temperature data).

A comprehensive description of all of these inputs and underlying mechanistic-empirical engineering principles, methods, and assumptions is beyond the scope of this report but is accessible from NCHRP (2004b). In addition to the incorporation of mechanistic approaches and the flexible user interface software, a key improvement in MEPDG from past design guides (e.g., AASHTO, 1993) is the development of the Enhanced Integrated Climate Model (EICM). The EICM is a one-dimensional coupled heat and moisture flow program that simulates changes in the behaviour and characteristics of pavement and subgrade material in response to climatic conditions (ARA Inc., 2004; NCHRP 2004b). This feature permits the calculation of transient distresses throughout the life of the pavement that are not tied to one particular test site or location. It must be noted that MEPDG is still being refined and improved and, although useful for exploratory studies such as the current investigation, it is not yet suitable as the primary decision input for pavement construction and rehabilitation (NCHRP, 2006a, 2006b).

Six test sites were selected from the Long Term Pavement Performance (LTPP) program (U.S. Department of Transportation, 2007) for analysis. The LTPP is composed of American, Canadian, and Danish test sites that are used to study the effect of different factors on the long term performance of pavements. There are approximately 129 test sites and 285 test sections across Canada (Table 8). Although each Canadian province is represented, almost 90 percent of sites are located in Alberta, Manitoba, Ontario, Quebec and Saskatchewan. The selected test sites are profiled in Table 9 and represent a range of pavement structures and materials that are found in Canada. Baseline traffic, pavement structure, and pavement material characteristics were extracted from the LTPP database (U.S. Department of Transportation, 2007) while climate data for the nearest suitable climate observing station were obtained from Environment Canada. The climate data consisted of hourly records of air temperature, relative humidity, cloud amount, and wind speed, and 6-hourly or daily records of precipitation for the period 1990-2005. Since MEPDG requires hourly data, the 6-hourly and daily precipitation amounts were distributed evenly across respective periods[13]. The percent sunshine variable required by MEPDG was derived from hourly cloud amount information. A detailed account of the material properties, default values, and assumptions used for each site is provided in Appendix C.

Table 8. Summary of LTPP test sites in Canada

Province	Total test sites	Percent of total test sites	Total test sections	Percent of total test sections
Alberta	19	14.7	32	11.2
British Columbia	4	3.1	9	3.2
Manitoba	23	17.8	85	29.8
New Brunswick	4	3.1	9	3.2
Newfoundland	3	2.3	5	1.8
Nova Scotia	1	0.8	5	1.8
Ontario	27	20.9	45	15.8
Prince Edward Island	3	2.3	9	3.2
Quebec	18	14.0	29	10.2
Saskatchewan	27	20.9	57	20.0
Total	**129**	**100.0**	**285**	**100.0**

A 20-year design life, commencing during the month of August, was chosen for the analysis of pavement performance for all MEPDG applications. The key analysis parameters and associated design thresholds are defined in Table 10. Limits, for example an IRI value of 2.7 m/km, are used as triggers for pavement repair, rehabilitation, and reconstruction decisions. A reliability factor is also assigned to each parameter to account for the various uncertainties in predicting future pavement deterioration. Results for the standard MEPDG output (average or 50 percent reliability) and 90 percent reliability level are reported in the current project. A reliability of 50 percent might represent a typical design criterion for a local or collector road while a reliability of 90 percent would be applied to a principal arterial or freeway.

[13] Tests were conducted to determine the effect of different downscaling approaches. MEPDG results were found to be insensitive to different approaches to distributing precipitation amounts thus the simple method was adopted.

Table 9. Case study site characteristics

PROVINCE	British Columbia	Alberta	Manitoba	Ontario	Quebec	Newfoundland
LTPP Site Identification	82-1005	81-1804	83-6450	87-1806	89-1021	85-1808
Climatic Region	Wet-freeze	Dry-freeze	Wet-freeze	Wet-freeze	Wet-freeze	Wet-freeze
Climate station reference	1108447 Vancouver International Airport	3012205 Edmonton International Airport	5023222 Winnipeg International Airport	6158733 L.B. Pearson International Airport	7025250 P.E. Trudeau International Airport	8403506 St. John's Airport
Latitude (degrees)	49.2	53.5	50.0	43.7	45.5	47.6
Longitude (degrees)	-123.1	-113.5	-97.2	-79.6	-73.6	-52.7
Elevation (m)	4.3	723.3	238.7	173.4	35.7	140.5
Traffic						
2-way AADTT**	1240	1420	498	2744	1912	256
Percentage of truck traffic in design lane	100	100	100	100	100	100
Pavement Structure						
Layer 1: Asphalt (cm)	9.7	8.4	5.1	4.1	5.3	8.1
Layer 2: Asphalt (cm)	-	-	5.6	10.2	-	-
Layer 3: Base (cm)	23.9	32.8	11.4	18.0	7.9	11.4
Layer 4: Subbase (cm)	31.0	24.6	10.7	79.2	38.1	43.2
Pavement Material						
Base	Crushed gravel	Crushed gravel	Crushed gravel	Crushed gravel	Crushed gravel	Crushed gravel
Subbase	River-run gravel	River-run gravel	River-run gravel	A-4	Crushed gravel	Crushed gravel
Subgrade**	SM	SM	SM	ML	SP	GW

* Average Annual Daily Truck Traffic
** SM-silty sand or silty gravelly sand, GW-gravel or sandy gravel, well-graded; ML-silts, sandy silts, or diatomaceous soils; SP-sand or gravelly sand, poorly graded

MEPDG was applied to the case study sites in order to evaluate changes in pavement performance. A series of analyses were conducted to understand the separate and combined influence of climate and climate change, pavement structure, and traffic growth as described below:

1) *Influence of climate and climate change alone*. Monthly scenarios for the CGCM2A2x and HadCM3B21 climate modeling experiments that were used in the freeze-thaw and PG analyses discussed previously (see Appendix A) were applied to the MEPDG control data at each site assuming no change in baseline traffic volume.
2) *Influence of structure type and baseline traffic volume*. The various structural types and baseline traffic volumes represented in the 6 case sites (see Appendix C) were evaluated using baseline and CGCM2A2x climate change scenarios for one location (Winnipeg, Manitoba).
3) *Combined influence of traffic growth and climate change*. Experiments from analysis 1 were re-run assuming a 4 percent increase in Annual Average Daily Truck Traffic (AADTT) and compared.

In total, 48 runs of MEPDG were completed in this analysis. Results are described in the following section.

Table 10. Analysis parameters used in MEPDG application (20-year design life)

Analysis Parameter	Limit/threshold	Reliability (%)
International Roughness Index (IRI)* (m/km)	2.7	50/90
AC longitudinal cracking (m/km)	378.8	50/90
AC alligator cracking (% surface coverage)	25.0	50/90
AC transverse cracking (m/km)	189.4	50/90
AC deformation (mm)	6.4	50/90
Total deformation (mm)**	19.1	50/90

*initial IRI=0.79 m/km **for all layers (asphalt, base, subbase, subgrade)

Influence of Climate and Climate Change Alone

Potential mid-century changes in precipitation and temperature relative to the climate model baseline (1961-1990) were extracted for each site and used to adjust hourly values in the baseline time series. For illustration, the scenarios applied to the Manitoba (Winnipeg) site are graphed in Figure 27. Significant variation is observed between months and between the CGCM2A2x and HadCM3B21 scenarios for both mean temperature (-0.2°C to +6.7°C) and precipitation (-18.2% to +50.1%) variables. The scenario data for all sites are documented in Appendix A. Only the climatic inputs were adjusted for the first analysis—baseline pavement structure and traffic variables remained constant as defined in Table 8.

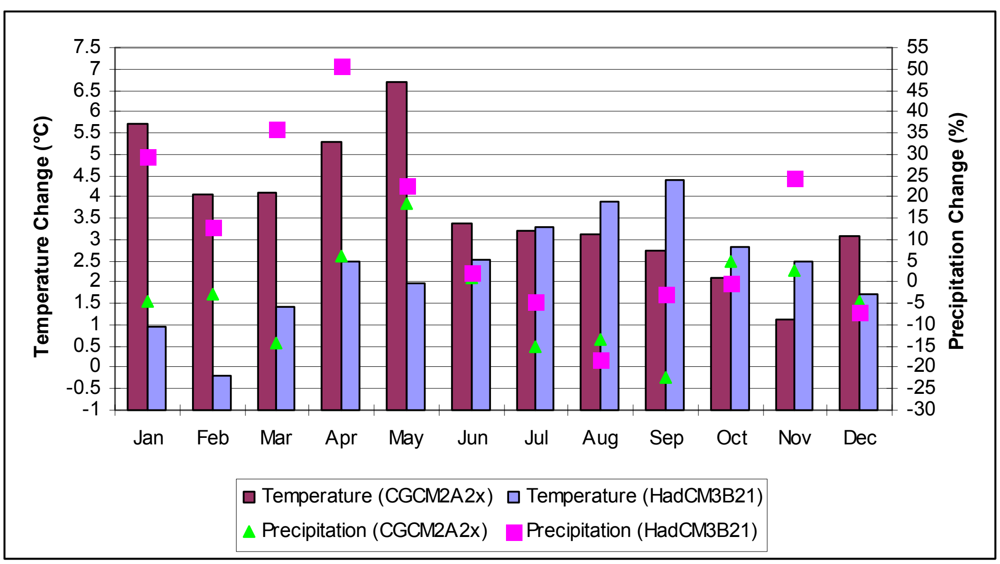


Figure 27. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Manitoba site (Winnipeg)

Changes in Pavement Deterioration

Baseline and climate change scenario results for all performance parameters and all sites are summarized in Table 11. Baseline values (reported in either m/km or mm) and relative percent changes for each climate scenario represent conditions at the completion of the 20-year design life (i.e., terminal results). Performance parameter values under baseline conditions varied considerably among the sites. For example, IRI values ranged from 1.55 m/km at the B.C. site to 2.54 m/km at the Manitoba site, reflecting differences in structure, traffic loads, and climate. The only distress variable that remained relatively constant across most sites was transverse cracking. Initiated by extreme cold temperatures, transverse cracking lengths quickly reached maximum values of about 400 m/km at all sites except the British Columbia (Vancouver) location which experiences the mildest climate among the sites analyzed. This result likely indicates an over-prediction of this particular form of cracking and underlying issues with the distress algorithms and assumptions within the MEPDG. In practice, it is believed that by adopting the PGAC, a significant portion of the transverse thermal cracking can be addressed.

Table 11. MEPDG pavement performance results for all sites (climate change alone)

Case Study Site	IRI (% change)*	Cracking (% change)*			Deformation (% change)*	
		Longitudinal	Alligator	Transverse	AC	Total**
British Columbia (baseline)	1.55 m/km	6.8 m/km	0.7%	19.1 m/km	2.1 mm	10.7 mm
CGCMA2x	-0.7	-1.9	7.5	-96.9	16.9	3.8
HadCM3B21	1.9	0.0	10.5	87.1	19.3	4.8
Alberta (baseline)	2.34 m/km	551.1 m/km	28.9%	399.6 m/km	5.5 mm	19.0 mm
CGCMA2x	1.3	9.3	11.4	0.0	22.7	-0.5
HadCM3B21	1.7	5.8	7.3	0.0	31.8	4.7
Manitoba (baseline)	2.54 m/km	450.8 m/km	48.2%	399.6 m/km	2.9 mm	14.5 mm
CGCMA2x	2.0	2.9	6.0	0.0	35.9	-0.9
HadCM3B21	2.4	2.9	5.8	0.0	34.1	2.3
Ontario (baseline)	1.92 m/km	33.3 m/km	4.6%	399.6 m/km	4.2 mm	12.1 mm
CGCMA2x	1.0	1.7	10.5	0.0	27.0	9.0
HadCM3B21	1.6	5.7	13.1	0.0	28.9	10.3
Quebec (baseline)	2.12 m/km	1647.7 m/km	0.5%	399.6 m/km	5.3 mm	21.8 mm
CGCMA2x	-0.9	0.0	4.4	0.0	13.9	-3.2
HadCM3B21	-0.5	-0.7	2.2	0.0	16.8	-0.8
Newfoundland (baseline)	1.79 m/km	5.3 m/km	0.1%	399.6 m/km	1.2 mm	9.1 mm
CGCMA2x	-1.1	5.4	14.3	0.0	21.9	-1.1
HadCM3B21	-0.6	4.3	14.3	0.0	21.9	0.6

*results rounded to one decimal (except absolute IRI values)
**includes all layers (asphalt, base, subbase, and subgrade)

As noted, the primary objective of the MEPDG analysis was to evaluate relative, not absolute, changes in pavement performance between baseline and future climate change scenarios. The most significant differences between baseline and future climate scenarios were observed for the asphalt concrete (AC) rutting parameter. AC rutting increased at all sites, from a minimum of 14 percent at the Quebec site (CGCM2A2x scenario) to a maximum of 36 percent at the Manitoba location (CGCM2A2x scenario). Increases relative to the baseline were similar (within in a few percent) for both climate change scenarios except for the Alberta site where the HadCM3B21 scenario produced about 9 percent more AC rutting than the CGCM2A2x scenario. Much less change was observed for the total rutting parameter which suggests that deformation was reduced in the lower layers thus compensating for AC rutting. Changes in total rutting ranged from a reduction of 3 percent at the Quebec site (CGCM2A2x scenario) to an increase of about 10 percent at the Ontario site (HadCM3B21 scenario). As with rutting in the AC layer, the changes relative to the baseline for both climate scenarios were consistently within a few percentage points of each other. However, the direction of the changes differed for the Alberta, Manitoba, and Newfoundland sites with slight reductions under the CGCM2A2x climate and small increases in total rutting under HadCM3B21 conditions.

In general, modest increases under climate change conditions were observed for the various cracking parameters relative to the baseline. A slight rise in longitudinal cracking was reported for most sites except for British Columbia and Quebec, where no change or small decreases were recorded. Somewhat larger increases, from 2 (Quebec site, HadCM3B21 scenario) to 14 (Newfoundland site, CGCM2A2x scenario) percent, were observed for alligator cracking. The high relative changes at the Newfoundland site are associated with very small absolute changes in baseline cracking though. In terms of transverse cracking, deterioration reached maximum values of approximately 400 m/km under each of the climate change scenarios tests as it did for the baseline run at 5 of the 6 sites, resulting in a zero net change. At the warmer British Columbia site, transverse cracking was virtually eliminated under the CGCM2A2x scenario (97 percent reduction) and almost doubled (87 percent increase) under HadCM3B21 conditions. Despite issues with this form of cracking in MEPDG, the British Columbia results for the CGCM2A2x scenario are intuitively consistent with our understanding of cracking processes and may be more representative of future patterns in much of southern Canada than results from the other sites. The increase in cracking stemming from the HadCM3B21 scenario is coincident with a regional area of relative cooling during the early winter period that is somewhat anomalous when compared to most areas in Canada.

The least amount of change between baseline and future climate scenarios was observed for the IRI performance parameter. Very small changes (i.e., less than 3 percent) in terminal IRI were observed under the CGCM2A2x and HadCM3B21 climate scenarios examined. Slight decreases in roughness were apparent at the two eastern (both scenarios) and British Columbia (CGCM2A2x scenario) sites while slight increases were apparent at the remaining locations.

Changes in the Timing of Maintenance Requirements

Terminal values of performance indicate the state of a pavement at the end of its service life. Just as important is the time-dependent evolution of deterioration relative to maintenance, rehabilitation and reconstruction thresholds. Parameter limits associated with a 20-year design life as defined in Table 10 were used to explore changes in the timing of maintenance requirements. Figures 28a-33b summarize when these limits were exceeded at the various sites for baseline and climate change scenarios. Figures denoted with an “a” or “b” show results obtained at the 50 and 90 percent reliability levels, respectively.

At the 50 percent reliability level, 11 out of 36 possible parameter limits (6 sites x 6 parameters) were exceeded at some point during the 20-year design life under baseline climate conditions.

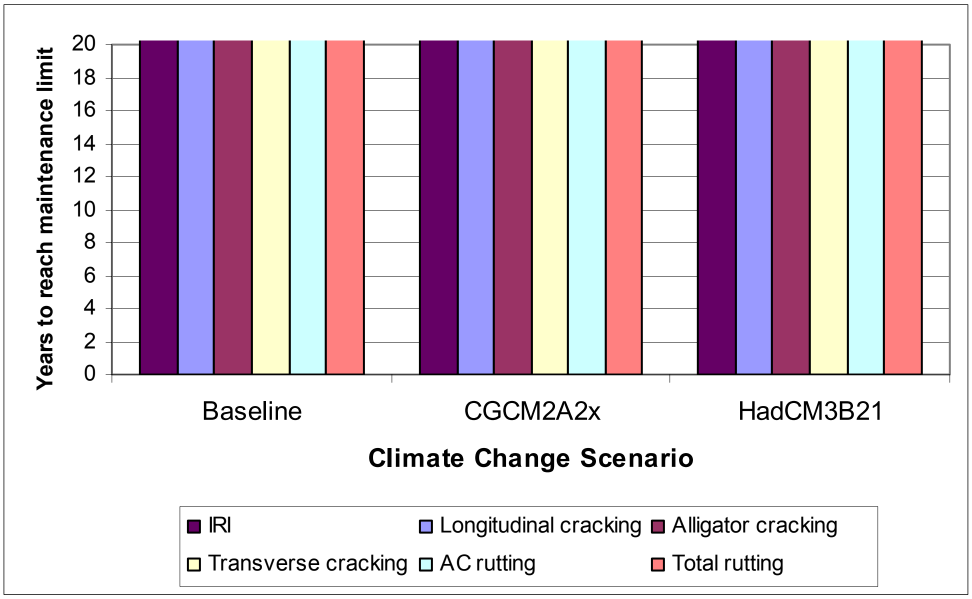
Thresholds were not achieved for any parameter at the British Columbia site or for the IRI and AC rutting parameters at any of the sites. Total rutting (all layers), longitudinal cracking, and alligator cracking criteria were met at 1 (Quebec, 10.9 years), 3 (Alberta, 14.8 years; Manitoba, 17.1 years; Quebec, 2.8 years), and 2 (Alberta, 17 years; Manitoba, 8.1 years) sites, respectively. With the exception of British Columbia, all sites reached transverse cracking thresholds early during the first winter season. As noted previously, transverse cracking would be negligible based on a proper PG selection.

After analyzing the climate change scenarios, two parameter limits (13 of 36) were added to those exceeded under baseline conditions. As with the baseline, no parameter limits were reached for the British Columbia site and IRI criteria were not met at any site under the CGCM2A2x or HadCM3B21 climate change scenarios. For most other parameters and sites, the general influence of climate change was to reduce the amount of time until maintenance, rehabilitation or reconstruction thresholds were met. The reductions ranged from less than 1 year (Manitoba, alligator cracking, CGCM2A2x and HadCM3B21 scenarios) to over 5 years (Alberta, AC rutting, HadCM3B21 scenario). Results for the Quebec site (total rutting, longitudinal cracking) and for the transverse cracking parameter were just the opposite, with climate change inducing a slight delay in the timing when limits were reached.

General results similar to those noted for the 50 percent reliability level were also realized at the 90 percent level. As expected, the more stringent failure criterion produced a greater number of exceedances (16 out of 30[14]) much earlier during the design life under baseline conditions, but the overall patterns remained similar. For example, no limits were reached at the British Columbia site. While IRI thresholds were not met at any site at the 50 percent reliability level, 3 sites exceeded thresholds at 90 percent reliability (Alberta, 14.3 years; Manitoba, 12.4 years; Quebec, 17.8 years). Total rutting, longitudinal cracking, and alligator cracking criteria were met at 2 (Alberta, 8 years; Quebec, 4.3 years), 4 (Alberta, 1.8 years; Manitoba, 1.8 years; Ontario, 11.8 years; Quebec, 0.7 years), and 2 (Alberta, 5.2 years; Manitoba, 2.1 years) sites, respectively. All sites other than British Columbia reached transverse cracking thresholds early during the first winter season.

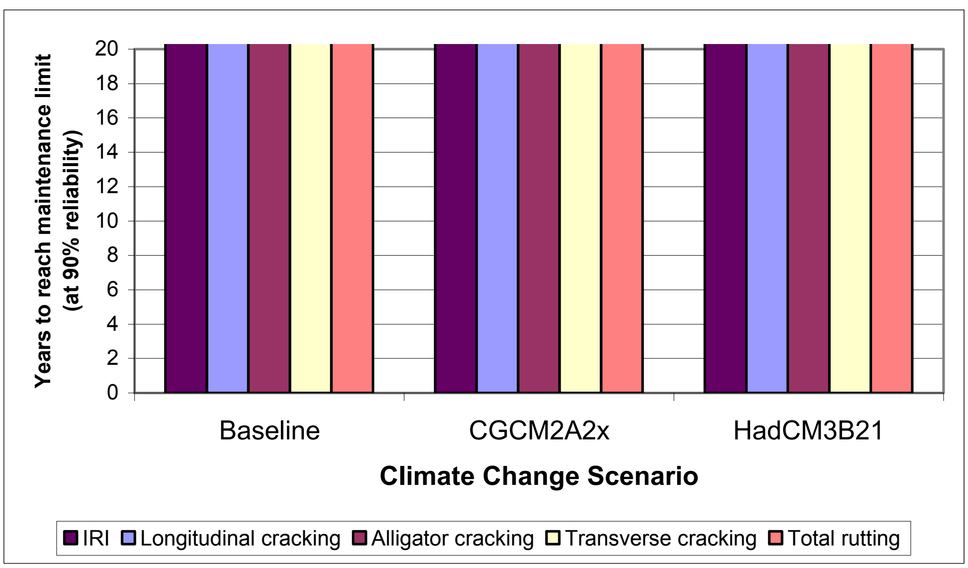
The parameter limits reached under the climate change scenarios were identical to those achieved under baseline conditions at the 90 percent reliability level. Once again, no thresholds were exceeded at the British Columbia site. At the remaining sites and consistent with observations at the 50 percent reliability level, the general effect of the climate change scenarios at the 90 percent reliability level was to shorten the length of time before IRI, longitudinal cracking, and alligator cracking thresholds were met and to delay the timing of reaching transverse cracking and total rutting limits. This pattern was not followed at the Alberta site, where total rutting thresholds were met earlier under the HadCM3B21 scenario, and at the Quebec site where additional time was required to meet IRI thresholds under both climate change scenarios. In all cases, the relative change between the baseline and climate change scenarios was less than one year.

[14] MEPDG does not provide an output for the AC rutting parameter for reliability levels other than the standard 50 percent level thus the total number of parameter limits is 30 (6 sites x 5 parameters).



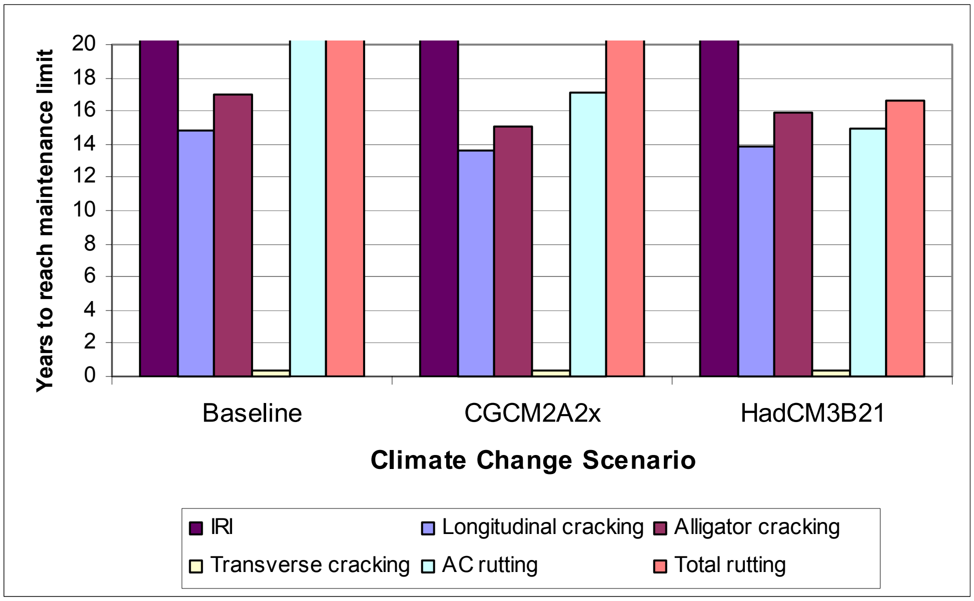
*values greater than 20 years indicate parameter limits not reached during design life

Figure 28a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the British Columbia site (Vancouver)



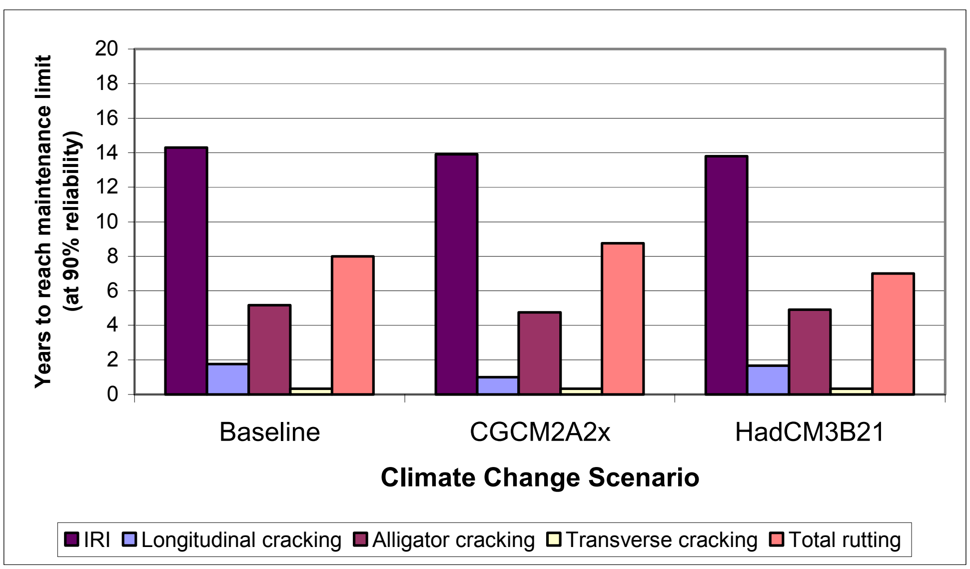
*values greater than 20 years indicate parameter limits not reached during design life

Figure 28b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the British Columbia site (Vancouver)



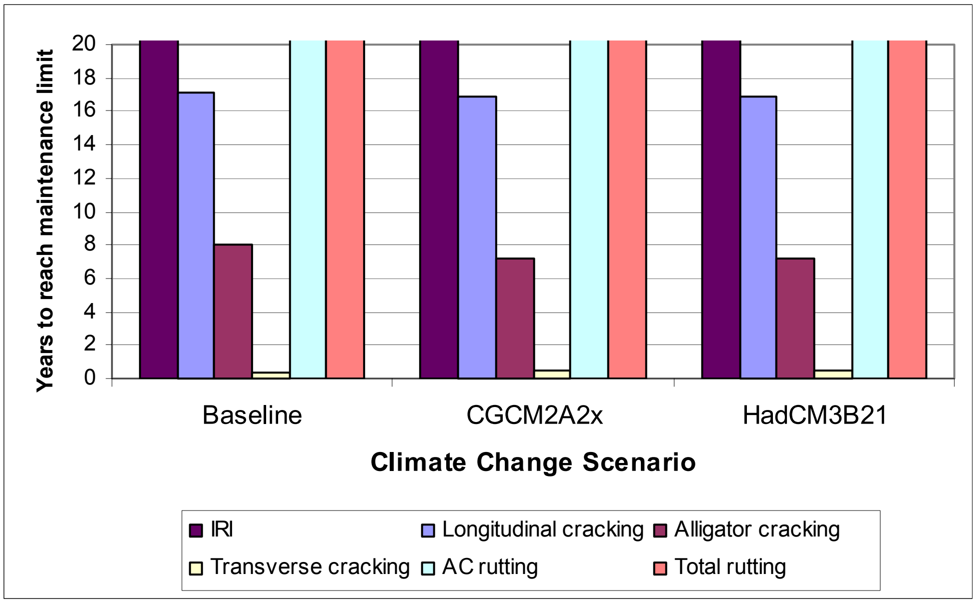
*values greater than 20 years indicate parameter limits not reached during design life

Figure 29a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Alberta site (Edmonton)



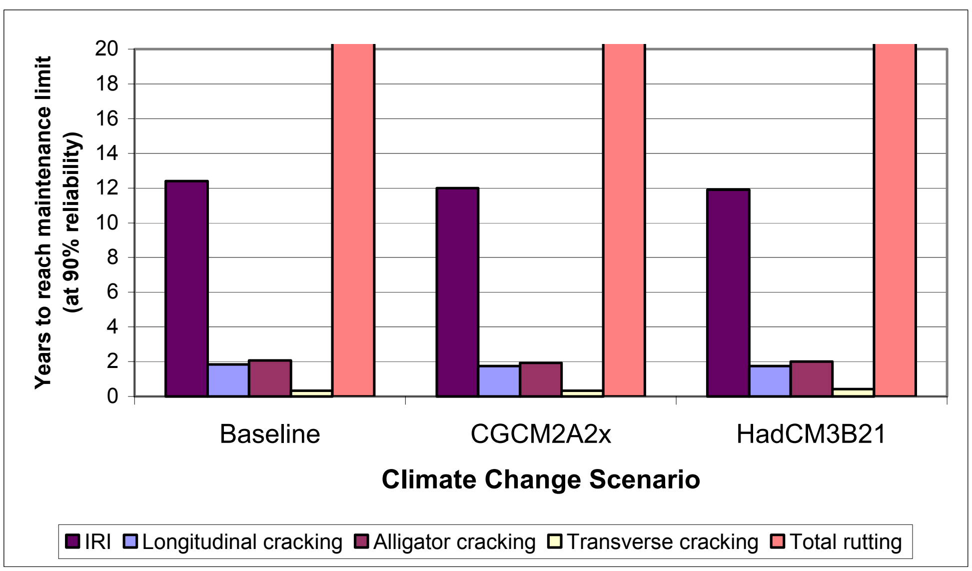
*values greater than 20 years indicate parameter limits not reached during design life

Figure 29b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Alberta site (Edmonton)



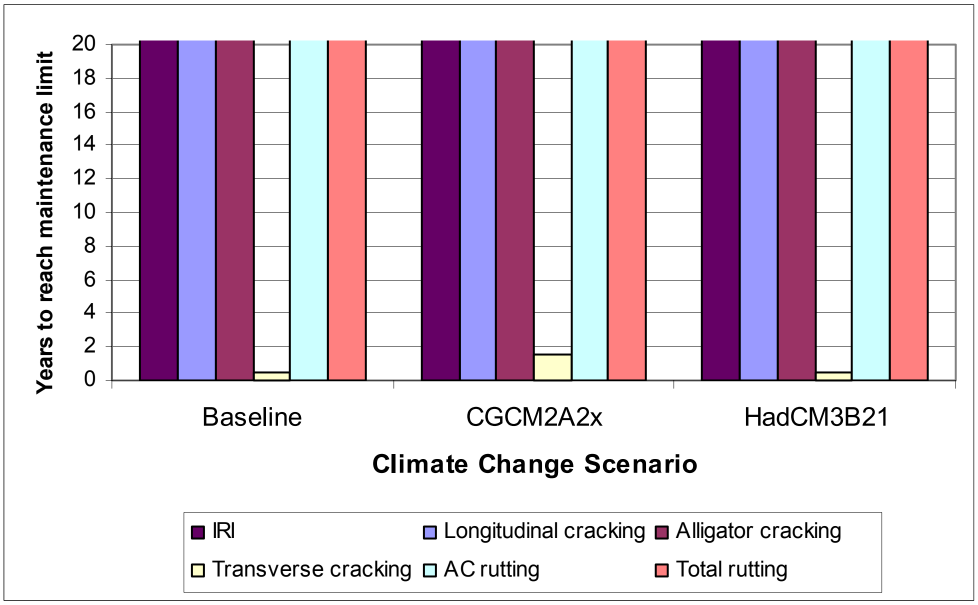
*values greater than 20 years indicate parameter limits not reached during design life

Figure 30a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Manitoba site (Winnipeg)



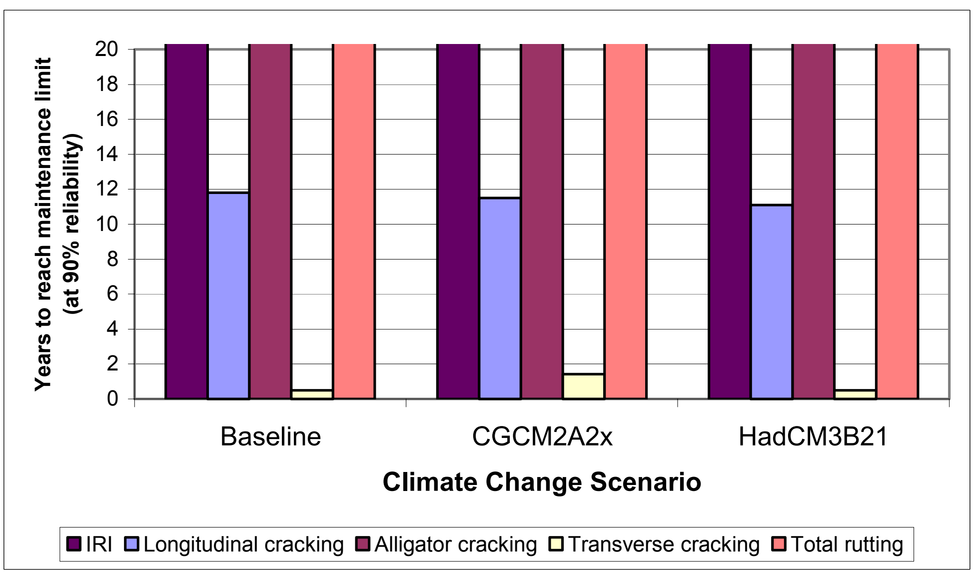
*values greater than 20 years indicate parameter limits not reached during design life

Figure 30b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Manitoba site (Winnipeg)



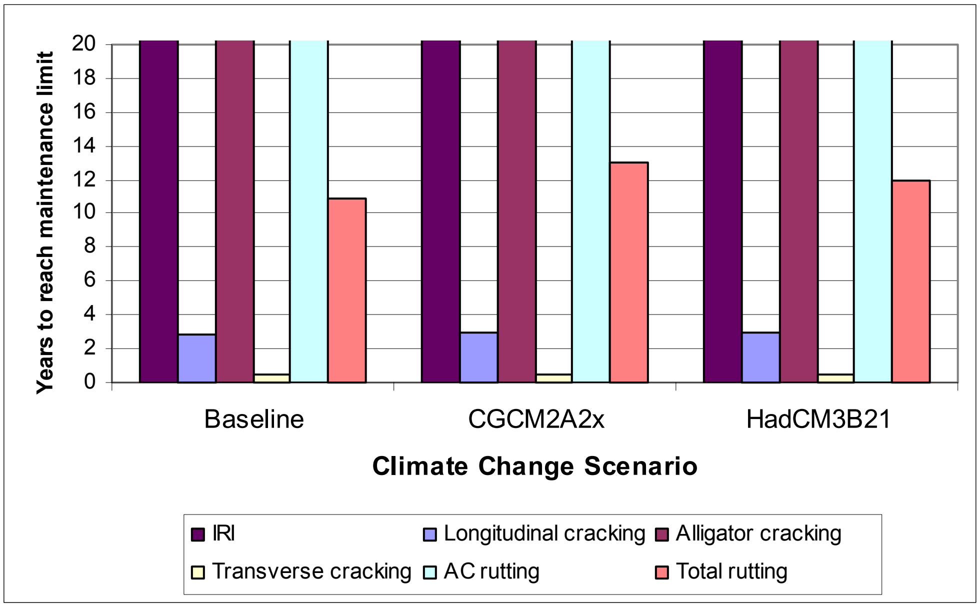
*values greater than 20 years indicate parameter limits not reached during design life

Figure 31a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Ontario site (Toronto)



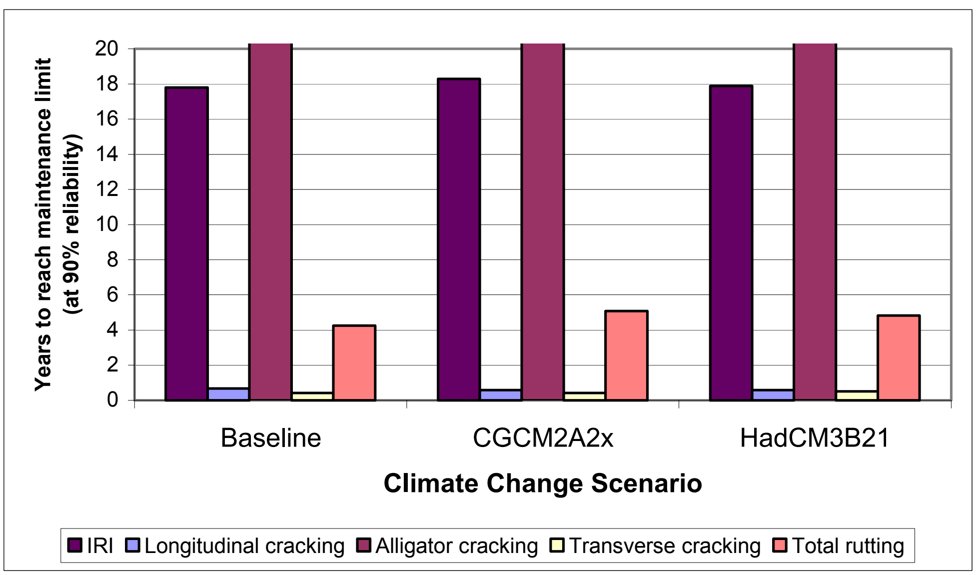
*values greater than 20 years indicate parameter limits not reached during design life

Figure 31b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Ontario site (Toronto)



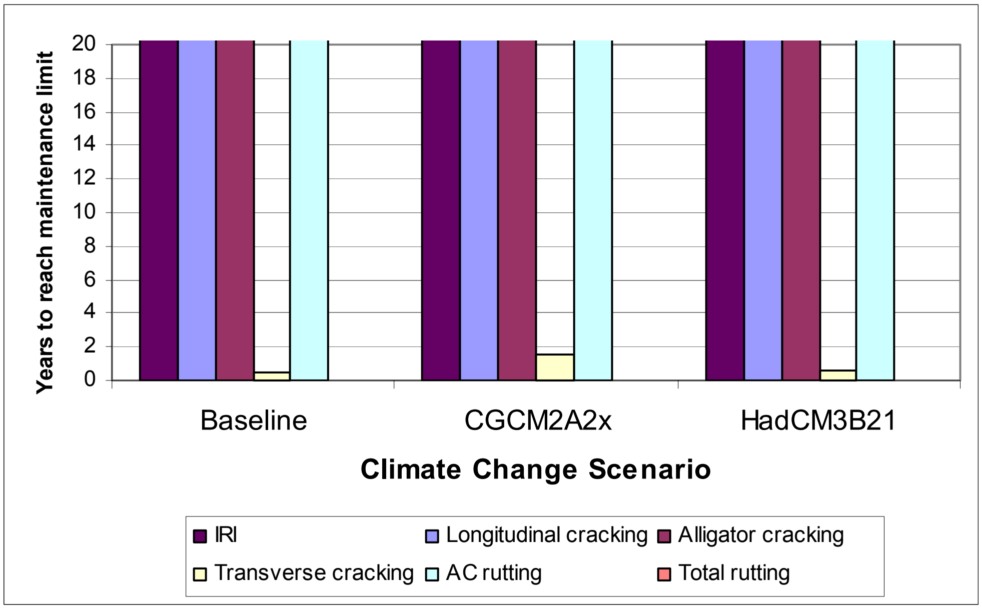
*values greater than 20 years indicate parameter limits not reached during design life

Figure 32a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Quebec site (Montreal)



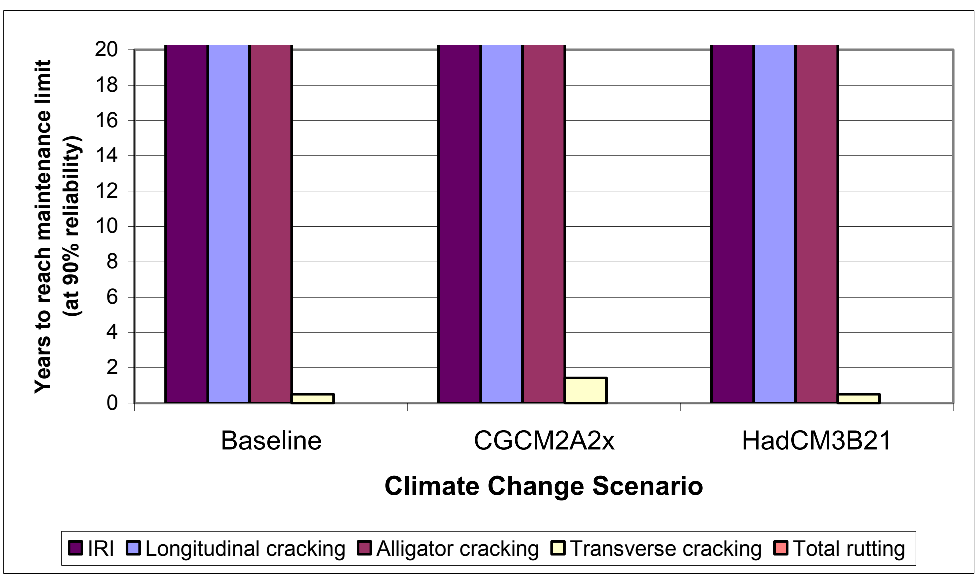
*values greater than 20 years indicate parameter limits not reached during design life

Figure 32b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Quebec site (Montreal)



*values greater than 20 years indicate parameter limits not reached during design life

Figure 33a. Years to reach performance parameter limits (50% reliability maintenance thresholds) under no traffic growth scenario at the Newfoundland site (St. John's)



*values greater than 20 years indicate parameter limits not reached during design life

Figure 33b. Years to reach performance parameter limits (90% reliability maintenance thresholds) under no traffic growth scenario at the Newfoundland site (St. John's)

Influence of Pavement Structure and Baseline Traffic

In addition to showing the relative impact of the climate change scenarios, the results from Table 11 suggest that other variables, especially pavement structure and baseline traffic, may be significant factors shaping pavement deterioration. To better understand the role of structural and baseline traffic assumptions, all of the structures represented in the case study were run through MEPDG under the same baseline climate and CGCM2A2x climate change scenario (Winnipeg, Manitoba). Terminal deterioration results for IRI, longitudinal cracking, alligator cracking, AC rutting, and total rutting indicators are presented in Figures 34-38. The most striking observation is that relative differences between various structure and traffic situations, as represented among the set of sites in the study, are much greater than those associated with changes in climate at the Winnipeg site. In particular, longitudinal and alligator cracking seem insensitive to changes in climate relative to variations in structure and traffic levels while AC rutting appears to be the most sensitive to shifts in climate among the indicators studied. Both the magnitude and direction of change are influenced by structural and traffic assumptions. For example, while the CGCM2A2x results for AC rutting were consistently higher than the baseline climate for all structures, relative rutting increased more for the Alberta structure (36 percent) than for the Newfoundland structure (18 percent). Changes in IRI, total rutting, and longitudinal cracking between the baseline climate and CGCM2A2x scenario were inconsistent across the structure types, increasing in some instances (e.g., IRI for Alberta, Manitoba and Ontario structures) and decreasing in others (e.g., IRI for British Columbia, Quebec and Newfoundland structures).

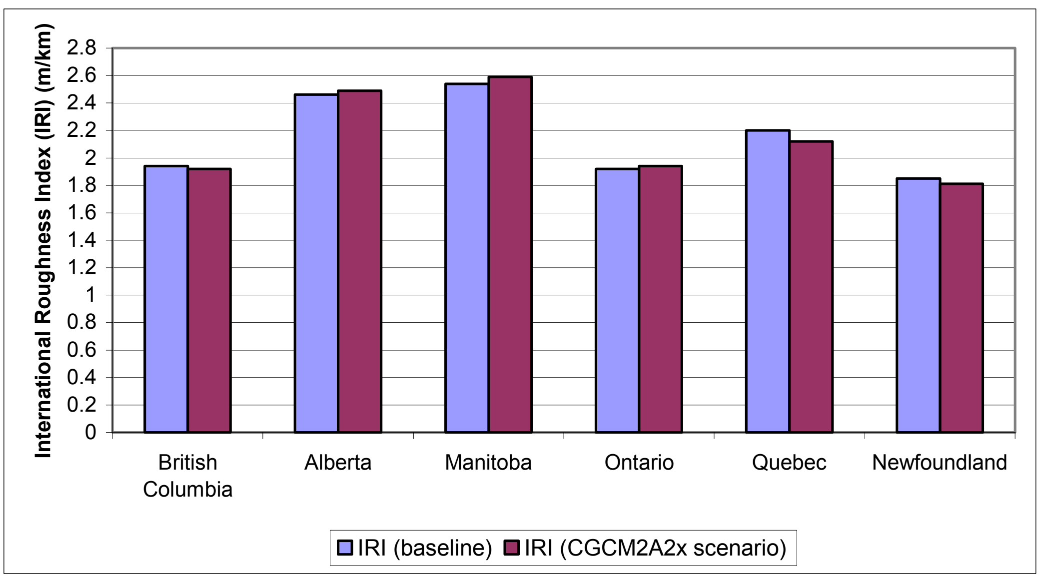


Figure 34. Changes in IRI resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

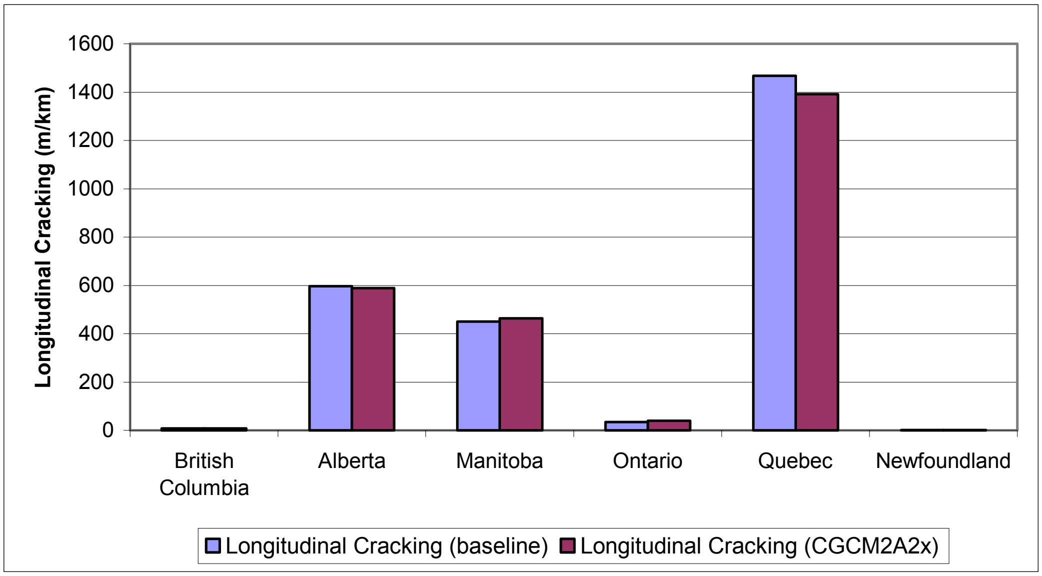


Figure 35. Changes in longitudinal cracking resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

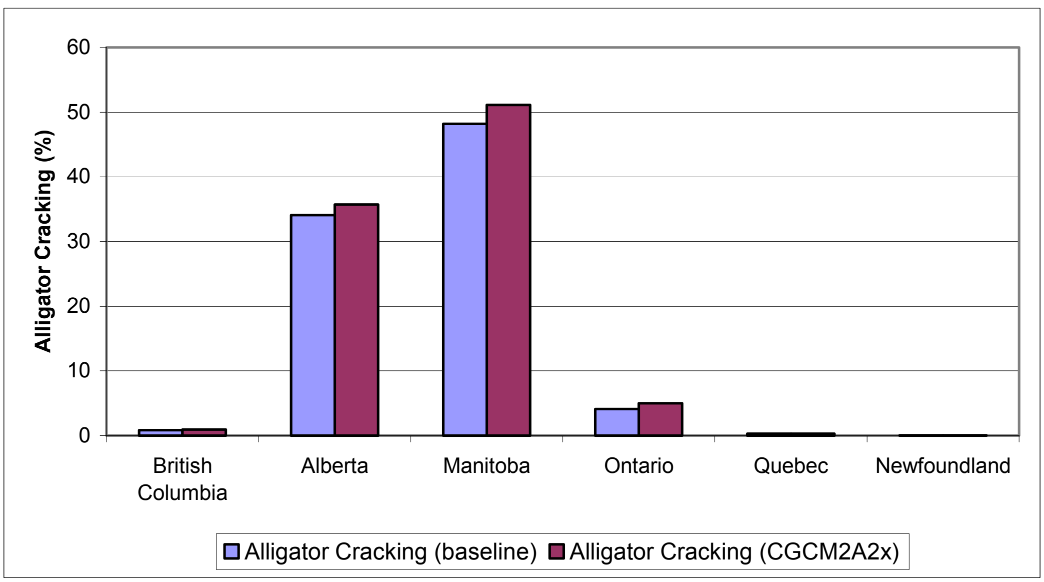


Figure 36. Changes in alligator cracking resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

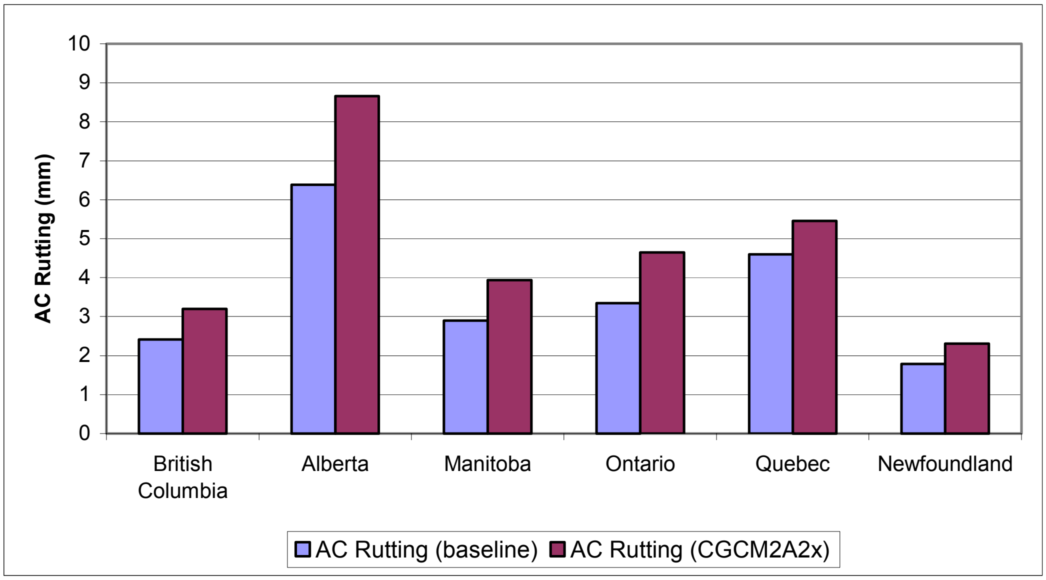


Figure 37. Changes in AC rutting resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

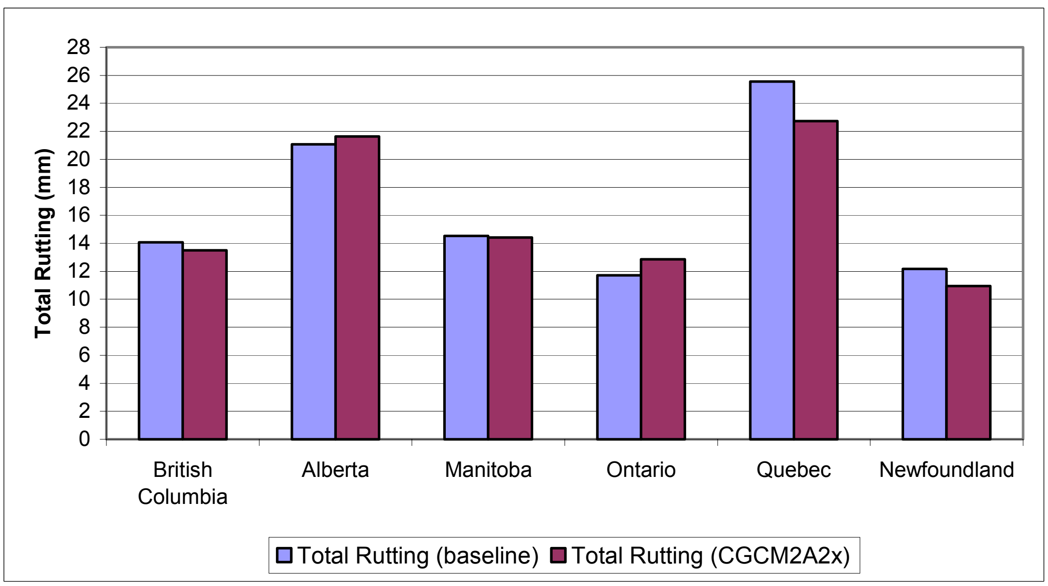


Figure 38. Changes in total rutting resulting from application of structure and traffic baselines from each study site to baseline climate and CGCM2A2x climate scenario data for Winnipeg, Manitoba

Combined Influence of Climate Change and Traffic Growth

While many structural factors or assumptions remain constant throughout the pavement design life, the amount of traffic does not. Loads in most regions of southern Canada are likely to increase through time in conjunction with trends in population and economic growth. In order to understand the effect of increasing traffic on baseline results, the MEPDG control data sets for each site were run again assuming a 4 percent per annum compound growth in Average Annual Daily Truck Traffic (AADTT). Four percent is a best practice value and is suitable for estimating AADTT growth over a 20-year design life. The resulting cumulative growth in heavy trucks for each site is illustrated in Figures 39-40.

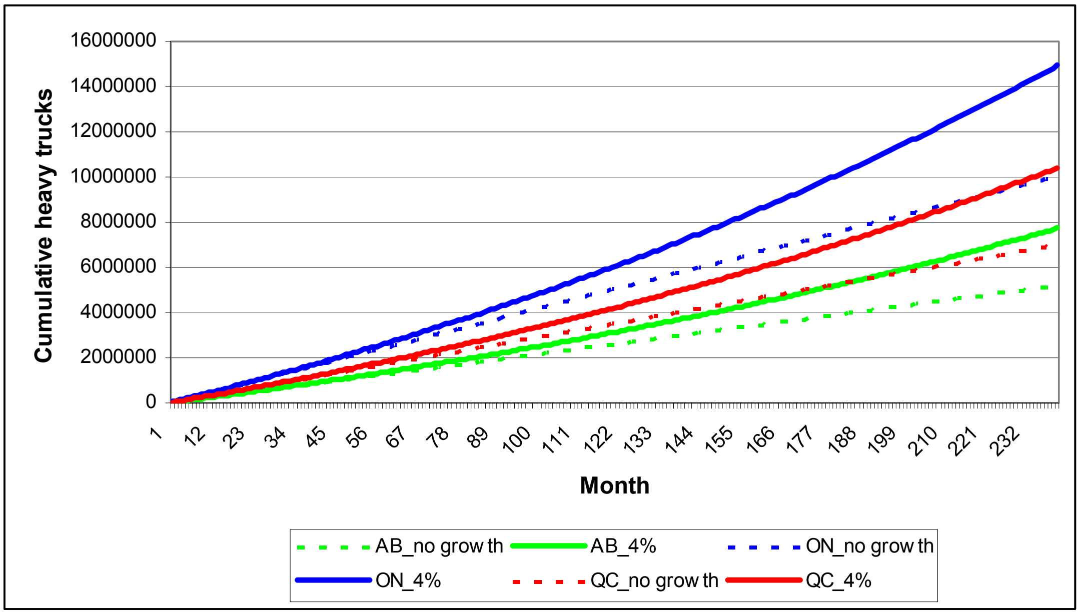


Figure 39. Changes in cumulative heavy trucks for no growth and 4 percent annual compound growth scenarios at Alberta, Ontario, and Manitoba sites

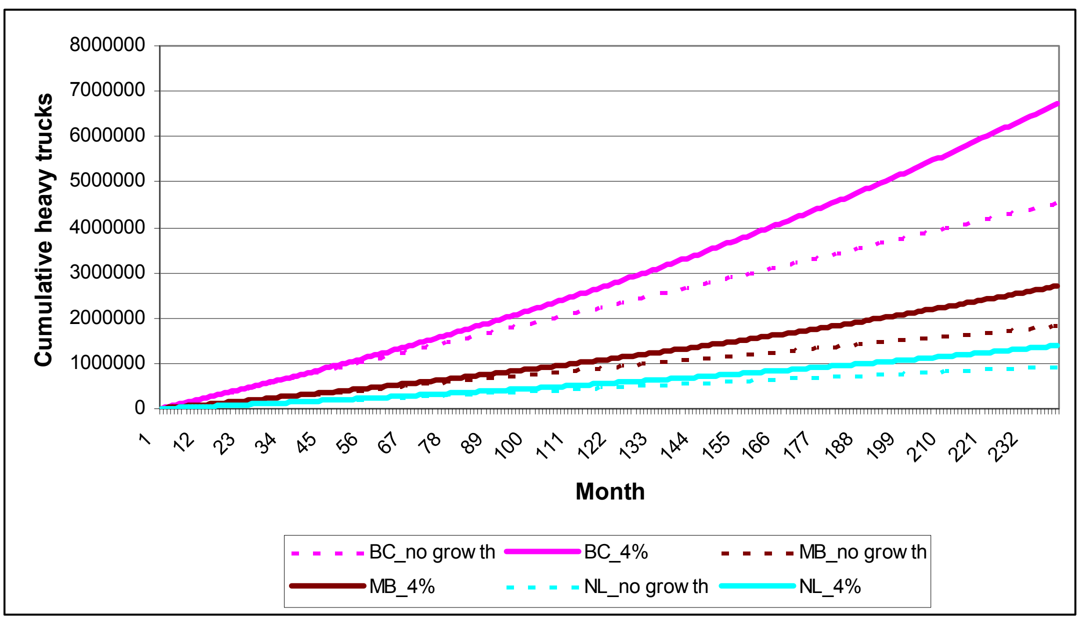


Figure 40. Changes in cumulative heavy trucks for no growth and 4 percent annual compound growth scenarios at Alberta, Ontario, and Manitoba sites

Results for both the static no growth and annual 4 percent growth scenarios, under baseline climate and climate change conditions, are presented in Tables 12-17. The tables are organized by performance parameter and include estimates of terminal deterioration and the timing of achieving maintenance-related thresholds. Terminal deterioration is expressed in absolute terms and as a relative percent of the control (no traffic growth, baseline climate) for each scenario combination. The timing of reaching critical thresholds is specified for both 50 and 90 percent reliability levels as determined by MEPDG.

As expected, greater loads induced greater terminal deterioration and earlier achievement of maintenance-related thresholds for all pavement distress indicators except for transverse cracking which is influenced primarily by climatic and material factors. Relative increases in AC and total rutting were consistent across all sites although somewhat less than the relative increase in terminal truck growth (49 percent). Increases in IRI and especially longitudinal and alligator cracking exhibited more variability across the sites. This observation is likely a function of the variability in pavement structures and baseline traffic volumes that was previously discussed.

The impacts of the CGCM2A2x and HadCM3B21 climate change scenarios relative to the no growth baseline that were described in detail for the first set of MEPDG analyses were generally unaffected by the application of a 4 percent per annum growth in traffic. While higher traffic loads increased the absolute deterioration and resulted in earlier achievement of maintenance-related thresholds, the relative changes from the CGCM2A2x or HadCM3B21 scenario to respective no growth and 4 percent growth traffic baseline climate scenarios did not deviate by more than 3 percent. This suggests that there is no significant synergistic effect between climate and traffic growth, as simulated through MEPDG.

Table 12. IRI performance results for all sites and scenarios

Case Study Site	International Roughness Index (IRI) m/km	Change relative to control (%)*	Years to 2.7 m/km maintenance threshold (50/90% reliability)* **
British Columbia			
CONTROL: Baseline climate + no traffic growth	1.55	-	nr/nr
CGCM2A2x + no traffic growth	1.54	-0.7	nr/nr
HadCM3B21 + no traffic growth	1.58	1.9	nr/nr
Baseline climate + 4% annual AADTT growth	1.58	1.9	nr/nr
CGCM2A2x + 4% annual AADTT growth	1.57	1.3	nr/nr
HadCM3B21 + 4% annual AADTT growth	1.61	3.9	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	2.34	-	nr/14.3
CGCM2A2x + no traffic growth	2.37	1.3	nr/13.9
HadCM3B21 + no traffic growth	2.38	1.7	nr/13.8
Baseline climate + 4% annual AADTT growth	2.53	8.1	nr/12.9
CGCM2A2x + 4% annual AADTT growth	2.59	10.7	nr/12.3
HadCM3B21 + 4% annual AADTT growth	2.60	11.1	nr/12.1
Manitoba			
CONTROL: Baseline climate + no traffic growth	2.54	-	nr/12.4
CGCM2A2x + no traffic growth	2.59	2.0	nr/12.0
HadCM3B21 + no traffic growth	2.60	2.4	nr/11.9
Baseline climate + 4% annual AADTT growth	2.85	12.2	18.9/11.0
CGCM2A2x + 4% annual AADTT growth	2.92	15.0	18.2/10.8
HadCM3B21 + 4% annual AADTT growth	2.95	16.1	18.1/10.8
Ontario			
CONTROL: Baseline climate + no traffic growth	1.92	-	nr/nr
CGCM2A2x + no traffic growth	1.94	1.0	nr/nr
HadCM3B21 + no traffic growth	1.95	1.6	nr/nr
Baseline climate + 4% annual AADTT growth	1.97	2.6	nr/nr
CGCM2A2x + 4% annual AADTT growth	1.99	3.7	nr/nr
HadCM3B21 + 4% annual AADTT growth	2.01	4.7	nr/nr
Quebec			
CONTROL: Baseline climate + no traffic growth	2.12	-	nr/17.8
CGCM2A2x + no traffic growth	2.10	-0.9	nr/18.3
HadCM3B21 + no traffic growth	2.11	-0.5	nr/17.9
Baseline climate + 4% annual AADTT growth	2.19	3.3	nr/16.8
CGCM2A2x + 4% annual AADTT growth	2.16	1.9	nr/17.1
HadCM3B21 + 4% annual AADTT growth	2.18	2.8	nr/16.8
Newfoundland			
CONTROL: Baseline climate + no traffic growth	1.79	-	nr/nr
CGCM2A2x + no traffic growth	1.77	-1.1	nr/nr
HadCM3B21 + no traffic growth	1.78	-0.6	nr/nr
Baseline climate + 4% annual AADTT growth	1.81	1.1	nr/nr
CGCM2A2x + 4% annual AADTT growth	1.79	0.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	1.80	0.6	nr/nr

*results rounded to one decimal place
**nr (not reached during 20-year design life)

Table 13. Longitudinal cracking performance results for all sites and scenarios

Case Study Site	Longitudinal Cracking*		
	m/km	Change relative to control (%)	Years to 378.8 m/km maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	6.8	-	nr/nr
CGCM2A2x + no traffic growth	6.7	-1.9	nr/nr
HadCM3B21 + no traffic growth	6.8	0.0	nr/nr
Baseline climate + 4% annual AADTT growth	12.0	76.3	nr/nr
CGCM2A2x + 4% annual AADTT growth	11.7	72.9	nr/nr
HadCM3B21 + 4% annual AADTT growth	12.0	76.8	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	551.1	-	14.8/1.8
CGCM2A2x + no traffic growth	602.3	9.3	13.7/1.0
HadCM3B21 + no traffic growth	583.3	5.8	13.8/1.7
Baseline climate + 4% annual AADTT growth	818.2	48.5	11.8/1.8
CGCM2A2x + 4% annual AADTT growth	873.1	58.4	10.8/1.0
HadCM3B21 + 4% annual AADTT growth	854.2	55.0	11.1/1.7
Manitoba			
CONTROL: Baseline climate + no traffic growth	450.8	-	17.1/1.8
CGCM2A2x + no traffic growth	464.0	2.9	16.8/1.8
HadCM3B21 + no traffic growth	464.0	2.9	16.9/1.8
Baseline climate + 4% annual AADTT growth	683.7	51.7	13.1/1.8
CGCM2A2x + 4% annual AADTT growth	697.0	54.6	12.9/1.8
HadCM3B21 + 4% annual AADTT growth	698.9	55.0	12.9/1.8
Ontario			
CONTROL: Baseline climate + no traffic growth	33.3	-	nr/11.8
CGCM2A2x + no traffic growth	33.9	1.7	nr/11.5
HadCM3B21 + no traffic growth	35.2	5.7	nr/11.1
Baseline climate + 4% annual AADTT growth	58.9	76.7	nr/9.8
CGCM2A2x + 4% annual AADTT growth	59.7	79.0	nr/9.4
HadCM3B21 + 4% annual AADTT growth	61.9	85.8	nr/9.2
Quebec			
CONTROL: Baseline climate + no traffic growth	1647.7	-	2.8/0.7
CGCM2A2x + no traffic growth	1647.7	0.0	3.0/0.6
HadCM3B21 + no traffic growth	1636.4	-0.7	3.0/0.6
Baseline climate + 4% annual AADTT growth	1789.8	8.6	2.8/0.7
CGCM2A2x + 4% annual AADTT growth	1789.8	8.6	2.9/0.6
HadCM3B21 + 4% annual AADTT growth	1784.1	8.3	2.9/0.6
Newfoundland			
CONTROL: Baseline climate + no traffic growth	5.3	-	nr/nr
CGCM2A2x + no traffic growth	5.6	5.4	nr/nr
HadCM3B21 + no traffic growth	5.6	4.3	nr/nr
Baseline climate + 4% annual AADTT growth	9.7	81.7	nr/nr
CGCM2A2x + 4% annual AADTT growth	10.2	91.2	nr/nr
HadCM3B21 + 4% annual AADTT growth	10.1	88.8	nr/nr

*results rounded to one decimal place
**nr (not reached during 20-year design life)

Table 14. Alligator cracking performance results for all sites and scenarios

Case Study Site	Alligator Cracking (%)* Coverage (%)	Change relative to control (%)	Years to 25% coverage maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	0.7	-	Nr/nr
CGCM2A2x + no traffic growth	0.7	7.5	Nr/nr
HadCM3B21 + no traffic growth	0.7	10.5	Nr/nr
Baseline climate + 4% annual AADTT growth	1.1	61.2	Nr/nr
CGCM2A2x + 4% annual AADTT growth	1.2	73.1	Nr/nr
HadCM3B21 + 4% annual AADTT growth	1.2	79.1	Nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	28.9	-	17.0/5.2
CGCM2A2x + no traffic growth	32.2	11.4	15.1/4.8
HadCM3B21 + no traffic growth	31.0	7.3	15.9/4.9
Baseline climate + 4% annual AADTT growth	40.5	40.1	13.8/4.9
CGCM2A2x + 4% annual AADTT growth	44.0	52.3	12.0/4.1
HadCM3B21 + 4% annual AADTT growth	42.9	48.4	12.8/4.8
Manitoba			
CONTROL: Baseline climate + no traffic growth	48.2	-	17.1/1.8
CGCM2A2x + no traffic growth	51.1	6.0	16.8/1.8
HadCM3B21 + no traffic growth	51.0	5.8	16.9/1.8
Baseline climate + 4% annual AADTT growth	59.8	24.1	7.1/2.1
CGCM2A2x + 4% annual AADTT growth	62.4	29.5	6.8/1.9
HadCM3B21 + 4% annual AADTT growth	62.4	29.5	6.8/2.0
Ontario			
CONTROL: Baseline climate + no traffic growth	4.6	-	nr/nr
CGCM2A2x + no traffic growth	5.1	10.5	nr/nr
HadCM3B21 + no traffic growth	5.2	13.1	nr/nr
Baseline climate + 4% annual AADTT growth	6.9	50.7	nr/20.0
CGCM2A2x + 4% annual AADTT growth	7.6	65.9	nr/18.9
HadCM3B21 + 4% annual AADTT growth	7.8	69.7	nr/18.5
Quebec			
CONTROL: Baseline climate + no traffic growth	0.5	-	nr/nr
CGCM2A2x + no traffic growth	0.5	4.4	nr/nr
HadCM3B21 + no traffic growth	0.5	2.2	nr/nr
Baseline climate + 4% annual AADTT growth	0.9	97.8	nr/nr
CGCM2A2x + 4% annual AADTT growth	0.9	104.4	nr/nr
HadCM3B21 + 4% annual AADTT growth	0.9	100.0	nr/nr
Newfoundland			
CONTROL: Baseline climate + no traffic growth	0.1	-	nr/nr
CGCM2A2x + no traffic growth	0.1	14.3	nr/nr
HadCM3B21 + no traffic growth	0.1	14.3	nr/nr
Baseline climate + 4% annual AADTT growth	0.1	71.4	nr/nr
CGCM2A2x + 4% annual AADTT growth	0.1	100.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	0.1	100.0	nr/nr

*results rounded to one decimal place
**nr (not reached during 20-year design life)

Table 15. Transverse cracking performance results for all sites and scenarios

Case Study Site	Transverse Cracking* m/km	Change relative to control (%)	Years to 189.4 m/km maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	19.1	-	nr/nr
CGCM2A2x + no traffic growth	0.6	-96.9	nr/nr
HadCM3B21 + no traffic growth	35.8	87.1	nr/nr
Baseline climate + 4% annual AADTT growth	19.1	0.0	nr/nr
CGCM2A2x + 4% annual AADTT growth	0.6	-96.9	nr/nr
HadCM3B21 + 4% annual AADTT growth	35.8	87.1	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.3/0.3
CGCM2A2x + no traffic growth	399.6	0.0	0.3/0.3
HadCM3B21 + no traffic growth	399.6	0.0	0.3/0.3
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.3/0.3
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	0.3/0.3
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.3/0.3
Manitoba			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.3/0.3
CGCM2A2x + no traffic growth	399.6	0.0	0.4/0.3
HadCM3B21 + no traffic growth	399.6	0.0	0.4/0.4
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.3/0.3
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	0.4/0.3
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.4/0.4
Ontario			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.5/0.5
CGCM2A2x + no traffic growth	399.6	0.0	1.5/1.4
HadCM3B21 + no traffic growth	399.6	0.0	0.5/0.5
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.5/0.5
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	1.5/1.4
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.5/0.5
Quebec			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.4/0.4
CGCM2A2x + no traffic growth	399.6	0.0	0.4/0.4
HadCM3B21 + no traffic growth	399.6	0.0	0.5/0.5
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.4/0.4
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	0.4/0.4
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.5/0.4
Newfoundland			
CONTROL: Baseline climate + no traffic growth	399.6	-	0.5/0.5
CGCM2A2x + no traffic growth	399.6	0.0	1.6/1.4
HadCM3B21 + no traffic growth	399.6	0.0	0.6/0.5
Baseline climate + 4% annual AADTT growth	399.6	0.0	0.5/0.5
CGCM2A2x + 4% annual AADTT growth	399.6	0.0	1.6/1.4
HadCM3B21 + 4% annual AADTT growth	399.6	0.0	0.6/0.5

*results rounded to one decimal place
**nr (not reached during 20-year design life)

Table 16. AC rutting performance results for all sites and scenarios

Case Study Site	Asphalt Concrete (AC) Rutting*		
	mm	Change relative to control (%)	Years to 6.4 mm maintenance threshold (50% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	2.1	-	nr
CGCM2A2x + no traffic growth	2.5	16.9	nr
HadCM3B21 + no traffic growth	2.5	19.3	nr
Baseline climate + 4% annual AADTT growth	2.6	21.6	nr
CGCM2A2x + 4% annual AADTT growth	3.0	40.9	nr
HadCM3B21 + 4% annual AADTT growth	3.1	44.1	nr
Alberta			
CONTROL: Baseline climate + no traffic growth	5.5	-	nr
CGCM2A2x + no traffic growth	6.8	22.7	17.1
HadCM3B21 + no traffic growth	7.3	31.8	14.9
Baseline climate + 4% annual AADTT growth	6.6	20.3	19.0
CGCM2A2x + 4% annual AADTT growth	8.1	47.0	13.1
HadCM3B21 + 4% annual AADTT growth	8.7	58.1	11.9
Manitoba			
CONTROL: Baseline climate + no traffic growth	2.9	-	nr
CGCM2A2x + no traffic growth	3.9	35.9	nr
HadCM3B21 + no traffic growth	3.9	34.1	nr
Baseline climate + 4% annual AADTT growth	3.5	21.0	nr
CGCM2A2x + 4% annual AADTT growth	4.7	62.8	nr
HadCM3B21 + 4% annual AADTT growth	4.7	60.3	nr
Ontario			
CONTROL: Baseline climate + no traffic growth	4.2	-	nr
CGCM2A2x + no traffic growth	5.4	27.0	nr
HadCM3B21 + no traffic growth	5.4	28.9	nr
Baseline climate + 4% annual AADTT growth	5.1	21.1	nr
CGCM2A2x + 4% annual AADTT growth	6.5	52.8	19.1
HadCM3B21 + 4% annual AADTT growth	6.6	55.2	19.0
Quebec			
CONTROL: Baseline climate + no traffic growth	5.3	-	nr
CGCM2A2x + no traffic growth	6.1	13.9	nr
HadCM3B21 + no traffic growth	6.2	16.8	nr
Baseline climate + 4% annual AADTT growth	6.5	21.5	19.9
CGCM2A2x + 4% annual AADTT growth	7.3	37.9	16.1
HadCM3B21 + 4% annual AADTT growth	7.5	41.1	15.8
Newfoundland			
CONTROL: Baseline climate + no traffic growth	1.2	-	nr
CGCM2A2x + no traffic growth	1.5	21.9	nr
HadCM3B21 + no traffic growth	1.5	21.9	nr
Baseline climate + 4% annual AADTT growth	1.4	19.3	nr
CGCM2A2x + 4% annual AADTT growth	1.8	47.1	nr
HadCM3B21 + 4% annual AADTT growth	1.8	47.1	nr

*results rounded to one decimal place
**nr (not reached during 20-year design life)

Table 17. Total rutting performance results for all sites and scenarios

Case Study Site	Total Rutting (all layers)*		
	mm	Change relative to control (%)	Years to 19.1 mm maintenance threshold (50/90% reliability)**
British Columbia			
CONTROL: Baseline climate + no traffic growth	10.7	-	nr/nr
CGCM2A2x + no traffic growth	11.1	3.8	nr/nr
HadCM3B21 + no traffic growth	11.2	4.8	nr/nr
Baseline climate + 4% annual AADTT growth	11.6	8.5	nr/nr
CGCM2A2x + 4% annual AADTT growth	12.0	12.8	nr/nr
HadCM3B21 + 4% annual AADTT growth	12.1	13.8	nr/nr
Alberta			
CONTROL: Baseline climate + no traffic growth	19.0	-	nr/8.0
CGCM2A2x + no traffic growth	18.9	-0.5	nr/8.8
HadCM3B21 + no traffic growth	19.9	4.7	16.7/7.0
Baseline climate + 4% annual AADTT growth	20.8	9.3	14.9/7.0
CGCM2A2x + 4% annual AADTT growth	20.9	9.6	15.1/7.8
HadCM3B21 + 4% annual AADTT growth	22.0	15.7	12.9/6.8
Manitoba			
CONTROL: Baseline climate + no traffic growth	14.5	-	nr/nr
CGCM2A2x + no traffic growth	14.4	-0.9	nr/nr
HadCM3B21 + no traffic growth	14.9	2.3	nr/nr
Baseline climate + 4% annual AADTT growth	15.8	8.5	nr/nr
CGCM2A2x + 4% annual AADTT growth	15.8	8.7	nr/20.0
HadCM3B21 + 4% annual AADTT growth	16.3	12.0	nr/18.8
Ontario			
CONTROL: Baseline climate + no traffic growth	12.1	-	nr/nr
CGCM2A2x + no traffic growth	13.2	9.0	nr/nr
HadCM3B21 + no traffic growth	13.3	10.3	nr/nr
Baseline climate + 4% annual AADTT growth	13.3	10.3	nr/nr
CGCM2A2x + 4% annual AADTT growth	14.6	21.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	14.8	22.7	nr/nr
Quebec			
CONTROL: Baseline climate + no traffic growth	21.8	-	10.9/4.3
CGCM2A2x + no traffic growth	21.1	-3.2	13.0/5.1
HadCM3B21 + no traffic growth	21.6	-0.8	11.9/4.8
Baseline climate + 4% annual AADTT growth	23.9	9.3	8.9/3.8
CGCM2A2x + 4% annual AADTT growth	23.2	6.1	10.8/4.9
HadCM3B21 + 4% annual AADTT growth	23.8	8.9	9.8/4.3
Newfoundland			
CONTROL: Baseline climate + no traffic growth	9.1	-	nr/nr
CGCM2A2x + no traffic growth	9.0	-1.1	nr/nr
HadCM3B21 + no traffic growth	9.1	0.6	nr/nr
Baseline climate + 4% annual AADTT growth	9.8	8.1	nr/nr
CGCM2A2x + 4% annual AADTT growth	9.7	7.0	nr/nr
HadCM3B21 + 4% annual AADTT growth	9.9	9.0	nr/nr

*results rounded to one decimal place
**nr (not reached during 20-year design life)

3.3 Discussion and Limitations

As with other forms of infrastructure, the fundamental concern related to a changing climate in pavement design and management is the potential for premature design failure. Current and past designs generally assume a static climate whose variability can be adequately determined from records of weather conditions which normally span less than 30 years and often less than 10 years. The notion of anthropogenic climate change challenges this assumption and raises the possibility that the frequency, duration or severity of thermal cracking, rutting, frost heave and thaw weakening may be altered leading to premature deterioration as indicated by trends in one or more of the performance indicators described earlier. The case studies provided empirical evidence to support this contention for several sites in Canada. The analysis of deterioration-relevant climate indicators at 17 sites suggests that, over the next 50 years, low temperature cracking will become less problematic; structures will freeze later and thaw earlier with correspondingly shorter freeze season lengths; and higher extreme in-service pavement temperatures will raise the potential for rutting. Evidence from the 6 sites examined in the MEPDG analysis was not as universal but nonetheless suggests that rutting (AC and total) and cracking (longitudinal and alligator) issues will be exacerbated by climate change with transverse cracking becoming less of a problem. In general, maintenance, rehabilitation or reconstruction will be required earlier in the design life. As important, the MEPDG analysis indicates that the absolute impacts of climate change are intimately tied to the type of structure, materials, and traffic conditions experienced at a particular site—to such an extent that a formal aggregate analysis of economic impacts was beyond the scope of the current investigation.

The results of this study are dependent on many assumptions, particularly those concerning representativeness of sites and manipulation of climate scenarios. Site selection for both case studies was driven by data availability (e.g., LTPP, Environment Canada) and engineering expertise. Every effort was made to select sections that were representative of climates typically experienced in southern Canada. Additional sites that capture an even broader range of climates and pavement structures found within Canada could have been analyzed and a greater number of climate change scenarios, and alternative or more sophisticated means of downscaling scenario data, could have been incorporated into the research—with concomitant increases in costs. While such additions would no doubt contribute to greater confidence in the results, it is likely that the general findings would not change significantly.

Accordingly, the discussion turns to an interpretation of results into practical recommendations for adaptation—the final steps in the climate impact assessment model proposed by Carter *et al*. (1999). The literature review and stakeholder discussions confirmed that technologies already exist to adequately manage any of the impacts uncovered in this study. By purposely applying design tools or thresholds presently used in pavement engineering research and practice (e.g., PGAC, freeze-thaw indices, MEPDG) to assess impacts, the authors also confirmed their efficacy at detecting changes associated with climate. None of the potential impacts suggested through this study fall beyond the range of conditions presently experienced in North America—analogous pavement structures and environmental and traffic situations abound among the agencies represented in the LTPP database. PG ratings and other material properties can be adjusted and structural designs can be strengthened for new asphalt pavements. Maintenance schedules can be advanced (or deferred) and systems can be put in place to monitor and predict freezing and thawing effects on pavement strength and restrict traffic accordingly.

For large, well-funded road authorities that manage much of the primary paved road network in Canada, the key adaptation issues will surround not how to deal with potential impacts but rather when to modify current design and maintenance practices. The basis for such decisions often falls back to an assessment of relative costs (between status quo and various designs or interventions) borne by the public, road users and, to the extent permitted in contractual agreements, by private sector construction and maintenance providers. As introduced in the literature review, pavement management systems and tools such as Life Cycle Cost Analysis (LCCA) are available to determine when a particular maintenance (e.g., crack sealing, patching, etc.), rehabilitation (e.g., AC overlay, cold in place recycling, etc.) or reconstruction activity should be implemented for a given network and section. The addition of climate change scenarios to typical 20+ year design evaluations into the LCCA process—essentially an extension of the MEPDG applications used in the current study—could be readily used to support future decisions. Regardless of future climate change, the reliability of such design evaluations could be improved by considering longer time series of climatic data to capture more variability.

Unfortunately, not all road authorities are equal in terms of the financial resources, technical expertise, and monitoring and information infrastructure available to implement and sustain a modern pavement management system. This concern may apply to secondary and tertiary low volume road networks that receive lower priority in larger agencies but is likely most relevant to rural and small urban local or municipal agencies where monitoring and modeling capacity may be limited and where engineering judgement is the basis for most decisions. Municipal partnerships and associations (e.g., Ontario Good Roads Association) and less formal collaborations will be critical in ensuring that these important elements of the road transportation system become aware of, monitor, and manage potential climate change impacts through emerging best practices.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

Relatively little research has been completed to investigate the potential impacts of climate change on pavement infrastructure despite the dependence of Canadian economic and social activity on road transport, and the documented influence of climate and other environmental factors on the deterioration of pavements. The influence of environmental factors has received considerable attention. The review of pavement management practices and engineering models and approaches used to monitor, assess and predict flexible pavement performance revealed that climate—and thus potentially climate change—is an important consideration in at least three deterioration processes: thermal cracking, frost heave and thaw weakening, and rutting. As with other forms of infrastructure, the fundamental concern related to a changing climate in pavement management is the potential for premature design failure.

Two sets of case studies were undertaken in order to investigate these generalized impacts of climate change in greater detail. Results for both are contingent on the realization of mid-century changes in climate derived from the CGCM2A2x and HadCM3B21 scenarios. These scenarios are moderate compared to those from other models.

The first case study examined deterioration-relevant climate indicators that are routinely applied or referenced in the management of pavement infrastructure for 17 Canadian sites. Main conclusions are noted below:

- Extreme annual minimum and 7-day mean maximum temperatures increased at all 17 sites under climate change scenarios relative to the baseline. Greater changes were apparent under the CGCM2A2x scenario as compared to the HadCM3B21 scenario.
- Increases in extreme annual minimum and 7-day mean maximum pavement temperatures derived from Superpave and RWIS-based equations were also observed, roughly proportional to changes in air temperature. This has important implications to the determination of appropriate Performance Grade (PG) ratings for asphalt cements.
- Minimum PG design temperature ratings as determined through the Superpave equation did not change relative to the baseline under the HadCM3B21 scenario. However, 7 of 17 sites warmed up by one PG category when CGCM2A2x scenario conditions were considered. Results were similar when based on the RWIS-derived pavement temperature equation.
- Maximum PG design temperature ratings as determined through the Superpave equation increased relative to the baseline by one increment at 6 of 17 sites under the HadCM3B21 scenario and at 4 sites under CGCM2A2x conditions.
- The RWIS-derived maximum pavement temperature equation produced more extreme results than the Superpave model. PG ratings at 13 sites increased by at least one increment under the HadCM3B21 climate change scenario and eleven of these sites also increased by one increment under the CGCM2A2x scenario. The inconsistency between RWIS and Superpave findings most likely relates to limitations in the range of air and pavement temperatures contained in the dataset used to derive the RWIS-equation.
- Large changes are also expected in the timing of the seasonal freeze and thaw and duration of the freeze season. Under the more extreme CGCM2A2x scenario, significant penetrations of frost into road structures may occur less than 50 percent of years in the B.C. Interior, southern Ontario, and coastal areas of Atlantic Canada. At other locations, freeze-up may be delayed from

1-4 weeks compared to current experience. The timing of critical thaw conditions will also be affected, in general occurring much earlier (10-31 days) than at present for the sites evaluated.
- More conservative results were associated with the HadCM3B21 scenario. Median critical freeze-up occurred 1-2 weeks later relative to the baseline for most sites and up to 28 days later for Kelowna, Windsor, Toronto, Halifax and St. John's. Critical thaw conditions occurred from 2 days to 2 weeks earlier than the baseline.
- The net effect of later freeze-up and earlier thaw is a reduced freeze season. Average freeze seasons were shortened by 8 percent at the Winnipeg site (HadCM3B21 scenario) to 98 percent at the Windsor and St. John's site (CGCM2A2x scenario). Where mean season length remained relatively long under the climate change scenarios (i.e., > 50 days), the standard deviation increased relative to the baseline. The greater variability between years may make management of SLRs and WWPs much more difficult as conditions transition under climate change.

The second set of case studies were conducted using the Mechanistic-Empirical Pavement Design Guide (MEPDG) and software, a new tool developed through the NCHRP/AASHTO. MEPDG was used to examine the relative impact of assumptions concerning pavement structure, material characteristics, traffic loads, and changes in climate on pavement performance. Main conclusions from the 6 sites studied include the following:

- Terminal pavement deterioration as modeled through MEPDG for 6 sites and reported in terms of IRI, AC and total rutting, and longitudinal, alligator, and transverse cracking, is sensitive to changes in climate.
- Differences between baseline and future climate scenarios were greatest for AC rutting (14-36 percent increase) across the sites. The increase in AC rutting was offset by decreased rutting in lower layers which resulted in small increases (1-10 percent) or slight reductions (1-3 percent) in total rutting relative to the baseline. This result is consistent with the combined effects of higher asphalt temperatures and less penetration of frost into lower layers. The differences between the CGCM2A2x and HadCM3B21 scenarios were generally less than 3 percent.
- Modest increases were generally observed for the various cracking parameters under climate change conditions relative to the baseline. Slight reductions (0-2 percent) in longitudinal cracking were observed for the Quebec and British Columbia sites with somewhat larger increases (0-9 percent) at the other sites. Alligator cracking increased at all locations from 2-14 percent. Minimal differences (3 percent or less) existed between the climate change scenarios except for transverse cracking at the British Columbia site.
- Very small changes in terminal IRI were observed between the baseline and future climate scenarios for all sites (-1 to 2 percent).
- Changes in terminal deterioration were reflected in the amount of estimated time required to reach critical maintenance thresholds for each performance parameter at 50 and 90 percent reliability levels. For both the baseline and future climate scenarios, about one-third of the total possible parameter limits were reached at the 50 percent reliability level while just over one-half of the thresholds were met at the 90 percent reliability level. At most sites, the general effect of the climate change scenarios was to reduce the amount of time until thresholds were met for longitudinal cracking, alligator cracking, IRI, and AC rutting, and to delay achievement of total rutting and transverse cracking limits. Relative changes between the baseline and climate change scenarios were typically small, ranging from 1-5 years at 50 percent reliability and generally less than 1 year at the 90 percent reliability level.
- The 4 percent per annum traffic growth scenario increased the absolute levels of pavement deterioration and resulted in earlier achievement of maintenance-related thresholds. However, the relative impact of climate change when evaluated under a scenario of increasing traffic was

found to be similar to that observed with no growth in traffic (less than 3 percent difference). This suggests that there is no substantive synergistic effect between climate and traffic growth, as simulated through MEPDG.

- The combined differences in pavement structure, materials, and baseline traffic, are relatively more important than climate in determining pavement deterioration and performance over its design life. The analysis of all 6 structures using baseline climate and future climate scenarios for Winnipeg, Manitoba also revealed that the AC rutting parameter is the most sensitive to shifts in climate relative to variations in structure and traffic levels; longitudinal and alligator cracking were least-sensitive. Both the magnitude and direction of pavement deterioration impacts associated with climate change were influenced by structural and traffic assumptions which suggests an interactive effect. Not surprisingly, weaker structures subject to relatively high base loads seem most vulnerable to changes in climate.

Pavement management systems in Canada are carefully engineered and adaptive. None of the potential impacts of climate change suggested through this study fall beyond the range of conditions presently experienced in North America. Material and other construction, monitoring, and maintenance technologies exist to manage all of the identified problems and it is highly likely that agencies will make the necessary adjustments and investments (e.g., higher PGs) to preserve the primary paved network. However, the more significant impacts associated with changes in climate may well be realized on the secondary or tertiary networks of provincial and municipal agencies where weak pavement structures coincide with excessive traffic loads.

4.2 Recommendations

Results from this study should be thoroughly discussed within the engineering community. Moving from exploratory research that raises awareness of climate change to practical guidance aimed at reducing costs and safeguarding infrastructure will require additional effort and collaboration. To this end, the authors will continue to take advantage of opportunities to present and deliberate findings at meetings of the Transportation Association of Canada, Canadian Technical Asphalt Association, and Transportation Research Board.

Pavement engineers, with assistance from government and academic climate change experts, should be encouraged to develop a protocol or guide for considering potential climate change in the development and evaluation of future designs and maintenance programs. Such an activity might be initiated through the Transportation Association of Canada or other multi-stakeholder association and leverage existing activities such as the implementation of MEPDG in Canada and the Canadian Climate Change Scenarios Network (CCSN). Incorporating other climate-related road infrastructure issues, for instance those associated with concrete pavements, surface-treated roads, airfields, bridges and culverts, would also be beneficial.

Environment Canada and other agencies should work with pavement engineers to facilitate greater application of environmental data in the design process and operational management of road networks. At a minimum, long time series of historic climatic and road weather observations—ideally greater than 30 years in the case of climate—should be incorporated into analyses of pavement deterioration and applicability of SLRs and WWPs or assignment of performance graded materials.

