City-scale modelling of road thermal and hydrological characteristics: Case study of Montreal

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ABSTRACT

The performance and management of road infrastructure are significantly impacted by climatic conditions. Climate-road interaction studies for future emission scenarios are therefore important to inform their design and management strategies. This study focusses on city-scale modelling of road thermal and hydrologic characteristics, for current and future climates, with city of Montreal, Canada as the case study. To this end, simulations using the Surface Prediction System (SPS) of Environment and Climate Change Canada, consisting of a land surface model CLASS (Canadian Land Surface Scheme) and Town Energy Balance model (TEB) for better representation of urban regions, including roads, at 250 m (0.0025°) resolution, spanning the 2001–2020 and 2041–2060 periods are used. These simulations are driven by atmospheric forcing data, derived from high-resolution 4-km regional climate model simulations, driven by European Centre for Medium-Range Weather Forecast's (ECMWF) fifth generation reanalysis product ERA5 and the Canadian Earth System model (CanESM2), with the future simulations corresponding to Representative Concentration Pathway (RCP) 8.5 scenario.

After confirming the ability of SPS and TEB in simulating mean land and road surface temperatures (RST) by comparing with satellite data derived from MODIS, the thermal and hydrologic attributes related to road failure mechanisms during cold (October-May) and warm (June–August) seasons are studied for two broad road categories: highways and local roads, with the latter consisting of arterials, collector roads, and local roads. Analysis of important cold season thermal attributes such as freeze-thaw cycles and winter partial thaws, that can lead to loss of structural support, surface distress and pavement damage, suggests reduced impacts in future climate associated with a 12.5% decrease in freeze thaw cycles and a 2% decrease in winter partial thaws. Although weight restriction days currently practiced preventing weakening of the pavement

and road layers during the thaw period should be continued, it is projected to occur on average 15 days earlier in future climate compared to current climate according to the analysis. However, the hydrologic characteristics for the cold season, such as road runoff, suggested to increase in the 12-15% range, coupled with increases in land runoff, may offset these benefits, pointing to the need for adequate drainage systems. The spatial patterns suggest generally higher increases in runoff for the local road network for regions with higher urban fractions. Unlike the cold season, future impacts on the road network during the warm season, associated with both thermal and hydrological characteristics, are projected to increase. For instance, the projected increase in warm season mean daily maximum RST in the 4 to 4.5°C range suggests the potential for more rutting events, particularly on highways. As for the cold season, projected increases in warm season road and land runoff, of about 25%, highlight the need for a thorough assessment of existing drainage systems.

This study, in addition to exploring the utility of TEB as a tool for studying thermal and hydrologic characteristics of roads, albeit its simplicity, provides useful information on the climate drivers related to road failure. Furthermore, the spatial differences in vulnerability obtained for the road categories can be helpful in prioritizing road sections for more detailed studies.

RÉSUMÉ

La performance et la gestion des infrastructures routières sont fortement impactées par les conditions climatiques. Les études sur l'interaction climat-route pour les futurs scénarios d'émissions sont donc importantes pour éclairer leurs stratégies de conception et de gestion. Cette étude se concentre sur la modélisation à l'échelle urbaine des caractéristiques thermiques et hydrologiques des routes, pour les climats actuels et futurs, avec la ville de Montréal, au Canada, comme étude de cas. À cette fin, des simulations utilisant le modèle SPS (Surface Prediction System) d'Environnement et Changement climatique Canada, composé d'un modèle de surface terrestre CLASS (Canadian Land Surface Scheme) et d'un modèle urbain Town Energy Balance (TEB) pour une meilleure représentation des régions urbaines, incluant les routes, à une résolution de 250 m (0,0025°), couvrant les périodes 2001-2020 et 2041-2060 sont utilisés. Ces simulations sont basées sur des données de forçage atmosphérique dérivées de simulations de modèles climatiques régionaux de 4 km à haute résolution, pilotées par le produit de réanalyse de cinquième génération du Centre européen pour les prévisions météorologiques à moyen terme ERA5 et le modèle CanESM2 (Canadian Earth System), avec les simulations du climat futur correspondant au scénario Representative Concentration Pathway (RCP) 8.5.

Après avoir confirmé la capacité des modèles SPS et TEB à simuler les températures moyennes des terres et des surfaces routières en comparant avec les données satellite dérivées de MODIS, les attributs thermiques et hydrologiques liés aux mécanismes de rupture des routes durant les saisons froide (octobre-mai) et chaude (juin-août) sont étudiés pour deux grandes catégories de routes: les autoroutes et les routes locales, ces dernières étant constituées d'artères, de routes collectrices et de routes locales. L'analyse des attributs thermiques importants de la saison froide, tels que les cycles de gel-dégel et les dégels partiels hivernaux, qui peuvent entraîner une perte du

support structurel, une détérioration de la surface et des dommages à la chaussée, suggère une réduction des impacts du climat futur associée à une diminution de 12,5 % des cycles de gel-dégel et une diminution de 2 % des dégels partiels hivernaux. Bien que les jours de restriction de poids actuellement pratiqués pour empêcher l'affaiblissement de la chaussée et de la route pendant la période de dégel devraient être maintenus, cela devrait se produire en moyenne 15 jours plus tôt dans le climat futur par rapport au climat actuel, selon l'analyse. Cependant, les caractéristiques hydrologiques de la saison froide, telles que le ruissellement des routes, qui devraient augmenter de 12 à 15 %, associées à une augmentation du ruissellement des terres, pourraient contrebalancer ces avantages, soulignant la nécessité de systèmes de drainage adéquats. Les schémas spatiaux suggèrent des augmentations généralement plus élevées du ruissellement pour le réseau routier local dans les régions ayant une fraction urbaine plus élevée. Contrairement à la saison froide, les impacts futurs sur le réseau routier pendant la saison chaude, associés aux caractéristiques thermiques et hydrologiques, devraient augmenter. Par exemple, l'augmentation projetée de la RST quotidienne maximale moyenne en saison chaude dans la plage de 4 à 4,5 °C suggère la possibilité d'une augmentation des épisodes d'orniérage, en particulier sur les autoroutes. En ce qui concerne la saison froide, l'augmentation prévue du ruissellement des routes et des terres pendant la saison chaude, d'environ 25 %, souligne la nécessité d'une évaluation approfondie des systèmes de drainage existants.

Cette étude, en plus d'explorer l'utilité du modèle TEB en tant qu'outil d'étude des caractéristiques thermiques et hydrologiques des routes, malgré sa simplicité, fournit des informations utiles sur les facteurs climatiques liés à la défaillance des routes. En outre, les différences spatiales de vulnérabilité obtenues pour les différentes catégories de routes peuvent être utiles pour prioriser des tronçons routiers pour des études plus détaillées.

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CONTRIBUTION OF AUTHORS

This thesis has been written following the Graduate and Postdoctoral Studies requirements for a manuscript-based thesis. The main findings of the research undertaken by the author as part of her master's program are presented in a single manuscript. The author carried out the numerical analysis and wrote the manuscript under the supervision of Prof. Laxmi Sushama (supervisor). The publication detail is presented below:

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Asphalt concrete
AC	Alligator cracking
BC	Block cracking
FDD	Freezing degree day
GCM	General Circulation Models
HMA	Hot mix asphalt
LC	Longitudinal cracking
LST	Land surface temperature
LTPP	Long-Term Pavement Performance
PFF	Pluvial flash flood
RCM	Regional Climate Models
RCP	Representative Concentration Pathways
RST	Road surface temperature
SPS	Surface Prediction System
SUPERPAVE	Superior Performing Asphalt Pavement
TC	Transverse cracking
TD	Thawing degree
TEB	Town Energy Balance model
UGM	Unbound granular materials
UHI	Urban heat island

CHAPTER 1 - INTRODUCTION

1.1 Background

Climate change, characterized by warmer temperatures and more frequent and intense heatwaves, shorter winter seasons, higher precipitation rates, and flash floods, has placed transportation infrastructure in the spotlight, given the huge impact of weather and climate on their functionality and durability (Kouroshnejad et al., 2023; Teufel & Sushama, 2022). Any adverse impact on the road network, which forms the backbone of cities, can lead to significant local and more widespread impacts. Development and implementation of climate change adaptation measures are considered crucial in increasing the overall resiliency of such infrastructure (Palko & Lemmen, 2017). This necessitates comprehensive information on projected changes to climatic variables/predictors important from road failure perspectives at engineering scales, as well as insights into road surface behavior under such evolving scenarios.

Moreover, there is a clear benefit to modeling interactively road surface temperatures (RST) and other road characteristics in climate models as it helps improve the realism of the simulated surface climate, the opportunity for which is better than ever before, given the increase in climate model resolutions such as the convection permitting resolutions, i.e., a few km to sub km scale (Prein et al., 2015; Teufel et al., 2021). Although computing resources could be a limitation in undertaking such high-resolution climate model simulations, very high-resolution offline simulations with emerging land models with better representation of urban regions, including roads, which represent the land part in climate models, can provide very useful insights to inform and develop climate change adaptation strategies to limit the adverse impacts of climate change on the road network/infrastructure.

1.2 Motivation

Similar to many other cities, Montreal's transportation system is mostly dependent on its road networks. These roadways support daily commuting/transportation and facilitate business activities (Tu et al., 2022). However, climate change is posing an increasing threat to the sustainability and performance of these roadways, especially with regard to extreme weather events such as heatwaves and flash floods. Furthermore, problems such as ground settlements and depressions caused by runoff can worsen pavement degradation, affecting drainage systems as well as the longevity of roads (Maadani et al., 2021). As mentioned earlier, it may be more beneficial to use interactive modeling of road surface conditions and RST in climate models to address these issues. This can be achieved through a more realistic modelling of the surface and urban characteristics in climate models. Notably, there is a gap in the existing literature when it comes to such studies over Canada.

In the context of a changing climate, a sophisticated framework is necessary to thoroughly understand the mechanisms leading to road failures, which vary with season. One of the primary concerns in cold regions is freeze-thaw cycles (Bilodeau et al., 2015). These cycles characterized by fluctuating temperatures have the potential to cause pavement cracking and surface distress. Variations in temperature and moisture content during freeze-thaw (FT) are key drivers behind the concerns impacting the mechanical stresses and strains experienced within pavement layers. Furthermore, a pavement's structural stability may be compromised by partial thaw conditions, increasing the likelihood of surface deformations such as rutting and cracking (Leong et al., 2005; Mills et al., 2009). The stability of unbound granular materials within the pavement structure is impacted by these deformations. Effective drainage systems are essential for mitigating the effects of inundation and intense precipitation which can eventually result in the accumulation of water on roadways (Mukherjee, 2014). Along with that, hot weather in the summer can cause a variety of road problems, including potholes, rutting, depressions, cracks, and more. Depressions, small bowl-shaped patches that are frequently accompanied by cracks, contribute to the roughness of pavement, posing hazards to vehicles and facilitating water collection. The lifespan of bituminous pavements is significantly shortened by surface cracks, which also serve as early warning signs for other types of cracks and accelerate the overall failure of the pavement. Potholes arise from the extreme fatigue cracking of road layers cause pavement to dislodge as vehicles pass over them (Wada, 2016). Also, rutting events, during summer period, lead to the formation of shallow grooves or trenches on pavement surfaces due to increased temperature and asphalt softening (Matulla et al., 2018). The interplay between these climate factors and failure mechanisms emphasizes how crucial it is to study the road infrastructure by taking climate change into account. The primary objective of this research is the city-scale modeling of the thermal and hydrological characteristics of the road network, which are connected to cold and warm season failure mechanisms. This evaluation is conducted through the application of a sophisticated framework - the Surface Prediction System (SPS) of Environment and Climate Change Canada, that incorporates a land surface model with a realistic depiction of the urban regions using the Town Energy Balance model (TEB), which includes a simplified road model, for current and future climates, for an extreme Greenhouse Gas emission scenario for the island of Montreal in Canada. The results of this study will serve as the basis for additional research, providing insightful information regarding road vulnerability.

1.3 Research objectives

This study comprehensively investigates the climate variables/predictors related to road failure mechanisms during cold and warm seasons using SPS simulations for current and future climates at 250 m resolution (250m), using atmospheric forcing from 4 km regional Global Environmental Multiscale (GEM) climate model simulations. The research aims to achieve the following objectives:

- Undertake an extensive literature review of existing mechanical and empirical road models and their application in understanding road failure mechanisms, emerging land models/modules of climate models with improved representation of urban regions – including roads, thermal and hydrologic related road failure mechanisms, and climate change impacts on roads.
- Setting up of numerical simulations using SPS over the experimental domain covering the island of Montreal and validating, quantitatively and qualitatively, SPS simulated land surface temperature and RST, using satellite data.
- Investigation of the differences between 2m temperature and RST characteristics and to demonstrate the limitations in using 2m temperature as a direct surrogate for RST.
- Assess projected changes to road thermal and hydrologic characteristics associated with road failure mechanisms for cold and warm seasons.
- Draw conclusions on the impact of climate change on the Montreal road network in current and future climates from thermal and hydrologic perspectives, while identifying/recommending future improvements/studies that can increase the robustness of the results of this study.

1.4 Thesis outline

The thesis is divided into five chapters: Chapter 1 provides a broad overview of the background, motivation for conducting the study, and objectives. Chapter 2 reviews literature pertinent to this study: empirical and physically based models of road surface temperature and the usefulness of emerging land models with improved representation of urban regions, roads, and related features, thermal and hydrology related road failure mechanisms and related climate variables in cold and warm seasons, and climate change impacts on road. Chapter 3 presents the main results of this study, i.e., city-scale modelling of road thermal and hydrologic characteristics and failure mechanisms: case study of Montreal, which is presented in the form of a journal article, following the article-based thesis format. Chapter 4 provides additional discussions and lastly, Chapter 5 summarizes the findings, offers ideas for additional pertinent research, and discusses limitations of this study.

CHAPTER 2 - LITERATURE REVIEW

Weather and climate influence substantially the performance and maintenance of road infrastructure, particularly within urban settings. Road networks, which are essential for the transportation of goods and individuals, are vulnerable to the effects of rising temperatures and changing precipitation patterns. These effects include concerns about road failure and deterioration which may impact structural soundness, design and upkeep, and difficulties faced during road construction and maintenance. The goal of this study is to develop city-scale understanding of the climate change vulnerabilities of the Island of Montreal's road network which can significantly contribute to their design and management and/or detailed additional analysis of road sections.

This chapter reviews advances in related topics such as modelling of road surface temperature: different approaches, road failure mechanisms and related climate variables and climate change impacts on roads.

2.1 Modelling of road surface temperature: Different approaches

RST predictions are important for the evaluation of pavement performance, understanding of traffic load response, and long-term pressures that the pavement will encounter during its operational life. The two commonly used methods of estimation are through: empirical models and physical models (Shi et al., 2020). Empirical models/methods make use of empirical relationships linking road temperature with air temperature, sky view factor, traffic density and/or other related variables.

The first attempt to estimate RST using empirical relations was made by Barber (1957) in 1957 using climate data. Years later, the Kentucky Department of Highways began researching temperature distribution characteristics of road surfaces (Southgate, 1968) and thereafter a great deal of research was done on this topic (Adwan et al., 2021; Chen et al., 2019; Di Mascio et al., 2007; Islam et al., 2015; Khadrawi et al., 2012; Minhoto et al., 2005; Mokoena et al., 2022; Park et al., 2016; Qin & Hiller, 2011; Shah et al., 2013; Singh et al., 2018; Wang et al., 2015). Empirical formulas from Long-Term Pavement Performance (LTPP) and Superior Performing Asphalt Pavement (SUPERPAVE) are used extensively in studies to calculate different (maximum, minimum, mid-depth, average) pavement temperatures. They developed equations to calculate pavement temperature from air temperature data (Bosscher et al., 1998). Where some research concentrated on equations developed from variables like pavement thickness, air and surface temperatures, and daytime hours to calculate pavement temperature (Gedafa et al., 2014).

For instance, Gedafa et al. (2014) proposed an empirical equation for mid-depth pavement temperature based on: (1) the time of day in decimal hours when measurements were taken, (2) pavement surface temperature, (3) average air temperature from the previous day, and (4) the thickness of the mid-depth layer. The terms which were significant at 5% significance level were included in the final model as:

$$T_{pav} = -5.374 - 0.752T_{sur} + 0.022T_{sur}^2 + 2.016T_{avg} - 0.032T_{sur} \times T_{avg} 1.549t_d - 0.022D, \quad (1)$$

where, T_{pav} is the layer mid-depth pavement temperature (°C), T_{sur} the pavement surface temperature (°C), T_{avg} the average previous day air temperature (°C), t_d the time of the day (hours), and D is the pavement mid-layer depth (mm). They used measurements of the pavement temperature from October 2007 to verify the model and reported that the model tends to over-predict mid-depth pavement temperatures by 1.5 °C even though it yields a mid-depth pavement temperature closest to the measured temperature (Fig. 2.1). They highlighted the need for additional validation procedures and thorough research to ensure the accuracy of the model.