In terms of future research, more analysis is required to understand the interactive effects among environmental, structural, traffic, maintenance, and construction variables. Additional studies should be conducted to assess the implications of climate variability and change on the more vulnerable elements of the road network, including municipal roads and components of the provincial networks subject to SLRs. In particular, there is a need to further explore the influence of variable sequences of climate events from construction to reconstruction using a combination of simulation (i.e., MEPDG), laboratory material testing, and distress survey data. Where possible, this research should be conducted through partnerships with specific agencies. As an example, members of the project team, led by Dr. Tighe, are working with the Ministry of Transportation of Ontario to better utilize RWIS in SLR applications (Huen *et al*., 2006).

5.0 REFERENCES

Abaza, K.A. 2002. Optimal flexible pavement life-cycle analysis model, *Journal of Transportation Engineering*, 128(6):542-549.

Al Assar, R., Z. He, S. Tighe and R. Haas. 2000 Simplified User Delay Cost Model For Pavement and Bridge Life Cycle Analysis. CD-ROM proceedings of the Transportation Association of Canada Annual Conference, Regina, AB.

Al-Masaeid, H.R. 1997. Impact of pavement conditions on rural road accidents, Canadian Jounral of Civil Engineering, 24:523-531.

Andrey, J and A. Snow 1998. Transportation Sector, in *Canada Country Study: Climate Impacts and Adaptations, Volume VII, National Sectoral Volume,* Chapter 8, pp. 405-447. Environment Canada.

Andrey, J., B. Mills, B. Jones, R. Haas and W. Hamlin, 1999. *Adaptation to Climate Change in the Canadian Transportation Sector*. Report submitted to Natural Resources Canada, Adaptation Liaison Office, Ottawa, Ontario.

Andrey, J. 2000. The transportation imperative: risks of mobility and mobility-related risks. *The Canadian Geographer,* 44:387-400.

Andrey, J., B. Mills and J. Vandermolen. 2001. *Weather Information and Road Safety*. ICLR Paper Series No.15, Institute for Catastrophic Loss Reduction, London, Ontario. 36 pp.

Andrey, J. and B. Mills 2003. Climate Change Impacts and Adaptation: A Canadian Perspective—Transportation. Report prepared for Transport Canada. University of Waterloo, Department of Geography and Adaptation and Impacts Research Group, MSC, Waterloo, Canada.

Andrey, J., B. Mills, F.J.Warren and D.S. Lemmen 2004. Transportation, Chapter 8 in D.S. Lemmen and F.J. Warren (Eds.) *Climate Change Impacts and Adaptation: A Canadian Perspective*. Government of Canada, Ottawa. pp. 131-149. http://adaptation.nrcan.gc.ca/perspective/index_e.php

Archilla, A.R. and S. Madanat 2001. Estimation of rutting models by combining data from different sources, *Journal of Transportation Engineering*, 127(5):379-389.

Arenson, L.U., D.C. Sego, and G. Newman. 2006. The use of a convective heat flow model in road designs for Northern regions. CD Proceedings of the EIC Climate Change Technology Conference, Engineering Institute of Canada, Ottawa, May 10-12, 2006. ISBN 1-4244-0218-2. 8pp.

AASHTO 1993. *AASHTO Guide for Design of Pavement Strutures*. American Association of State Highway and Transportation Officials, Washington, D.C.

ARA Inc. 2004. Environmental effects, Part 2, chapter 3 in NCHRP, *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. 50pp.

Austroads 2004. *Impact of Climate Change on Road Infrastructure*. AP-R243. Austroads Incorporated, Sydney, Australia.

Barrow E., B. Maxwell, and P. Gachon (Eds.), (2004). *Climate Variability and Change in Canada: Past, Present and Future*, ACSD Science Assessment Series No. 2, Meteorological Service of Canada, Environment Canada, Toronto, Ontario, 114 p.

Berengier, M.C. and F. Anfosso-Ledee 1998. State-of-the-art prediction and control of road traffic noise in France, *Transportation Research Record*, 1626:71-77.

Beaulac, I., G. Doré, G. Grondin, and A. Guimond. 2006. Impacts de la fonte du pergélisol et adaptations des infrastructures de transport routier et aérien au Nunavik. CD Proceedings of the EIC Climate Change Technology Conference, Engineering Institute of Canada, Ottawa, May 10-12, 2006. ISBN 1-4244-0218-2. 11pp.

Birgisson, B. and B.E. Ruth 2003. Improving performance through consideration of terrain conditions - Soils, drainage, and climate, *Transportation Research Record*, 1819(1):369-377.

Birgisson, B., J. Ovik and D.E. Newcomb. 2000. Analytical predictions of seasonal variations in flexible pavements, *Transportation Research Record*, 1730:81-90.

Black, G.W. Jr. and L.E. Jackson 2000. Pavement surface water phenomena and traffic safety, *Institute of Transportation Engineers (ITE) Journal*, 70(2):32-37.

Boutonnet, M., P. Lerat, D. Saint-Laurent and Y. Savard. 2003. Thermal aspect of frost-thaw pavement dimensioning: In situ measurement and numerical modeling, *82nd Annual Meeting Preprint CD-ROM,* proceedings of the Transportation Research Board annual meeting, January 2003, Washington, D.C.

Brennan, D., U. Akpan, I. Konuk, A. Zebrowski. 2001. Random field modelling of rainfall induced soil movement. Report prepared for the Climate Change Action Fund, Natural Resources Canada. 85 pp.

Brown, W.G. 1964. Difficulties associated with predicting depth of freeze or thaw, *Canadian Geotechnical Journal*, 1:215-226.

Bruce, J.P., I. Burton, H. Martin, B. Mills and L. Mortsch 2000. *Water Sector: Vulnerability and Adaptation to Climate Change*. Final report prepared for Natural Resources Canada, Climate Change Action Fund. Global Change Strategies International Inc. and Meteorological Service of Canada, Ottawa. http://www.gcsi.ca/downloads/ccafwater.pdf.

Burton, I., R.W. Kates and G.F. White. 1993. *The Environment As Hazard*. The Guilford Press, New York.

Carter, T.R., M.L. Parry, S. Nishioka, and H. Harasawa 1994. *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Environmental Change Unit, University of Oxford and Center for Global Environmental Studies, London.

CCSN 2005. Canadian Climate Scenarios Network. Adaptation and Impacts Research Division, Environment Canada. http://www.ccsn.ca.

Chen, D.-H., D.-F. Lin and H.-L. Luo. 2003. Effectiveness of preventative maintenance treatments using fourteen SPS-3 sites in Texas, *Journal of Performance of Constructed Facilities*, 17(3):136-143.

Ciro, G.A. and M.C. Alfaro. 2006. Adaptation strategies for road embankments on permafrost affected by climate warming. CD Proceedings of the EIC Climate Change Technology Conference, Engineering Institute of Canada, Ottawa, May 10-12, 2006. ISBN 1-4244-0218-2. 10pp.

Clayton, A., J. Montufar, and R. McGregor 2006. *Using Intelligent Transportation Systems to Adapt to Potential Climate Change Impacts on Seasonal Truck Weight Limits*. Report prepared for the Climate Change Impacts and Adaptation Program, Natural Resources Canada. Transportation Information Group, University of Manitoba, and EBA Engineering Consultants Ltd., Winnipeg, MB. 60pp.

CMIP 2001. Coupled Model Intercomparison Project. http://www-pcmdi.llnl.gov/cmip/. Accessed June 2001.

Collop, A.C., D. Cebon and M.S.A. Hardy 1992. *A Visco-elastic Approach to Rutting in Flexible Pavements*, CUED/C-MECH/TR 49. University of Cambridge Transportation Research Group, Cambridge, UK. http://www-mech.eng.cam.ac.uk/trg/publications/downloads/damage/damage1.pdf

CRRL (Cold Regions Research and Engineering Lab) 2002. *Army MSSR* http://www.msrr.army.mil/index.cfm?top_level=ORG_A_1000136&taxonomy=ORG

CSHRP (Canadian Strategic Highway Research Program) 2000. *Seasonal Load Restrictions in Canada and around the World*. Technical Brief #21 http://www.cshrp.org/english/tech_briefs.html. Accessed June 18, 2004.

Dewan, S.A. and R.E. Smith. 2002. Estimating International Roughness Index from pavement distresses to calculate vehicle operating costs for the San Francisco Bay area, *Transportation Research Record*, 1816:65-72.

Dore, G. 1995. *The Development of Models to Predict Pavement Performance in Frost Conditions*. Prepared for the Canadian Strategic Highway Research Program. http://www.cshrp.org/products/bayesian/PQ/pqh1.htm

Doré, G., M. Flamand and P. Pascale. 2002. Anaysis of wavelength content of longitudinal profiles for C-LTPP test sections, *Canadian Journal of Civil Engineering*, 29: 50-57.

Easa, S.M., A. Shalaby, and A.O.A. El Halim 1996. Reliability-based model for predicting pavement thermal cracking, *Journal of Transportation Engineering*, 122(5):374-380.

El Hussein, H.M., K.W. Kim, and J. Penniah. 1998. Asphalt concrete damage associated with extreme low temperatures, *Journal of Materials in Civil Engineering*, 10(4):269-274.

Epps, A. 2000. Design and analysis system for thermal cracking in asphalt concrete, *Journal of Transportation Engineering*, 126(4):300-307.

FHWA. 1990. *An Advanced Course in Pavement Management Systems*. Federal Highway Administration, Course Notes, Washington, D.C.

Flato, G. and G.J. Boer. 2001. Warming asymmetry in climate change simulations, *Geophysical Research Letters*, 28(1):195-198.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C., and Weaver, A.J., 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate, *Climate Dynamics*, 16(6):451-467.

Fradette, N., P. Pascale, G. Doré and S. Hébert 2005. Evolution of pavement winter roughness, *84th Annual Meeting Preprint CD-ROM,* proceedings of the Transportation Research Board annual meeting, January 2005, Washington, D.C.

Fülöp, I.A., I. Bogardi, A. Gulyas and M. Csicsely-Tarpay 2000. Use of friction and texture in pavement performance modeling, *Journal of Transportation Engineering*, 126(3): 243-248.

Giese, J.K., R.J. Griffin, and D.A. Kuemmel 2001. Public perceptions of the Midwest's pavements: Explaining the relationship between pavement quality and driver satisfaction, *Transportation Research Record*, 1769:61-70.

Gołebiewski, R., R. Makarewicz, M. Nowak, and A. Preis 2003. Traffic noise reduction due to the porous road surface, *Applied Acoustics*, 64(5):481–494.

Goodman, S.N. 2001. Assessing variability of surface distress surveys in Canadian long-term pavement performance program, Transportation Research Record, 1764:112-118.

Gordon, C., C. Cooper, C.A. Senior, H. Banks, J.M. Gregory, T.C. Johns, J.F.B. Mitchell and R.A. Wood. 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Climate Dynamics*, 16:147-168.

Goyette, S., N. A. McFarlane, and G.M. Flato 2000. Application of the Canadian Regional Climate model to the Laurentian Great Lakes region: Implementation of a lake model, *Atmosphere-Ocean*, 38(3):481-503.

Haas, R., W. R. Hudson and J. Zaniewski. 1994. *Modern Pavement Management*. Kreiger Publishing Company, Florida.

Haas, R., W. R. Hudson and S. Tighe. 2001. Maximizing customer benefits as the ultimate goal of pavement management, National Academy Standard, 5th International Conference on Managing Pavements, Seattle Washington, August. 17 pp.

Haas, R. (ed.) 1997. *Pavement Design and Management Guide*. Transportation Association of Canada, Ottawa, ON.

Haas, R. 2001. Reinventing the (pavement management) wheel. Distinguished lecture, Fifth International Conference on Managing Pavements, August 11-14, 2001Seattle, WA.

Haas, R., L.C. Falls, D. MacLeod and S. Tighe. 2004. Climate impacts and adaptions on roads in Northern Canada, Cold Climates Conference, Regina, AB. 18 pp.

Haas, R., N. Li, and S. Tighe. 1999. *Roughness Trends at C-SHRP LTPP Sites*. Transportation Asscoiation of Canada, Ottawa, ON. 97 pp.

Hall, F., S. Wakefield, and A. Al-Kaisy 2001. Freeway quality of service: What really matters to drivers and passengers, *Transportation Research Record*, 1776:17-23.

Hassan, Y., S.M. Easa and A.O. Abd El Halim 1998. State-of-the-art of three-dimensional highway geometric design, *Canadian Journal of Civil Engineering*, 25(3):500-511.

He, Z., G. Kennepohl, Y. Cai, and R. Haas. 1997. Development of performance models for Ontario's new mechanistic-empirical pavement design method. Volume I, Proceedings of the 8th International Conference on Asphalt Pavements, Seattle, Washington. pp. 43-60.

Herman, S.C. (ed.) 1984. The Influence of Roadway Surface Discontinuities on Safety: A state-of-the-art Review. Transportation Research Board, Washington, D.C.

Heydinger, A.G. 2003. Evaluation of seasonal effects on subgrade soils, *Transportation Research Record*, 1821: 47-55.

Hinzman, L.D., N. Bettez, F.S. Chapin, M. Dyurgerov, C. Fastie, B. Griffith, R.D. Hollister, A. Hope, H.P. Huntington, A. Jensen, D. Kane, D.R. Klein, A. Lynch, A. Lloyd, A.D. McGuire, F. Nelson, W.C. Oechel,T. Osterkamp, C. Racine,V. Romanovsky, D. Stow, M. Sturm, C.E.Tweedie, G.Vourlitis, M.Walker, D.Walker, P.J.Webber, J.Welker, K.Winker and K.Yoshikawa. 2005. Evidence and implications of recent climate change in terrestrial regions of the Arctic, *Climatic Change*, 72: 251–298.

Hong, H.P., and S. Somo. 2001. Probabilistic assessment of pavement conditions, *Canadian Journal of Civil Engineering*, 28(5):813-822.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Da, K. Maskell, and C.A. Johnson (eds.) *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, 2001. http://www.grida.no/climate/ipcc_tar/wg1/index.htm. Accessed July 2002

Huen, K., S. Tighe, B. Mills, and C. Haas. 2006. *Using Road Weather Information Systems (RWIS) to Control Load Restrictions on Gravel and Surface Treated Highways: Phase I Final Report*. Prepared for the Highway Infrastructure Innovation Funding Program, Engineering Standards Branch, Ontario Ministry of Transportation. Department of Civil Engineering, University of Waterloo, Waterloo, ON. 63pp.

Innes, J.D., F.R. Wilson and D.R. Goguen. 1998. Designing skid resistance testing programs using videotaped road inventory data, *Canadian Journal of Civil Engineering*, 25(5):950-955.

Instanes, A., O. Anisimov, L. Brigham, D. Goering, L.N. Khrustalev, B. Ladanyi, and J.O. Larsen. 2005. Infrastructure: Buildings, Support Systems, and Industrial Facilities, chapter 16 in ACIA, *Arctic Climate Impact Assessment—Scientific Report*, Cambirdge University Press, New York. pp.907-944.

IPCC 2000. *Special Report on Emission Scenarios: Summary for Policymakers*. Special Report of IPCC Working Group III. WMO and UNEP. http://www.ipcc.ch/pub/sres-e.pdf. Accessed July 2002.

IPCC 2001. *Summary for Policymakers: A Report of Working Group I of the Intergovernmental Panel on Climate Change*. http://www.ipcc.ch/pub/spm22-01.pdf. Accessed June 2001.

IPCC 2007. *Climate Change 2007: The Physical Science Basis, Summary for Policymakers*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/.

IPCC-TGCIA 1999. Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version 1. Prepared by T.R. Carter, M. Hulme and M. Lal, Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69 pp.

Irwin, N.A., and W.F. Johnson. 1990. The implications of long-term climatic changes on transportation in Canada, Transportation Research Record, 1267:12-25.

Joint CSHRP/Quebec Bayesian Application Project. 2000a. *The Development of Models to Predict Pavement Performance in Frost Conditions: 7. Cracking Model*. www.cshrp.org/products/bayesian/PQ/pqh4.htm. Accessed June 18, 2004.

Joint CSHRP/Quebec Bayesian Application Project. 2000b. *The Development of Models to Predict Pavement Performance in Frost Conditions: 6. Roughness Model*. www.cshrp.org/products/bayesian/PQ/pqh3.htm. Accessed June 18, 2004.

Jong, D.-T., P.J. Bosscher and C.H. Benson. 1998. Field assessment of changes in pavement moduli caused by freezing and thawing, *Transportation Research Record*, 1615:41-48.

Kaku, J., M. Hiroe, S. Kuwano and S. Namba 2004. Sleep disturbance by traffic noise: an experimental study in subjects' own houses using a portable CD player, *Journal of Sound and Vibration*, 277(3): 459-464.

Kates, R.W., Ausubel, J.H. and M. Berberian (eds). 1985. *Climate Impact Assessment: Studies of the Interaction of Climate and Society*. John Wiley, New York.

Katz, R.W. 2002: Techniques for estimating uncertainty in climate change scenarios and impact studies. *Climate Research*, 20:167-185.

Kestler, M.A. 2003. Techniques for extending the life of low-volume roads in seasonal frost areas, *Transportation Research Record*, 1819: 275-284.

Kliewer, J.E., H. Zeng and T.S. Vinson. 1996. Aging and low-temperature cracking of asphalt concrete mixture, *Journal of Cold Regions Engineering*, 10(3):134-148.

Konrad, J.-M. and M. Shen. 1997. Prediction of the spacing between thermal contraction cracks in asphalt pavements, *Canadian Journal of Civil Engineering*, 24:288-302.

Landers, S., W. Bekheet, and L.C. Falls 2003. Cohen's weighted kappa statistic in quality control-quality assurance procedures: Application to network-level contract pavement surface condition surveys in British Columbia, Canada, *Transportation Research Record*, 1860:103-108.

Lee, C. and J. Rochat. 2002. FHWA Model Predicts Noise Impacts, *Public Roads*, 65(5), March/April.

Leong, P., S. Tighe and G. Doré. 2005. Using LTPP data to develop spring load restrictions: A pilot study, *84th Annual Meeting Preprint CD-ROM,* proceedings of the Transportation Research Board annual meeting, January 9-13, 2005, Washington, D.C.

Li, Y. and S. Madanat 2002. A steady-state solution for the optimal pavement resurfacing problem, *Transportation Research Part A*, 36:525-535.

Liu, C. and R. Herman. 1996. New approach to roadway performance indices, *Journal of Transportation Engineering*, 122(5):329-336.

Manitoba Transportation and Government Services. 2004. Manitoba's Spring Load Restriction Program. http://www.gov.mb.ca/tgs/transreg/compreg/spring-restrict.html Accessed June 18, 2004.

Marshall, C., R. Meier and M. Welch. 2001. Seasonal temperature effects on flexible pavements in Tennessee, *Transportation Research Record*, 1764: 89-96.

Masson, J.-F., P. Collins, and P.-P. Légaré. 1999. Performance of pavement crack sealants in cold urban conditions, *Canadian Journal of Civil Engineering*, 26(4):395-401.

Mehta, Y. and R. Roque 2003. Evaluation of FWD data for determination of layer moduli of pavements, *Journal of Materials in Civil Engineering*, 15(1):25-31.

Mills, B. and Andrey, J. 2003. Climate Change and Transportation: Potential Interactions and Impacts. Proceedings of the Potential Impacts of Climate Change on Transportation workshop, October 1-2, 2002, Washington, D.C. USDOT Center for Climate Change and Environmental Forecasting and Federal Research Partnership (DOT, DOE, EPA, USGCRP).

Minnesota DOT (Department of Transportation) 2004. *Spring Load Restrictions*. http://www.mrr.dot.state.mn.us/research/seasonal_load_limits/thawindex/thawdefs.asp Accessed June 18, 2004.

Mishalani, R. and A. Kumar 2005. Impacts of temperature time series on pavement rutting progression, *84th Annual Meeting Preprint CD-ROM,* proceedings of the Transportation Research Board annual meeting, January 2005, Washington, D.C.

Montufar, J. and A. Clayton. 2002. Seasonal weight limits on prairie region highways: opportunities for rationalization and harmonization, *Canadian Journal of Civil Engineering*, 29: 8-16.

Monutfar, J. and R. McGregor 2006. Using Intelligent Transportation Systems to Adapt to Potential Climate Change Impacts on Seasonal Truck Weight Limits. CD Proceedings of the EIC Climate Change Technology Conference, Engineering Institute of Canada, Ottawa, May 10-12, 2006. ISBN 1-4244-0218-2.

Moreno, R.A. *et al.* 1996. Industry, Energy and Transportation: Impacts and Adaptation, in R.T.Watson, M.C.Zinyowera, R.H.Moss (eds.) *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, contribution of Working Group II to the Second Assessment of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK. pp. 364-398.

MTO 1989. Manual for Condition Rating of Flexible Pavements Distress Manifestations, SP-024. Ministry of Transportation of Ontario, Downsview, Ontario.

MTO 2006. Road Weather Information System data for New Liskeard, Long Lac, and Gormley sites. Ministry of Transportation of Ontario, St. Catharines, Ontario.

NBDOT (New Brunswick Department of Transportation) 1995. *Prediction of Rutting in Alternative Asphalt Concrete Overlay Methods*. Research Section, Engineering Services Division. http://www.cshrp.org/products/bayesian/nb/nbtoc.htm

NCHRP 2002a. Contributions of Pavement Structural Layers to Rutting of Hot Mix Asphalt Pavements, NCHRP Report 468. National Cooperative Highway Research Program, Transportation Research Board, National Research Council. Washington, D.C. http://gulliver.trb.org/publications/nchrp/nchrp_rpt_468-c.pdf

NCHRP 2002b. Flexible Pavement Design and Rehabilitation Procedure, NCHRP Project 1-37A. National Cooperative Highway Research Program, Transportation Research Board, National Research Council. Washington, D.C. http://www.2002designguide.com/presentations%202003/TRB2003Flexible.pdf

NCHRP 2004a. Public Benefits of Highway System Preservation and Maintenance, NCHRP Synthesis 330. National Cooperative Highway Research Program, Transportation Research Board, National Research Council. Washington, D.C.

NCHRP 2004b. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Washington, D.C. http://www.trb.org/mepdg/home.htm.

NCHRP 2006a. Independent review of Mechanistic-Empirical Design Guide and Software, *Research Results Digest 307*, National Cooperative Highway Research Program, Transportation Research Board. 32pp.

NCHRP 2006b. Changes to the Mechanistic-Empirical Design Guide Software through version 9.000, July 2006, *Research Results Digest 308*, National Cooperative Highway Research Program, Transportation Research Board. 22pp.

Nikolaides, A. 2000. Rutting and volumetric properties of SMA mixtures, *Proceedings of the Institution of Civil Engineers, Transportation*, 141(3): 135-141.

Nix, F.P., M. Boucher and B. Hutchinson 1992. Road costs, in *Directions: The Final Report of the Royal Commission on National Passenger Transportation-Volume 4*. Ottawa, Ontario. p.1014.

OHMPA (Ontario Hot Mix Asphalt Producers). 1999. The ABCs of PGAC. Ontario Hot Mix Asphalt Producers Association fact sheet, 2 (April).

Ohrstrom, E. 2004. Longitudinal surveys on effects of changes in road traffic noise: Effects on sleep assessed by general questionnaires and 3-day sleep logs, *Journal of Sound and Vibration*, 276(3-5): 713-727.

Ouyang, Y. and S. Madanat 2004. Optimal scheduling of rehabilitation activities for multiple pavement facilities: exact and approximate solutions, *Transportation Research Part A*, 38:347-365.

Park, D.-Y., N. Buch and K. Chatti. 2001. Effective layer temperature prediction model and temperature correction via falling weight deflectometer deflections, *Transportation Research Record*, 1764: 97-111.

Parm, S. 2007. Patterns of spatial and temporal variability in spring thaw timing for secondary pavements in southern Canada. Masters of Environmental Studies thesis, Department of Geography, University of Waterloo.

Paterson, W. 1986. International Roughness Index: Relationship to Other Measures of Roughness and Riding Quality, *Transportation Research Record*, 1084:49-59.

Phillips, S. 2002. Determining the performance of quieter road surfaces, *Proceedings of the Institution of Civil Engineers-Transport*, 153(2):111-120.

Prozzi, J.A. and S.M. Madanat 2003. Incremental nonlinear model for predicting pavement serviceability, *Journal of Transportation Engineering*, 129(6):635-641.

Raad, L., S. Saboundjian, P. Sebaaly and J. Epps. 1998. Thermal cracking models for AC and modified AC mixes in Alaska, *Transportation Research Record*, 1629:117-126.

Ramia, A.P., N. Ali, and K. Speiran 1995. *Evaluation of Rutting in Nova Scotia's Special "B" Asphalt Concrete Overlays*.

Ranieri, V. 2002. Runoff control in porous pavements, *Transportation Research Record*, 1789:46-55.

Raymond, C., S. Tighe, R. Haas, and L. Rothenburg. 2003. Development of Canadian asphalt pavement deterioration models to benchmark performance, *Canadian Journal of Civil Engineering*, 30:637-643.

Richardson, S. 1996. *Valuation of the Canadian Road and Highway System*. TP 1279E. Transport Canada, Ottawa.

Samson, M. and L. Fréchette. 1995. *Seasonal Variation of Pavement Strength Based on Benkelman Beam Rebounds*. Report prepared for the Canadian Strategic Highway Research Program as part of the Canadian Long-term Pavement Performance Project.

Sebaaly, P.E., A. Lake and J. Epps. 2002. Evaluation of low-temperature properties of HMA mixtures, *Journal of Transportation Engineering*, 128(6): 578-586.

Semenov, M., R. Brooks, E. Barrow, and C. Richardson. 1998. Comparison of the WGEN and LARS-WG stochastic weather generators in diverse climates, *Climate Research*, 10:95-107.

Semenov, M.A. and E.M. Barrow 1997. Use of a stochastic weather generator in the development of climate change scenarios, *Climatic Change*, 35:397-414.

Shafizadeh K. and F. Mannering. 2003. Acceptability of pavement roughness an urban highways by driving public, *Transportation Research Record*, 1860:187-193.

Shalaby, A., S.M. Easa, and A.O. Abd El Halim 1998. *Investigation of Thermal Cracking on C-SHRP Test Sections.* http://www.ce.umanitoba.ca/~shalaby/files/csce98.pdf

Shen, W. and D.J. Kirkner. 2001. Thermal cracking of viscoelastic asphalt-concrete pavement, *Journal of Engineering Mechanics*, 127(7):700-709.

Shenoy, A. 2002. Single-event cracking temperature of asphalt pavements directly from bending beam rheometer data, *Journal of Transportation Engineering*, 128(5): 465-471.

Sherwood, P.T. and P.G. Roe 1986. Winter air temperatures in relation to frost damage in roads, Research Report 45. Transport and Road Research Laboratory, Department of Transport, Crowthorne, Berkshire, UK.

SHRP. 1990. Distress Identification Manual for the Long Term Pavement Performance Studies. Strategic Highway Research Program, Washington, D.C.

Simonsen, E., V.C. Janoo and U. Isacsson 1997. Prediction of temperature and moisture changes in pavement structures, *Journal of Cold Regions Engineering*, 11(4), 291-307.

Smith, S.L., M.M. Burgess, and J.A. Heginbottom. 2001. Permafrost in Canada, a challenge to northern development; in G.R. Brooks (ed.) *A Synthesis of Geological Hazards in Canada*, Geological Survey of Canada, Bulletin 548, pp. 241–264.

Start, M.R., J. Kim, and W.D. Berg 1998. Potential safety cost-effectiveness of treating rutted pavements, *Transportation Research Record*, 1629:208-213.

TAC 1999. Geometric Design Guide for Canadian Roads. Transportation Association of Canada, Ottawa, ON. 830pp.

TC 2000. *Transportation in Canada 2000 Annual Report*. TP13198E. Transport Canada, Ottawa, ON. http://www.tc.gc.ca/.

TC 2002. *Transportation in Canada 2002 Annual Report*. TP13198E. Transport Canada, Ottawa, ON. http://www.tc.gc.ca/.

TC 2003. *Transportation in Canada 2003 Annual Report*. TP13198E. Transport Canada, Ottawa, ON. http://www.tc.gc.ca/.

Tighe, S., R. Haas and N. Li. 2001.Overlay Performance in the Canadian Strategic Highway Research Program's LTPP Study, *Transportation Research Record*, 1778:191-200.

Tighe, S and R. Haas. 2001. Managing Paved Road Assets Effectively, *Canadian Technical Asphalt Association Proceedings*, Volume XLVI, Winnipeg, November 2000. pp. 407-422.

Tighe, S. 1999. *An Integrated Model to Assess Asphalt Cement Quality on Low Temperature Performance and Life Cycle Cost* (section 2.4), Ph.D. thesis, University of Waterloo, Department of Civil Engineering, Waterloo, Ontario.

Tighe, S. 2001. Guidelines for probabilistic pavement life cycle cost analysis, *Transportation Research Record*, 1769:28-38.

Tighe, S., N. Li, L. Cowe Falls and R. Haas 2000. Incorporating road safety into pavement management, *Transportation Research Record*, 1699:1-10.

Transport Canada 2000. Canadian Vehicle Survey, 2000. http://www.tc.gc.ca/pol/en/cvs/files/TC_2000_CVS%20Report_E.pdf

TRB 2004. Moisture Sensitivity of Asphalt Pavements: A National Seminar, February 4-6, 2003, San Diego, California. Transportation Research Board, National Academies. pp. 186-206. http://trb.org/publications/conf/reports/moisture/05_TOP5.pdf. Accessed January 2005.

Tsai, Y. and J.S. Lai 2002. Framework and strategy for implementing an information technology-based pavement management system, *Transportation Research Record*, 1816:56-64.

U.S. Department of Transportation 2007. Long Term Pavement Performance (LTPP) program. Federal Highways Administration. http://www.fhwa.dot.gov/pavement/ltpp/.

USFHWA 2002. Superpave Asphalt Mixture Design, workshop workbook, version 8.0. Federal Highway Administration, Department of Transportation. http://www.tfhrc.gov/pavement/asphalt/prodrsrch/mixturedesign/mixdsgn.pdf

Uzan, J. 2004. Permanent deformation in flexible pavements, *Journal of Transportation Engineering*, 130(1):6-13.

Vadakpat, G., S. Stoffels, and K. Dixon 2000. Road user cost models for network-level pavement management, *Transportation Research Record*, 1699:49-57.

Wall, James III and M.R. Smith 1998. Life-cycle Cost Analysis in Pavement Design-Interim Technical Bulletin. FHWA-SA-98-079. U.S. Federal Highway Administration, Washington, D.C.

Walton, D., J.A. Thomas and P.D. Cenek 2004. Self and others' willingness to pay for improvements to the paved road surface, *Transportation Research Part A*, 38(7):483-494

Watson, D.K. and R.K.N.D. Rajapakse. 2000. Seasonal variation in material properties of a flexible pavement, *Canadian Journal of Civil Engineering*, 27:44-54.

White, T.D. and B. Coree. 1990. Threshold pavement thickness to survive spring thaw. Third International Conference on Bearing Capacity of Roads and Airfield, Trondheim, Norway.

Wilby, R.L., C.W. Dawson, and E.M. Barrow 2002. SDSM-a decision support tool for the assessment of regional climate change impacts, *Environmental and Modelling Software*, 17(2):145-157.

Wilks, D.S. and R.L. Wilby 1999. The weather generation game: a review of stochastic weather models, *Progress in Physical Geography*, 23(3):329-357.

Wright, J.F., C. Duchesne, M. Nixon, and M. Côté. 2002. Ground thermal modeling in support of terrain evaluation and route selection in the Mackenzie River valley. Report prepared for the Climate Change Action Fund, Natural Resources Canada. 53 pp.

Xiao, J., B.T. Kulakowski, and M. El-Gindy. 2000. Prediction of wet-pavement accidents: fuzzy logic model, *Transportation Research Recor*, 1717:28-36.

Yavuzturk, C., K. Ksaibati, and A.D. Chiasson 2005. Assessment of temperature fluctuations in asphalt pavements due to thermal environmental conditions using a two-dimensional, transient finite-difference approach, *Journal of Materials in Civil Engineering*, 17(4):465-475.

Zhang, Z.M., G. Claros, L. Manuel and I. Damnjanovic. 2003. Development of structural condition index to support pavement maintenance and rehabilitation decisions at network level, *Transportation Research Record*, 1827:10-17.

Zimmerman, K.A. and D.G. Peshkin 2003. Pavement management perspective on integrating preventive maintenance into a pavement management system, *Transportation Research Record*, 1827:3-9.

Zuo, G., R.W. Meier and E.C. Drumm. 2002. The effect of temperature averaging on predicted pavement life, 81st Annual Meeting Pre-print CD-ROM, proceedings of the Transportation Research Board annual meeting, January 2002, Washington, D.C.

APPENDIX A
CLIMATE CHANGE SCENARIO INFORMATION FOR CASE STUDY SITES

Table A-1. CGCM2A2x mean monthly temperature change scenarios (2049-60 relative to 1961-90) for case study sites

	Temperature Change (2049-2060 relative to 1961-1990 baseline) (°C)											
Site	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Vancouver	2.15	2.72	2.60	2.27	1.90	1.86	1.95	1.95	1.99	1.69	1.84	1.77
Kelowna	2.35	3.03	2.64	3.10	2.08	1.89	2.11	2.03	2.03	1.58	1.76	1.55
Calgary	5.37	5.06	4.54	4.97	4.69	2.45	2.31	2.46	2.30	1.59	1.36	1.32
Edmonton	5.62	3.88	3.31	3.49	5.86	2.65	2.31	2.09	1.90	1.38	1.00	2.84
Regina	5.95	5.79	6.27	6.46	5.38	3.24	3.06	3.22	2.95	2.13	1.40	2.46
Winnipeg	5.70	4.06	4.10	5.30	6.68	3.36	3.22	3.11	2.76	2.09	1.12	3.07
Thunder Bay	4.71	3.37	2.79	1.36	3.44	3.50	3.01	2.39	2.46	1.88	0.83	3.63
North Bay	5.62	4.56	2.96	1.23	4.00	2.83	2.60	2.17	2.46	2.32	1.62	0.55
Windsor	4.79	5.44	5.03	5.16	3.23	2.85	2.82	2.55	2.88	2.38	1.82	1.33
Muskoka	5.62	4.56	2.96	1.23	4.00	2.83	2.60	2.17	2.46	2.32	1.62	0.55
Toronto	4.44	5.57	4.42	4.74	3.46	2.75	2.76	2.60	2.76	2.36	1.82	1.49
Ottawa	5.34	4.07	2.83	1.50	3.64	2.79	2.61	2.23	2.54	2.32	1.55	0.82
Montreal	5.34	4.07	2.83	1.50	3.64	2.79	2.61	2.23	2.54	2.32	1.55	0.82
Quebec City	4.90	4.06	2.46	1.18	3.46	2.75	2.71	2.30	2.61	2.35	1.48	0.84
Fredericton	4.01	4.33	1.95	1.25	3.21	2.65	2.79	2.36	2.55	2.36	1.56	0.76
Halifax	2.61	4.15	1.99	2.30	2.20	2.53	2.83	2.40	2.40	2.36	1.78	1.32
St. John's	3.91	4.47	3.15	1.67	2.96	2.65	3.12	2.40	2.22	2.13	1.59	1.07

Table A-2. CGCM2A2x mean monthly precipitation change scenarios (2049-60 relative to 1961-90) for case study sites

	Precipitation Change (2049-2060 relative to 1961-1990 baseline) (%)											
Site	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Vancouver	7.05	2.25	-0.71	-2.93	-17.57	-8.72	-13.21	5.36	4.99	-0.10	19.50	9.07
Kelowna	5.50	1.81	-1.86	-0.96	-15.32	-9.28	-7.22	1.34	6.75	4.65	18.59	7.13
Calgary	-4.65	10.75	-6.80	21.82	7.15	0.74	-22.07	-2.80	-7.73	5.11	7.47	3.36
Edmonton	6.67	5.78	0.20	1.42	20.12	17.25	-5.14	-2.05	10.20	8.93	10.18	6.56
Regina	0.91	3.77	5.84	25.68	27.22	7.93	-21.31	-10.54	-20.83	10.99	6.47	4.20
Winnipeg	-4.37	-2.86	-14.15	6.00	18.55	0.85	-14.97	-13.24	-22.23	5.05	2.83	-4.46
Thunder Bay	2.52	15.88	-12.82	1.71	17.97	7.10	-1.87	-8.94	-7.23	-11.55	11.04	6.30
North Bay	-1.98	-1.34	-4.11	12.72	9.37	3.03	7.66	6.59	-0.85	7.87	-0.20	-12.58
Windsor	-3.22	1.73	0.25	5.96	4.38	-3.31	-8.98	-4.41	0.66	2.75	-10.94	1.48
Muskoka	-1.98	-1.34	-4.11	12.72	9.37	3.03	7.66	6.59	-0.85	7.87	-0.20	-12.58
Toronto	-5.84	-1.89	-5.49	8.28	-1.21	-8.27	1.44	6.80	0.10	-4.89	-7.57	-0.25
Ottawa	-4.21	-2.16	-5.54	10.56	7.81	0.83	6.96	13.77	4.08	1.24	-0.86	-4.03
Montreal	-4.21	-2.16	-5.54	10.56	7.81	0.83	6.96	13.77	4.08	1.24	-0.86	-4.03
Quebec City	-3.50	-1.23	-1.61	9.01	8.65	-0.45	9.59	12.94	4.74	2.28	2.89	5.46
Fredericton	0.49	-2.78	3.78	7.81	10.92	-2.44	6.02	0.81	4.96	1.77	7.29	4.18
Halifax	-1.21	-5.31	1.88	1.55	2.39	0.36	2.83	-1.94	5.52	2.31	12.93	-0.36
St. John's	-5.88	-4.68	-2.57	-1.18	4.50	-6.36	-0.06	-0.88	4.45	-5.95	7.01	-3.64

Table A-3. HadCM3B21 mean monthly temperature change scenarios (2049-60 relative to 1961-90) for case study sites

	Temperature Change (2049-2060 relative to 1961-1990 baseline) (°C)											
Site	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Vancouver	-1.13	-1.47	0.44	2.73	1.87	2.04	2.37	1.82	2.54	2.09	1.47	2.06
Kelowna	-0.13	-0.50	0.53	2.46	1.59	2.21	3.93	4.76	4.59	2.08	1.83	1.96
Calgary	1.15	0.05	0.83	1.04	1.45	2.40	4.13	4.53	4.90	2.36	2.10	2.76
Edmonton	0.87	0.41	0.75	0.95	1.27	2.17	3.91	4.04	4.49	2.37	2.45	2.25
Regina	0.94	-0.50	0.99	1.71	1.53	2.46	3.50	3.94	4.58	2.72	2.52	2.01
Winnipeg	0.96	-0.17	1.44	2.50	1.99	2.53	3.30	3.88	4.38	2.81	2.49	1.73
Thunder Bay	0.89	0.24	1.43	2.20	2.29	2.77	2.97	2.92	3.18	2.43	2.23	2.19
North Bay	2.04	1.46	2.16	2.90	2.71	3.09	2.94	3.16	2.20	2.03	2.24	2.46
Windsor	1.57	0.93	1.50	2.95	2.82	2.58	2.70	3.45	2.14	2.44	2.14	2.53
Muskoka	2.44	1.35	1.91	3.01	2.79	2.73	2.77	3.34	2.27	2.16	2.47	2.13
Toronto	2.44	1.35	1.91	3.01	2.79	2.73	2.77	3.34	2.27	2.16	2.47	2.13
Ottawa	1.88	1.11	1.95	2.70	2.85	2.90	3.05	3.78	2.35	2.04	2.48	1.99
Montreal	1.88	1.11	1.95	2.70	2.85	2.90	3.05	3.78	2.35	2.04	2.48	1.99
Quebec City	2.30	1.76	1.89	2.52	2.85	2.75	2.94	3.48	1.93	1.66	2.41	2.08
Fredericton	2.50	1.98	1.94	2.11	2.45	2.87	2.70	3.57	1.86	1.70	2.47	2.18
Halifax	2.50	1.98	1.94	2.11	2.45	2.87	2.70	3.57	1.86	1.70	2.47	2.18
St. John's	1.65	1.41	1.54	1.36	1.46	2.32	2.42	3.19	2.54	1.66	1.55	2.15

Table A-4. HadCM3B21 mean monthly precipitation change scenarios (2049-60 relative to 1961-90) for case study sites

	Precipitation Change (2049-2060 relative to 1961-1990 baseline) (%)											
Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Vancouver	-11.69	-4.52	-0.65	10.23	1.80	-18.87	-26.45	-23.69	-15.49	12.45	3.83	-6.30
Kelowna	-0.93	-5.35	2.73	10.31	-4.04	-16.99	-46.40	-63.62	-27.62	7.90	7.23	-1.86
Calgary	48.98	31.35	13.32	14.14	2.51	-7.51	-3.53	-31.58	-33.22	-16.13	29.05	19.86
Edmonton	45.80	20.37	26.60	6.16	13.54	3.17	-19.06	-32.87	-28.34	-11.04	26.57	6.33
Regina	31.75	10.53	31.14	30.31	7.98	-7.20	-10.01	-12.91	-16.02	-5.37	44.73	2.15
Winnipeg	29.64	12.93	35.80	50.59	22.81	2.28	-4.50	-18.19	-2.66	-0.13	24.49	-6.86
Thunder Bay	7.20	1.98	17.28	24.28	2.24	13.55	-7.28	-7.16	-27.60	1.71	32.50	-3.90
North Bay	19.98	-17.73	23.68	24.91	19.32	17.18	1.94	2.28	-13.63	-6.57	7.11	-2.05
Windsor	4.02	2.77	-4.76	-0.54	20.59	10.48	-8.88	-21.17	15.39	-4.32	6.41	-5.97
Muskoka	8.40	-5.52	8.27	2.87	13.94	9.56	3.48	-15.95	-4.04	0.86	11.55	-2.65
Toronto	8.40	-5.52	8.27	2.87	13.94	9.56	3.48	-15.95	-4.04	0.86	11.55	-2.65
Ottawa	4.50	6.91	4.27	-3.98	12.81	1.14	15.42	-14.11	12.80	-2.40	4.96	3.43
Montreal	4.50	6.91	4.27	-3.98	12.81	1.14	15.42	-14.11	12.80	-2.40	4.96	3.43
Quebec City	4.89	13.22	24.51	9.54	4.67	9.30	19.01	4.46	3.59	-2.01	-0.52	8.60
Fredericton	8.34	15.81	13.03	8.34	0.36	-0.56	6.17	-8.64	0.74	-23.23	-8.02	-1.54
Halifax	8.34	15.81	13.03	8.34	0.36	-0.56	6.17	-8.64	0.74	-23.23	-8.02	-1.54
St. John's	-0.45	-2.13	-3.89	-1.17	-6.16	-0.03	-6.15	-1.32	-3.28	-5.47	-0.75	-0.28

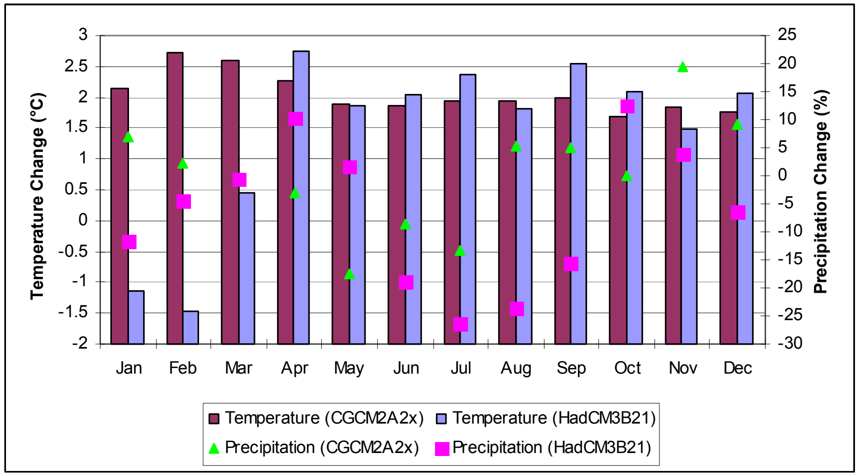


Figure A-1. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the British Columbia site (Vancouver)

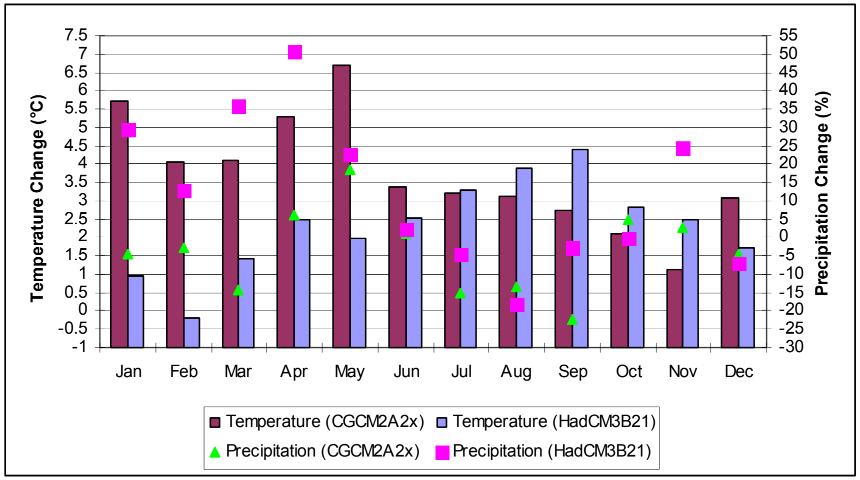


Figure 29. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Manitoba site (Winnipeg)

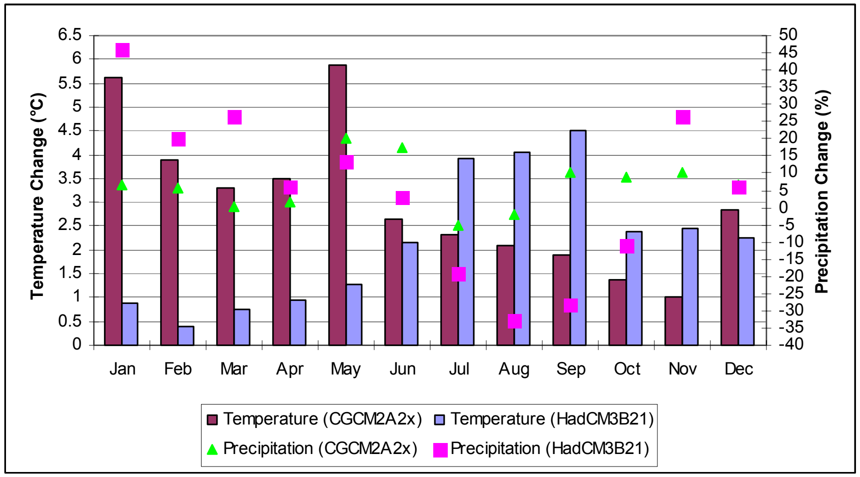


Figure 28. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Alberta site (Edmonton)

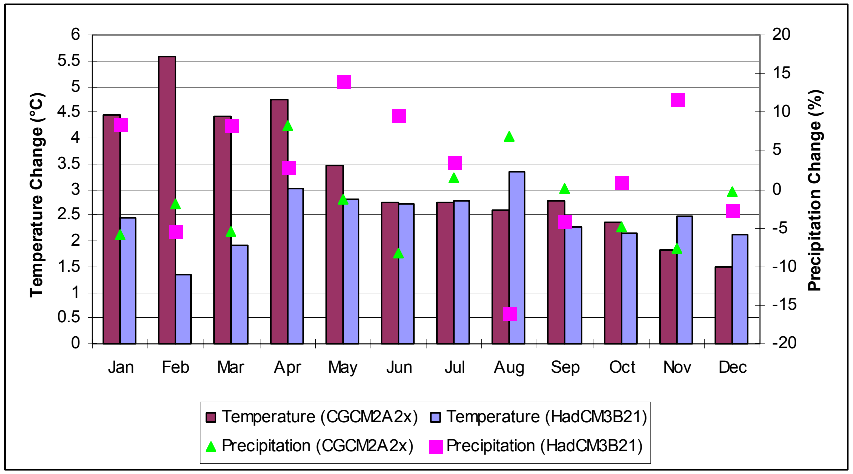


Figure 30. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Ontario site (Toronto)

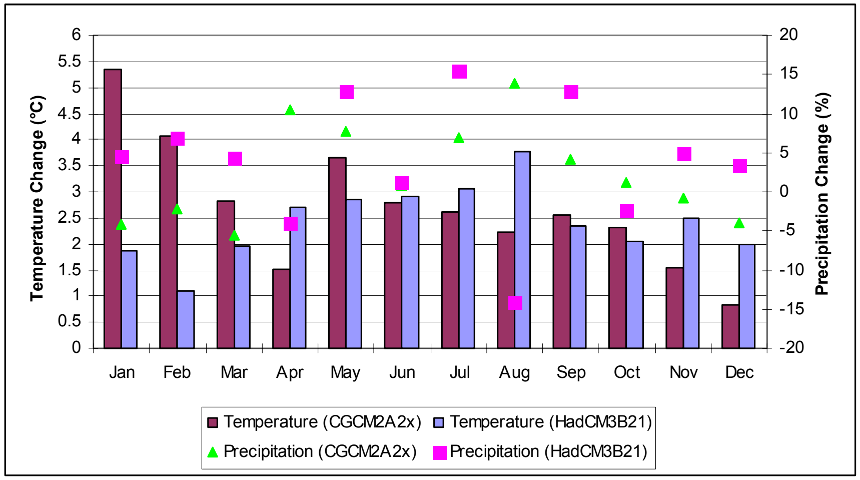


Figure 31. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Quebec site (Montreal)

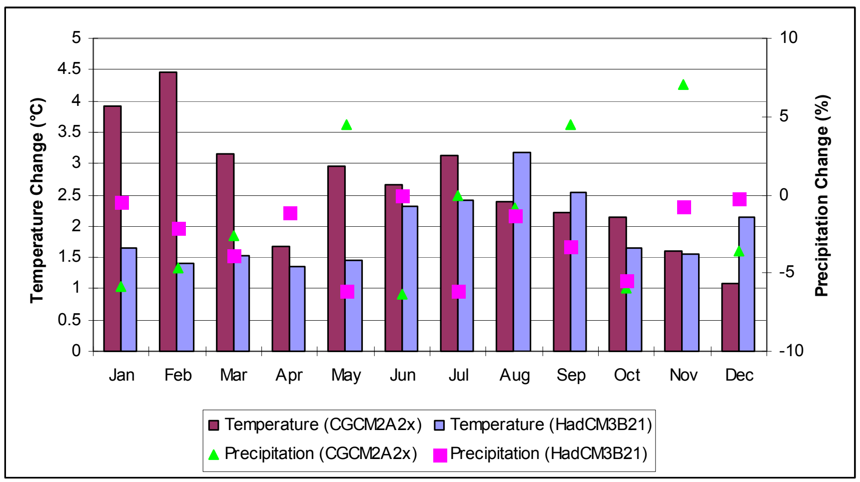


Figure 32. CGCM2A2x and HadCM3B21 temperature and precipitation change scenarios (2050s) for the Newfoundland site (St. John's)

APPENDIX B
DETERIORATION-RELEVANT CLIMATE INDICATOR RESULTS FOR ALL CASE STUDY SITES

CASE STUDY SITE: VANCOUVER

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Vancouver (1108447)	49.2	123.1	4.3	10.1	1199.0

*1971-2000 climate normals

Table B-1. Vancouver minimum daily air temperature

		Climate Change Scenario	
STATISTIC	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	6.3	8.2	7.6
Standard Deviation	5.4	5.4	6.2
Minimum	-16.5	-14.9	-15.2
Lower Quartile	2.4	4.3	3
Median	6.5	8.4	8.3
Upper Quartile	10.7	12.5	12.6
Maximum	19.8	21.8	22.1

*n=54750

Table B-2. Vancouver 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	13.6	15.9	15.3
Standard Deviation	5.9	5.7	6.6
Minimum	-1.8	0.7	-2.1
Lower Quartile	8.7	11.2	9.4
Median	13.3	15.6	15.9
Upper Quartile	18.8	20.8	21.1
Maximum	29.5	31.6	31.4

*n=54750

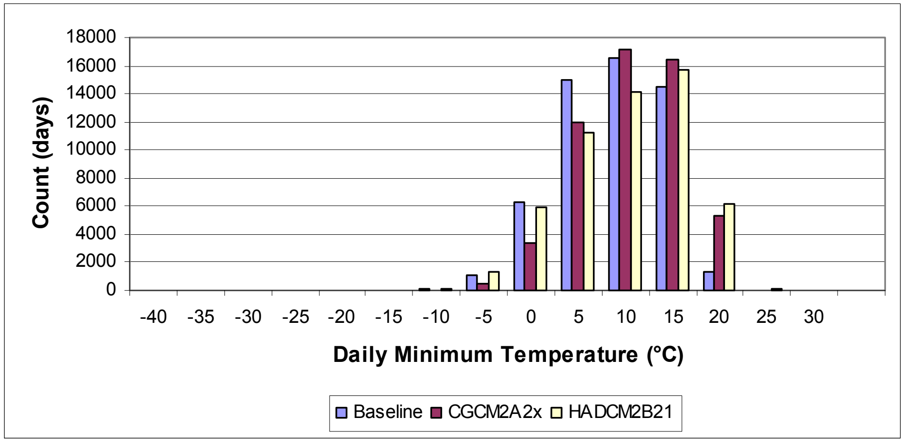


Figure B-1. Vancouver minimum daily temperature distribution (n=54750)

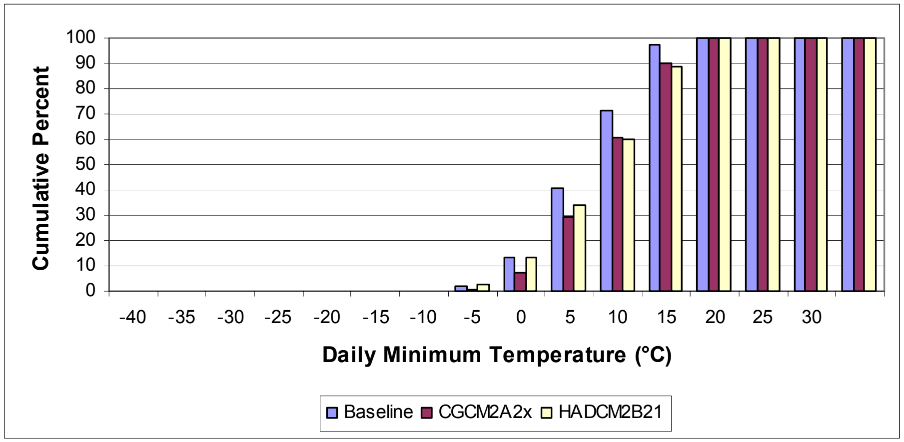


Figure B-2. Vancouver minimum daily temperature cumulative percent distribution (n=54750)

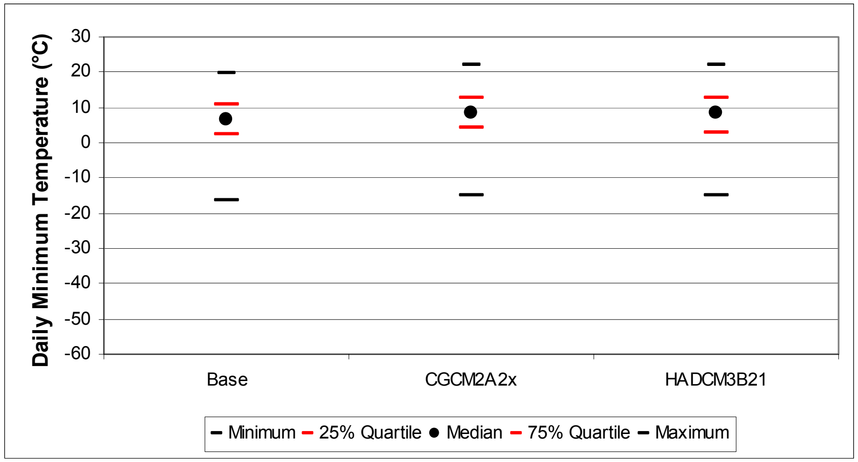


Figure B-3. Vancouver minimum daily temperature distribution: quartile statistics (n=54750)

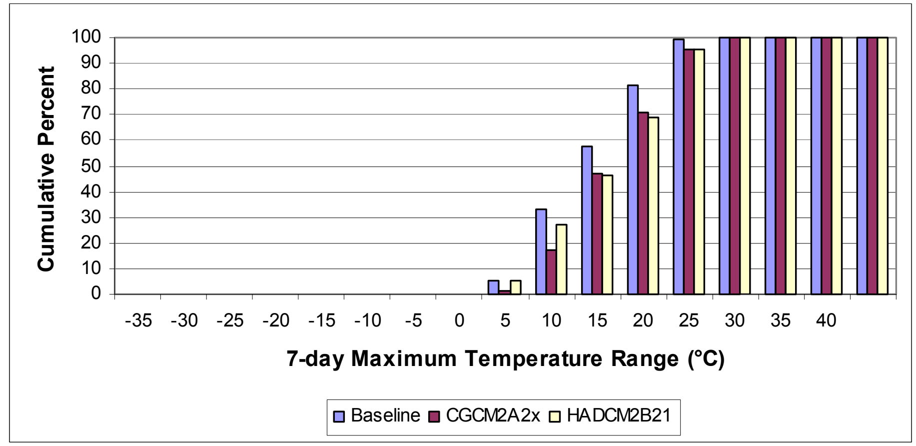


Figure B-5. Vancouver 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

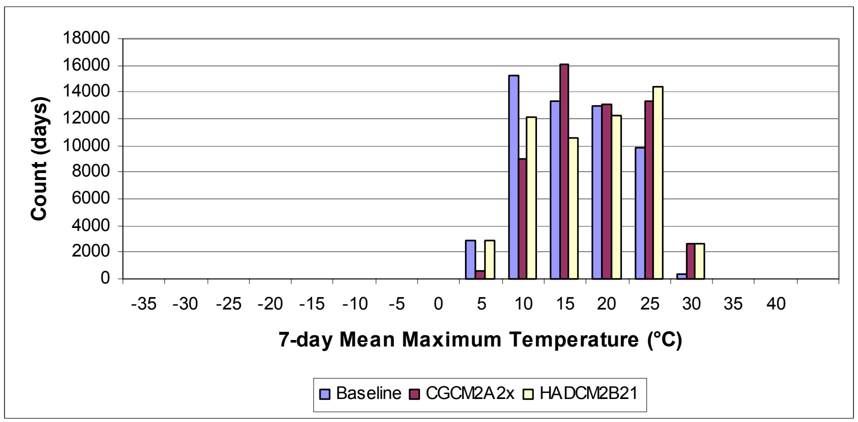


Figure B-4. Vancouver 7-day mean maximum daily temperature distribution (n=54750)

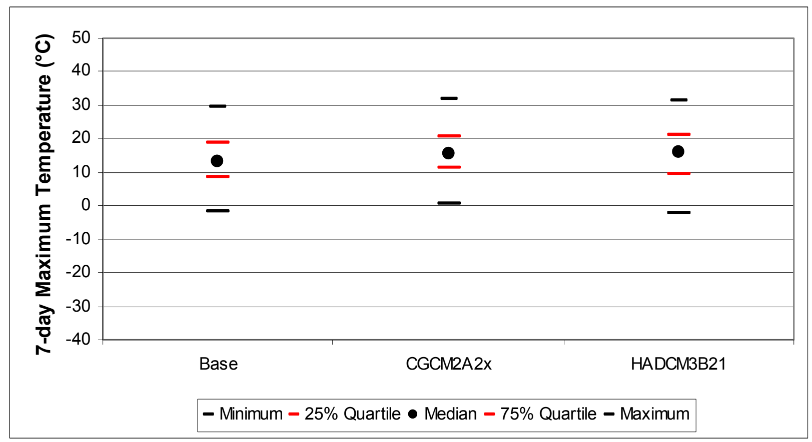


Figure B-6. Vancouver 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-3. Vancouver annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-9.3	-7.4	-10.0
Standard Deviation	2.3	2.3	2.1
Minimum	-16.5	-14.9	-15.2
Lower Quartile	-10.6	-8.8	-11.2
Median	-9.2	-7.3	-10.0
Upper Quartile	-7.5	-5.7	-8.6
Maximum	-4.4	-2.6	-5.7

*n=150

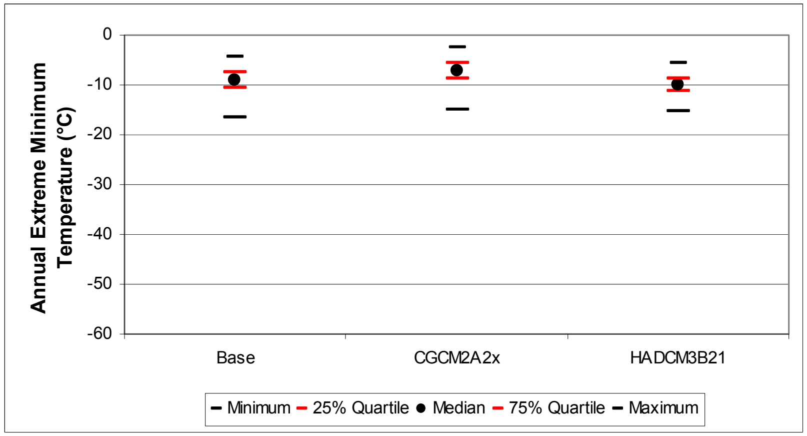


Figure B-7. Vancouver annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-4. Vancouver annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	25.0	27.1	27.1
Standard Deviation	1.2	1.2	1.2
Minimum	21.5	23.4	24.0
Lower Quartile	24.2	26.3	26.3
Median	24.9	27.0	27.1
Upper Quartile	25.7	27.9	27.8
Maximum	29.5	31.6	31.4

*n=150

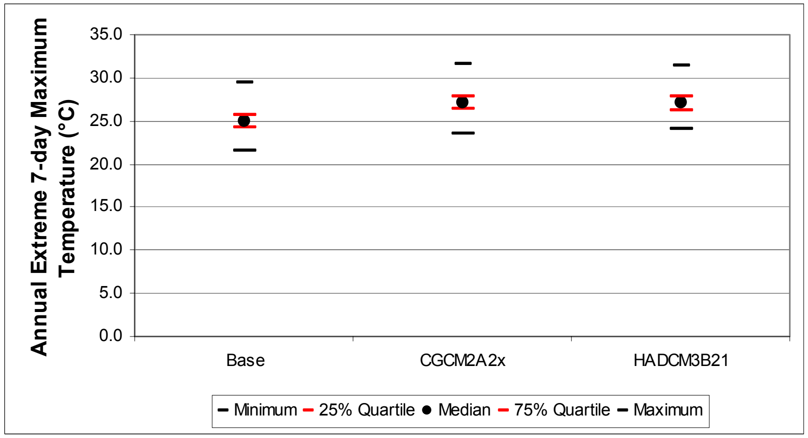


Figure B-8. Vancouver annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-5. Vancouver Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	Climate Change Scenario HadCM3B21
Superpave-derived low PG threshold (°C)	-14.7	-13.3	-15.0
Superpave-derived high PG threshold (°C)	49.2	50.9	50.8
98th percentile annual minimum temperature	-14.0	-12.3	-13.9
Ontario RWIS-based low PG threshold (°C)	-11.6	-10.0	-11.5
98th percentile annual extreme 7-day mean maximum temperature	28.2	30.4	30.2
Ontario RWIS-based high PG threshold (°C)	41.7	45.1	44.7

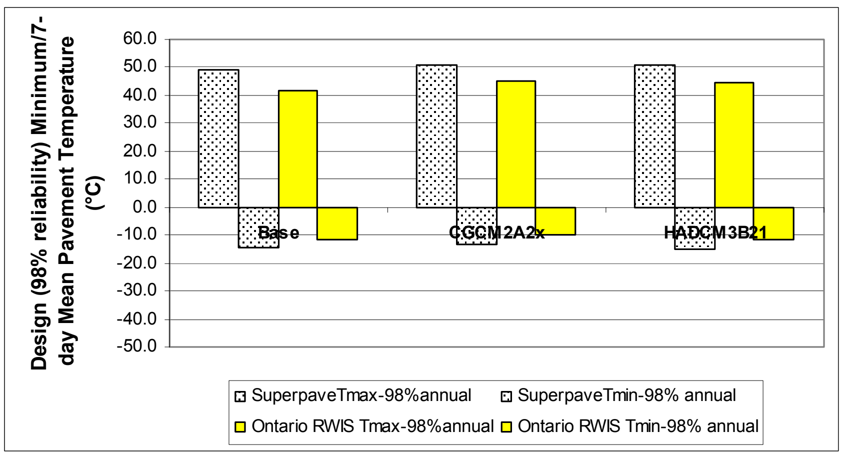


Figure B-9. Vancouver estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

CASE STUDY SITE: KELOWNA

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Kelowna (1123970)	49.9	119.4	429.5	7.7	380.5

*1971-2000 climate normals

Table B-6. Kelowna minimum daily air temperature

STATISTIC	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	1.3	3.5	3.1
Standard Deviation	7.5	7.3	8.0
Minimum	-38.1	-35.6	-37.8
Lower Quartile	-3.7	-1.4	-2.4
Median	1.8	3.9	3.7
Upper Quartile	7.2	9.2	9.3
Maximum	23.2	25.4	25.1

*n=54750

Table B-7. Kelowna 7-day mean maximum daily air temperature

STATISTIC	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	14.0	16.3	16.5
Standard Deviation	10.1	10.0	11.7
Minimum	-12.9	-11	-13.2
Lower Quartile	5.4	7.7	6.2
Median	14.1	16.9	16.7
Upper Quartile	22.6	24.8	26.6
Maximum	36.9	39.0	42.2

*n=54750

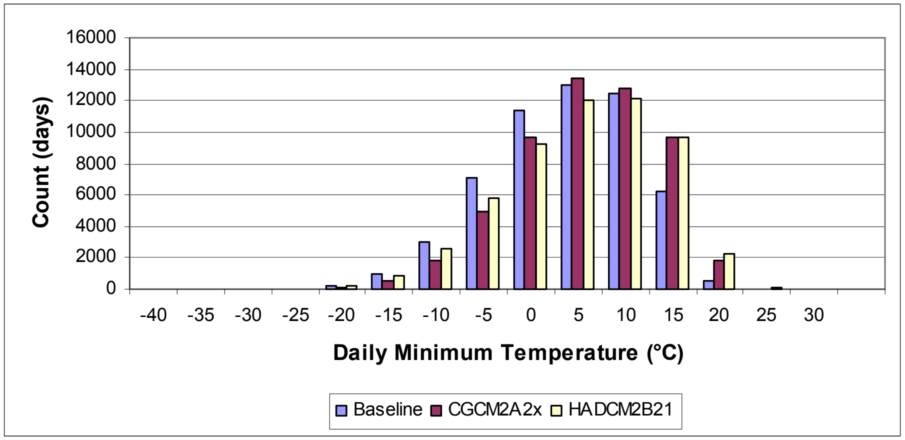


Figure B-10. Kelowna minimum daily temperature distribution (n=54750)

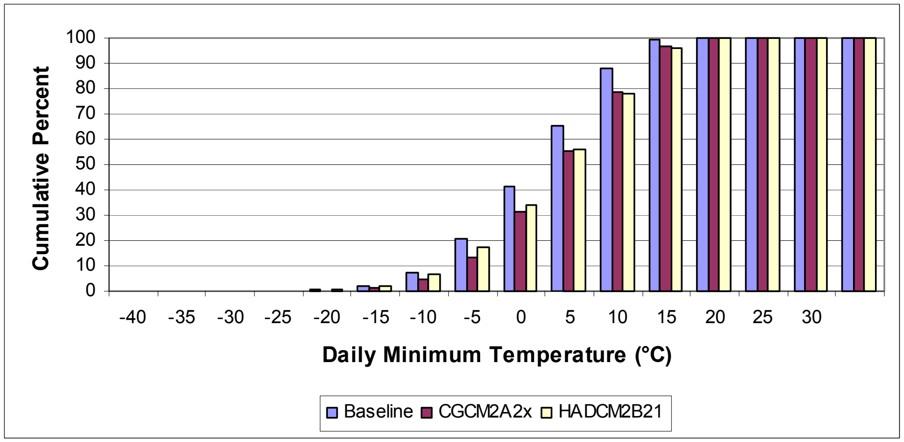


Figure B-11. Kelowna minimum daily temperature cumulative percent distribution (n=54750)

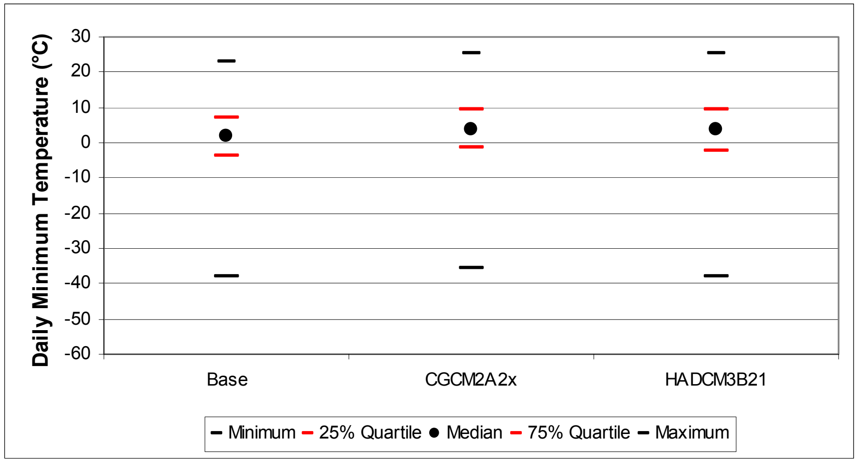


Figure B-12. Kelowna minimum daily temperature distribution: quartile statistics (n=54750)

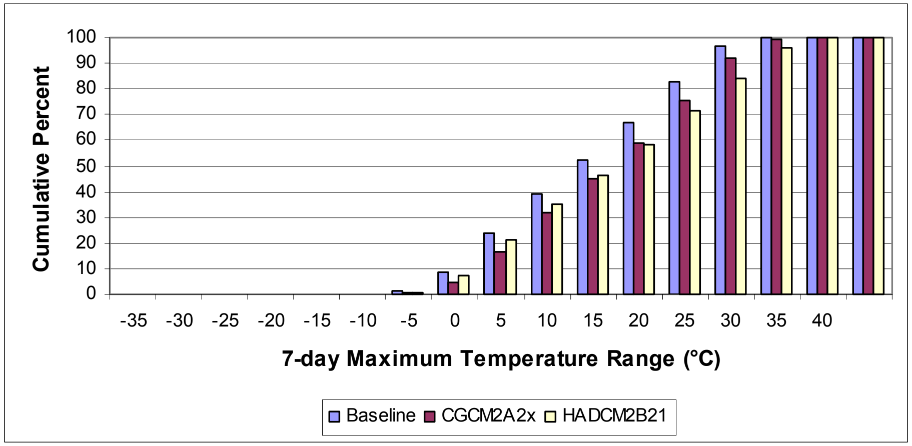


Figure B-14. Kelowna 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

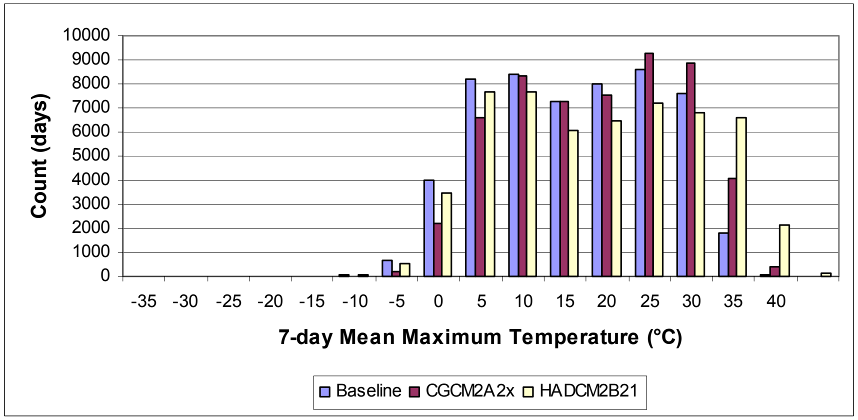


Figure B-13. Kelowna 7-day mean maximum daily temperature distribution (n=54750)

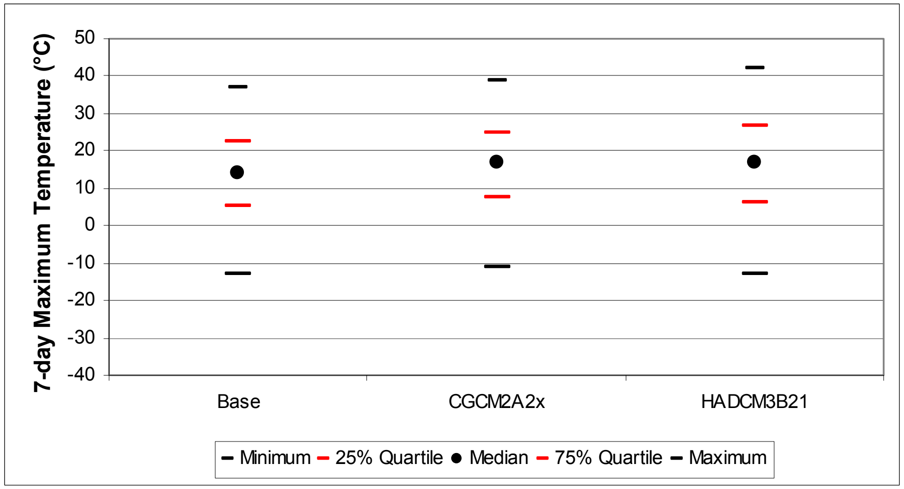


Figure B-15. Kelowna 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-8. Kelowna annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC	**Baseline***	**CGCM2A2x***	**HadCM3B21***
Mean	-21.6	-19.2	-21.4
Standard Deviation	3.1	3.1	3.1
Minimum	-38.1	-35.6	-37.8
Lower Quartile	-23.5	-20.875	-23.3
Median	-21.1	-18.75	-21.3
Upper Quartile	-19.5	-17.1	-19.2
Maximum	-15.1	-12.9	-14.7

*n=150

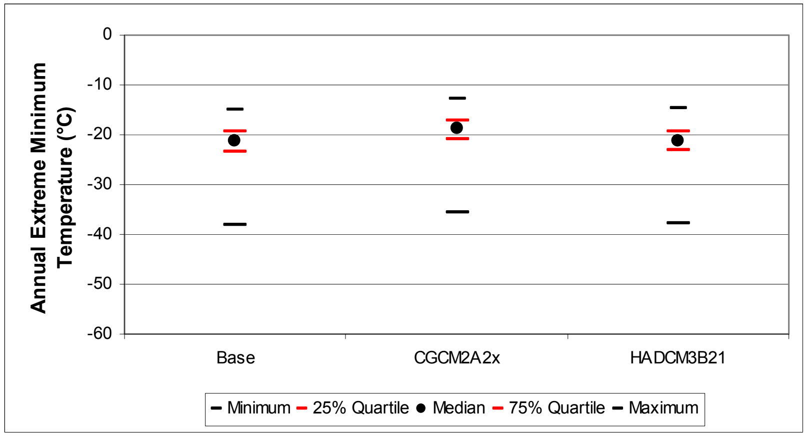


Figure B-16. Kelowna annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-9. Kelowna annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC	**Baseline***	**CGCM2A2x***	**HadCM3B21***
Mean	32.5	34.7	38.1
Standard Deviation	1.9	1.9	2.0
Minimum	27.9	30.2	33.8
Lower Quartile	31.1	33.3	36.5
Median	32.4	34.5	38.0
Upper Quartile	33.9	36.0	39.8
Maximum	36.9	39.0	42.2

*n=150

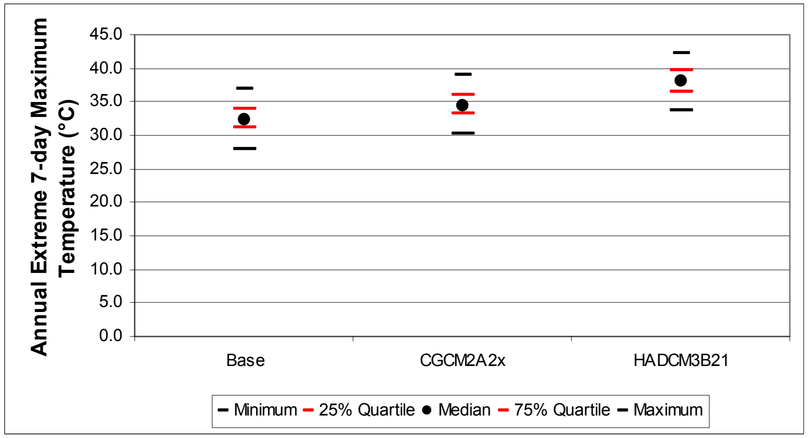


Figure B-17. Kelowna annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-10. Kelowna Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-24.6	-22.8	-24.5
Superpave-derived high PG threshold (°C)	55.3	57.0	59.7
98th percentile annual minimum air temperature	-27.9	-25.3	-28.4
Ontario RWIS-based low PG threshold (°C)	-23.1	-21.1	-23.5
98th percentile annual extreme 7-day mean maximum air temperature	36.1	38.3	41.9
Ontario RWIS-based high PG threshold (°C)	54.4	58.1	64.4

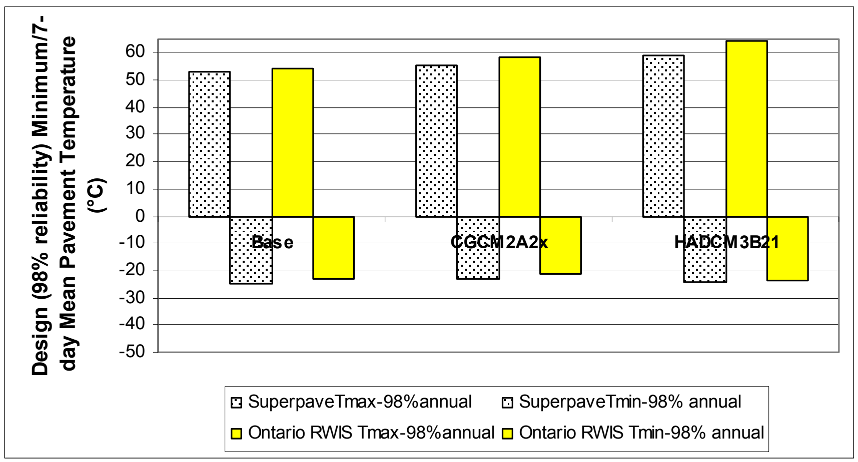


Figure B-18. Kelowna estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-11. Kelowna freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	22.1	4.2	16.6
Standard Deviation	17.6	9.2	16.3
Minimum	0.0	0.0	0.0
Lower Quartile	7.0	0.0	0.0
Median	20.0	0.0	12.0
Upper Quartile	34.0	0.0	28.0
Maximum	74.0	46.0	64.0

*n=150

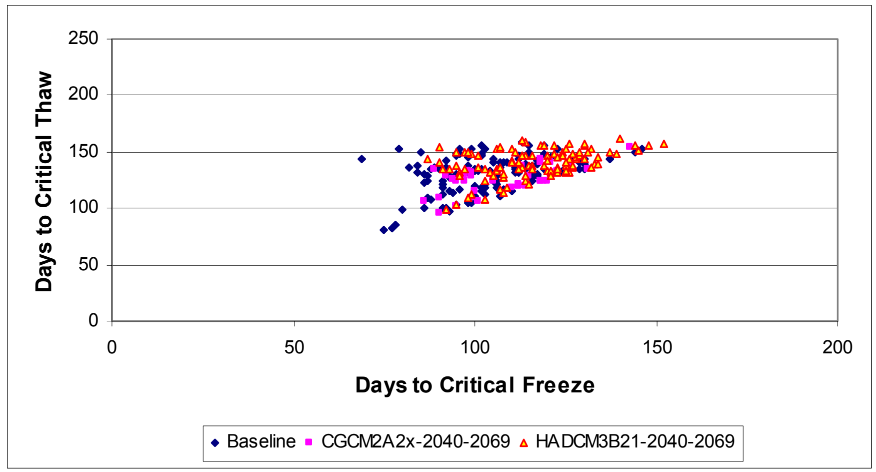


Figure B-19. Kelowna estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

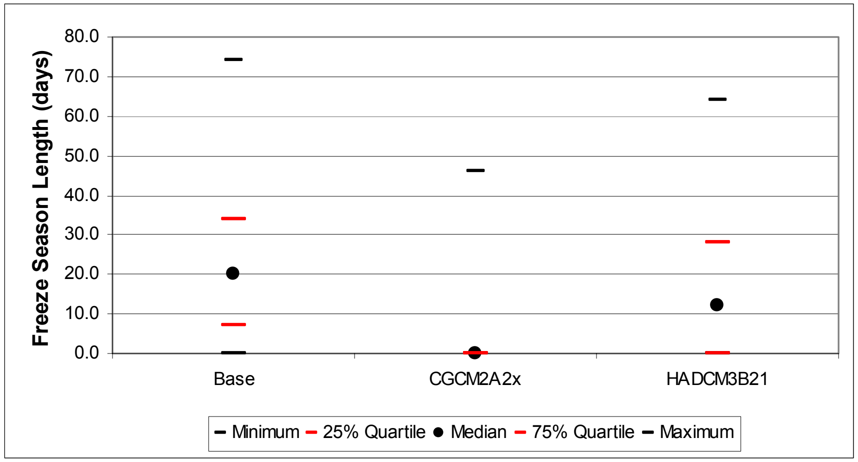


Figure B-20. Kelowna estimated freeze season length distribution: quartile statistics (n=150)

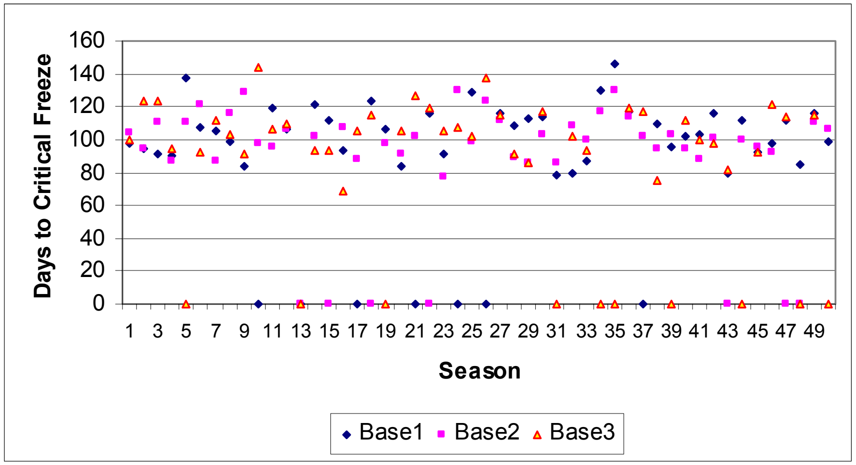


Figure B-21. Kelowna estimated days to critical FI (baseline series)

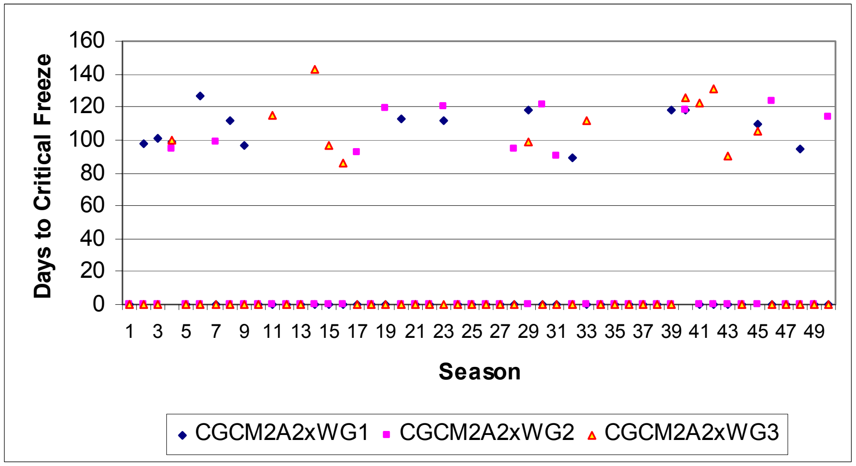


Figure B-22. Kelowna estimated days to critical FI (CGCM2A2x scenario series)

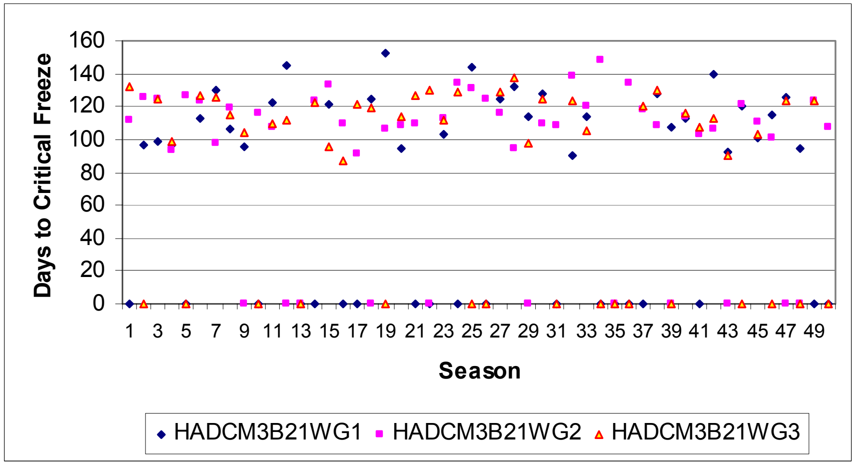


Figure B-23. Kelowna estimated days to critical FI (HadCM3B21 scenario series)

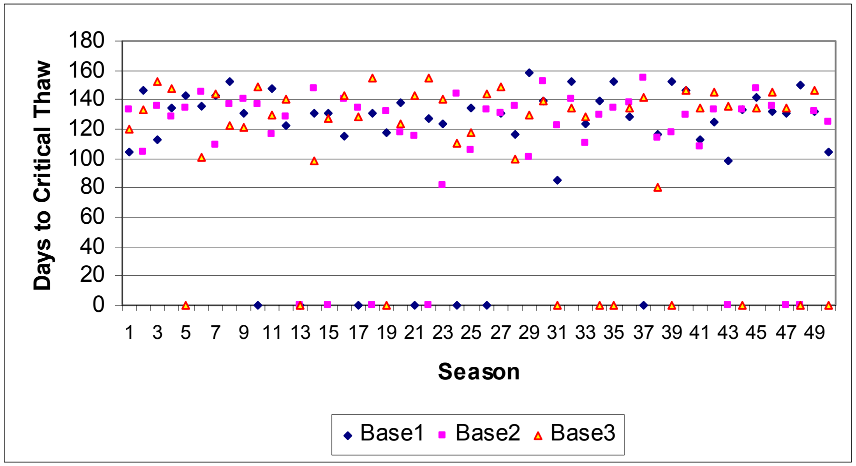


Figure B-24. Kelowna estimated days to critical TI (baseline series)

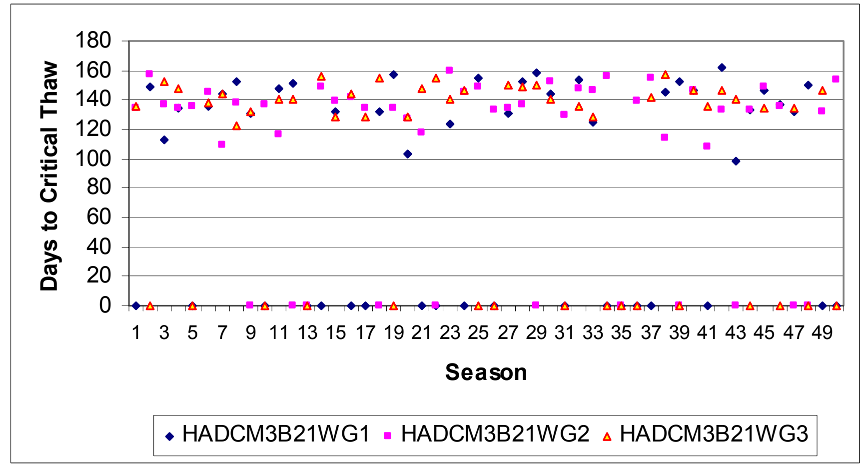


Figure B-26. Kelowna estimated days to critical TI (HadCM3B21 scenario series)

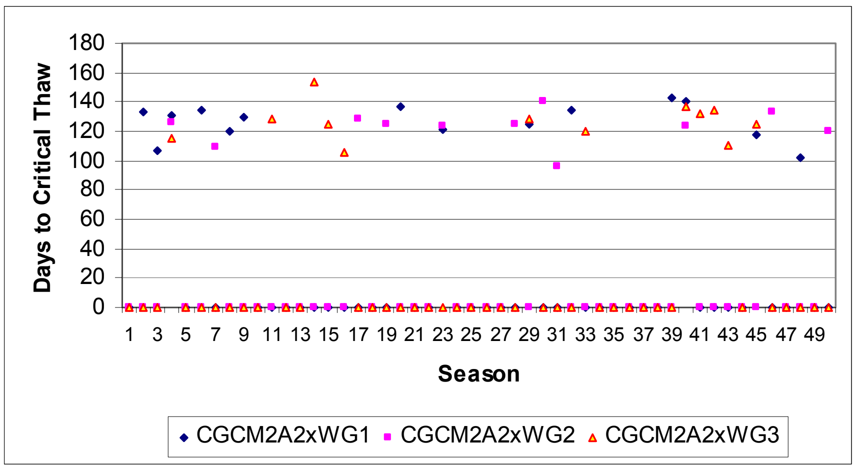


Figure B-25. Kelowna estimated days to critical TI (CGCM2A2x scenario series)

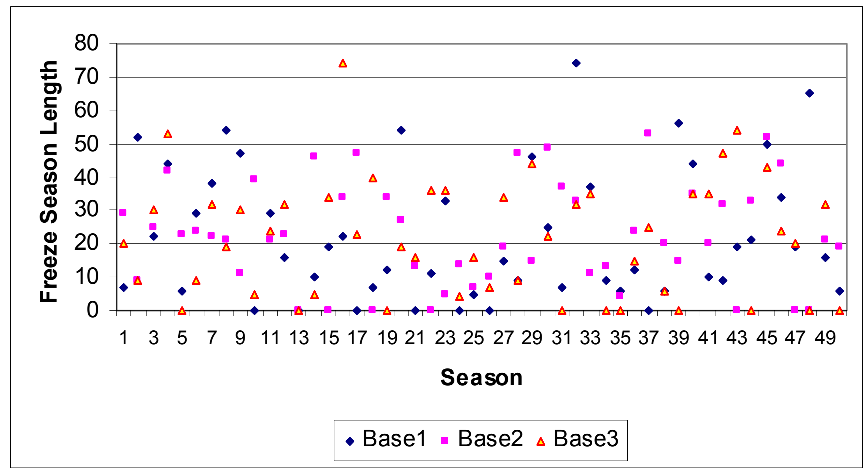


Figure B-27. Kelowna estimated freeze season length (baseline series)

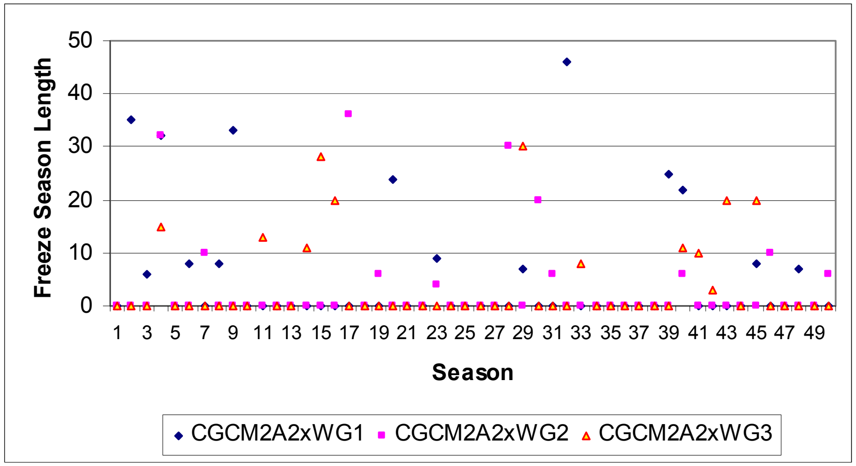


Figure B-28. Kelowna estimated freeze season length (CGCM2A2x scenario series)

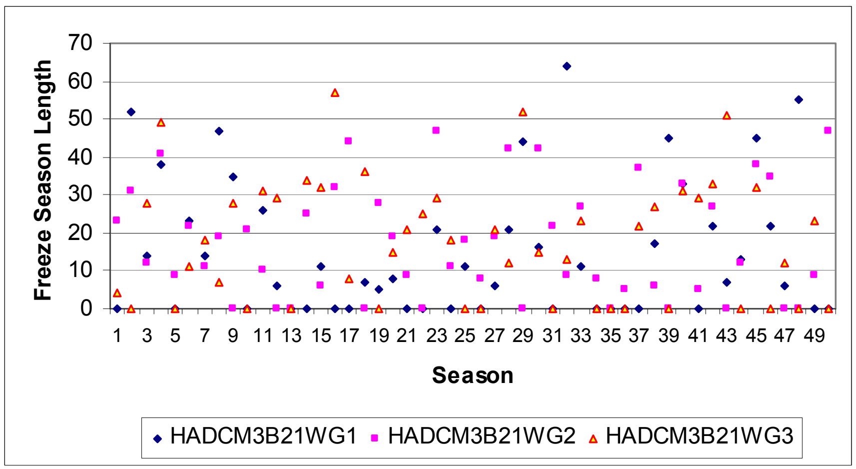


Figure B-29. Kelowna estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: CALGARY

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Calgary (3031093)	51.0	114.0	1084.1	2.4	482.7

*1971-2000 climate normals

Table B-12. Calgary minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-2.6	1.0	-0.4
Standard Deviation	10.4	9.8	11.0
Minimum	-55.9	-50.1	-54.1
Lower Quartile	-9.5	-5.4	-7.9
Median	-0.8	3.1	1
Upper Quartile	5.8	8.9	8.7
Maximum	21.1	28.1	24

*n=54750

Table B-13. Calgary 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	10.2	13.1	12.6
Standard Deviation	10.4	10.4	11.6
Minimum	-31.8	-28.0	-30.5
Lower Quartile	2.3	4.9	3.3
Median	11.2	14.4	13.1
Upper Quartile	19.0	22.1	22.6
Maximum	37.5	40.3	42.8

*n=54750

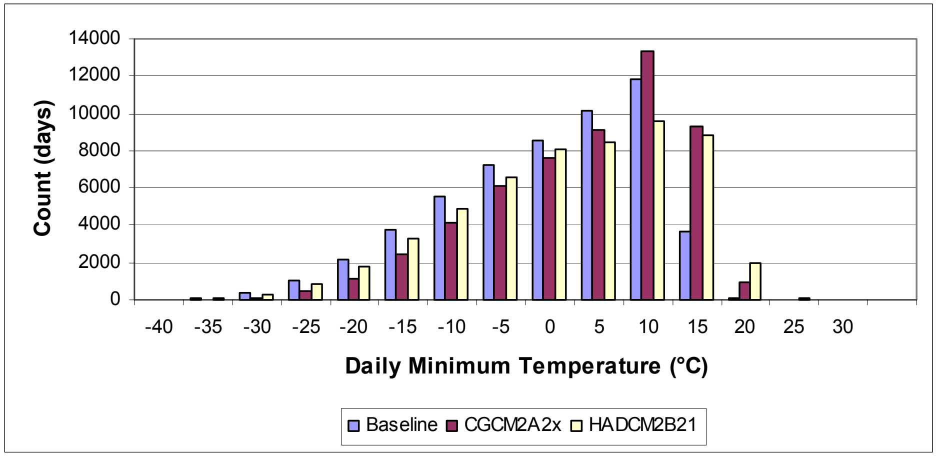


Figure B-30. Calgary minimum daily temperature distribution (n=54750)

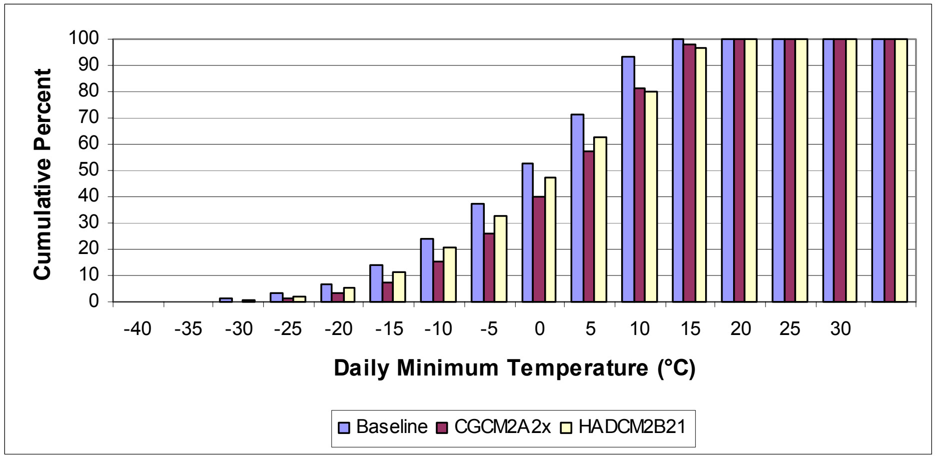


Figure B-31. Calgary minimum daily temperature cumulative percent distribution (n=54750)

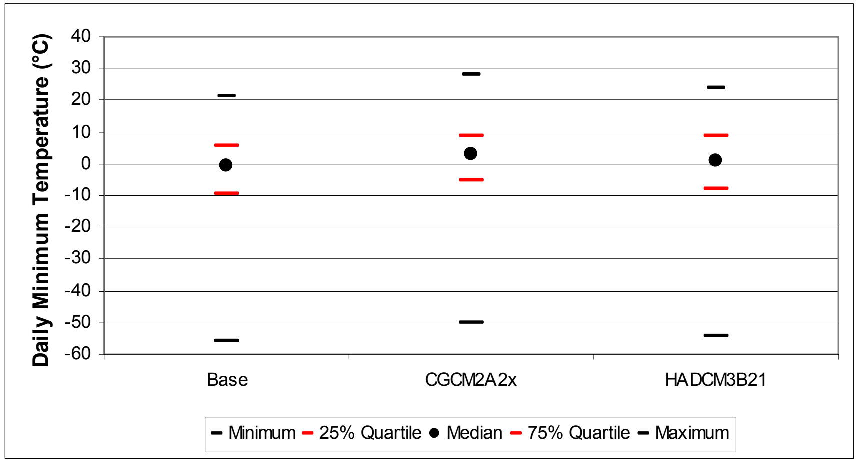


Figure B-32. Calgary minimum daily temperature distribution: quartile statistics (n=54750)

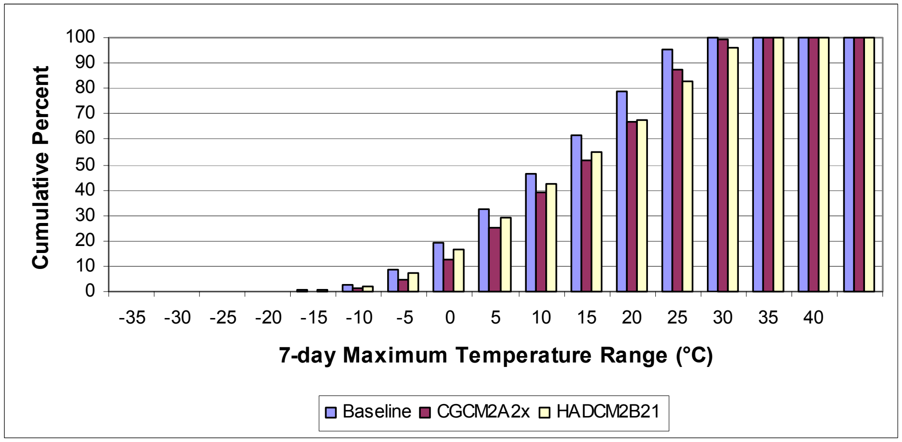


Figure B-34. Calgary 7-day means maximum daily temperature cumulative percent distribution (n=54750)

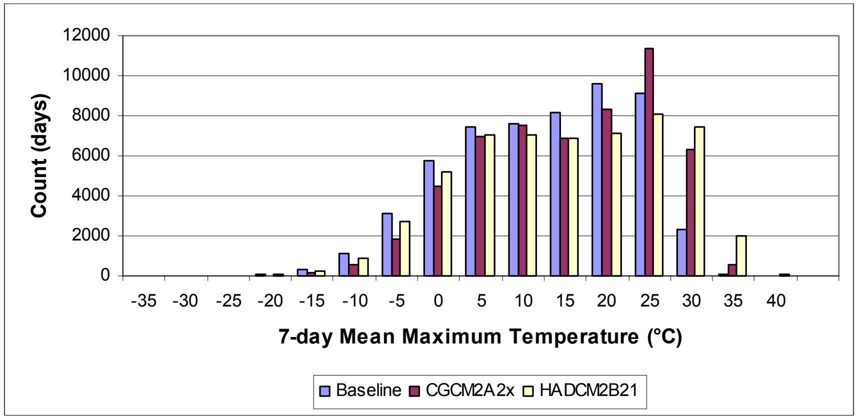


Figure B-33. Calgary 7-day mean maximum daily temperature distribution (n=54750)

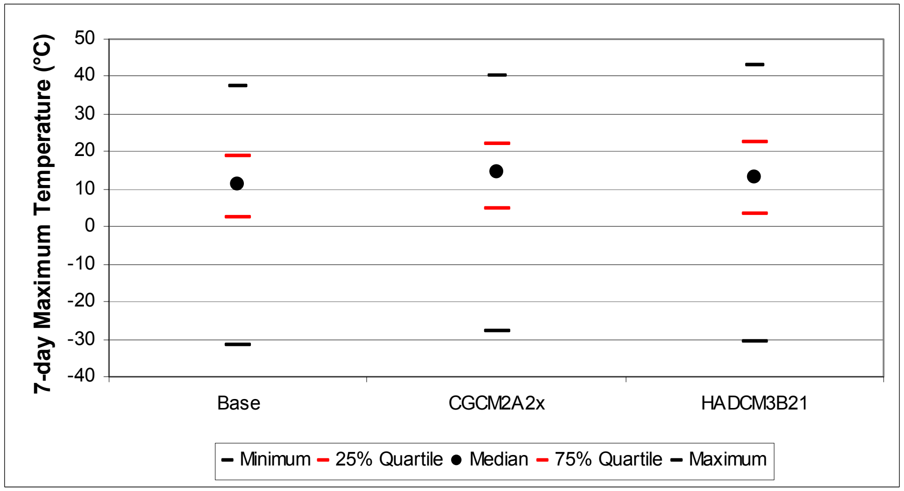


Figure B-35. Calgary 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-14. Calgary annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-36.4	-31.4	-34.8
Standard Deviation	4.5	4.6	4.5
Minimum	-55.9	-50.1	-54.1
Lower Quartile	-39.1	-34.3	-37.6
Median	-36.3	-31.5	-34.5
Upper Quartile	-33.1	-28.0	-31.5
Maximum	-26.2	-22.5	-23.5

*n=150

Table B-15. Calgary annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	28.3	30.7	33.3
Standard Deviation	1.9	2.0	2.1
Minimum	25.1	27.2	29.6
Lower Quartile	26.9	29.4	32.0
Median	27.9	30.4	32.8
Upper Quartile	29.2	31.8	34.5
Maximum	37.5	40.3	42.8

*n=150

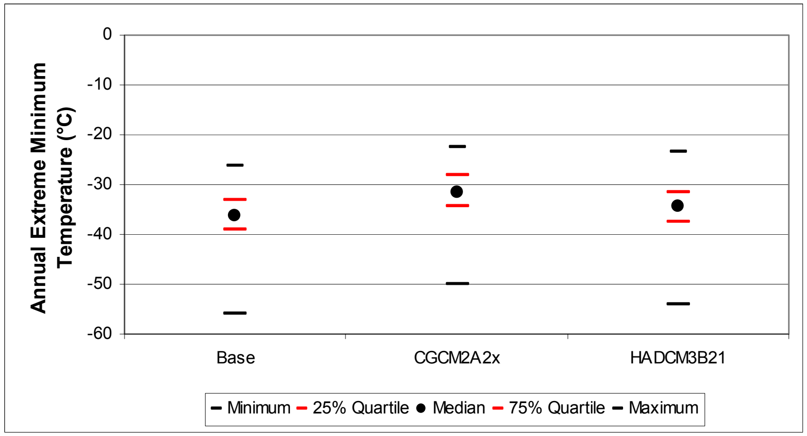


Figure B-36. Calgary annual extreme minimum temperature distribution: quartile statistics (n=150)

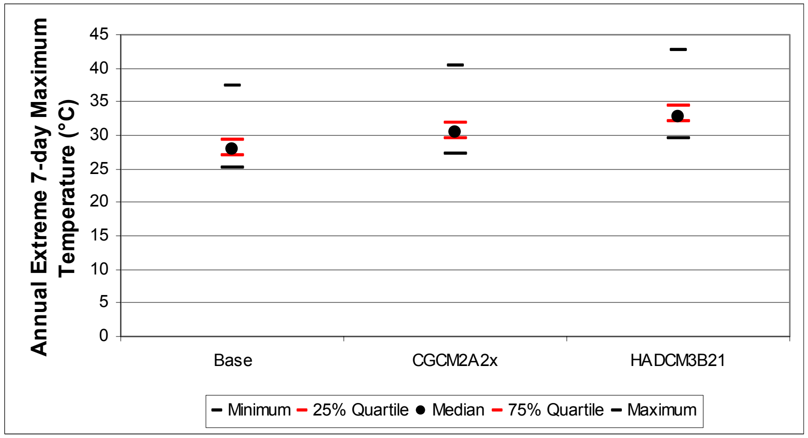


Figure B-37. Calgary annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-16. Calgary Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-37.4	-33.9	-36.2
Superpave-derived high PG threshold (°C)	51.7	53.7	55.8
98th percentile annual minimum air temperature	-45.5	-41.4	-44.4
Ontario RWIS-based low PG threshold (°C)	-34.9	-32.5	-34.3
98th percentile annual extreme 7-day mean maximum air temperature	32.6	34.6	37.8
Ontario RWIS-based high PG threshold (°C)	48.7	51.9	57.3

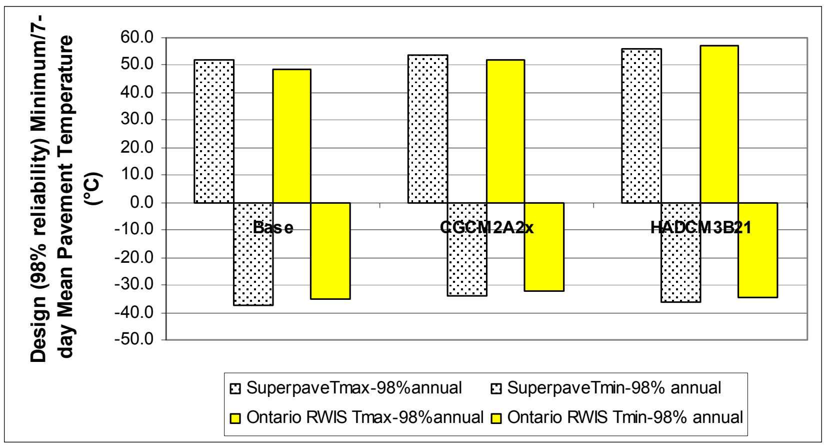


Figure B-38. Calgary estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-17. Calgary freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	67.9	27.1	49.4
Standard Deviation	33.5	19.0	30.4
Minimum	4.0	0.0	5.0
Lower Quartile	43.5	12.0	21.0
Median	70.5	21.0	49.5
Upper Quartile	91.0	39.0	74.0
Maximum	136.0	78.0	121.0

*n=150

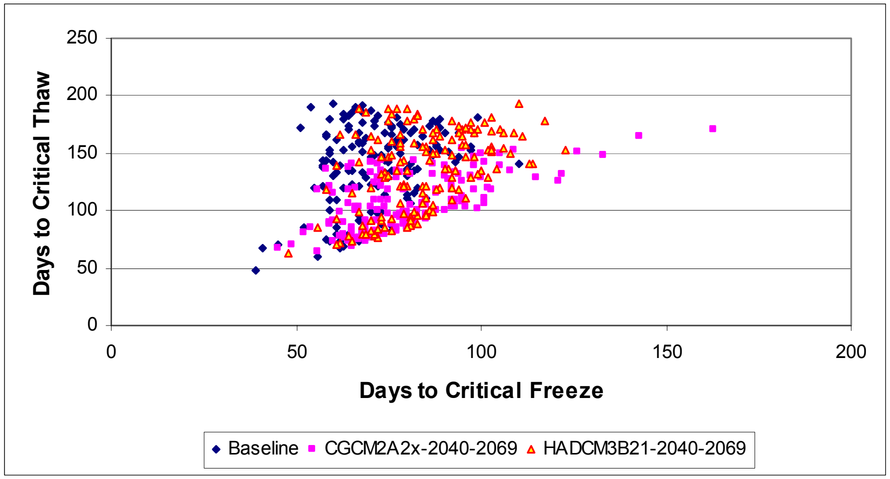


Figure B-39. Calgary estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

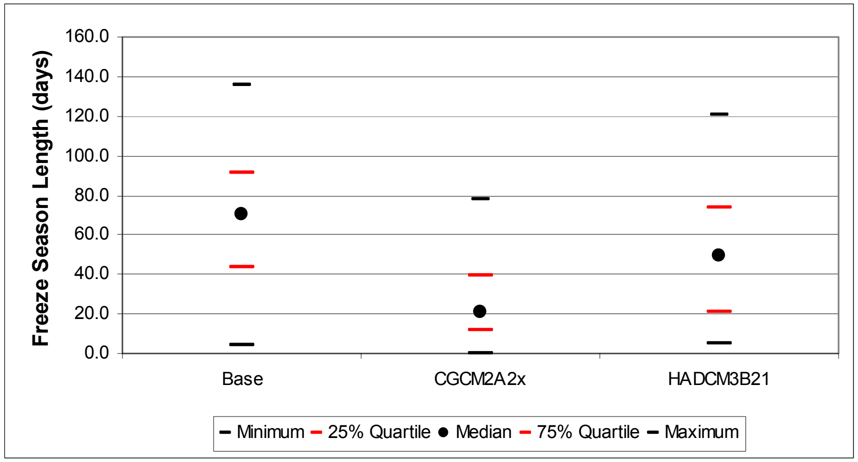


Figure B-40. Calgary estimated freeze season length distribution: quartile statistics (n=150)

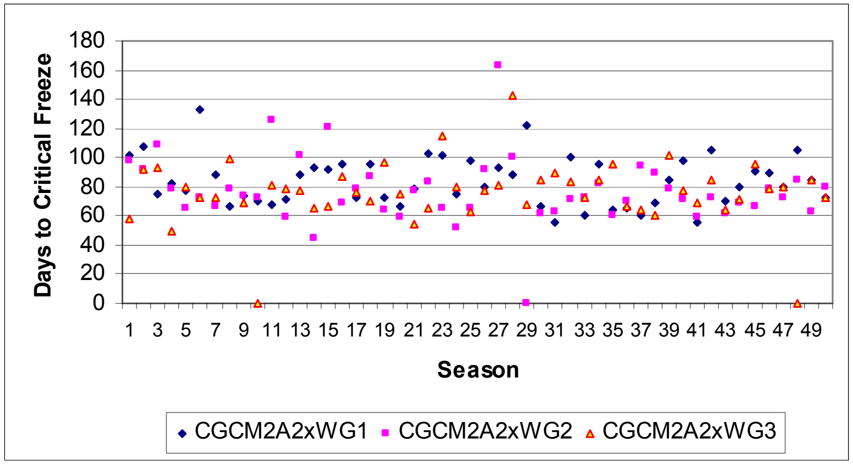


Figure B-42. Calgary estimated days to critical FI (CGCM2A2x scenario series)

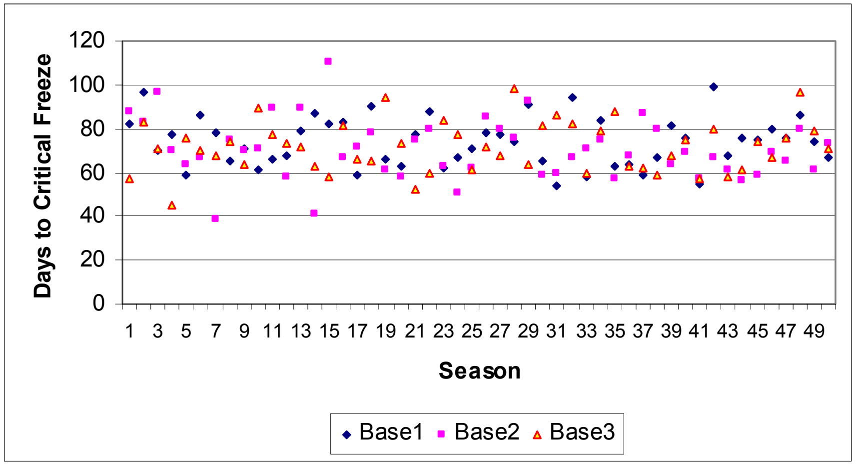


Figure B-41. Calgary estimated days to critical FI (baseline series)

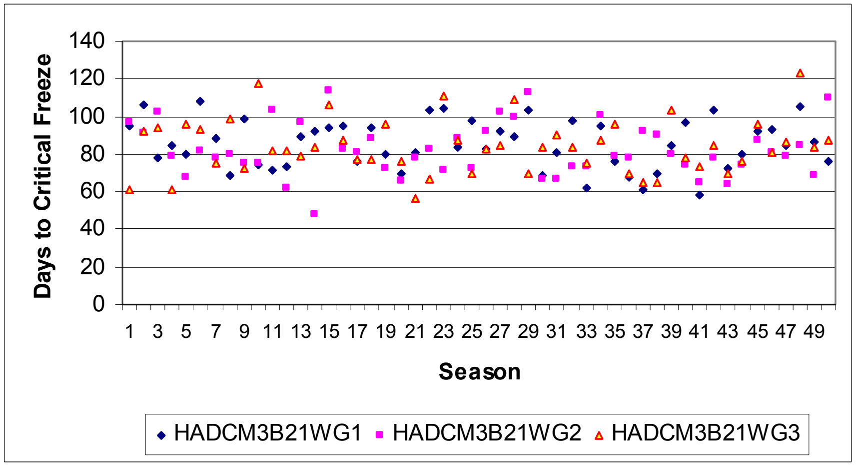


Figure B-43. Calgary estimated days to critical FI (HadCM3B21 scenario series)

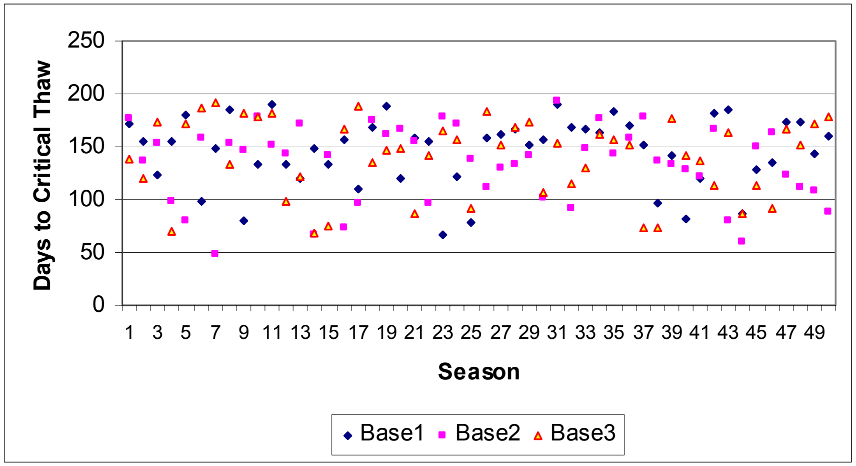


Figure B-44. Calgary estimated days to critical TI (baseline series)

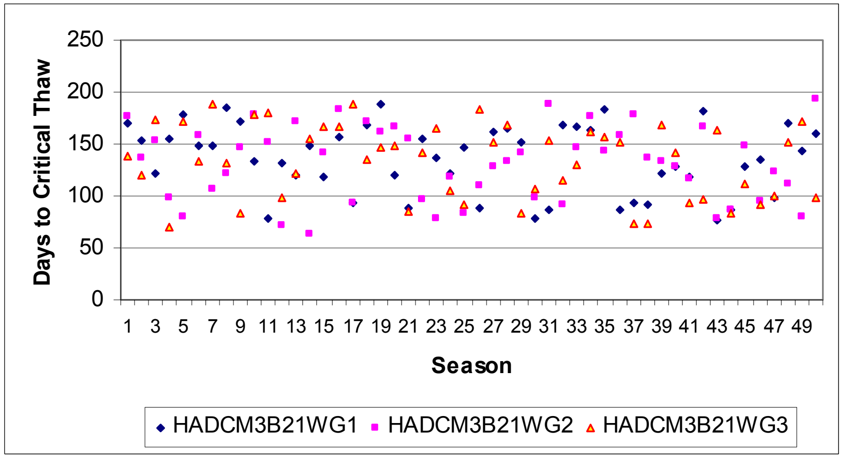


Figure B-46. Calgary estimated days to critical TI (HadCM3B21 scenario series)

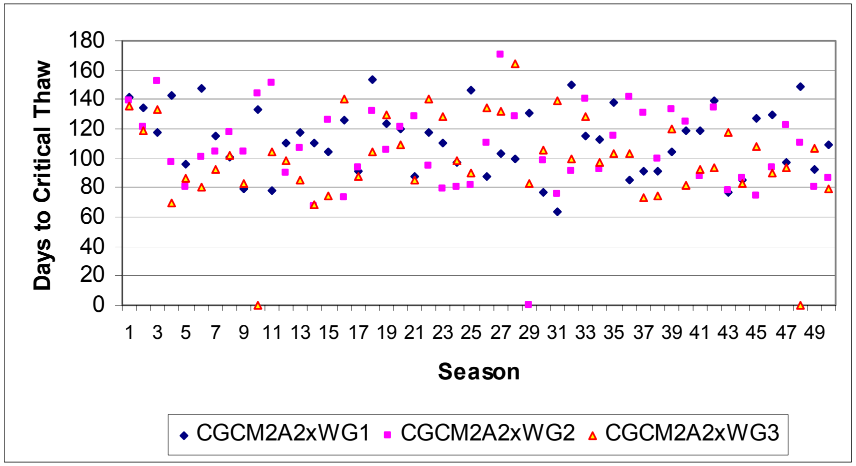


Figure B-45. Calgary estimated days to critical TI (CGCM2A2x scenario series)

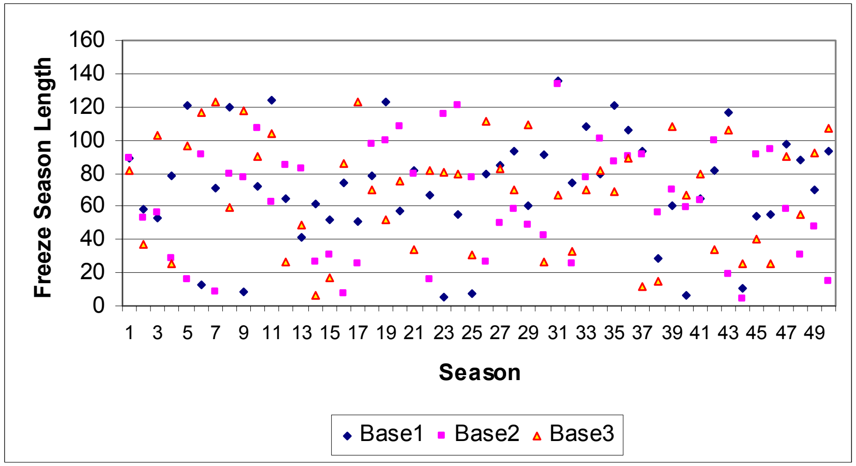


Figure B-47. Calgary estimated freeze season length (baseline series)

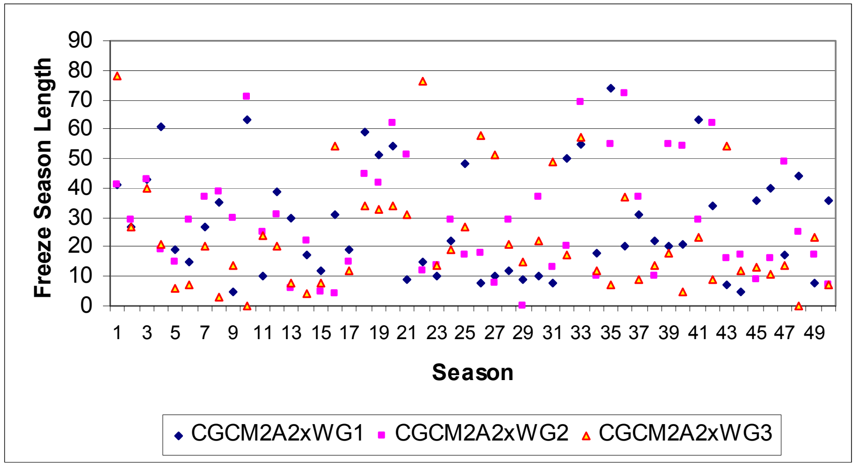


Figure B-48. Calgary estimated freeze season length (CGCM2A2x scenario series)

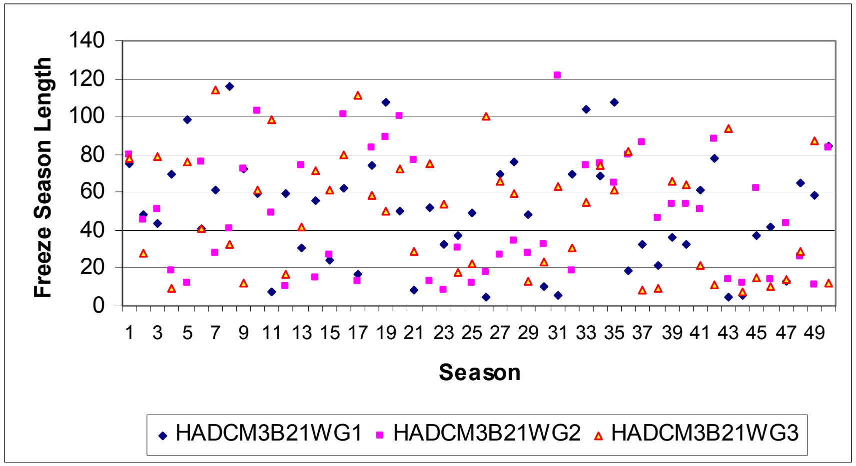


Figure B-49. Calgary estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: EDMONTON

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Edmonton (3012205)	53.5	113.5	723.3	4.1	412.6

*1971-2000 climate normals

Table B-18. Edmonton minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-4.0	-0.5	-2.0
Standard Deviation	11.7	11.3	12.2
Minimum	-54.8	-48.8	-53.4
Lower Quartile	-12.2	-8.7	-10.7
Median	-1.8	1.5	-0.1
Upper Quartile	5.8	9.1	8.3
Maximum	21.2	23.1	24.7

*n=54750

Table B-19. Edmonton 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	8.5	11.2	10.8
Standard Deviation	12.0	11.9	13.1
Minimum	-30.2	-25.8	-29.0
Lower Quartile	-1.3	1.2	-0.1
Median	9.8	12.2	11.8
Upper Quartile	19.3	22.0	22.9
Maximum	32.6	35.7	37.8

*n=54750

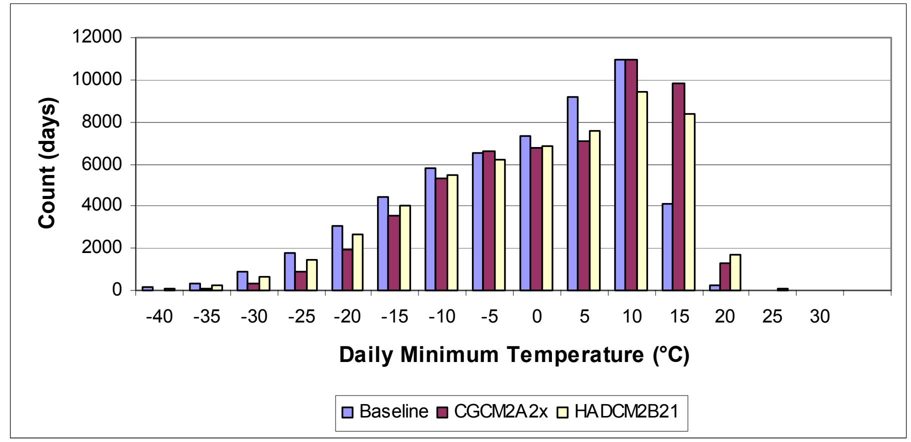


Figure B-50. Edmonton minimum daily temperature distribution (n=54750)

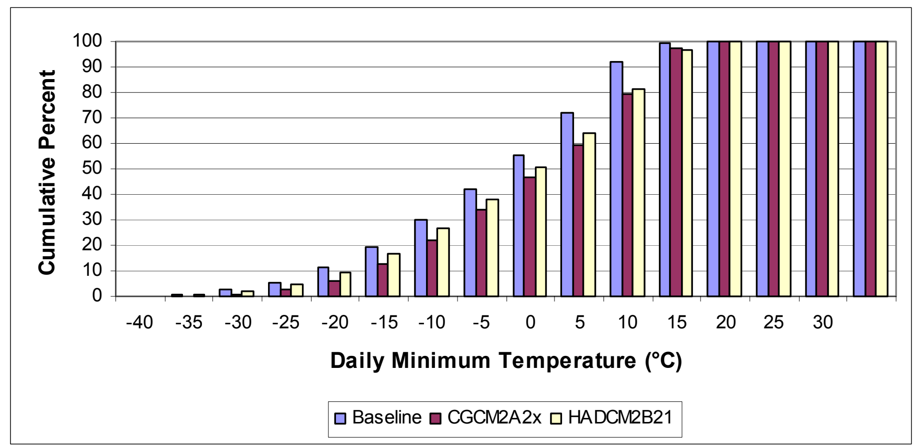


Figure B-51. Edmonton minimum daily temperature cumulative percent distribution (n=54750)

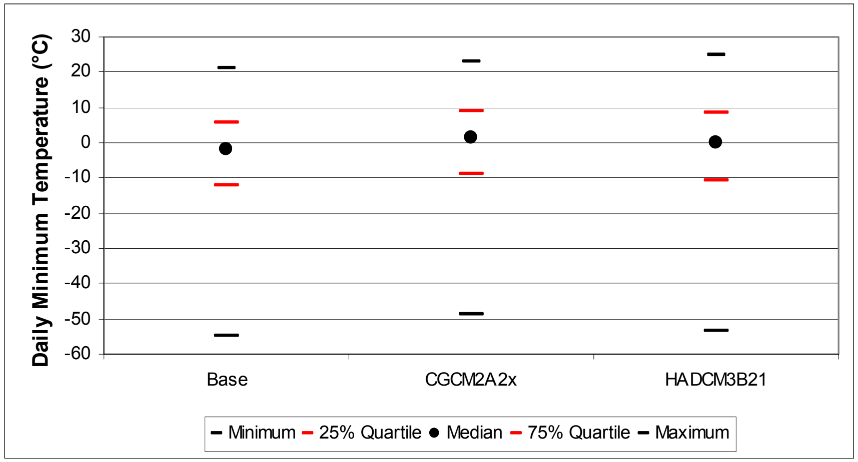


Figure B-52. Edmonton minimum daily temperature distribution: quartile statistics (n=54750)

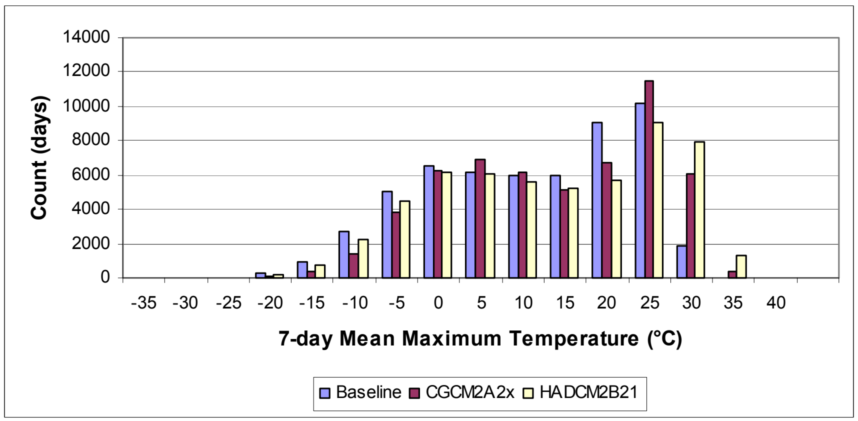


Figure B-53. Edmonton 7-day mean maximum daily temperature distribution (n=54750)

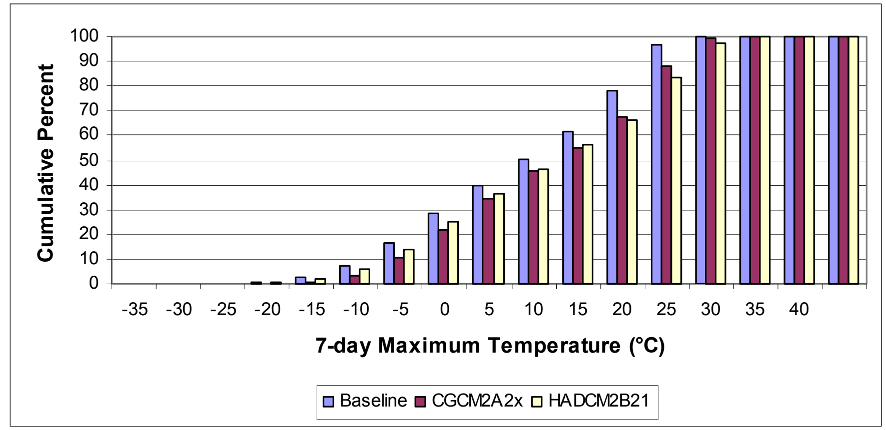


Figure B-54. Edmonton 7-day means maximum daily temperature cumulative percent distribution (n=54750)

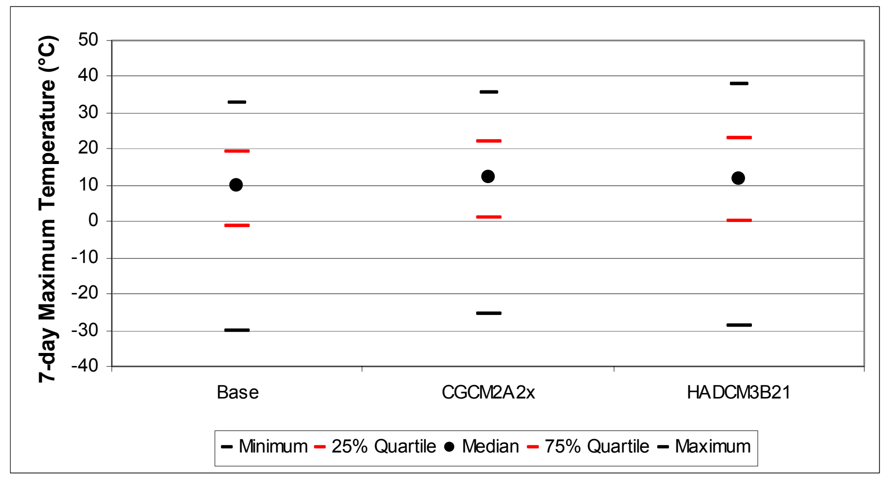


Figure B-55. Edmonton 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-20. Edmonton annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-40.4	-35.2	-38.9
Standard Deviation	5.0	4.7	5.0
Minimum	-54.8	-48.8	-53.4
Lower Quartile	-43.5	-38.0	-42
Median	-40.2	-34.7	-38.4
Upper Quartile	-37.0	-32.1	-35.8
Maximum	-29.9	-24.2	-28.0

*n=150

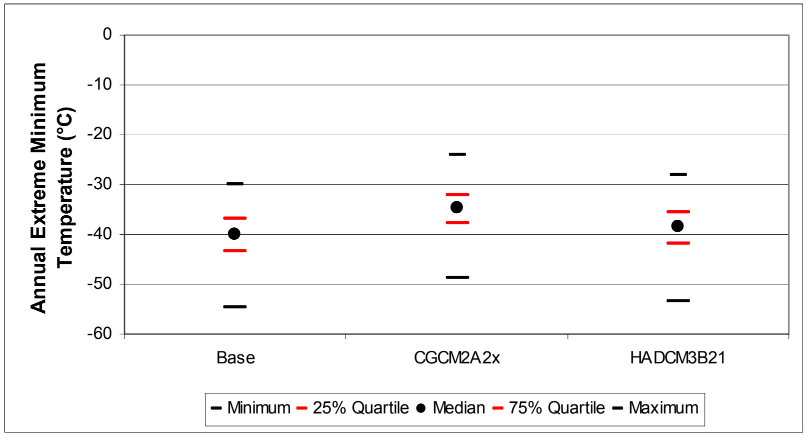


Figure B-56. Edmonton annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-21. Edmonton annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	27.4	30.1	32.0
Standard Deviation	1.7	1.8	1.9
Minimum	23.3	26.3	28.4
Lower Quartile	26.2	29.1	30.6
Median	27.2	30.0	31.8
Upper Quartile	28.7	31.3	33.1
Maximum	32.6	35.7	37.8

*n=150

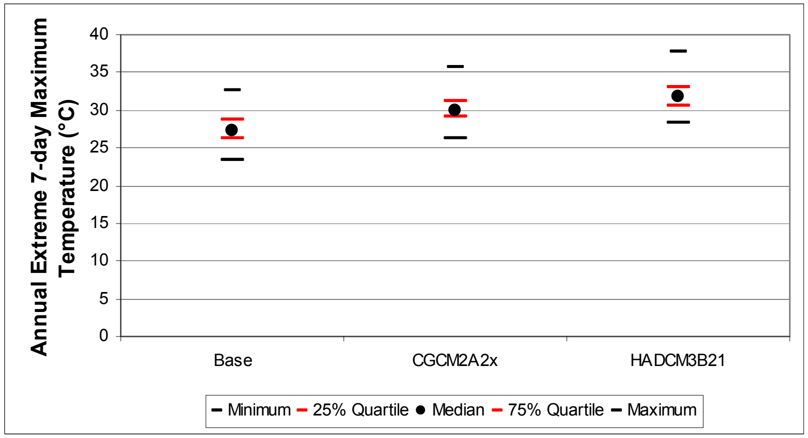


Figure B-57. Edmonton annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-22. Edmonton Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-41.9	-37.8	-40.8
Superpave-derived high PG threshold (°C)	50.3	52.4	53.9
98th percentile annual minimum air temperature	-52.6	-46.6	-50.7
Ontario RWIS-based low PG threshold (°C)	-38.8	-35.6	-37.8
98th percentile annual extreme 7-day mean maximum air temperature	31.6	34.2	36.6
Ontario RWIS-based high PG threshold (°C)	47.1	51.3	55.3

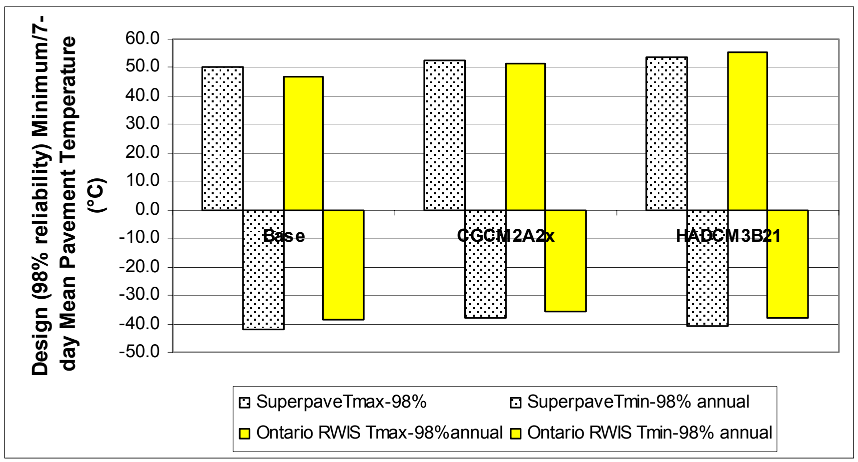


Figure B-58. Edmonton estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-23. Edmonton freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	103.6	65.5	88.4
Standard Deviation	35.9	37.9	36.5
Minimum	6.0	5.0	4.0
Lower Quartile	92.0	28.3	74.0
Median	115.0	69.0	99.0
Upper Quartile	130.0	97.5	115.0
Maximum	150.0	130.0	142.0

*n=150

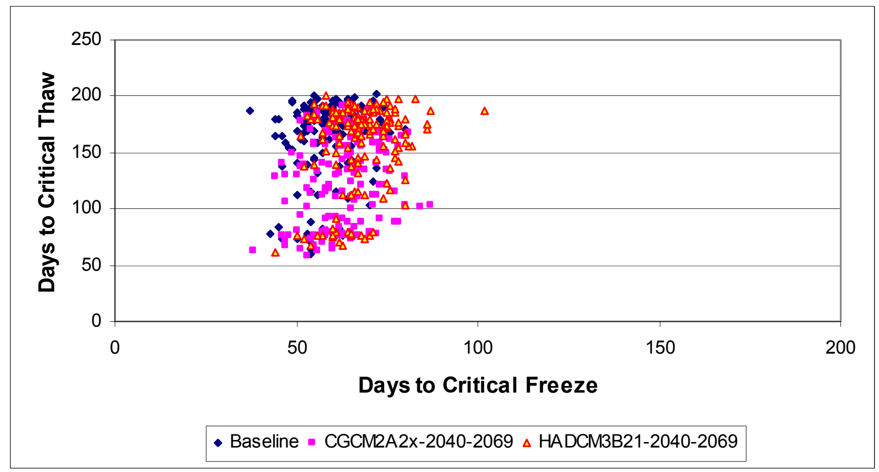


Figure B-59. Edmonton estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

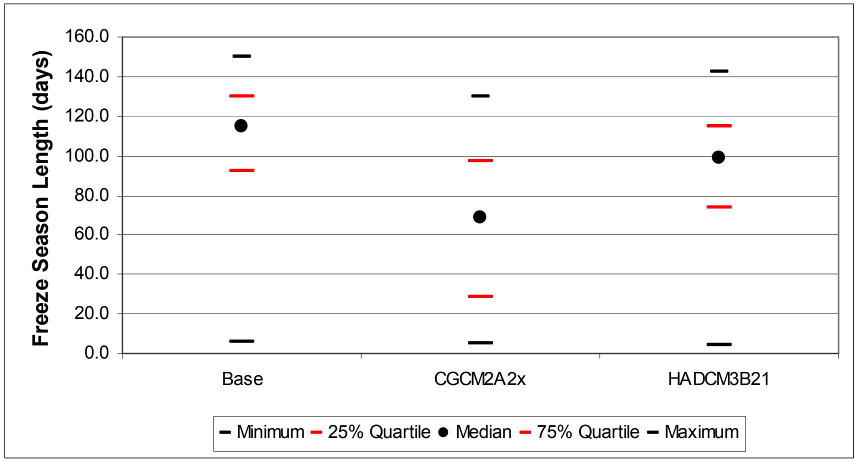


Figure B-60. Edmonton estimated freeze season length distribution: quartile statistics (n=150)

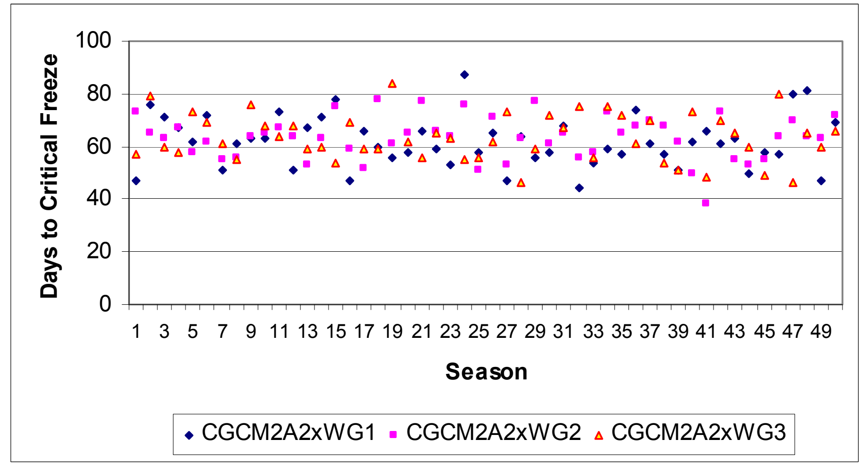


Figure B-62. Edmonton estimated days to critical FI (CGCM2A2x scenario series)

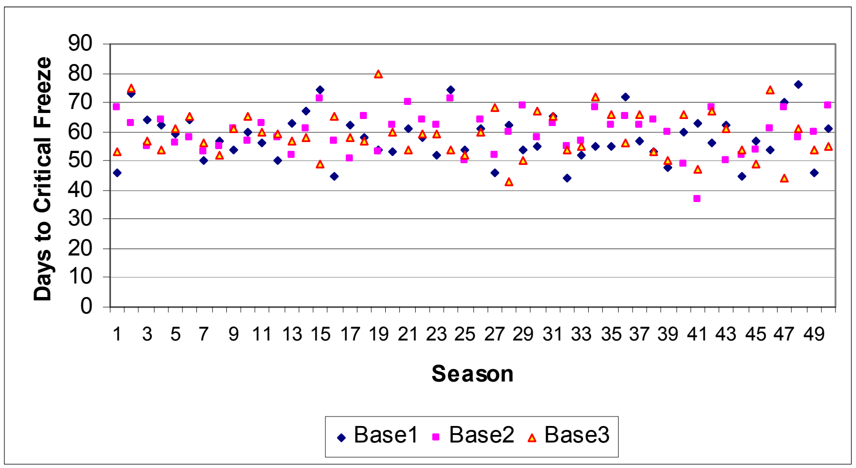


Figure B-61. Edmonton estimated days to critical FI (baseline series)

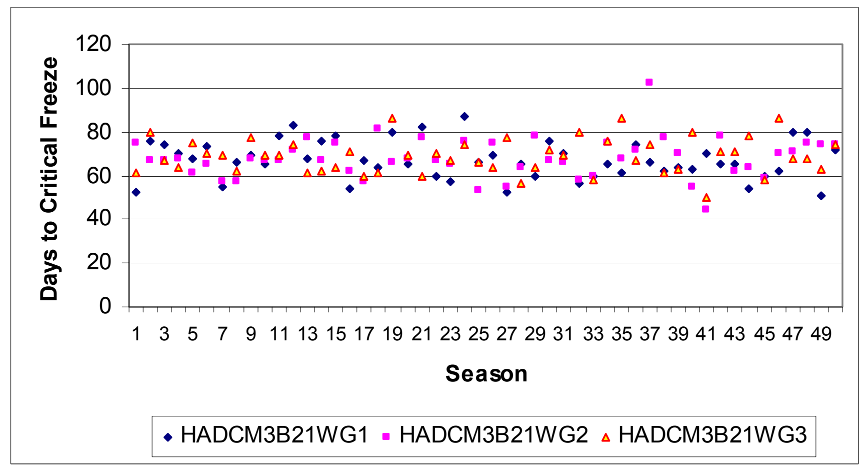


Figure B-63. Edmonton estimated days to critical FI (HadCM3B21 scenario series)

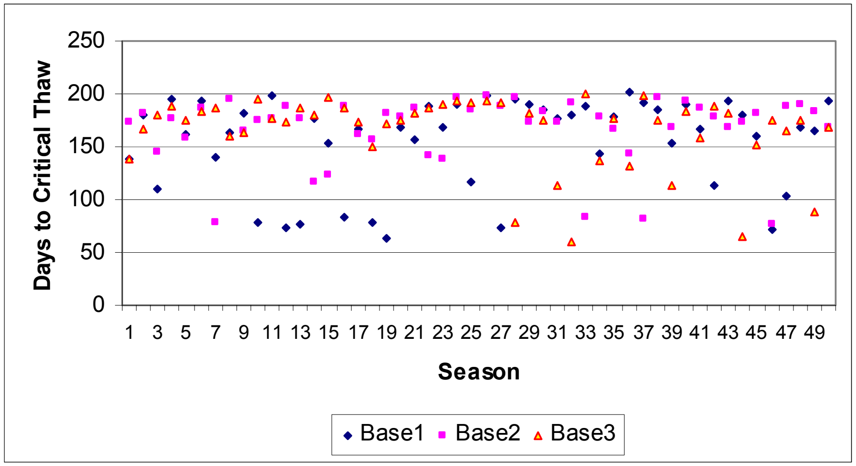


Figure B-64. Edmonton estimated days to critical TI (baseline series)

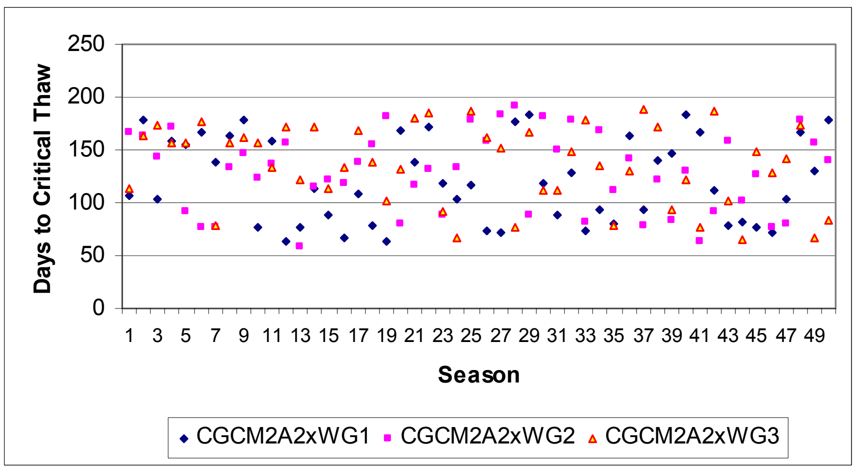


Figure B-65. Edmonton estimated days to critical TI (CGCM2A2x scenario series)

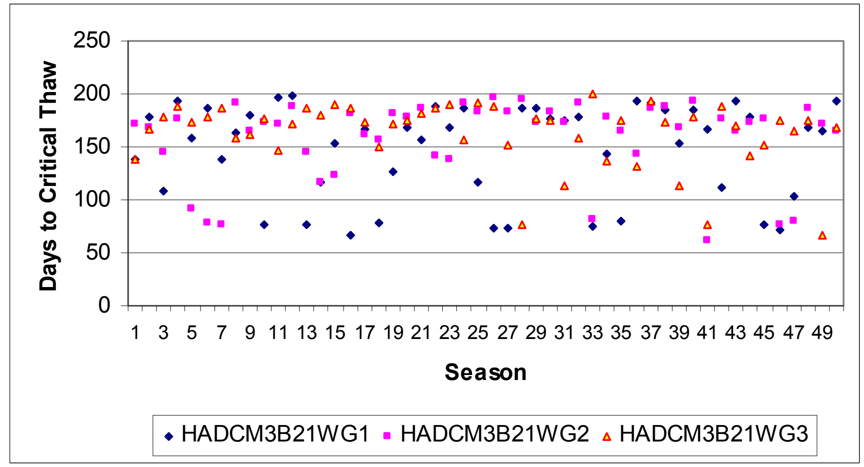


Figure B-66. Edmonton estimated days to critical TI (HadCM3B21 scenario series)

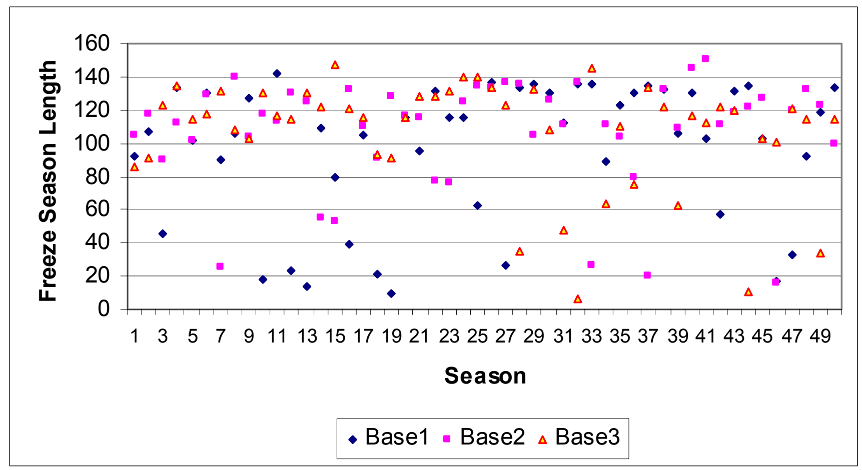


Figure B-67. Edmonton estimated freeze season length (baseline series)

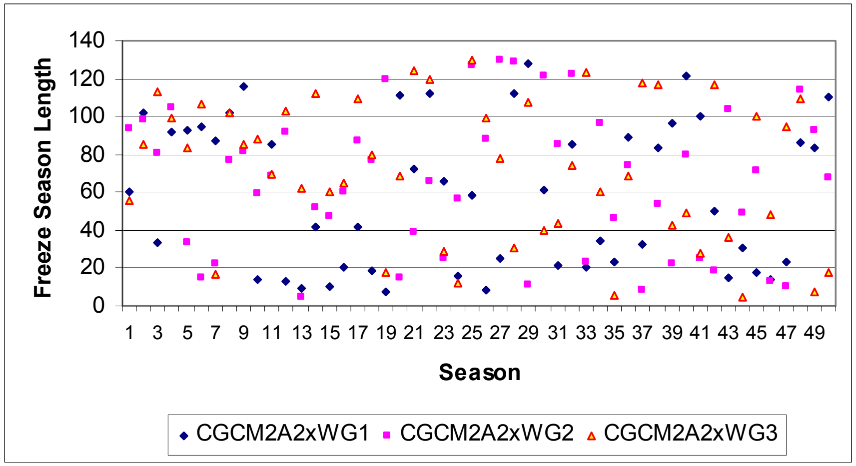


Figure B-68. Edmonton estimated freeze season length (CGCM2A2x scenario series)

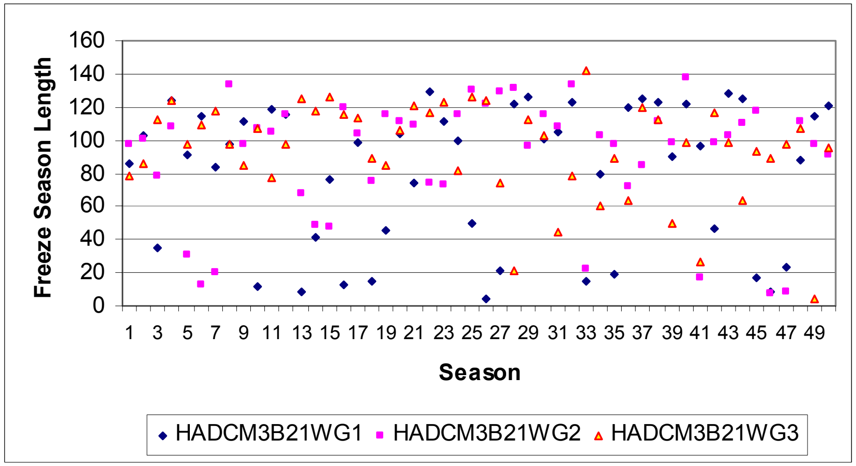


Figure B-69. Edmonton estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: REGINA

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Regina (4016560)	50.5	104.6	577.3	2.8	388.1

*1971-2000 climate normals

Table B-24. Regina minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-3.7	0.4	-1.5
Standard Deviation	12.9	12.0	13.6
Minimum	-55.9	-49.3	-55.6
Lower Quartile	-13.0	-8.4	-11.5
Median	-1.7	2.3	0.4
Upper Quartile	7.1	10.3	9.8
Maximum	24.5	27.1	28.4

*n=54750

Table B-25. Regina 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	8.9	13.1	11.3
Standard Deviation	13.7	13.8	14.9
Minimum	-30	-25.5	-29.7
Lower Quartile	-2.8	0.9	-1.7
Median	10.3	15.0	12.8
Upper Quartile	21.3	25.8	24.8
Maximum	37.9	41.7	43.0

*n=54750

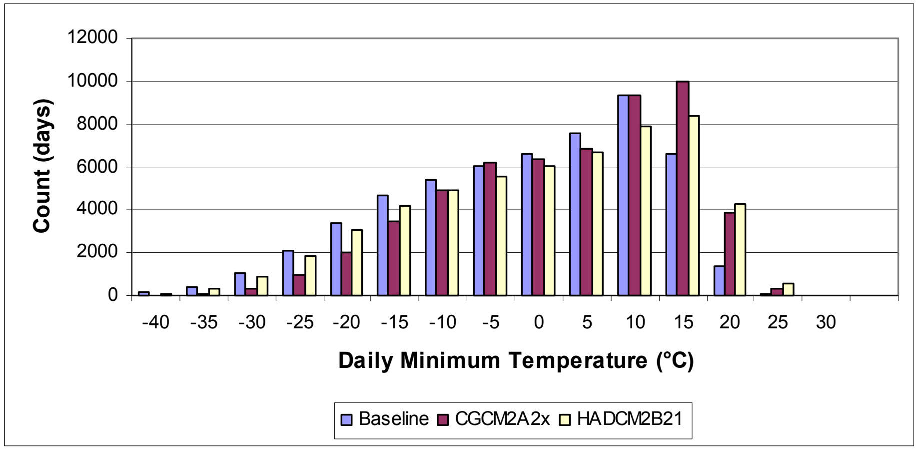


Figure B-70. Regina minimum daily temperature distribution (n=54750)

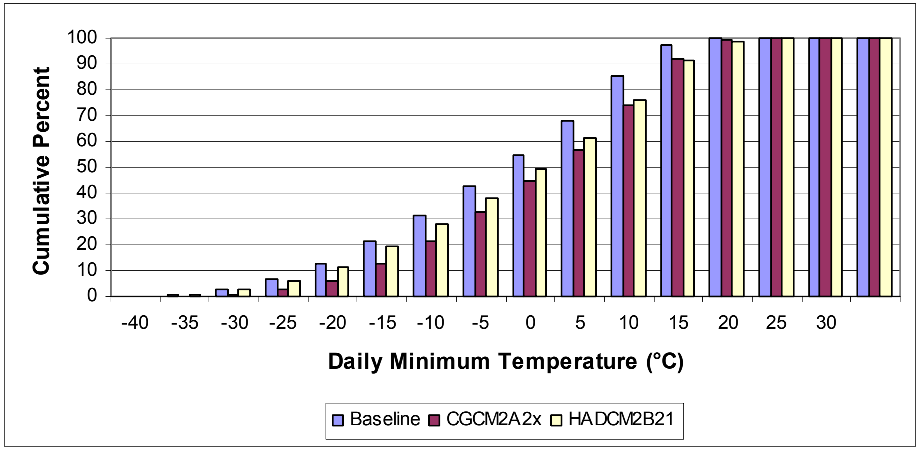


Figure B-71. Regina minimum daily temperature cumulative percent distribution (n=54750)

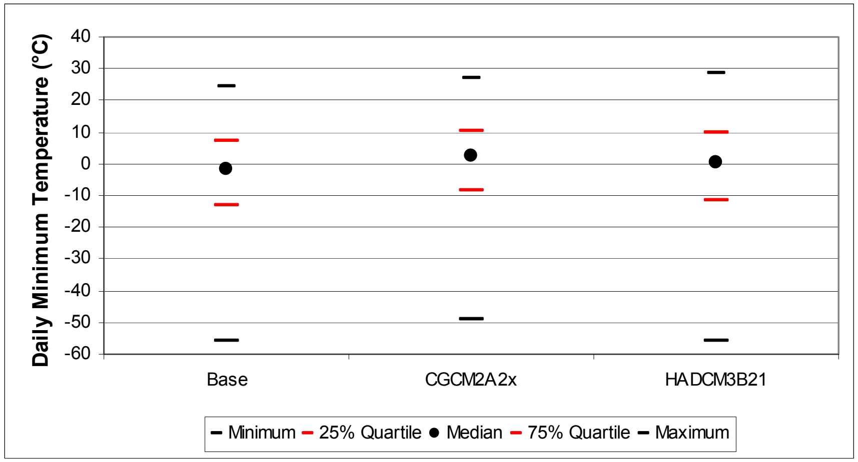


Figure B-72. Regina minimum daily temperature distribution: quartile statistics (n=54750)

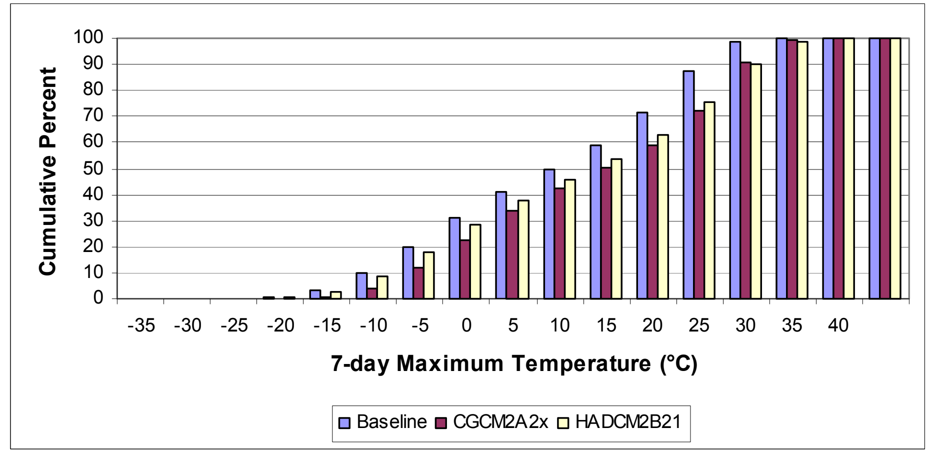


Figure B-74. Regina 7-day means maximum daily temperature cumulative percent distribution (n=54750)

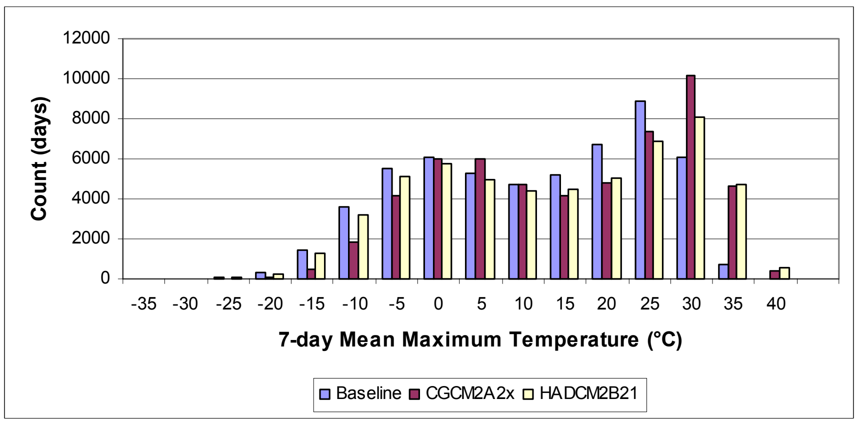


Figure B-73. Regina 7-day mean maximum daily temperature distribution (n=54750)

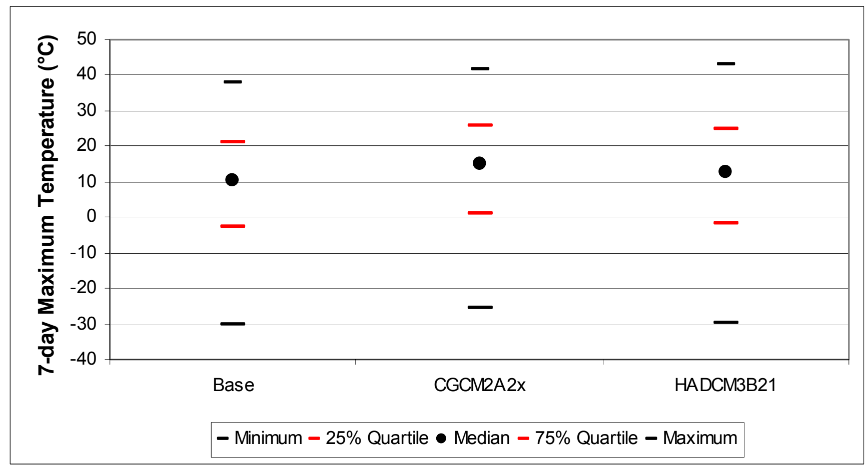


Figure B-75. Regina 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-26. Regina annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-40.3	-34.7	-39.5
Standard Deviation	4.5	4.4	4.5
Minimum	-55.9	-49.3	-55.6
Lower Quartile	-42.4	-37.2	-42.2
Median	-40.0	-34.3	-39.3
Upper Quartile	-37.4	-31.8	-36.5
Maximum	-27.7	-24.3	-27.6

*n=150

Table B-27. Regina annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	31.2	35.1	35.7
Standard Deviation	2.0	2.0	2.3
Minimum	26.8	31.2	30.9
Lower Quartile	29.5	33.6	34.1
Median	30.9	34.8	35.5
Upper Quartile	32.6	36.2	37.1
Maximum	37.9	41.7	43.0

*n=150

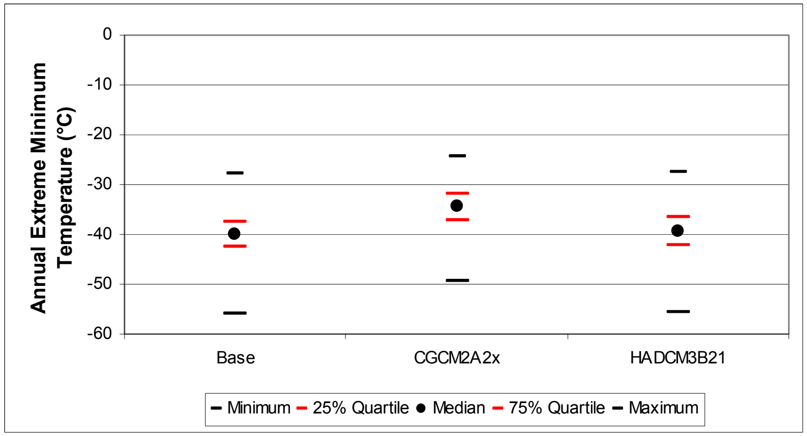


Figure B-76. Regina annual extreme minimum temperature distribution: quartile statistics (n=150)

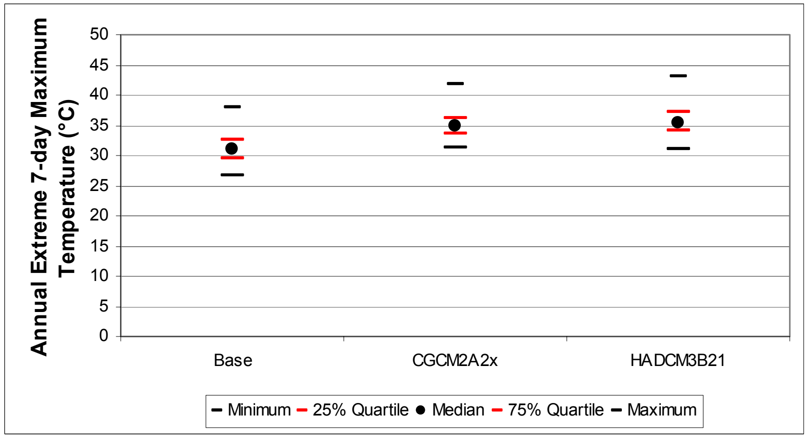


Figure B-77. Regina annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-28. Regina Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-39.9	-35.9	-39.3
Superpave-derived high PG threshold (°C)	54.2	57.2	57.9
98th percentile annual minimum air temperature	-52.0	-47.1	-50.5
Ontario RWIS-based low PG threshold (°C)	-38.5	-35.8	-37.7
98th percentile annual extreme 7-day mean maximum air temperature	36.1	40.2	40.9
Ontario RWIS-based high PG threshold (°C)	54.4	61.4	62.7

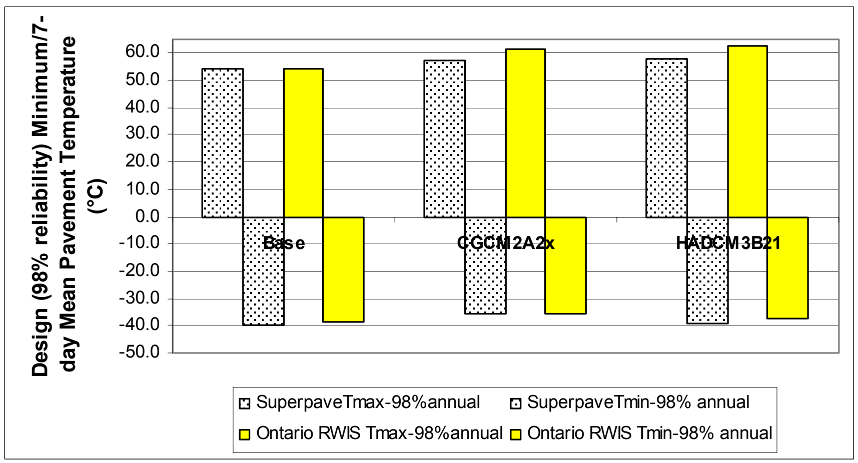


Figure B-78. Regina estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-29. Regina freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	118.3	79.6	104.5
Standard Deviation	18.7	26.1	23.8
Minimum	9.0	6.0	4.0
Lower Quartile	112.0	67.3	100.0
Median	120.0	84.5	110.0
Upper Quartile	129.8	97.8	117.0
Maximum	155.0	120.0	136.0

*n=150

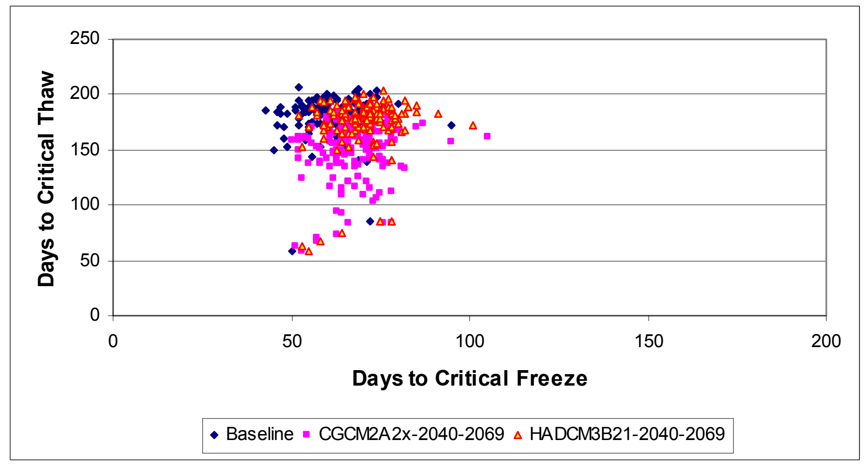


Figure B-79. Regina estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

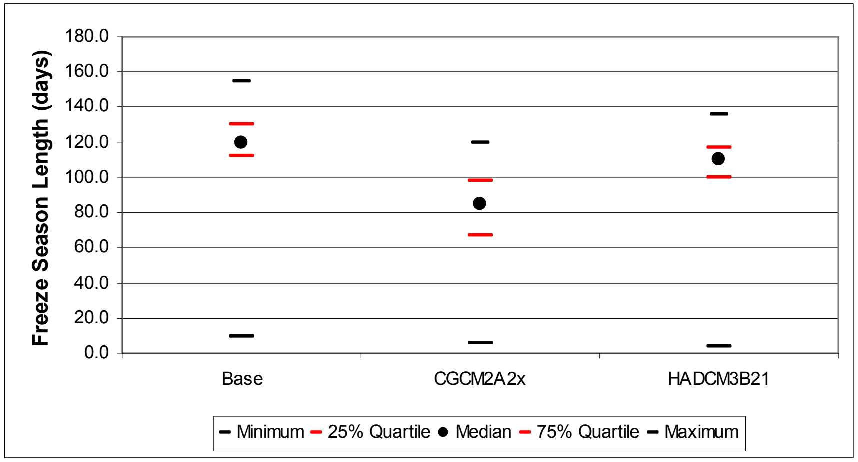


Figure B-80. Regina estimated freeze season length distribution: quartile statistics (n=150)

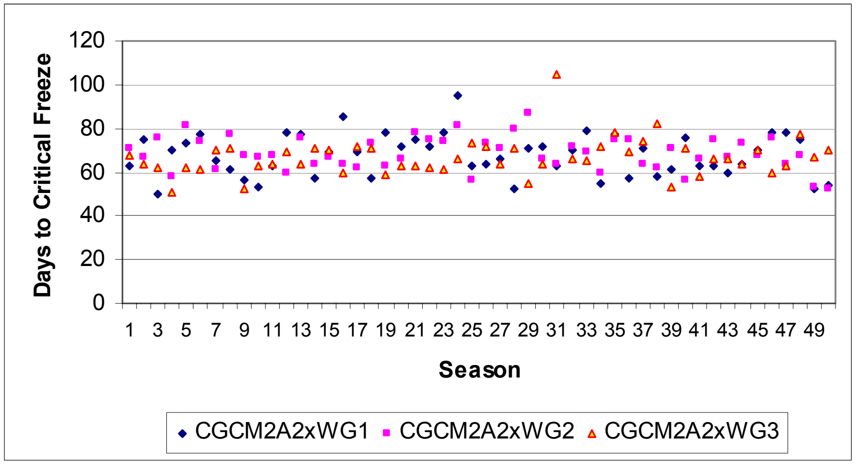


Figure B-82. Regina estimated days to critical FI (CGCM2A2x scenario series)

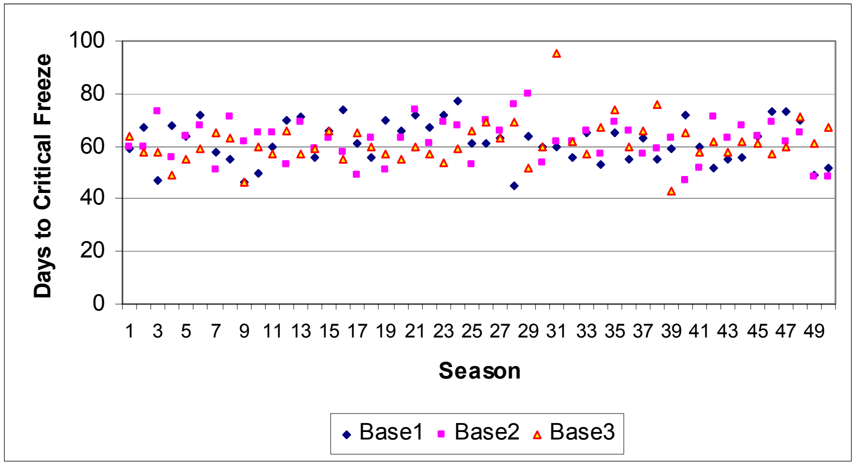


Figure B-81. Regina estimated days to critical FI (baseline series)

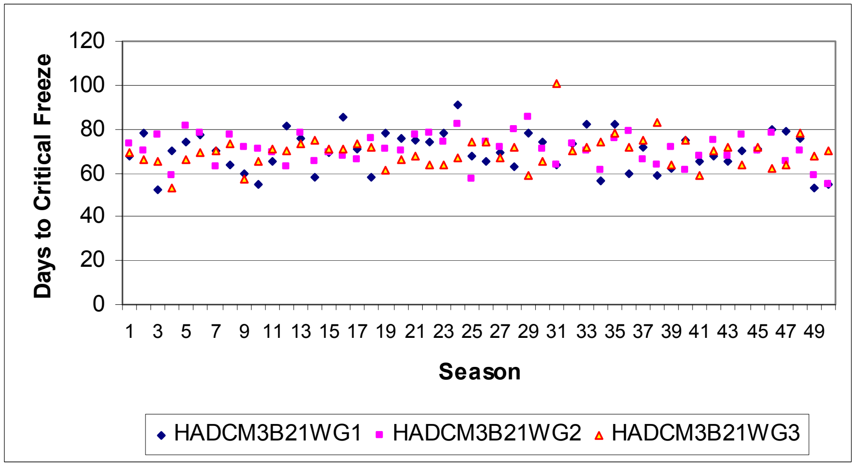


Figure B-83. Regina estimated days to critical FI (HadCM3B21 scenario series)

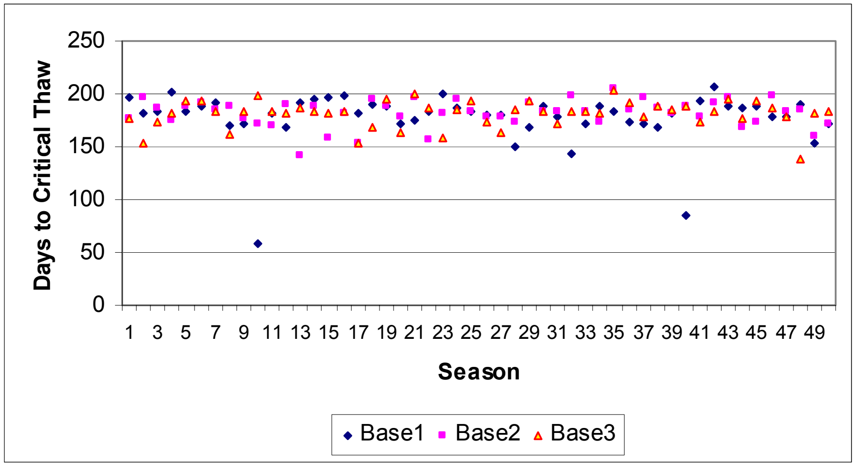


Figure B-84. Regina estimated days to critical TI (baseline series)

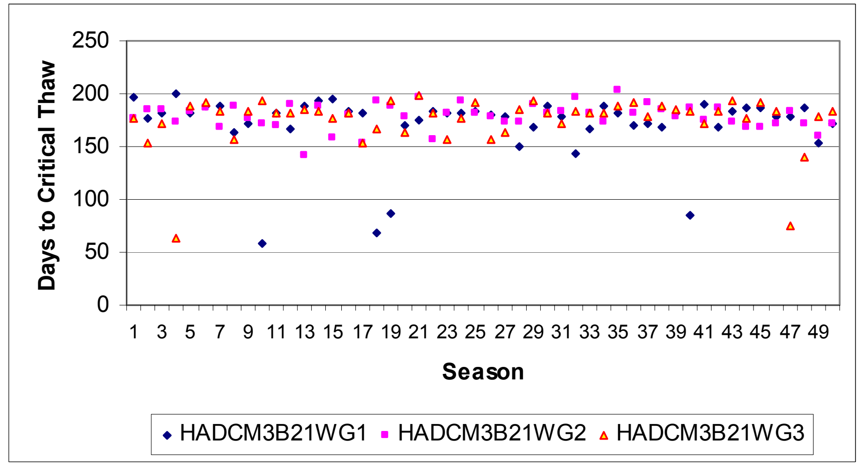


Figure B-86. Regina estimated days to critical TI (HadCM3B21 scenario series)

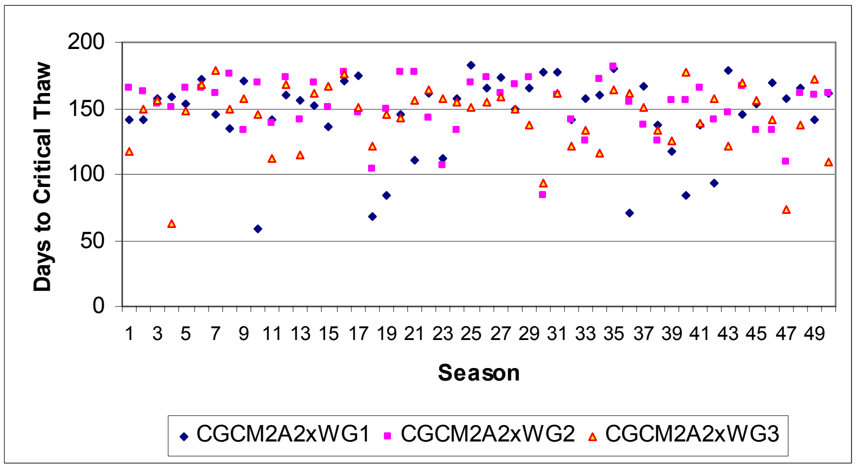


Figure B-85. Regina estimated days to critical TI (CGCM2A2x scenario series)

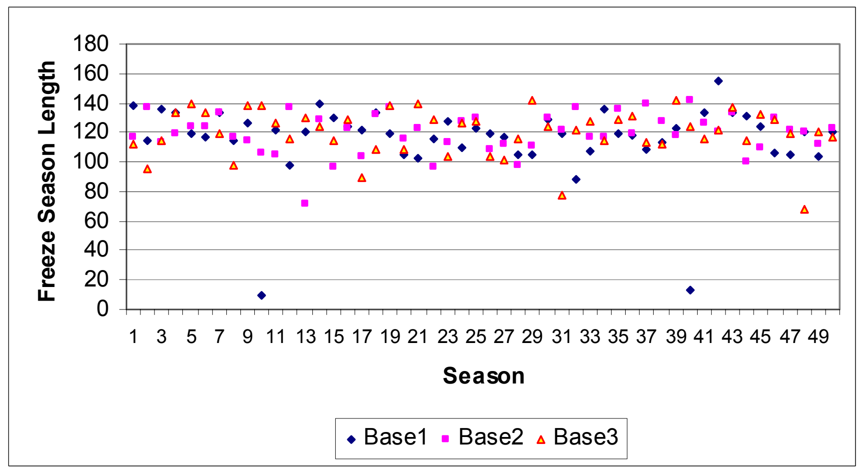


Figure B-87. Regina estimated freeze season length (baseline series)

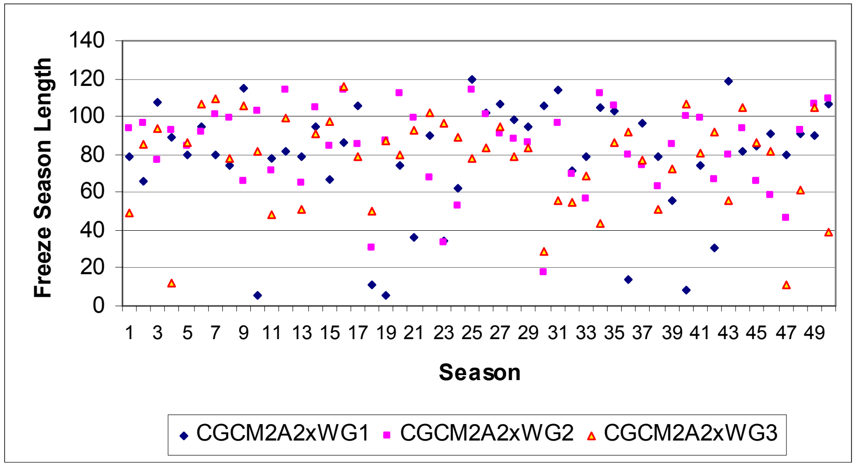


Figure B-88. Regina estimated freeze season length (CGCM2A2x scenario series)