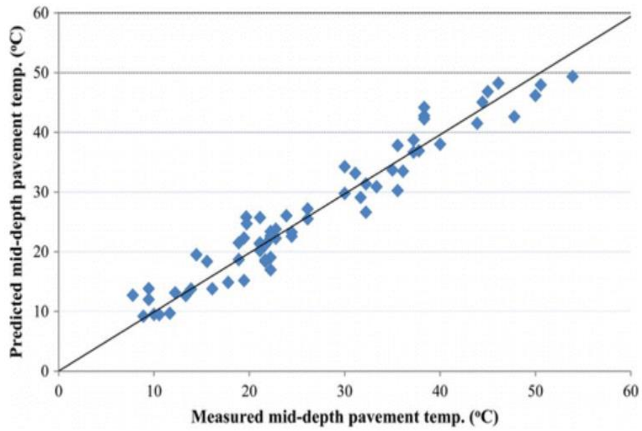

Fig. 2.1 Comparison of measured and predicted mid-depth pavement temperatures (Gedafa et al., 2014).

Likewise, Asefzadeh et al. (2017) concentrated on developing an empirical model based on two years of field data collected in Edmonton, Alberta. They utilized empirical formulas developed through SUPERPAVE and LTPP for the lowest and highest pavement temperatures and temperatures at different pavement depths. Lowest pavement temperature on top layer and lowest pavement temperature at a particular depth are calculated by considering following equations:

$$T_d = T_{air(m)} + 0.051d - 0.000063d^2 \quad (2)$$

$$T_{pav} = 0.859T_{air(m)} + (0.002 - 0.007T_{air})H + 0.17 \quad (3)$$

where, T_d is the minimum pavement temperature (°C) at depth *d (mm)*, T_{pav} is minimum top layer pavement temperature (°C), $T_{air(m)}$ is minimum one-day air temperature (°C), and H is the total depth of the pavement(mm).

Asefzadeh et al. (2017) also measured pavement and air temperatures at various test sites in Edmonton, Alberta, to create new model (statistical model) to improve the binder selection process for SUPERPAVE. Recorded field data between September 1st and October 31st, 2016, were utilized to confirm the model's accuracy in predicting the road temperatures. With a strong correlation (R^2=0.996) between the mean daily temperature and the temperature from the statistical model (Fig 2.2), the presented statistical model by Asefzadeh et al. (2017) is expected to perform well at predicting the temperatures in roads located at the same latitude and in weather conditions similar to Edmonton.

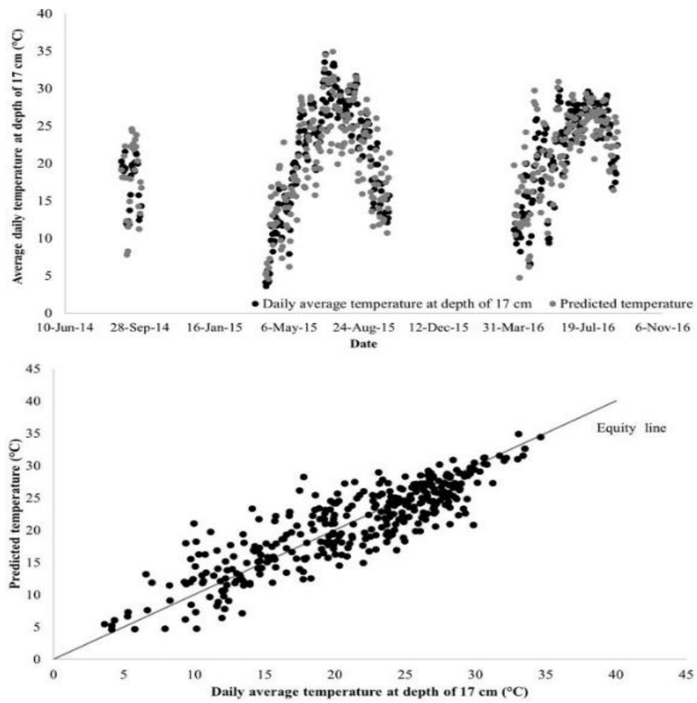

Fig. 2.2 Predicted versus measured temperatures at a depth of 17 cm during the warm season (Asefzadeh et al., 2017).

These investigations offer insightful information about pavement temperature analysis. However, they are location-specific, and it is essential to validate the performance of each model using additional field data from diverse road pavements and it is important to note that these models rely on statistical analysis rather than theoretical derivation. As a result, they might not fully capture the entire process of heat transfer within the pavement. Thus, the accuracy of these empirical relations remains uncertain.

The second approach utilizes physically based models, which offer a more thorough knowledge of the underlying processes influencing temperature characteristics of the road infrastructure. Physical models consider the fundamentals of heat transport, the thermal properties of materials, and the interactions between different forcings, in contrast to empirical models, which only consider statistical correlations between variables, particularly in scenarios where local conditions and materials may differ from the norm. Two such physically based models – RoadSurf and Town energy balance model (TEB) – are discussed here.

RoadSurf model:

The Finnish Meteorological Institute's (FMI) 1D simulation model RoadSurf calculates vertical heat transfer in the ground and at the ground–atmosphere interface (Fig. 2.3). As input/forcing data, the model requires air temperature, relative humidity, wind speed, precipitation, and short- and long-wave radiation. The model's output includes surface friction, road surface temperature, and classified variables that describe both specific road conditions and traffic conditions at a broader level (Kangas et al., 2015).

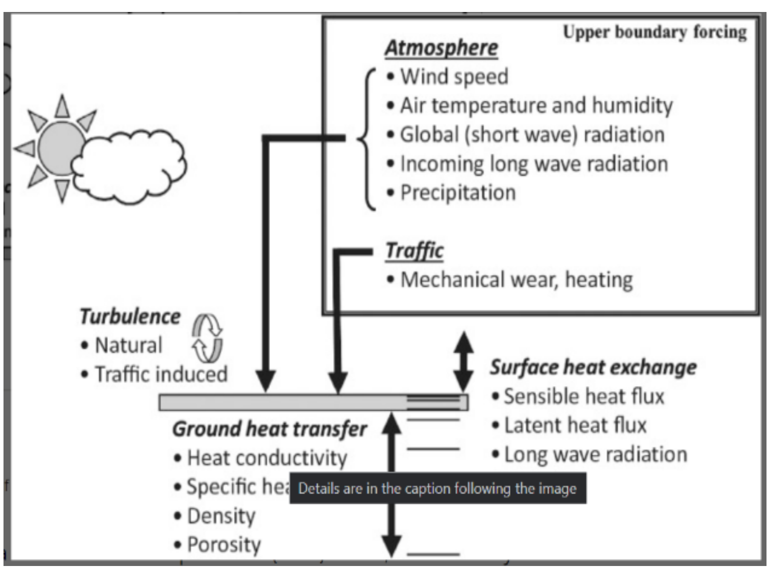

Fig. 2.3 Energy balance schematic of the RoadSurf model (Kangas et al., 2015).

Physically, the model operates by solving the energy balance at the ground surface, which can be written as:

$$G = I_{NET} - H - LE + PC \tag{4}$$

where, G is the heat flux into the ground, I_{NET} is net radiation on the surface, H is the sensible and LE the latent turbulent heat flux from the ground surface, and PC describes heat flow due to phase change (freezing/melting). 1D Heat conduction equation is applied to estimate layer temperatures as:

$$\frac{\partial T(z,t)}{\partial t} = K_g \frac{\partial^2 T(z,t)}{\partial z^2}, \qquad K_g = \frac{k_g}{\rho_g c_g} \tag{5}$$

where, z is the vertical distance below ground, t is time, K_g is the thermal diffusivity, k_g heat conductivity, ρ_g density and c_g specific heat capacity of the ground. In addition to that, the model assesses hydrological conditions of the surface based on various storage terms that describe the amount of water, snow, ice and frost on the surface. The storage sizes for water (S_w), ice (S_i), track ice (S_{ii}), snow (S_s) and frost (S_f) are controlled by conservation equations as follows:

$$\frac{dS_w}{dt} = \emptyset_{PR} - \emptyset_E + \emptyset_M - \emptyset_F - W_w \tag{6}$$

$$\frac{dS_i}{dt} = \emptyset_F - \emptyset_M + \emptyset_S + K_{rf} W_s - W_i, \qquad K_{rf} = 0.5 \tag{7}$$

$$\frac{dS_{ii}}{dt} = \emptyset_F - \emptyset_M + \emptyset_S + K_{rf} W_s - W_{ii}, \qquad K_{rf} = 0.5 \tag{8}$$

$$\frac{dS_s}{dt} = \emptyset_{PS} - \emptyset_M - \emptyset_F - W_S \tag{9}$$

$$\frac{dS_f}{dt} = \emptyset_D - \emptyset_M - W_S \tag{10}$$

where, the Φ terms indicate source/sink terms with the subscripts PR, PS, E, F, M, S and D denoting precipitation (rain and snow), evaporation, freezing, melting, sublimation and desublimation, respectively. The W terms represent the wear (or actual rate of wear) of the substance in question caused by the traffic.

In order to examine the current state of roads and walkways in Finland, Toivonen et al. (2019) utilized the RoadSurf model. They reported biases in the ±2 °C range when comparing with measurements from 25 weather stations around Finland for the 2002–2014 period, with 57% of the biases linked to biases in the driving air temperature. According to the study, the lack of road maintenance option in the model affected its performance, causing it to overestimate ice and snow but underestimate water and they concluded that despite these issues, RoadSurf performed well, making it a suitable tool for studying future road weather conditions with climate projections from RCMs.

Likewise, Freistetter et al. (2022) also applied RoadSurf to study roads and walkways in Finland, Norway, and Sweden. They used observations of road surface temperature and road surface conditions from 5 stations in Sweden (2015–2018) and 5 stations in Norway (2015–2018) in hourly resolution for the validation of the model and found good agreement between model and observations.

Town Energy Balance (TEB) model:

The regional road weather models have the potential to be coupled with climate models to establish two-way feedback mechanisms between the atmosphere and surface, thereby enabling a more realistic simulation of the surface climate, while also being able to obtain useful information regarding road characteristics. Complex physically based models can be difficult to directly integrate into climate models, but simpler models, such as TEB, can be effectively incorporated. TEB model, developed by (Masson, 2000a), is an urban surface scheme based on urban energy budget.

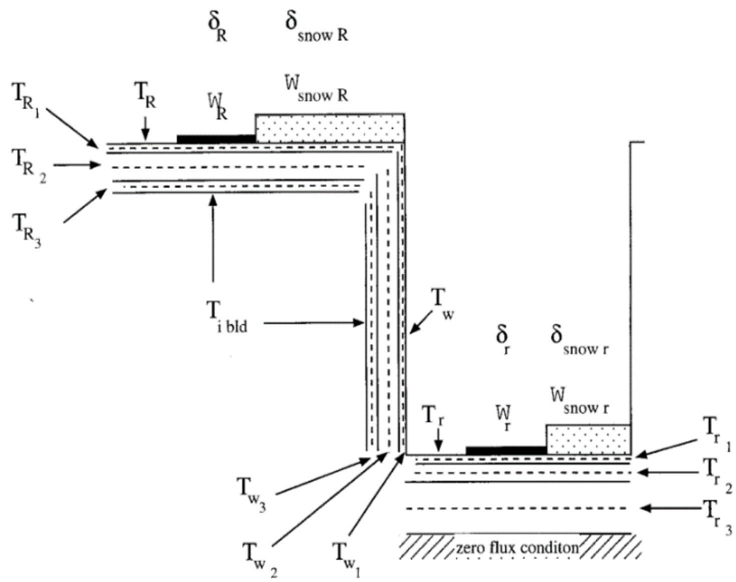

Fig 2.4. Discretization of the surfaces (roof, wall, road) and prognostic variables (Masson, 2000a): layer temperatures T_{*k} (* = R, w, r; here three layers are displayed for each surface, so k = 1, 2, 3), surface water content W_* (* = R, r), surface snow content W_{snow*} (* = R, r). The layer temperatures are representative of the middle of each layer (dotted lines). The surface temperatures are assumed to be equal to the surface-layer temperature: $T_* = T_{*k}$ .The internal building temperature T_{ibld} is prescribed. Fractions of water or snow (δ_* and δ_{*snow} respectively).

TEB introduces a simplified representation of urban geometry, where buildings and roads are generalized as canyons (see Fig 2.4). It divides the urban energy budget into separate parts, including roofs, roads, and walls, with orientation effects averaged for roads and walls. Additionally, up to two energy budgets are considered for snow cover on roofs or roads. TEB assumes buildings have uniform height and width, and they are situated along roads forming canyons. This simplified approach allows for a relatively straightforward urban representation in weather/climate models. Energy budget concepts serve as the basis for the equations controlling the temperature variations within each layer. The general prognostic equations for evolution of surface temperature for the surface layers of the roof, wall, and road is given as:

$$C_{*_1}\frac{\partial T_{*_1}}{\partial t} = (1-\delta_{snow*})\frac{1}{d_{*_1}}\left(S_*^* + L_*^* - H_* - LE_* - G_{*_{1,2}}\right) + \delta_{snow*}\frac{1}{d_{*_1}}\left(G_{*_{snow,1}} - G_{*_{1,2}}\right), \quad (11)$$

where, *: R (roof), r (road) or w (wall), T_{*_k}: temperature of layer k (k=1 : surface layer), C_{*_k}: heat capacity, d_{*_k}: layer thickness, δ_{snow*}: snow fraction on the surface ($\delta_{snow\,w}$ = 0), S_*^*: net solar radiation, L_*^*: net infra-red radiation, H_*: sensible heat flux, LE_*: latent heat flux, $G_{*_{1,2}}$: conduction heat flux between surface layer and underlying layer, $G_{*_{snow,1}}$: conduction heat flux between surface layer and base of snow layer. The default number of layers for roofs, walls and roads is three.

Lemonsu et al. (2015) used TEB offline simulations for Paris, looking at how the urban climate changed over time, from the year 1900. Using technical assumptions about building characteristics and a socio-economic land-use transport interaction model, NEDUM-2D, they constructed maps of city evolution and sprawl scenarios. They considered meteorological forcing for an ensemble of heat-wave conditions that vary in strength and duration and found that TEB, using these two inputs, simulated reasonably well the urban climate of Paris, particularly heat island (UHI), and the thermal comfort levels for both indoor and outdoor locations.

Similarly Zsebeházi and Szépszó (2020) also applied TEB integrated in the land surface model SURFEX in offline mode to study urban and suburban seasonal temperature cycle and daily urban heat island (UHI) evolutions in Budapest (Fig 2.5). For a better simulation of surface and urban climate, road surface temperatures and conditions should always be modeled interactively. The road model in TEB has never been explored in detail in any of the previous studies despite its potential to provide realistic road surface temperatures.

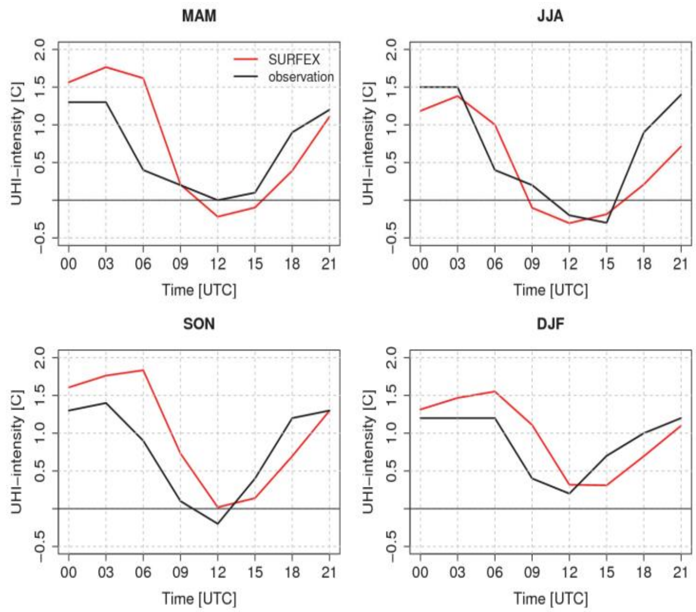

Fig 2.5. Daily cycle of UHI in each season according to the SURFEX and station measurements in the reference points for 2001–2010 (Zsebeházi & Szépszó, 2020).