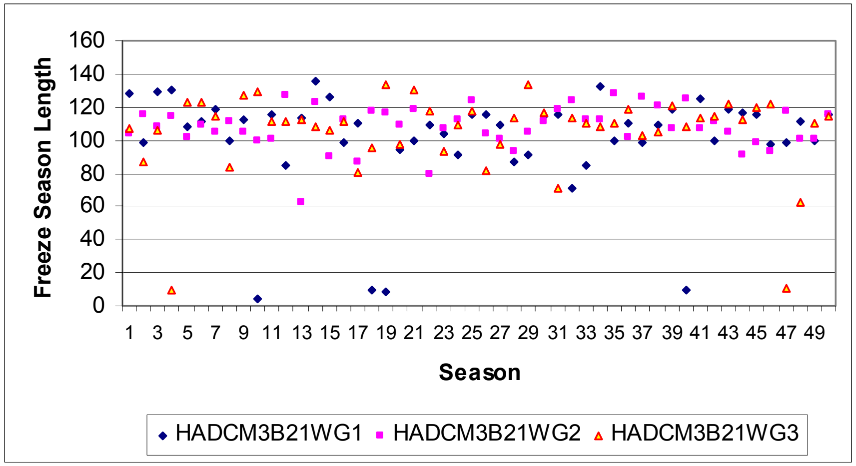


Figure B-89. Regina estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: WINNIPEG

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Winnipeg (5023222)	50.0	97.2	238.7	2.6	513.7

*1971-2000 climate normals

Table B-30. Winnipeg minimum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-3.2	0.4	-1.2
Standard Deviation	13.8	13.4	14.4
Minimum	-52.5	-47.5	-52.2
Lower Quartile	-13.7	-10	-12.2
Median	-1.0	2.5	1.1
Upper Quartile	8.4	11.9	11.0
Maximum	27.7	30.1	30.7

*n=54750

Table B-31. Winnipeg 7-day mean maximum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	8.1	12.0	10.3
Standard Deviation	14.2	14.4	15.3
Minimum	-30.9	-25.9	-30.7
Lower Quartile	-4.4	-1.1	-3.4
Median	9.7	13.6	12.1
Upper Quartile	21.3	25.7	24.7
Maximum	36.5	41.2	40.4

*n=54750

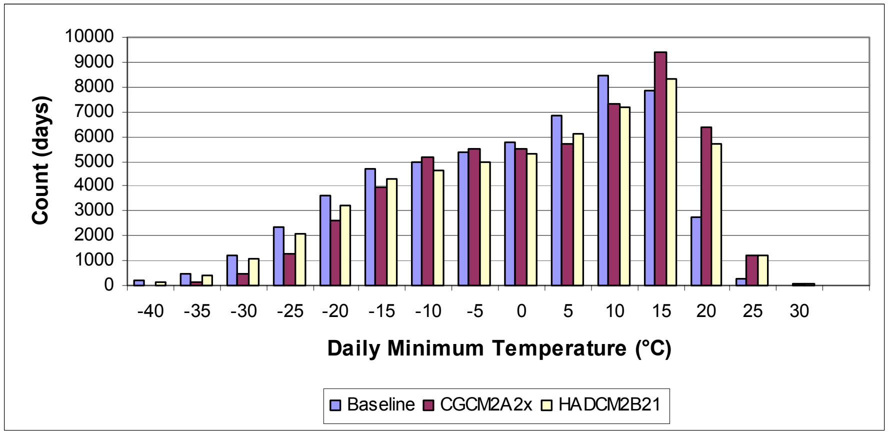


Figure B-80. Winnipeg minimum daily temperature distribution (n=54750)

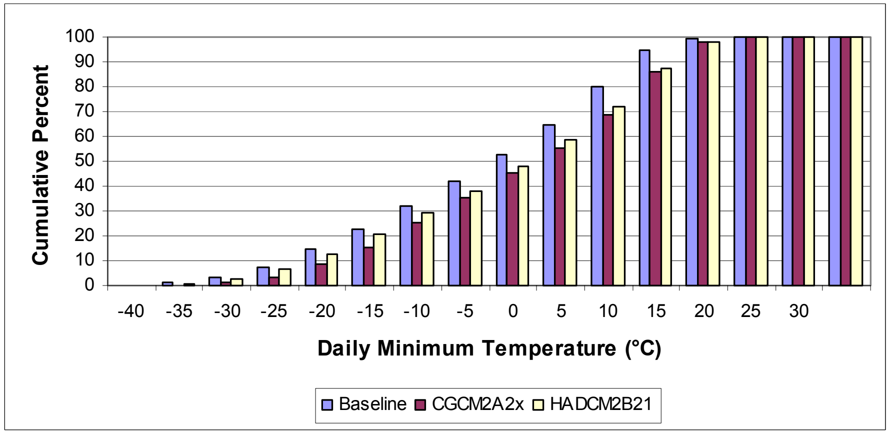


Figure B-81. Winnipeg minimum daily temperature cumulative percent distribution (n=54750)

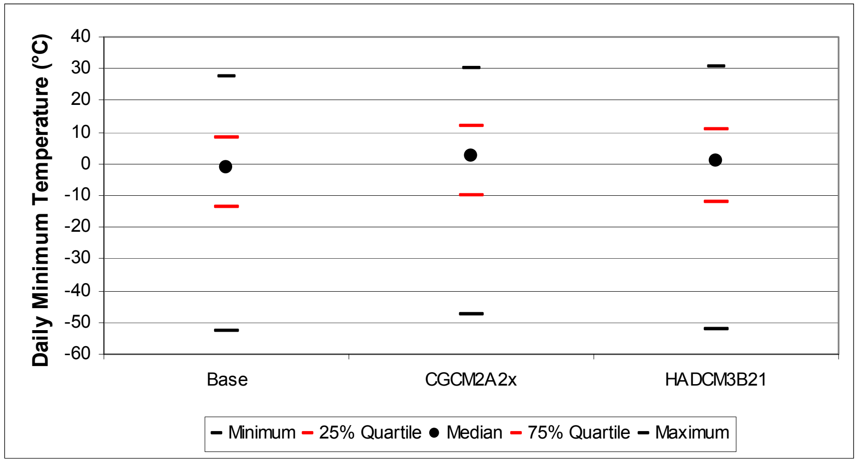


Figure B-82. Winnipeg minimum daily temperature distribution: quartile statistics (n=54750)

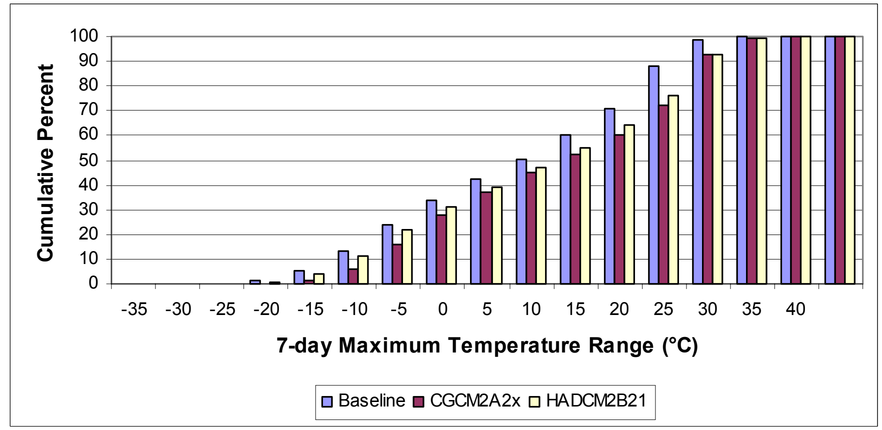


Figure B-84. Winnipeg 7-day means maximum daily temperature cumulative percent distribution (n=54750)

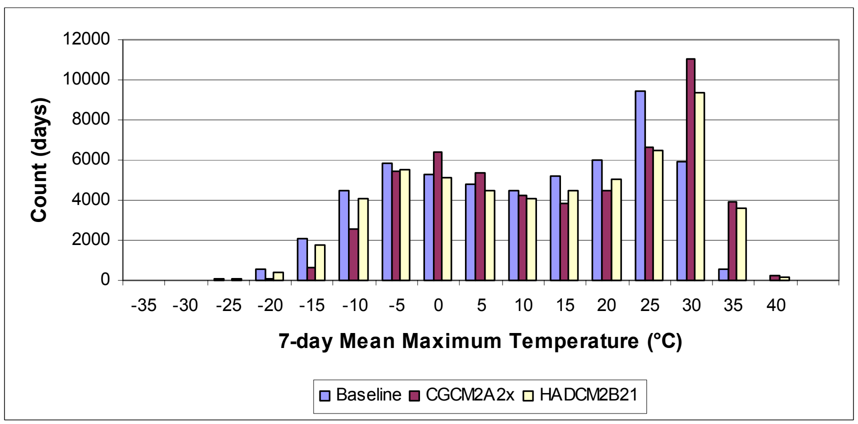


Figure B-83. Winnipeg 7-day mean maximum daily temperature distribution (n=54750)

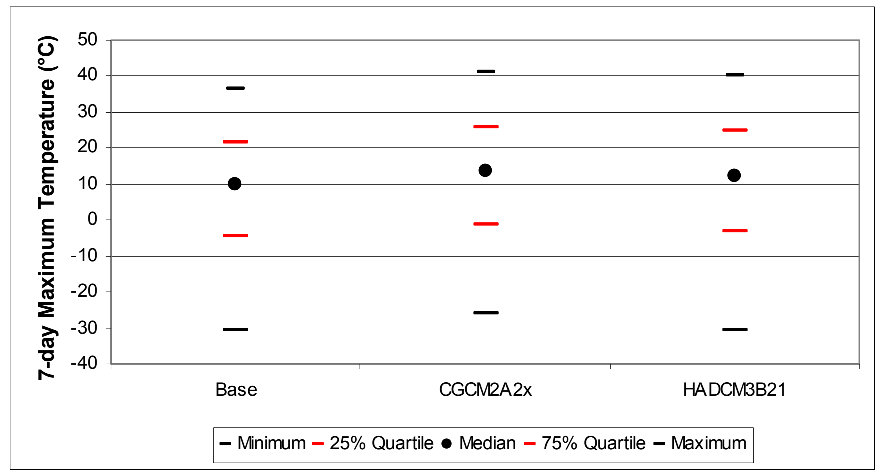


Figure B-85. Winnipeg 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-32. Winnipeg annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC (°C)	**Baseline***	**CGCM2A2x***	**HadCM3B21***
Mean	-40.5	-35.7	-39.8
Standard Deviation	4.4	4.3	4.4
Minimum	-52.5	-47.5	-52.2
Lower Quartile	-42.9	-38.1	-42.2
Median	-40.8	-35.7	-39.7
Upper Quartile	-37.6	-32.7	-36.8
Maximum	-31.0	-26.0	-30.6

*n=150

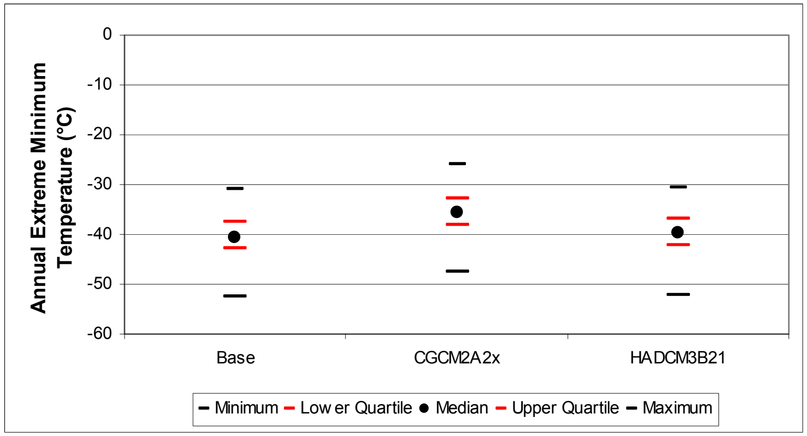


Figure B-86. Winnipeg annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-33. Winnipeg annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC (°C)	**Baseline***	**CGCM2A2x***	**HadCM3B21***
Mean	30.6	34.4	34.3
Standard Deviation	1.7	1.9	1.7
Minimum	26.8	30.0	30.6
Lower Quartile	29.5	33.1	33.0
Median	30.4	34.05	34.3
Upper Quartile	31.6	35.4	35.3
Maximum	36.5	41.2	40.4

*n=150

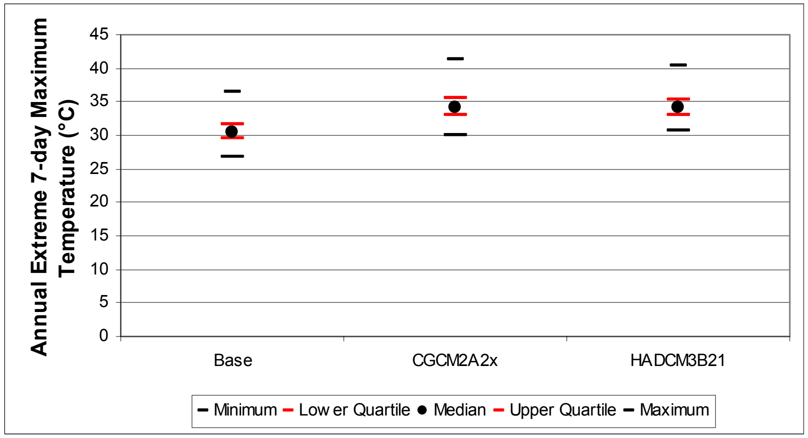


Figure B-87. Winnipeg annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-34. Winnipeg Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-39.7	-36.2	-39.2
Superpave-derived high PG threshold (°C)	53.6	56.7	56.5
98th percentile annual minimum air temperature	-49.5	-45.0	-49.0
Ontario RWIS-based low PG threshold (°C)	-37.2	-34.6	-36.9
98th percentile annual extreme 7-day mean maximum air temperature	34.6	38.5	38.0
Ontario RWIS-based high PG threshold (°C)	51.9	58.5	57.6

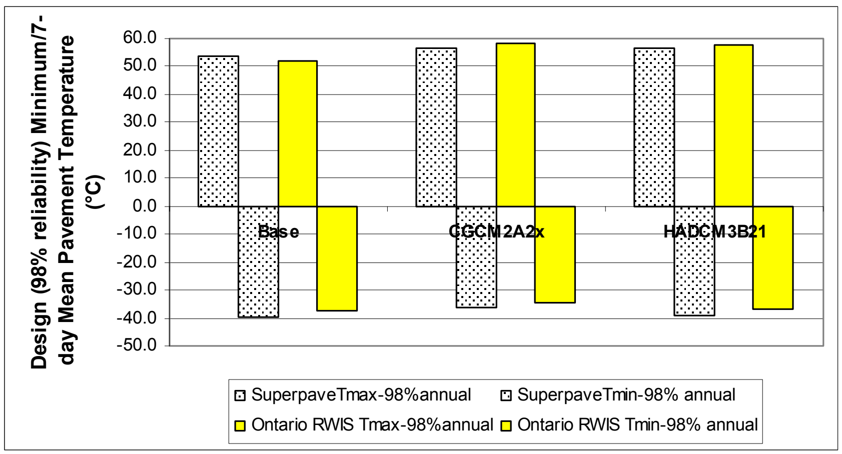


Figure B-88. Winnipeg estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-35. Winnipeg freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	121.9	101.1	112.1
Standard Deviation	18.5	21.5	14.4
Minimum	4.0	15.0	18.0
Lower Quartile	116.0	95.3	104.0
Median	124.0	105.5	113.0
Upper Quartile	132.0	114.8	121.0
Maximum	148.0	131.0	145.0

*n=150

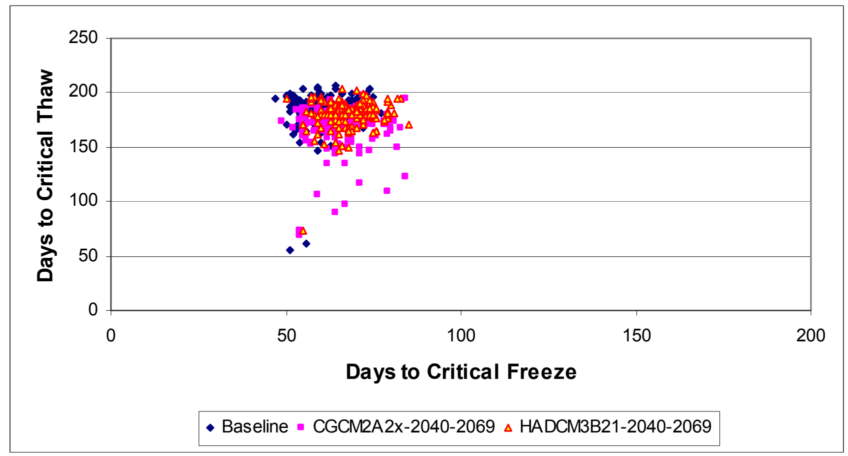


Figure B-89. Winnipeg estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

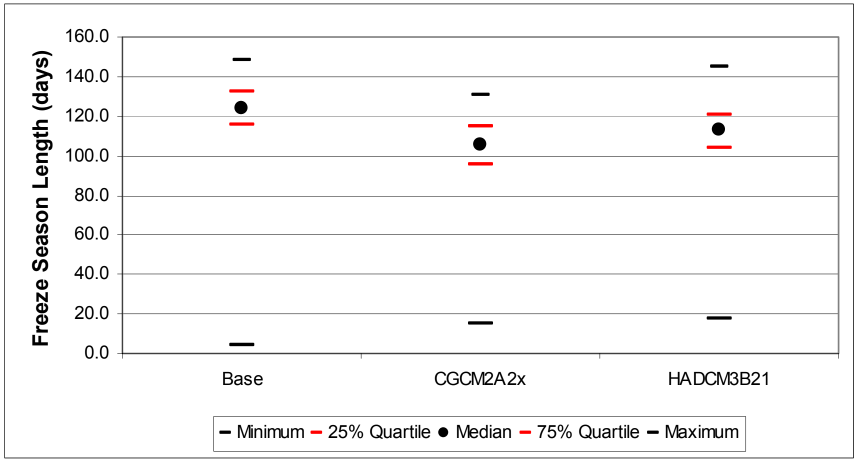


Figure B-90. Winnipeg estimated freeze season length distribution: quartile statistics (n=150)

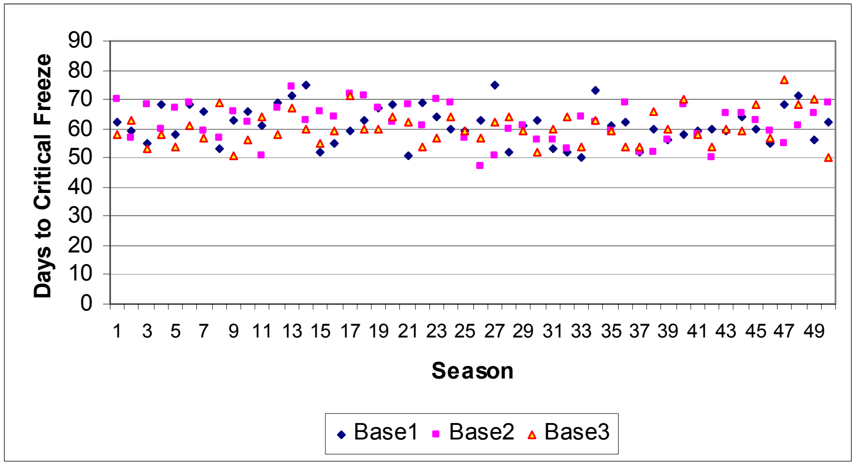


Figure B-91. Winnipeg estimated days to critical FI (baseline series)

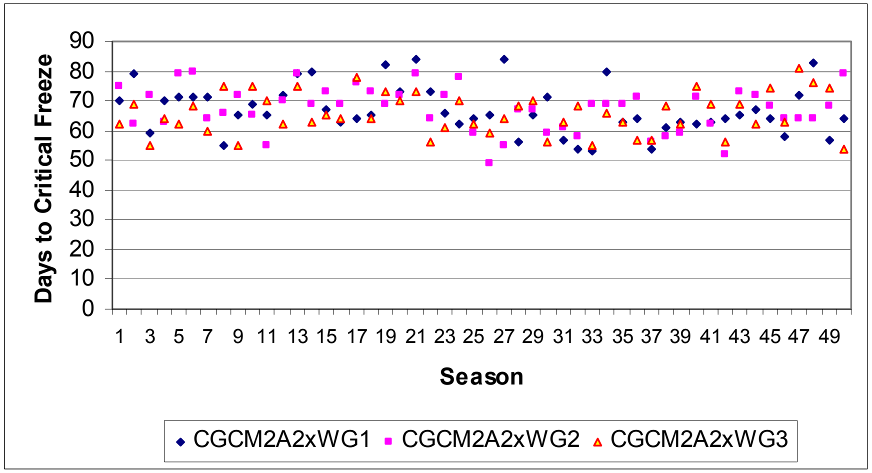


Figure B-92. Winnipeg estimated days to critical FI (CGCM2A2x scenario series)

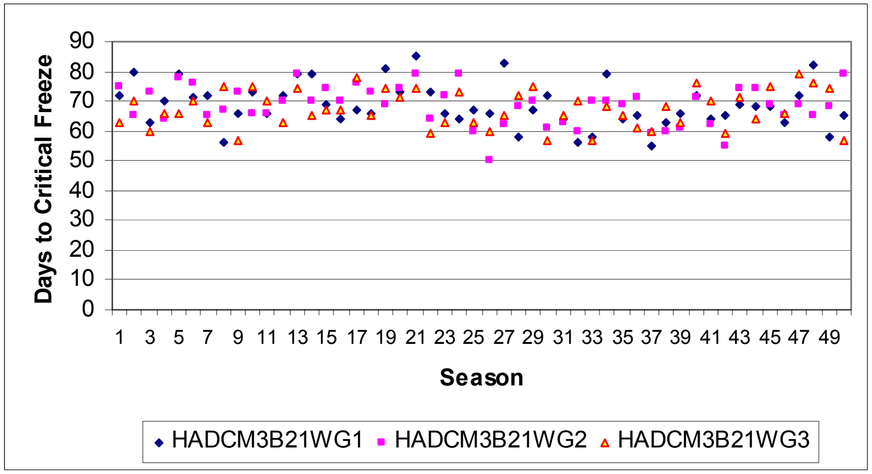


Figure B-93. Winnipeg estimated days to critical FI (HadCM3B21 scenario series)

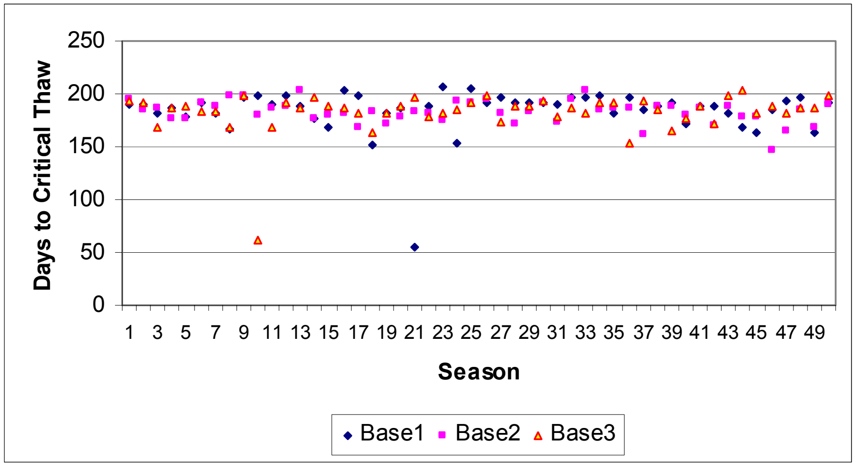


Figure B-94. Winnipeg estimated days to critical TI (baseline series)

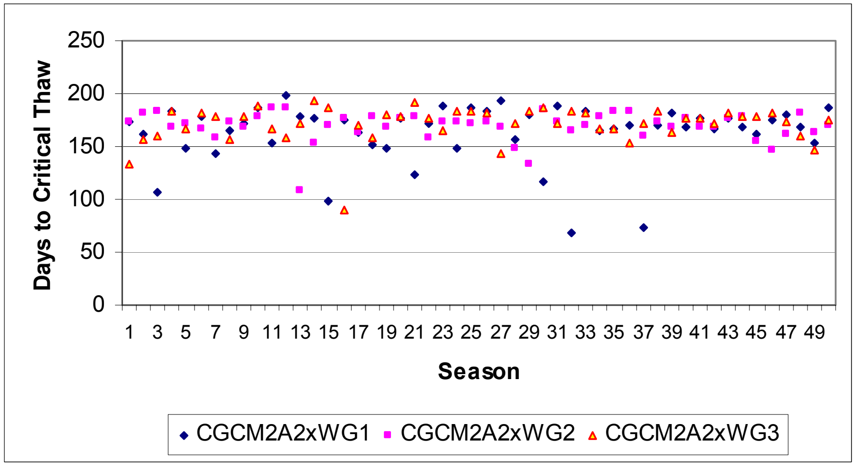


Figure B-95. Winnipeg estimated days to critical TI (CGCM2A2x scenario series)

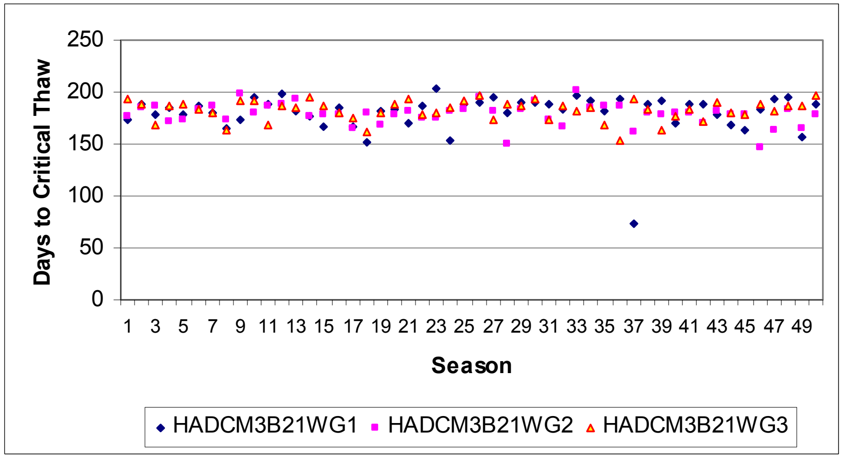


Figure B-96. Winnipeg estimated days to critical TI (HadCM3B21 scenario series)

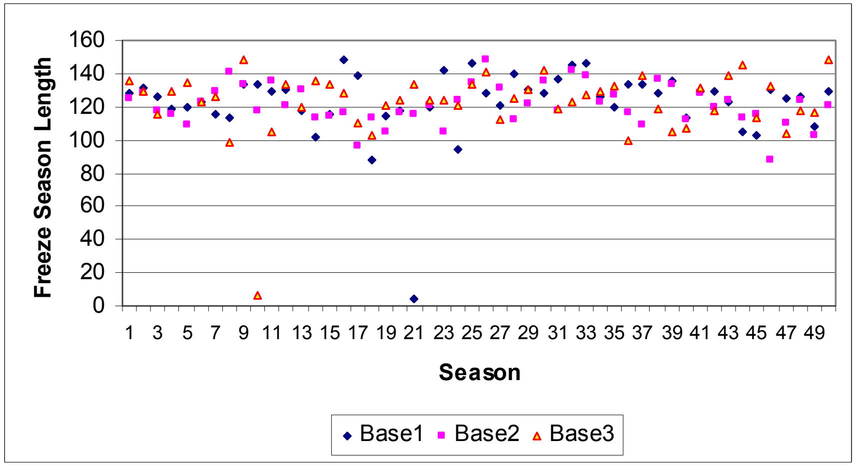


Figure B-97. Winnipeg estimated freeze season length (baseline series)

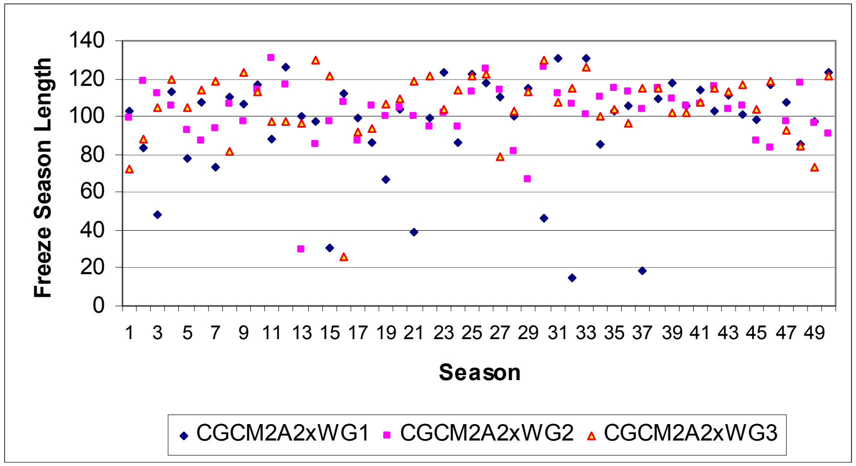


Figure B-98. Winnipeg estimated freeze season length (CGCM2A2x scenario series)

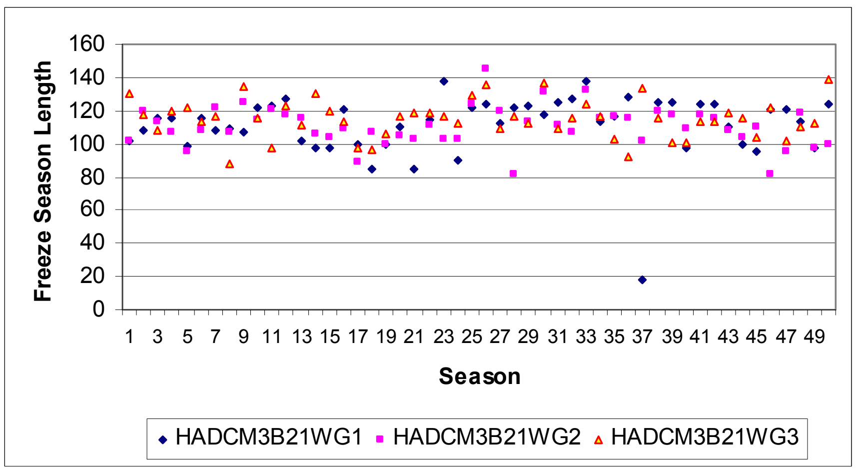


Figure B-99. Winnipeg estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: THUNDER BAY

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Thunder Bay (6048261)	48.4	89.3	199.0	2.5	711.6

*1971-2000 climate normals

Table B-36. Thunder Bay minimum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-3.6	-0.5	-1.4
Standard Deviation	12.2	11.6	12.7
Minimum	-50.7	-46.2	-50.1
Lower Quartile	-12.2	-8.9	-10.5
Median	-1.5	0.8	0.8
Upper Quartile	6.4	9.1	8.9
Maximum	24.4	27.2	27.1

*n=54750

Table B-37. Thunder Bay 7-day mean maximum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	8.5	10.9	10.6
Standard Deviation	11.7	11.9	12.7
Minimum	-23.3	-19.6	-23.0
Lower Quartile	-1.9	0.1	-0.7
Median	9.2	11.2	11.7
Upper Quartile	19.2	22.2	22.3
Maximum	32.9	36.3	36.4

*n=54750

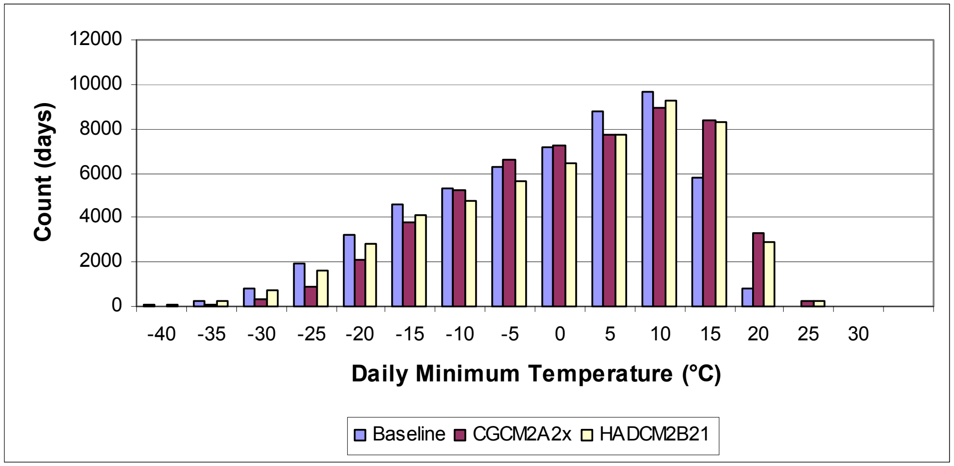


Figure B-100. Thunder Bay minimum daily temperature distribution (n=54750)

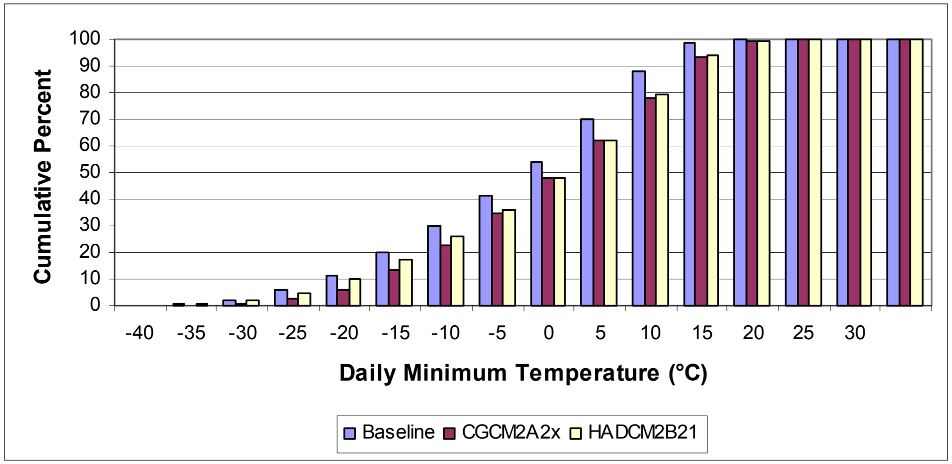


Figure B-101. Thunder Bay minimum daily temperature cumulative percent distribution (n=54750)

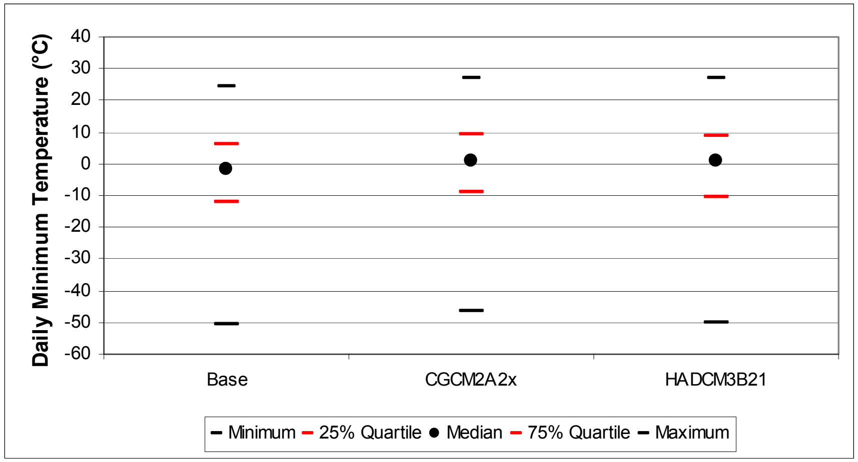


Figure B-102. Thunder Bay minimum daily temperature distribution: quartile statistics (n=54750)

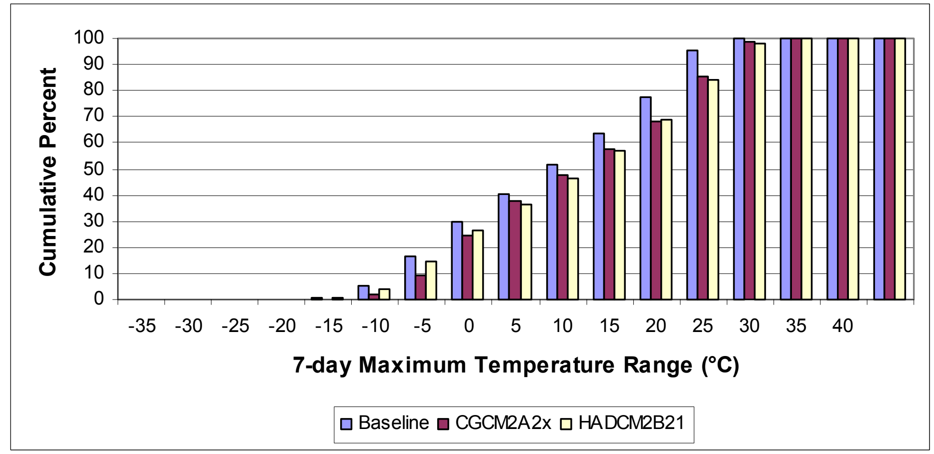


Figure B-104. Thunder Bay 7-day means maximum daily temperature cumulative percent distribution (n=54750)

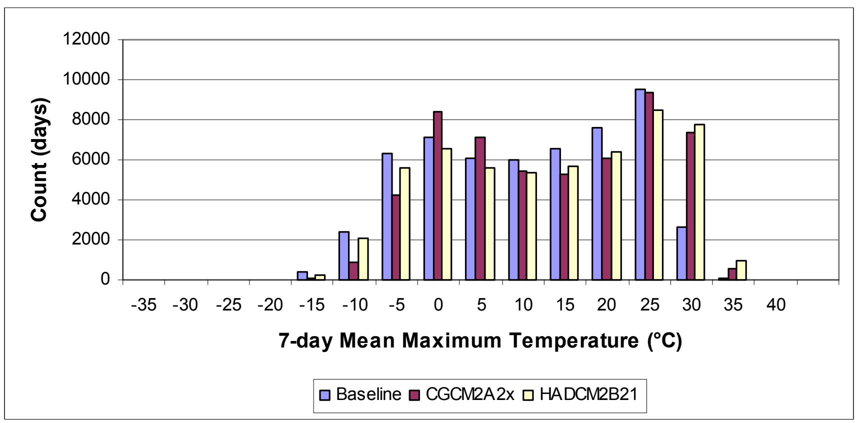


Figure B-103. Thunder Bay 7-day mean maximum daily temperature distribution (n=54750)

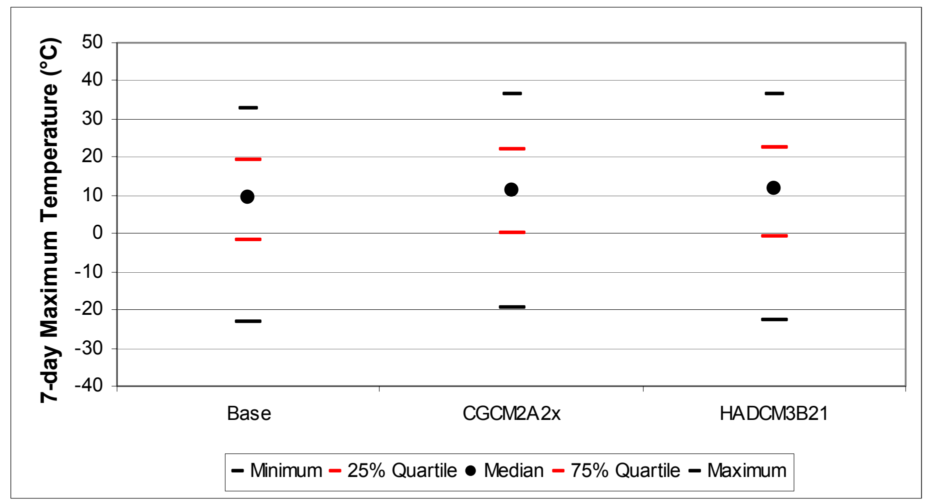


Figure B-105. Thunder Bay 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-38. Thunder Bay annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	-38.7	-33.7	-37.8
Standard Deviation	3.7	3.7	3.8
Minimum	-50.7	-46.2	-50.1
Lower Quartile	-41.4	-36.5	-40.4
Median	-38.5	-33.4	-37.4
Upper Quartile	-36.2	-30.9	-35.1
Maximum	-31.3	-26.7	-30.4

*n=150

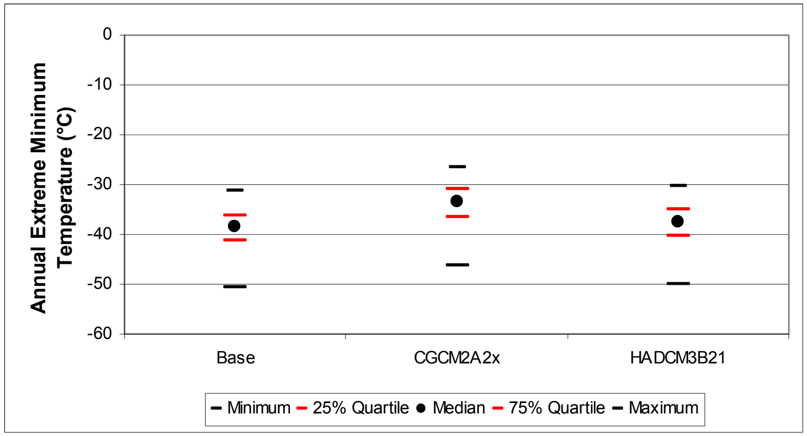


Figure B-106. Thunder Bay annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-39. Thunder Bay annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	28.1	30.8	31.3
Standard Deviation	1.6	1.6	1.6
Minimum	24.4	27.4	27.5
Lower Quartile	27.1	29.7	30.3
Median	28.1	30.8	31.2
Upper Quartile	29.2	31.8	32.4
Maximum	32.9	36.3	36.4

*n=150

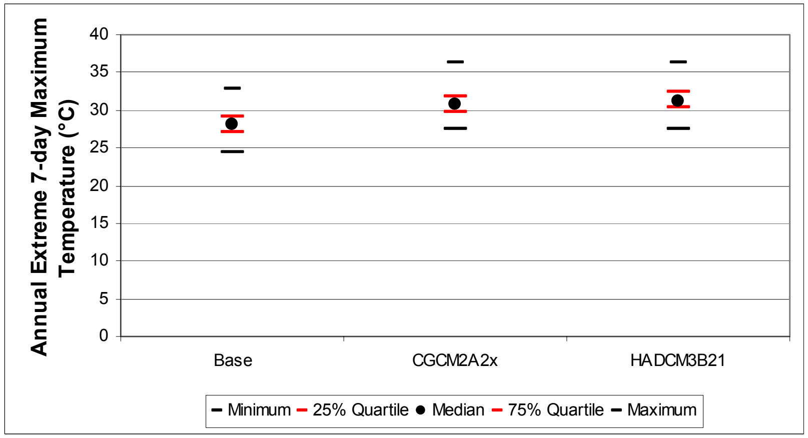


Figure B-107. Thunder Bay annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-40. Thunder Bay Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-37.1	-33.4	-36.4
Superpave-derived high PG threshold (°C)	52.1	54.2	54.5
98th percentile annual minimum air temperature	-46.3	-40.9	-45.2
Ontario RWIS-based low PG threshold (°C)	-35.4	-32.2	-34.8
98th percentile annual extreme 7-day mean maximum air temperature	31.7	34.3	34.7
Ontario RWIS-based high PG threshold (°C)	47.2	51.5	52.1

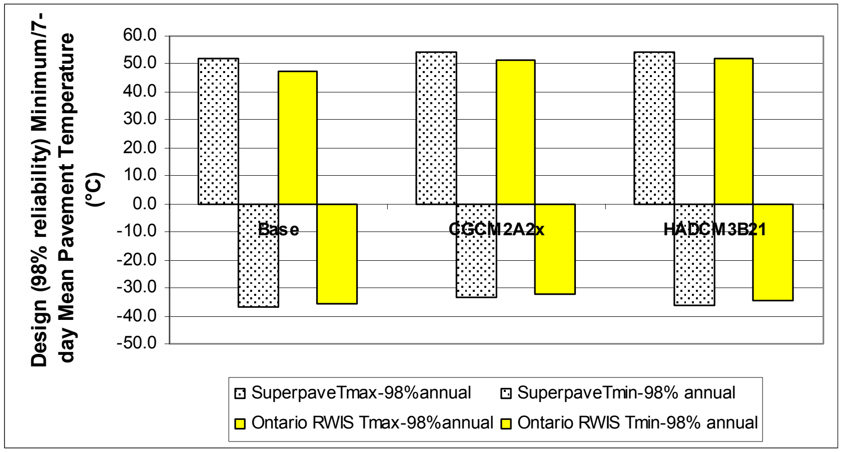


Figure B-108. Thunder Bay estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-41. Thunder Bay freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	114.5	94.6	100.9
Standard Deviation	18.0	21.8	14.1
Minimum	5.0	16.0	22.0
Lower Quartile	109.0	89.0	94.3
Median	118.0	99.0	103.0
Upper Quartile	124.0	107.0	109.0
Maximum	143.0	138.0	133.0

*n=150

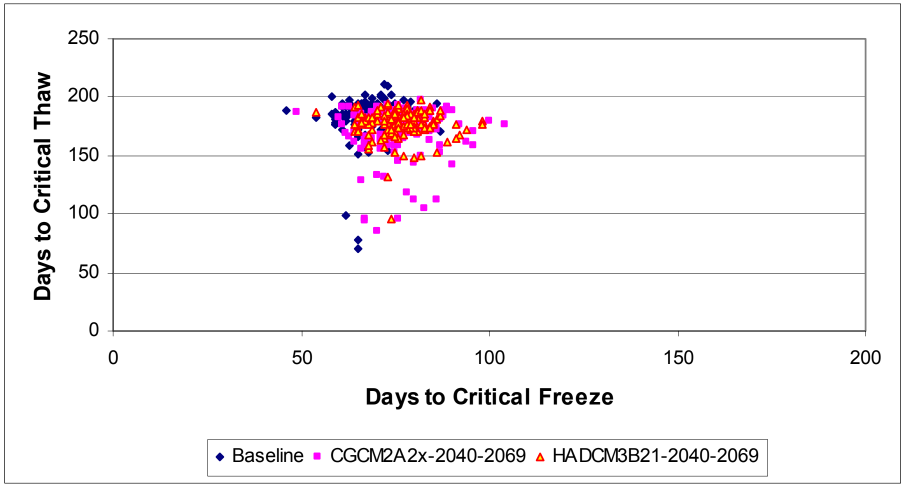


Figure B-109. Thunder Bay estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

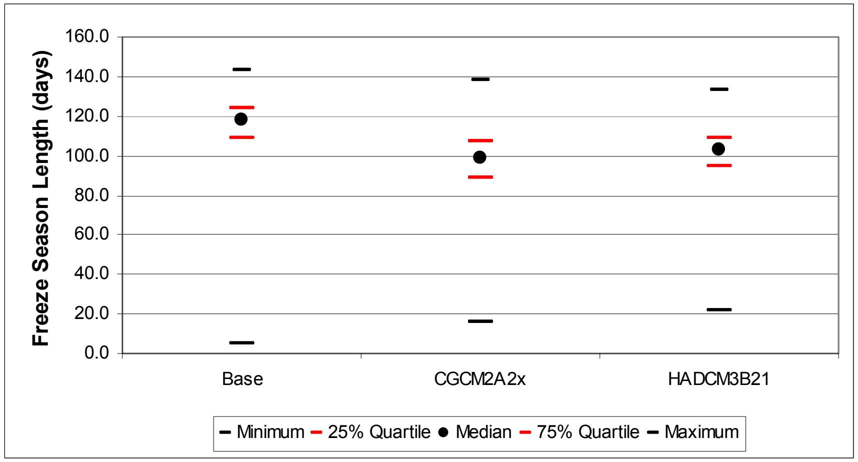


Figure B-110. Thunder Bay estimated freeze season length distribution: quartile statistics (n=150)

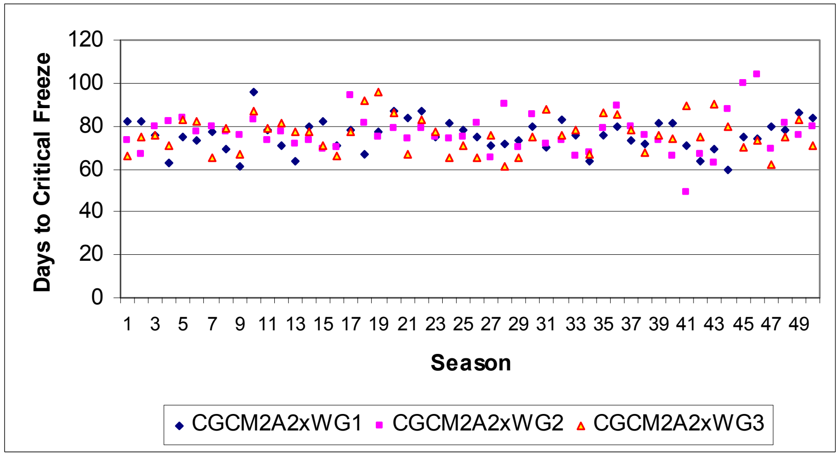


Figure B-112. Thunder Bay estimated days to critical FI (CGCM2A2x scenario series)

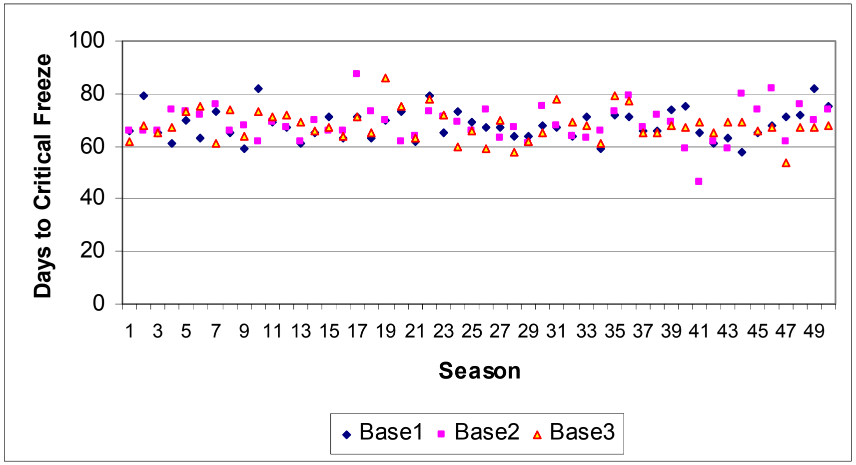


Figure B-111. Thunder Bay estimated days to critical FI (baseline series)

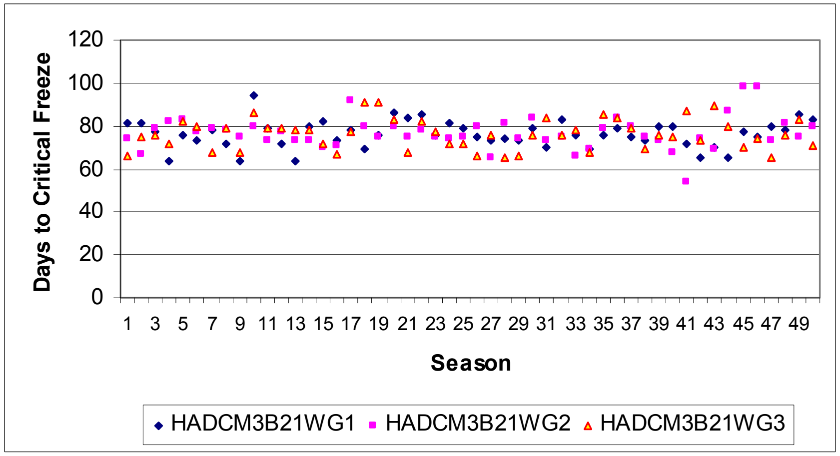


Figure B-113. Thunder Bay estimated days to critical FI (HadCM3B21 scenario series)

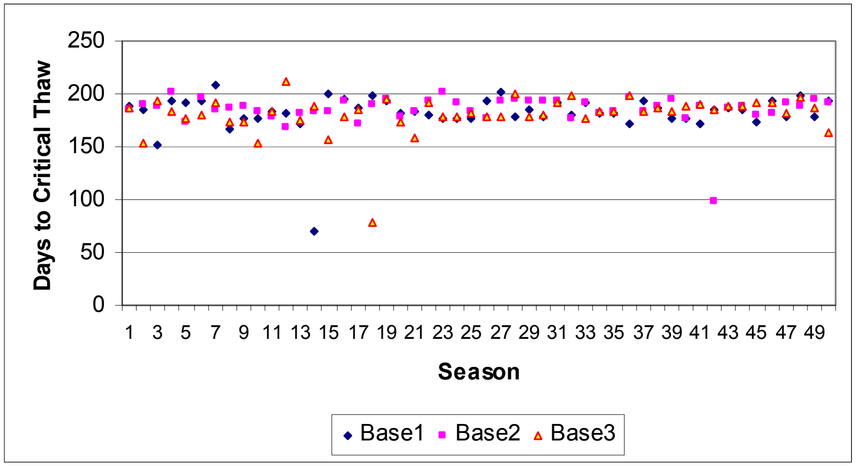


Figure B-114. Thunder Bay estimated days to critical TI (baseline series)

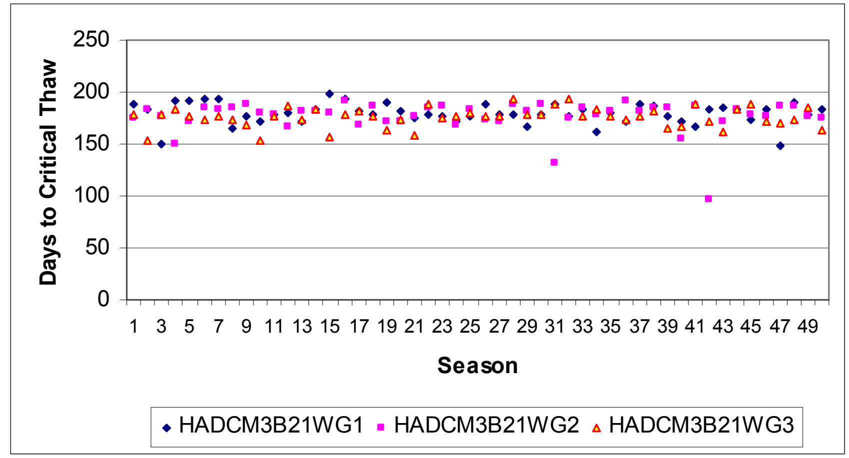


Figure B-116. Thunder Bay estimated days to critical TI (HadCM3B21 scenario series)

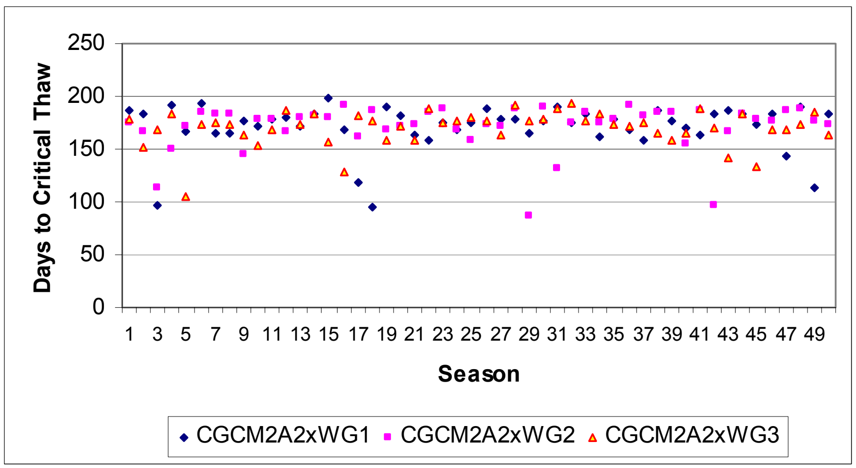


Figure B-115. Thunder Bay estimated days to critical TI (CGCM2A2x scenario series)

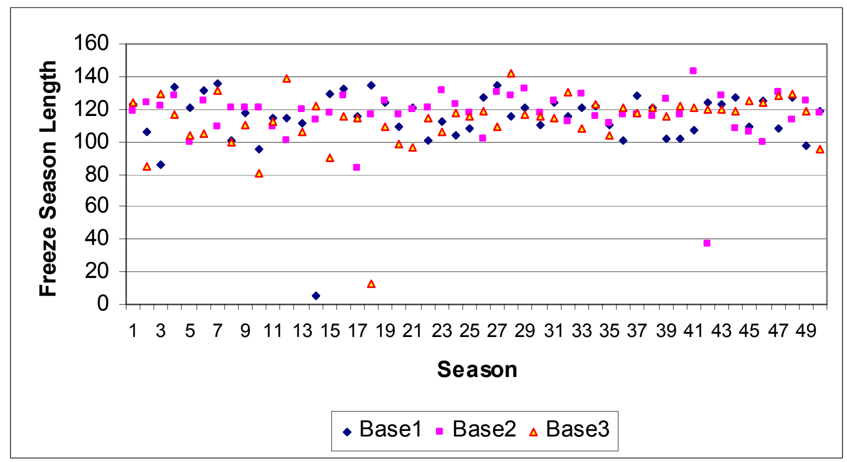


Figure B-117. Thunder Bay estimated freeze season length (baseline series)

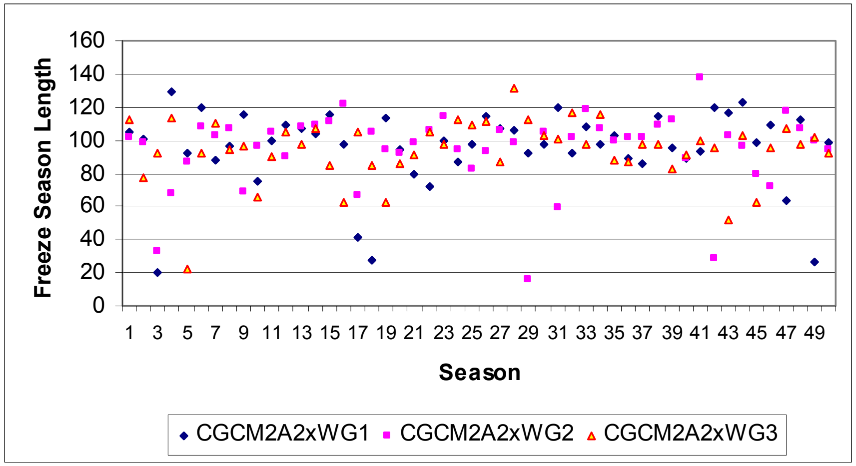


Figure B-118. Thunder Bay estimated freeze season length (CGCM2A2x scenario series)

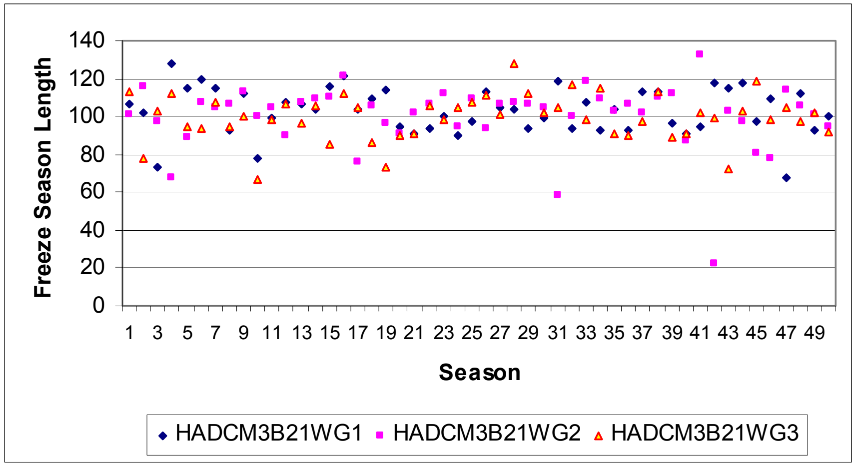


Figure B-119. Thunder Bay estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: NORTH BAY

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
North Bay (6085700)	46.4	78.4	370.3	3.8	1007.7

*1971-2000 climate normals

Table B-42. North Bay minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-1.1	2.0	1.4
Standard Deviation	12.0	11.3	12.1
Minimum	-47.1	-40.2	-44.9
Lower Quartile	-10.0	-6.5	-7.5
Median	0.5	2.9	2.9
Upper Quartile	8.8	11.7	11.4
Maximum	25.6	27.9	28.6

*n=54750

Table B-43. North Bay 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	8.6	11.0	11.0
Standard Deviation	11.5	11.6	12.0
Minimum	-23.2	-20.3	-21.6
Lower Quartile	-1.5	0.5	0.3
Median	9.3	11.4	11.7
Upper Quartile	19.2	22.0	22.2
Maximum	31.4	35.2	34.2

*n=54750

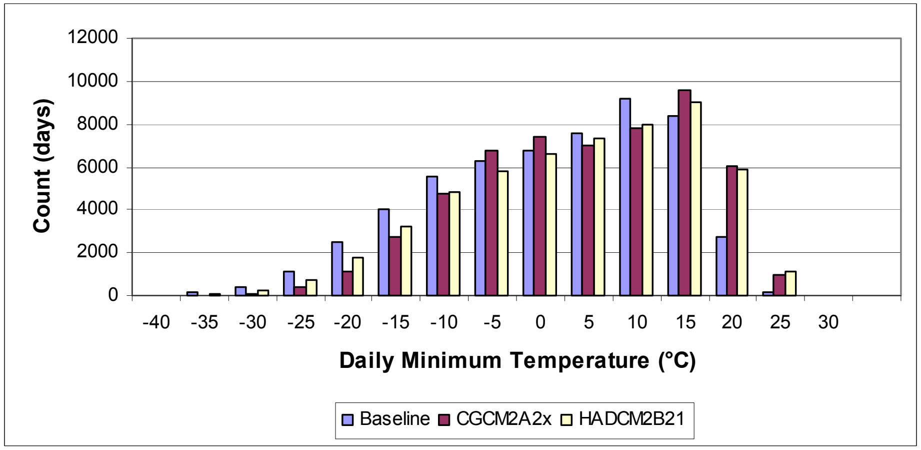


Figure B-120. North Bay minimum daily temperature distribution (n=54750)

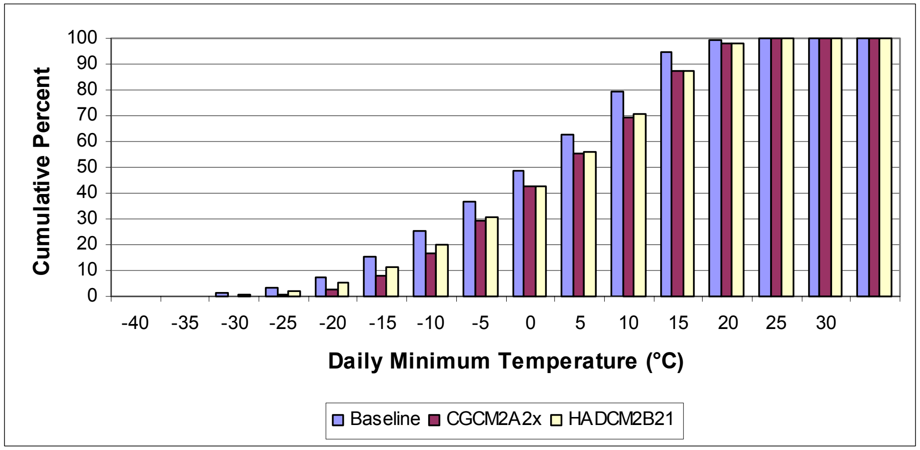


Figure B-121. North Bay minimum daily temperature cumulative percent distribution (n=54750)

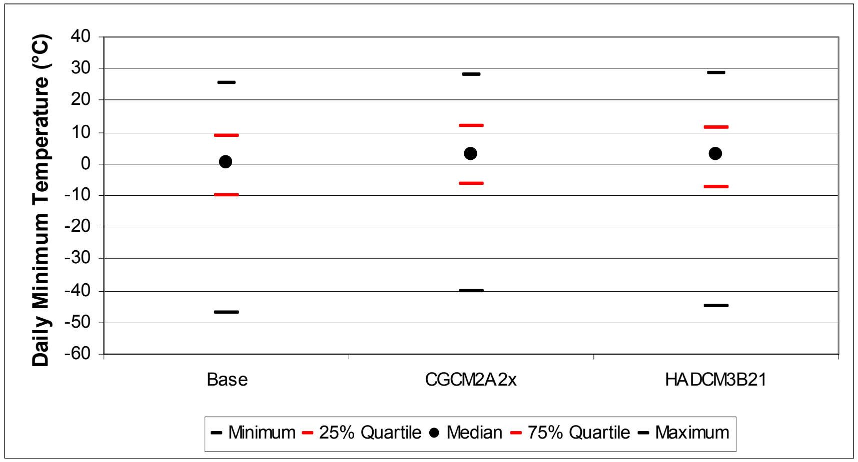


Figure B-122. North Bay minimum daily temperature distribution: quartile statistics (n=54750)

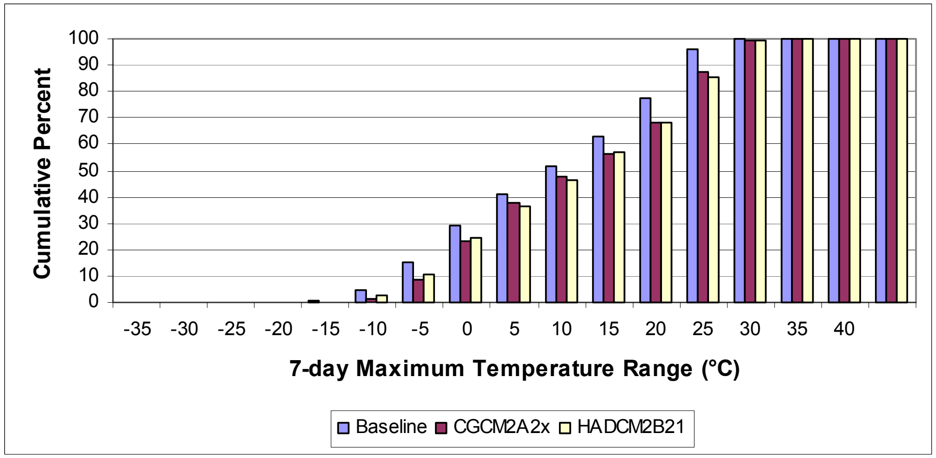


Figure B-124. North Bay 7-day means maximum daily temperature cumulative percent distribution (n=54750)

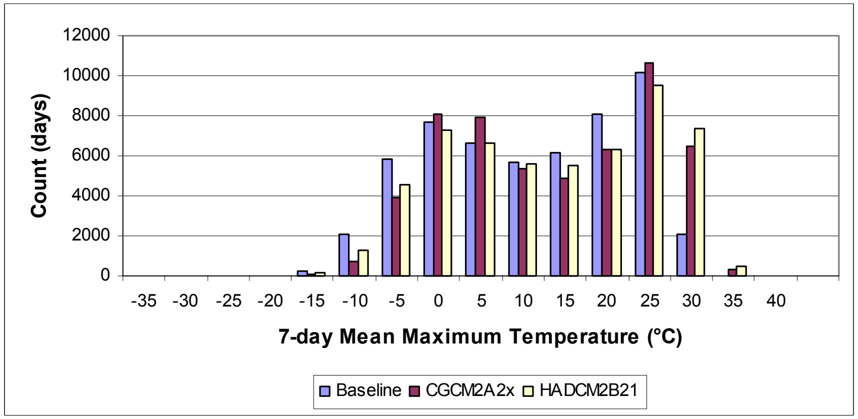


Figure B-123. North Bay 7-day mean maximum daily temperature distribution (n=54750)

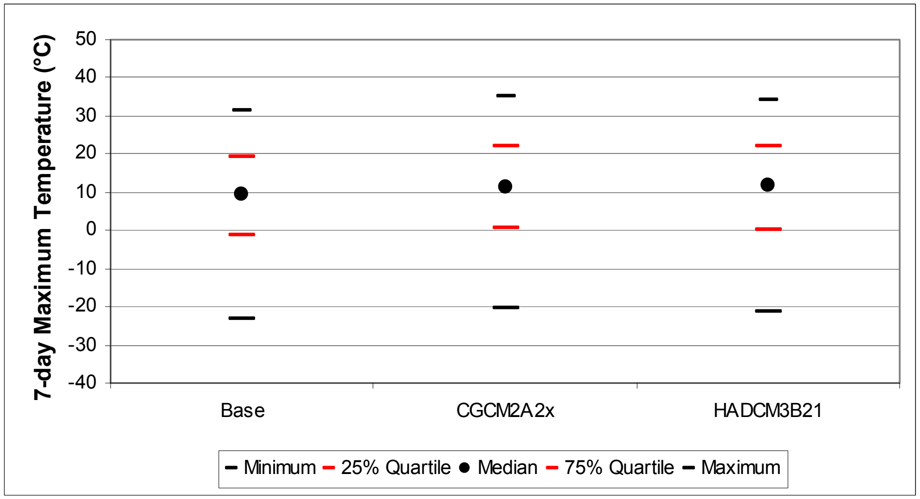


Figure B-125. North Bay 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-44. North Bay annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-35.3	-29.5	-33.0
Standard Deviation	3.8	3.8	3.8
Minimum	-47.1	-40.2	-44.9
Lower Quartile	-38.4	-32.5	-36.0
Median	-34.9	-28.9	-32.7
Upper Quartile	-32.2	-26.7	-30.1
Maximum	-28.3	-22.2	-26.2

*n=150

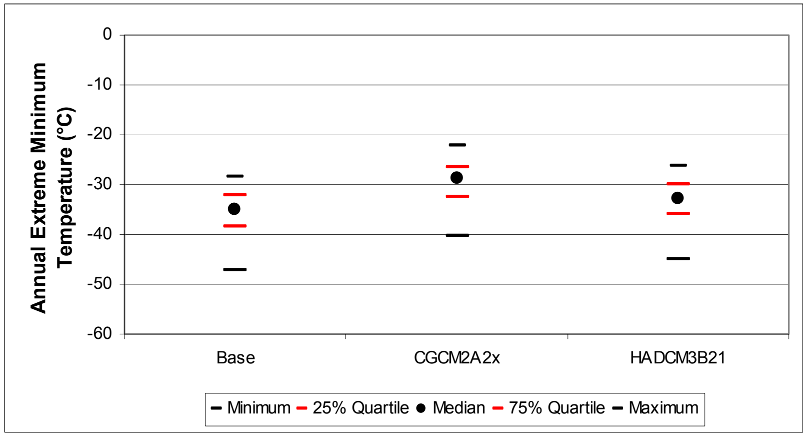


Figure B-126. North Bay annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-45. North Bay annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	27.4	30.1	30.4
Standard Deviation	1.5	1.6	1.5
Minimum	24.4	26.8	27.5
Lower Quartile	26.4	28.8	29.3
Median	27.3	29.9	30.2
Upper Quartile	28.2	30.9	31.1
Maximum	31.4	35.2	34.2

*n=150

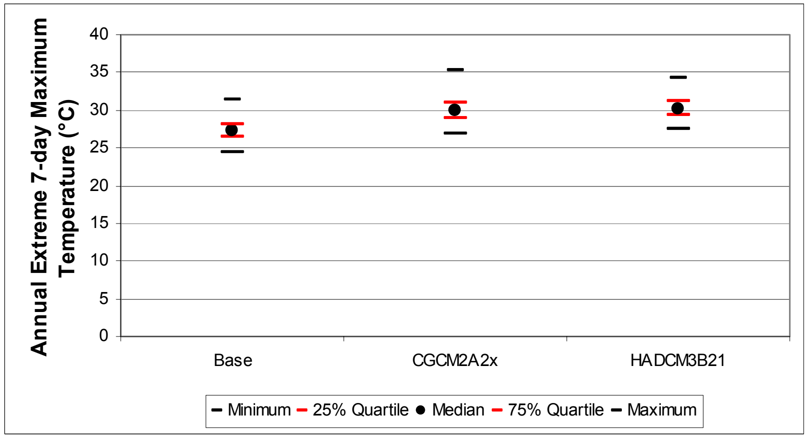


Figure B-127. North Bay annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-46. North Bay Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-33.9	-29.7	-32.3
Superpave-derived high PG threshold (°C)	51.9	54.0	54.2
98th percentile annual minimum air temperature	-43.5	-37.5	-41.2
Ontario RWIS-based low PG threshold (°C)	-33.8	-30.0	-32.4
98th percentile annual extreme 7-day mean maximum air temperature	30.8	33.2	33.7
Ontario RWIS-based high PG threshold (°C)	45.8	49.6	50.5

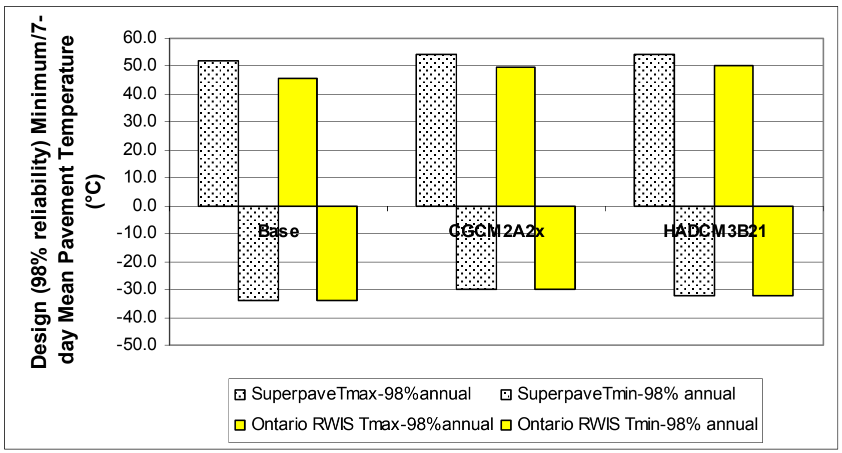


Figure B-128. North Bay estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-47. North Bay freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	107.7	68.5	84.2
Standard Deviation	16.0	30.2	21.3
Minimum	7.0	3.0	7.0
Lower Quartile	98.0	42.5	76.3
Median	110.0	71.5	89.0
Upper Quartile	117.8	91.8	96.0
Maximum	140.0	120.0	131.0

*n=150

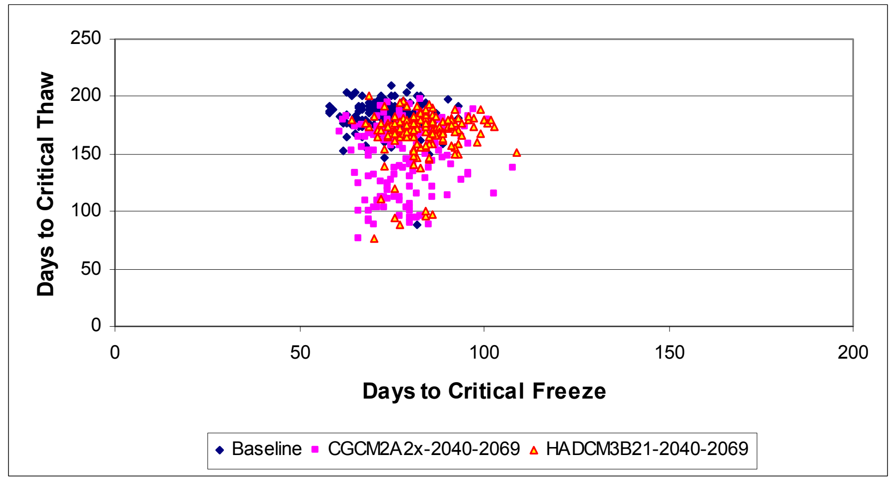


Figure B-129. North Bay estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

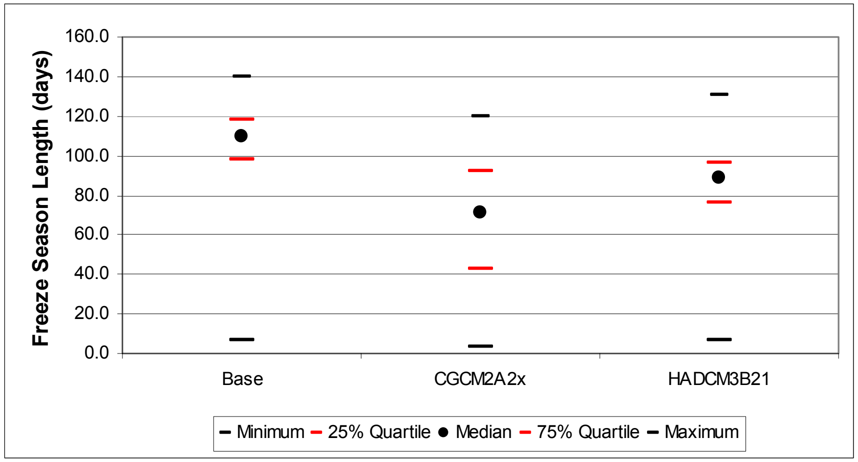


Figure B-130. North Bay estimated freeze season length distribution: quartile statistics (n=150)

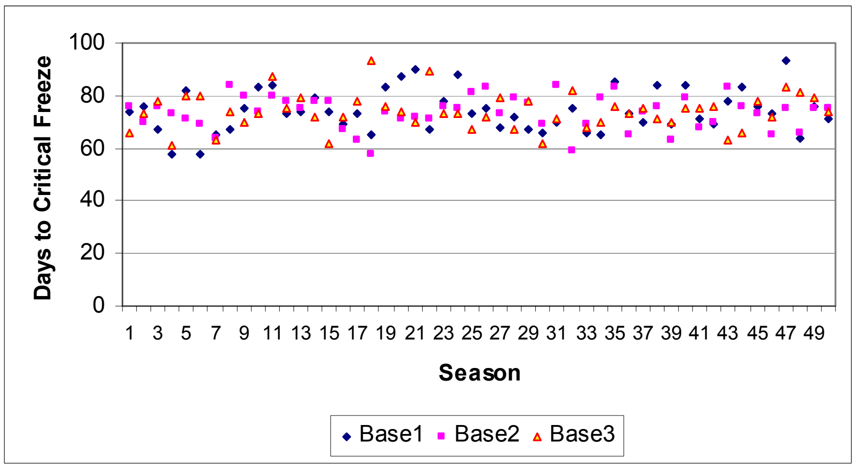


Figure B-131. North Bay estimated days to critical FI (baseline series)

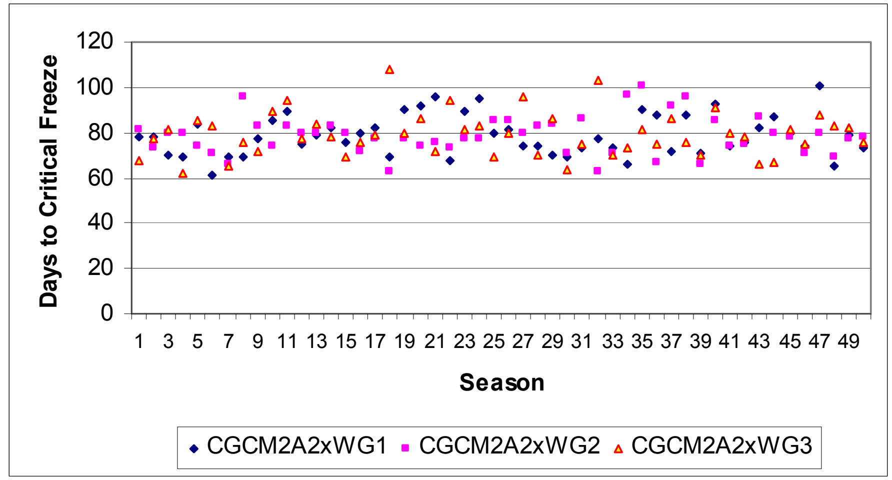


Figure B-132. North Bay estimated days to critical FI (CGCM2A2x scenario series)

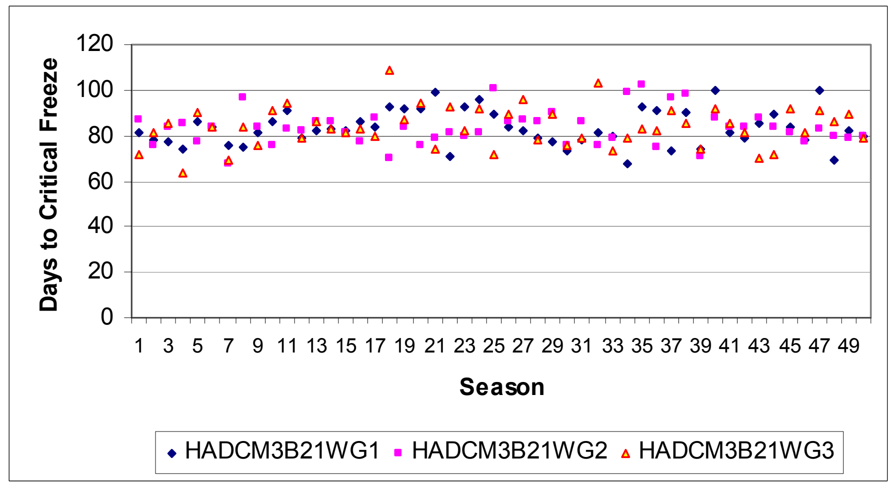


Figure B-133. North Bay estimated days to critical FI (HadCM3B21 scenario series)

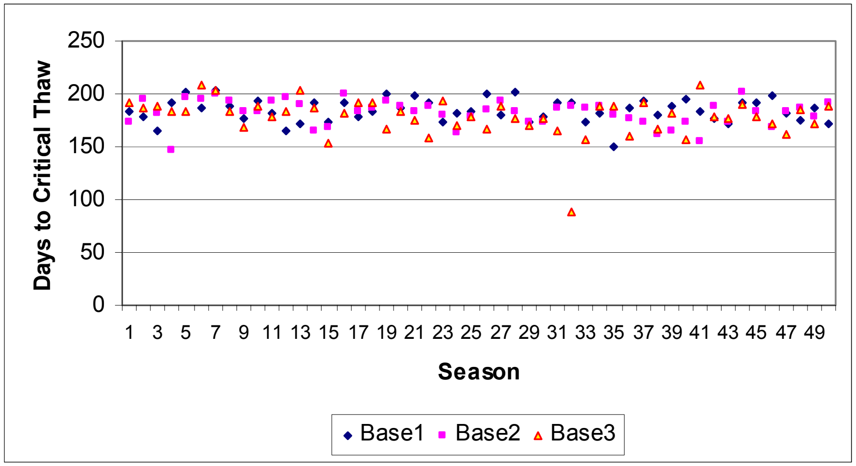


Figure B-134. North Bay estimated days to critical TI (baseline series)

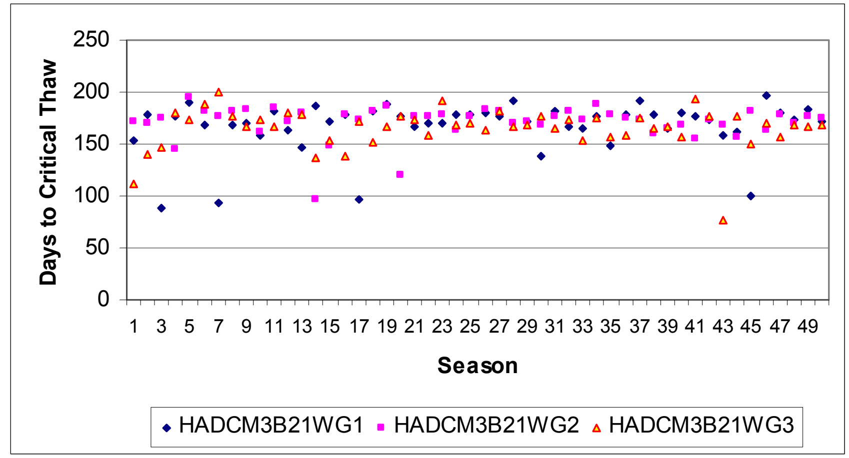


Figure B-136. North Bay estimated days to critical TI (HadCM3B21 scenario series)

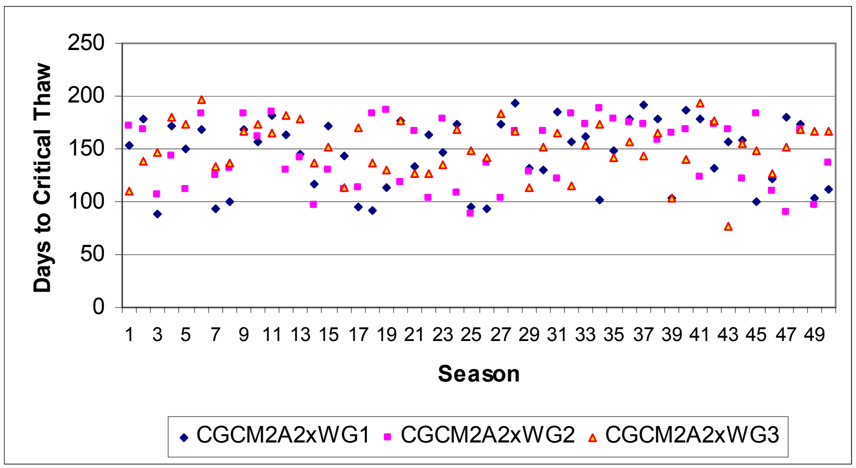


Figure B-135. North Bay estimated days to critical TI (CGCM2A2x scenario series)

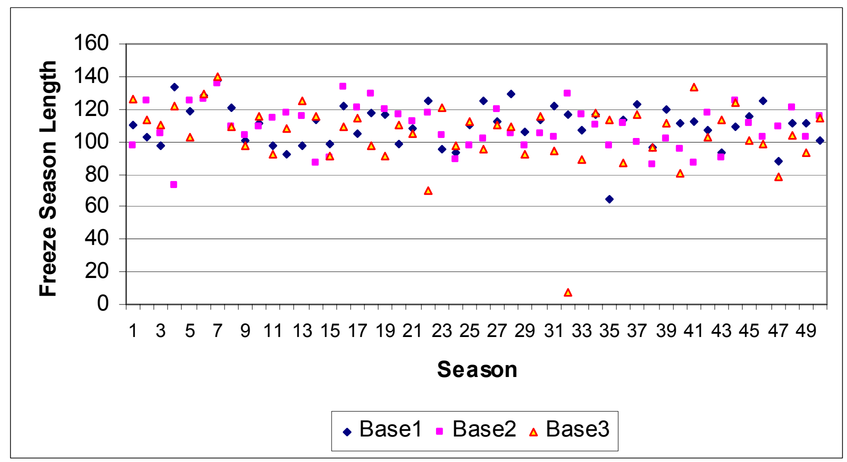


Figure B-137. North Bay estimated freeze season length (baseline series)

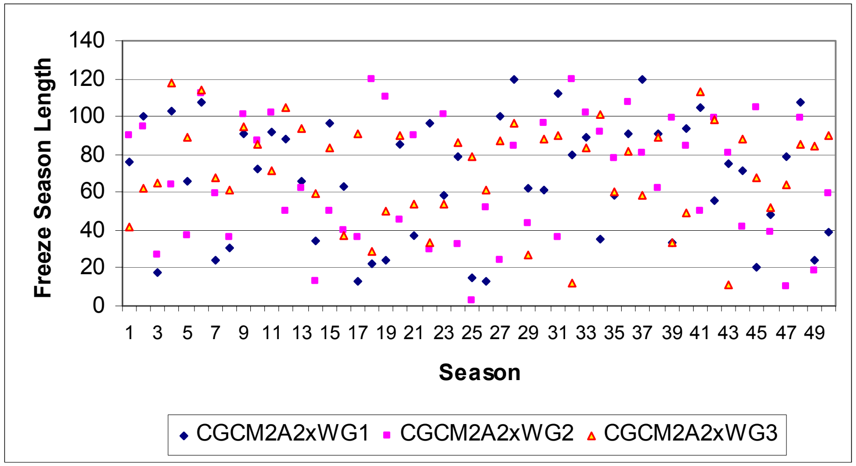


Figure B-138. North Bay estimated freeze season length (CGCM2A2x scenario series)

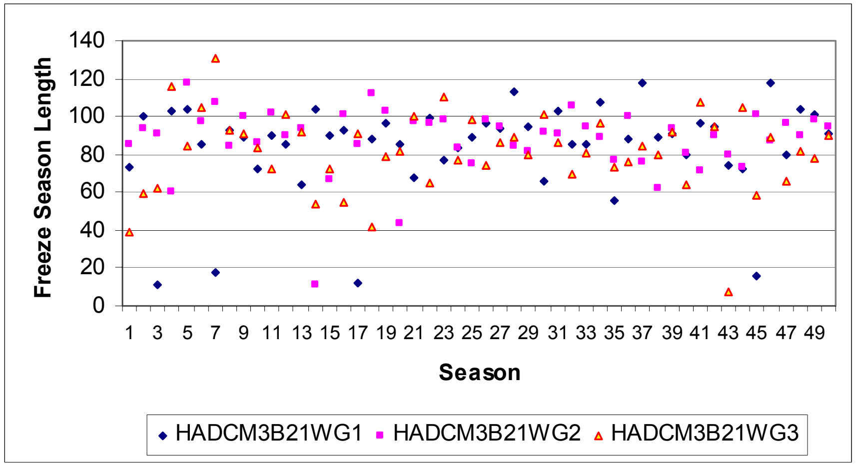


Figure B-139. North Bay estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: MUSKOKA

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Muskoka (6115525)	44.9	79.3	281.9	4.9	1098.6

*1971-2000 climate normals

Table B-48. Muskoka minimum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-0.8	2.4	1.7
Standard Deviation	11.3	10.7	11.4
Minimum	-51.7	-45.3	-49.3
Lower Quartile	-8.5	-5.1	-6.0
Median	0.9	3.5	3.3
Upper Quartile	8.2	11.1	10.7
Maximum	28.0	30.1	30.6

*n=54750

Table B-49. Muskoka 7-day mean maximum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	10.6	13.0	13.1
Standard Deviation	10.9	11.1	11.5
Minimum	-16.3	-13.3	-15.4
Lower Quartile	0.8	2.8	2.8
Median	11.2	13.4	13.8
Upper Quartile	20.8	23.6	23.9
Maximum	32.2	35.6	35.5

*n=54750

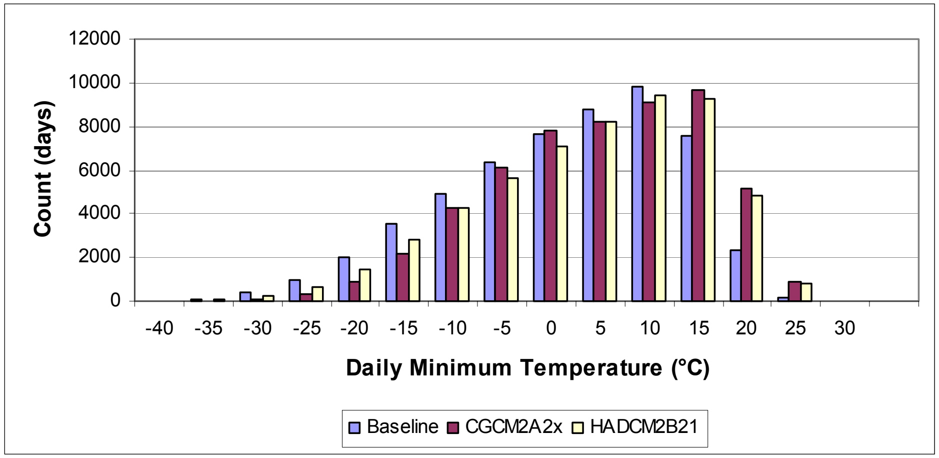


Figure B-140. Muskoka minimum daily temperature distribution (n=54750)

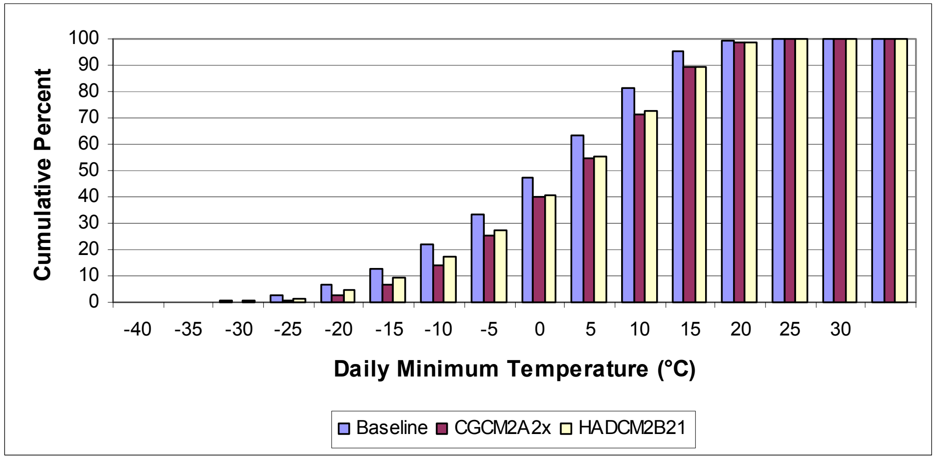


Figure B-141. Muskoka minimum daily temperature cumulative percent distribution (n=54750)

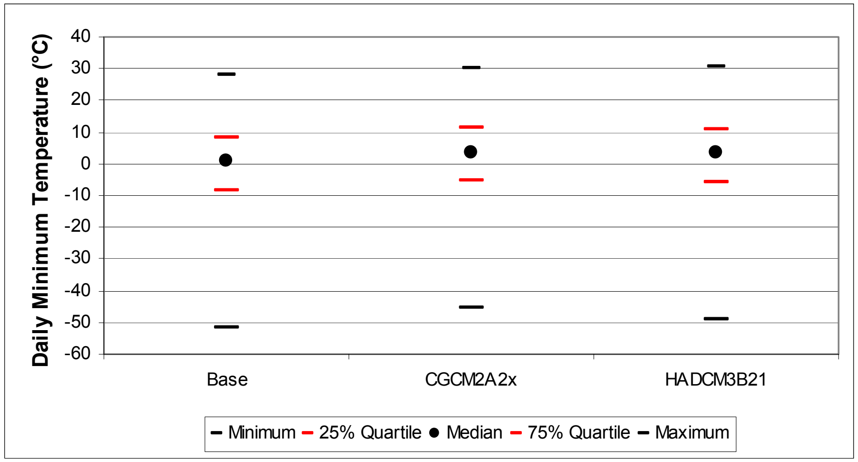


Figure B-142. Muskoka minimum daily temperature distribution: quartile statistics (n=54750)

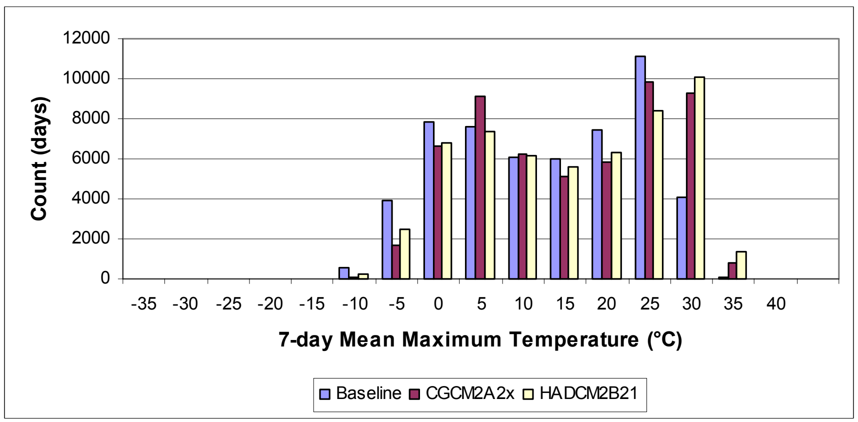


Figure B-143. Muskoka 7-day mean maximum daily temperature distribution (n=54750)

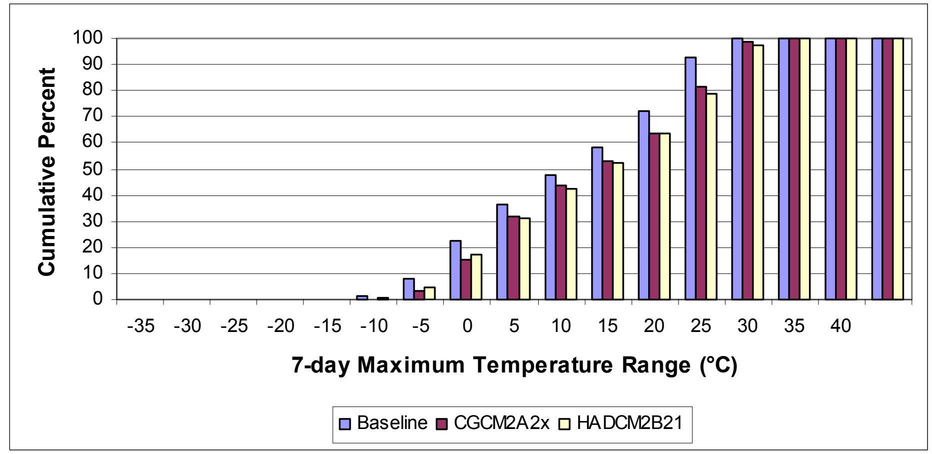


Figure B-144. Muskoka 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

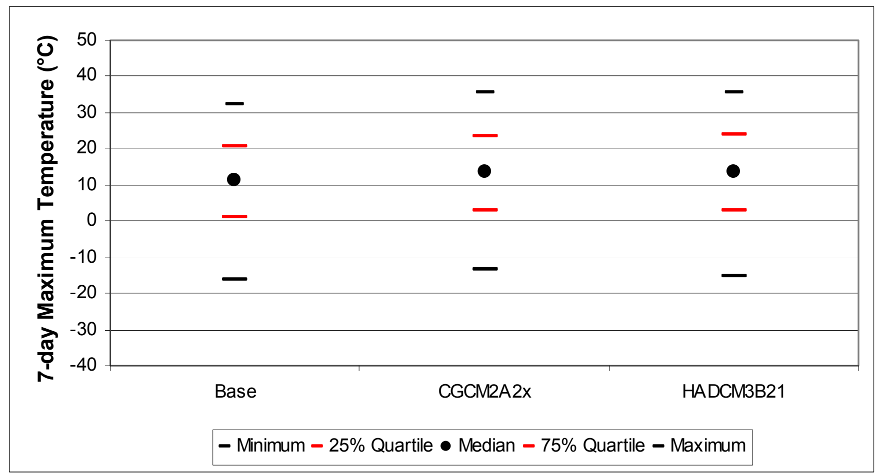


Figure B-145. Muskoka 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-50. Muskoka annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-35.1	-29.3	-32.7
Standard Deviation	4.4	4.3	4.4
Minimum	-51.7	-45.3	-49.3
Lower Quartile	-38.0	-31.7	-35.7
Median	-34.8	-28.7	-32.5
Upper Quartile	-31.8	-26.4	-29.3
Maximum	-24.4	-18.5	-22.2

*n=150

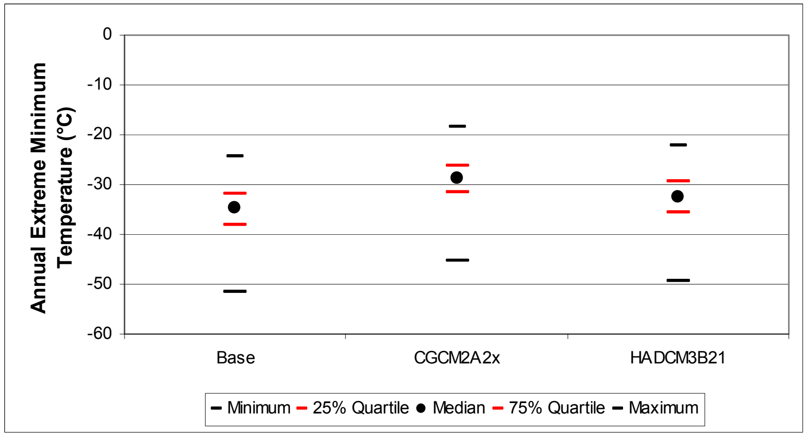


Figure B-146. Muskoka annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-51. Muskoka annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	28.4	31.1	31.6
Standard Deviation	1.4	1.6	1.3
Minimum	25.8	27.9	29.0
Lower Quartile	27.5	29.9	30.6
Median	28.4	31.1	31.6
Upper Quartile	29.3	32.0	32.4
Maximum	32.2	35.6	35.5

*n=150

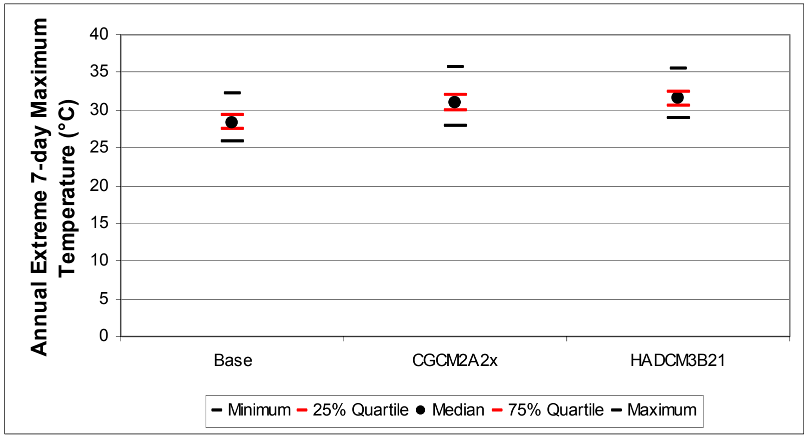


Figure B-147. Muskoka annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-52. Muskoka Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-34.0	-29.7	-32.3
Superpave-derived high PG threshold (°C)	53.0	55.2	55.4
98th percentile annual minimum air temperature	-43.0	-38.6	-40.8
Ontario RWIS-based low PG threshold (°C)	-33.4	-30.7	-32.1
98th percentile annual extreme 7-day mean maximum air temperature	31.8	34.7	34.5
Ontario RWIS-based high PG threshold (°C)	47.4	52.2	51.8

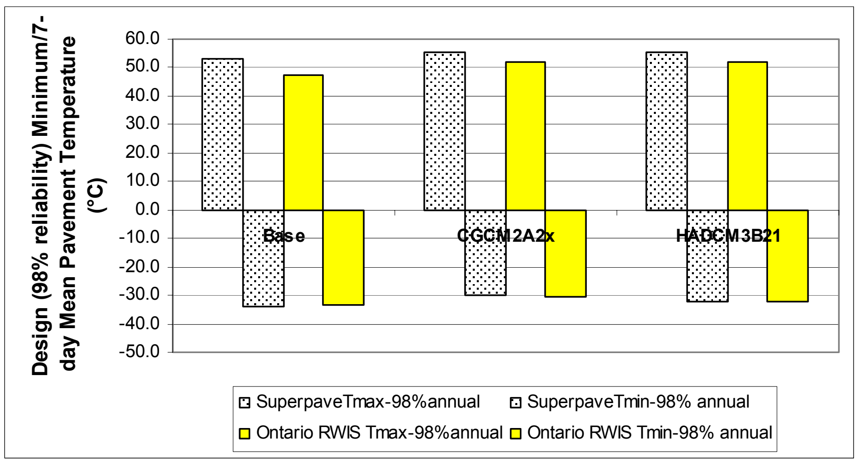


Figure B-148. Muskoka estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-53. Muskoka freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	87.7	42.3	61.3
Standard Deviation	21.4	25.6	24.1
Minimum	7.0	0.0	4.0
Lower Quartile	79.3	21.3	47.3
Median	91.0	37.5	68.0
Upper Quartile	102.0	63.8	79.0
Maximum	87.7	42.3	61.3

*n=150

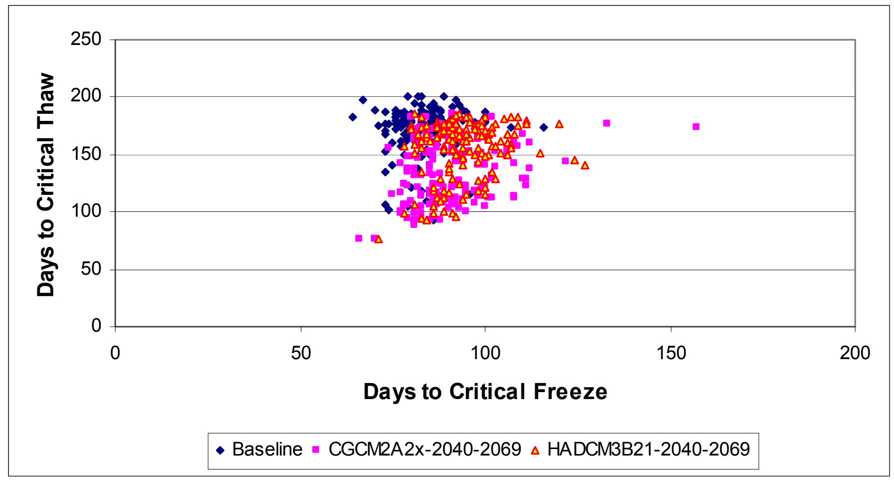


Figure B-149. Muskoka estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

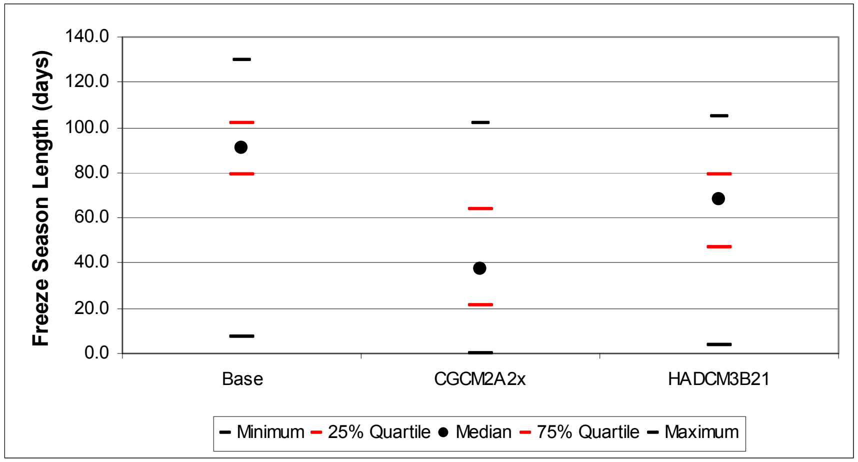


Figure B-150. Muskoka estimated freeze season length distribution: quartile statistics (n=150)

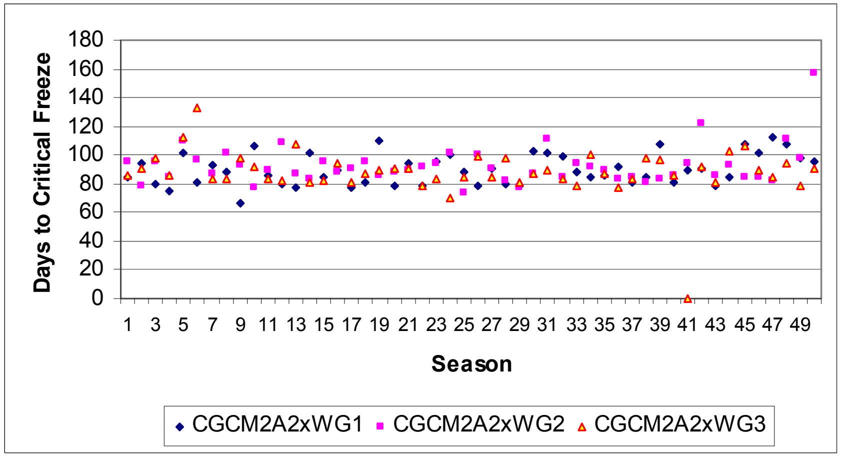


Figure B-152. Muskoka estimated days to critical FI (CGCM2A2x scenario series)

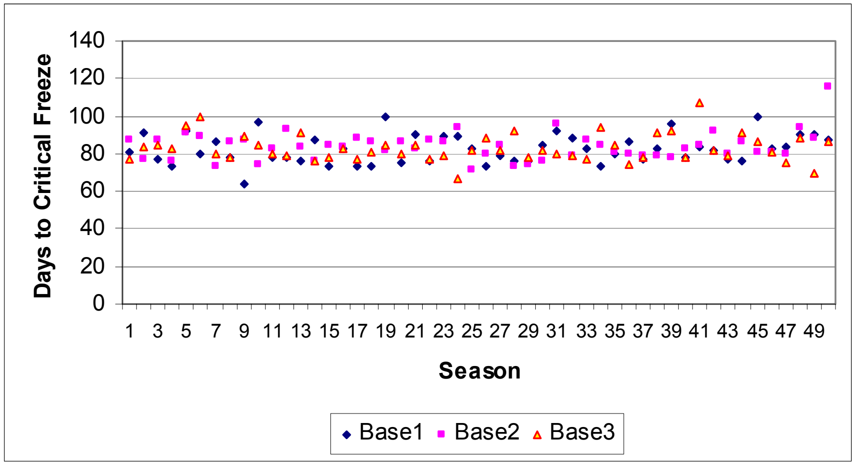


Figure B-151. Muskoka estimated days to critical FI (baseline series)

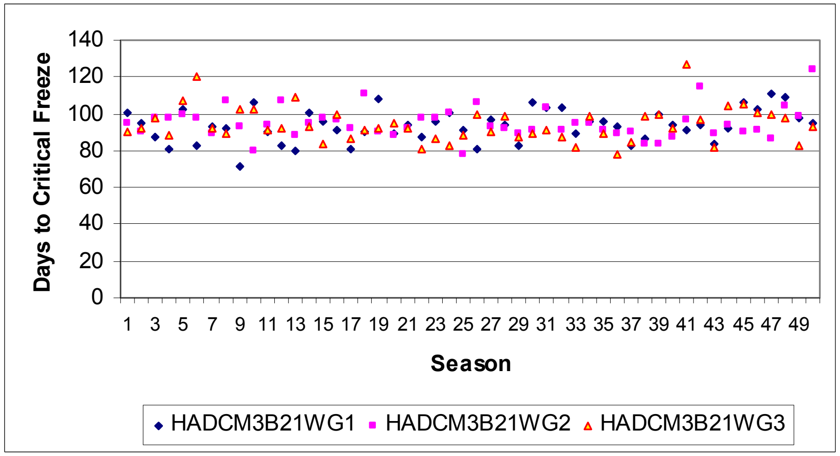


Figure B-153. Muskoka estimated days to critical FI (HadCM3B21 scenario series)

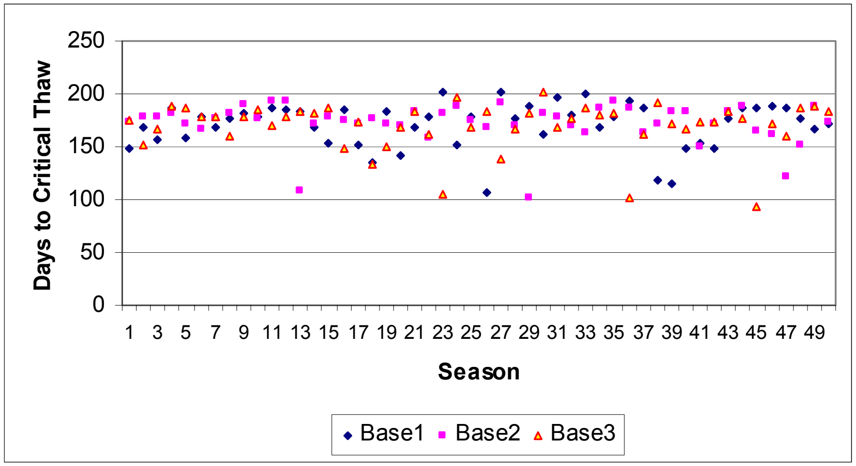


Figure B-154. Muskoka estimated days to critical TI (baseline series)

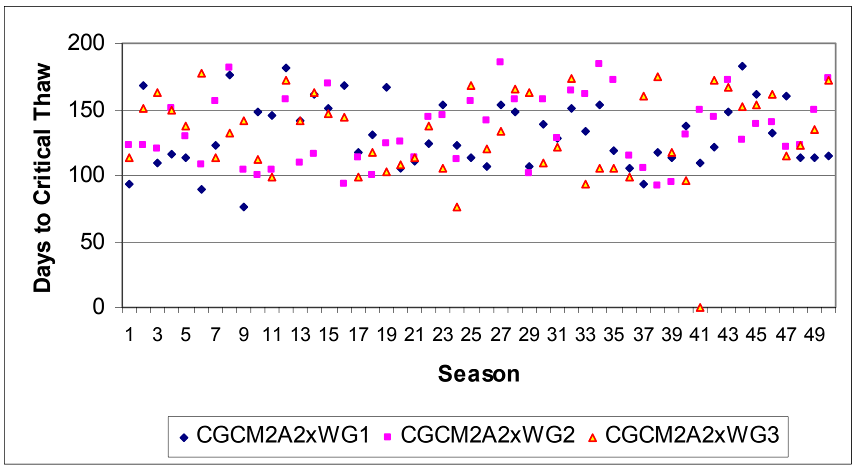


Figure B-155. Muskoka estimated days to critical TI (CGCM2A2x scenario series)

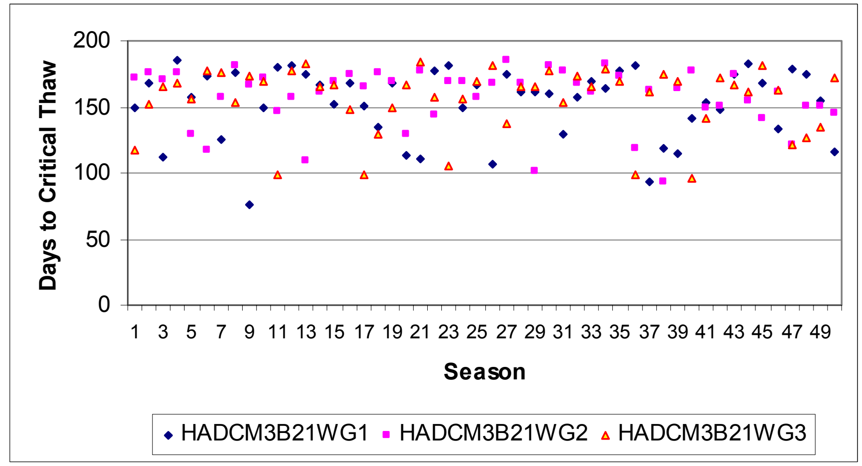


Figure B-156. Muskoka estimated days to critical TI (HadCM3B21 scenario series)

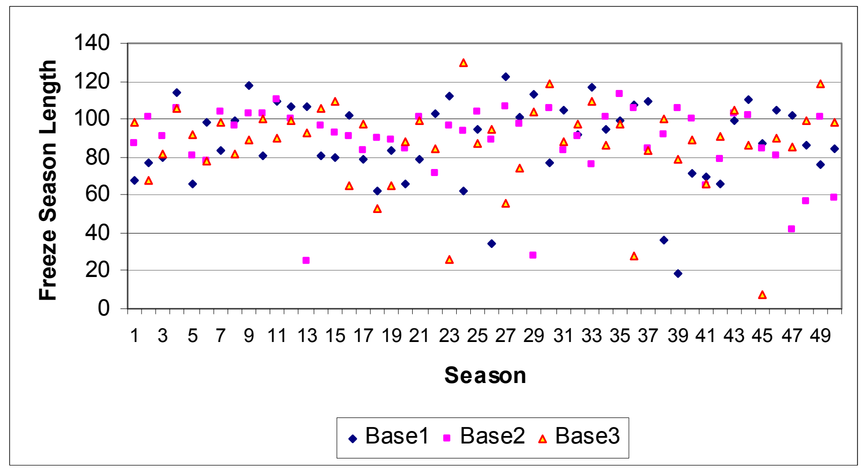


Figure B-157. Muskoka estimated freeze season length (baseline series)

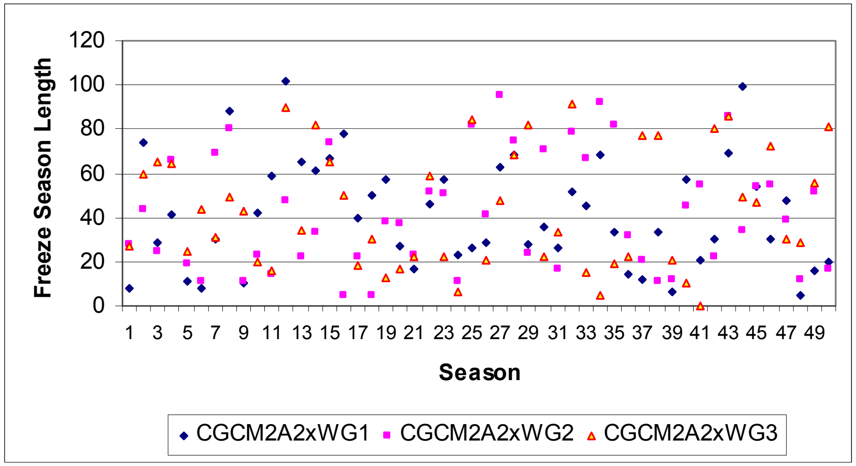


Figure B-158. Muskoka estimated freeze season length (CGCM2A2x scenario series)

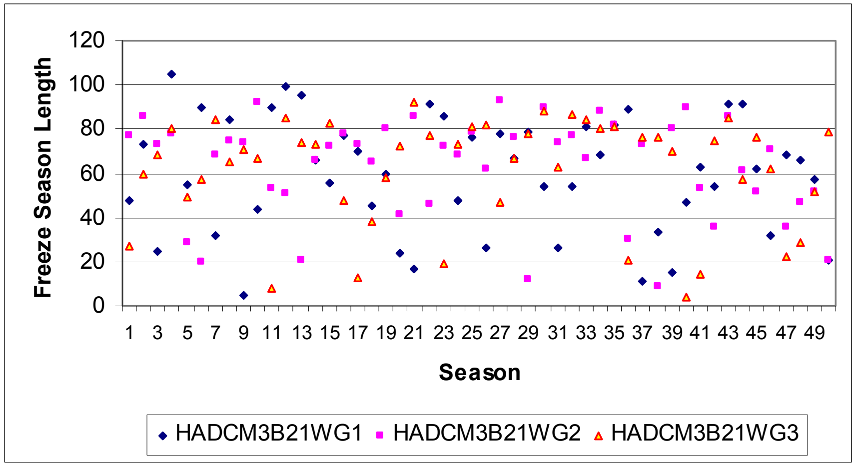


Figure B-159. Muskoka estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: WINDSOR

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Windsor (6139525)	42.3	82.9	189.6	9.4	918.3

*1971-2000 climate normals

Table B-54. Windsor minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	4.7	8.4	6.9
Standard Deviation	9.7	9.0	10.0
Minimum	-28.4	-24.8	-26.1
Lower Quartile	-2.8	1.7	-0.8
Median	5.0	8.5	7.3
Upper Quartile	12.9	15.9	15.4
Maximum	28.4	31.4	30.6

*n=54750

Table B-55. Windsor 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	14.0	17.2	16.5
Standard Deviation	10.5	10.4	11.2
Minimum	-12.0	-9.3	-10.6
Lower Quartile	4.6	7.8	6.5
Median	14.4	17.9	17.0
Upper Quartile	23.8	26.8	26.9
Maximum	38.0	40.5	41.2

*n=54750

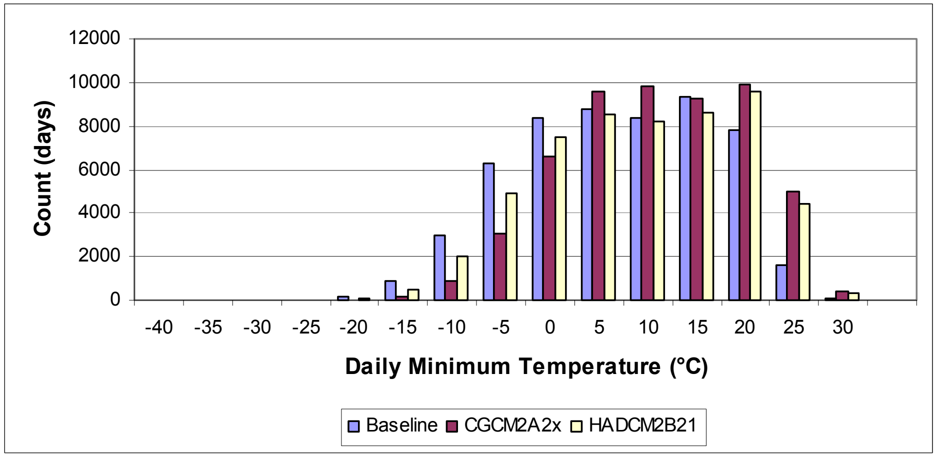


Figure B-160. Windsor minimum daily temperature distribution (n=54750)

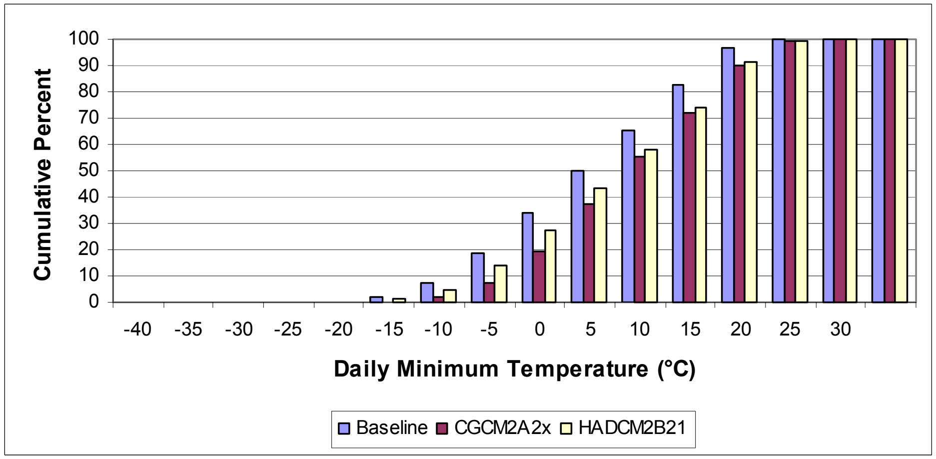


Figure B-161. Windsor minimum daily temperature cumulative percent distribution (n=54750)

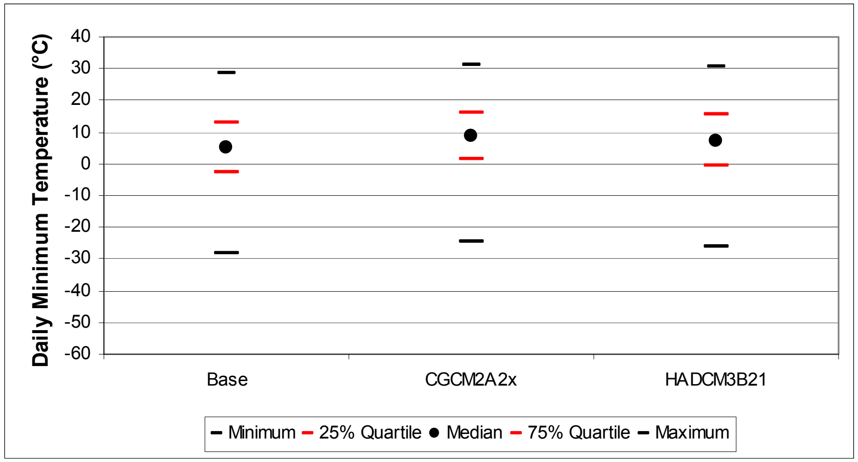


Figure B-162. Windsor minimum daily temperature distribution: quartile statistics (n=54750)

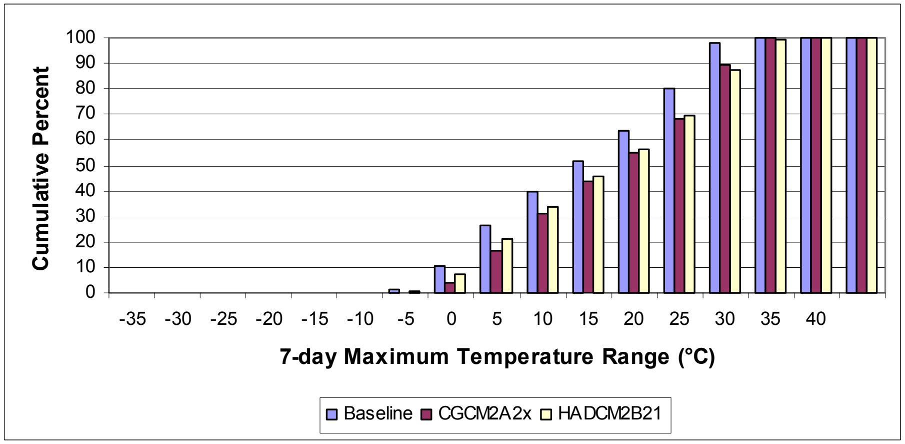


Figure B-164. Windsor 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

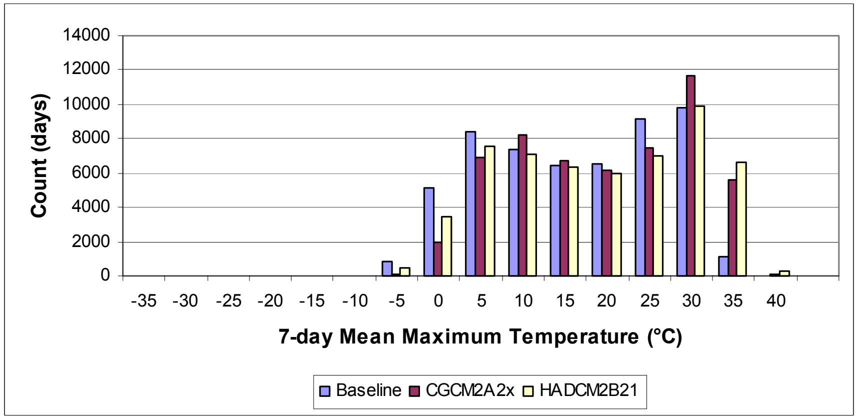


Figure B-163. Windsor 7-day mean maximum daily temperature distribution (n=54750)

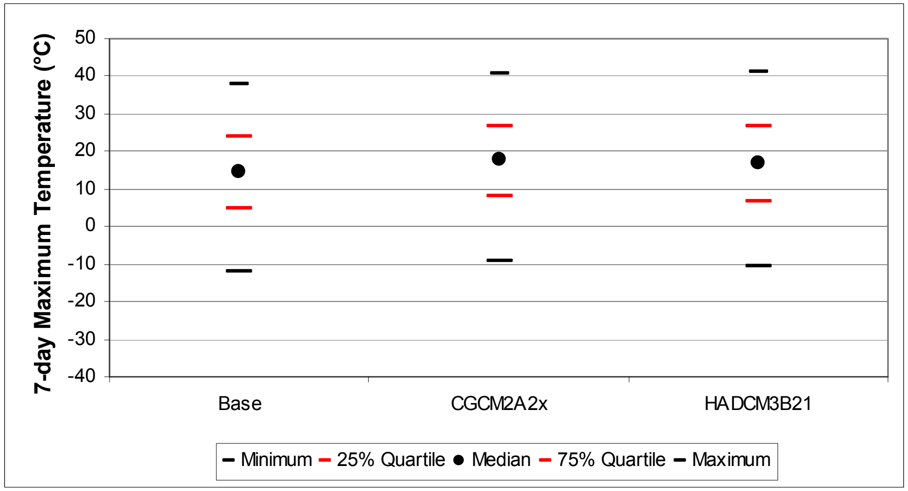


Figure B-165. Windsor 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-56. Windsor annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-20.5	-15.3	-18.8
Standard Deviation	2.8	2.8	2.7
Minimum	-28.4	-24.8	-26.1
Lower Quartile	-22.4	-16.8	-20.8
Median	-20.5	-15.0	-18.8
Upper Quartile	-18.5	-13.4	-16.8
Maximum	-13.8	-8.8	-12.2

*n=150

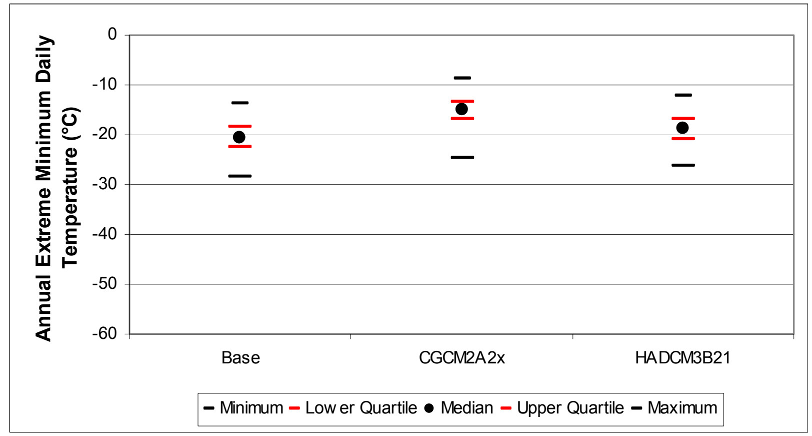


Figure B-166. Windsor annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-57. Windsor annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	31.4	34.1	34.9
Standard Deviation	1.5	1.5	1.5
Minimum	27.4	30.0	31.0
Lower Quartile	30.3	33.1	33.9
Median	31.2	34.0	34.8
Upper Quartile	32.4	35.1	35.7
Maximum	38.0	40.5	41.2

*n=150

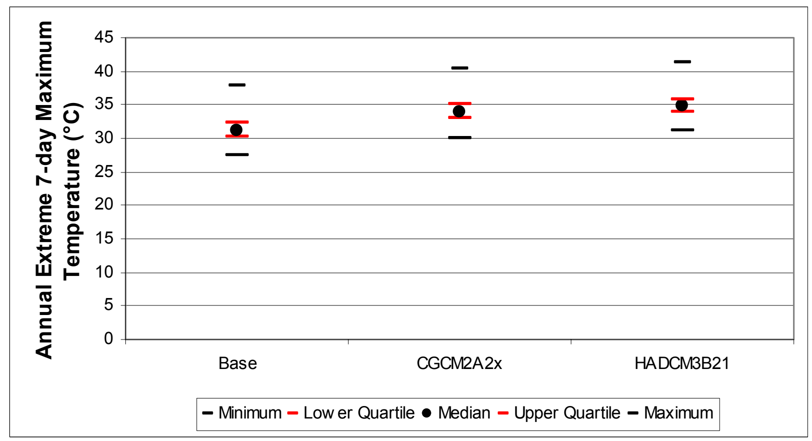


Figure B-167. Windsor annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-58. Windsor Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-20.7	-16.9	-19.4
Superpave-derived high PG threshold (°C)	55.9	58.0	58.6
98th percentile annual minimum air temperature	-25.8	-21.1	-23.7
Ontario RWIS-based low PG threshold (°C)	-21.5	-17.7	-19.8
98th percentile annual extreme 7-day mean maximum air temperature	34.9	37.3	38.0
Ontario RWIS-based high PG threshold (°C)	52.4	56.5	57.7

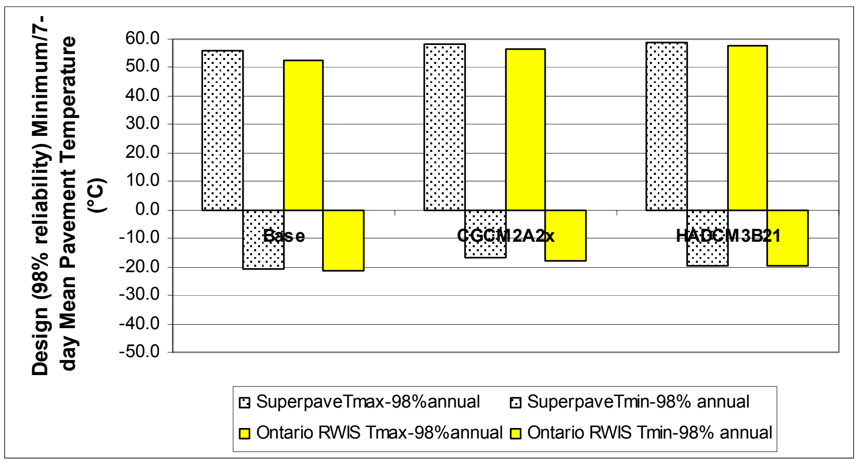


Figure B-168. Windsor estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-59. Windsor freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	30.1	0.7	12.4
Standard Deviation	19.0	3.9	14.3
Minimum	0.0	0.0	0.0
Lower Quartile	15.0	0.0	0.0
Median	30.0	0.0	8.0
Upper Quartile	43.0	0.0	20.8
Maximum	91.0	36.0	74.0

*n=150

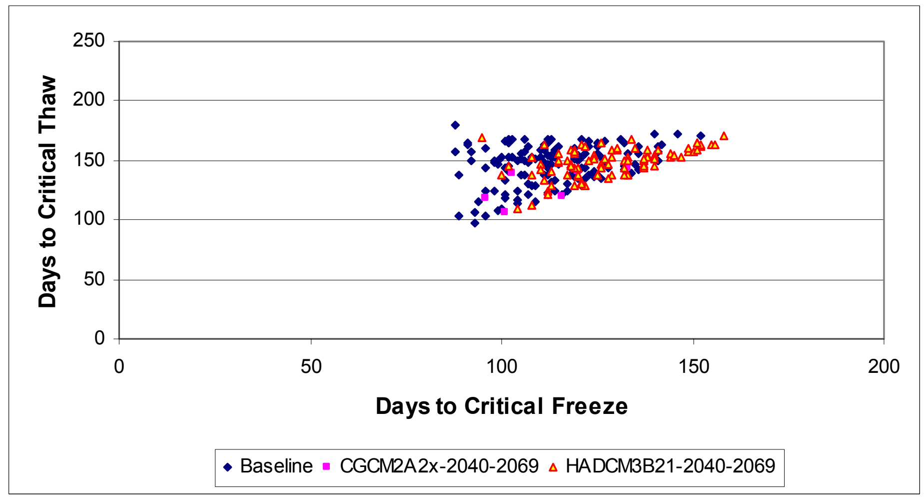


Figure B-169. Windsor estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

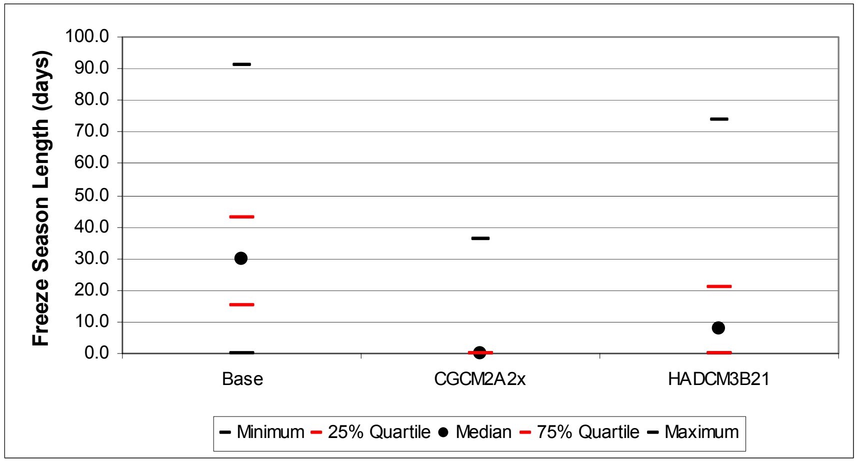


Figure B-170. Windsor estimated freeze season length distribution: quartile statistics (n=150)

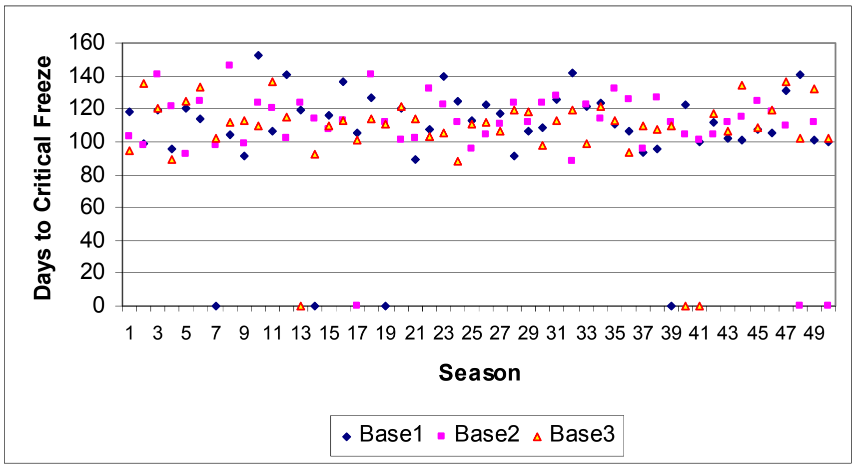


Figure B-171. Windsor estimated days to critical FI (baseline series)

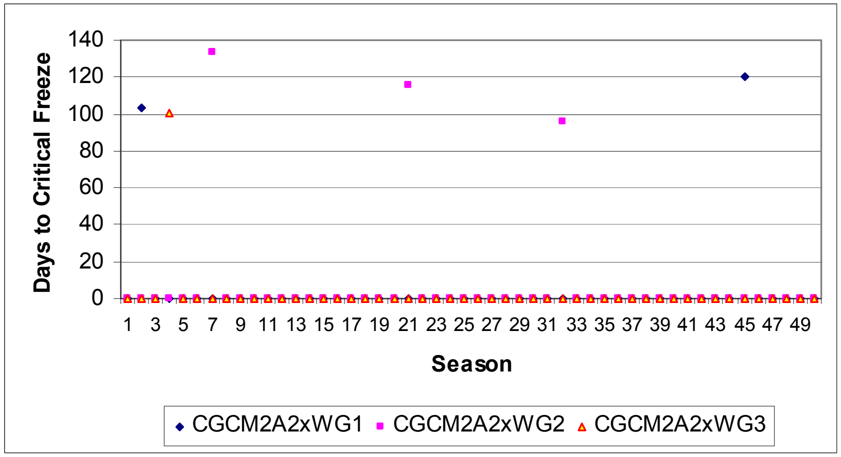


Figure B-172. Windsor estimated days to critical FI (CGCM2A2x scenario series)

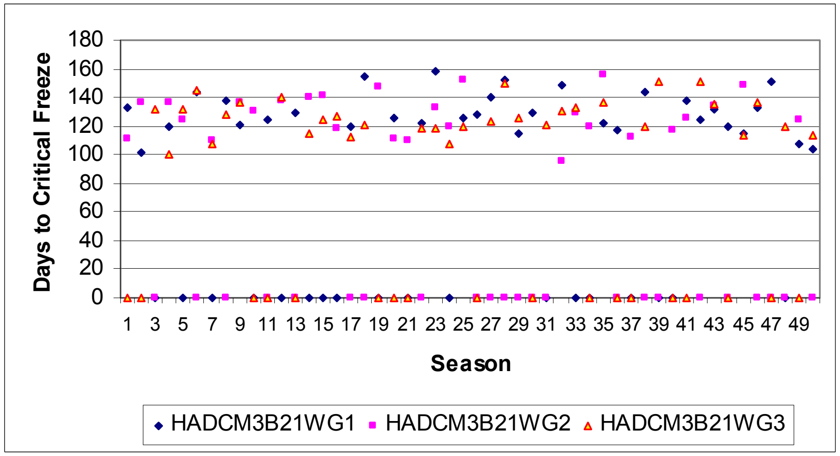


Figure B-173. Windsor estimated days to critical FI (HadCM3B21 scenario series)

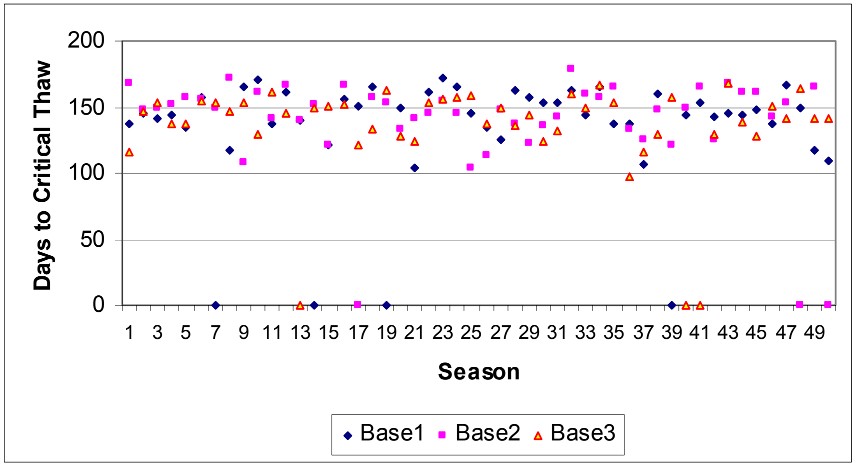


Figure B-174. Windsor estimated days to critical TI (baseline series)

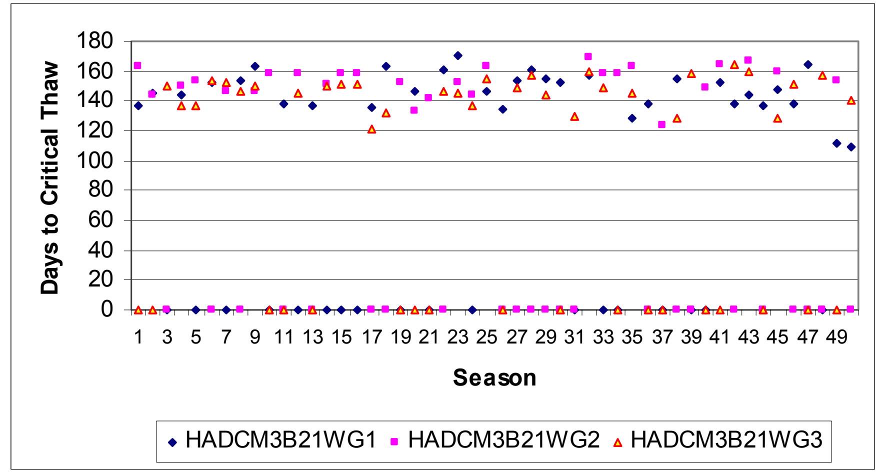


Figure B-176. Windsor estimated days to critical TI (HadCM3B21 scenario series)

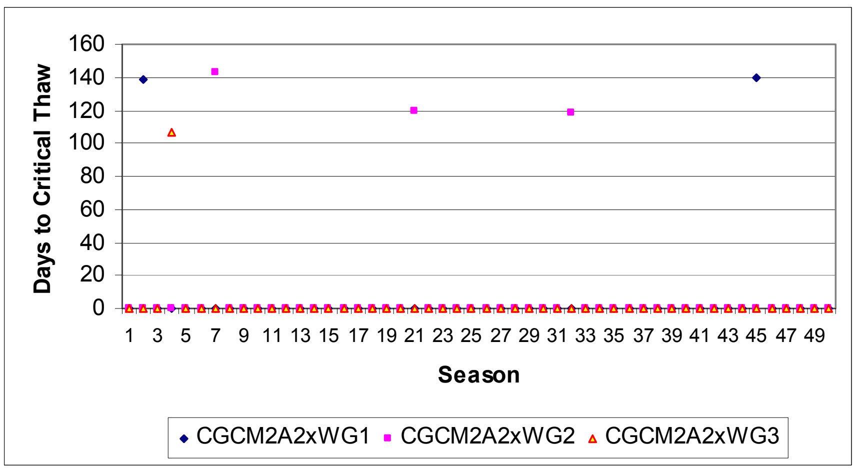


Figure B-175. Windsor estimated days to critical TI (CGCM2A2x scenario series)

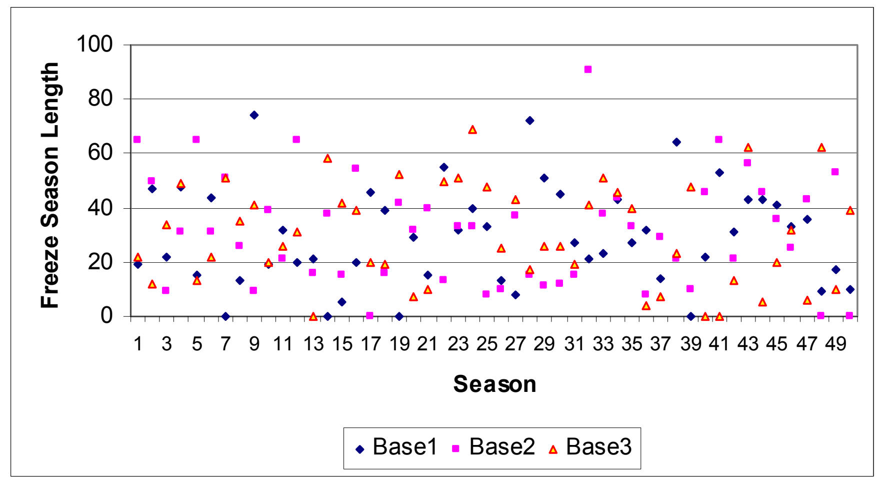


Figure B-177. Windsor estimated freeze season length (baseline series)

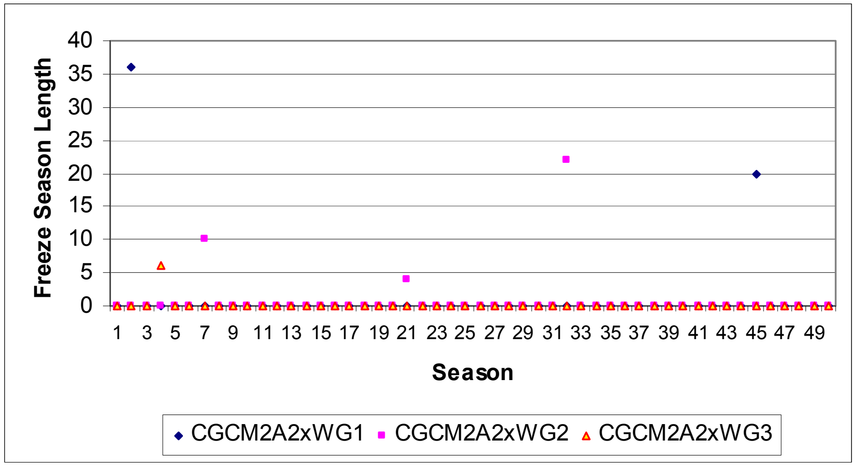


Figure B-178. Windsor estimated freeze season length (CGCM2A2x scenario series)

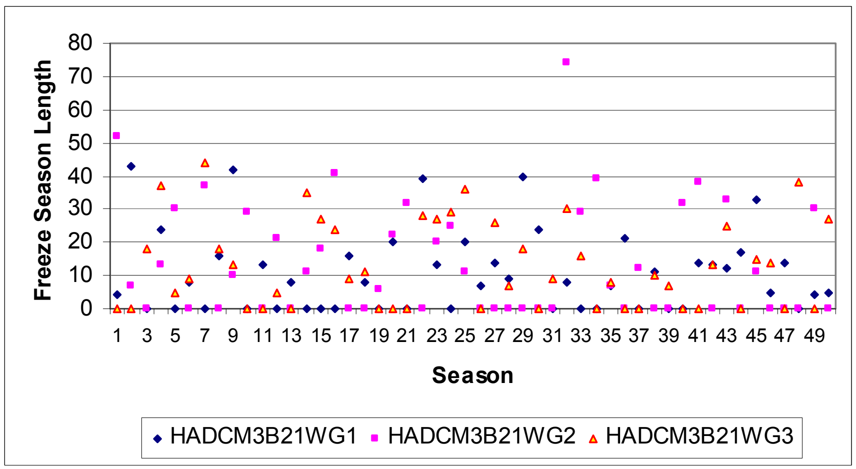


Figure B-179. Windsor estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: TORONTO

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Toronto (6158733)	43.7	79.6	173.4	7.5	792.7

*1971-2000 climate normals

Table B-60. Toronto minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	2.4	6.1	4.8
Standard Deviation	9.9	9.1	10.0
Minimum	-33.2	-27.4	-31.0
Lower Quartile	-4.9	-0.6	-2.5
Median	3.0	6.5	5.4
Upper Quartile	10.5	13.5	13.0
Maximum	28.0	30.9	30.6

*n=54750

Table B-61. Toronto 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	12.5	15.5	15.0
Standard Deviation	10.6	10.6	11.2
Minimum	-15.0	-12.3	-13.5
Lower Quartile	3.0	5.9	4.9
Median	12.8	16.1	15.4
Upper Quartile	22.4	25.4	25.4
Maximum	34.1	37.6	37.6

*n=54750

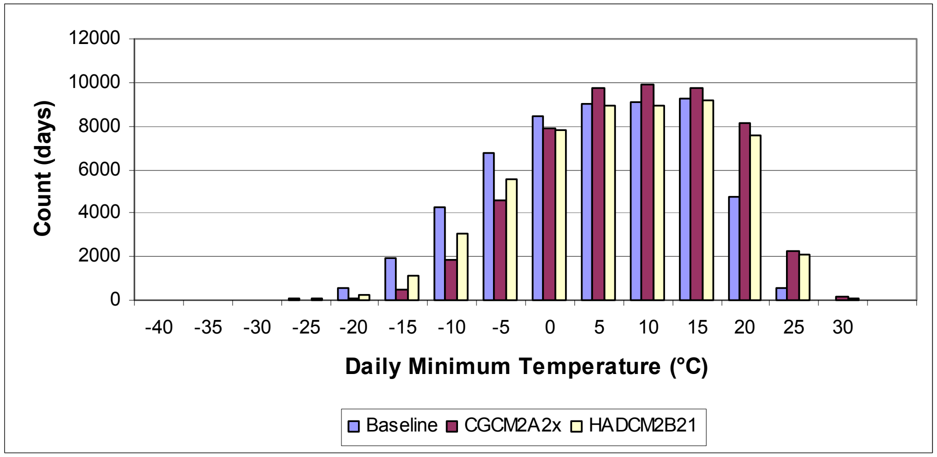


Figure B-180. Toronto minimum daily temperature distribution (n=54750)

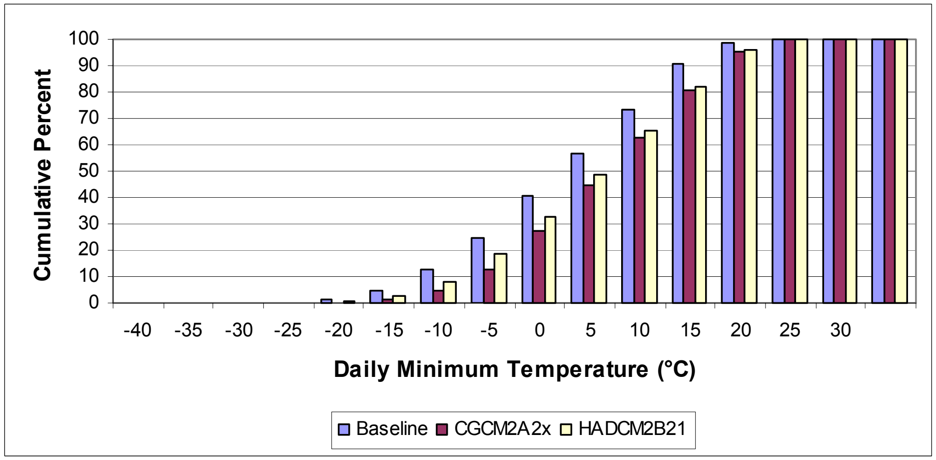


Figure B-181. Toronto minimum daily temperature cumulative percent distribution (n=54750)

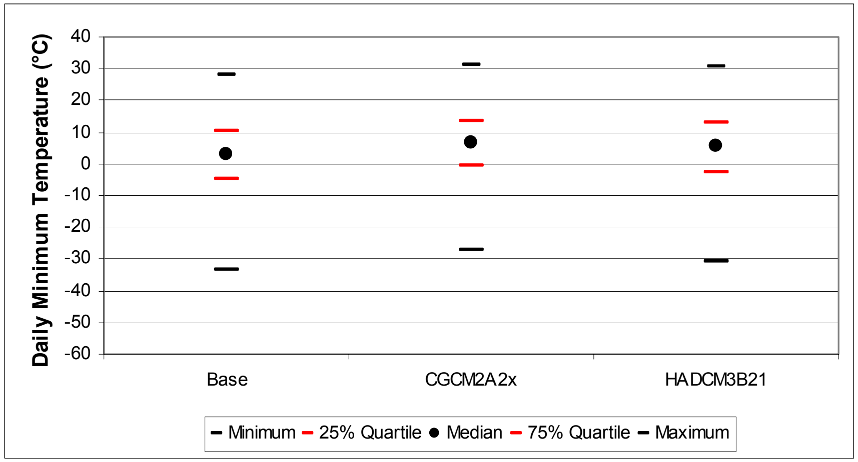


Figure B-182. Toronto minimum daily temperature distribution: quartile statistics (n=54750)

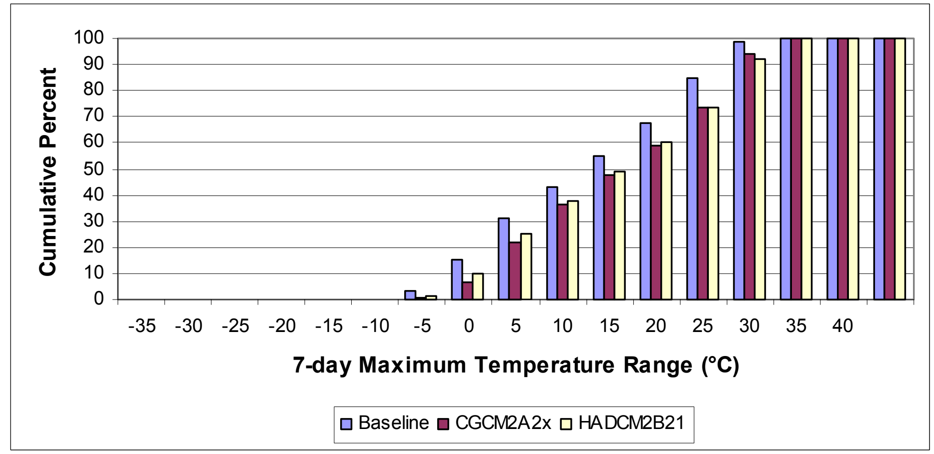


Figure B-184. Toronto 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

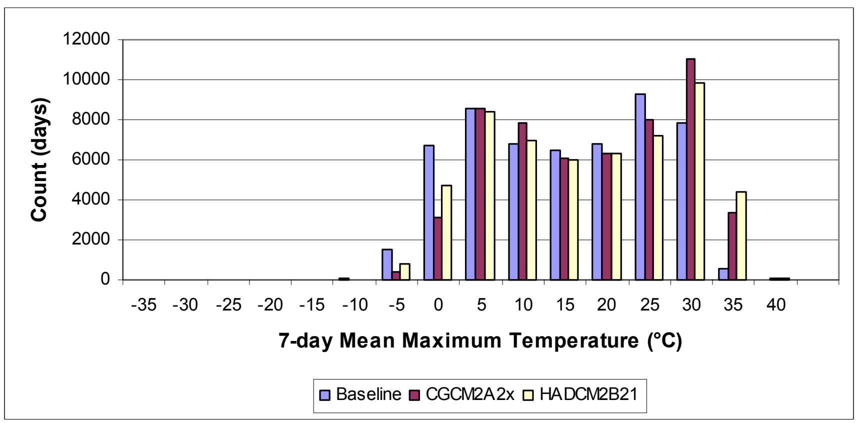


Figure B-183. Toronto 7-day mean maximum daily temperature distribution (n=54750)

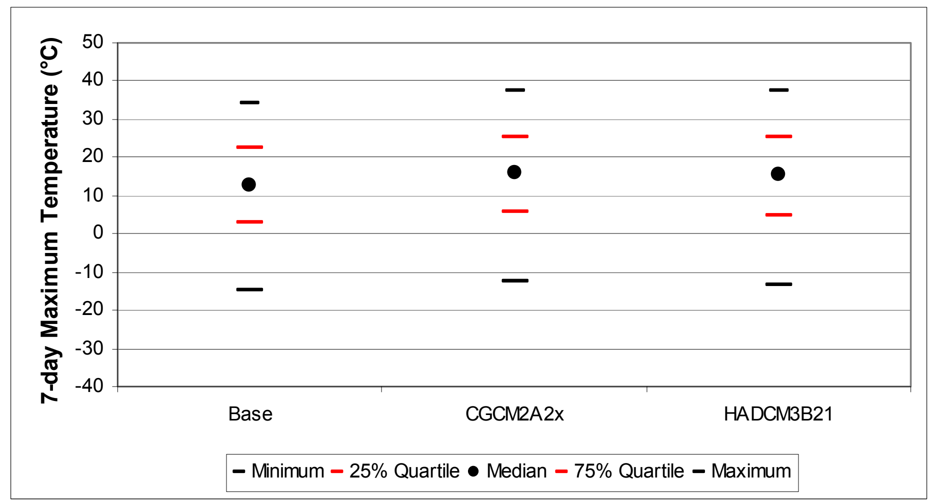


Figure B-185. Toronto 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-62. Toronto annual extreme minimum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-24.7	-18.9	-22.4
Standard Deviation	3.4	3.3	3.4
Minimum	-33.2	-27.4	-31.0
Lower Quartile	-26.8	-21.0	-24.7
Median	-24.3	-19.1	-22.0
Upper Quartile	-22.7	-16.6	-20.4
Maximum	-17.7	-11.2	-15.1

*n=150

Table B-63. Toronto annual extreme 7-day mean maximum air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	30.6	33.2	33.8
Standard Deviation	1.5	1.5	1.5
Minimum	27.2	30.1	30.7
Lower Quartile	29.6	32.1	32.7
Median	30.6	33.2	33.8
Upper Quartile	31.6	34.1	35.0
Maximum	34.1	37.6	37.6

*n=150

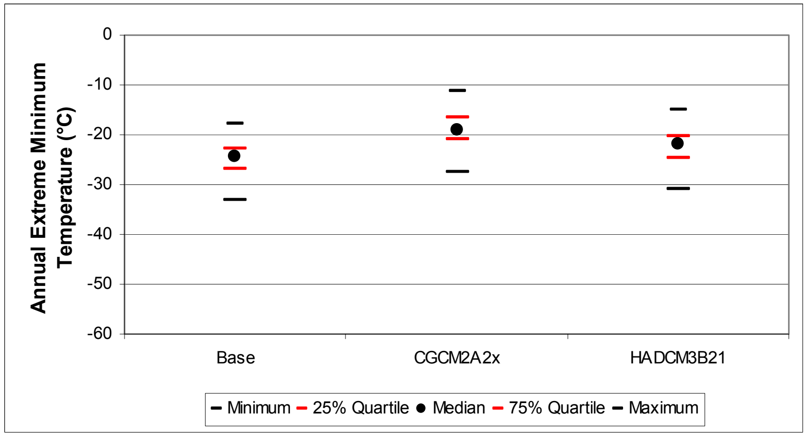


Figure B-186. Toronto annual extreme minimum temperature distribution: quartile statistics (n=150)

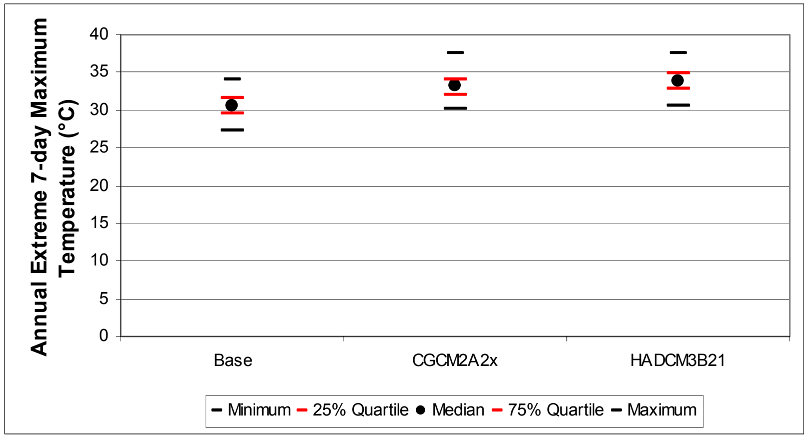


Figure B-187. Toronto annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-64. Toronto Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-24.8	-20.5	-23.2
Superpave-derived high PG threshold (°C)	55.0	57.0	57.5
98th percentile annual minimum air temperature	-32.4	-26.2	-30.1
Ontario RWIS-based low PG threshold (°C)	-26.4	-21.8	-24.8
98th percentile annual extreme 7-day mean maximum air temperature	33.9	36.5	36.8
Ontario RWIS-based high PG threshold (°C)	50.8	55.1	55.6

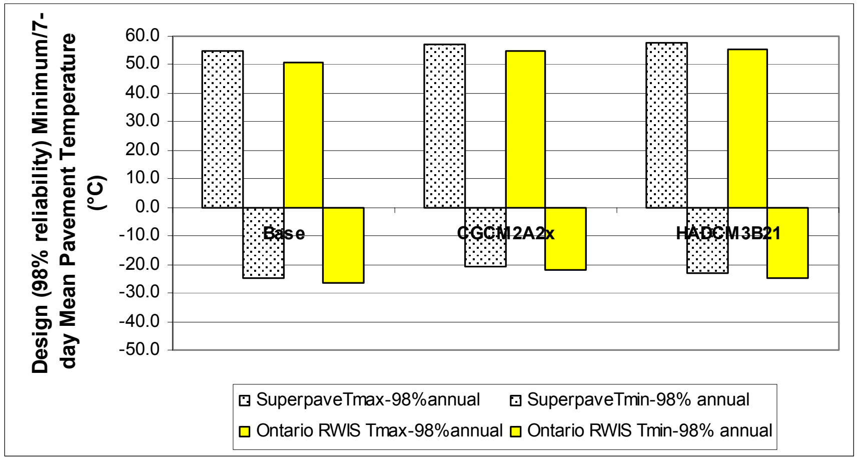


Figure B-188. Toronto estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-65. Toronto freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	55.4	6.5	29.6
Standard Deviation	21.7	10.2	17.4
Minimum	4.0	0.0	0.0
Lower Quartile	41.8	0.0	17.0
Median	60.5	0.0	30.0
Upper Quartile	72.8	9.8	42.0
Maximum	95.0	47.0	78.0

*n=150

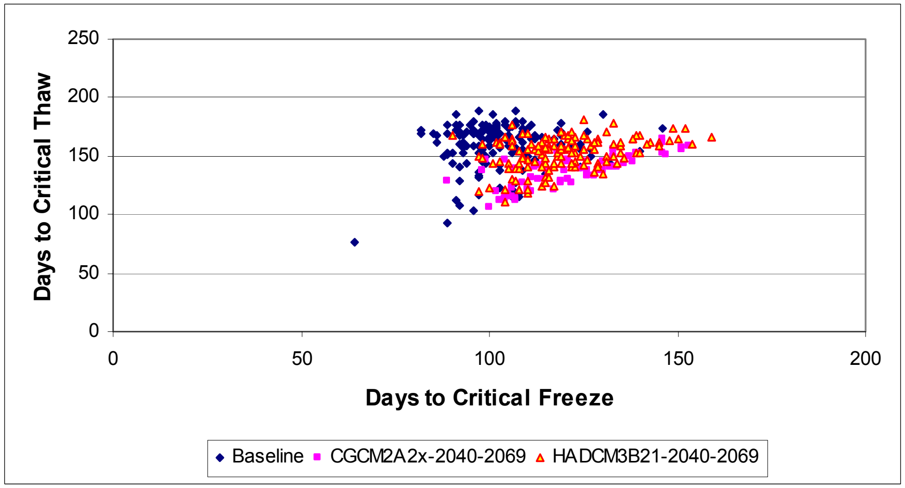


Figure B-189. Toronto estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

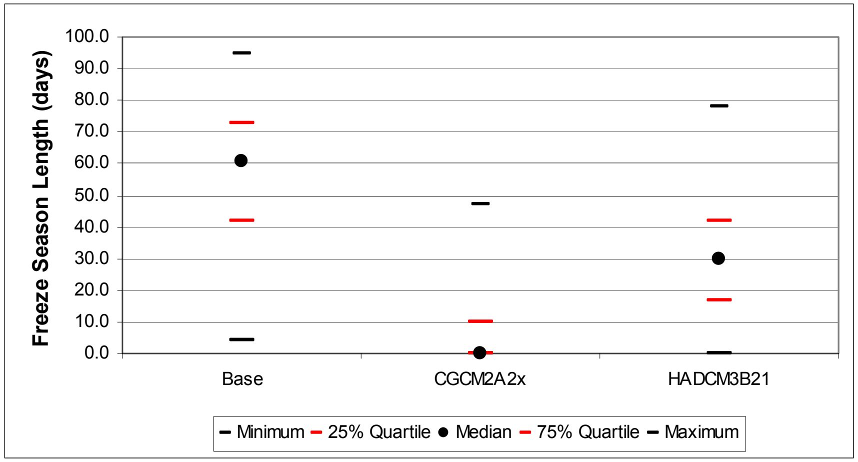


Figure B-190. Toronto estimated freeze season length distribution: quartile statistics (n=150)

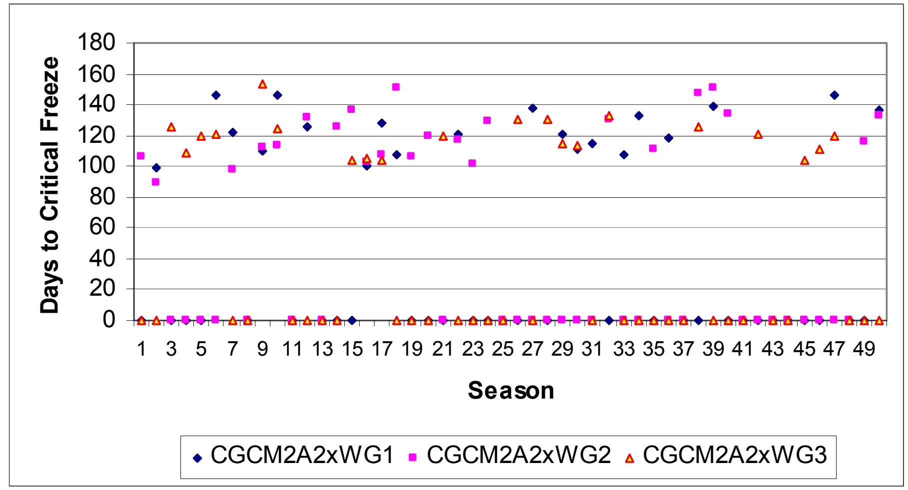


Figure B-192. Toronto estimated days to critical FI (CGCM2A2x scenario series)

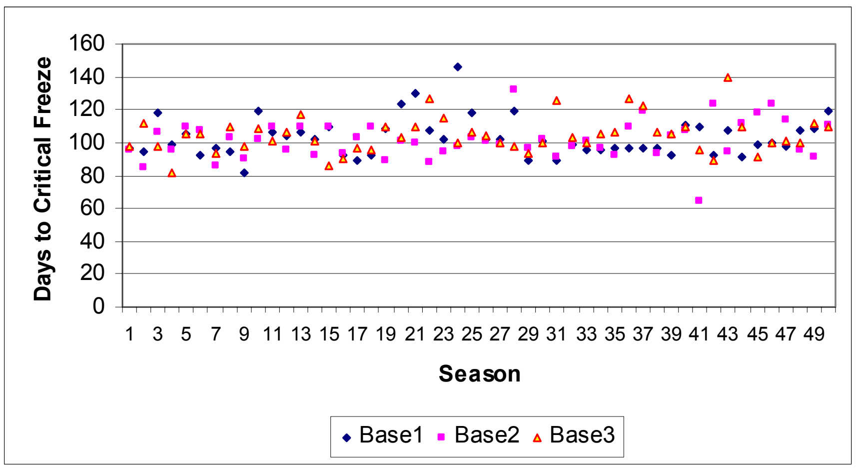


Figure B-191. Toronto estimated days to critical FI (baseline series)

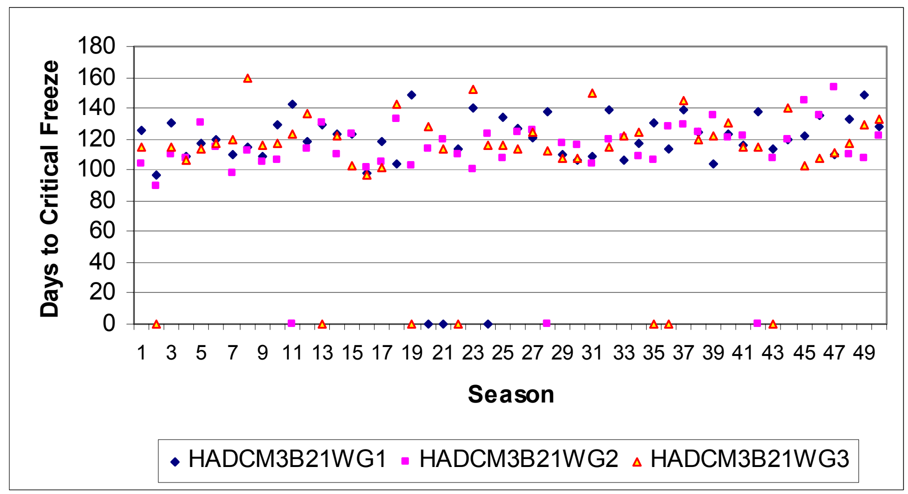


Figure B-193. Toronto estimated days to critical FI (HadCM3B21 scenario series)

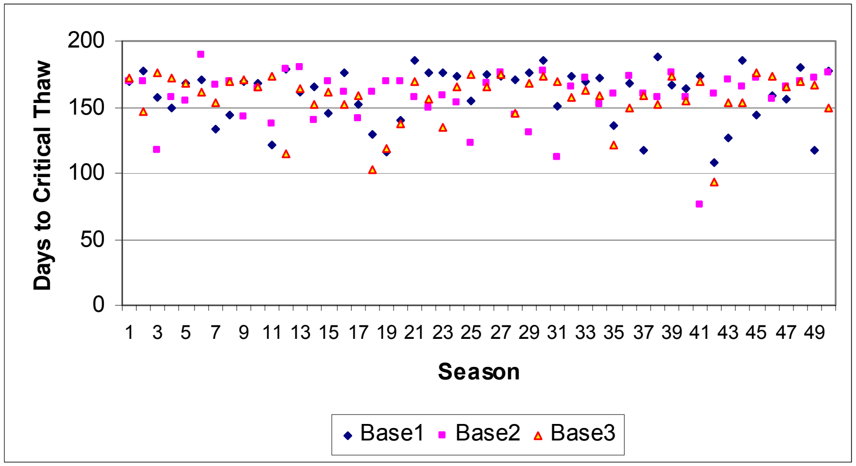


Figure B-194. Toronto estimated days to critical TI (baseline series)

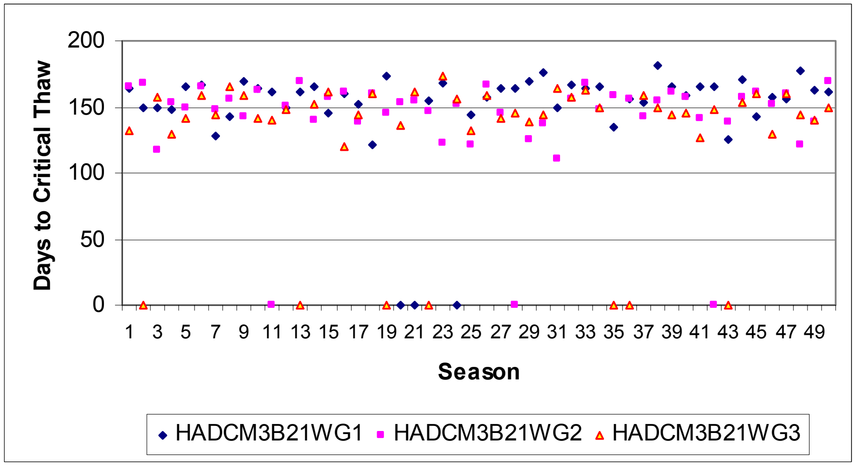


Figure B-196. Toronto estimated days to critical TI (HadCM3B21 scenario series)

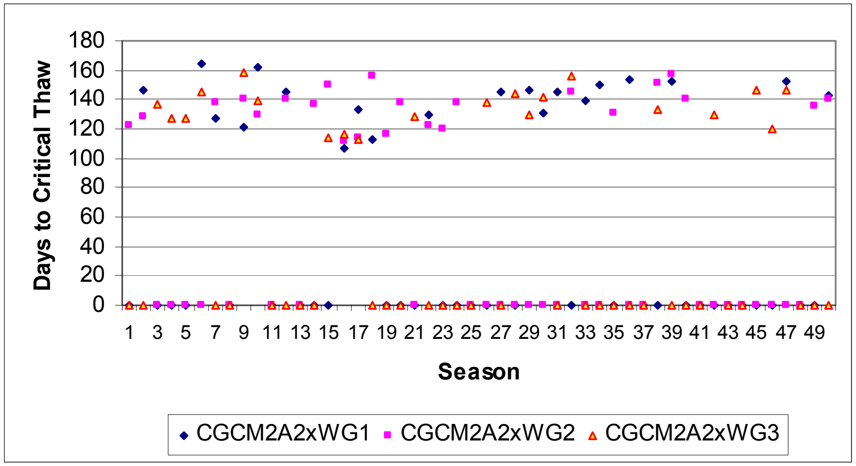


Figure B-195. Toronto estimated days to critical TI (CGCM2A2x scenario series)

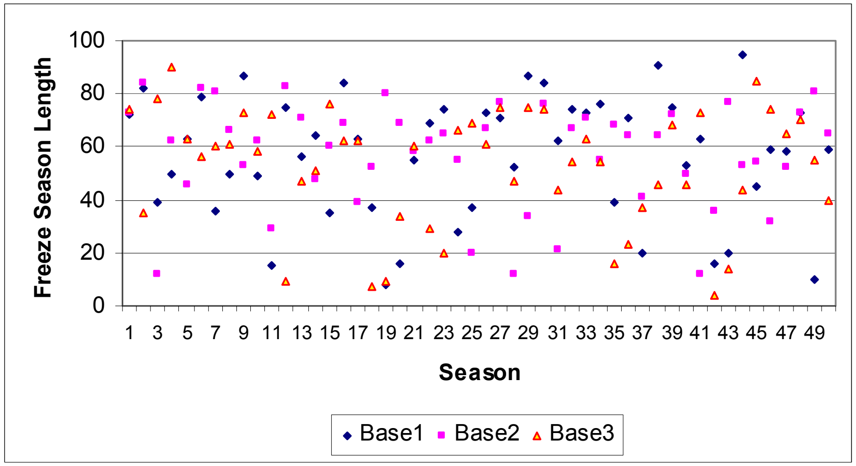


Figure B-197. Toronto estimated freeze season length (baseline series)

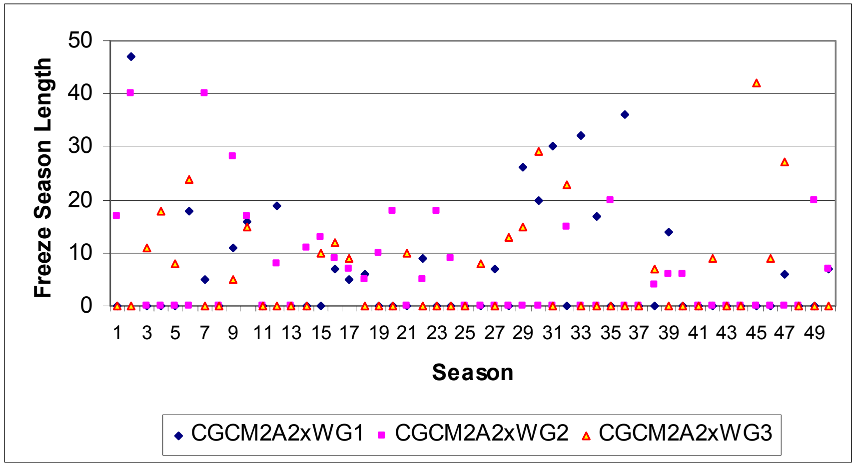


Figure B-198. Toronto estimated freeze season length (CGCM2A2x scenario series)

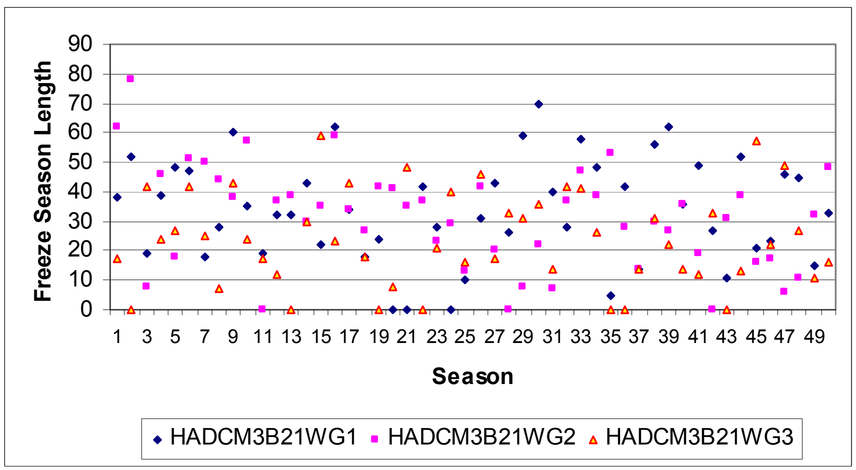


Figure B-199. Toronto estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: OTTAWA

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Ottawa (6106000)	45.3	75.7	114.0	6.0	943.5

*1971-2000 climate normals

Table B-66. Ottawa minimum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	0.9	4.0	3.3
Standard Deviation	11.4	10.8	11.7
Minimum	-41.8	-37.9	-39.6
Lower Quartile	-7.6	-4.2	-5.3
Median	2.1	4.5	4.4
Upper Quartile	10.5	13.4	13.2
Maximum	25.8	28.2	28.9

*n=54750

Table B-67. Ottawa 7-day mean maximum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	10.9	13.3	13.3
Standard Deviation	11.8	11.9	12.5
Minimum	-18.4	-15.8	-17.2
Lower Quartile	0.4	2.3	2.0
Median	11.5	13.7	14.0
Upper Quartile	21.9	24.6	25.0
Maximum	34.9	37.0	38.3

*n=54750

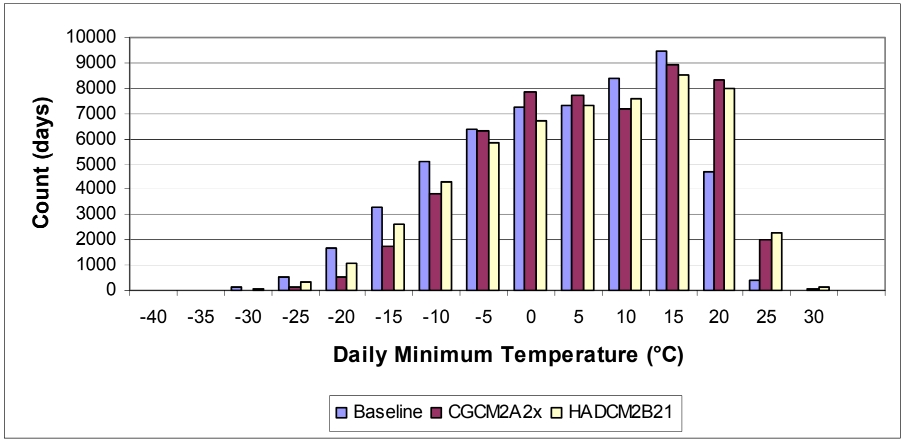


Figure B-200. Ottawa minimum daily temperature distribution (n=54750)