There might not be a clear-cut solution when it comes to selecting between empirical and physical models. Interactive modeling of roads in climate models is often advantageous for both better simulation of surface climate and road temperatures.

2.2 Road failure mechanisms and related climate variables

Road failure mechanisms refer to the various ways in which road infrastructure can degrade due to a combination of environmental and climatic factors. The initiation and course of these mechanisms are significantly influenced by several climate variables. This part of the chapter examines various road failure mechanisms, the climate predictors associated with them and linked literature studies.

The four major categories of common asphalt pavement surface failures in both cold and warm seasons and their subcategories are shown in Table 2.1:

Cracking	Surface Deformation	Disintegration	Surface Defects
i)Fatigue cracking	i) Rutting	i) Potholes	i) Ravelling
ii)Longitudinal Cracking	ii) Corrugations	ii) Patches	ii) Bleeding
iii) Transverse Cracking	iii) Shoving		iii) Polishing
iv) Block Cracking	iv) Depressions		iv) Delamination
v) Slippage Cracking	v) Swell		
vi) Reflective Cracking			
vii) Edge Cracking			

Table 2.1 Types of Bituminous Road Pavement Failure (Wada, 2016).

Cracking, a significant contributor to pavement deterioration, in both the cold and warm season, comes in various forms. The pavement load support properties are considerably reduced by alligator cracking/fatigue cracking, which is brought on by frequent traffic loading. This cracking pattern leads to the loss of support from the base, sub-base, or sub-grade, often due to issues like poor drainage, freeze-thaw or spring thaw, stripping of the surface layer, increased loading beyond the design limit, or poor construction practices. In order to prevent more damage, longitudinal cracks that run parallel to the centerline of the road should be repaired using the proper techniques. Similarly, transverse cracks must be considered to stop further degradation. Interconnected fractures that split the pavement into uneven pieces are the characteristic of block cracking. Inadequate construction compaction or transverse and longitudinal fractures crossing might cause it.

Surface deformations occur when one of the pavement layers experiences failure or weakness mainly due to traffic movement. Rutting, swelling and corrugation types of pavement deformation are brought on by heavy loads that are applied repeatedly. As a result, different pavement layers become unstable because of poor compaction, high wheel loads, poor design, and insufficient pavement thickness, especially at higher temperatures when the pavement is soft. In order to preserve the road from these failures, appropriate repair techniques must be used.

Pavement disintegration is the process by which it gradually breaks up into small, loose pieces. Patches (areas of pavement replaced with new materials to repair existing pavement) and potholes (small, bowl-shaped depressions that penetrate through the hot mix asphalt layer down to the base course) are two common forms of pavement disintegration.

Surface defects, related to issues in the surface layer, encompass ravelling, bleeding, and polishing. Bleeding is the process by which an asphalt film forms on the pavement's surface; this is usually brought on by an excessive amount of asphalt or by inadequate compaction. As a result of traffic wear and environmental factors, polishing smooths the pavement surface, gradually decreasing skid resistance (Yang et al., 2020).

The main thermal and hydrological predictors related to the above discussed failures are presented in the following sections.

2.2.1 Thermal related climate predictors and sensitivities

Temperature is a critical climate variable that exerts both short-term and long-term effects on the road’s structure, encompassing safety concerns for travelers and transportation workers. The concerns related to temperature fluctuations vary between cold and warm seasons, each presenting distinct challenges for road surfaces. Changes in warm season road thermal characteristics may trigger surface softening, fatigue cracking, and longitudinal and transverse rutting. These may reduce the pavement's ability to withstand fatigue, which may result in compaction loss and issues with stability brought on by seasonal expansion and contraction (Wu et al., 2020). On the other hand, cold season climate predictors like partial thawing and freeze thaw cycles can results in issues including frost heaving, ice conditions, and snow accumulation, and lead to surface deterioration and fractures (Moretti & Loprencipe, 2018). So, this part of chapter covers the cold and warm season thermal related climate predictors and related road failures.

In Quebec, Bilodeau et al. (2015) investigated the permanent deformation of roads during winter partial thaws.

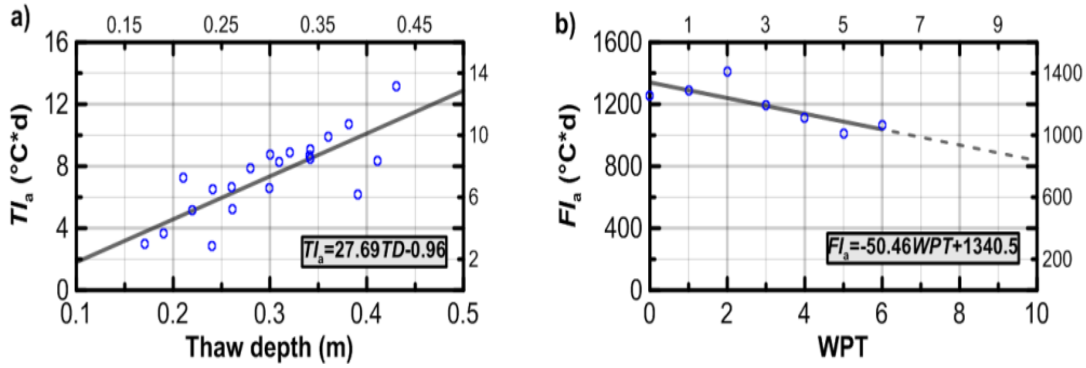

Fig. 2.6 a) Relationship between air thawing index and thaw depth; b) Relationship between air freezing index and the number of winter partial thaws (Bilodeau et al., 2015).

They determined partial thaws using climatic index, and the air freezing index (Fig 2.6). Bilodeau et al. (2015) found that the pavement service life could be reduced by approximately 10% due to the winter partial thaws, with variations ranging from 4 to 17%.

Matulla et al. (2018) conducted research on the Iberian Peninsula and Fennoscandia to determine the frequency of rutting events on road surfaces. Fig. 2.7 from the study conclude the need for expensive repair and maintenance in the region's road network. The study findings suggest an increasing occurrence of landslides, pavement blow-ups, and rutting in Central Europe, posing a growing threat to road surfaces.

Likewise, Kwiatkowski et al. (2020) investigated the winter impacts, especially freezing and thawing, on pavements in the Netherlands. To predict the impacts on pavements performance they established a relationship between air and road temperatures and correlated pavement performance with FT cycles.

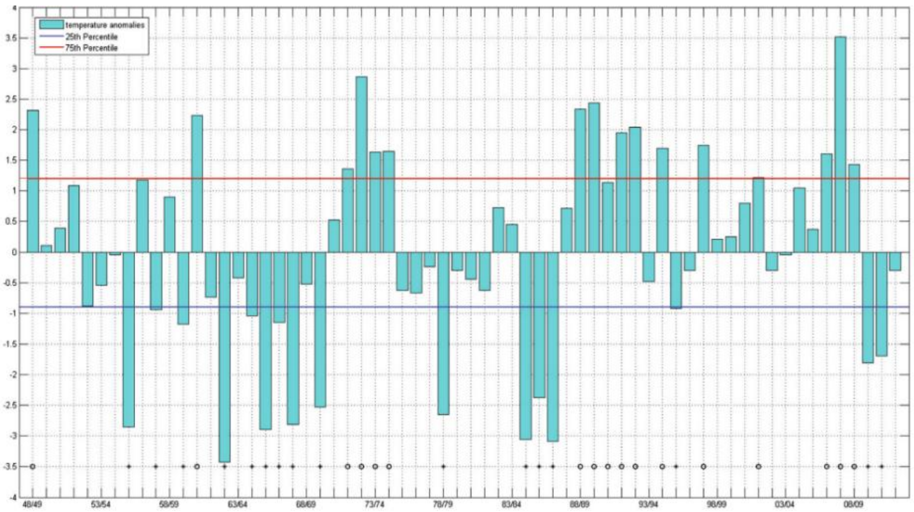

Fig. 2.7 Time series of winter temperature anomalies over roads in Fennoscandia and the Baltic Sea relative to their long-term average. Negative/positive values indicate cold/warm winter seasons. After about 20 years of rather warm winter seasons (1987/1988–2008/2009) cold winter conditions occurred recently again (x-axis: winters, y-axis: °C) (Matulla et al., 2018).

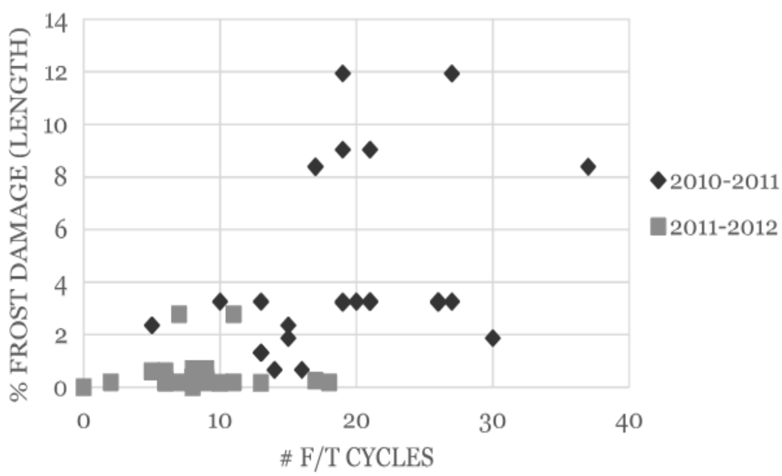

Fig. 2.8 Winter damage in relation to freeze–thaw cycles (Kwiatkowski et al., 2020).

The study predicted the roadway's damage with climatic stressors such as, temperature, precipitation, and freeze-thaw cycles, by using a stressor-response modeling technique and valuated damages resulting from FT (Fig. 2.8) cycles, by focusing on eight different road sections located in different regions.

2.2.2 Hydrology related climate predictors and sensitivities

In addition to thermal-related concerns, in both warm and cold seasons, road infrastructure is consistently at risk from road runoff and precipitation patterns (de Abreu et al., 2022). Precipitation patterns, combined with an increase in runoff, erosion and flooding can have a significant impact on the resilience and safety of transportation networks. Moreover, there is a possibility that the existing drainage system could be overwhelmed by precipitation and runoff (Pregnolato et al., 2017). These incidents not only disrupt transportation but also place significant strain on maintenance and repair budgets (Pang et al., 2022). So, this part covers the hydrology related climate predictors and related failures and issues in both cold and warm climates.

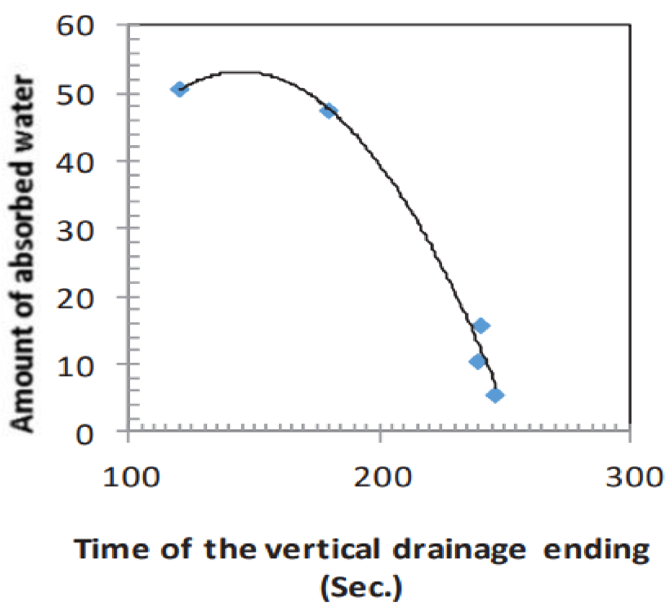

Fig.2.9. The relationship between amount of absorbed water (Liter) by road section and time of vertical drainage ending for rain intensity 116ml/min (Al-adili et al., 2018).

Though research on the hydrologic impacts on road systems and drainage design are limited, Al-adili et al. (2018) conducted a research to establish the effect of heavy rainfall on a chosen pavement layers, and then to study the drainage design, material selection and rutting resistance of the flexible pavement using a laboratory simulation model. In this study, testing began with wheel track passes, initially without load and rain. Subsequently, a load was incrementally applied, and distresses appeared when the wheel track load was increased to 150 psi under high-intensity rain with extended duration (Fig 2.9). They concluded that the road and drainage systems can be seriously harmed by the increased rainfall and runoff.

In Addis Ababa, Ethiopia, Adugna et al. (2019) carried out in-depth field studies with an emphasis on stormwater management concerns and existing drainage capacity (Fig 2.10).

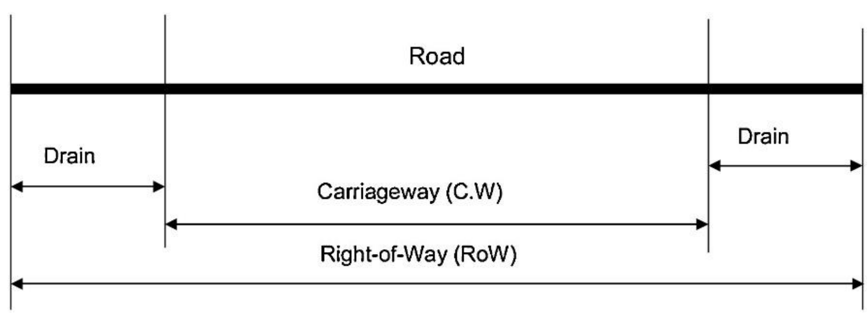

Fig. 2.10 Profile of measured road and drain section (Adugna et al., 2019).

They surveyed 469 road segments (74 km) and evaluated the current road drainage capacity to hold the runoff, using ArcGIS, and discovered that, in 14% of the new city's road and 28% of the old city's road, the drainage is insufficient, which may have caused flash floods and road surface damage.

Kouroshnejad et al. (2023) investigated, using a novel methodology, the dynamics of the interactions between traffic and flash floods in Ottawa, Canada. Their study combined the high-resolution regional climate model GEM, the hydrodynamic model PCSWMM (developed by

Computational Hydraulics International), and a GIS-based transport network model. An extensive examination of pluvial flash floods (PFF) and their consequences on road traffic was made possible by this integrated system.

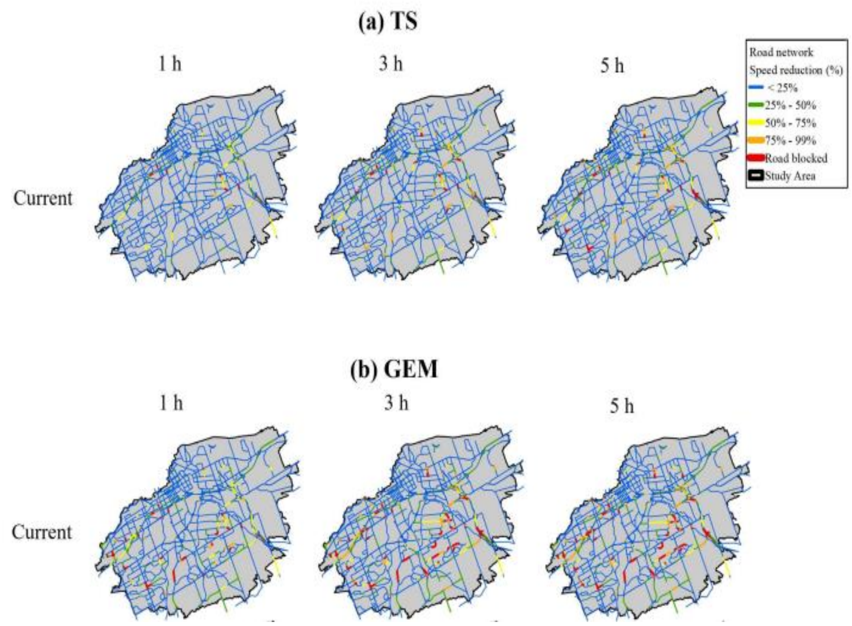

Fig. 2.11 Speed reduction (in percentage) for 100-year 1-h (first column), 3-h (second column), and 5-h (third column) precipitation events for current period (a) Temperature scaling (TS) based and (b) GEM-based approaches (Kouroshnejad et al., 2023).

The findings indicate a rise in travel delays ranging from 57% to 77% for flash floods. This increase results from a general speed reduction in road links, especially in areas where flood depths are higher, with certain road segments experiencing a 3% to 5% rise (Fig. 2.11). Despite certain limitations related to traffic modeling, this study provides insightful information that can act as a basis for future research.

2.3 Climate change impact on roads

The changing climate is a source of mounting concern for transportation infrastructure, particularly road network failures, in both the warm and cold climates, as it directly results from shifting environmental conditions. Countries around the world are increasingly focusing on how future climate variations may impact road network performance (Qiao et al., 2020). The precise effects will differ by region due to varying climate change patterns and the unique attributes of road structures. Extensive research has been dedicated to forecasting the long-term climate shifts and their far-reaching consequences, spanning from decades to centuries (Wang et al., 2019).

For instance, Mills et al. (2009) used empirical equations from the SUPERPAVE and LTPP programs to estimate pavement temperature from air temperature data and evaluated the pavement deterioration-relevant climate indicators (performance grade asphalt cement (PGAC), and freezing indices and thawing indices) at 17 sites in southern Canada, over the next 50 years, starting from 2000. Mills et al. (2009) applied equations (12) and (13) for the maximum and minimum pavement temperatures, as follows:

$$T_{p\,max} = 54.325432 + 0.78T_{air\,max} - 0.0025Lat^2 - 15.14log_{10}(H+25) + z(9 + 0.16\sigma^2_{T\,air\,max})^{0.5} \quad (12)$$

$$T_{p\,min} = -1.56 + 0.72T_{air\,min} - 0.004Lat^2 + 6.26log_{10}(H+25) - z(4.4 + 0.52\sigma^2_{T\,air\,min})^{0.5} \quad (13)$$

where, $T_{p\,max}$ and $T_{p\,min}$ are the maximum and minimum pavement temperatures (°C), $T_{air\,max}$ and $T_{air\,min}$ are the average annual extreme maximum and minimum daily air temperatures (°C), *Lat* is the latitude of location (decimal degrees), *H* is depth from surface (mm), *z* is *z*-score for appropriate level of reliability assuming standard normal distribution (*z* = 2.055, 98% reliability) and $\sigma_{Tair\,min}$ is the standard deviation of annual extreme minimum daily air temperature (°C). They reported that low-temperature cracking will pose less of an issue, and road structures will freeze later and thaw earlier. Additionally, according to their study results, higher extreme in-service pavement temperatures are anticipated to increase the risk of rutting.

In the West Midlands of the United Kingdom, A. K. Andersson and L. Chapman (2011) investigated the temperature fluctuations and aimed to estimate how much the severity of winters would change and how that might affect the roads over the course of the next century. The study used World Meteorological Organization data and UK Climate Impacts Program scenarios for the 2020s, 2050s, and 2080s. They highlighted a 50% decrease in the number of road accidents brought on by slippery roads due to decreases in freezing days. However, the paper concludes with a caution against becoming careless with winter maintenance schedules.

Chinowsky and Arndt (2012) used a stressor-response methodology to analyze the effects of climatic stressors on Mozambique road infrastructure. They considered temperature changes, precipitation variations, storm features, and wind speeds to estimate the impact on pavements and related infrastructure. Data from two global climate simulation models, the Hadley Centre HadAM3H – HAD and Max-Planck Institute ECHAM4/OPYC3-MPI, were used to drive the numerical regional climate model RCAO. The study showed an increased rutting and cracking in future road infrastructure from rising temperatures.

Fifer Bizjak et al. (2017) investigated the freeze-thaw cycles, higher temperatures, and intense rainfall trends and their effects in European road network, using data from global climate models, using A2 scenario (higher greenhouse gas emission) and B2 scenario (lower greenhouse gas emission) as defined by the IPCC. According to their study, pavement and related infrastructure are found to be significantly impacted by these variables, notably, asphalt layers are vulnerable to temperature fluctuations, leading to issues like rutting and stripping. Across all of Europe, they found noticeable damage from temperatures surpassing freezing as derived from six-hourly temperature data.

Shao et al. (2017) assessed climate change effects on Southeast Queensland over a 90-year period, with a specific focus on road pavement. They utilized the Austroads Climate Tool (Byrne & Aguiar, 2010) to acquire historical and projected climate data for selected locations in the region. Their study's analysis of climate change trends across seven typical Southeast Queensland locations reveals an upward trend in temperature, with an average increase of 1.1°C from 2007 to 2040, 2.4°C by 2070, and 3.7°C by 2099, indicates the significance of climate change. In summary, they showed reduced rainfall slows flexible pavement deterioration, while higher temperatures are likely to induce material expansion and increase deformation, particularly rutting.

Hori et al. (2018b) conducted research on the effects of climate change on winter road networks for the northern regions of Ontario, particularly analyzing the Freezing Degree Days (FDD). Multi-model ensembles of Global Climate Models (GCMs) and Regional Climate Models (RCMs) under various Representative Concentration Pathways (RCPs) are used in the study. According to the research, climate are projected to be unfavorable for winter road construction by the middle of the century. Nonetheless, the study highlights the uncertain viability and longevity of winter roads in the future, highlighting the necessity of long-term planning and adaptation methods at the local and governmental levels.

Using RoadSurf Freistetter et al. (2022) simulated the climate change impacts on future roads and walkways for mid- and end-century in Finland, Norway and Sweden for RCP 8.5 scenario. Their results suggest strong road surface temperature increases (Fig 2.12), especially in southern Finland (+5.1 °C) and Sweden (+7.1 °C), with less snowy and icy road surface conditions. Furthermore , according to the results zero-degree-crossing days mostly decreased in autumn and spring by up to 7 days and increased in winter by up to 5 days in future.

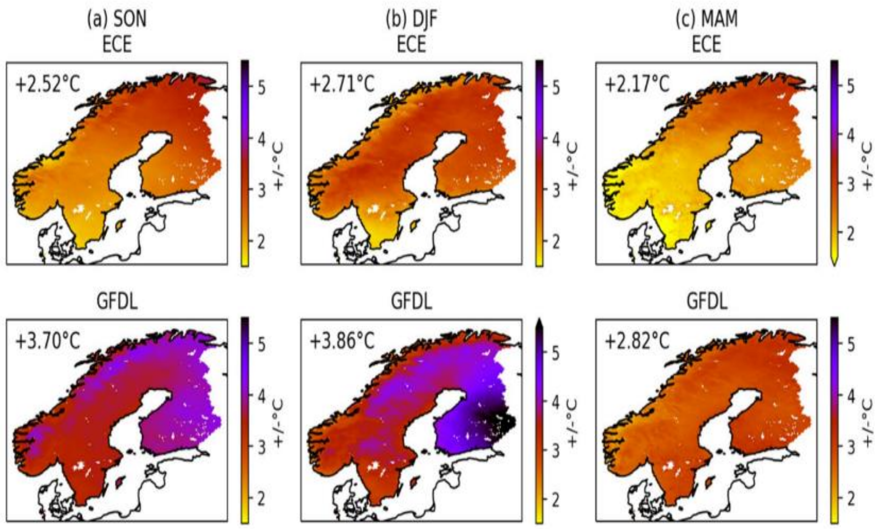

Fig. 2.12 Projected seasonal road surface temperature change in Finland, Norway and Sweden in the mid-century period (2041–2060) compared to the historical period, as estimated by ECE-HCLIM38-ALADIN-RoadSurf (top row) and GFDL-HCLIM38-ALADIN-RoadSurf (bottom row) for the RCP8.5 scenario (1986–2005) (Freistetter et al., 2022).

The question of climate impacts on road surfaces remains complex and demands ongoing research, particularly in the context of urban areas where more precise and detailed studies are essential.

2.4 Knowledge gaps and conclusions

The modelling of the urban climate has become of great interest in recent years with a primary focus on using air temperature data to estimate road surface temperature. While physically based road models have been applied in many studies to understand road characteristics, it will be useful for climate models to interactively model road characteristics by incorporating simplified road models, which will enable better simulation of the near surface climate, while providing useful road-related information.

Furthermore, the influence that climatic conditions have on the management and operation of road infrastructure is significant. In particular, research on the relationship between climate and road thermal and hydrologic regimes for future emission scenarios is essential for shaping road system design and management practices. While some models are emerging to address this need, comprehensive simulations and studies into road failure mechanisms remain conspicuously absent, especially in the context of Canada.

This thesis addresses some of these knowledge gaps through two key approaches: (1) by applying the surface prediction system (SPS) framework consisting of the land surface model CLASS (Canadian Land Surface Scheme), and the Town Energy Balance model (TEB) for the studied urban region and (2) by carrying out an in-depth assessment of the thermal and hydrological characteristics of roads in the Island of Montreal, with an emphasis on the effects of climate change on road failures.

CHAPTER 3 - CITY-SCALE MODELLING OF ROAD THERMAL AND HYDROLOGIC CHARACTERISTICS AND FAILURE MECHANISMS: CASE STUDY OF MONTREAL

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Abstract

Climate of a region significantly influences the performance and management of road infrastructure. Climate-road interaction studies for future greenhouse gas emission scenarios are therefore key to informing their design and management strategies and to enhance their climate resilience. This study focusses on city-scale modelling of road thermal and hydrologic characteristics that are associated with road failure, for the current 2001–2020 and future 2041–2060 periods, for RCP8.5 scenario, for the City of Montreal in Canada. To this end, current and future simulations using the surface prediction system (SPS) framework, consisting of a land surface model with realistic representation of urban regions, including roads, using the Town Energy Balance model (TEB), at 250 m resolution, are used.

After confirming the ability of SPS in simulating land and road surface temperature characteristics by comparing against MODIS data, selected road failure predictors for the cold (October–May) and warm (June–August) seasons are studied for two broad road categories: highways and local roads. Projected decreases to the cold season daily freeze-thaw and partial thaws by 12.5% and 2%, respectively, for the future period suggests potentially lower damages compared to current period for both highways and local roads. However, projected increases in road and total surface runoff in the 12–15% range, due to the higher rainfall to snowfall ratio in future climate during the cold season, point to an increase in drainage-related road failures. Analysis supports practicing load restriction days to lessen deterioration of road and pavement layers during spring thaw but necessitates an earlier start by 2 weeks in future climate given early thaw in a warmer climate.

For the warm season, projected increases in daily maximum and minimum temperatures and road and total surface runoff in the 25% range suggest increased chances of road failure from rutting and drainage issues. Analysis performed separately for the highways and local roads reveal important spatial variability, which can be helpful in prioritizing road sections for more detailed analysis. This study thus provides useful information that will inform future studies and the development of sustainable adaptation strategies for the Montreal road system.

Keywords: Road network, Climate change impacts, Road failure, Road thermal and hydrologic characteristics, Island of Montreal.

3.1 Introduction

Like in many other cities, road network in Montreal is the backbone of the transport system, supporting daily commuting, business operations, and social interactions (Tu et al., 2022). Due to Montreal's harsh climate, road construction and maintenance encounter challenges, which lead to pavement damage and deterioration (Maadani et al., 2021). The performance and longevity of roads are further threatened by climate change, particularly by extreme weather events (Maadani et al., 2021). For instance, flooding-related depressions and ground settlements can contribute to damage, impacting both durability and drainage systems of roads (Vaillancourt et al., 2019).

In cold regions, critical concerns for road design revolve around freezing and thawing. Higher frequency of freeze-thaw cycles can accelerate pavement deterioration, through frost heave and thaw weakening. To mitigate road and pavement damage during spring thaw, when the bearing capacity can be significantly low, load regulations are placed that limit vehicle loads during this period. Weight limitations are imposed to almost all public highways in Quebec, unlike most other Canadian provinces that only impose restrictions on certain road sections. This is primarily due to the significant frost depth and age of the road network in Quebec (Bilodeau & Doré, 2020).

For road temperature estimations, two methods are commonly employed. The first method utilizes empirical models, where the road temperature is generally estimated based on air temperature and related variables (A. Andersson & L. Chapman, 2011; Asefzadeh et al., 2017; Diefenderfer et al., 2006; Gedafa et al., 2014; Hambly et al., 2013; Hori et al., 2018a; Islam et al., 2015; Kršmanc et al., 2013; Li et al., 2018; Lukanen et al., 2000; Makkonen et al., 2014; Mills et al., 2009; Park et al., 2001). The Superior Performing Asphalt Pavement (SUPERPAVE) and Long-Term Pavement Performance (LTPP) programs provide empirical equations for estimating different road/pavement-related temperatures. Mills et al. (2009) in their study to determine the suitable performance grade asphalt cement ratings utilized the LTPP formulas at 17 southern Canadian sites, including Montreal. Teltayev and Radovskiy (2018) developed empirical models for estimating maximum pavement temperature based on the maximum air temperature and hourly solar radiation in their study to assess low temperature cracking on road surface. However, the accuracy of these empirical relations remain uncertain. It is important to note that empirical models rely on statistical analysis rather than theoretical derivation. As a result, they might not fully capture the entire process of heat transfer within the pavement/road.

The second approach involves the use of physically based models, for regional and local applications. Several countries have developed their own regional road weather models (Fujimoto et al., 2012; Kangas et al., 2015). Road weather models primarily forecast the temperature of the road surface, the quantity of snow, ice, or water on it, and occasionally include friction and driving conditions (Juga et al., 2013; Kangas et al., 2015). RoadSurf is one such model, developed by Finnish Meteorological Institute (FMI) to strengthen the services towards more efficient estimation of rapidly varying conditions of the road surface and to issuing warnings of hazardous traffic conditions to the public at a national scale (Kangas et al., 2015). The model calculates vertical heat transfer in the ground and at the ground-atmosphere interface, considering the special conditions prevailing at the road surface and the ground below it. It also considered hydrological surface condition based on various storage terms that describe the amount of water, snow, ice and frost, which change based on precipitation, evaporation, condensation, melting and freezing, as well as traffic wear. This model has also been applied to study climate change impacts on roads and walkways in Finland, Norway and Sweden (Freistetter et al., 2022), when driven by atmospheric forcing from climate models. These models can be coupled with climate models to capture two-way feedback, which could be more realistic. While incorporating highly detailed physically based road models into climate models might be difficult, simpler models can be used. The benefits will be twofold – the realism of the climate model can be improved, while road-relevant outputs can be used to inform the development of sustainable road design and management strategies. Recently, climate models, in their effort to improve representation of urban regions, have utilized urban models such as the Town Energy Balance (TEB) model, which is based on a generalization of the local canyon geometry (Masson, 2000). Studies utilizing such models have heavily focused on assessing the urban climate. Lemonsu et al. (2015) examined the evolution of the urban climate of Paris using offline TEB simulations for various future emission scenarios. Hamdi et al. (2015) applied SURFEX (Surface Externalize) land surface model, with TEB, over Brussels and Paris to study future changes to urban climate characteristics. The same model, i.e. SURFEX with TEB, was also used by Zsebeházi and Szépszó (2020), but coupled to the ALADIN regional climate model to study urban and suburban seasonal temperature cycles and daily urban heat island (UHI) evolution in Budapest. The road model in TEB has never been extensively validated in any existing studies. Albeit its simplicity, integrated modelling of roads in climate models will be beneficial as it will not only improve the realism of the model but will enable use of road temperature characteristics in road-related adaptation studies, which are generally based on air temperatures as mentioned earlier. As the diurnal and annual variability of road temperature can be very different from that of air temperature, road temperature data from models such as TEB, run in offline or coupled mode, can be beneficial.

The main objective of this study is to model the thermal and hydrological characteristics of the urban road network of Montreal for current and future climates and to understand their vulnerability by studying selected climate predictors linked to road failure for cold and warm seasons using high resolution, 250 m, simulations performed over the study region using the

Surface Prediction System (SPS) framework. Lack of city-scale modelling of the road network for the study region is the main motivation for this study, which can provide useful insights in the city's effort to improve climate resiliency of its infrastructure.

This paper is organized into five main sections, including the introduction. Section 2 gives details of the modelling framework, simulations, observation datasets used for validation, and the methods used to estimate thermal and hydrologic attributes that are associated with road failure. Section 3 discusses model validation and characteristics of climate predictors associated with failure mechanisms in current climate. Projected changes to thermal and hydrologic characteristics are presented in Section 4. Summary and conclusions are provided in Section 5.

3.2 Model, observed data, and methods

3.2.1 Model and experimental domain

The SPS framework, consisting of the land surface model CLASS (Verseghy, 1991) and TEB (Masson, 2000a), is applied over the Greater Montreal region, at 0.0025° (250 m) resolution. TEB is used to represent/model urban fractions/regions, while CLASS models the rest of the land surface and associated physical processes.

CLASS models separately the energy and water balances of the soil, snow, and vegetation canopy. The basic prognostic variables consist of the temperatures and the liquid and frozen moisture contents of various soil layers; the mass, temperature, density, albedo, and liquid water content of the snowpack; the temperature of the vegetation canopy and the mass of intercepted rain and snow; the temperature and depth of ponded water on the soil surface; and an empirical vegetation growth index. More details about CLASS can be found in Verseghy (1991, 1993, 2012), while (Teufel et al., 2021) and (Teufel & Sushama, 2021) present applications of CLASS over Canada.