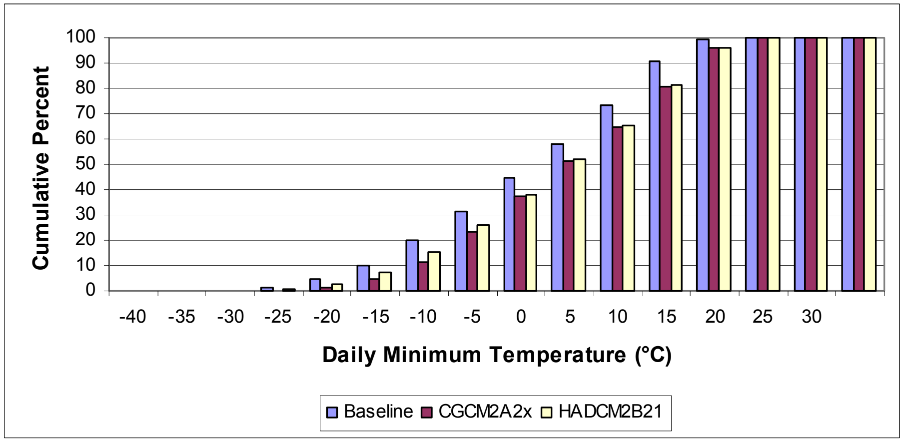


Figure B-201. Ottawa minimum daily temperature cumulative percent distribution (n=54750)

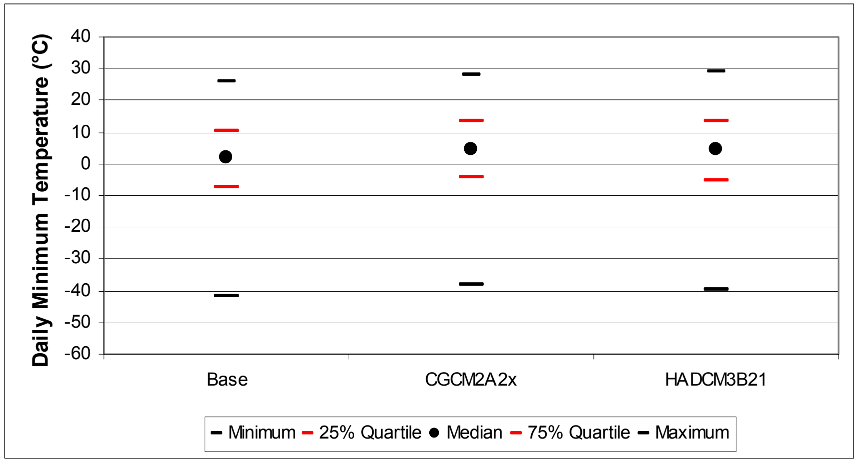


Figure B-202. Ottawa minimum daily temperature distribution: quartile statistics (n=54750)

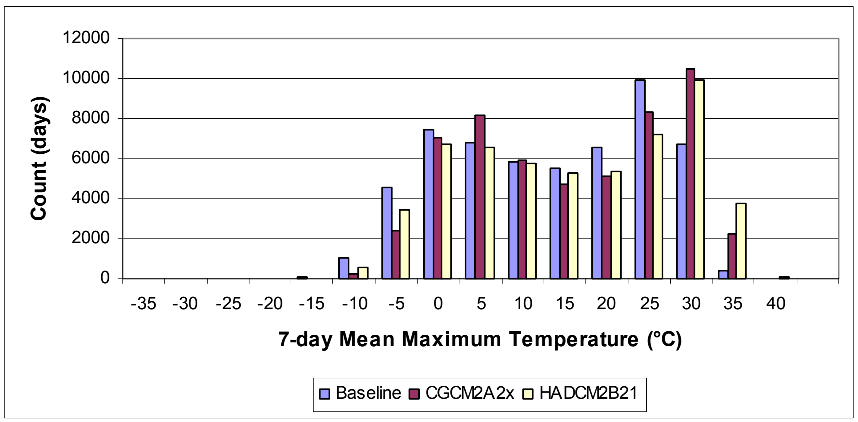


Figure B-203. Ottawa 7-day mean maximum daily temperature distribution (n=54750)

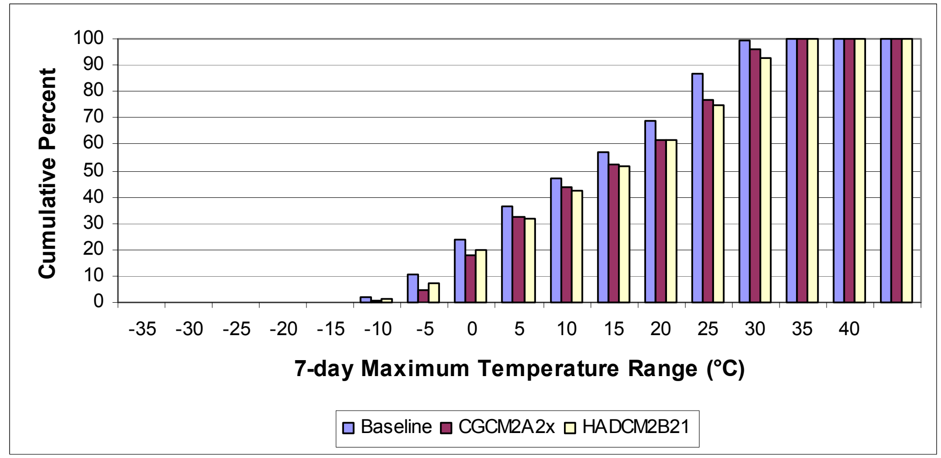


Figure B-204. Ottawa 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

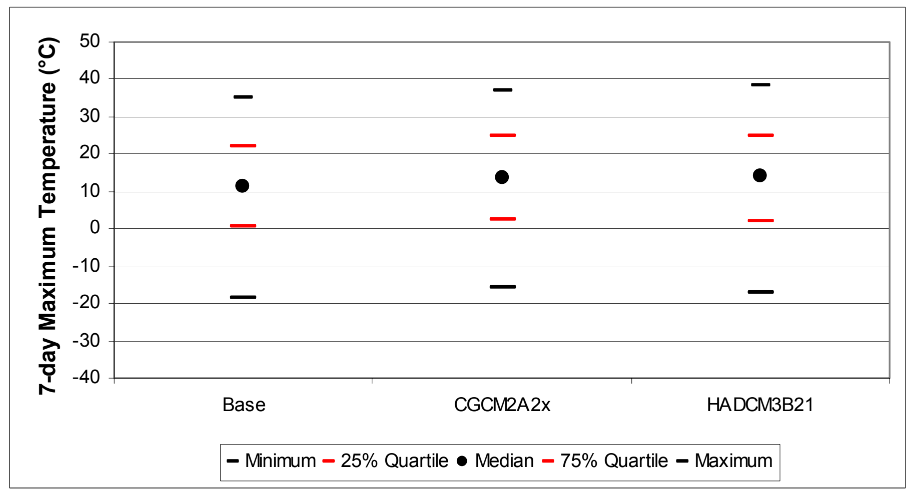


Figure B-205. Ottawa 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-68. Ottawa annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-30.3	-25.0	-28.4
Standard Deviation	3.4	3.3	3.4
Minimum	-41.8	-37.9	-39.6
Lower Quartile	-32.8	-27.4	-30.7
Median	-29.9	-24.9	-28.2
Upper Quartile	-27.9	-22.7	-25.9
Maximum	-23.2	-18.0	-21.3

*n=150

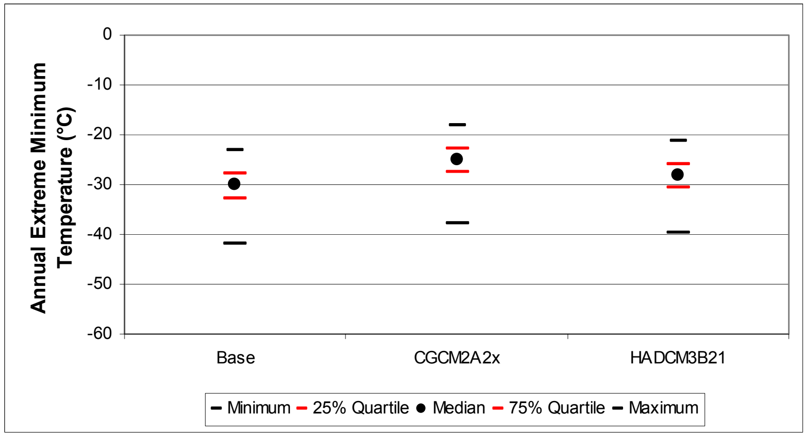


Figure B-206. Ottawa annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-69. Ottawa annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	30.2	32.6	33.6
Standard Deviation	1.6	1.6	1.6
Minimum	26.1	27.9	29.8
Lower Quartile	29.2	31.6	32.6
Median	30.1	32.5	33.5
Upper Quartile	31.1	33.6	34.6
Maximum	34.9	37.0	38.3

*n=150

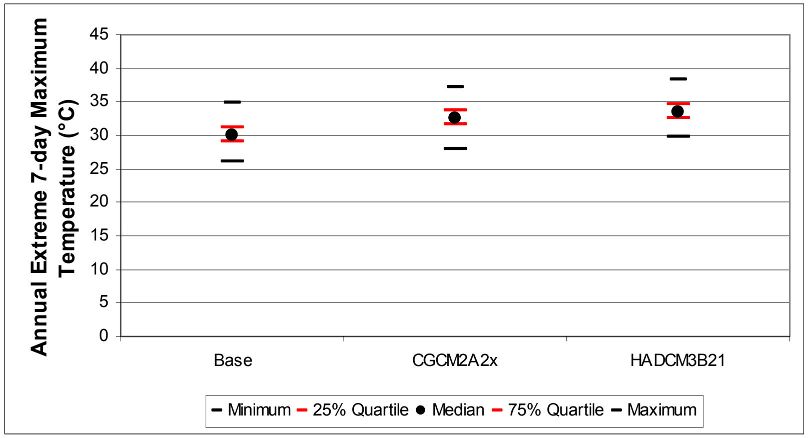


Figure B-207. Ottawa annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-70. Ottawa Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-29.5	-25.6	-28.1
Superpave-derived high PG threshold (°C)	54.4	56.3	57.0
98th percentile annual minimum air temperature	-37.6	-31.8	-35.9
Ontario RWIS-based low PG threshold (°C)	-30.0	-26.0	-28.9
98th percentile annual extreme 7-day mean maximum air temperature	33.4	36.0	37.1
Ontario RWIS-based high PG threshold (°C)	50.0	54.3	56.1

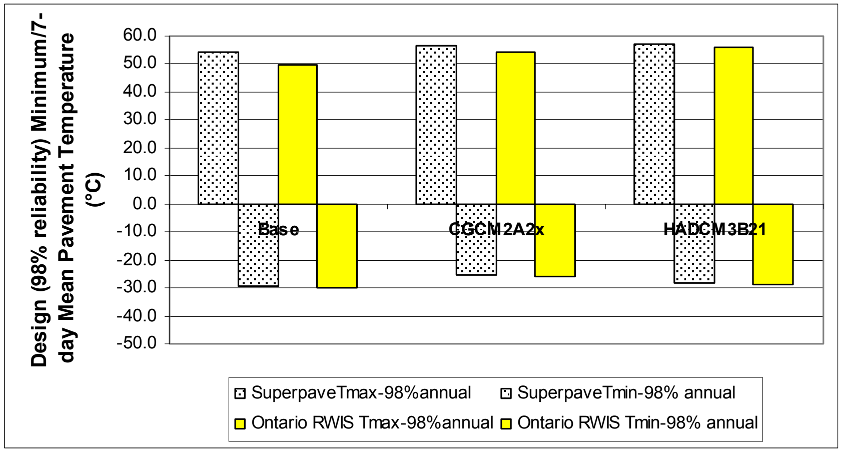


Figure B-208. Ottawa estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-71. Ottawa freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	87.3	49.9	68.8
Standard Deviation	20.4	25.0	19.8
Minimum	6.0	0.0	6.0
Lower Quartile	80.0	29.3	61.3
Median	91.0	51.0	71.5
Upper Quartile	98.8	70.8	82.0
Maximum	124.0	108.0	108.0

*n=150

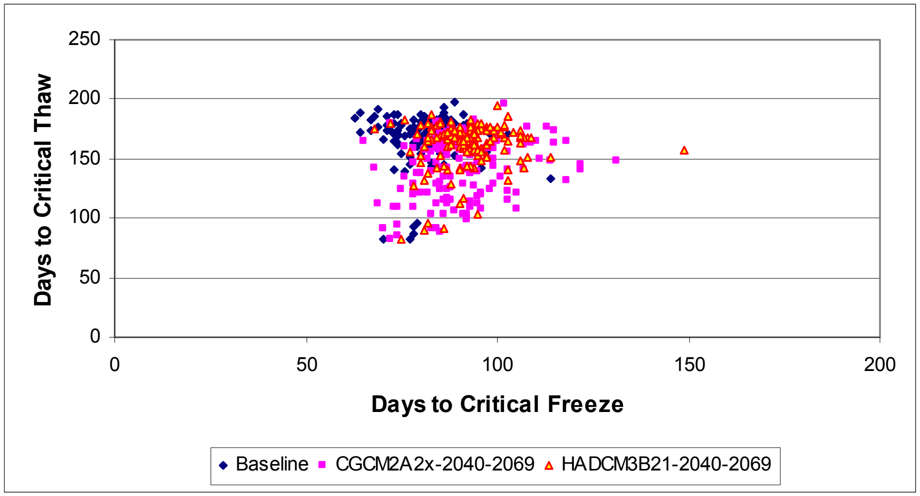


Figure B-209. Ottawa estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

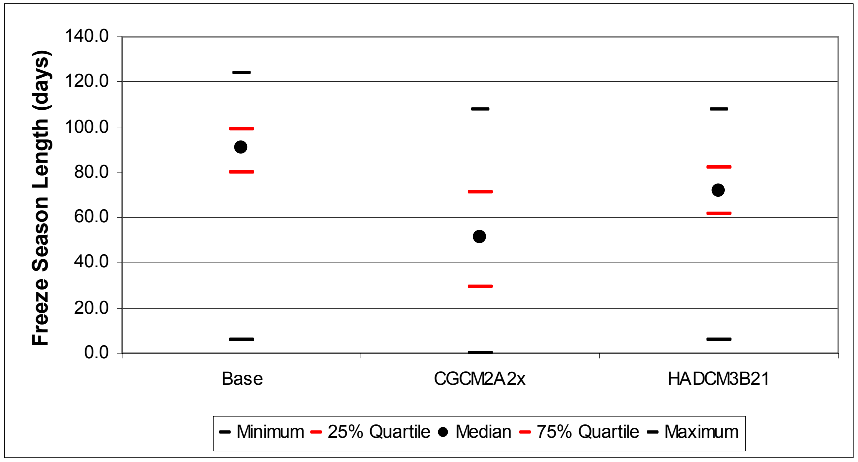


Figure B-210. Ottawa estimated freeze season length distribution: quartile statistics (n=150)

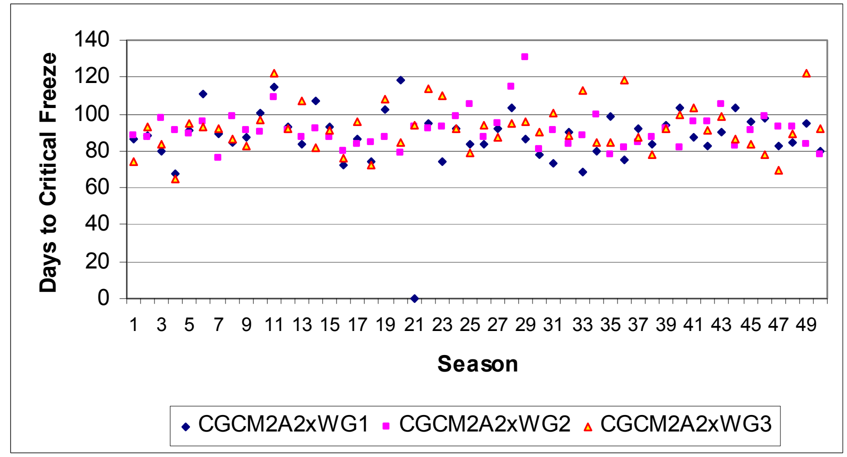


Figure B-212. Ottawa estimated days to critical FI (CGCM2A2x scenario series)

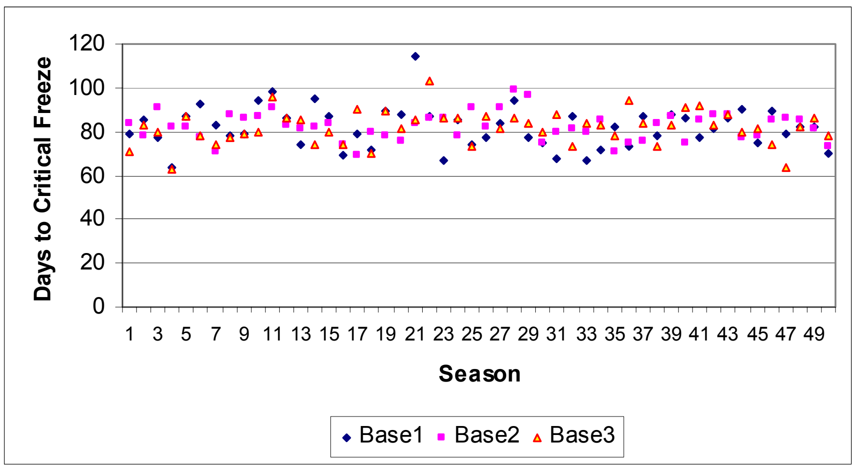


Figure B-211. Ottawa estimated days to critical FI (baseline series)

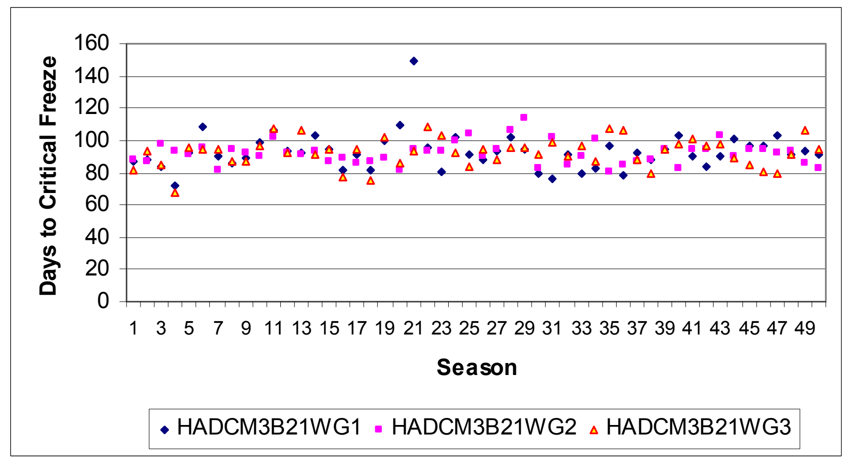


Figure B-213. Ottawa estimated days to critical FI (HadCM3B21 scenario series)

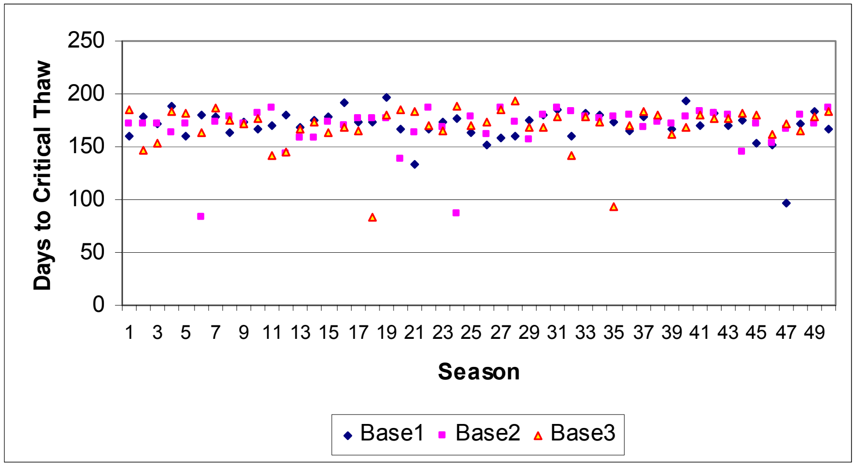


Figure B-214. Ottawa estimated days to critical TI (baseline series)

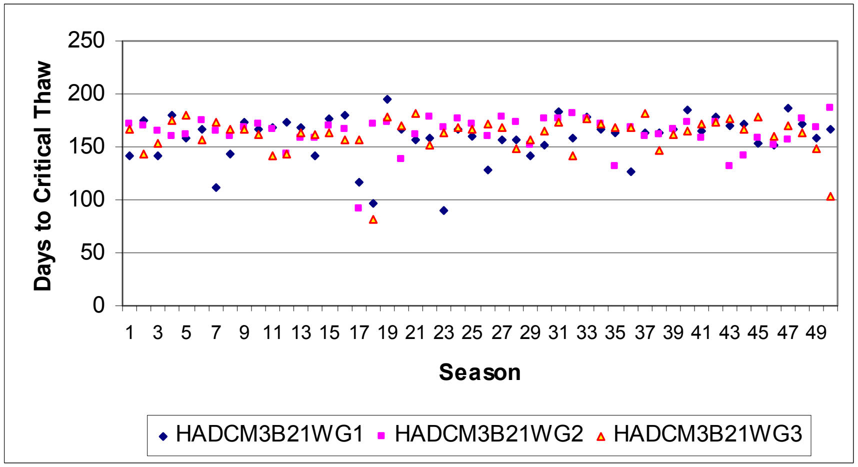


Figure B-216. Ottawa estimated days to critical TI (HadCM3B21 scenario series)

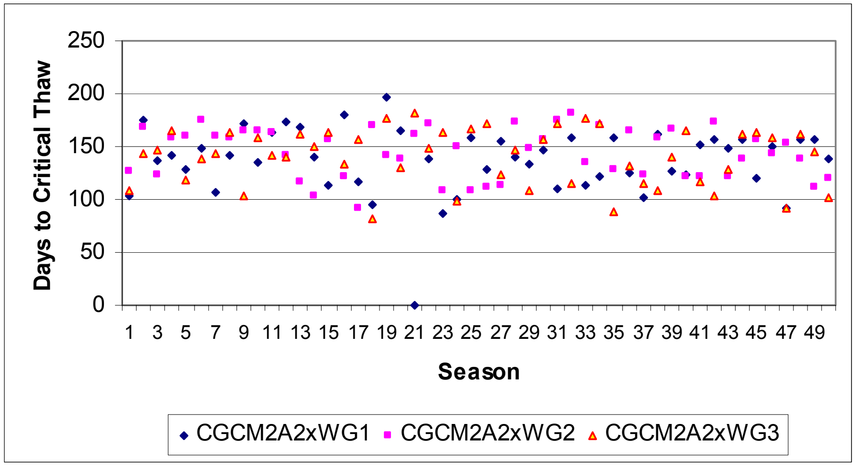


Figure B-215. Ottawa estimated days to critical TI (CGCM2A2x scenario series)

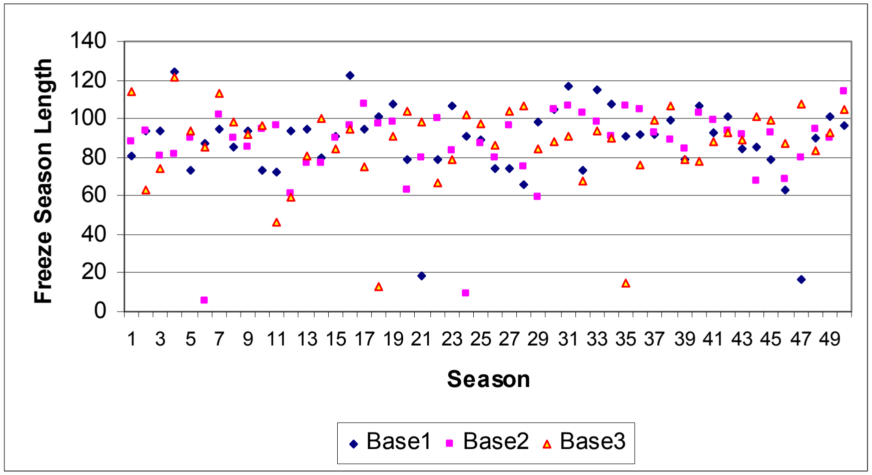


Figure B-217. Ottawa estimated freeze season length (baseline series)

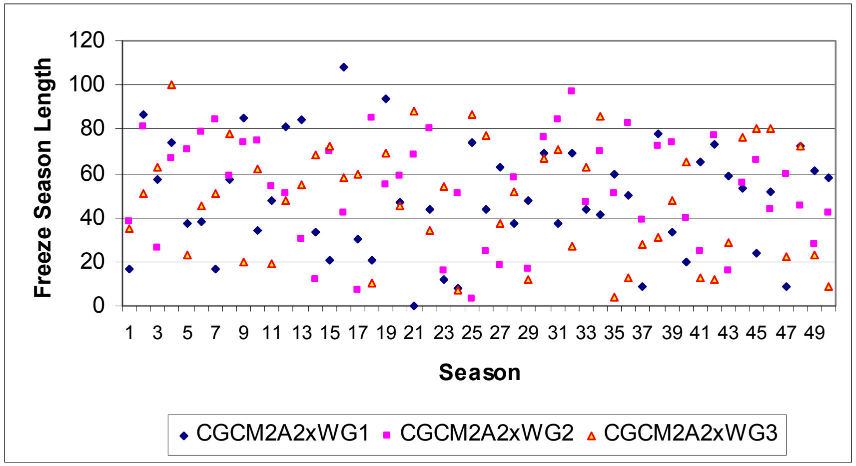


Figure B-218. Ottawa estimated freeze season length (CGCM2A2x scenario series)

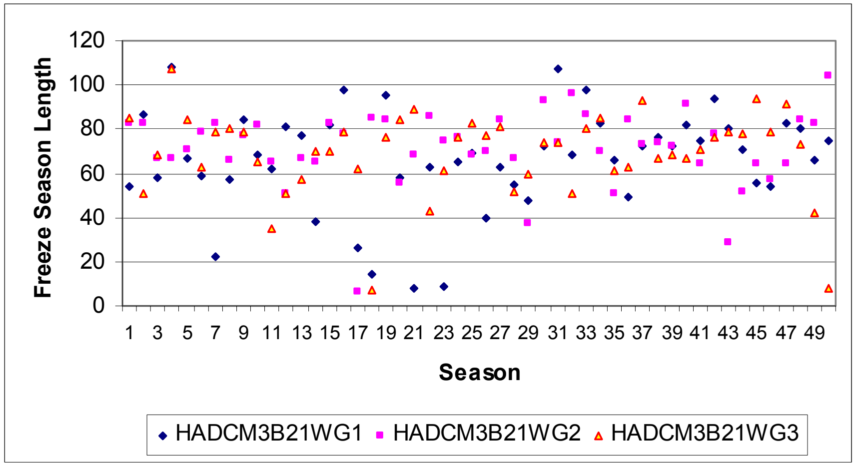


Figure B-219. Ottawa estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: MONTREAL

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Montreal (7025250)	45.5	73.6	35.7	6.2	978.9

*1971-2000 climate normals

Table B-72. Montreal minimum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	1.5	4.6	3.9
Standard Deviation	11.4	10.8	11.7
Minimum	-41.4	-37.0	-39.2
Lower Quartile	-6.8	-3.5	-4.6
Median	2.8	5.2	5.1
Upper Quartile	11.0	13.8	13.6
Maximum	28.5	31.1	31.7

*n=54750

Table B-73. Montreal 7-day mean maximum daily air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	11.1	13.4	13.5
Standard Deviation	11.5	11.7	12.3
Minimum	-20.9	-16.8	-19.4
Lower Quartile	0.8	2.8	2.6
Median	11.9	14.1	14.4
Upper Quartile	21.9	24.6	25.0
Maximum	34.1	37.0	37.1

*n=54750

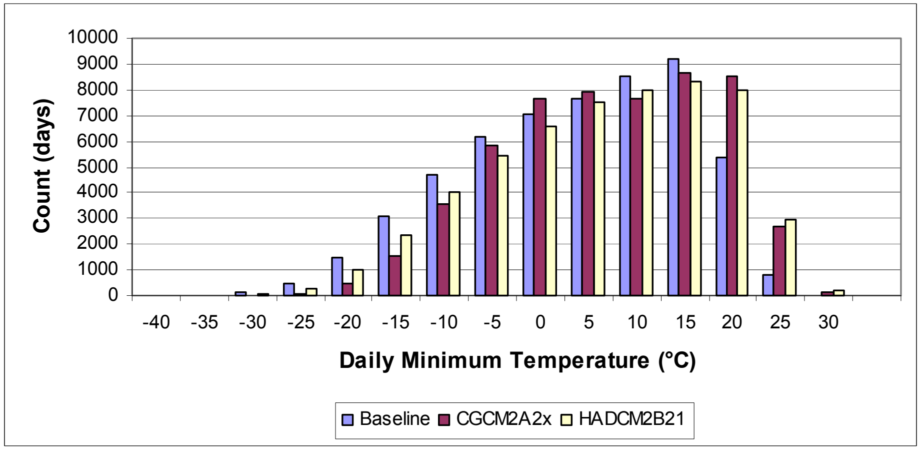


Figure B-220. Montreal minimum daily temperature distribution (n=54750)

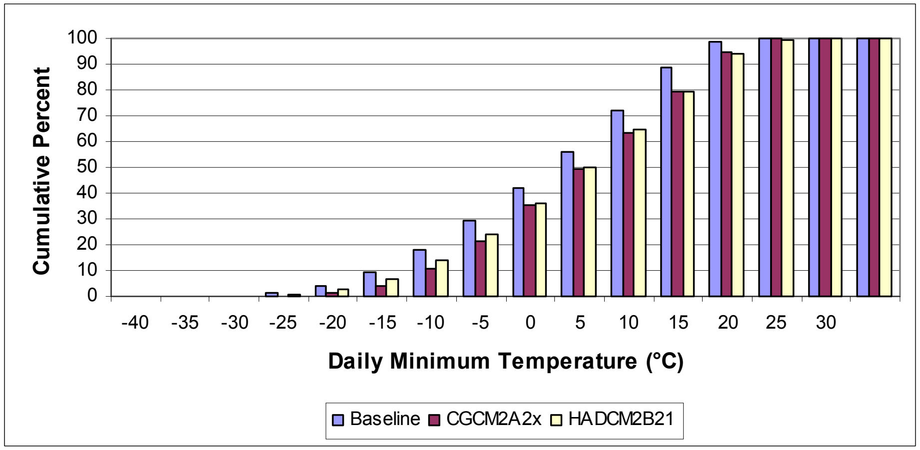


Figure B-221. Montreal minimum daily temperature cumulative percent distribution (n=54750)

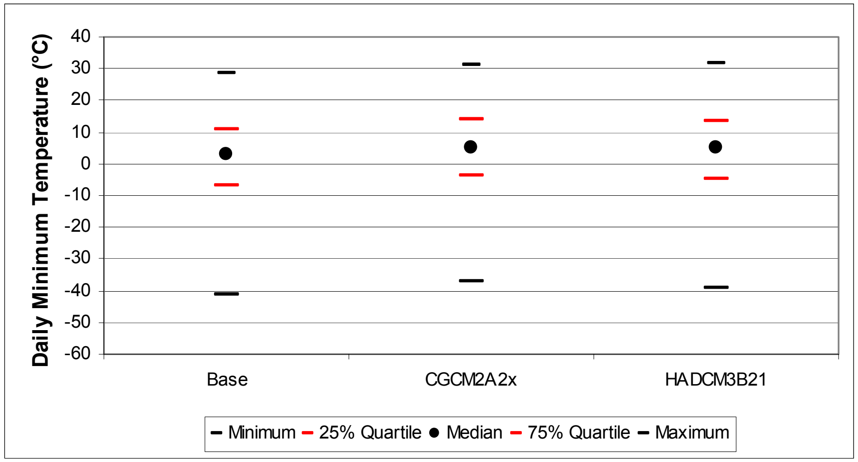


Figure B-222. Montreal minimum daily temperature distribution: quartile statistics (n=54750)

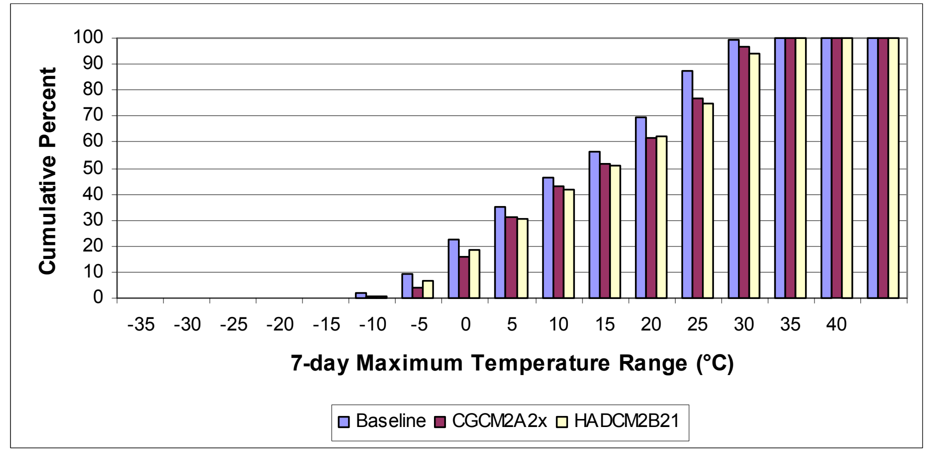


Figure B-224. Montreal 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

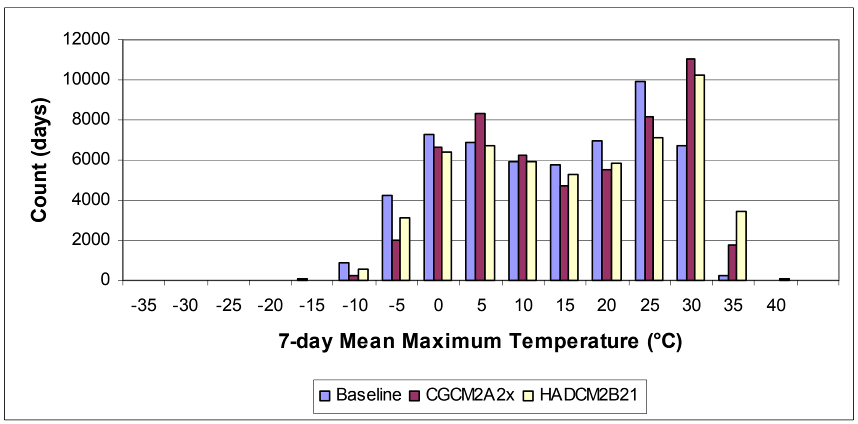


Figure B-223. Montreal 7-day mean maximum daily temperature distribution (n=54750)

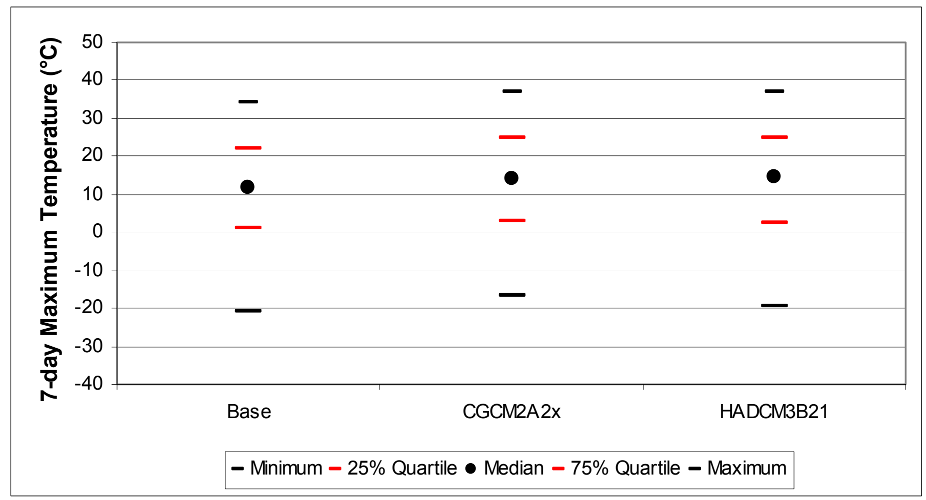


Figure B-225. Montreal 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-74. Montreal annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	-29.8	-24.4	-27.9
Standard Deviation	3.9	3.7	3.9
Minimum	-41.4	-37.0	-39.2
Lower Quartile	-32.0	-26.4	-30.2
Median	-29.7	-24.2	-27.7
Upper Quartile	-27.0	-21.9	-25.1
Maximum	-23.2	-17.0	-21.0

*n=150

Table B-75. Montreal annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	29.7	32.2	33.2
Standard Deviation	1.3	1.3	1.3
Minimum	27.3	29.8	30.5
Lower Quartile	28.7	31.4	32.2
Median	29.7	32.0	33.1
Upper Quartile	30.5	32.9	34.0
Maximum	34.1	37.0	37.1

*n=150

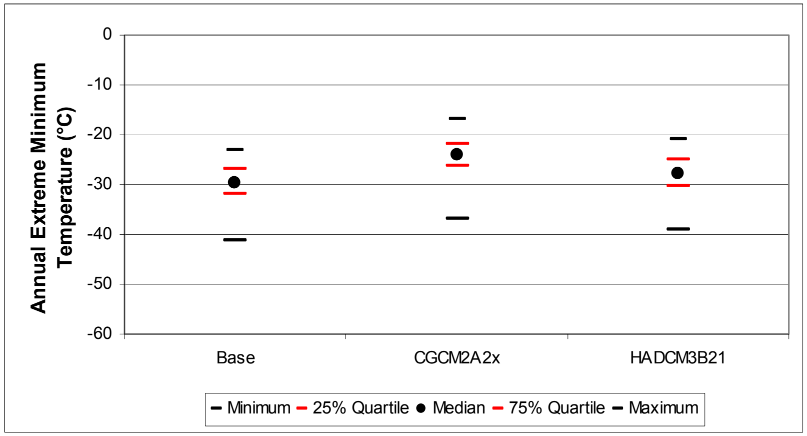


Figure B-226. Montreal annual extreme minimum temperature distribution: quartile statistics (n=150)

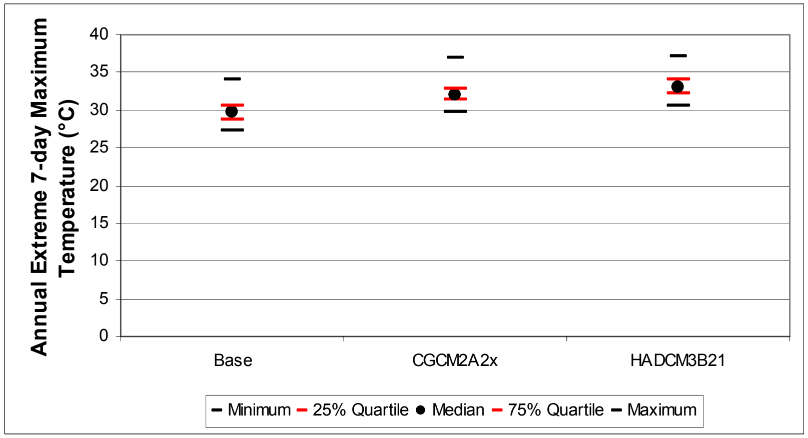


Figure B-227. Montreal annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-76. Montreal Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-29.8	-25.7	-28.4
Superpave-derived high PG threshold (°C)	53.8	55.7	56.5
98th percentile annual minimum air temperature	-39.2	-33.8	-37.5
Ontario RWIS-based low PG threshold (°C)	-31.1	-27.4	-30.0
98th percentile annual extreme 7-day mean maximum air temperature	33.0	35.2	36.5
Ontario RWIS-based high PG threshold (°C)	49.3	53.0	55.2

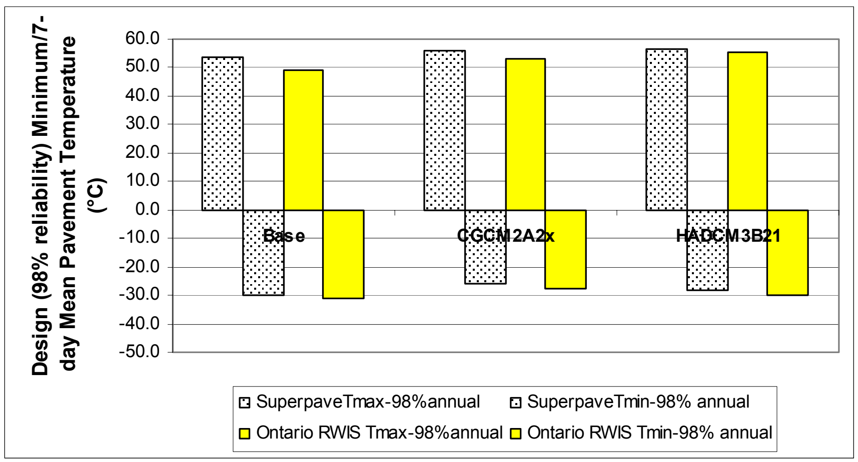


Figure B-228. Montreal estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-77. Montreal freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	82.4	39.5	62.5
Standard Deviation	19.0	22.5	19.9
Minimum	4.0	4.0	7.0
Lower Quartile	76.0	19.0	56.3
Median	87.0	36.5	67.0
Upper Quartile	93.0	58.8	76.0
Maximum	115.0	85.0	95.0

*n=150

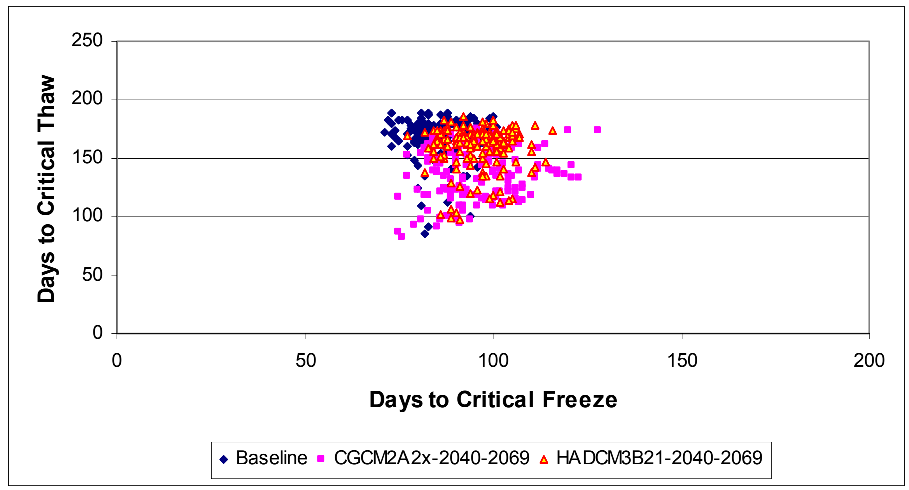


Figure B-229. Montreal estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

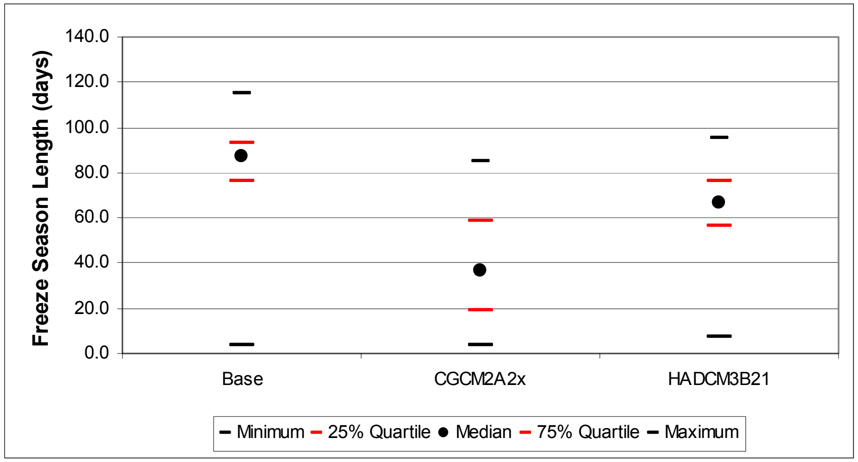


Figure B-230. Montreal estimated freeze season length distribution: quartile statistics (n=150)

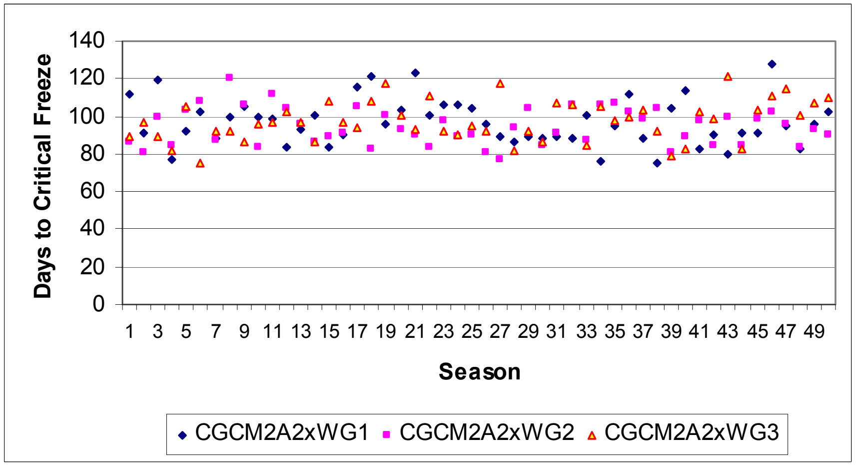


Figure B-232. Montreal estimated days to critical FI (CGCM2A2x scenario series)

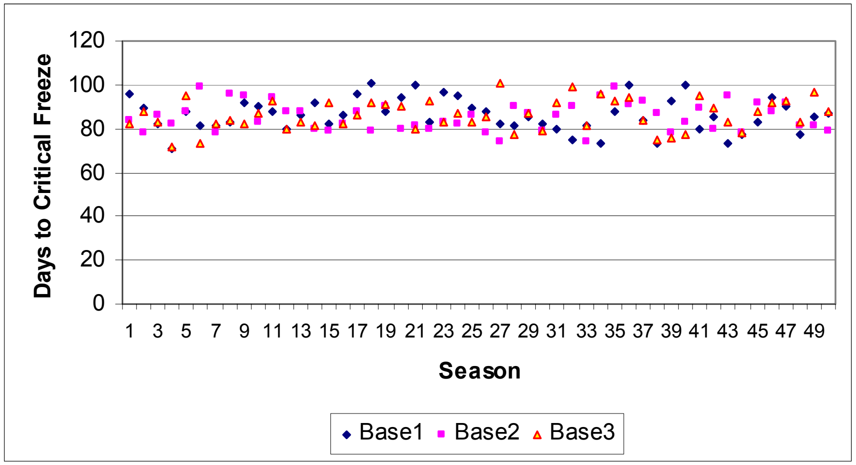


Figure B-231. Montreal estimated days to critical FI (baseline series)

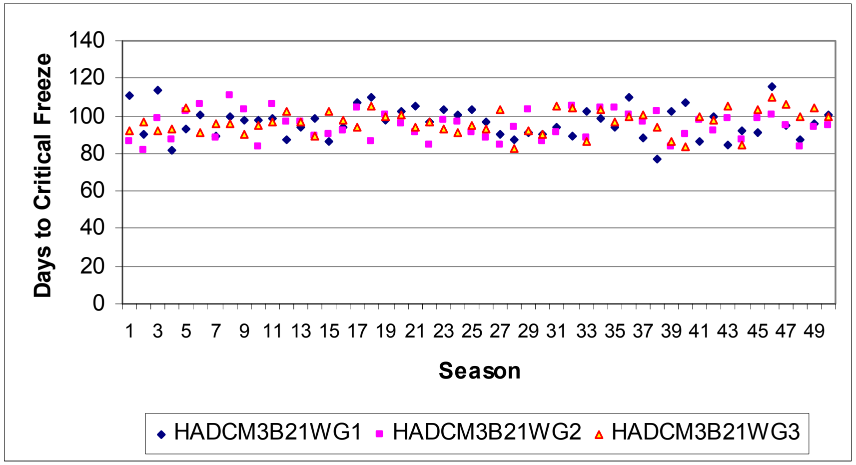


Figure B-233. Montreal estimated days to critical FI (HadCM3B21 scenario series)

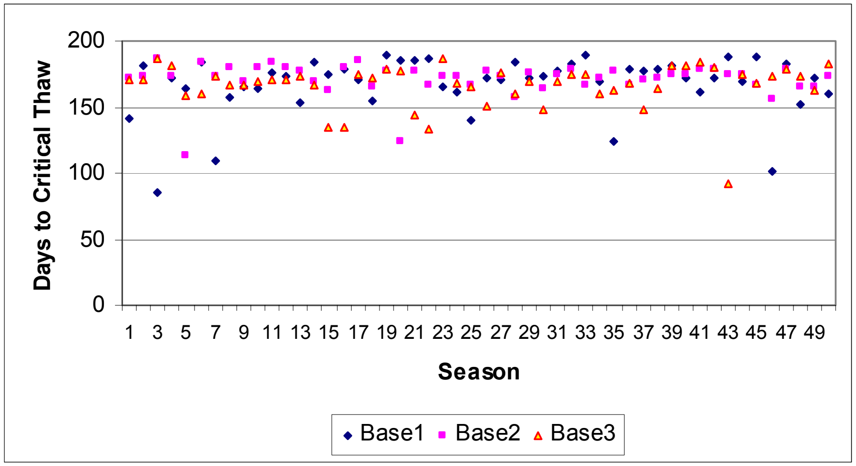


Figure B-234. Montreal estimated days to critical TI (baseline series)

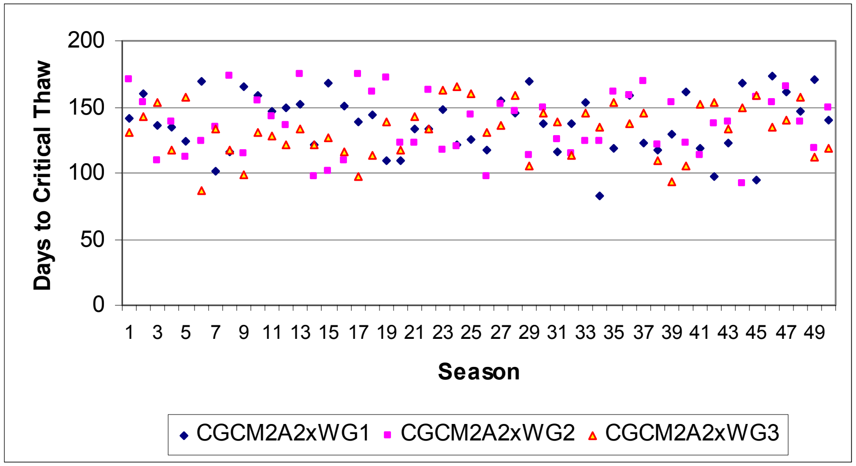


Figure B-235. Montreal estimated days to critical TI (CGCM2A2x scenario series)

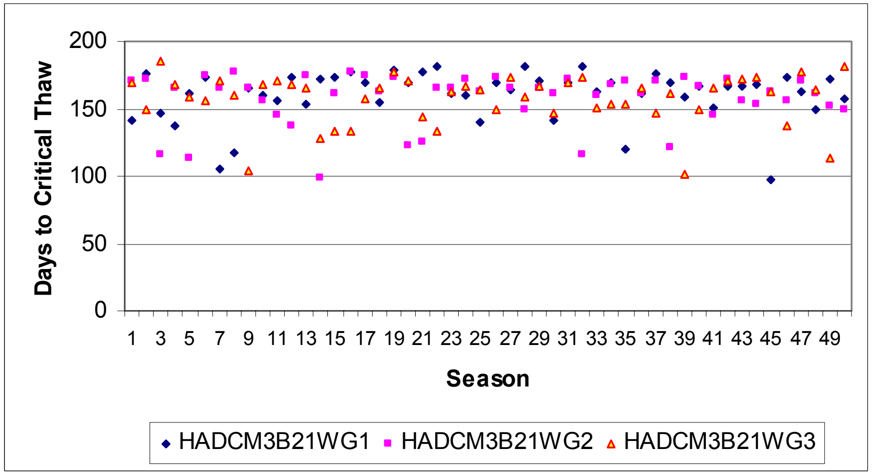


Figure B-236. Montreal estimated days to critical TI (HadCM3B21 scenario series)

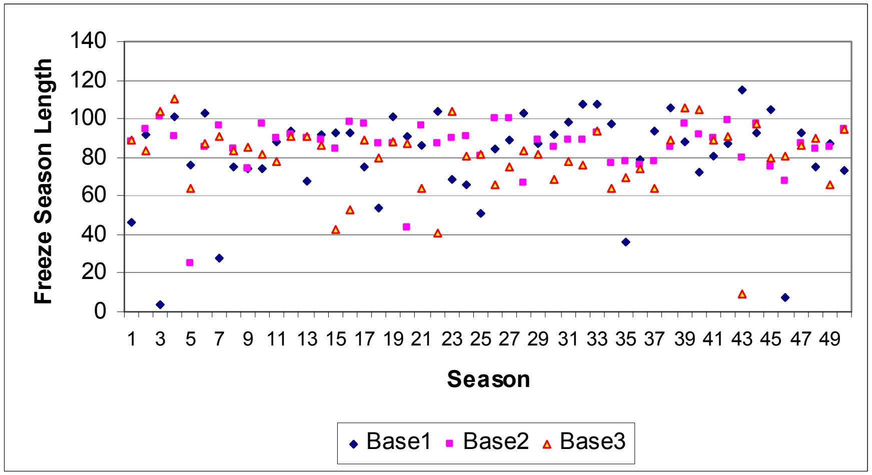


Figure B-237. Montreal estimated freeze season length (baseline series)

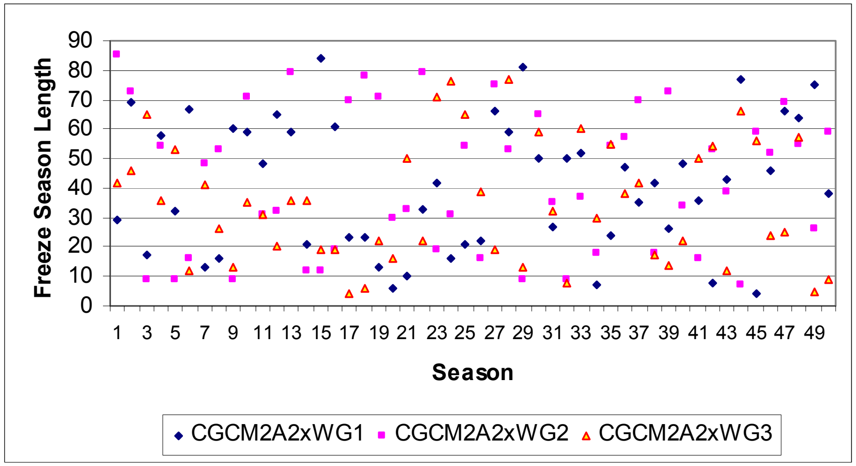


Figure B-238. Montreal estimated freeze season length (CGCM2A2x scenario series)

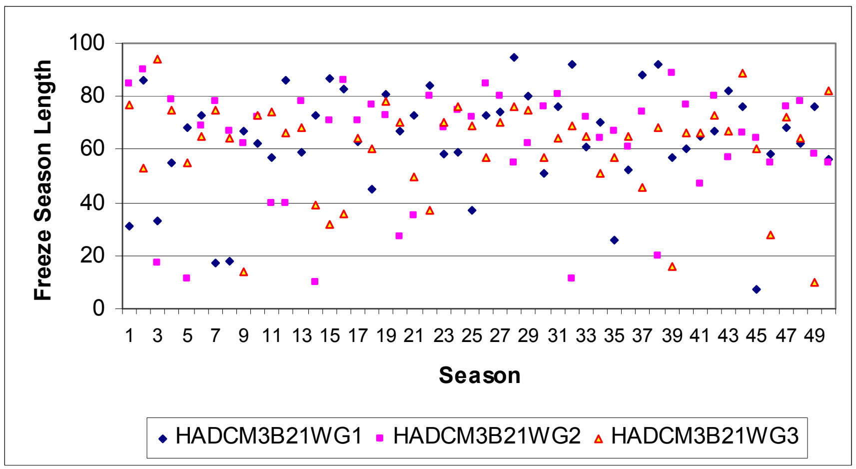


Figure B-239. Montreal estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: QUEBEC

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Quebec (7016294)	46.8	71.2	74.4	4.0	1207.7

*1971-2000 climate normals

Table B-78. Quebec minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	-0.9	2.1	1.6
Standard Deviation	11.5	10.9	11.5
Minimum	-42.8	-36.6	-40.4
Lower Quartile	-9.3	-6.1	-6.8
Median	0.7	2.9	2.9
Upper Quartile	8.5	11.4	11.0
Maximum	26.4	28.9	29.5

*n=54750

Table B-79. Quebec 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	9.1	11.3	11.4
Standard Deviation	11.7	11.9	12.2
Minimum	-23.8	-21.6	-22.0
Lower Quartile	-1.5	0.2	0.3
Median	9.5	11.7	11.8
Upper Quartile	20.0	22.7	22.9
Maximum	32.0	35.1	34.8

*n=54750

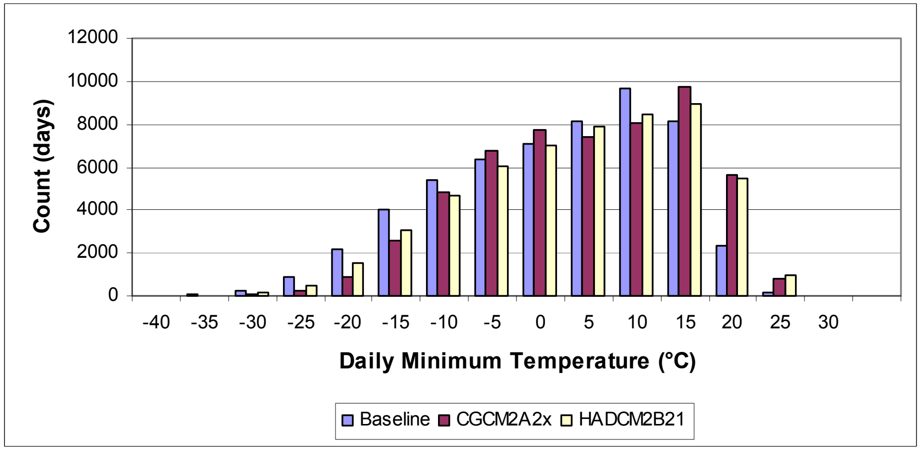


Figure B-240. Quebec minimum daily temperature distribution (n=54750)

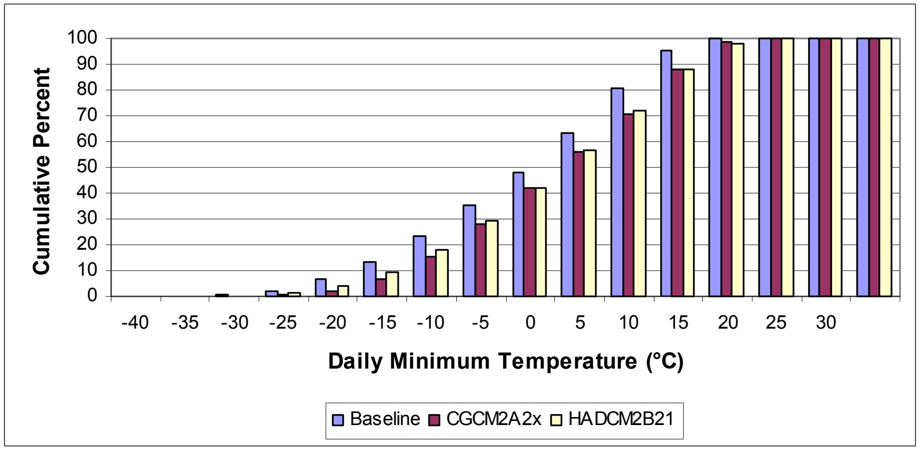


Figure B-241. Quebec minimum daily temperature cumulative percent distribution (n=54750)

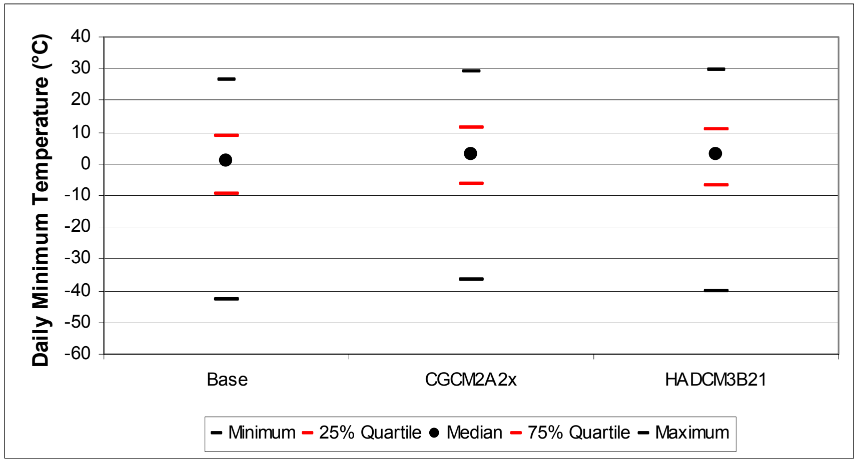


Figure B-242. Quebec minimum daily temperature distribution: quartile statistics (n=54750)

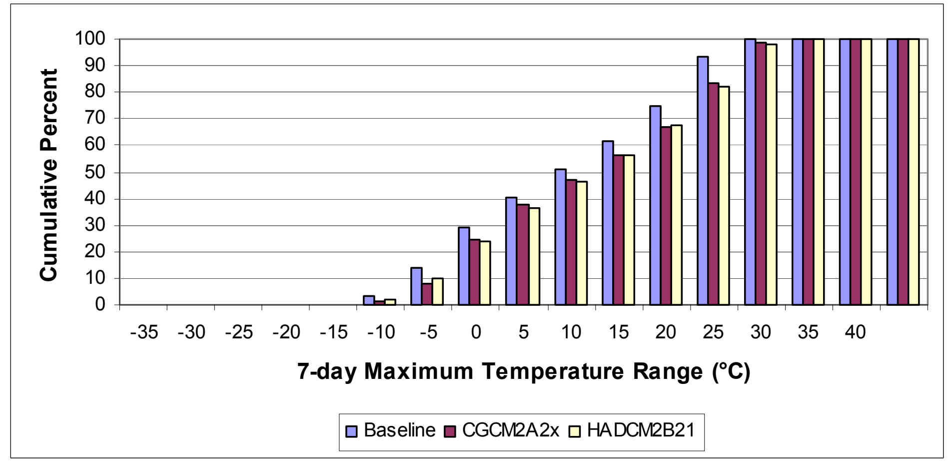


Figure B-244. Quebec 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

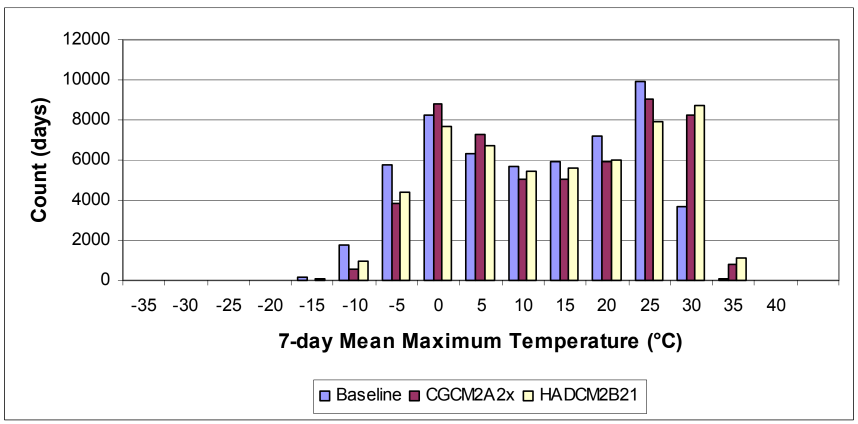


Figure B-243. Quebec 7-day mean maximum daily temperature distribution (n=54750)

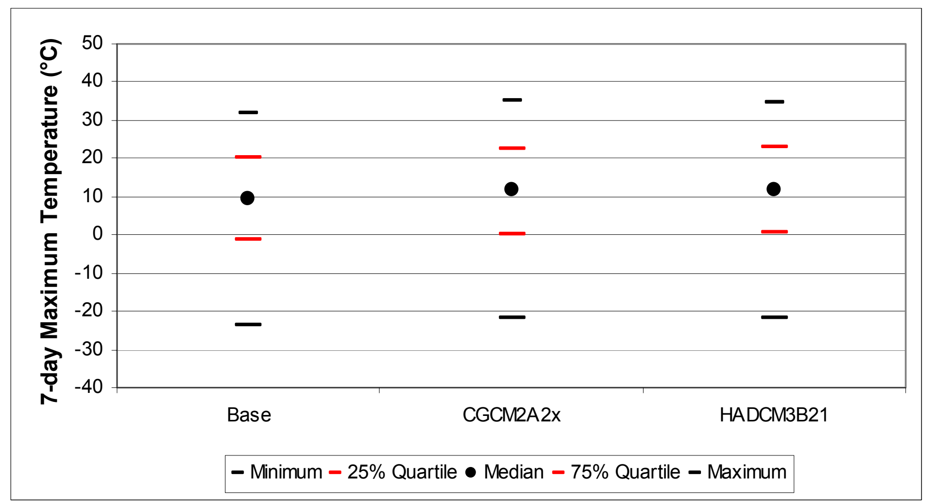


Figure B-245. Quebec 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-80. Quebec annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	-33.2	-27.5	-30.6
Standard Deviation	3.7	3.5	3.7
Minimum	-42.8	-36.6	-40.4
Lower Quartile	-35.2	-29.3	-32.8
Median	-32.6	-26.8	-30.1
Upper Quartile	-30.6	-25.6	-28.2
Maximum	-23.7	-20.3	-21.4

*n=150

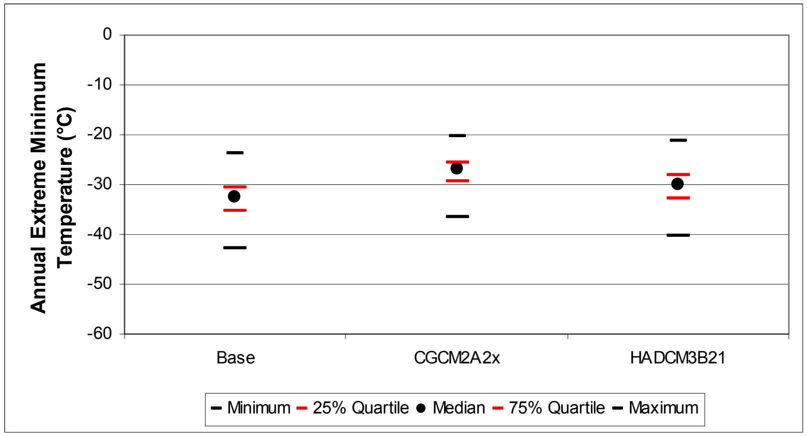


Figure B-246. Quebec annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-81. Quebec annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	Climate Change Scenario HadCM3B21*
Mean	28.5	31.1	31.5
Standard Deviation	1.3	1.4	1.3
Minimum	25.2	28.2	28.1
Lower Quartile	27.6	30.1	30.6
Median	28.5	31.1	31.5
Upper Quartile	29.3	32.0	32.4
Maximum	32.0	35.1	34.8

*n=150

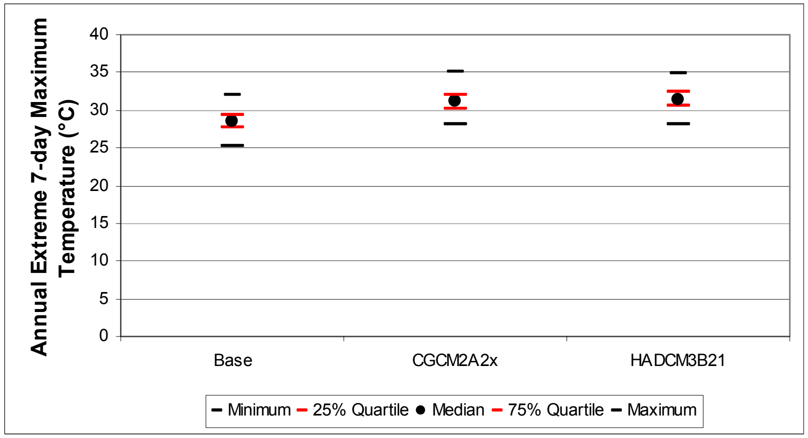


Figure B-247. Quebec annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-82. Quebec Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-32.4	-28.1	-30.6
Superpave-derived high PG threshold (°C)	52.6	54.7	54.9
98th percentile annual minimum air temperature	-41.4	-35.7	-38.9
Ontario RWIS-based low PG threshold (°C)	-32.5	-28.7	-30.9
98th percentile annual extreme 7-day mean maximum air temperature	31.4	34.1	34.2
Ontario RWIS-based high PG threshold (°C)	46.7	51.2	51.2

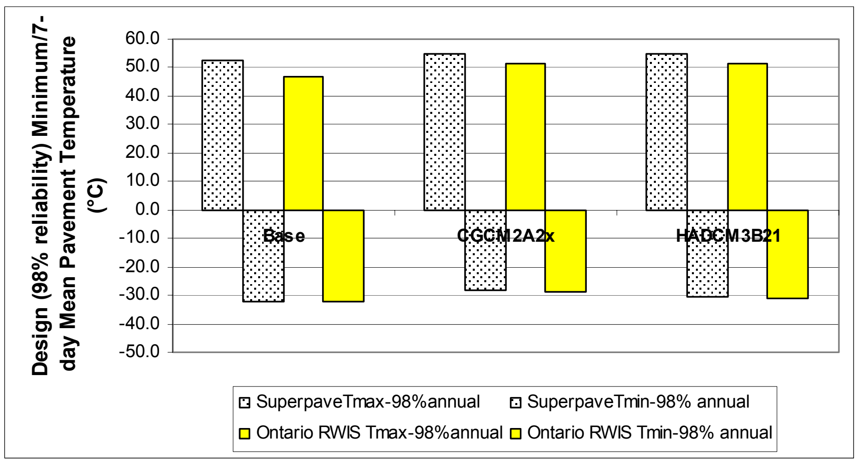


Figure B-248. Quebec estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-83. Quebec freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	107.1	75.5	82.1
Standard Deviation	13.9	28.1	20.5
Minimum	11.0	5.0	4.0
Lower Quartile	101.0	60.3	76.0
Median	110.0	84.0	86.0
Upper Quartile	115.0	95.0	94.0
Maximum	132.0	115.0	116.0

*n=150

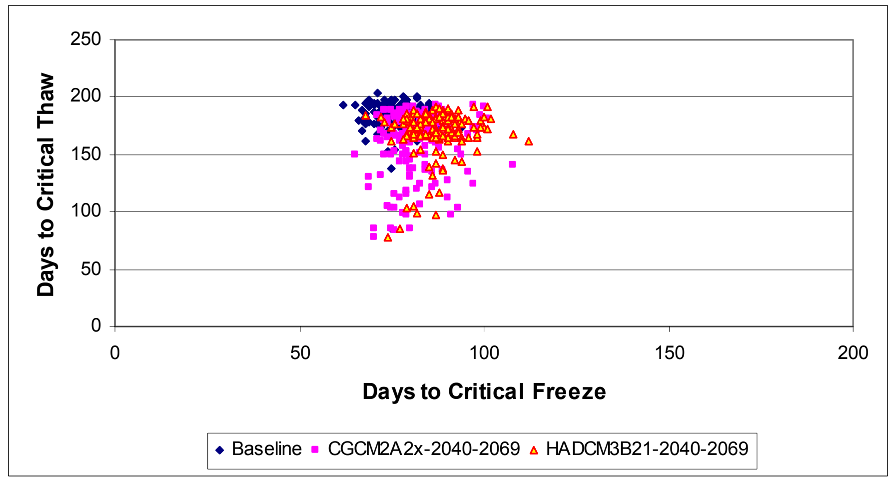


Figure B-249. Quebec estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

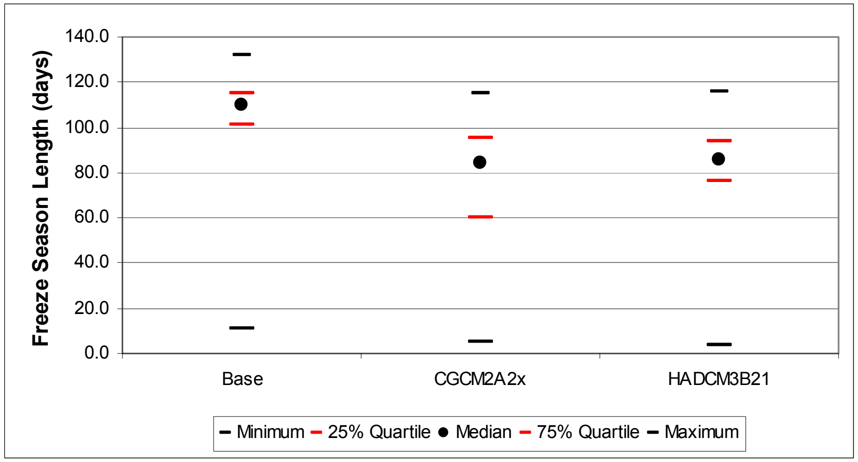


Figure B-250. Quebec estimated freeze season length distribution: quartile statistics (n=150)

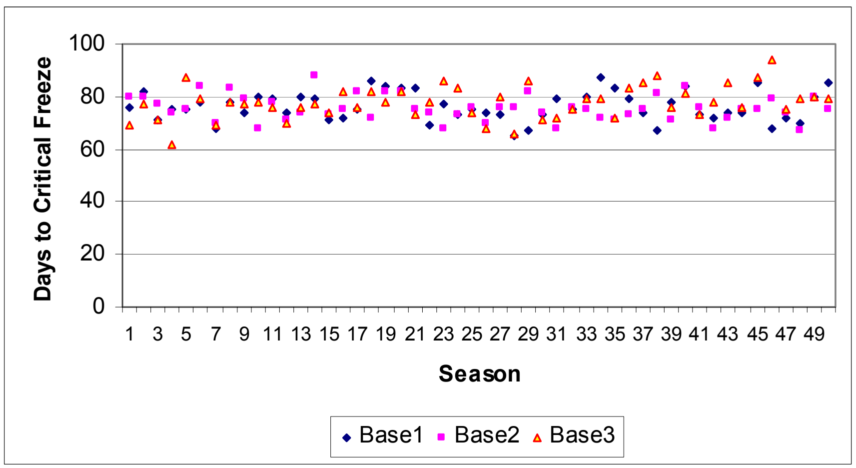


Figure B-251. Quebec estimated days to critical FI (baseline series)

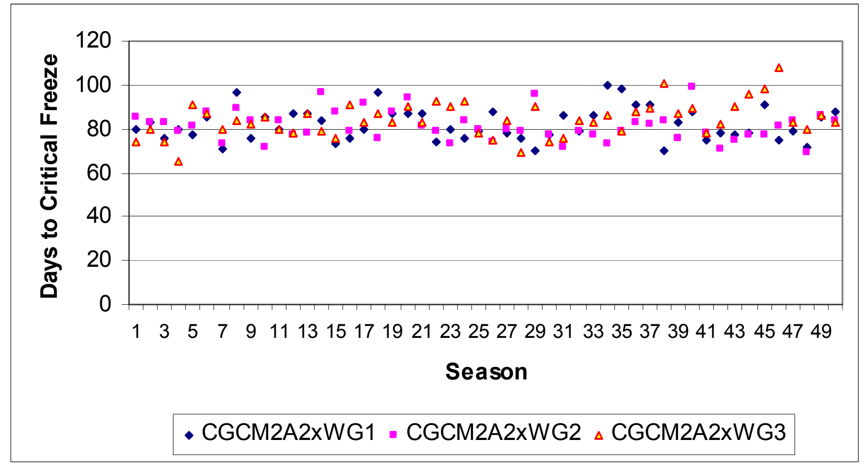


Figure B-252. Quebec estimated days to critical FI (CGCM2A2x scenario series)

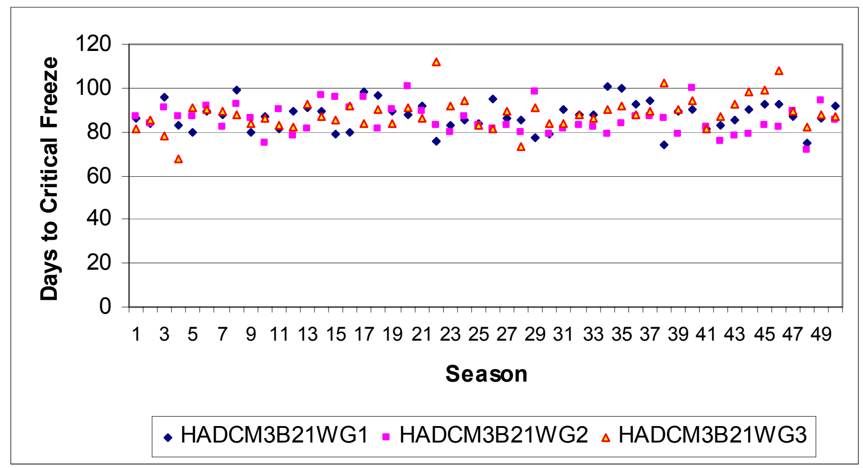


Figure B-253. Quebec estimated days to critical FI (HadCM3B21 scenario series)

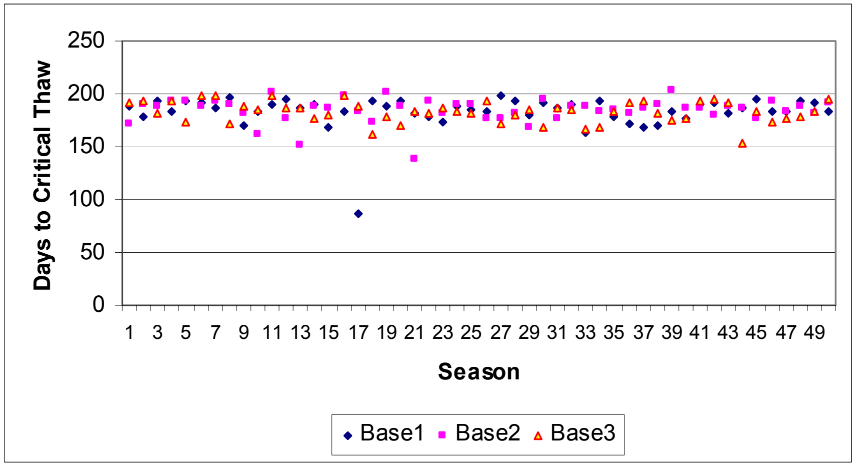


Figure B-254. Quebec estimated days to critical TI (baseline series)

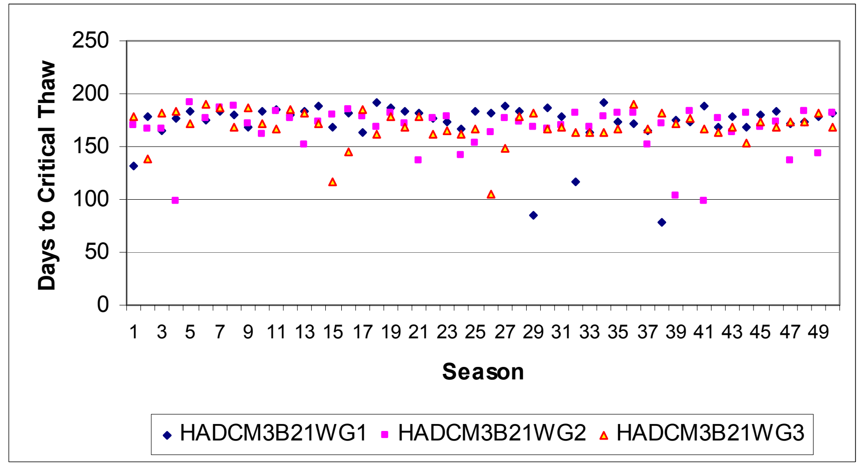


Figure B-256. Quebec estimated days to critical TI (HadCM3B21 scenario series)

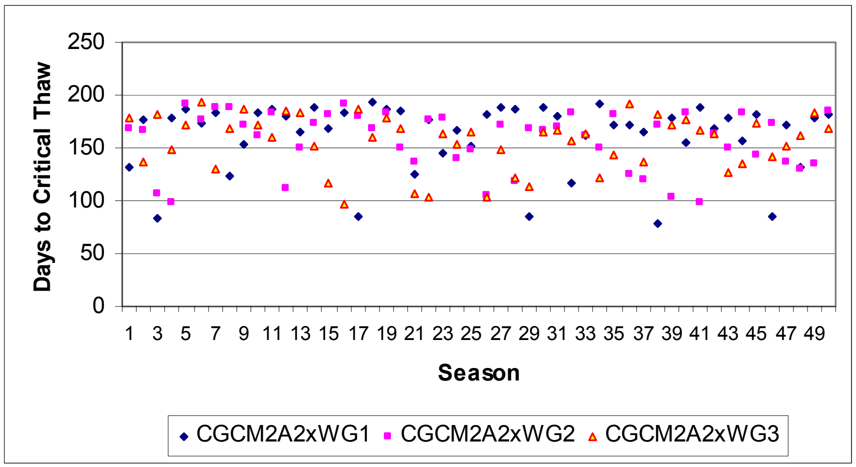


Figure B-255. Quebec estimated days to critical TI (CGCM2A2x scenario series)

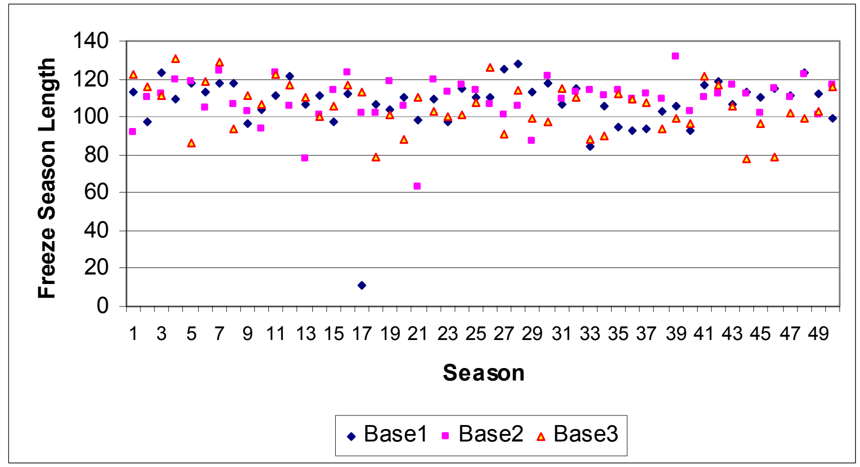


Figure B-257. Quebec estimated freeze season length (baseline series)

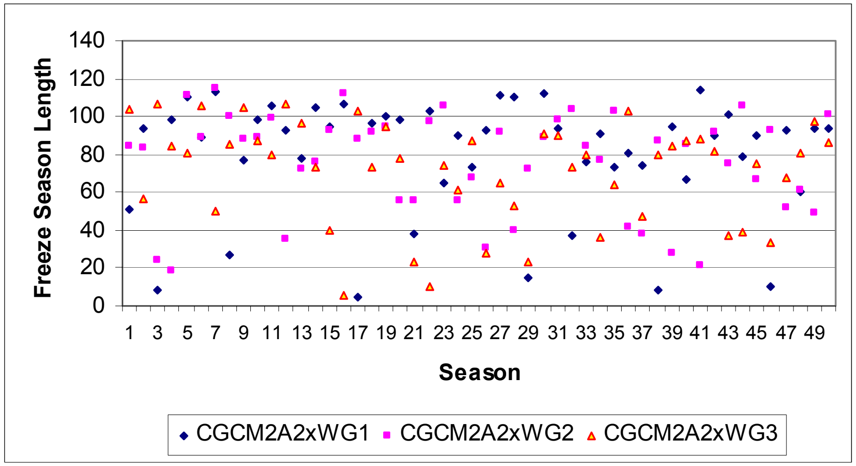


Figure B-258. Quebec estimated freeze season length (CGCM2A2x scenario series)

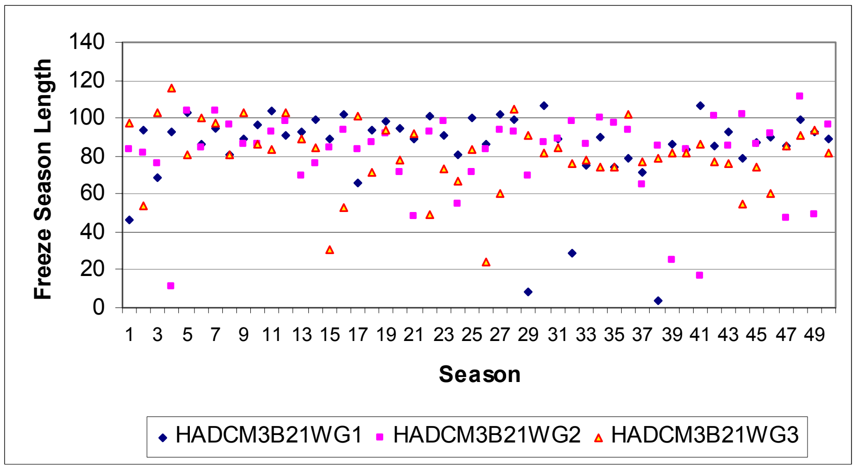


Figure B-259. Quebec estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: FREDERICTON

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Fredericton (8101500)	46.0	66.7	20.7	5.3	1143.3

*1971-2000 climate normals

Table B-84. Fredericton minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	**Baseline***	**CGCM2A2x***	**HadCM3B21***
Mean	-0.4	2.5	2.1
Standard Deviation	10.8	10.3	10.8
Minimum	-43.2	-37.0	-40.4
Lower Quartile	-7.9	-5.0	-5.4
Median	0.8	2.9	2.9
Upper Quartile	8.2	11.1	10.8
Maximum	28.9	31.3	32.1

*n=54750

Table B-85. Fredericton 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	**Baseline***	**CGCM2A2x***	**HadCM3B21***
Mean	11.1	13.2	13.3
Standard Deviation	10.7	11.1	11.2
Minimum	-15.2	-13.4	-13.4
Lower Quartile	1.6	3.1	3.4
Median	11.3	13.5	13.4
Upper Quartile	21.1	23.8	23.8
Maximum	33.3	35.7	36.4

*n=54750

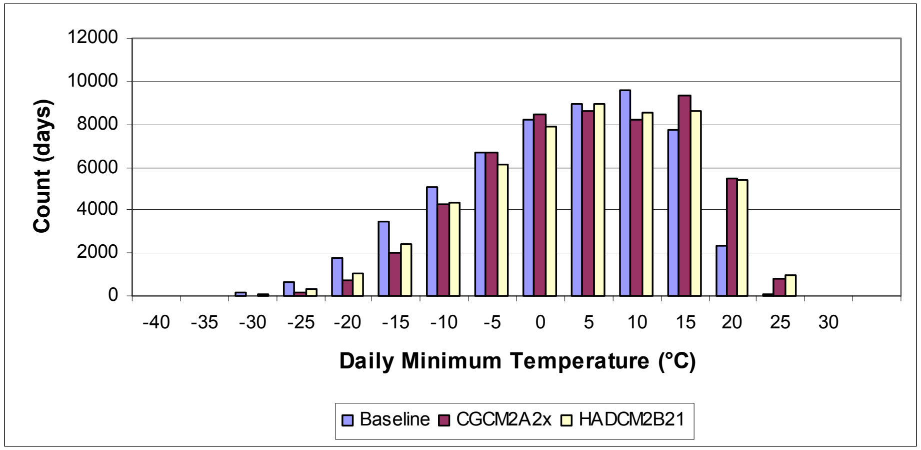


Figure B-260. Fredericton minimum daily temperature distribution (n=54750)

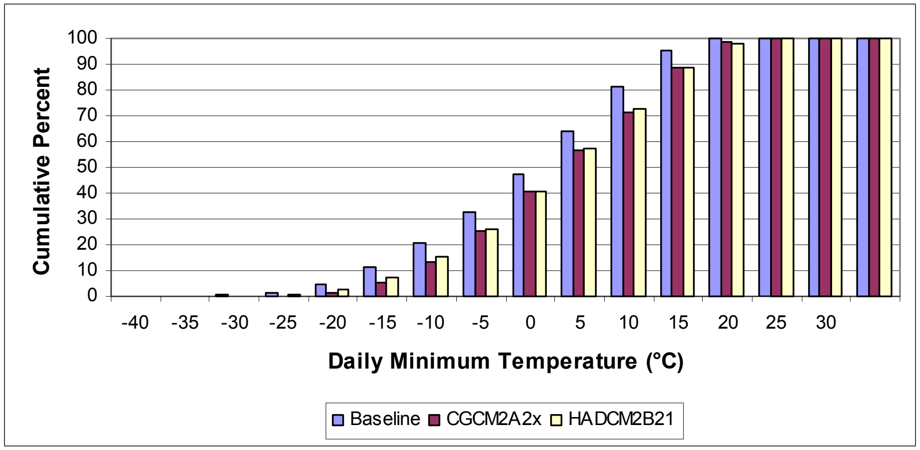


Figure B-261. Fredericton minimum daily temperature cumulative percent distribution (n=54750)