TEB is a physical model for the urban energy budget, which approximates the complex geometry of cities with the canyon concept (Masson, 2000a). The city's complex surface shape leads to the categorization of the urban energy budget into three components: walls, roadways, and roofs. In TEB, any road orientation is possible, and all roads have the same likelihood of existing. The road lengths are considered significantly greater than their widths. Within a given model grid cell, it is assumed that the buildings bordering the street canyon are the same height and width. City features are described by three main parameters: building height, building aspect ratio (rate of building height and roof width), and canyon aspect ratio (rate of building height and canyon width) for each grid cell. TEB computes moisture budget for both roof and road as well as the energy budget for roof, wall, and road separately. TEB uses a simplified representation for roads, which comprises of three distinct layers. The top layer is an asphalt layer, which is 8 cm thick. The middle and bottom dry soil layers are 20 cm and 100 cm thick, respectively Both roofs and roads intercept liquid precipitation; the road reservoir has a limited capacity of 1 kg/m^2 causing any excess water to be lost as runoff. Similarly, a snow scheme is implemented in each surface type (roof, wall, and road). The snow fraction on roof or road surfaces is set equal to a function of the snow interception reservoir, which of capacity 1 kg/m^2. For the pavement and building fractions, the properties are specified using recent information from OpenStreetMap, a worldwide collaborative project that compiles various types of information from Global Position System devices, aerial photographs, and local sources to provide freely editable maps (Belair et al., 2018). The total urban fraction over the study region, represented in Fig. 3.1b, is the sum of the above two variables. Canadian Vector Data (CanVec) version 9.0 which is based on the National Topographic Database (NTDB), the Geobase initiative, and radar data from Landsat 7, SPOT, and Radarsat are used to estimate TEB-related parameters such as building height, canyon aspect ratio, road (wall/roof) albedo and emissivity, and roughness length (Oh & Sushama, 2021; Roberge & Sushama, 2018).

The atmospheric forcings required for SPS are incoming shortwave and longwave radiation, air temperature, wind speed and wind direction, specific humidity, surface pressure and precipitation. These forcings can be supplied either by measurements or available atmospheric model results. In this study these forcings are derived from downscaled reanalysis and climate model outputs as discussed below. The TEB scheme is active for grids with an urban percentage greater than zero. The TEB scheme has extensively been assessed across diverse cities and climatic conditions in combination with land surface models, both in offline and coupled modes, as evidenced by studies conducted by Hamdi et al. (2012); Masson (2000b); Masson et al. (2002); Roberge and Sushama (2018); Teufel et al. (2023); Teufel et al. (2021).

3.2.2 Observed data

Due to the widespread availability, extensive regional coverage, comparable scale to models, and regular periodicity, temperature products from satellite remote-sensing systems are viable sources for model validation. The Moderate Resolution Imaging Spectroradiometer (MODIS) sensors onboard the Terra satellite offer land surface temperature (LST) data globally over cloud-free regions, twice a day, at 10:30 and 22:30 local solar time for the 2001–2020 period at 1 km resolution. In this study, the MOD11A1 collection 6.1 products are used to validate the LST and road surface temperature (RST). MOD11A1 contains LST for the day and night passes of Terra.

The MODIS LST data at 1 km resolution is interpolated to the reference 250 m grid for validating modelled LST. To validate RST, in the absence of other data, RST for grid cells with urban fractions higher than 50% and 80% are compared with MODIS LST, as the RST contribution to LST can be considered dominant for those grid cells.

3.2.3 Methods

For this study, three SPS simulations are performed. The first one, a validation simulation, is driven by the atmospheric forcing obtained from downscaled ERA5 (Hersbach et al., 2020) for the 2001–2020 period. This simulation will be referred to as SPS_ERA5. The second and third SPS simulations correspond to current and near future climates, i.e., 2001–2020 and 2041–2060 periods respectively, driven by atmospheric forcing from the downscaled Second-Generation Canadian Earth System Model (CanESM2) to 4 km using the Global Environmental Multiscale (GEM) model, for the Representative Concentration Pathway (RCP) 8.5 scenario. These simulations will be referred to as SPS_CanESM2 along with appropriate periods. The RCP8.5 scenario corresponds to the highest greenhouse gas emissions scenario and does not include any specific climate mitigation target, leading to a radiative forcing of 8.5 W/m^2 at the end of 21st century (Riahi et al., 2011).

Analysis for highways and local roads (Fig. 3.1c) are performed separately for better assessment, where arterials, collector roads, and local roads are collectively referred to as local roads. It is important to note that the future simulation does not take into consideration changes in land use, including urban area expansions.

The first step, prior to assessing projected changes to road failure-related climate variables/predictors, is to test the ability of the model in simulating LST and RST by comparing SPS_ERA5 with observations. This includes validating spring (MAM) and summer (JJA) LST and RST by comparing them with MODIS as discussed in Section 3.2.2. Validation for winter is not considered since snow cover and reduced solar radiation can impact the accuracy of MODIS temperature, making them less reliable for the analysis. For the purpose of analyzing climate predictors related to road failures, two seasons, namely warm (June–August) and cold (October–May) are considered.

3.2.3.1 Cold season road failure predictors

Thermal characteristics:

The temperature attributes related to cold season road failure considered in this study are daily freeze-thaw cycles and partial/spring thaws. A daily freeze-thaw (F-T) cycle occurs when the daily maximum and minimum temperatures are, respectively, above and below 0 °C (Maadani et al., 2021). F-T cycles can produce surface distress and lead to cracking and damage to roads due to the repeated freeze and thaw events.

Partial thaws, following the Minnesota Department of Transportation method (2004), which has been subsequently modified and adjusted by later studies (Leong et al., 2005; Mills et al., 2009), are defined as events of at least one day duration during which a minimum thawing index (TI) of 7.4 degree-days is reached (which is considered necessary to reach a thaw depth of 30 cm), followed by a freezing day (Bilodeau et al., 2015); Here, surface thawing index is the summation of the degree-days with mean daily RST above 0 ºC. Load restrictions (LR) are generally imposed to help prevent early deterioration, cracking, and structural failures associated with severe loads on pavement during the spring thaw, when road layers may become saturated and weakened because of partial thaw conditions and trapped water. Following Van Deusen et al. (1998), LR are considered necessary when TI reaches 30 degree-days within seven days of attaining TI of 13-degree days, in order to make sure that the thaw has prolonged sufficiently to weaken the structure (Mills et al., 2009).

Hydrologic characteristics:

Land surface runoff accumulation in low-lying areas during high intensity rainfall events and/or inadequate road drainage has the potential to saturate road layers impacting the structural integrity, including erosion of road edges, premature deterioration of roadways and the development of adverse safety conditions. In the presence of cracks and rutting, this runoff can infiltrate into the pavement, potentially compromising its structural stability. Furthermore, maintaining dry pavement surfaces are critical to reduce the risk of hydroplaning (Mukherjee, 2014).

Both road and total land surface runoff are the hydrologic characteristics considered in this study. Road runoff can be related to snowmelt and rain, although regular snow removal from roads can reduce the snowmelt component of road runoff. In the simulations considered in this study, snow removal is implemented for all types of roads and thus road runoff is primarily due to rainfall. TEB considers a road reservoir capacity of 1 kg/m², and excess water is considered as road runoff.

3.2.3.2 Warm season road failure predictors

Thermal characteristics:

Temperature fluctuations can cause a variety of issues, including potholes, rutting, depressions, cracks, and more. Depressions, small bowl-shaped patches that are frequently accompanied by cracks, contribute to the roughness of pavement, posing hazards to vehicles and facilitating water collection. The lifespan of bituminous pavements is significantly shortened by surface cracks, which also serve as early warning signs for other types of cracks and accelerate the overall failure of the pavement. Potholes, which arise from the extreme fatigue cracking of road layers, cause pavement to dislodge as vehicles pass over them. Also, rutting events, during summer period, lead to the formation of shallow grooves or trenches on pavement surfaces due to increased temperature and asphalt softening.

This study mainly focus on warm season rutting events, i.e., formation of shallow grooves or trenches on pavement surfaces due to high temperatures and asphalt softening, which are assumed to occur when the maximum (minimum) road surface temperature, RSTmax (RSTmin), exceeds 45°C (20°C) (Matulla et al., 2018).

Hydrologic characteristics:

As for cold season, road and total surface runoff are considered in this study for warm season. Seasonal variations in temperature make runoff more noticeable during the warm season since heavy rain and storms are characteristics of this season, which can overstress the drainage systems. Furthermore, cracks and rutted road surfaces can lead to water infiltration, potentially causing structural damage and risks related to erosion. Thus, warm season runoff studies are essential for improving infrastructure and drainage system vulnerabilities.

3.3 Results

3.3.1 Model validation and analysis in current climate

Prior to the investigation of the impacts of projected changes on road thermal and hydrologic characteristics, the ability of the SPS framework in simulating LST and RST is investigated. MODIS average daily LST for the 2001–2020 period for spring and summer (Fig. 3.2a) show temperatures in the 9 to 12 °C and 26 to 29 °C ranges, respectively. However, the distinct lower shoreline temperatures varying in the 5 to 7 °C and 20 to 25 °C ranges, respectively, for spring and summer, can partly be due to the dominant sea breeze effect, given that Montreal is surrounded by water. The weaker land breeze could be due to the relatively warmer temperatures over land during nighttime, given the fabric of the island of Montreal with high density of buildings which leads to high UHI even during night-time.

Comparing SPS_ERA5 and MODIS LST for spring shows biases mostly in the ± 2 °C range, with underestimations noted for the central regions, where even higher biases can be noted. This is primarily due to the biases in the driving atmospheric forcing, mainly temperature (Fig. A.1 of appendix A); it must be noted that the 4 km GEM simulation did not include TEB and therefore there is a negative temperature bias over the central region with high fraction of urban regions.

The biases along the shoreline, on the other hand, is positive and is due to the lack of representation of sea/land breeze in this offline simulation that is not coupled to an atmospheric model. This highlights the significance of a coupled simulation, since the driving data affects the temperature even with the better urban representation in the current model, in addition to the lack of representation of atmospheric processes and two-way feedback between the land and atmosphere. Similar biases are also noted during summer, although the bias in the central region is reduced and appear scattered.

Since the study is mainly focusing on RST, Fig. 3.2b shows a scatter plot that compares RST with MODIS data, for grid cells where the road fraction is greater than 50% and 80% (left panel of Fig. 3.2b), which primarily includes highways and a few local roads, for spring and summer. This comparison is justified given the higher contribution of RST towards LST for these grid cells. Correlation coefficient (R) of the order of 0.67 and 0.72 are noted when comparing cells with road fraction higher than 50% and 80%, respectively. These comparisons suggest that SPS values are within the broad limit of observed temperature values from MODIS and that the current framework can be employed in studying climate change impacts to the road network at city scale.

Given the use of 2 m air temperature in many empirical RST models, the differences in the diurnal and annual cycles of RST and 2 m temperature for spring and summer are investigated in current climate by utilizing SPS_ERA5 outputs, for highways and local roads, separately. Accordingly, the average diurnal RST is in the 18.5–20 °C range during spring (bottom panel of Fig. 3.3a), and 25–27°C during summer (bottom panel of Fig. 3.3b). Air temperature, which is the measure of the heat energy in the atmosphere can fluctuate rapidly, while the temperature of the pavement, the RST, varies slowly when compared to air temperature and is influenced by solar radiation absorption and heat retention. As expected, the amplitudes of the RST diurnal cycles are higher than that of the 2 m temperature by 8°C and 12°C, respectively, for spring and summer (Fig. 3.3). The amplitude of the annual cycle of daily RST and 2 m air temperature (Fig. 3.4a) also exhibits considerable variation in the 8–9 °C range, with highways exhibiting differences of up to 10 ºC. Furthermore, the mean RST differs from the mean 2m air temperature (Fig. 3.4b) by up to 10 °C for both spring and summer seasons. In both seasons, there is a lower temperature difference of about 4–6°C observed in certain less urbanized areas due to reduced heat absorption and retention, even though other regions are showing a difference of nearly 20% in RST when compared to air temperature. These significant differences further underscore the necessity of employing physically based models to estimate RST rather than relying solely on empirical models of RST based on air temperature.

Additionally, a comparison between SPS_ERA5 and SPS_CanESM2 summer RST for the 2001–2020 period (Fig. 3.5) reveals a somewhat higher temperature in SPS_CanESM2 compared to SPS_ERA5. This difference can be attributed to the higher positive bias in the driving data for SPS_CanESM2, i.e., GEM downscaled CanESM2, which is known for its warm bias (Diro & Sushama, 2017).

3.3.2 Projected changes to road failure predictors

To investigate potential road failure mechanisms, it is important to consider the projected changes to relevant climate variables/predictors. Projected changes to the diurnal variations in RST for the 2041–2060 period with respect to the 2001–2020 period for spring and summer are shown in Fig. 3.6. The projected increases in the diurnal variation of RST for spring go up to 1°C, with higher values noted for the western part of the island compared to the eastern part, which matches the spatial patterns of projected increases in the driving air temperature (see Fig. A.1 of appendix A). For summer the projected increases in the diurnal cycle show no particular spatial pattern, but values of up to 1.5 °C are noted for some grid cells. Fig.3.7 shows projected changes to annual variation in RST from SPS_CanESM2, indicating potential increases of approximately 1.5°C for local roads, while most of the highway regions displaying an increase of up to 2°C, during the 2041–2060 period when compared to the 2001–2020 period. The warming projected for winter RST is somewhat similar for summer, which is responsible for the small projected increases in the mean annual temperature variation. To understand better, Fig.3.8 further provides an illustration of the projected changes to mean RST for the future 2041–2060 period with respect to current climate. These projections indicate increases of up to 3°C in spring and up to 4°C in the summer. In comparison to local roads, highways undergo slightly higher degree of change, around 4.3°C, especially in summer.

3.3.2.1 Cold season road failure predictors

<u>Thermal characteristics:</u>

Fig. 3.9 displays projected changes to the number of daily F-T cycles for the cold season. In the current climate an average of 50 to 80 events are noted for local roads and 80 to 100 events for highways. The highways and local roads passing through the central regions show relatively smaller values, perhaps due to the relatively higher temperature values in this core urban region, which can prevent minimum temperatures from going below 0 ºC on as many days as for other regions during the shoulder months. The projection for the future period suggests a decrease in the number of F-T events for highways and local roads. With warmer road temperatures in the future, fewer days with daily minimum RST that are just below freezing are projected for the study region. This implies reduced surface distress in the future climate compared to the current climate.

It must be noted that projected changes to daily F-T cycles vary with region, and regions to the north of the experimental domain will experience increases in daily F-T cycles in future climate based on analysis over larger regions (Bilodeau et al., 2015).

The number of winter partial thaw events for both current and future periods are shown in Fig. 3.10a. In general, the majority of roads experience between 3 to 4 partial thaw events per year in current climate, while on highways there are 5 to 7 events. Results point to a projected decrease by 1.5 to 2 partial thaw events annually on highways and a decrease of around 1 to 1.5 events for areas with high urban fractions or on local roads. This could be related to the general warming trends, resulting in fewer occurrences of lower temperatures compared to the current period and localized microclimates. This is in line with (Bilodeau et al., 2015), who reported potential increases in partial thaws for northern Quebec and decreases for southern Quebec, where the study region is located. The decreases in partial thaws will thus reduce potential damage in future climate associated with partial thaws, through reduced influence on the long-term deformation behavior of unbound granular materials caused by expansion and contraction.

It is worth noting that in partial thaw conditions, asphalt surface, which is inadequately supported and subject to substantial stress, can experience an adverse impact on its performance. It is therefore useful to practice LR in future climate as well. According to Fig. 3.10b, LR will need to start earlier in future climate, given earlier thaw; It is anticipated that the LR start date will need to be shifted 2 weeks earlier. This shift is crucial for preventing premature damage, cracking, and structural failures caused by heavy truck loads.

Hydrologic characteristics:

Fig. 3.11 shows the road runoff during the cold season for both present and future climates. In current climate the road runoff values range from 2 to 2.4 mm/day in core urban regions, while they are slightly smaller for regions particularly to the west of island, which is directly linked with the precipitation pattern (see Fig. A.2 of appendix A). When local roads and highways are taken into account independently, these conclusions still hold true. In future climate road runoff generally increases, with areas of higher urban fractions showing higher values for both local roads and highways. There is an approximate 15% increase in runoff on highways and local roads, mostly associated with rising temperatures leading to higher rain to snow ratio. This can intensify water infiltration into road/pavement cracks, accelerating road deterioration. Furthermore, existing drainage infrastructure may become overwhelmed by the increased volume of road runoff and land surface runoff in its vicinity (see Fig. A.3 of appendix A), potentially causing localized flooding, and posing risks to roadways and nearby properties. The need for effective drainage systems and water treatment measures remains paramount to ensure the longevity and safety of the road infrastructure in a changing climate.

3.3.2.2 Warm season road failure predictors

Thermal characteristics:

The RST projections for summer, as illustrated in Fig. 3.8, indicate an anticipated increase of up to 3.6°C for the 2041–2060 period relative to the current 2001–2020 period. Certain areas may even see a 4°C increase during the summer period, with highways showing a more pronounced effect due to heat retaining nature of the highly urbanized areas. Projected changes to mean maximum RST exhibit similar pattern as that of mean RST in future. This is strongly correlated with an increase in rutting events, as seen in Fig. 3.12a.

In the current climate, up to 12 rutting events are observed on average, while highways show up to 14. The findings of the study reveal a concerning increase by 10 to 17 events. This increase is particularly noticeable on highways showing a more evident impact than on local roads. The higher traffic and larger loads on highways can further exacerbate pavement stress, leading to more frequent rutting events.

<u>Hydrologic characteristics:</u>

Similar to the cold season, projected increases in road runoff are projected during the warm season (Fig .3.12b). In the current 2001–2020 period, road runoff values range between 2.2 and 2.5 mm/day in less urbanized regions, while core urban regions experience runoff ranging from 2.7 to 3 mm/day, showing that road runoff is more pronounced during the warm season compared to the cold season. There is a 25% projected increase in road runoff values in the near future, which can be attributed to projected increase in future rainfall. The total surface runoff (Fig. A.3 of appendix A) shows a noticeable projected increase of up to 0.6 mm/day within core urban areas in summer season, which is approximately 30% increase compared to 2001–2020 period. This finding further underscores the importance of adapting drainage systems and management strategies to address changing seasonal runoff dynamics, ensure their resilience and sustainability in a changing climate.

3.4 Discussion and conclusions

The potential impacts of a warming climate on the road network of the Island of Montreal is assessed for the future 2041–2060 period relative to the current 2001–2020 period, for RCP8.5 scenario. Unlike previous studies that estimated RST based on 2m air temperature using empirical relations, this study uses a physically based, albeit simple, road model incorporated into a land-urban model to directly assess the road thermal and hydrologic characteristics, offering valuable insights related to their variability for highways and local roads. The model's ability to reproduce RST, despite the lack of direct RST observation data, seemed reasonable in comparison with MODIS for grid cells with larger influence of RST on LST.

Analysis of selected cold and warm season climate predictors of road failure in current and future climates suggests potential decreases in road damages/failure associated with thermal characteristics such as daily F-T cycles and partial thaws during cold season; F-T cycles are projected to decrease by 12.5% on average, while partial thaw events are projected to decrease by 1.5 to 2 events on highways and by 1 to 1.5 events on local roads. Load restriction that is practiced currently over the region during spring thaw to prevent deterioration of pavement and road layers can be useful in future climate as well but will need to be implemented earlier than in current climate by roughly 2 weeks according to the analysis. However, results point to potential increases in road failures associated with hydrologic characteristics, particularly road and total surface runoff, which are expected to increase in the 12–15% and 14–16% ranges, respectively, emphasizing the importance of adequate drainage system consideration.

As for warm season, both thermal and hydrologic characteristics point towards potential increases in road vulnerability. Increases in daily maximum temperatures in the 3.8–4°C range for the warm season suggest potential increases in road failure in the form of more rutting events (10 to 17 events), particularly on highways, which can soften and weaken asphalt, eventually impacting the performance. A substantial increase in warm season road and land runoffs, i.e., by about 25%, particularly for the high-density urban regions and highways, highlights the need for a thorough assessment of existing drainage systems.

Some of the limitations of this study are discussed here. Lack of direct RST observations limited detailed assessment of model performance in this study. It will be useful to establish a RST observation framework, which can guide development and validation of future road models, including those based on machine learning approaches. Furthermore, the roads were all assumed to be at the surface level, which is not the case for some sections of the highways, which may have biased the RST estimations. Similarly, driving data from a single climate model and single emission scenario are considered in this study, which limited uncertainty quantification. Driving data from multiple models for multiple scenarios should be considered in future studies to facilitate better quantification of uncertainties. Even better is to undertake GEM-CLASS-TEB simulations at the same high resolution as in this study, as offline simulations are unable to capture the two-way feedback between land and atmosphere. Future studies can focus on such coupled simulations, which will be more realistic. Despite the limitations discussed here, this study provides useful information that can guide future detailed studies and/or development of sustainable adaptation strategies for the road network of the Island of Montreal.

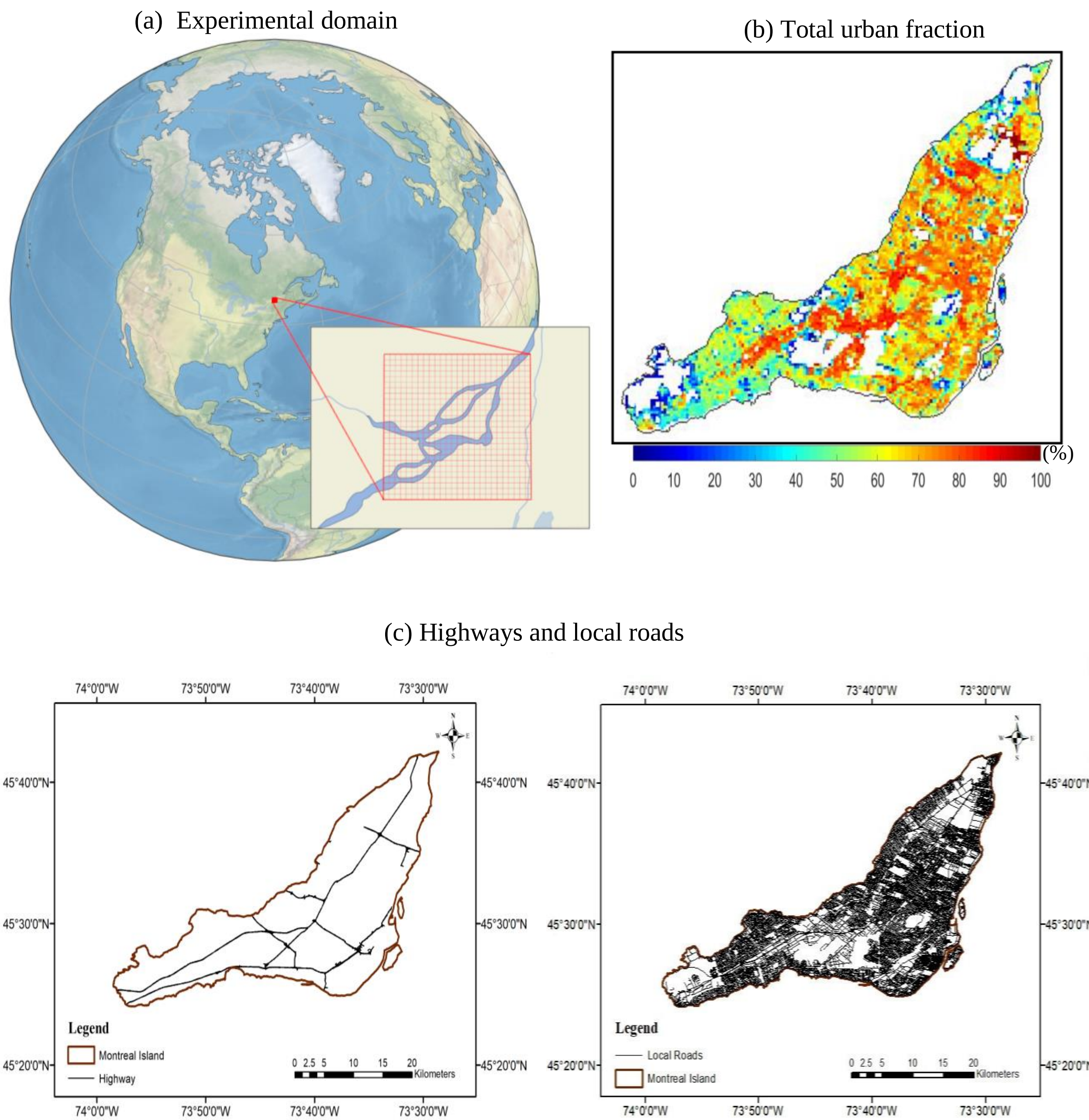

Figure 3.1: (a) SPS experimental domain at 250 m resolution; gridlines correspond to every 25th grid point, (b) urban fractions for the 250 m resolution grid cells over Montreal Island, excluding grid cells with parks and airport**,** and (c) two categories of roads, highways (left) and local roads (right) over Montreal, considered for analysis.

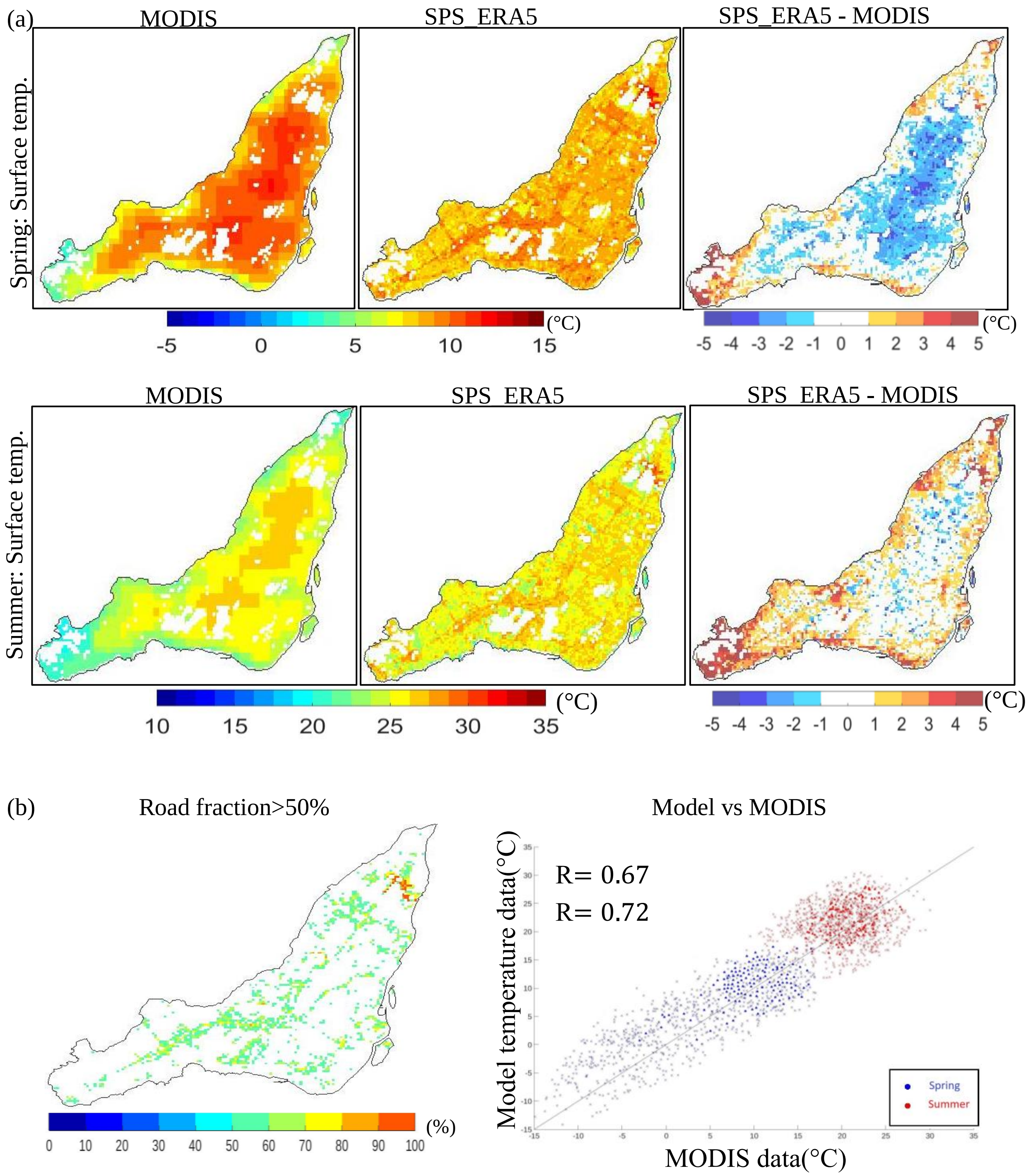

Figure 3.2: (a) Spring (top panel) and summer (bottom panel) surface temperature from MODIS (in °C) (first column), and SPS_ERA5 (in °C) (second column) for (2001–2020), and their respective biases (third column). (b) Grid cells with road fraction greater than 50% (left) and scatter plot (right) of MODIS LST vs. modelled RST for these grid cells; filled triangles are used to distinguish points corresponding to grid cells with road fraction higher than 80% in the scatter plot.

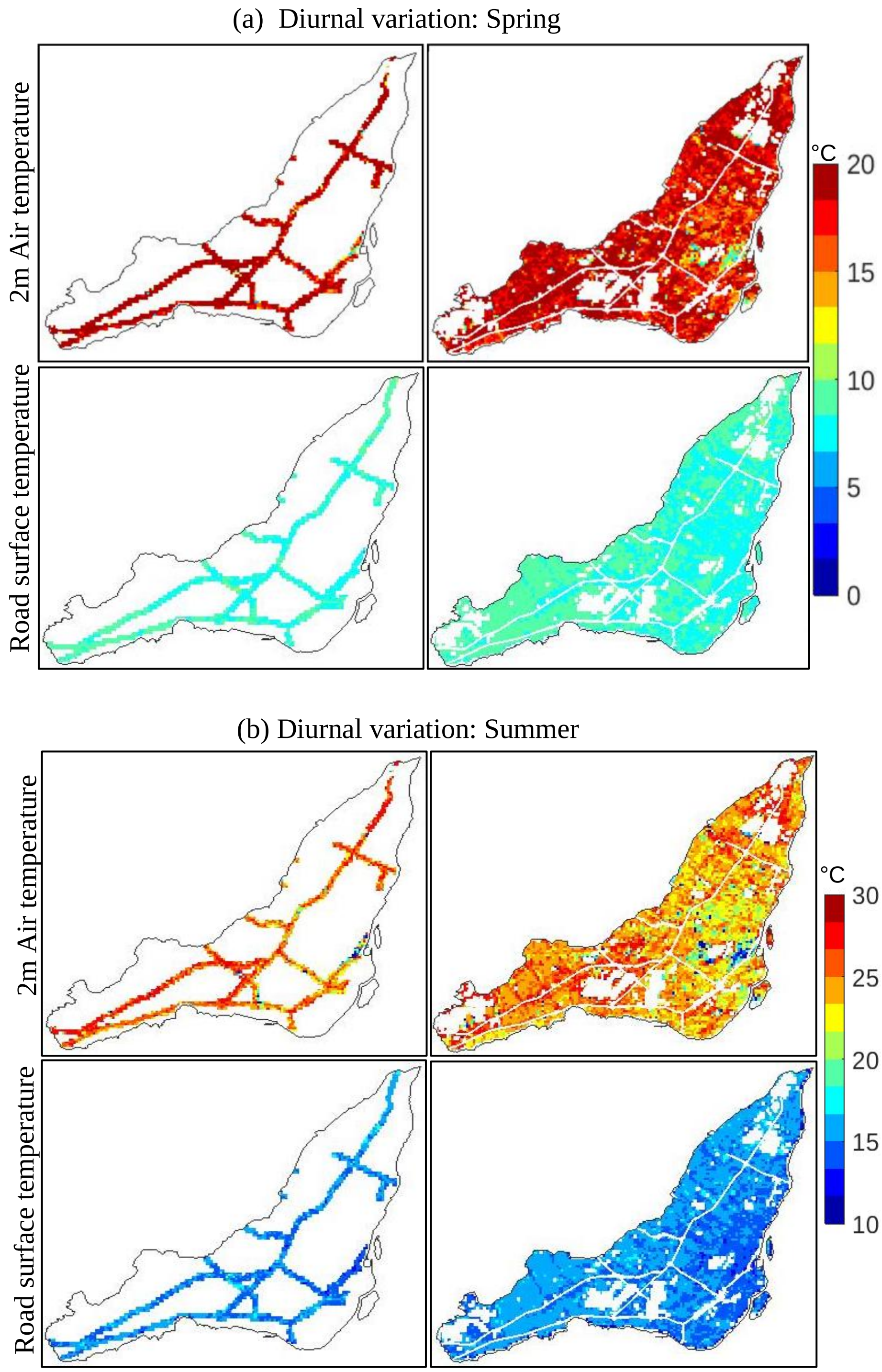

Figure 3.3: Mean diurnal variation of SPS_ERA5 simulated road surface temperature (in °C) (top) and 2 m air temperature (in °C) (bottom) for (a) spring and (b) summer for the 2001–2020 period. Left (right) column corresponds to highways (local roads).