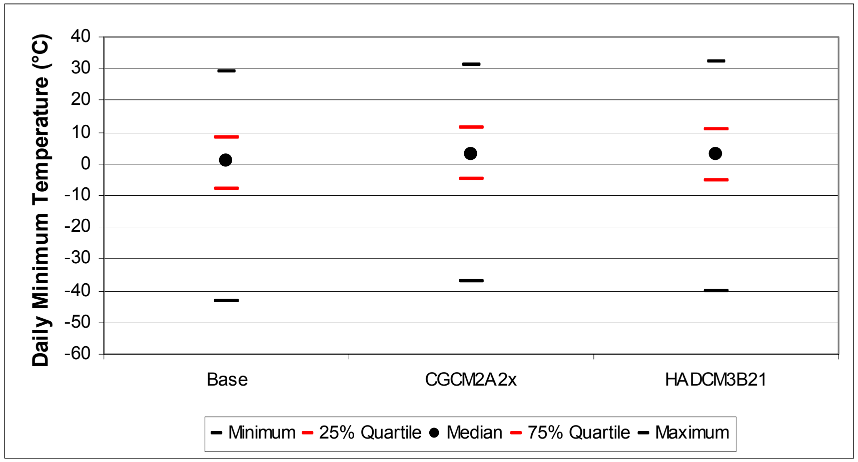


Figure B-262. Fredericton minimum daily temperature distribution: quartile statistics (n=54750)

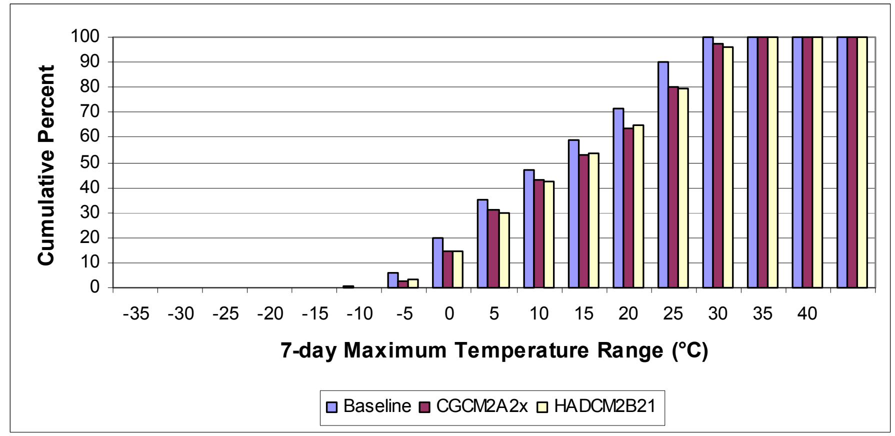


Figure B-264. Fredericton 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

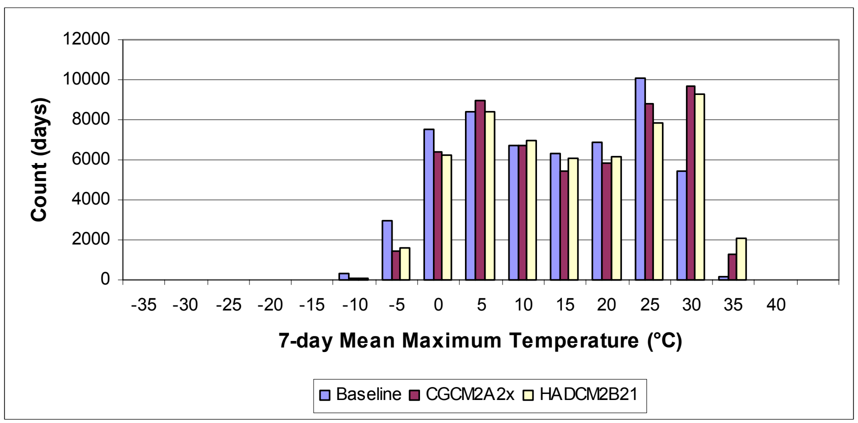


Figure B-263. Fredericton 7-day mean maximum daily temperature distribution (n=54750)

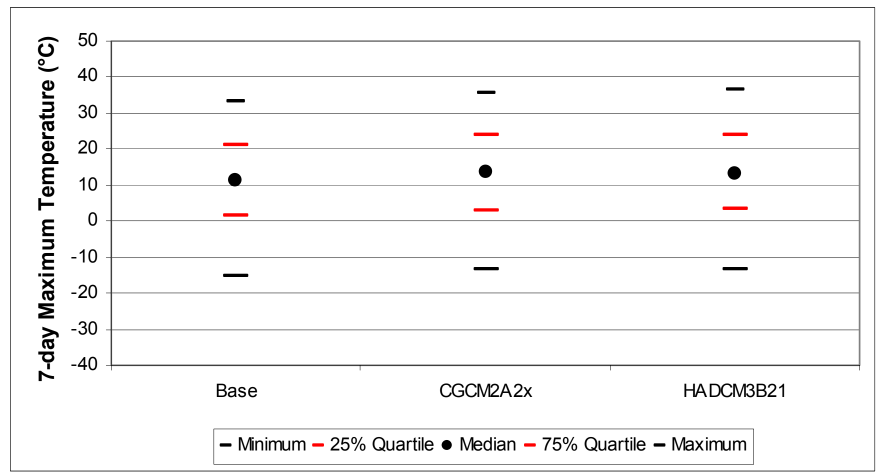


Figure B-265. Fredericton 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-86. Fredericton annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-31.6	-26.2	-28.7
Standard Deviation	3.5	3.4	3.5
Minimum	-43.2	-37.0	-40.4
Lower Quartile	-34.0	-28.3	-31.1
Median	-31.5	-25.8	-28.8
Upper Quartile	-29.2	-23.9	-26.4
Maximum	-22.1	-18.9	-19.3

*n=150

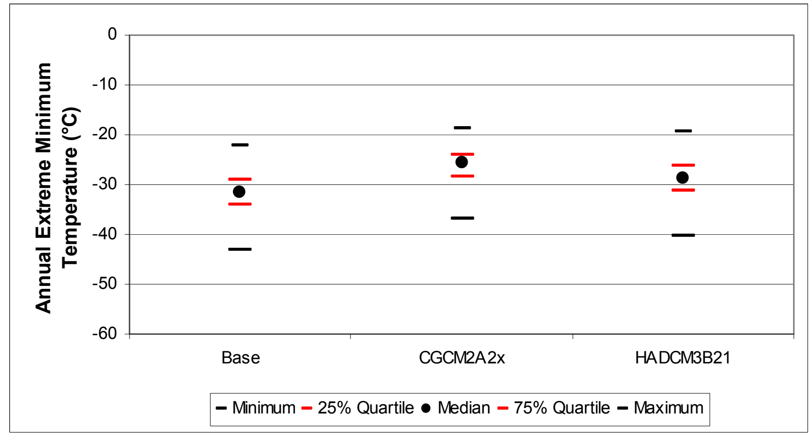


Figure B-266. Fredericton annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-87. Fredericton annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	29.4	31.9	32.5
Standard Deviation	1.4	1.4	1.4
Minimum	26.0	28.2	29.1
Lower Quartile	28.5	30.9	31.5
Median	29.2	31.6	32.2
Upper Quartile	30.3	32.8	33.3
Maximum	33.3	35.7	36.4

*n=150

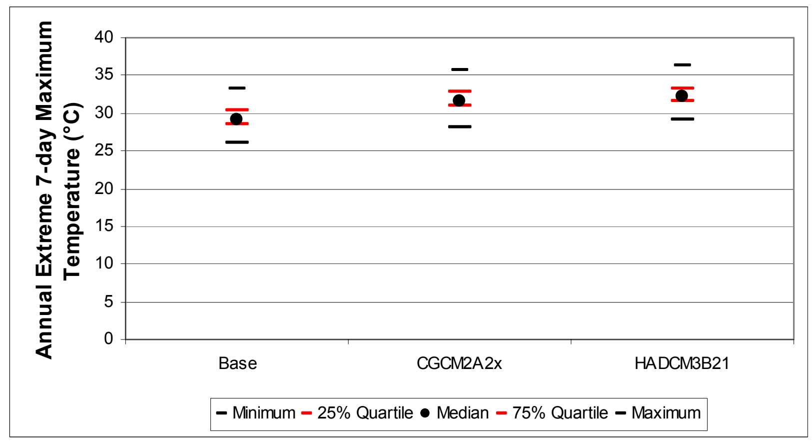


Figure B-267. Fredericton annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-88. Fredericton Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-30.7	-26.7	-28.7
Superpave-derived high PG threshold (°C)	53.5	55.4	55.9
98th percentile annual minimum air temperature	-39.2	-35.0	-36.4
Ontario RWIS-based low PG threshold (°C)	-31.1	-28.3	-29.2
98th percentile annual extreme 7-day mean maximum air temperature	32.8	35.3	35.8
Ontario RWIS-based high PG threshold (°C)	48.9	53.1	54.0

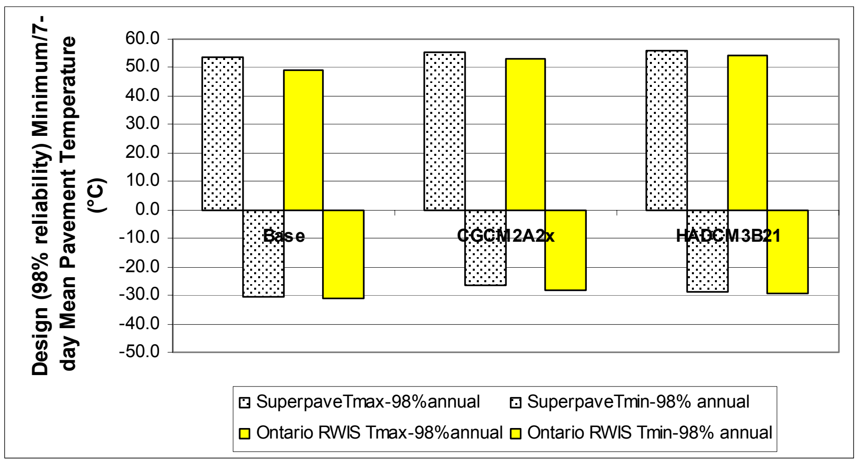


Figure B-268. Fredericton estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-89. Fredericton freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	85.0	47.7	57.6
Standard Deviation	18.4	23.9	20.9
Minimum	7.0	5.0	7.0
Lower Quartile	78.0	27.5	46.3
Median	86.5	47.5	63.0
Upper Quartile	96.8	68.0	71.8
Maximum	118.0	104.0	102.0

*n=150

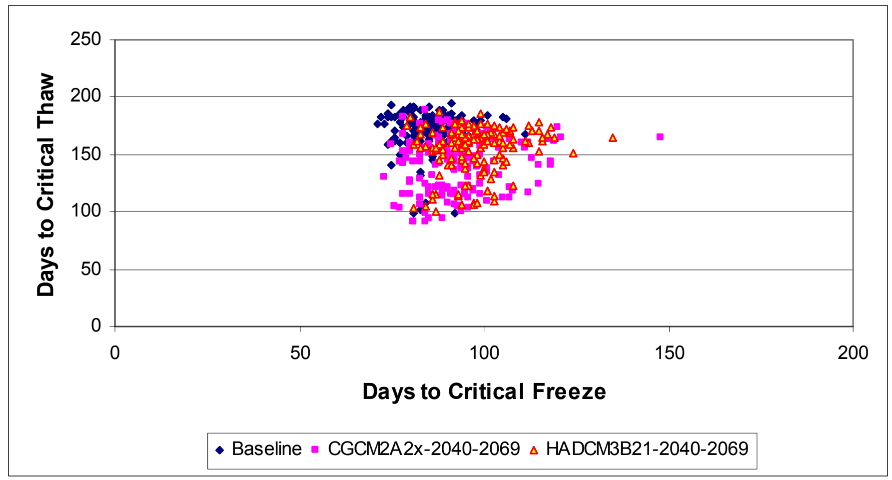


Figure B-269. Fredericton estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

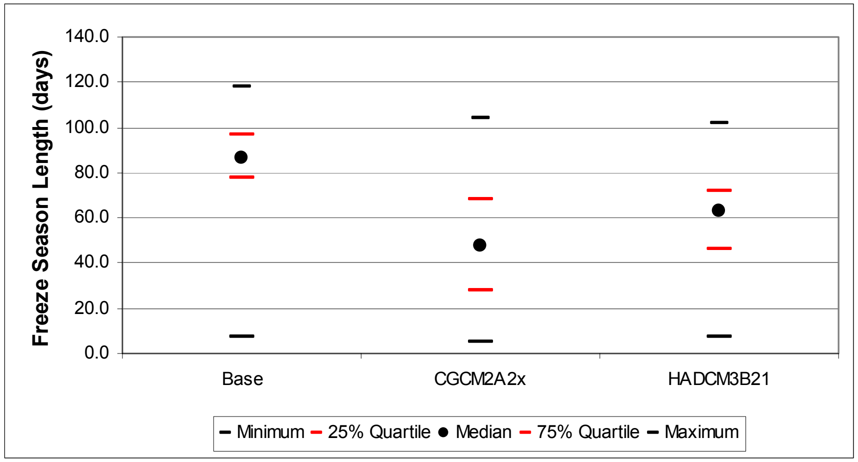


Figure B-270. Fredericton estimated freeze season length distribution: quartile statistics (n=150)

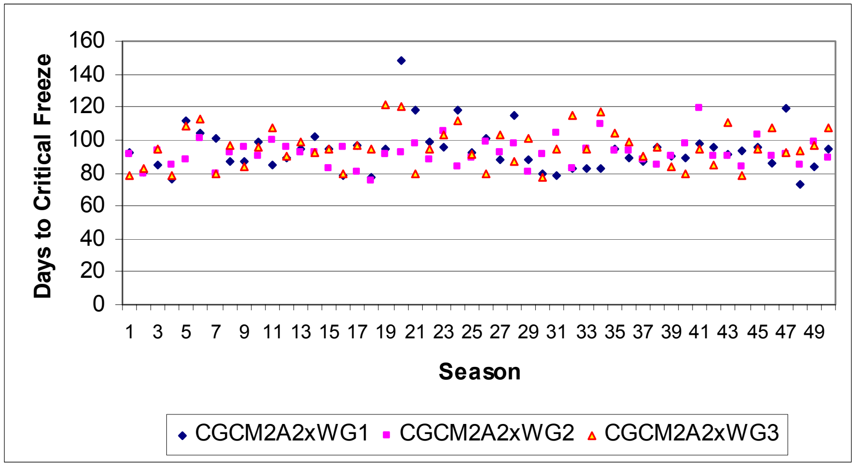


Figure B-272. Fredericton estimated days to critical FI (CGCM2A2x scenario series)

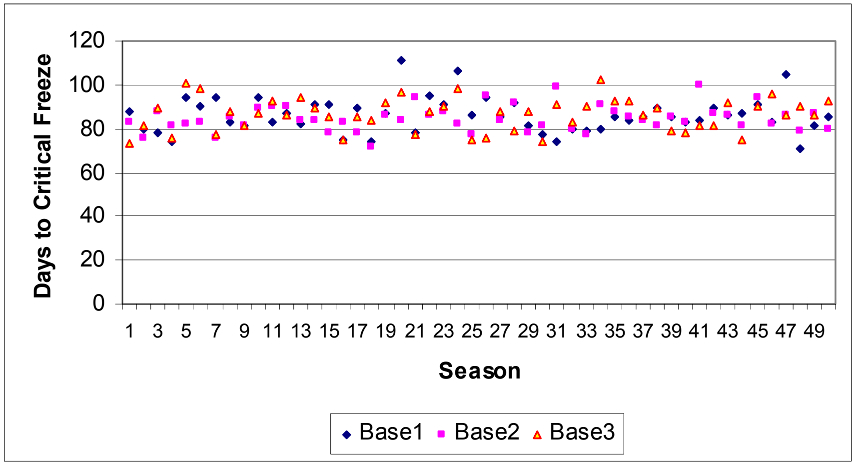


Figure B-271. Fredericton estimated days to critical FI (baseline series)

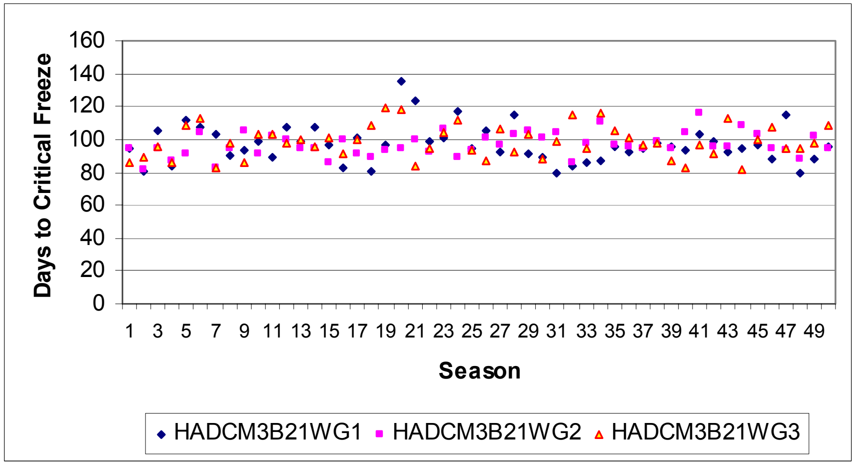


Figure B-273. Fredericton estimated days to critical FI (HadCM3B21 scenario series)

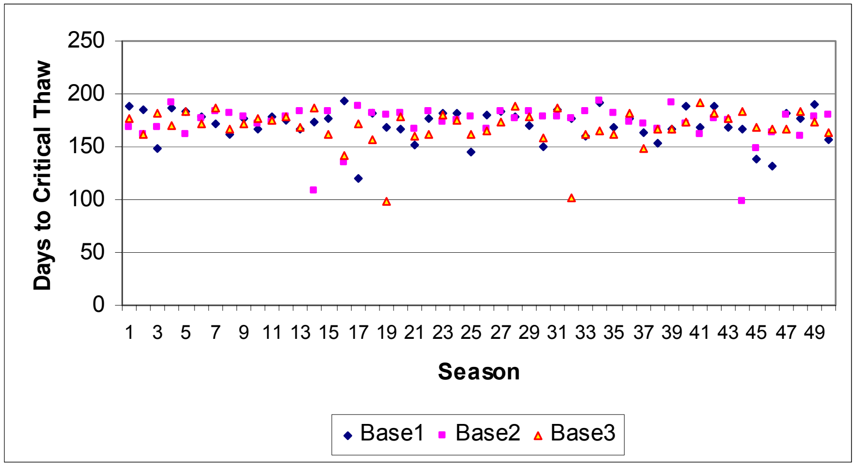


Figure B-274. Fredericton estimated days to critical TI (baseline series)

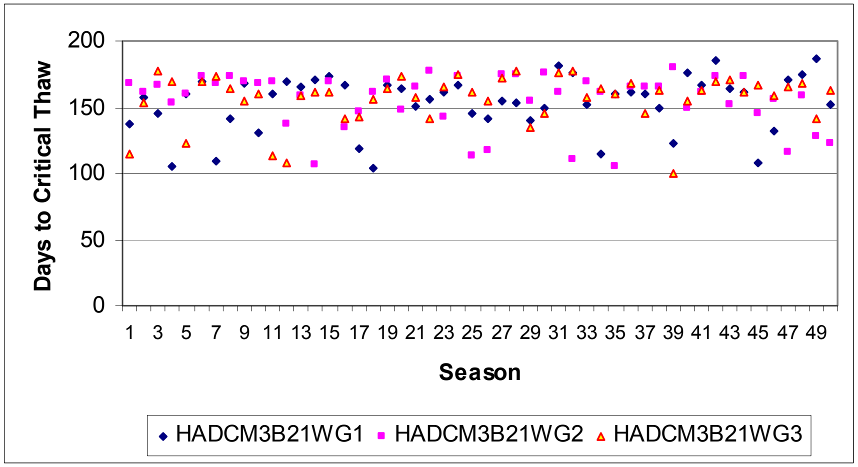


Figure B-276. Fredericton estimated days to critical TI (HadCM3B21 scenario series)

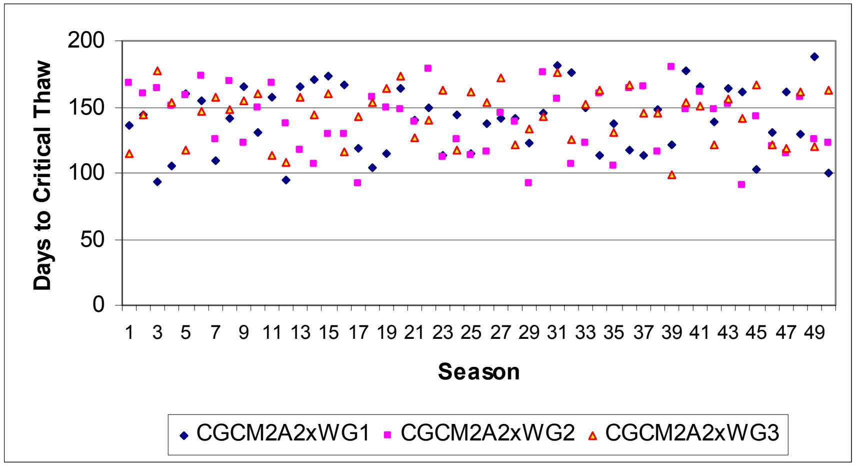


Figure B-275. Fredericton estimated days to critical TI (CGCM2A2x scenario series)

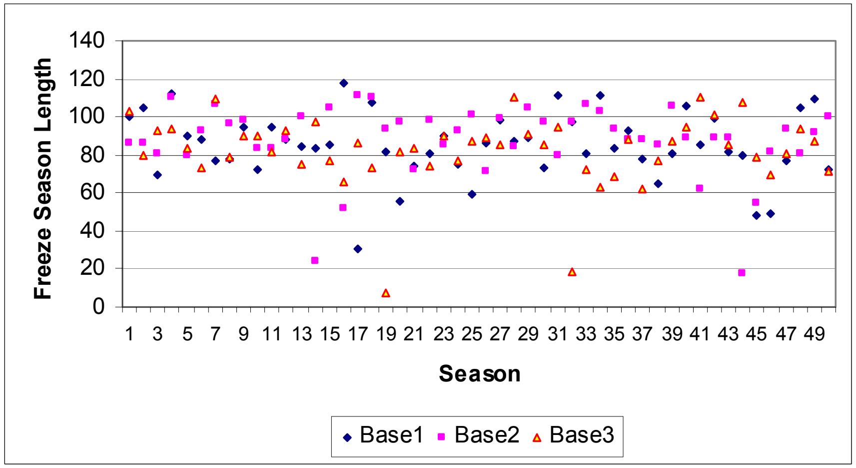


Figure B-277. Fredericton estimated freeze season length (baseline series)

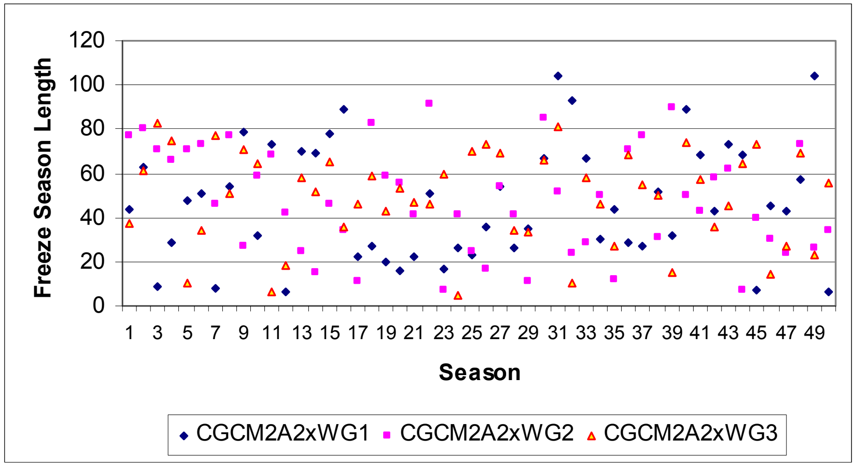


Figure B-278. Fredericton estimated freeze season length (CGCM2A2x scenario series)

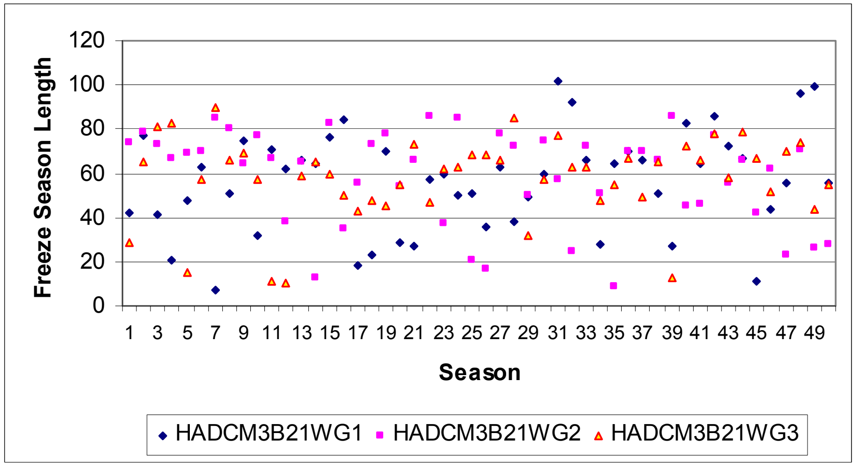


Figure B-279. Fredericton estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: HALIFAX

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
Halifax (8202250)	44.6	63.6	145.4	6.3	1452.2

*1971-2000 climate normals

Table B-90. Halifax minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	1.5	4.3	4.1
Standard Deviation	9.2	8.9	9.3
Minimum	-31.8	-27.5	-28.9
Lower Quartile	-5.1	-2.3	-2.6
Median	2.2	4.3	4.3
Upper Quartile	9.2	11.9	11.7
Maximum	22.6	25.3	26.0

*n=54750

Table B-91. Halifax 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	10.9	13.1	13.1
Standard Deviation	9.2	9.4	9.6
Minimum	-15.7	-13.1	-13.6
Lower Quartile	2.8	4.8	4.7
Median	10.9	13.3	13.1
Upper Quartile	19.3	21.7	21.9
Maximum	30.5	32.7	33.5

*n=54750

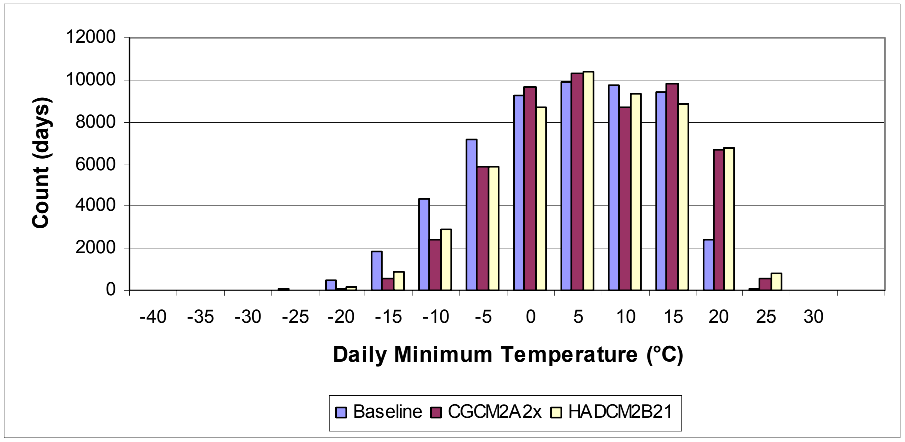


Figure B-280. Halifax minimum daily temperature distribution (n=54750)

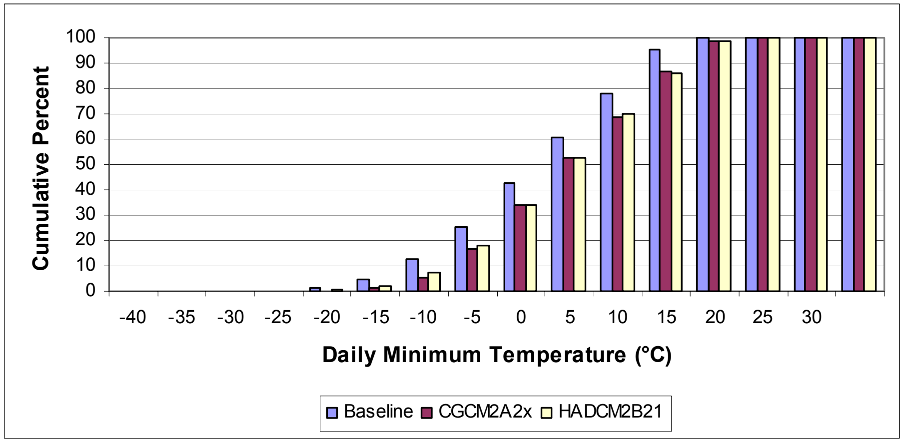


Figure B-281. Halifax minimum daily temperature cumulative percent distribution (n=54750)

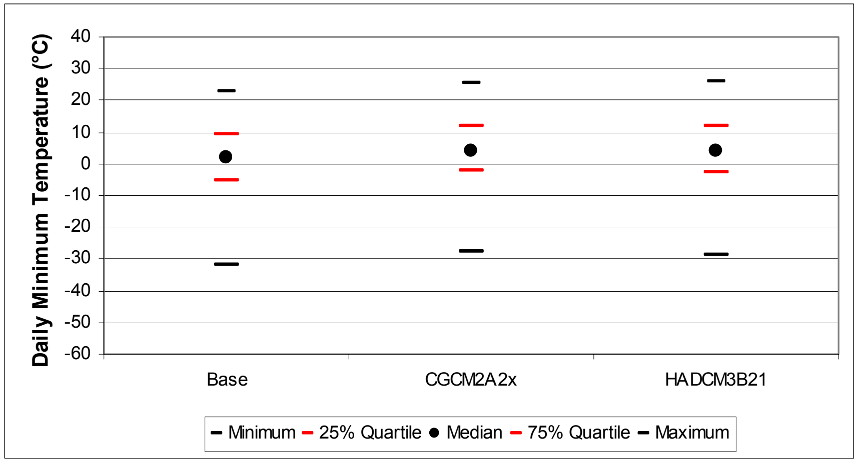


Figure B-282. Halifax minimum daily temperature distribution: quartile statistics (n=54750)

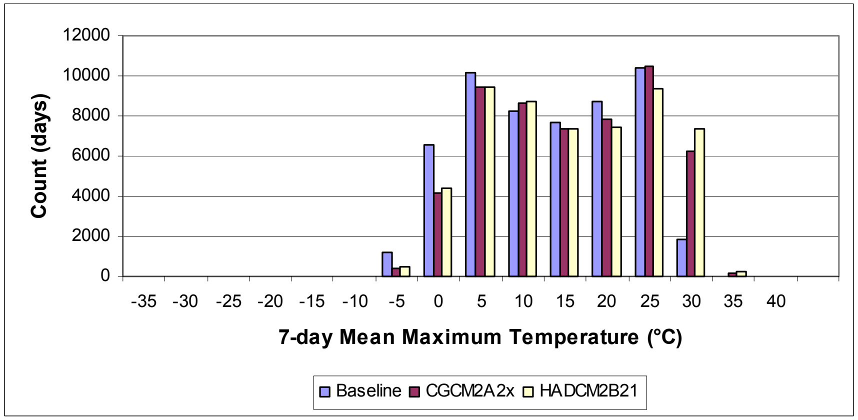


Figure B-283. Halifax 7-day mean maximum daily temperature distribution (n=54750)

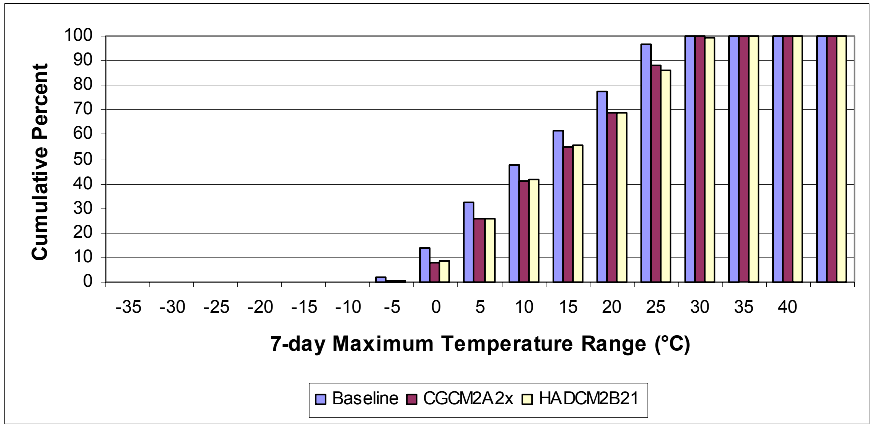


Figure B-284. Halifax 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

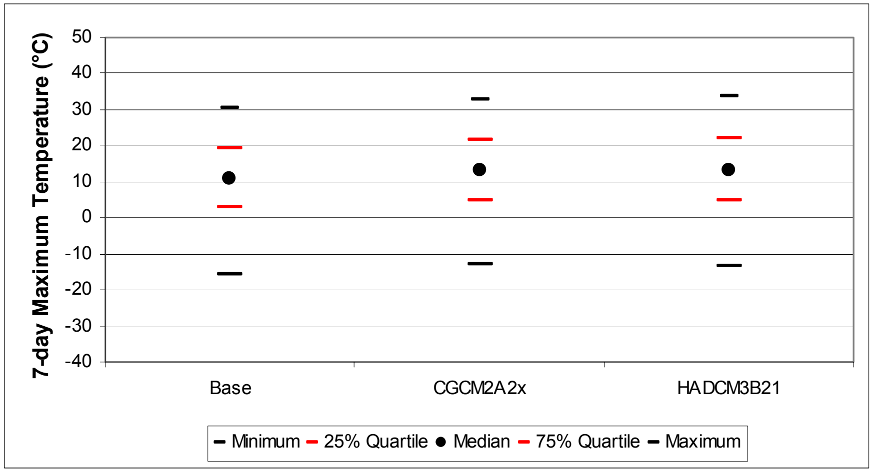


Figure B-285. Halifax 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-92. Halifax annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-23.9	-19.5	-21.1
Standard Deviation	3.3	2.9	3.2
Minimum	-31.8	-27.5	-28.9
Lower Quartile	-26.1	-21.5	-23.2
Median	-23.8	-19.5	-21.0
Upper Quartile	-21.2	-17.2	-18.3
Maximum	-17.2	-13.7	-14.6

*n=150

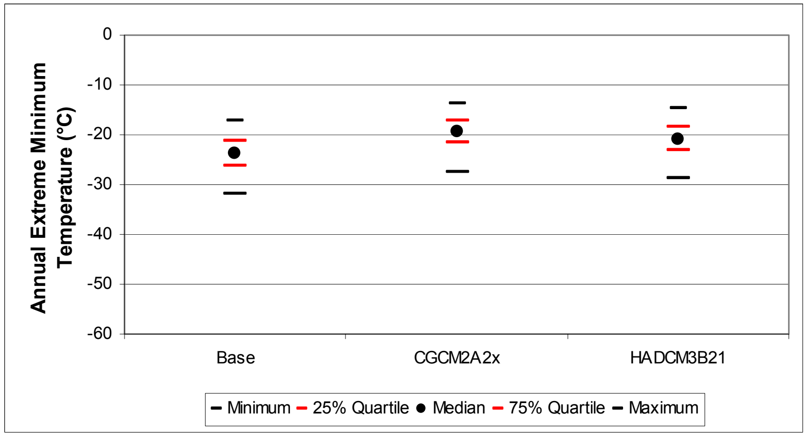


Figure B-286. Halifax annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-93. Halifax annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	27.0	29.3	30.0
Standard Deviation	1.1	1.1	1.1
Minimum	24.4	26.7	27.6
Lower Quartile	26.2	28.6	29.3
Median	26.8	29.2	29.9
Upper Quartile	27.7	30.0	30.7
Maximum	30.5	32.7	33.5

*n=150

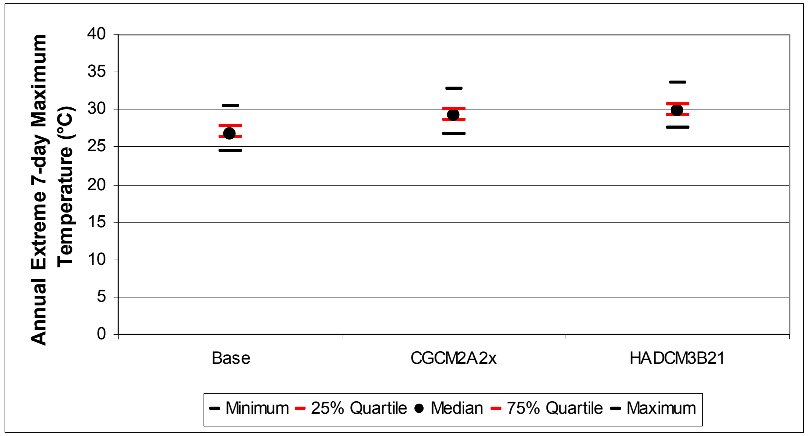


Figure B-287. Halifax annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-94. Halifax Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-24.5	-20.9	-22.4
Superpave-derived high PG threshold (°C)	51.8	53.6	54.2
98th percentile annual minimum air temperature	-30.1	-25.3	-27.212
Ontario RWIS-based low PG threshold (°C)	-24.8	-21.1	-22.6
98th percentile annual extreme 7-day mean maximum air temperature	29.6	31.8	32.7
Ontario RWIS-based high PG threshold (°C)	43.9	47.4	48.8

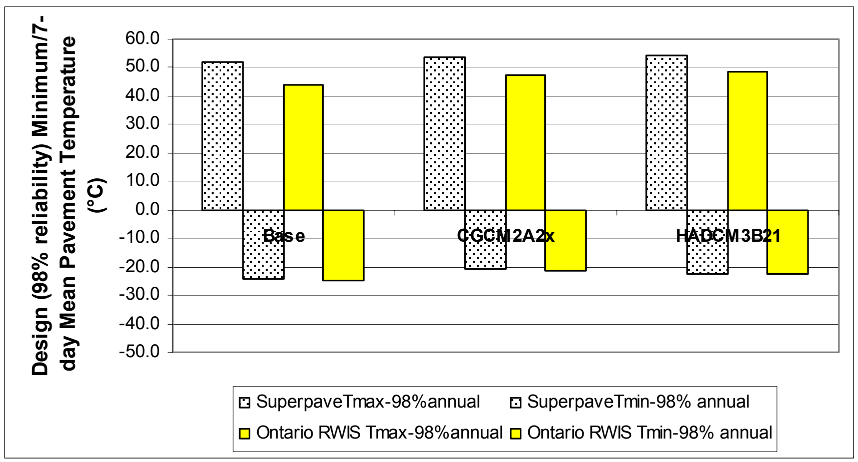


Figure B-288. Halifax estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-95. Halifax freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	56.5	14.6	25.2
Standard Deviation	22.5	16.0	19.1
Minimum	5.0	0.0	0.0
Lower Quartile	45.0	0.0	9.0
Median	59.0	8.0	21.5
Upper Quartile	73.0	26.0	40.0
Maximum	105.0	73.0	74.0

*n=150

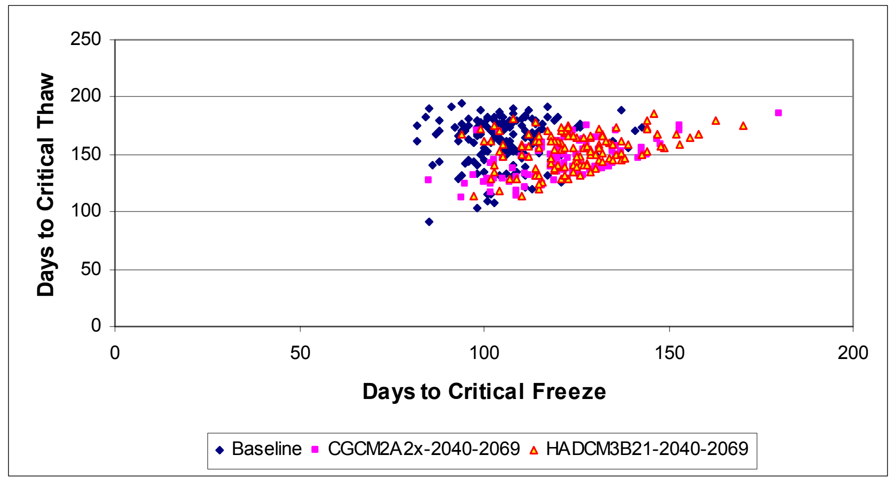


Figure B-289. Halifax estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

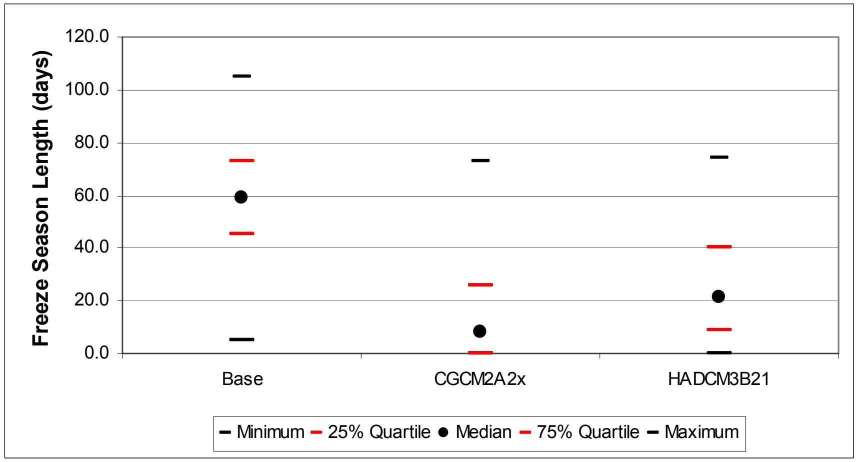


Figure B-290. Halifax estimated freeze season length distribution: quartile statistics (n=150)

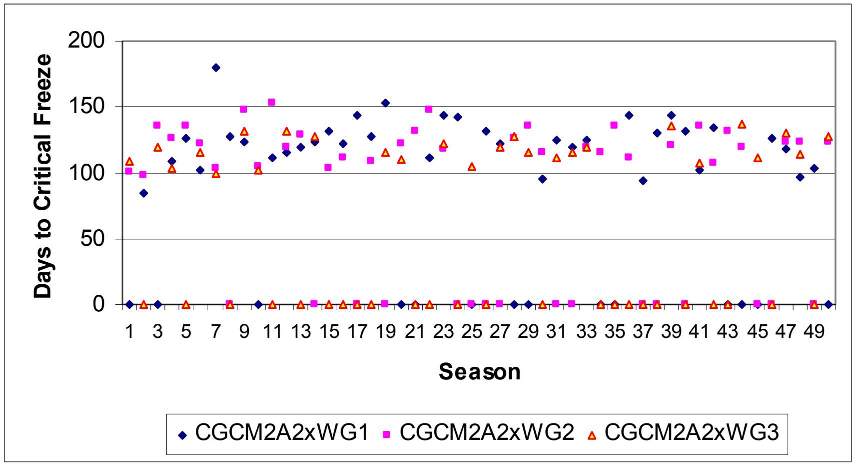


Figure B-292. Halifax estimated days to critical FI (CGCM2A2x scenario series)

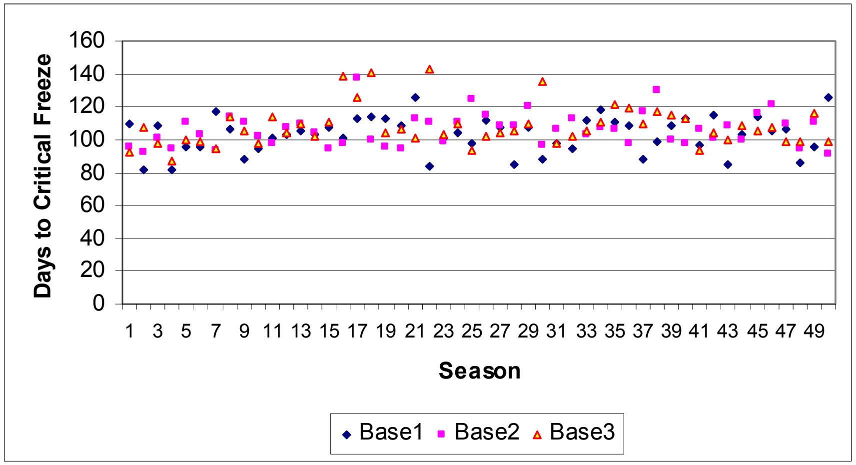


Figure B-291. Halifax estimated days to critical FI (baseline series)

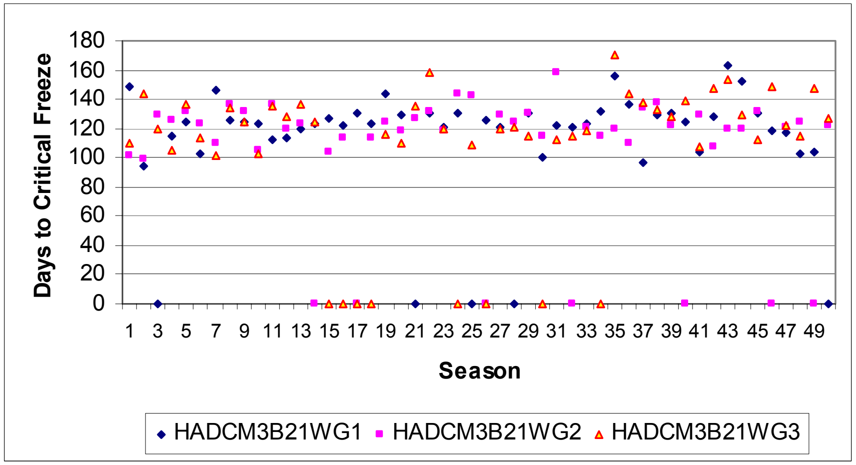


Figure B-293. Halifax estimated days to critical FI (HadCM3B21 scenario series)

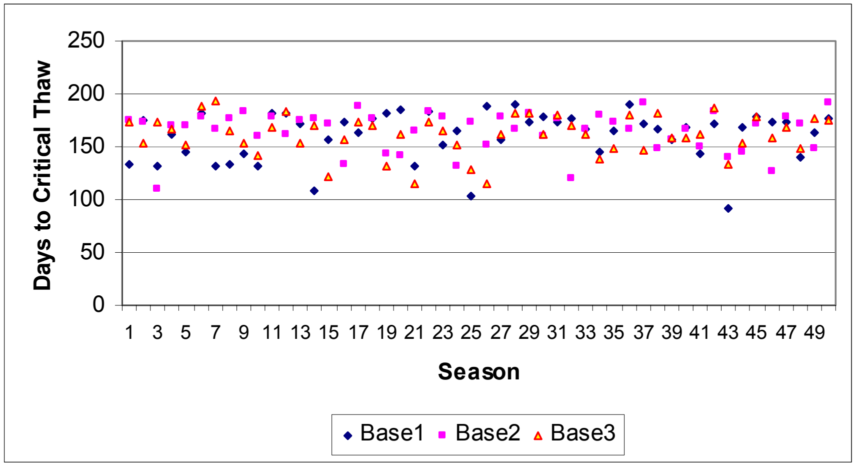


Figure B-294. Halifax estimated days to critical TI (baseline series)

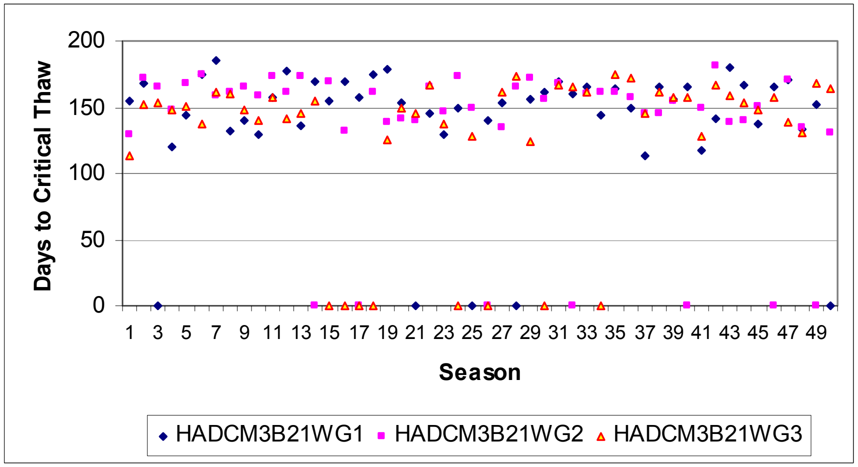


Figure B-296. Halifax estimated days to critical TI (HadCM3B21 scenario series)

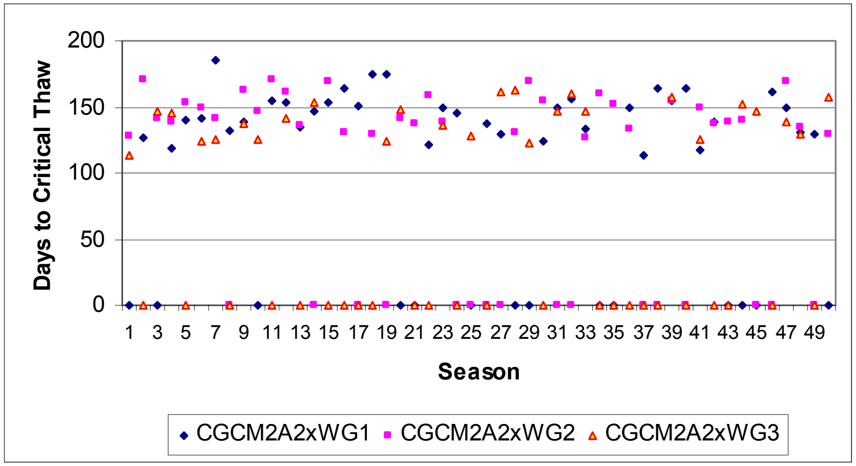


Figure B-295. Halifax estimated days to critical TI (CGCM2A2x scenario series)

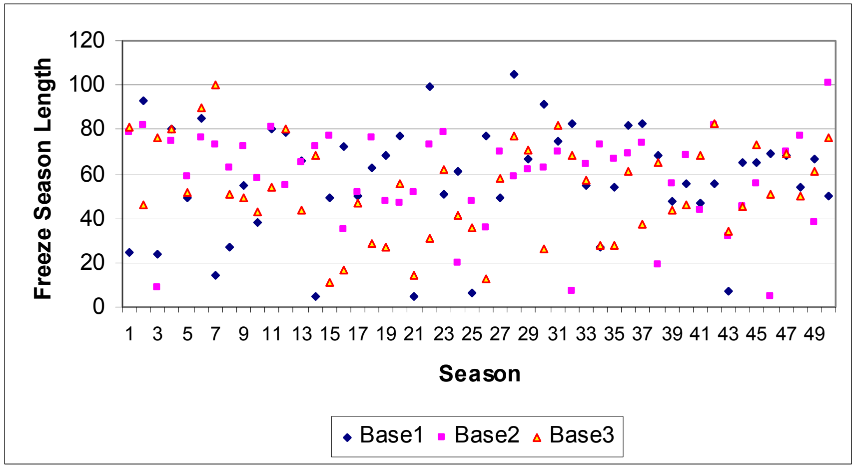


Figure B-297. Halifax estimated freeze season length (baseline series)

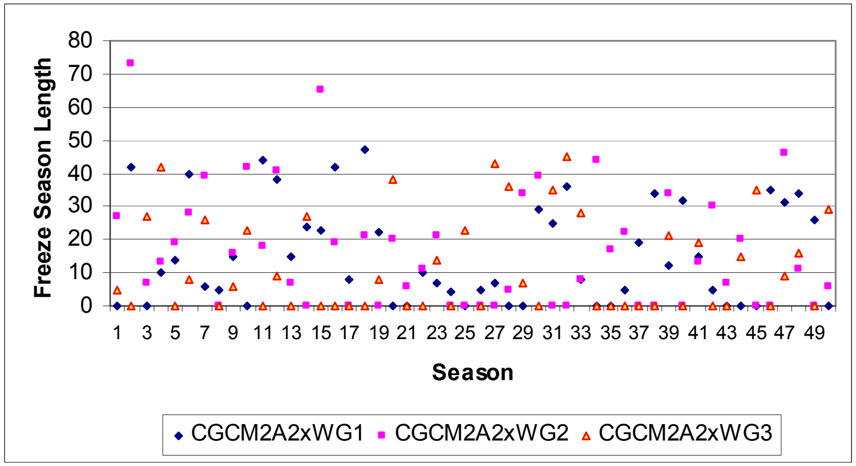


Figure B-298. Halifax estimated freeze season length (CGCM2A2x scenario series)

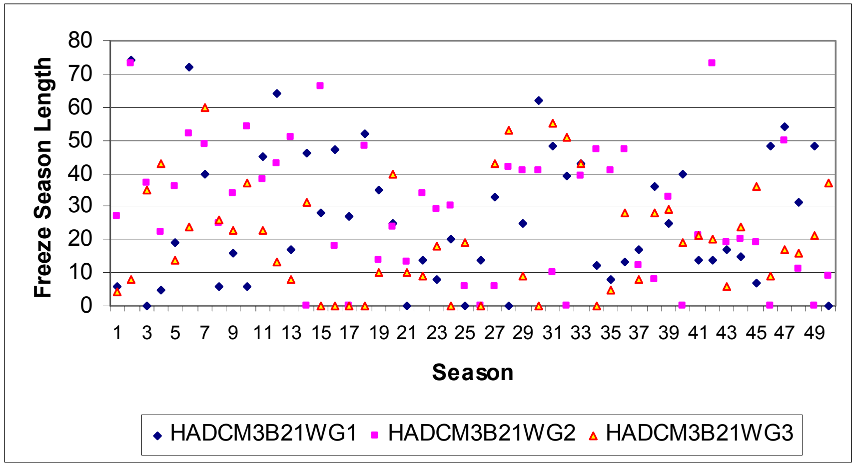


Figure B-299. Halifax estimated freeze season length (HadCM3B21 scenario series)

CASE STUDY SITE: ST. JOHN'S

City (MSC Observing Station reference)	Lat	Long	Elevation (m)	Mean Annual Temperature* (°C)	Mean Total Precipitation* (mm)
St. John's (8403506)	47.6	52.7	140.5	4.7	1513.7

*1971-2000 climate normals

Table B-96. St. John's minimum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	0.8	4.0	2.9
Standard Deviation	7.6	7.0	7.8
Minimum	-27.7	-20.9	-25.6
Lower Quartile	-4.6	-1.2	-2.7
Median	0.9	3.5	2.6
Upper Quartile	6.9	9.6	9.1
Maximum	21.8	24.6	24.9

*n=54750

Table B-97. St. John's 7-day mean maximum daily air temperature

		Climate Change Scenario	
STATISTIC (°C)	Baseline*	CGCM2A2x*	HadCM3B21*
Mean	8.7	11.0	10.6
Standard Deviation	7.8	8.0	8.5
Minimum	-11.2	-8.4	-10.1
Lower Quartile	2.0	4.0	3.4
Median	8.0	10.1	9.7
Upper Quartile	15.7	18.3	18.1
Maximum	30.3	32.7	33.4

*n=54750

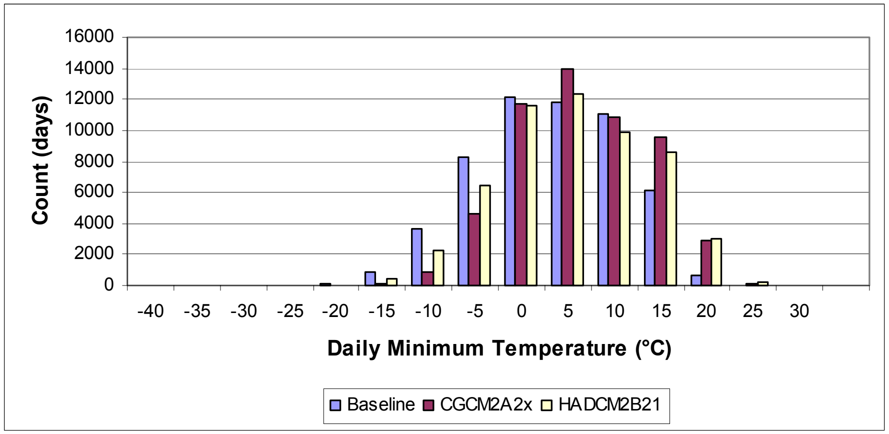


Figure B-300. St. John's minimum daily temperature distribution (n=54750)

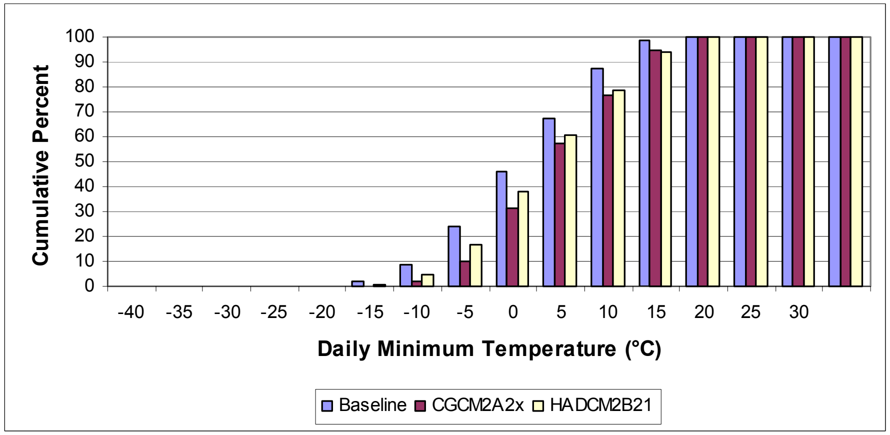


Figure B-301. St. John's minimum daily temperature cumulative percent distribution (n=54750)

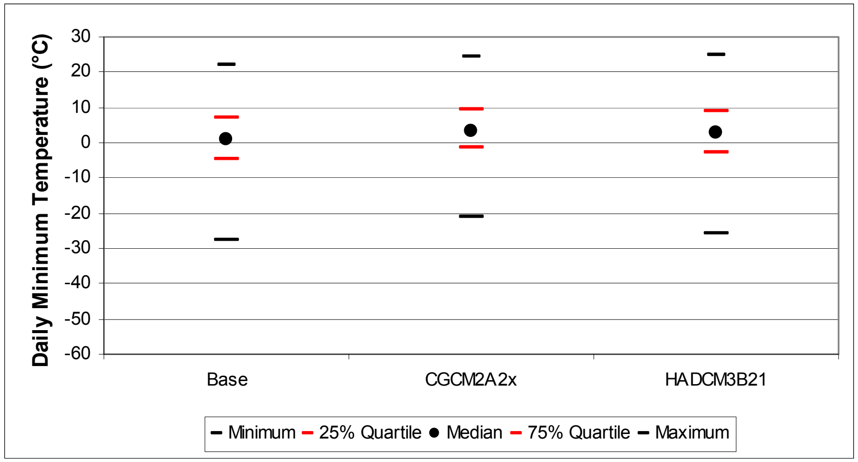


Figure B-302. St. John's minimum daily temperature distribution: quartile statistics (n=54750)

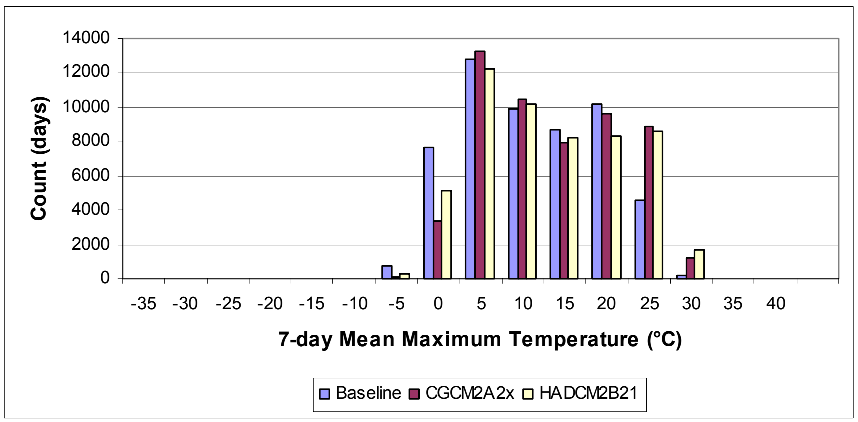


Figure B-303. St. John's 7-day mean maximum daily temperature distribution (n=54750)

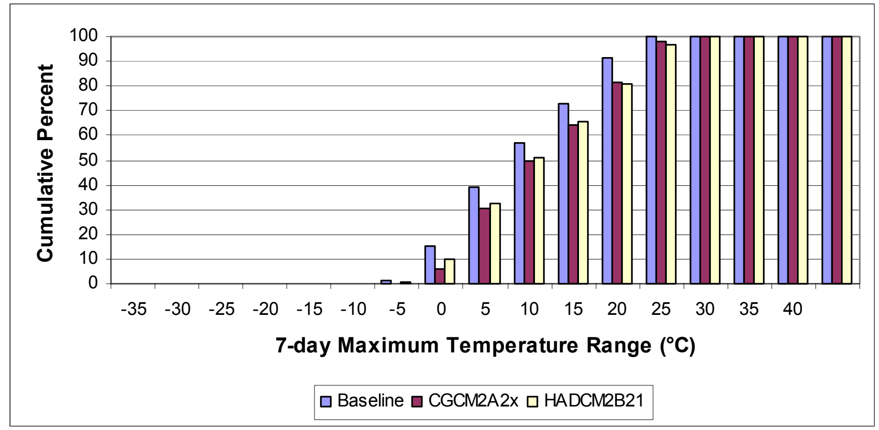


Figure B-304. St. John's 7-day mean maximum daily temperature cumulative percent distribution (n=54750)

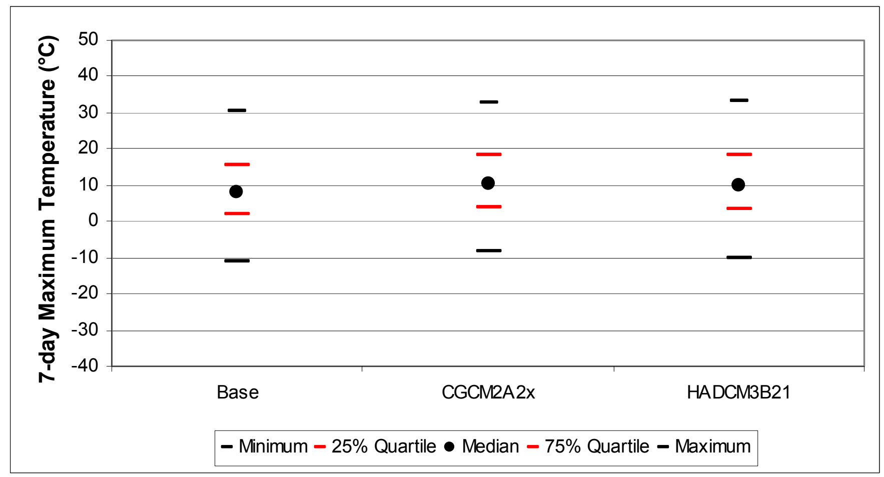


Figure B-305. St. John's 7-day mean maximum daily temperature distribution: quartile statistics (n=54750)

Table B-98. St. John's annual extreme minimum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	-19.9	-14.4	-17.7
Standard Deviation	2.4	2.2	2.4
Minimum	-27.7	-20.9	-25.6
Lower Quartile	-21.5	-15.8	-19.2
Median	-19.5	-14.2	-17.4
Upper Quartile	-17.8	-12.6	-15.9
Maximum	-14.7	-9.3	-12.8

*n=150

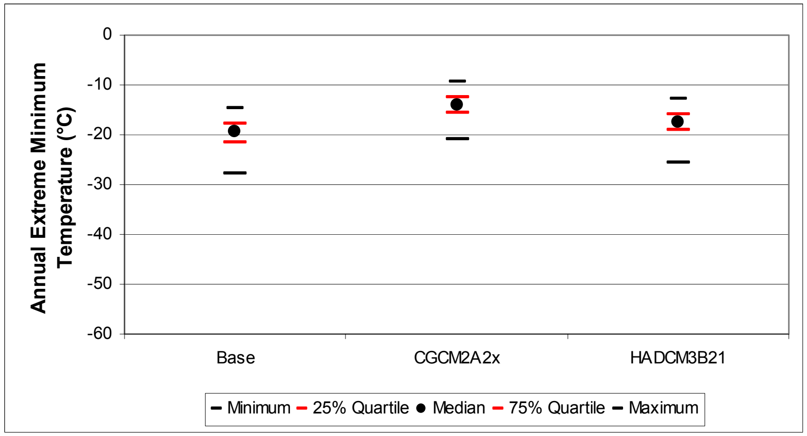


Figure B-306. St. John's annual extreme minimum temperature distribution: quartile statistics (n=150)

Table B-99. St. John's annual extreme 7-day mean maximum air temperature

STATISTIC (°C)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	24.3	26.8	27.2
Standard Deviation	1.6	1.6	1.6
Minimum	21.5	23.7	24.3
Lower Quartile	23.1	25.5	26.1
Median	24.1	26.8	27.1
Upper Quartile	25.3	27.7	28.2
Maximum	30.3	32.7	33.4

*n=150

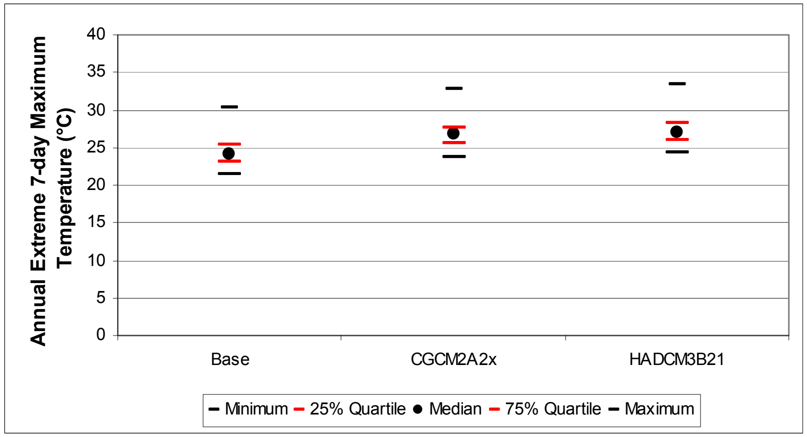


Figure B-307. St. John's annual extreme 7-day mean maximum daily temperature distribution: quartile statistics (n=150)

Table B-100. St. John's Performance Grade (PG) design pavement temperature summary

STATISTIC	Baseline	Climate Change Scenario CGCM2A2x	HadCM3B21
Superpave-derived low PG threshold (°C)	-21.8	-17.676794	-20.2403732
Superpave-derived high PG threshold (°C)	49.2	51.2	51.5
98th percentile annual minimum air temperature	-24.9	-19.506	-22.608
Ontario RWIS-based low PG threshold (°C)	-20.8	-16.376953	-18.9532219
98th percentile annual extreme 7-day mean maximum air temperature	28.0	31.1	31.0
Ontario RWIS-based high PG threshold (°C)	41.3	46.3	46.1

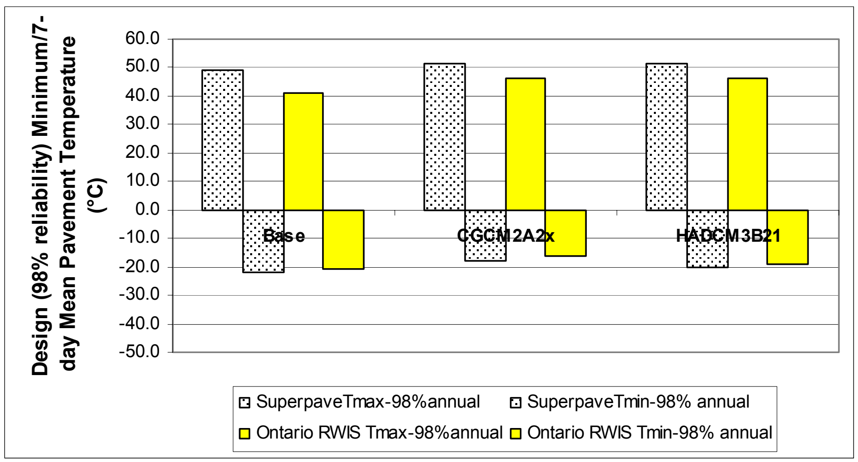


Figure B-308. St. John's estimated low and high Performance Grade (PG) temperature ratings (design 98% reliability minimum and 7-day mean maximum temperatures)

Table B-101. St. John's freeze season length

STATISTIC (days)	Baseline*	Climate Change Scenario CGCM2A2x*	HadCM3B21*
Mean	56.0	0.9	23.2
Standard Deviation	21.8	3.1	16.8
Minimum	6.0	0.0	0.0
Lower Quartile	42.0	0.0	9.3
Median	59.0	0.0	22.0
Upper Quartile	72.0	0.0	35.5
Maximum	107.0	15.0	72.0

*n=150

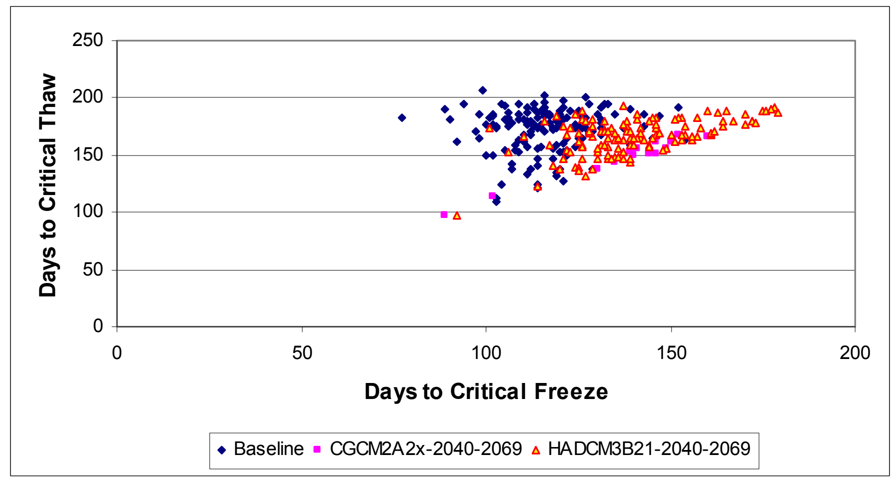


Figure B-309. St. John's estimated number of days to Critical Freeze Index (FI) and Thaw Index (TI)

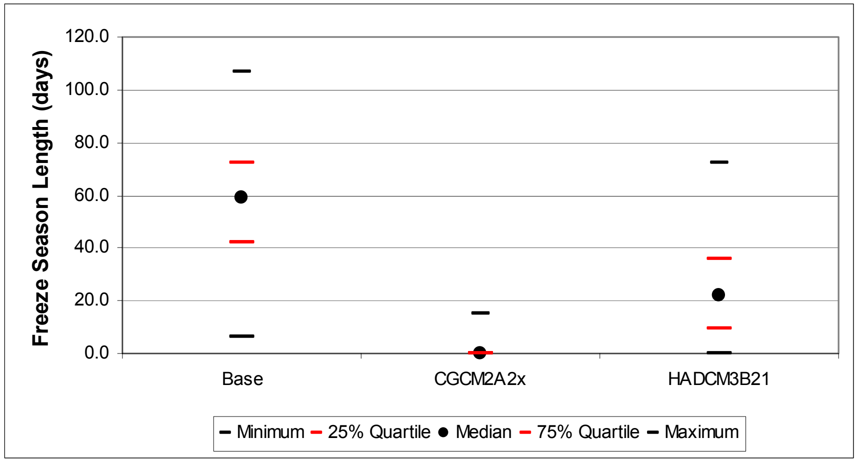


Figure B-310. St. John's estimated freeze season length distribution: quartile statistics (n=150)

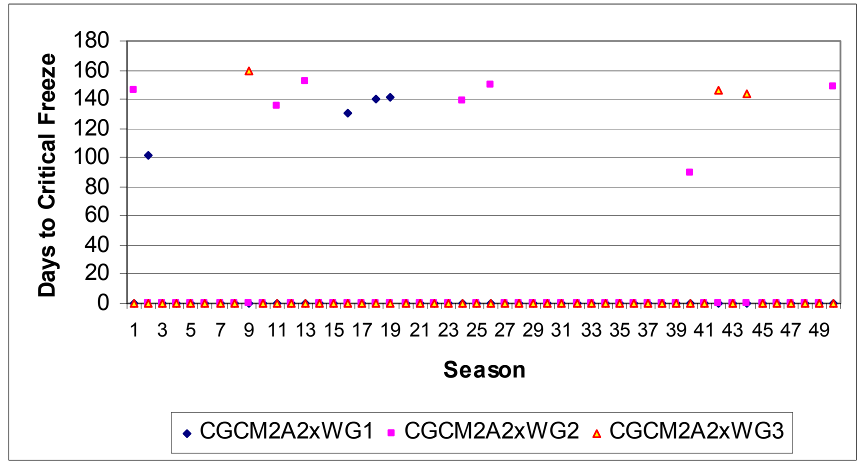


Figure B-312. St. John's estimated days to critical FI (CGCM2A2x scenario series)

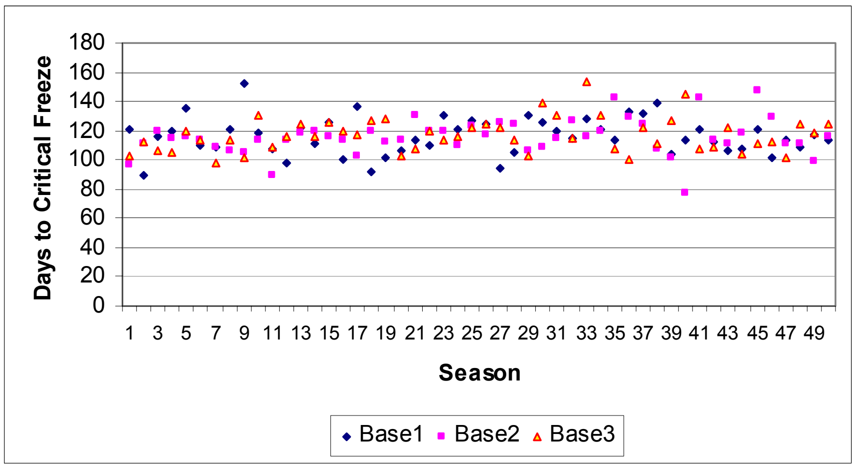


Figure B-311. St. John's estimated days to critical FI (baseline series)

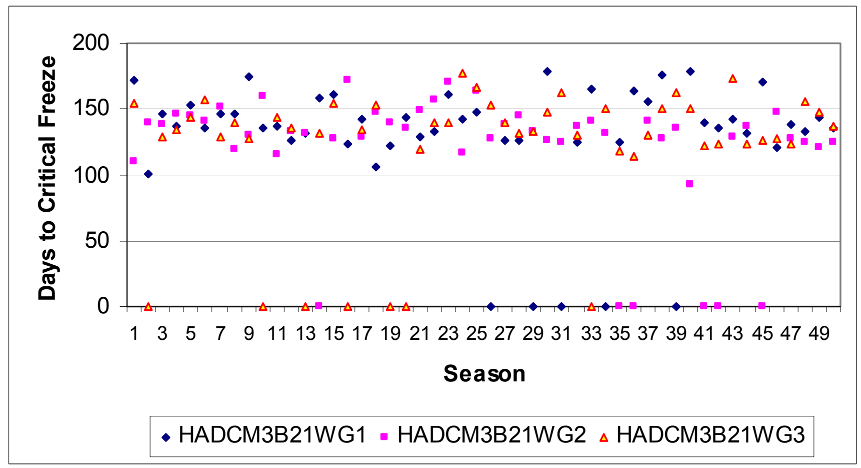


Figure B-313. St. John's estimated days to critical FI (HadCM3B21 scenario series)

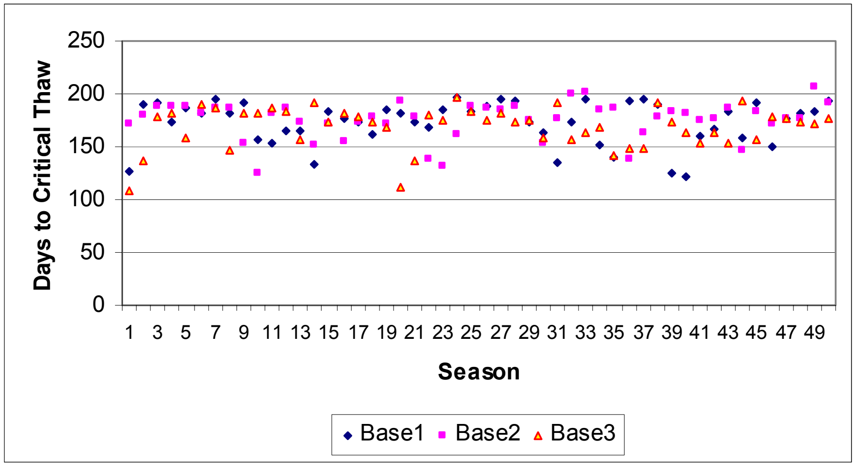


Figure B-314. St. John's estimated days to critical TI (baseline series)

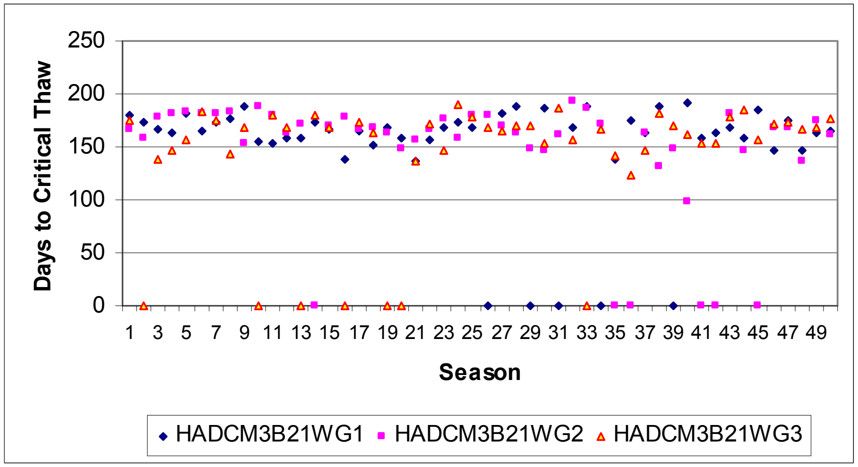


Figure B-316. St. John's estimated days to critical TI (HadCM3B21 scenario series)

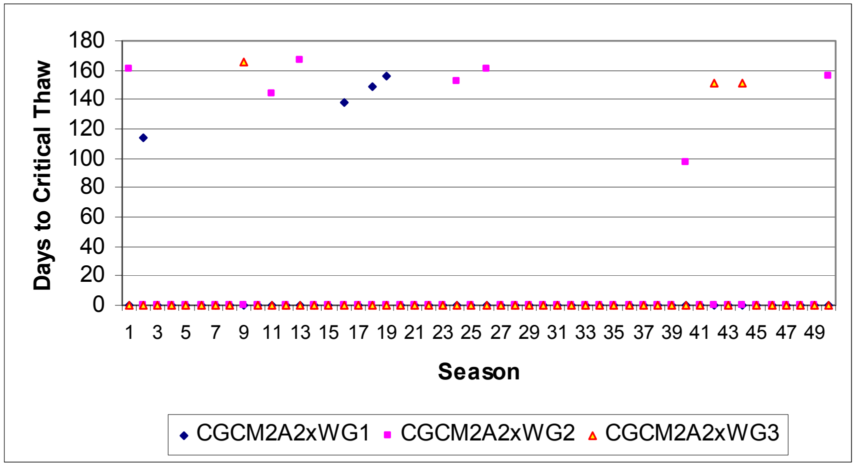


Figure B-315. St. John's estimated days to critical TI (CGCM2A2x scenario series)

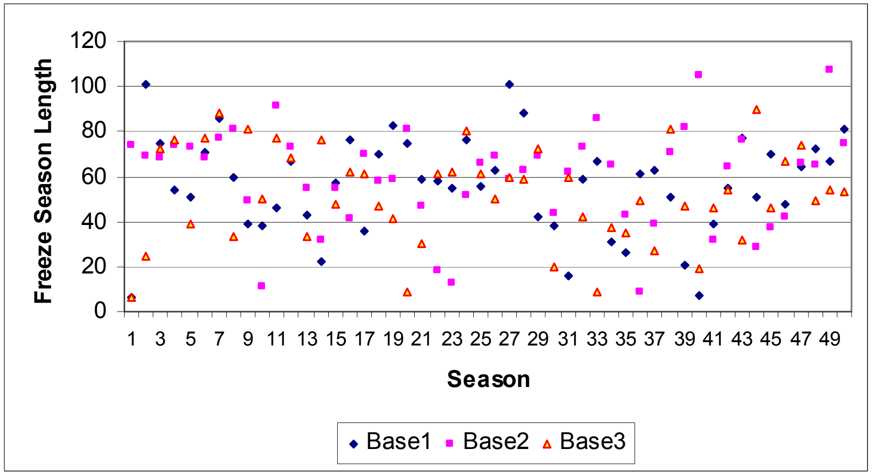


Figure B-317. St. John's estimated freeze season length (baseline series)

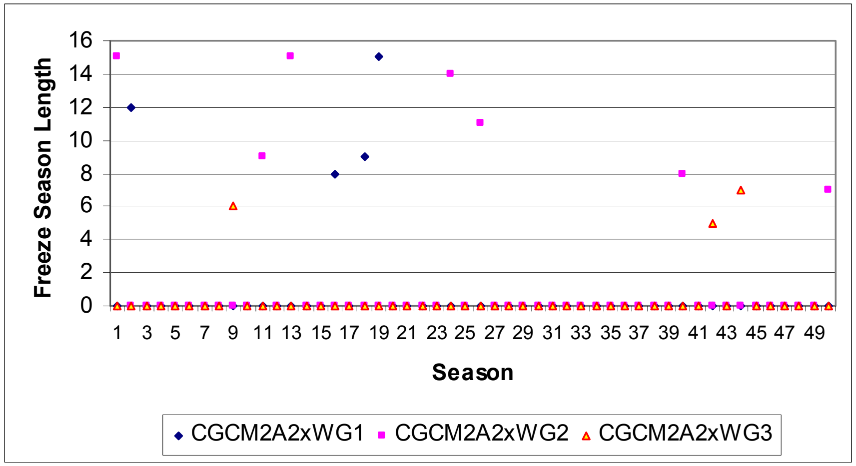


Figure B-318. St. John's estimated freeze season length (CGCM2A2x scenario series)

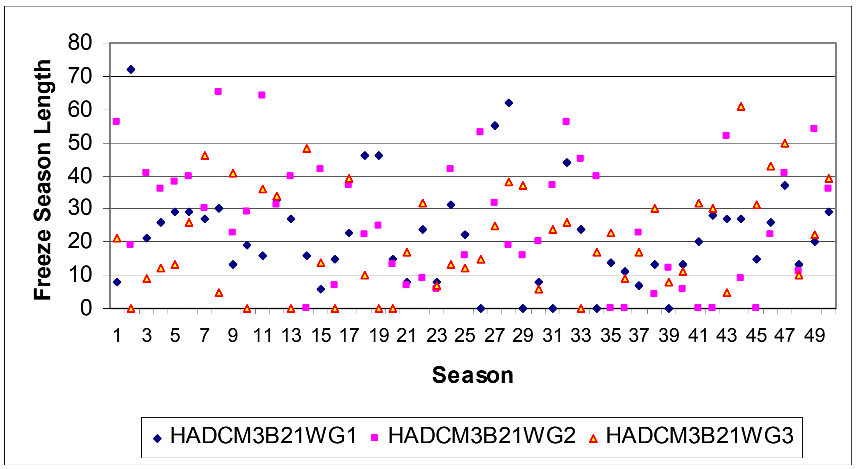


Figure B-319. St. John's estimated freeze season length (HadCM3B21 scenario series)

APPENDIX C:
MATERIAL PROPERTY ASSUMPTIONS USED IN MEPDG ANALYSES

Table C-1. Asphalt Properties (Layer 1)

Province	Site ID	Gradation (%)				Binder			General						
		Σ Ret 3/4	Σ Ret 3/8	Σ Ret #4	Pass #200	Type	Grade	Used	Temp	Binder C.	A. Voids	U. Weight	Poisson	T. Cap	H. Cap
AB	81-1804-1	0	23	43	7	Pen	150 - 200	200 - 300	70	6.4	7	142	0.35	0.67	0.23
BC	82-1005-1	0	24	42	6	AC	8	10	70	5.6	2.6	149	0.35	0.67	0.23
MB	83-6450-1	0	16	32	3	Cutback	3000	200 - 300	70	3.8	7.7	162	0.35	0.67	0.23
NF	85-1808-1	0	16	44	3	Pen	120 - 150	120 - 150	70	6	2.1	152	0.35	0.67	0.23
ON	87-1806-1	0	12	37.5	9.9	Pen	85 - 100	85 - 100	70	5.6	5.4	182	0.35	0.67	0.23
PQ	89-1021-1	0	26	41	5	Pen	85 - 100	85 - 100	70	4.9	1.8	154	0.35	0.67	0.23

Table C-2. Asphalt Properties (Layer 2)

Province	Site ID	Gradation (%)				Binder			General						
		Σ Ret 3/4	Σ Ret 3/8	Σ Ret #4	Pass #200	Type	Grade	Used	Temp	Binder C.	A. Voids	U. Weight	Poisson	T. Cap	H. Cap
MB	84-1684-1	0	16	32	3	Cutback	3000	200 - 300	70	3.8	7.7	162	0.35	0.67	0.23
ON	87-1806-1	0	12	37.5	9.9	Pen	85 - 100	85 - 100	70	5.4	5.4	148	0.35	0.67	0.23

Table C-3. Base Properties

Province	Site ID	Strength Properties			ICM								
		Poisson	Ko	Modulus	PI	% Pass #4	D60	% Pass 200	Dry UW	Gs	Hyd Con	GWC	Deg Sat
AB	81-1804-1	0.35	0.5	40000	2	45	15	8	122.3	2.67	344	11.3	83.2
BC	82-1005-1	0.35	0.5	40000	2	53	6.5	3	122.3	2.67	221	11.2	82.5
MB	83-6450-1	0.35	0.5	40000	2	59	6	6.9	122.3	2.67	204	11.8	83
NF	85-1808-1	0.35	0.5	40000	2	56	6	3	122.3	2.67	204	11.2	82.5
ON	87-1806-1	0.35	0.5	38500	1	53.2	6.5	2.3	122.2	2.66	221	11.1	81.9
PQ	89-1021-1	0.35	0.5	40000	2	35	10	2.2	122.3	2.67	302	11.1	82.3

Table C-4. Subbase Properties

Province	Site ID	Strength Properties			ICM								
		Poisson	Ko	Modulus	PI	% Pass #4	D60	% Pass 200	Dry UW	Gs	Hyd Con	GWC	Deg Sat
AB	81-1804-1	0.35	0.5	38500	1	30	15	7	122..3	2.67	344	11.2	82.6
BC	82-1005-1	0.35	0.5	38500	0	63	4	2.7	122.2	2.66	125	11.1	82
MB	83-6450-1	0.35	0.5	38500	1	75	2	9	122.3	2.67	37	11.2	82.7
NF	85-1808-1	0.35	0.5	40000	2	47	12.5	2	122.3	2.67	331	11.1	82.2
ON	87-1806-1	0.35	0.5	29000	0	88	0.4	0.5	128	2.65	0.359	8.6	78
PQ	89-1021-1	0.35	0.5	38500	1	44	7	5.5	122.3	2.67	236	11.2	82.4

Table C-5. Subgrade Properties

Province	Site ID	Strength Properties			ICM								
		Poisson	Ko	Modulus	PI	% Pass #4	D60	% Pass 200	Dry UW	Gs	Hyd Con	GWC	Deg Sat
AB	81-1804-1	0.35	0.5	32000	1	80	0.3	10	110.1	2.67	0.12	11.2	82.8
BC	82-1005-1	0.35	0.5	32000	1	80	0.3	10	110.1	2.67	0.12	11.2	82.8
MB	83-6450-1	0.35	0.5	32000	5	80	0.3	10	109.5	2.68	0.12	11.8	84.1
NF	85-1808-1	0.35	0.5	40000	0	20	8	5	120.3	2.65	263	7	78
ON	87-1806-1	0.35	0.5	20000	7.5	95	0.05	80	102.1	2.72	0	15.8	86.8
PQ	89-1021-1	0.35	0.5	28000	0	80	1	10	115	26.5	6.85	8.6	78

APPENDIX D:
MEPDG SENSITIVITY ANALYSIS RESULTS

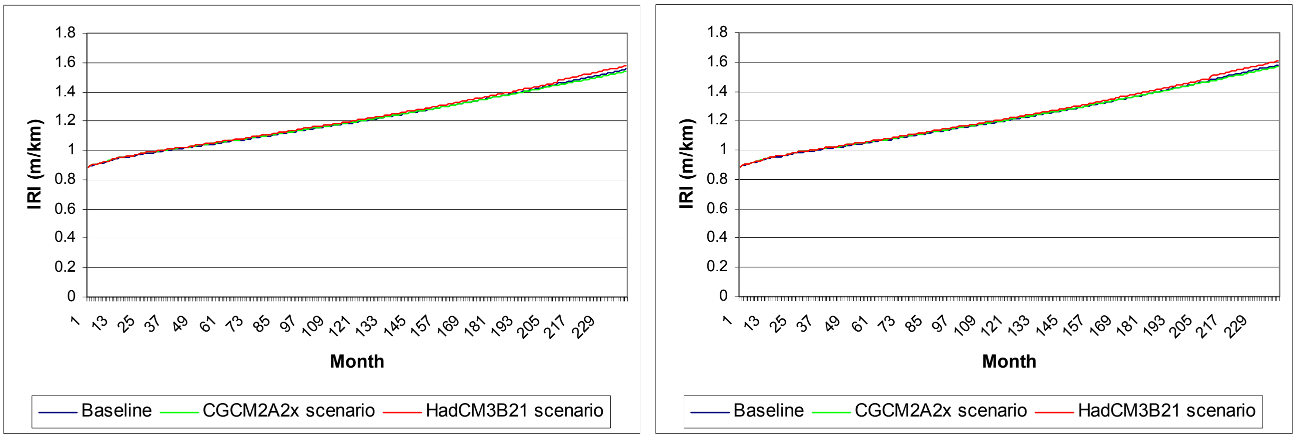


Figure D-1. IRI performance at the British Columbia site (Vancouver) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