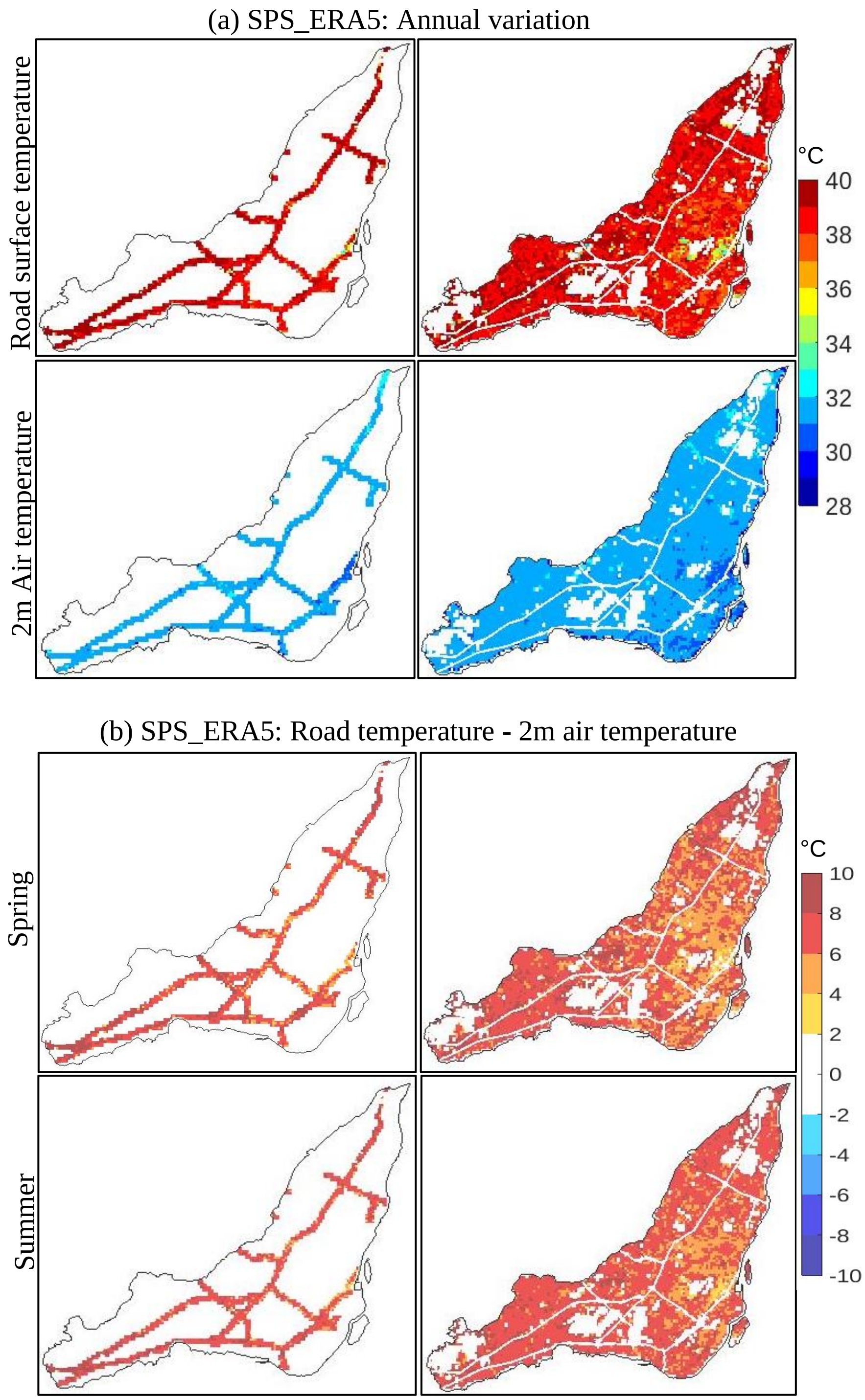

Figure 3.4: (a) Mean annual variation of SPS_ERA5 road surface temperature (in °C) (top) and 2 m air temperature (in °C) (bottom) for the 2001–2020 period. (b) Differences between SPS_ERA5 simulated mean road surface temperature (in °C) and 2 m air temperature (in °C) for spring (top) and summer (bottom) for the 2001–2020 period. Left (right) column corresponds to highways (local roads).

Summer: Road surface temperature

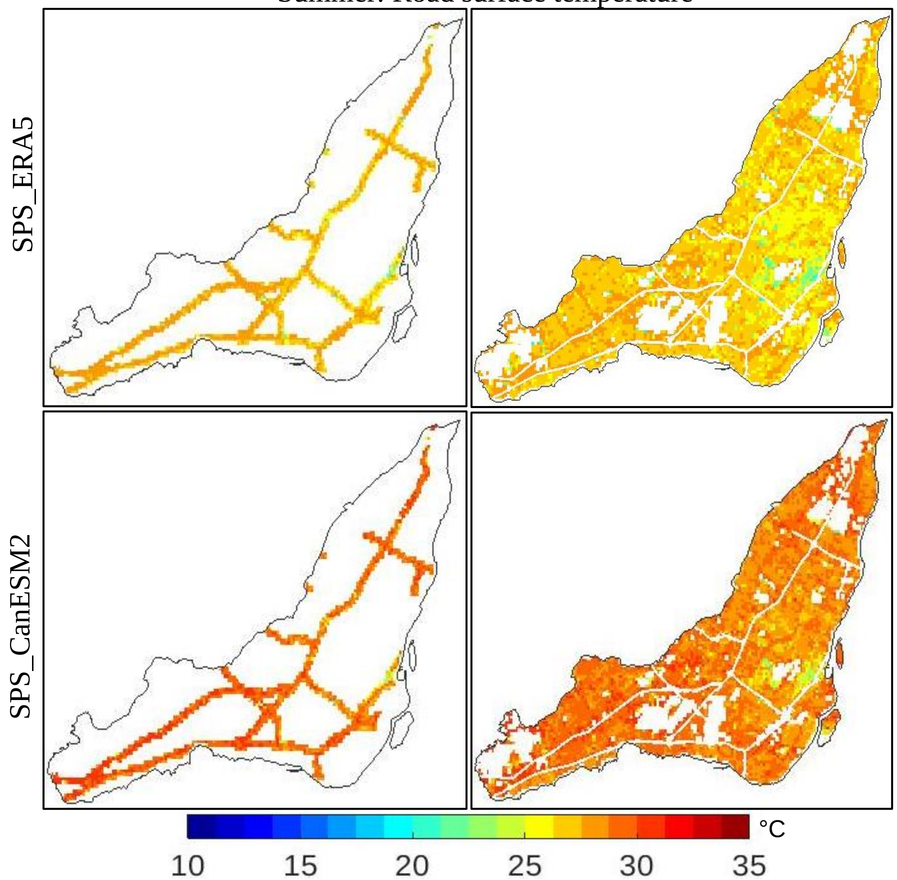

Figure 3.5: Mean annual variation of summer road surface temperature from SPS_ERA5 (in °C) (top) and SPS_CanESM2 (in °C) (bottom) for the 2001–2020 period. Left (right) column corresponds to highways (local roads).

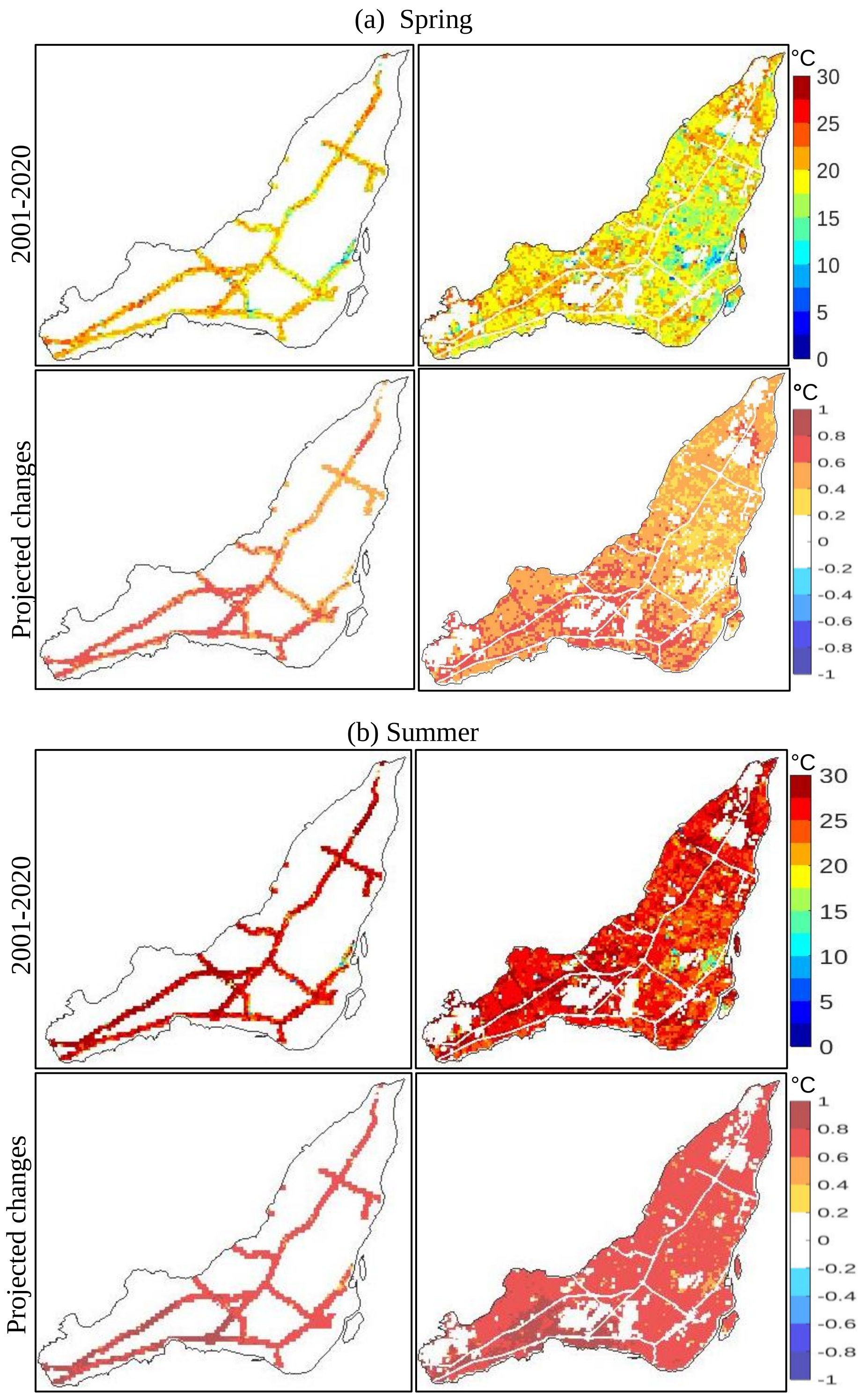

Figure 3.6: Mean diurnal variation of SPS_CanESM2 road surface temperatures (in °C) for 2001–2020 (top panel) and their projected changes for the future 2041–2060 period (in °C) (bottom panel) for (a) spring and (b) summer. Left (right) column corresponds to highways (local roads).

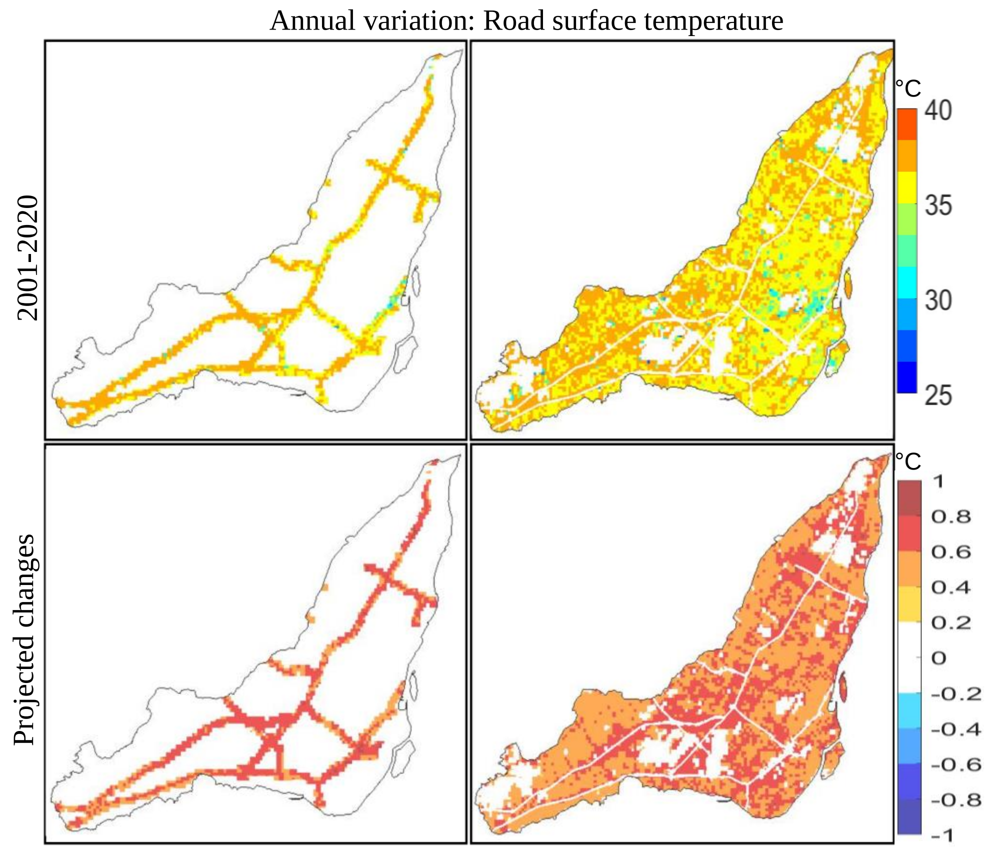

Figure 3.7: (a) Mean annual variation of SPS_CanESM2 RST (in °C) for the current 2001–2020 period (top panel) and projected changes for the future 2041–2060 period (bottom panel). Left (right) column corresponds to highways (local roads).

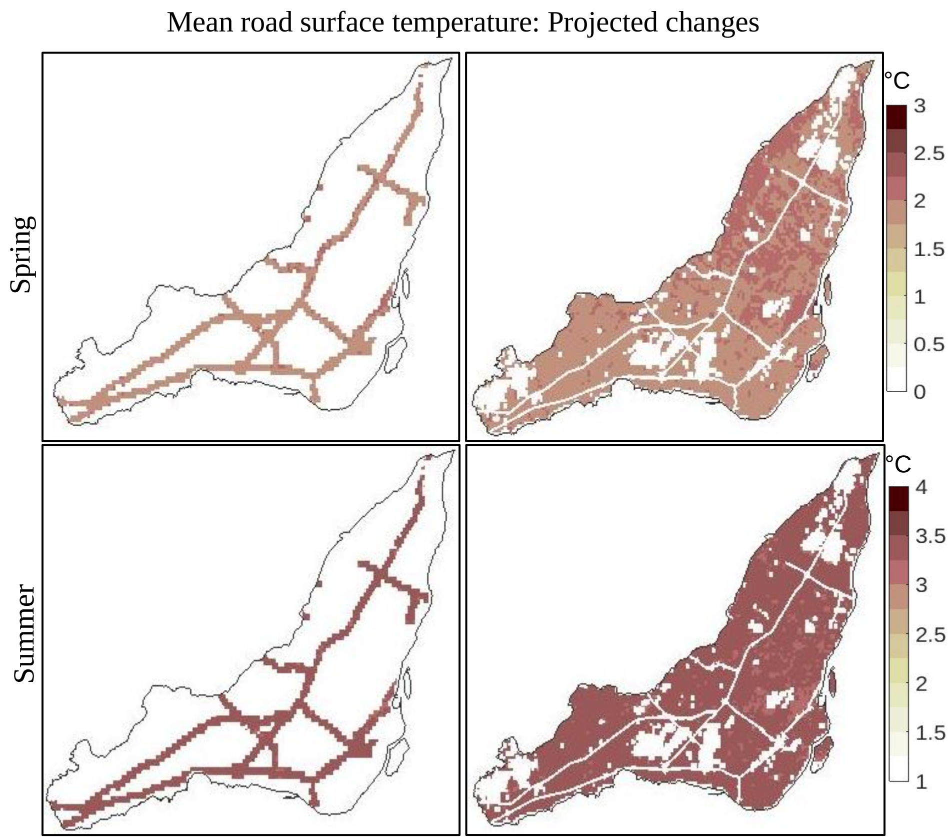

Figure 3.8 Projected changes to road surface temperature (in °C) for spring (top panel) and summer (bottom panel). Left (right) column corresponds to highways (local roads).