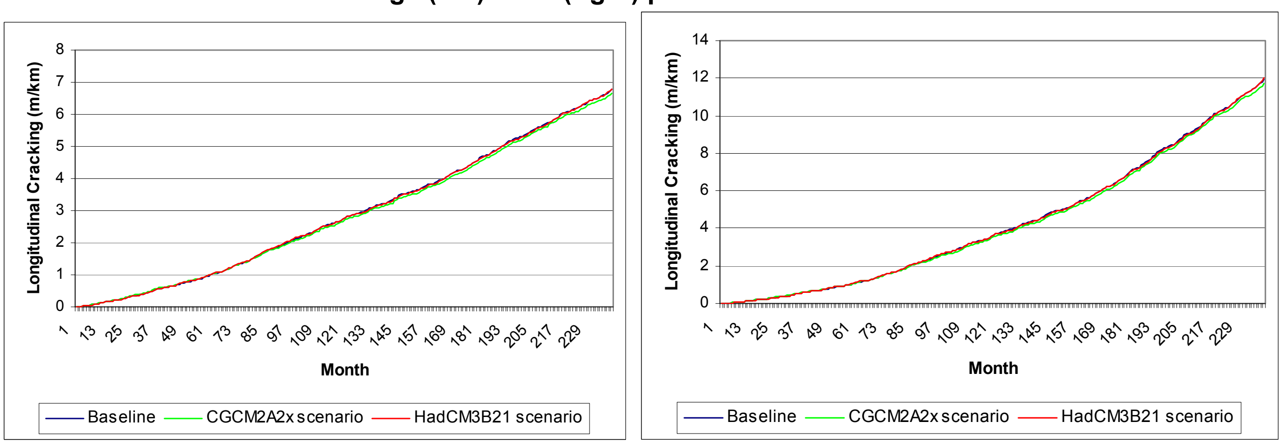


Figure D-2. Longitudinal cracking performance at the British Columbia site (Vancouver) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

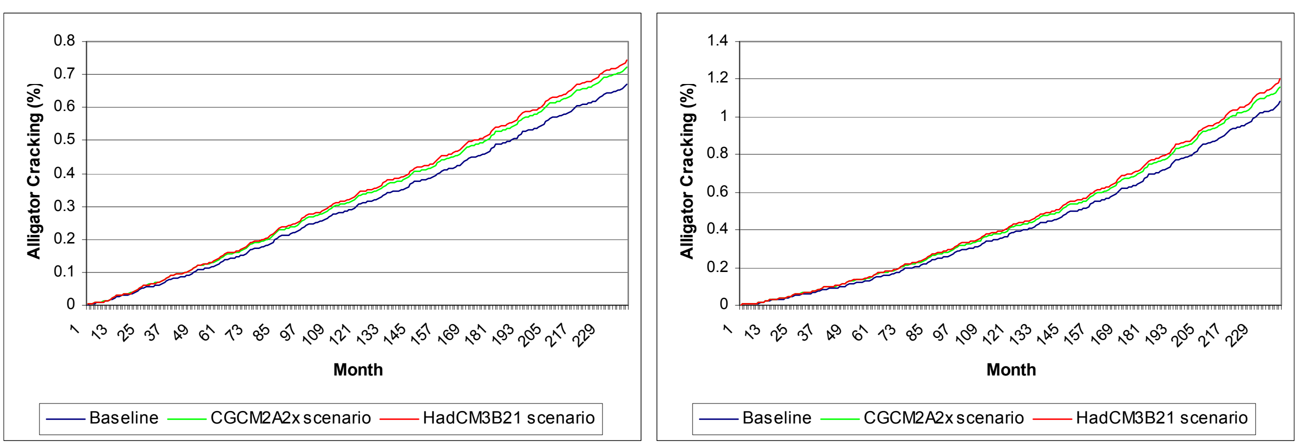


Figure D-3. Alligator cracking performance at the British Columbia site (Vancouver) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

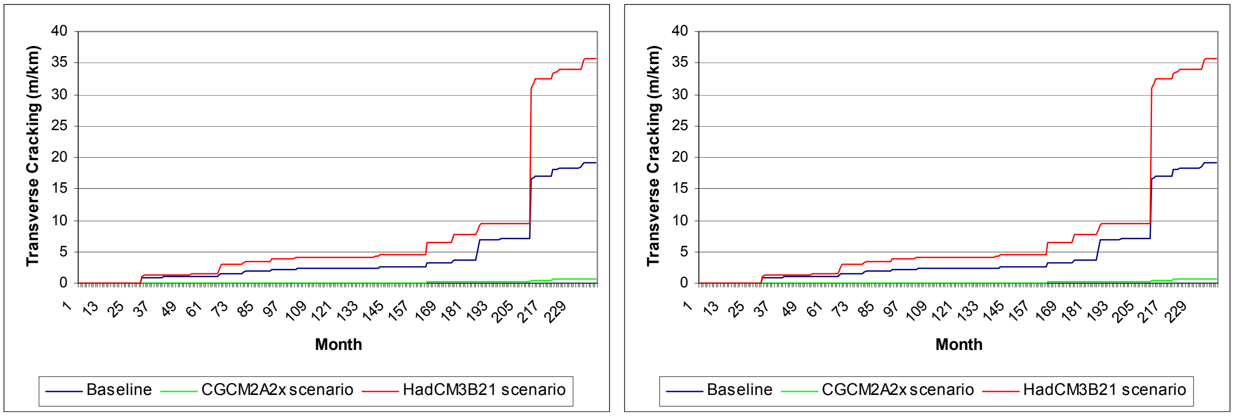


Figure D-4. Transverse cracking performance at the British Columbia site (Vancouver) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

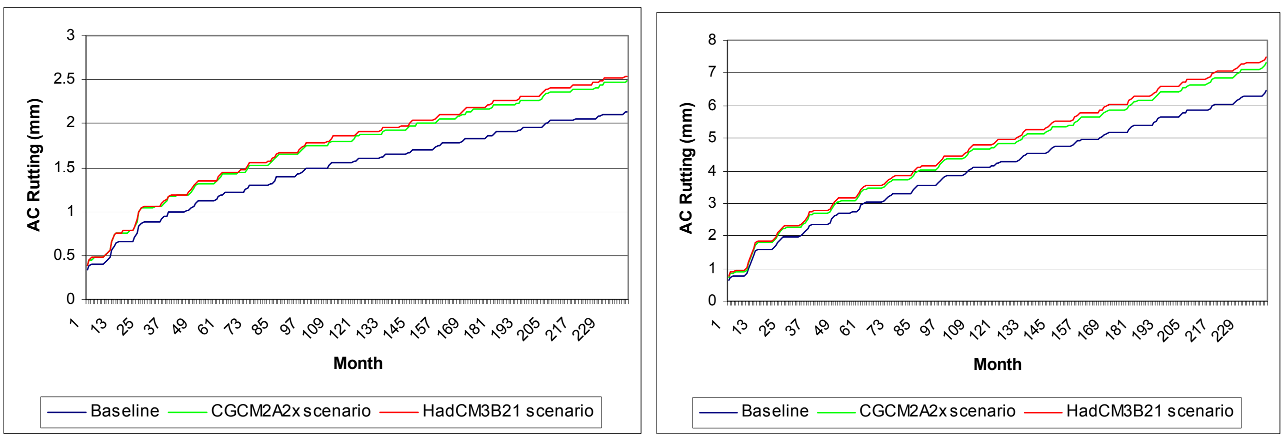


Figure D-5. AC rutting performance at the British Columbia site (Vancouver) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

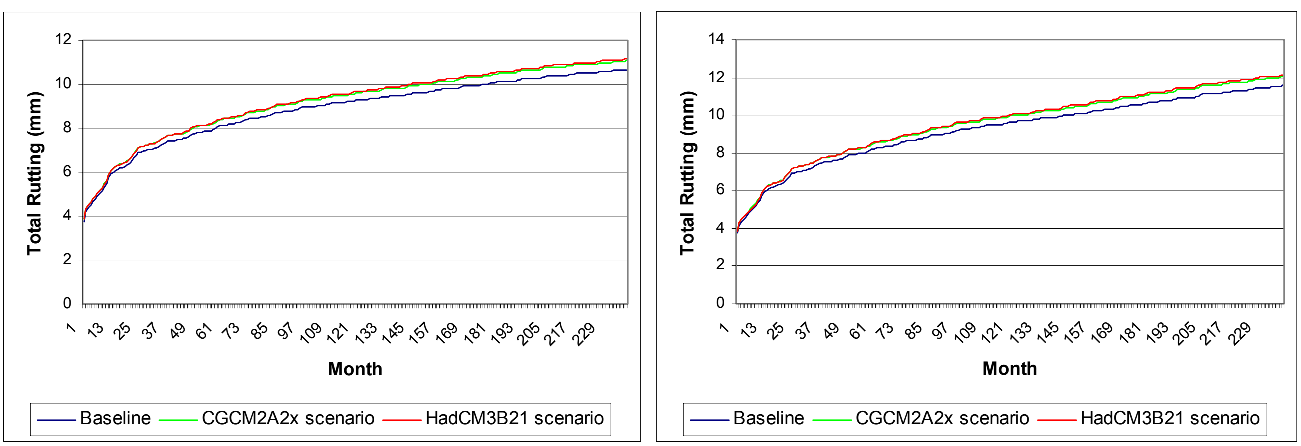


Figure D-6. Total rutting performance at the British Columbia site (Vancouver) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

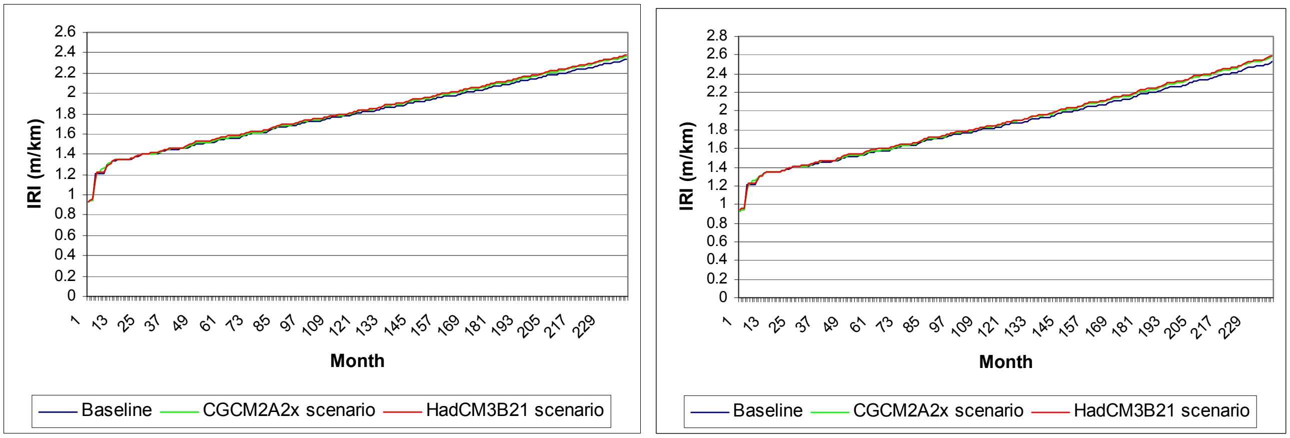


Figure D-7. IRI performance at the Alberta site (Edmonton) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

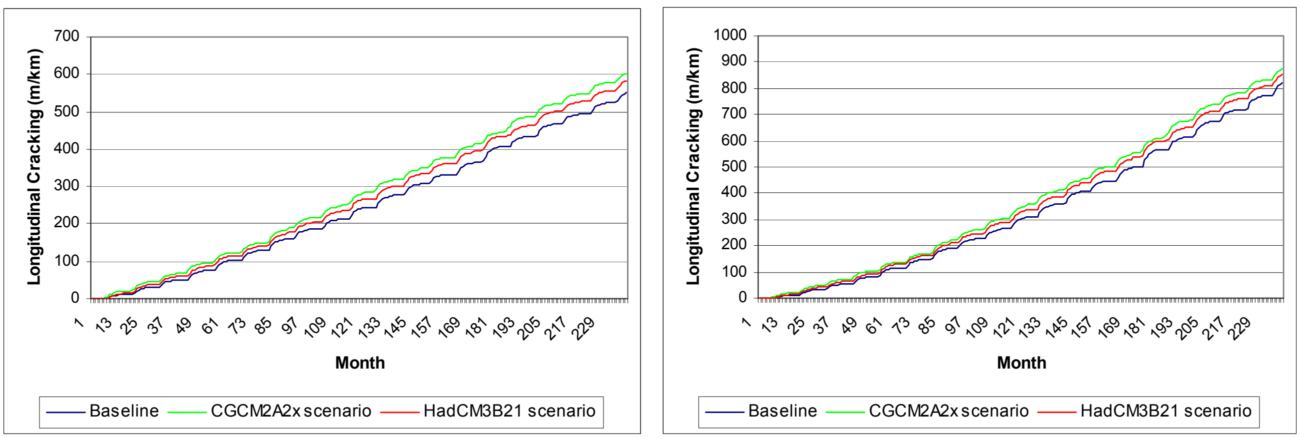


Figure D-8. Longitudinal cracking performance at the Alberta site (Edmonton) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

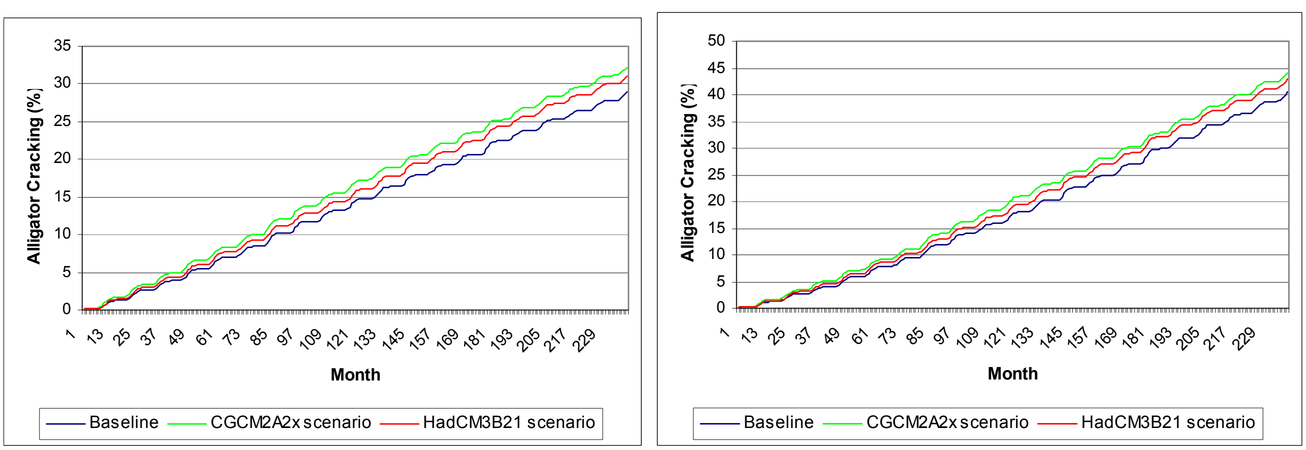


Figure D-9. Alligator cracking performance at the Alberta site (Edmonton) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

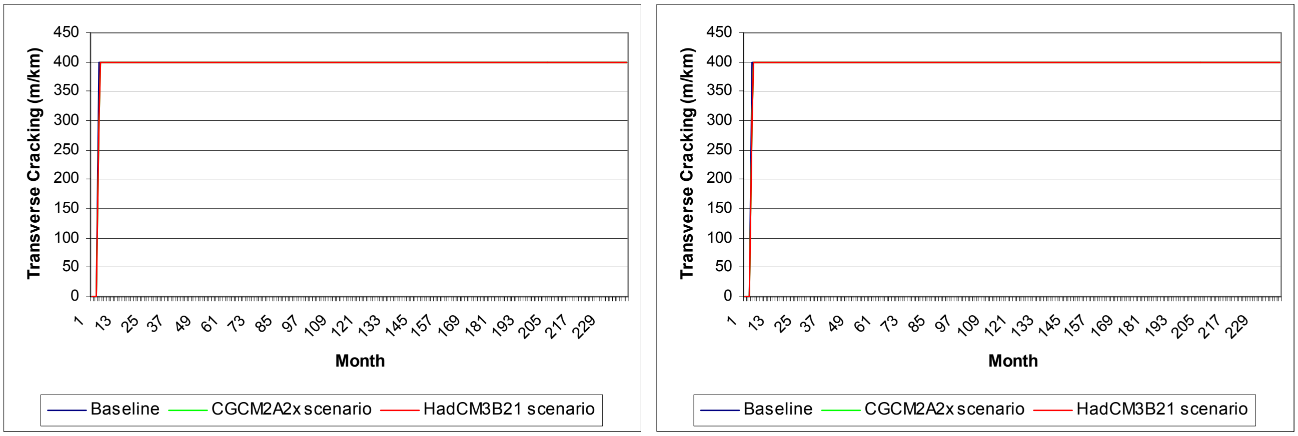


Figure D-10. Transverse cracking performance at the Alberta site (Edmonton) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

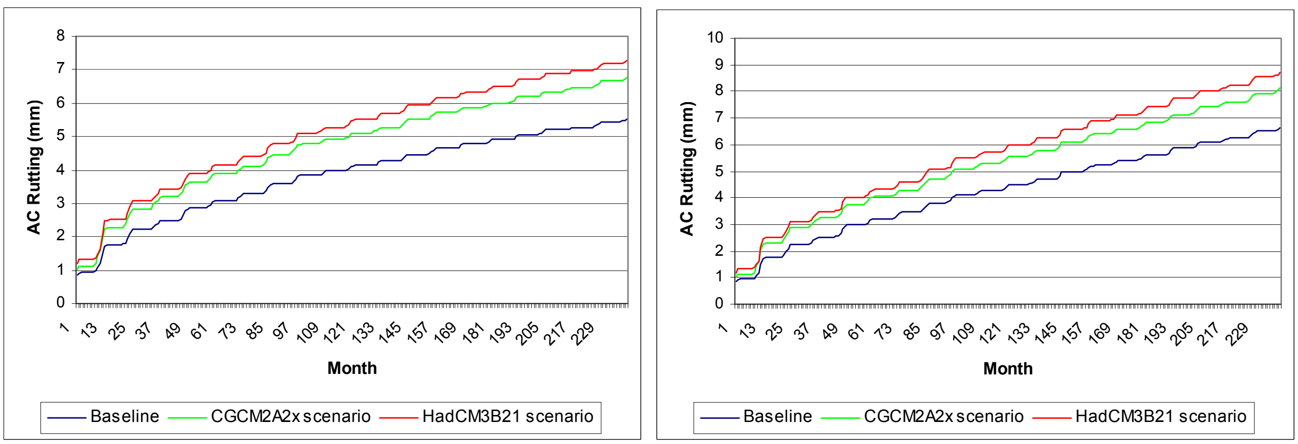


Figure D-11. AC rutting performance at the Alberta site (Edmonton) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

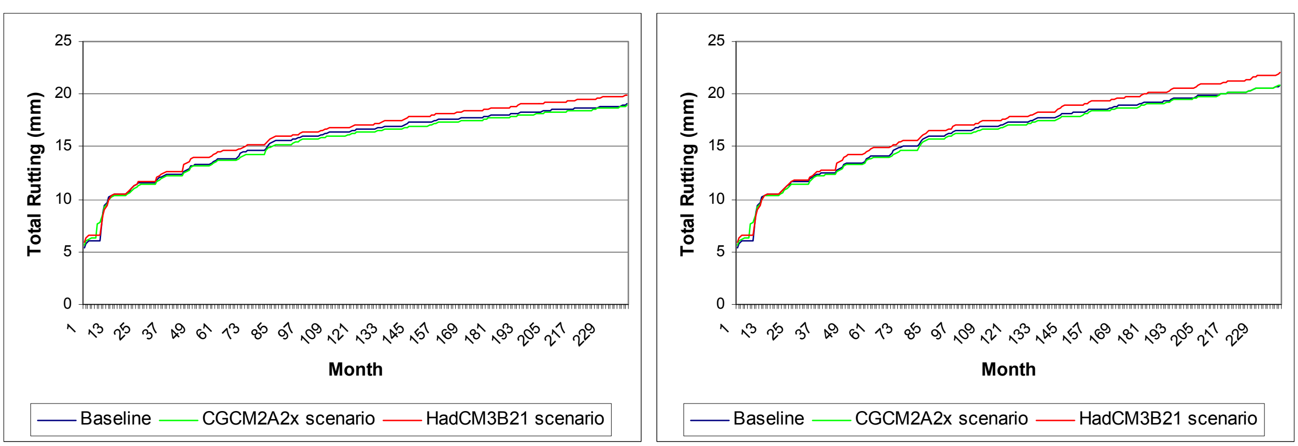


Figure D-12. Total rutting performance at the Alberta site (Edmonton) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

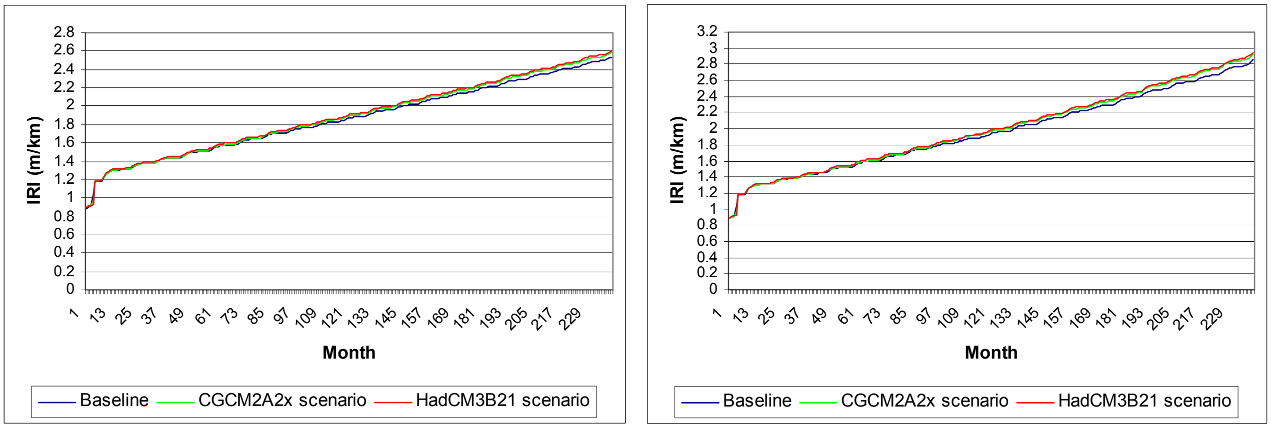


Figure D-13. IRI performance at the Manitoba site (Winnipeg) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

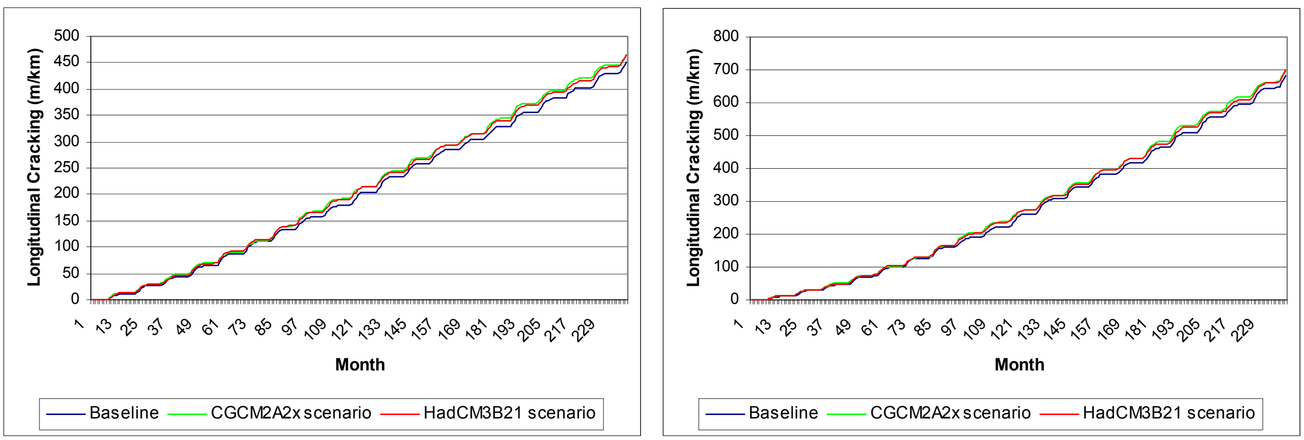


Figure D-14. Longitudinal cracking performance at the Manitoba site (Winnipeg) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

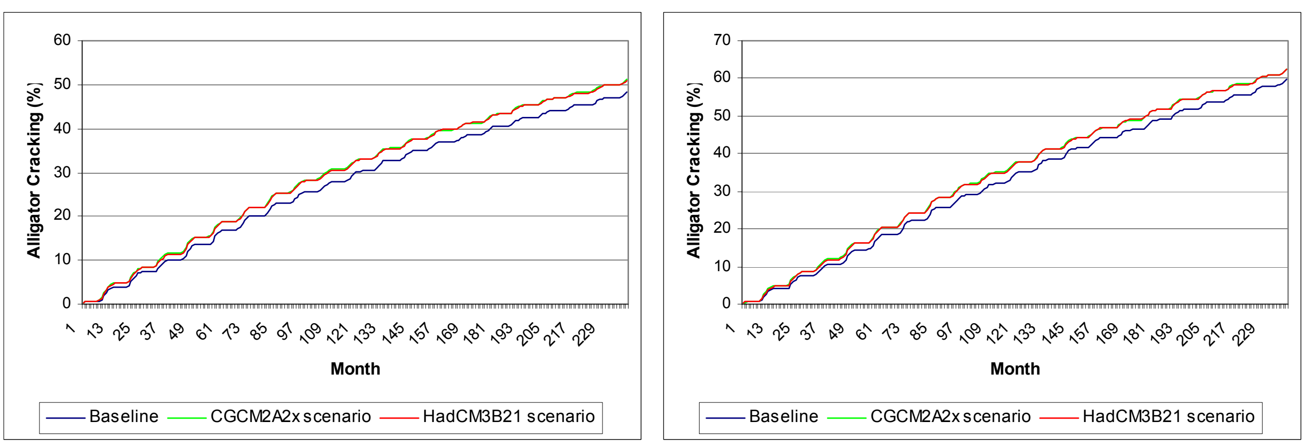


Figure D-15. Alligator cracking performance at the Manitoba site (Winnipeg) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

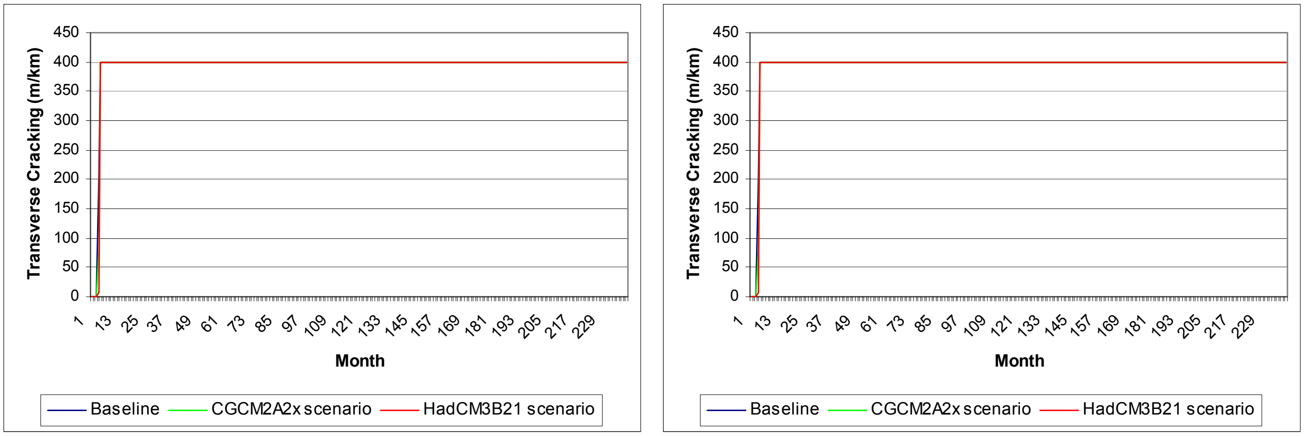


Figure D-16. Transverse cracking performance at the Manitoba site (Winnipeg) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

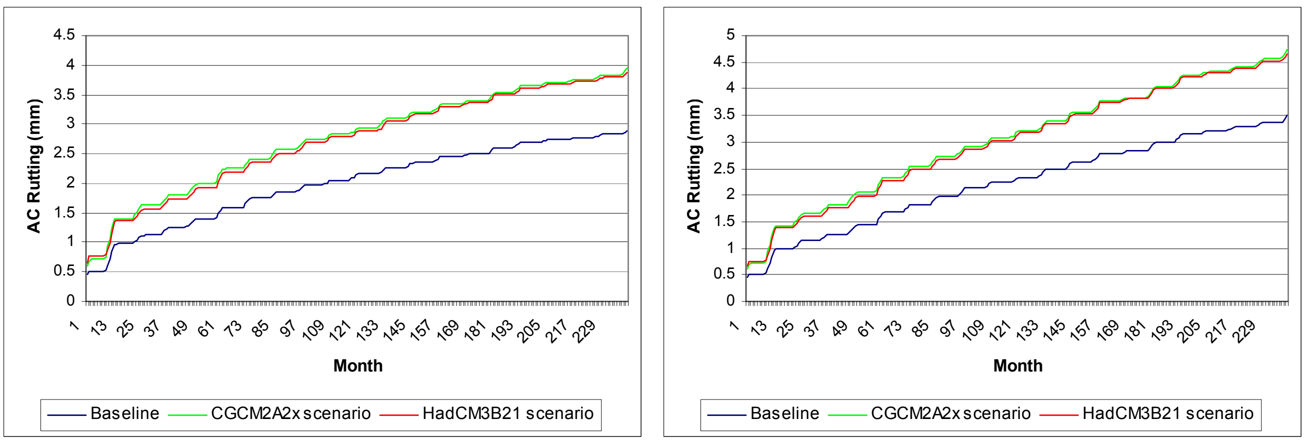


Figure D-17. AC rutting performance at the Manitoba site (Winnipeg) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

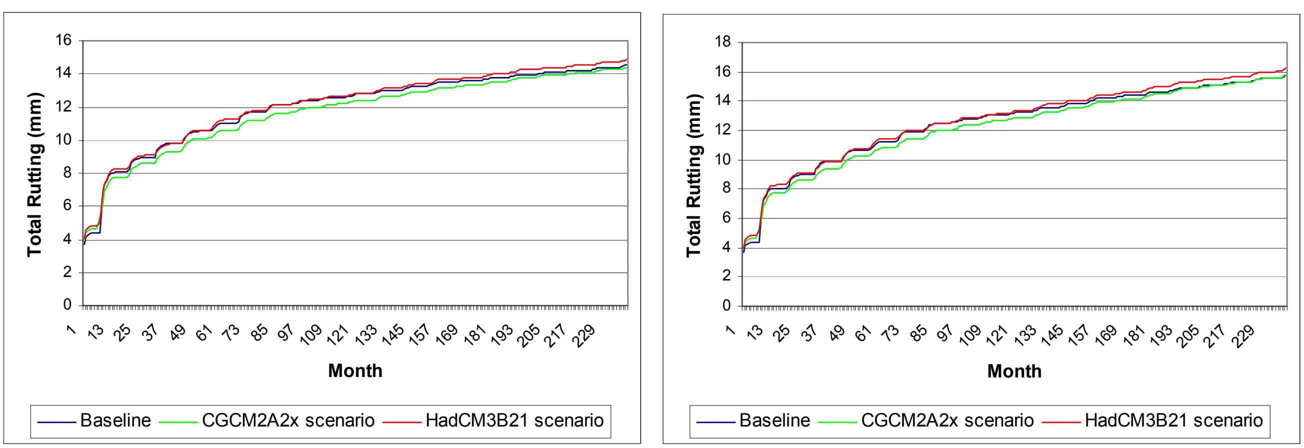


Figure D-18. Total rutting performance at the Manitoba site (Winnipeg) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

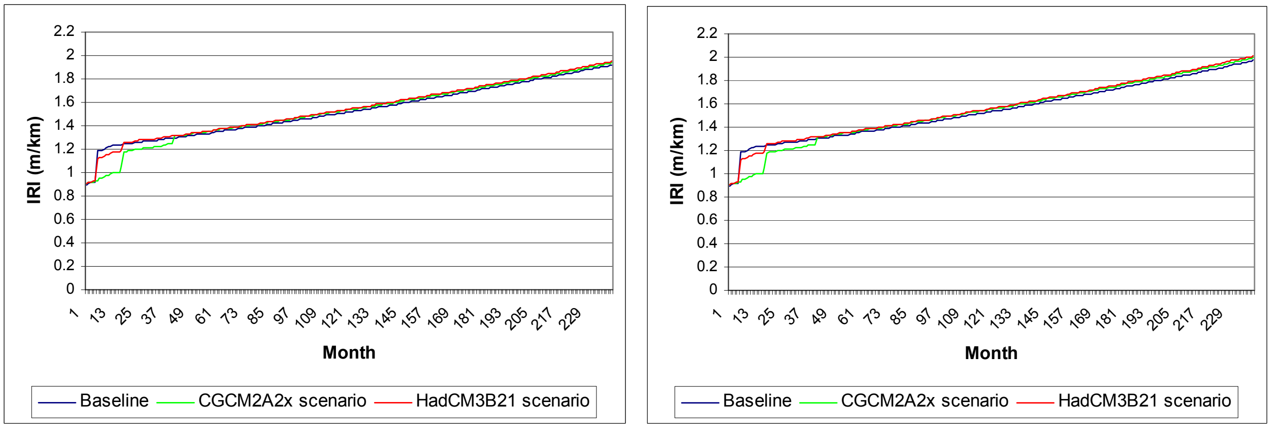


Figure D-19. IRI performance at the Ontario site (Toronto) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

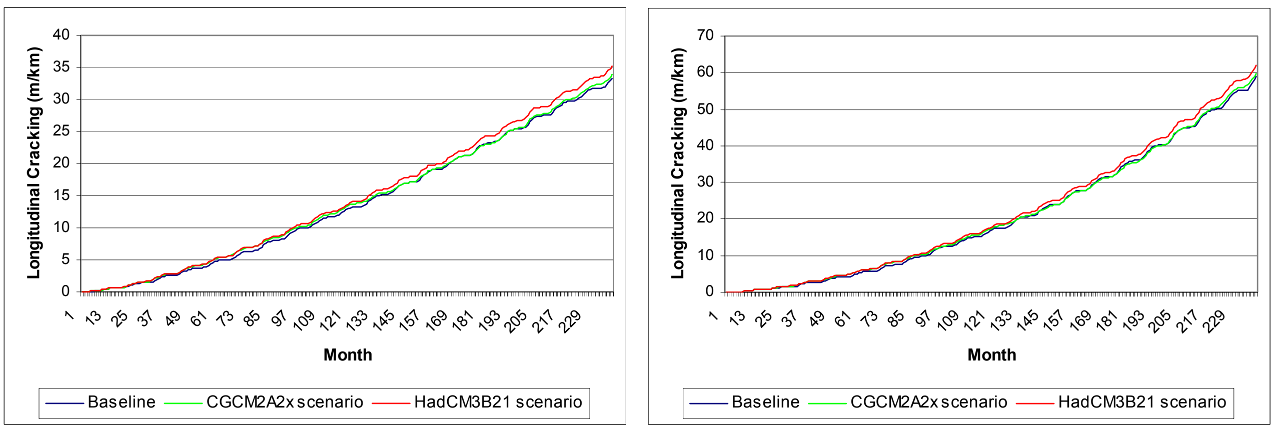


Figure D-20. Longitudinal cracking performance at the Ontario site (Toronto) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

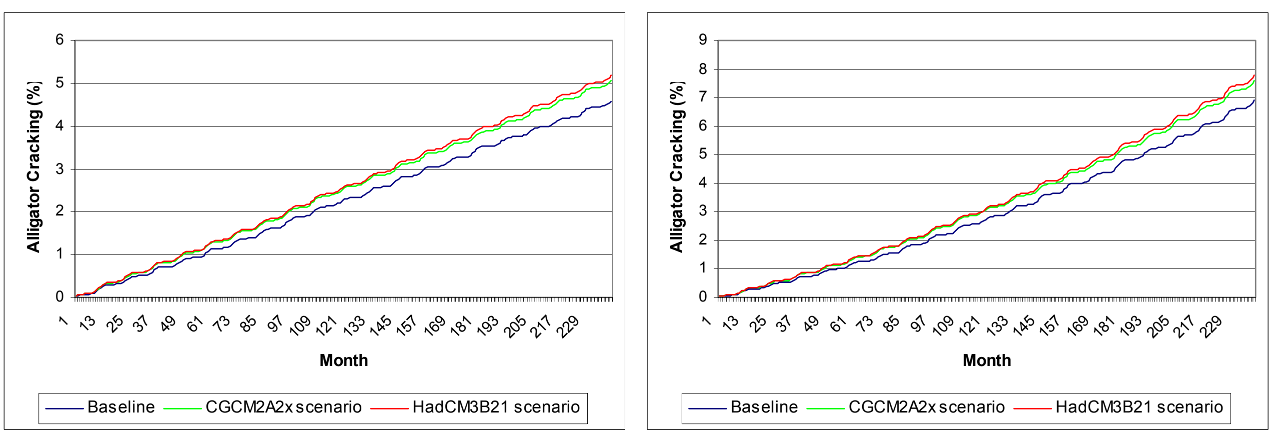


Figure D-21. Alligator cracking performance at the Ontario site (Toronto) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

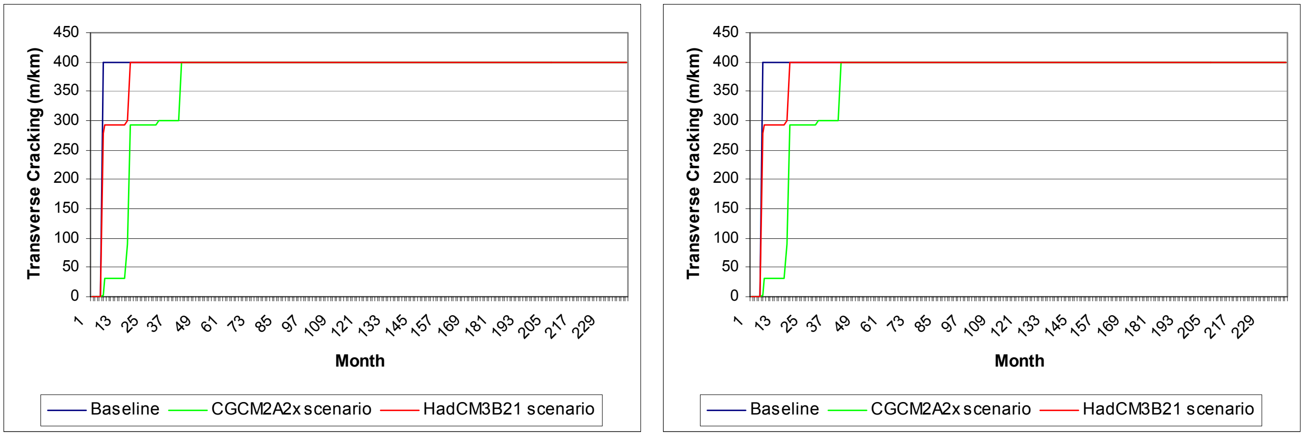


Figure D-22. Transverse cracking performance at the Ontario site (Toronto) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

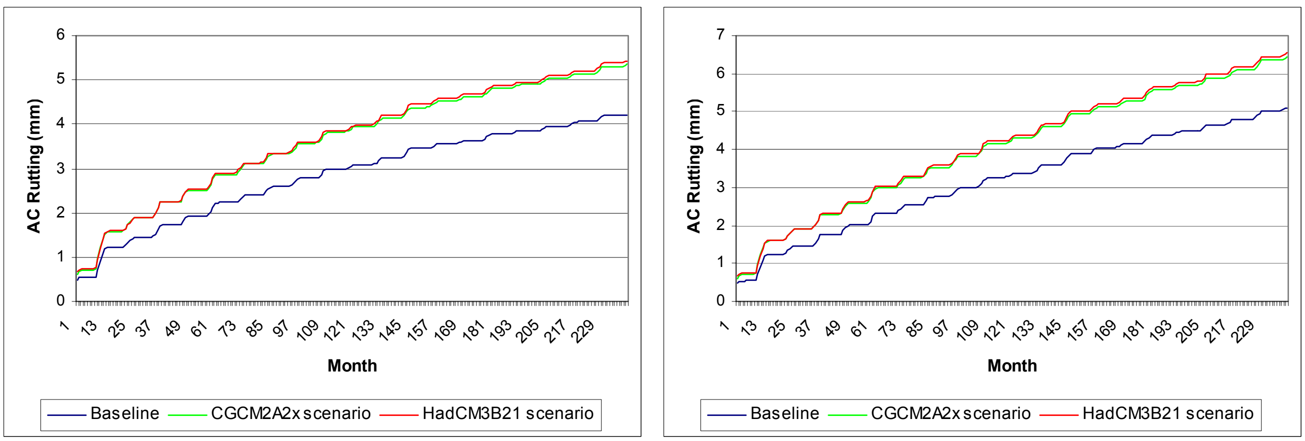


Figure D-23. AC rutting performance at the Ontario site (Toronto) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

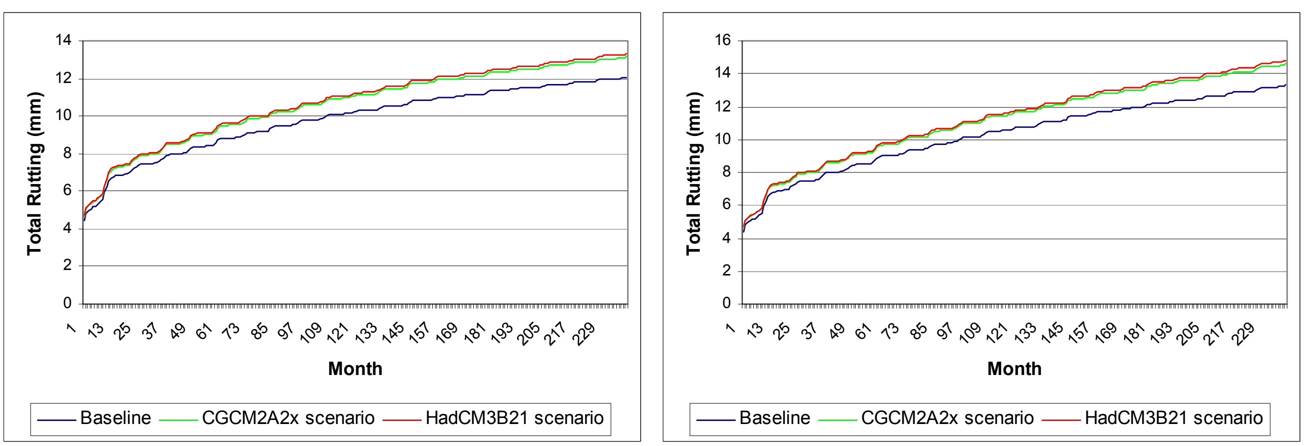


Figure D-24. Total rutting performance at the Ontario site (Toronto) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

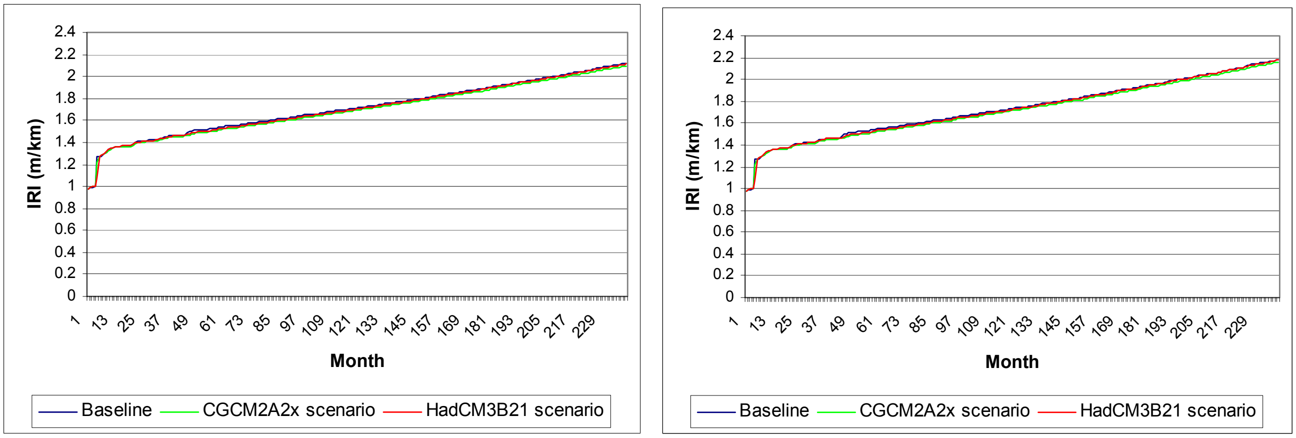


Figure D-25. IRI performance at the Quebec site (Montreal) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

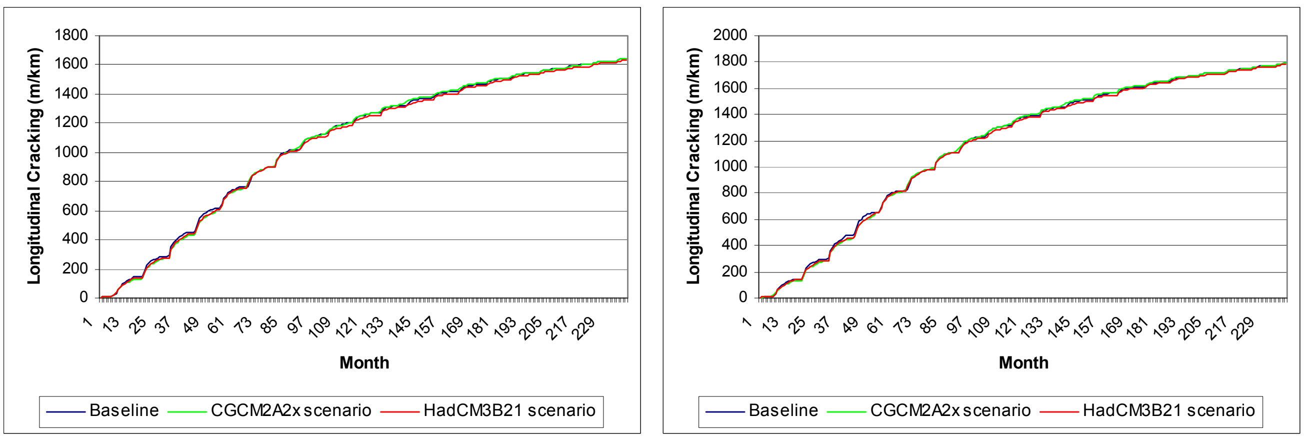


Figure D-26. Longitudinal cracking performance at the Quebec site (Montreal) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

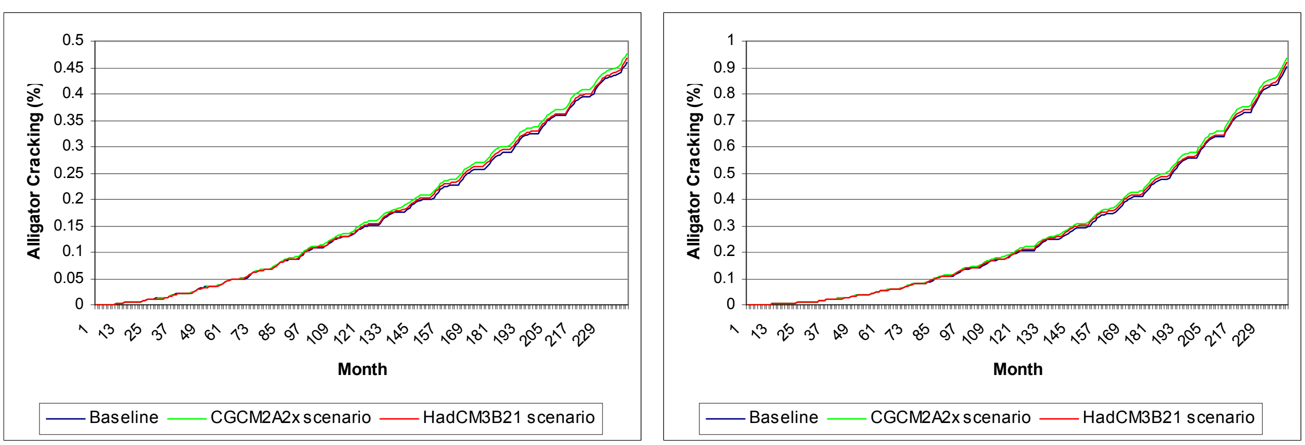


Figure D-27. Alligator cracking performance at the Quebec site (Montreal) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

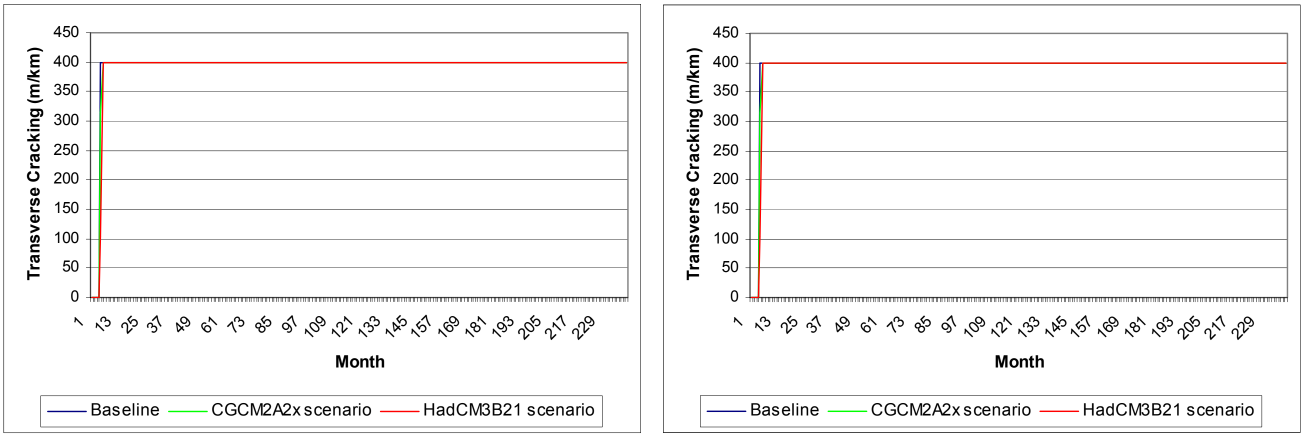


Figure D-28. Transverse cracking performance at the Quebec site (Montreal) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

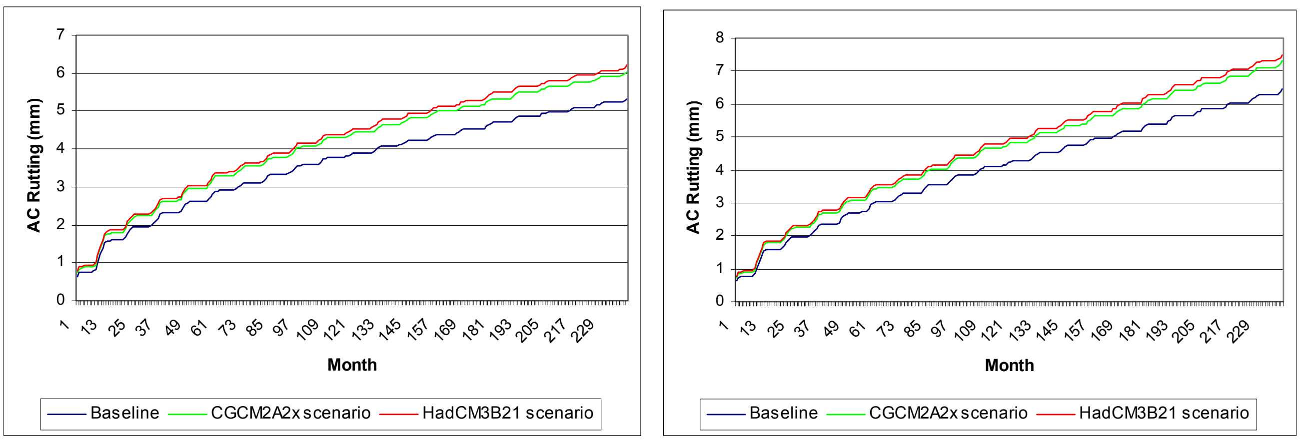


Figure D-29. AC rutting performance at the Quebec site (Montreal) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

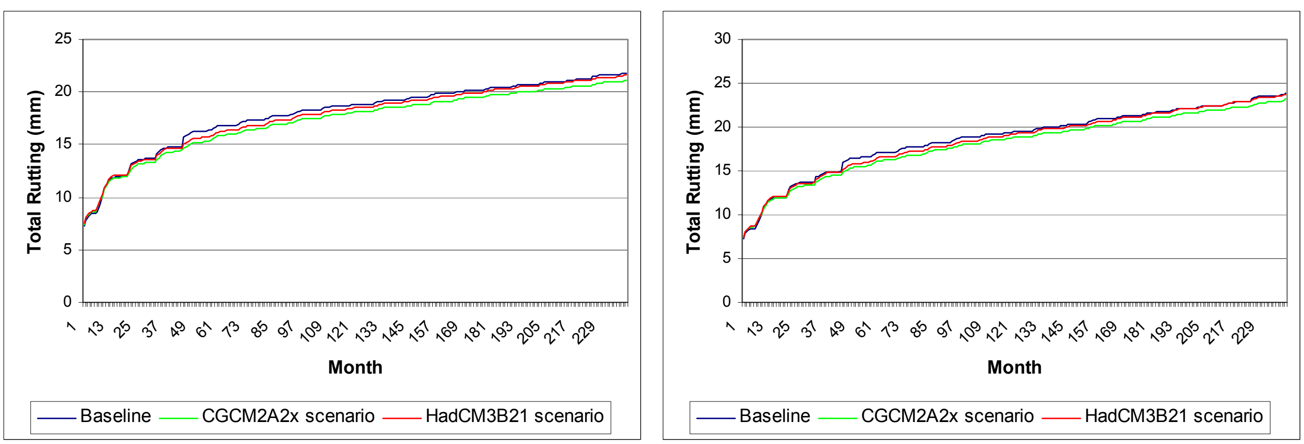


Figure D-30. Total rutting performance at the Quebec site (Montreal) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

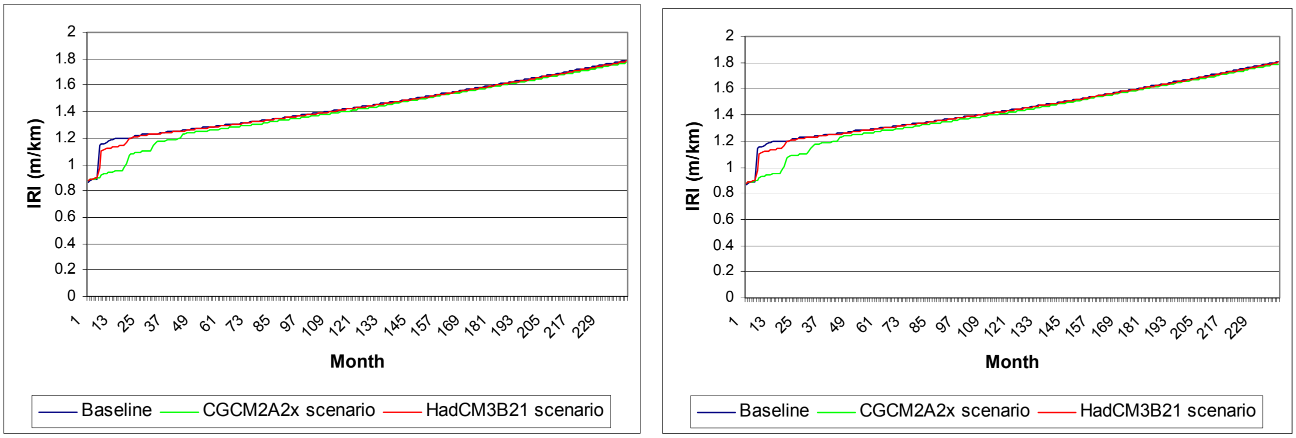


Figure D-31. IRI performance at the Newfoundland site (St. John's) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

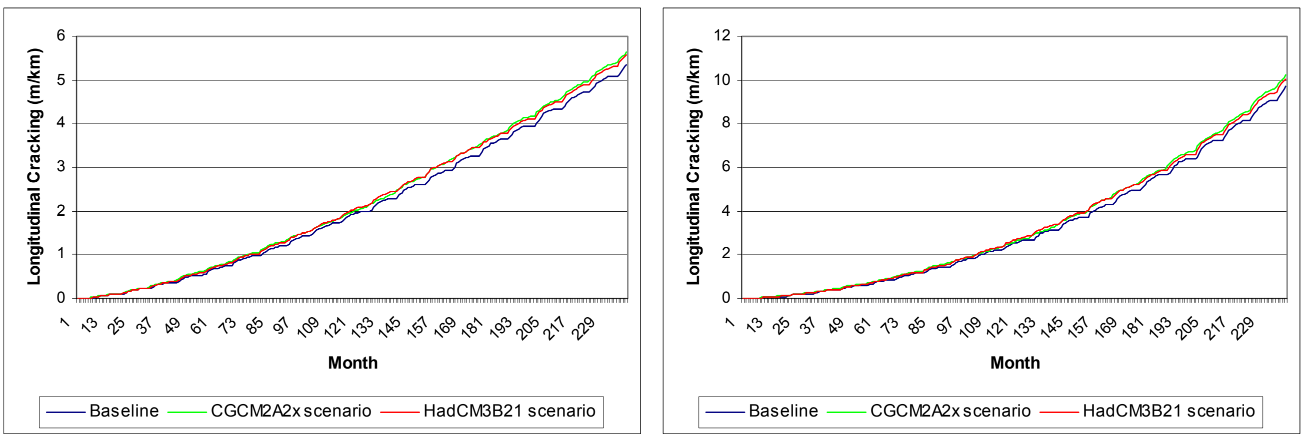


Figure D-32. Longitudinal cracking performance at the Newfoundland site (St. John's) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

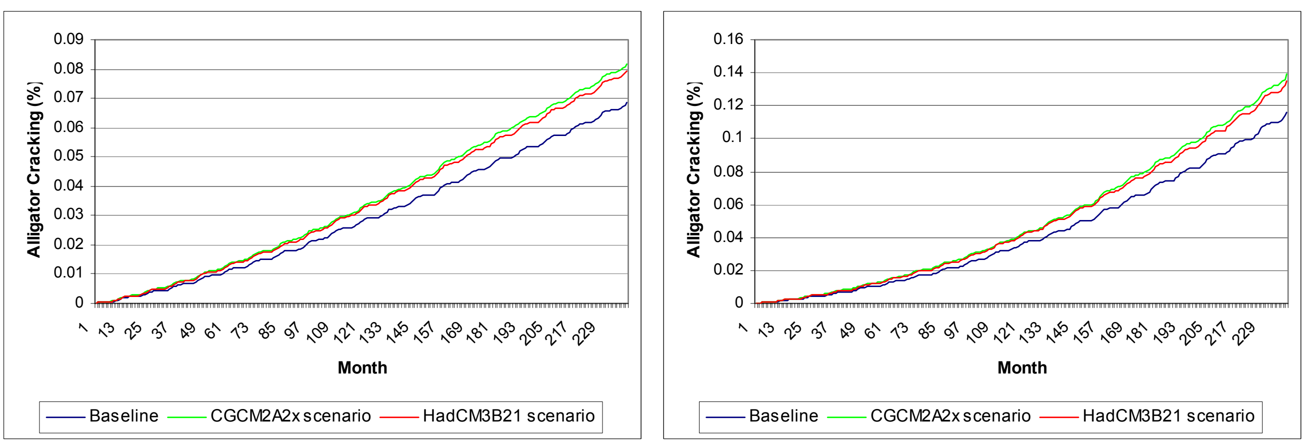


Figure D-33. Alligator cracking performance at the Newfoundland site (St. John's) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

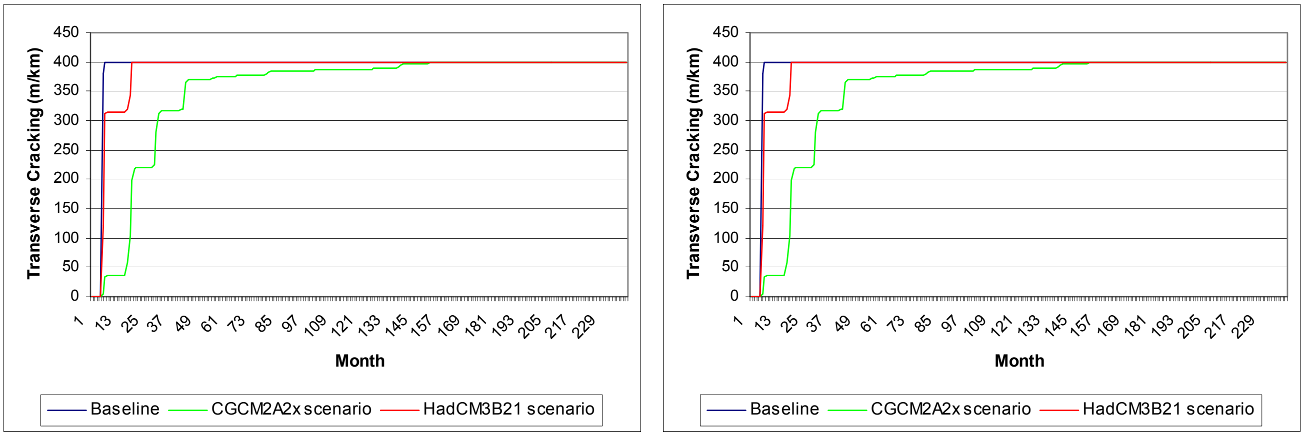


Figure D-34. Transverse cracking performance at the Newfoundland site (St. John's) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

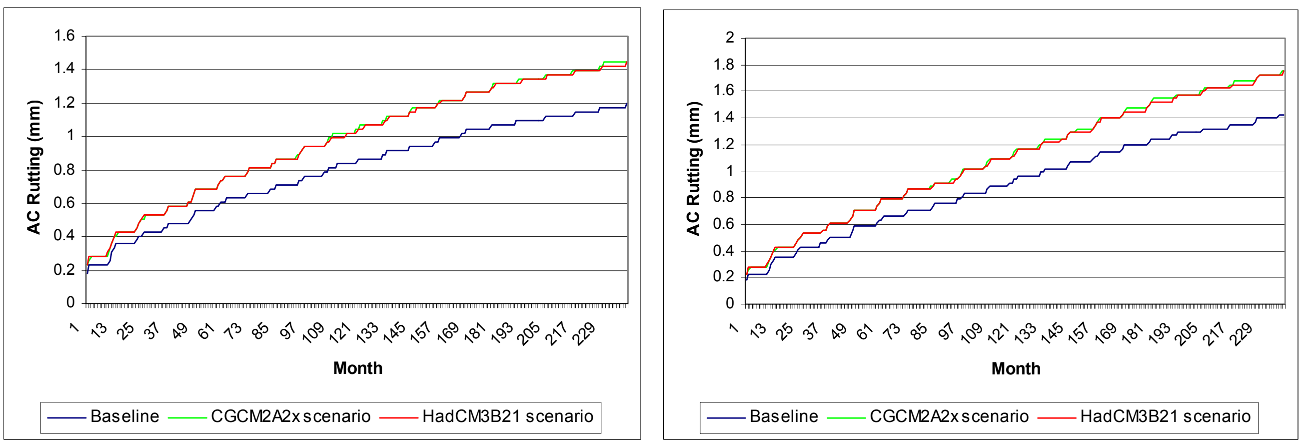


Figure D-35. AC rutting performance at the Newfoundland site (St. John's) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic

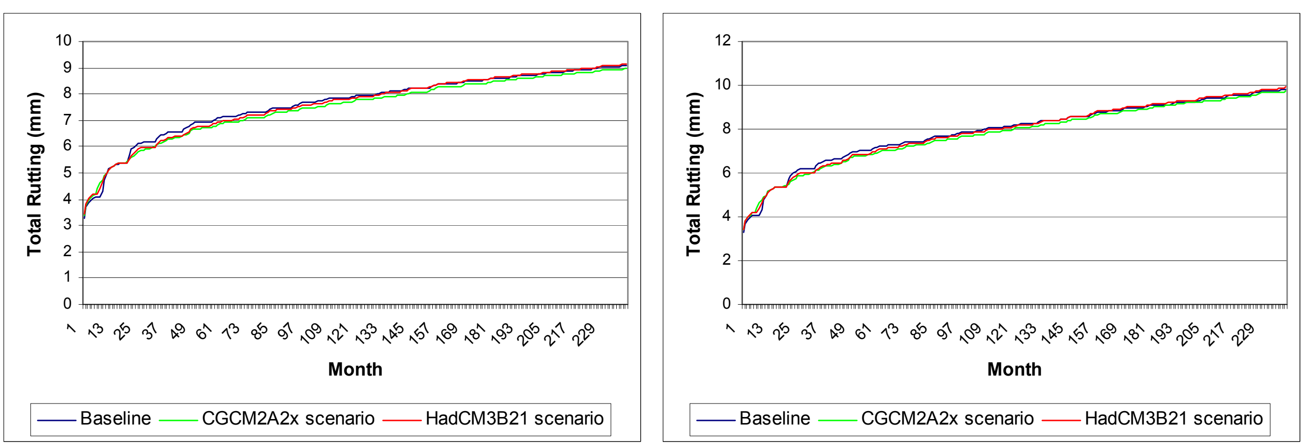
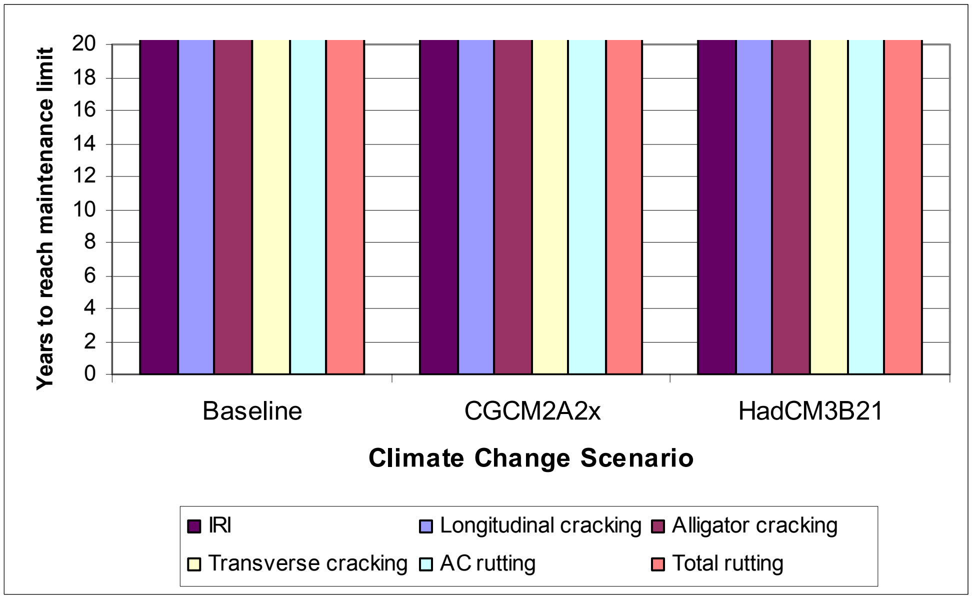
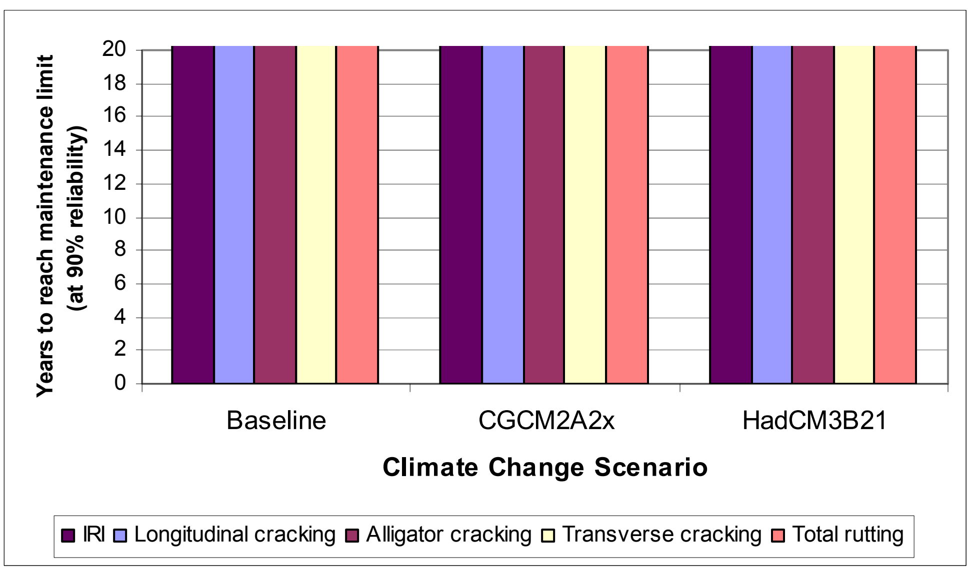


Figure D-36. Total rutting performance at the Newfoundland site (St. John's) under baseline and future climate scenarios assuming 0(left) and 4(right) percent annual increase in traffic



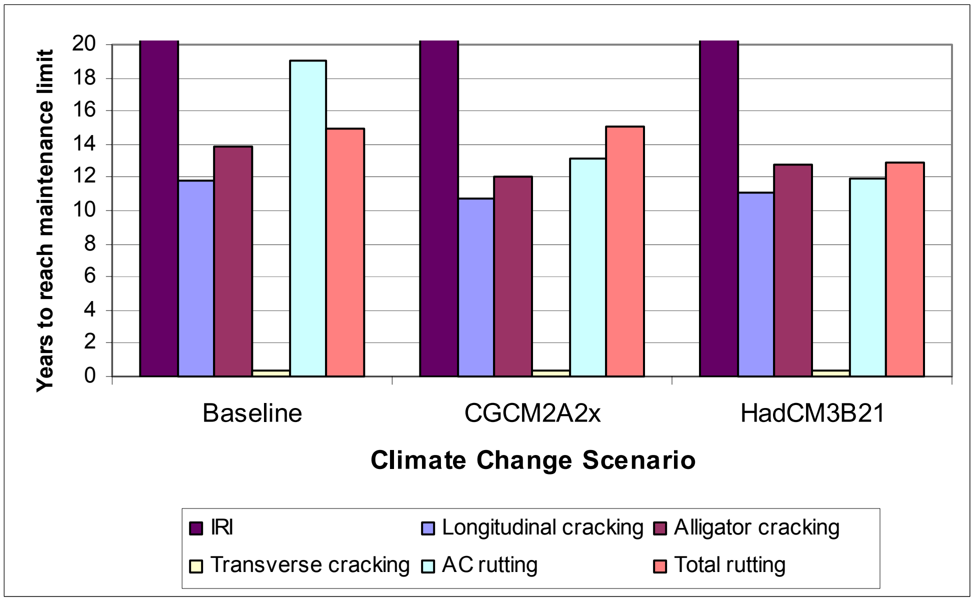
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-37. Years to reach performance parameter limits (50% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the British Columbia site (Vancouver)



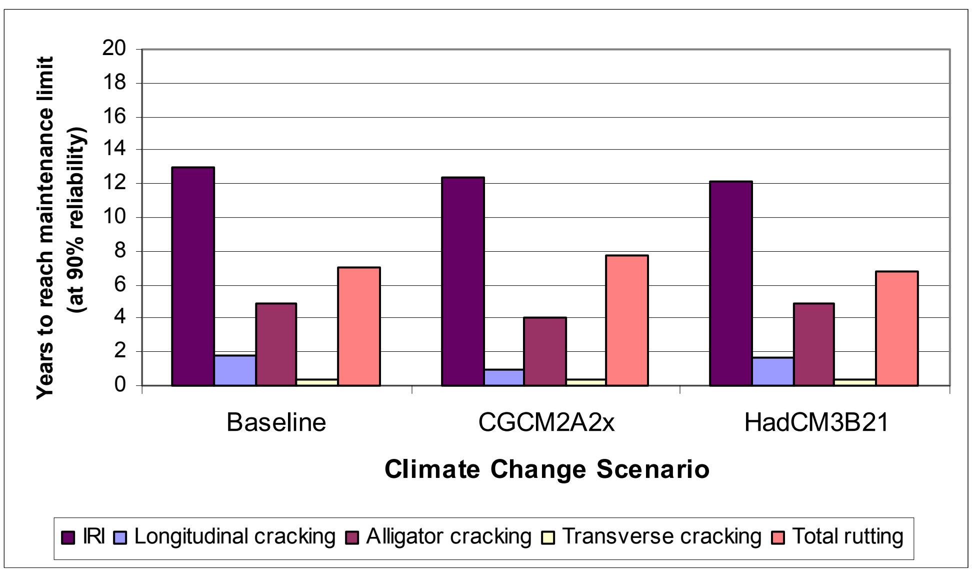
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-38. Years to reach performance parameter limits (90% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the British Columbia site (Vancouver)



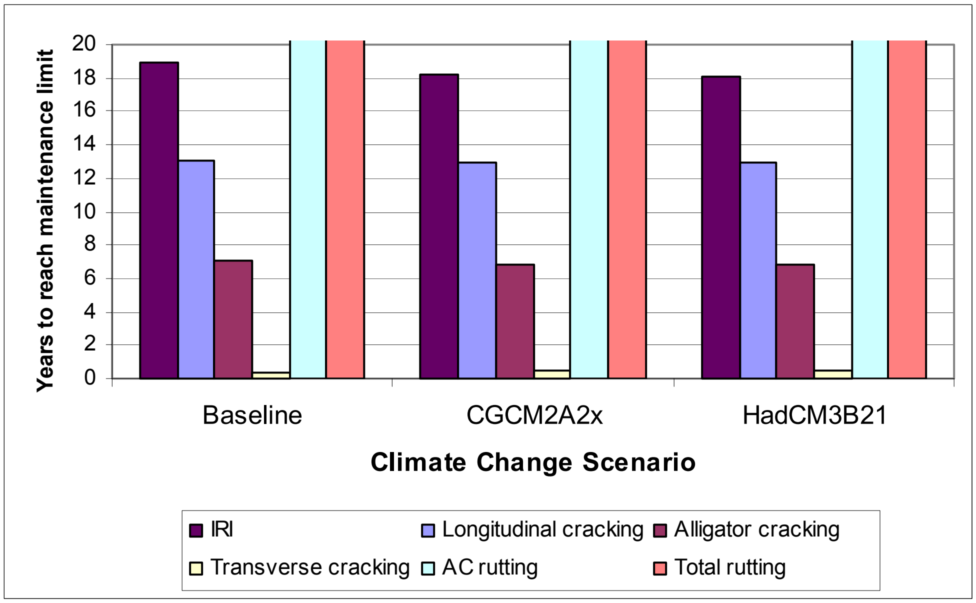
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-39. Years to reach performance parameter limits (50% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Alberta site (Edmonton)



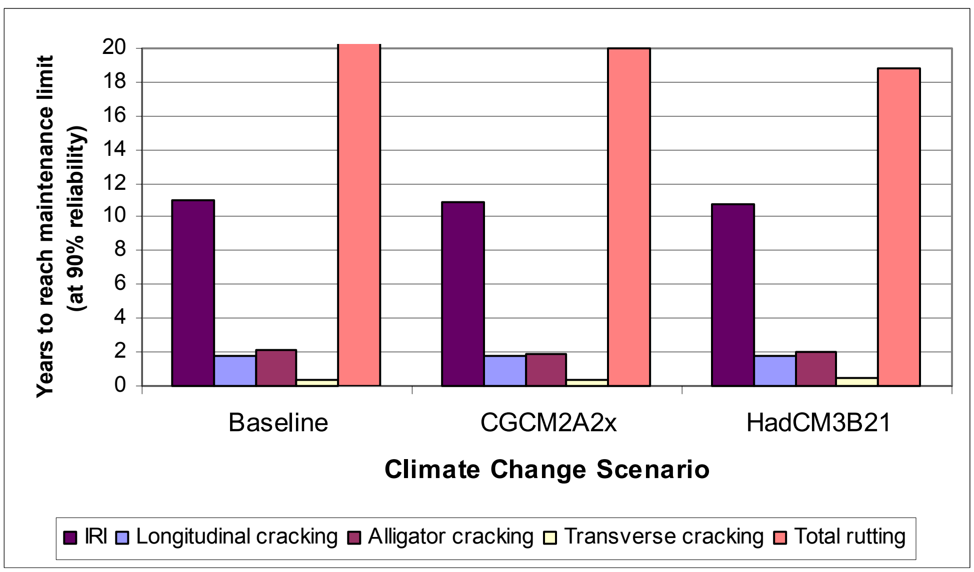
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-40. Years to reach performance parameter limits (90% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Alberta site (Edmonton)



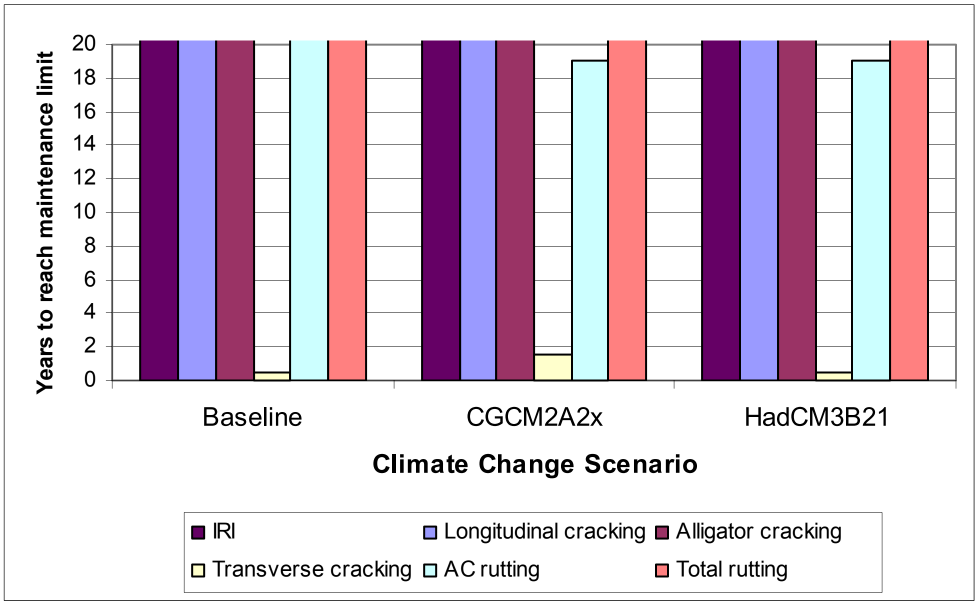
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-41. Years to reach performance parameter limits (50% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Manitoba site (Winnipeg)



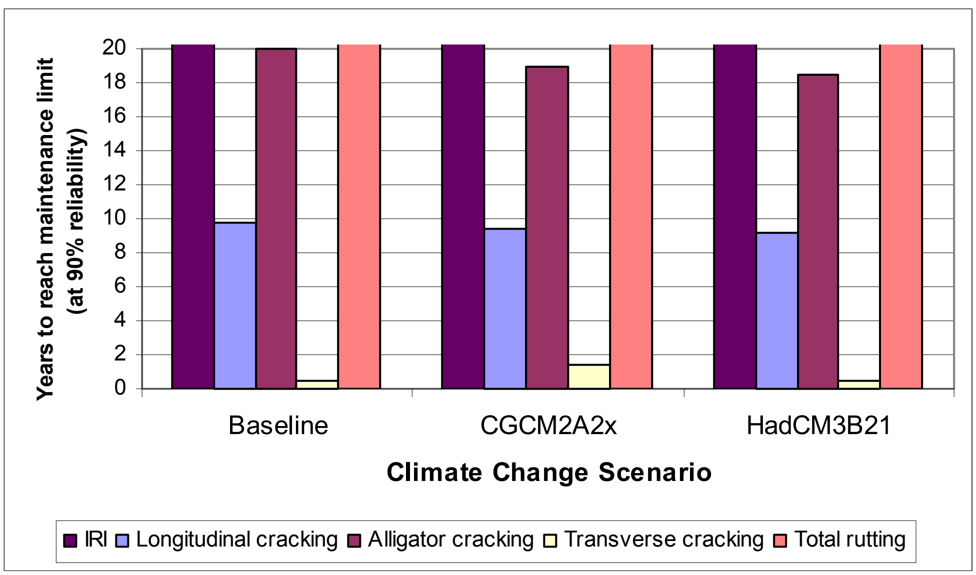
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-42. Years to reach performance parameter limits (90% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Manitoba site (Winnipeg)



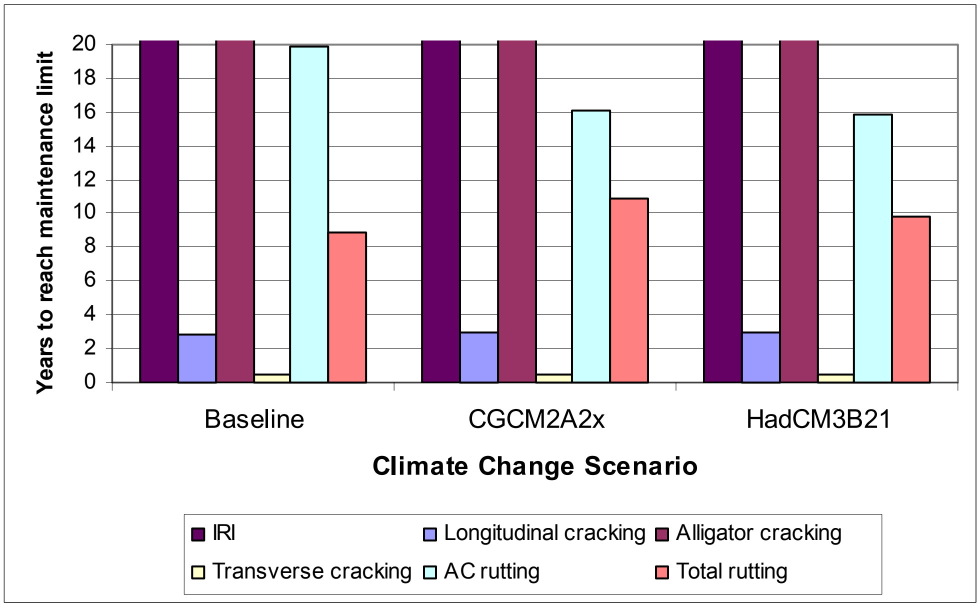
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-43. Years to reach performance parameter limits (50% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Ontario site (Toronto)



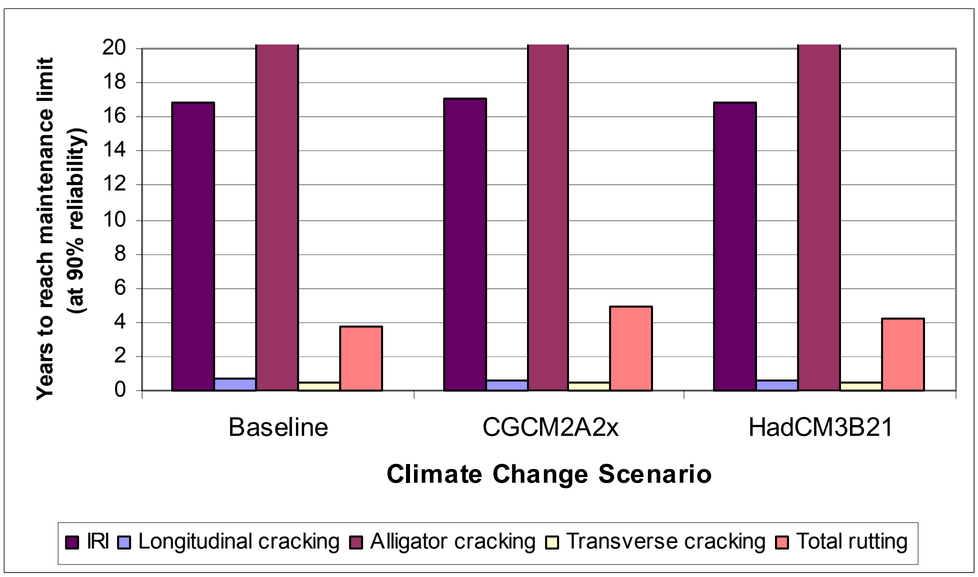
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-44. Years to reach performance parameter limits (90% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Ontario site (Toronto)



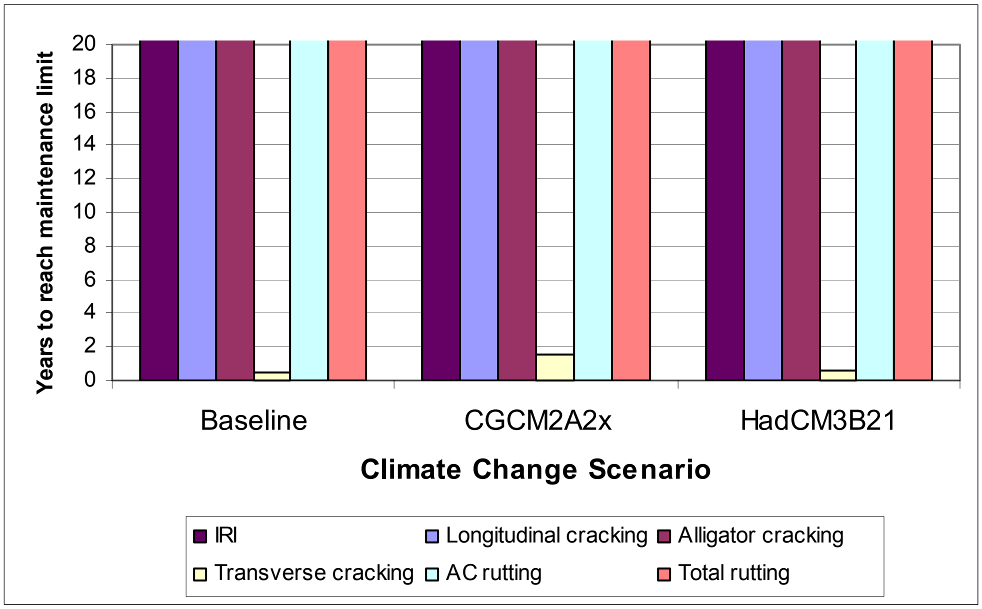
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-45. Years to reach performance parameter limits (50% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Quebec site (Montreal)



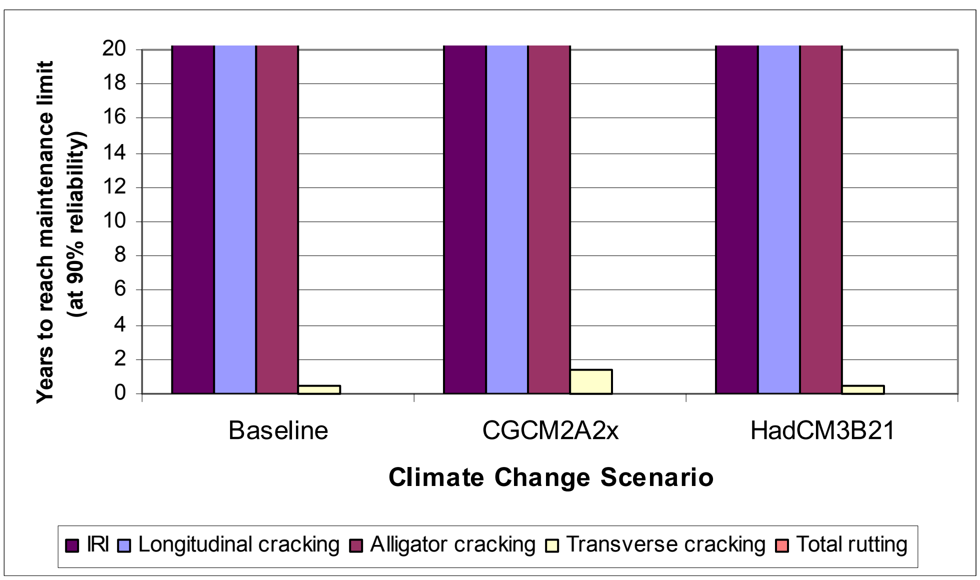
*values greater than 20 years indicate parameter limits not reached during design life

Figure D-46. Years to reach performance parameter limits (90% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Quebec site (Montreal)



*values greater than 20 years indicate parameter limits not reached during design life

Figure D-47. Years to reach performance parameter limits (50% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Newfoundland site (St. John's)



*values greater than 20 years indicate parameter limits not reached during design life

Figure D-48. Years to reach performance parameter limits (90% reliability maintenance thresholds) under 4 percent annual traffic growth scenario at the Newfoundland site (St. John's)