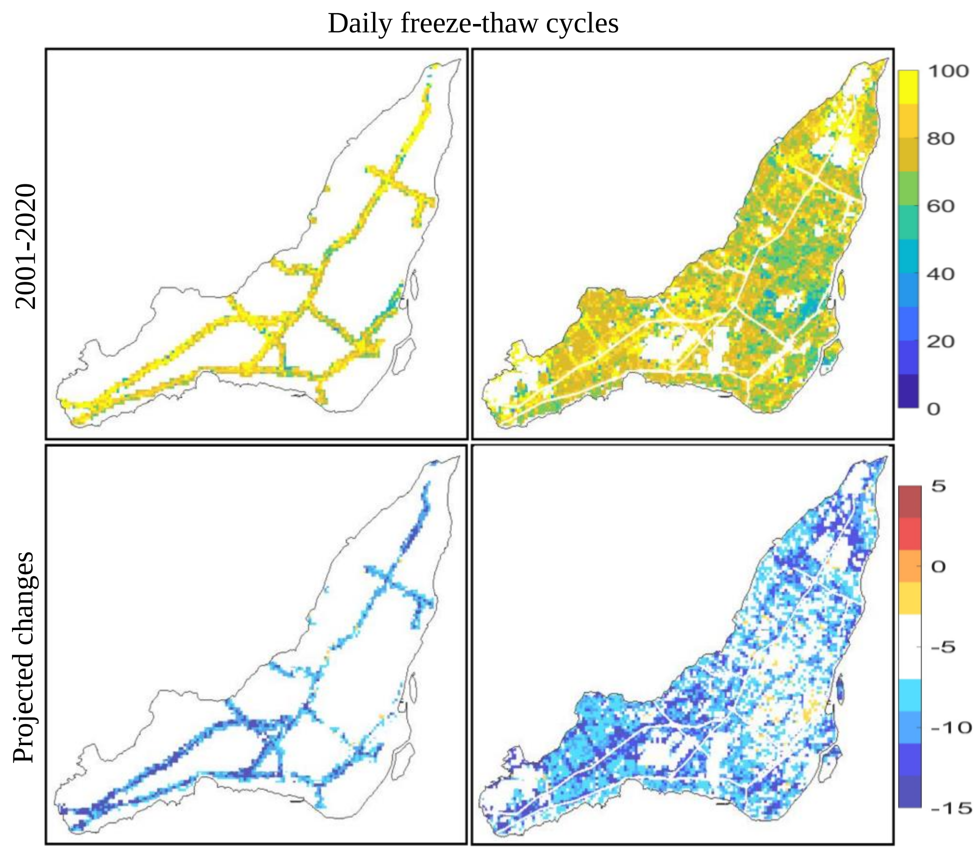

Figure 3.9: Mean frequency of freeze-thaw cycles for the 2001–2020 period (top panel) and its projected changes for the future 2041–2060 period (bottom panel). Left (right) column corresponds to highways (local roads).

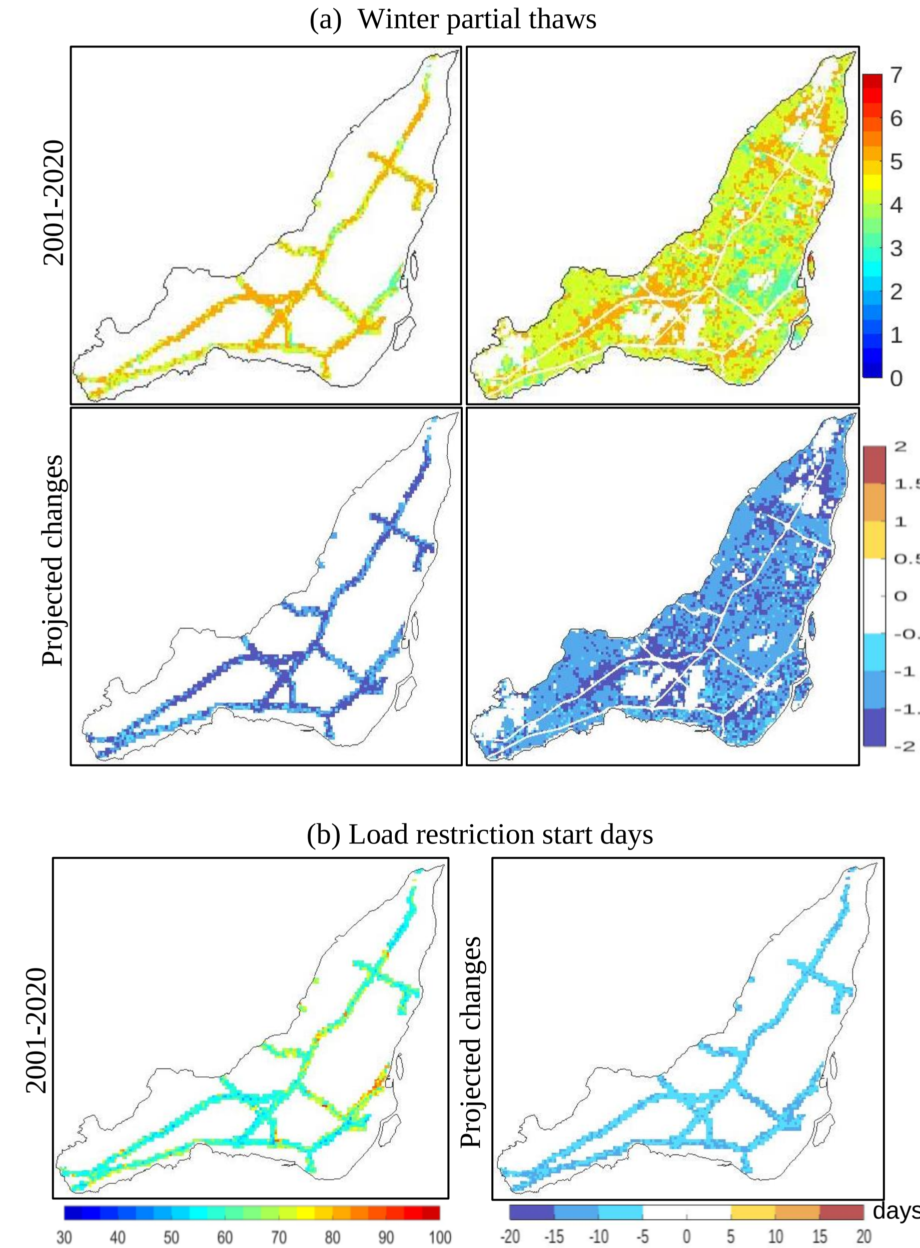

Figure 3.10: (a) Mean number of partial thaws for current period (top panel) and respective projected changes for the future period (bottom panel). (b) Mean start dates of load restriction period for the 2001–2020 period (left) and their projected changes for the future 2041–2060 period (right). Left (right) column corresponds to highways (local roads).

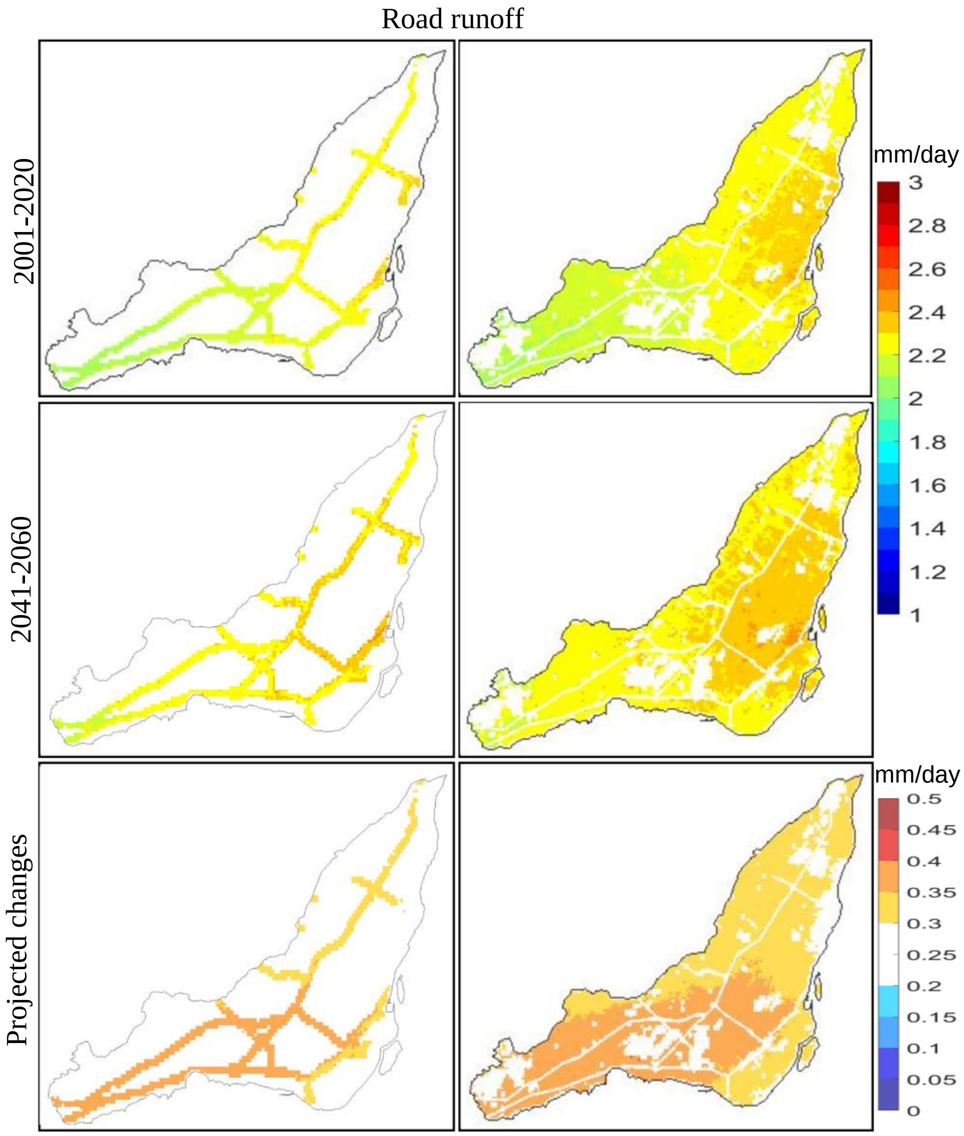

Figure 3.11: Mean daily road runoff (in mm/day) for cold season for the 2001–2020 (top panel) and 2041–2060 (middle panel) and their projected changes (bottom panel). Left (right) column corresponds to highways (local roads).

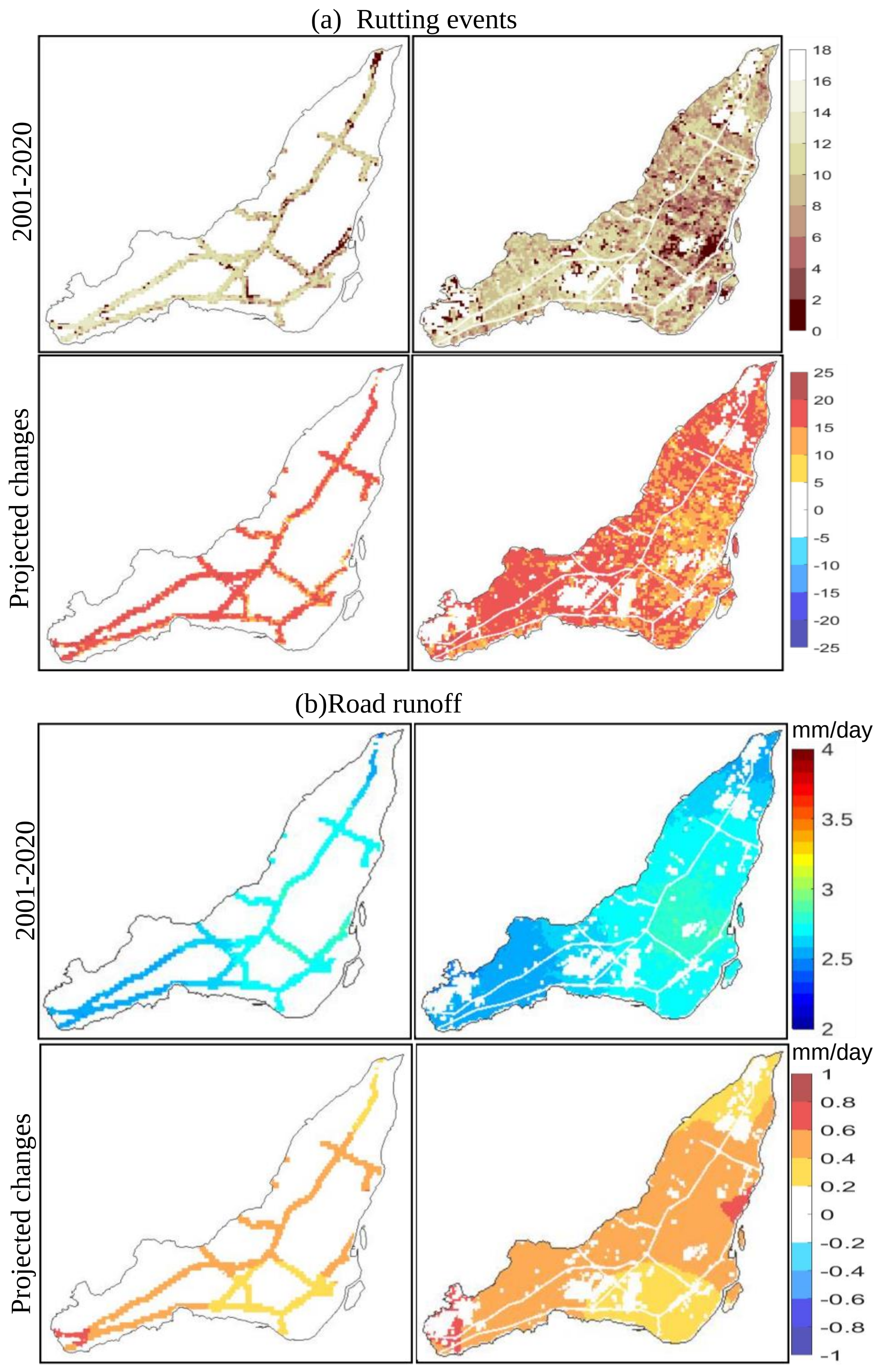

Figure 3.12: (a) Frequency of warm season rutting events for the 2001–2020 period (top panel) and their projected changes for the 2041–2060 future period (bottom panel). (b) Mean daily warm season road runoff (in mm/day) for the 2001–2020 period (top panel) and their projected changes for the 2041–2060 future period (bottom panel). Left (right) column corresponds to highways (local roads).

CHAPTER 4 - DISCUSSION

This chapter provides additional discussion on the main assumptions and limitations of this study and also explores the added value that can be obtained by employing coupled simulations, i.e., CLASS with TEB coupled to an atmospheric model such as GEM.

Montreal's harsh climate poses unique challenges for road construction and maintenance, resulting in increased difficulties and issues related to pavement damage and deterioration. Therefore, this paper analyzed potential impacts of climate change on Montreal island's road system by assessing projected changes to road thermal and hydrological variables, which is a growing area of concern these days. The study shows the significant influence of rising temperatures and rainfall on the managerial and engineering aspects of road infrastructure. Unlike earlier studies, which frequently used empirical relations and simple physically based road-only models to estimate road temperatures, this method makes use of a framework which include integration of a surface model and an urban model (TEB), providing a more precise representation of the urban environment, including road networks.

From the study results the impacts of freeze-thaw cycles (Fig 3.9) and spring partial thaws (Fig 3.10(a)) seem to be less in future climate compared to current climate. However, results suggest earlier start of load restriction days to minimize impacts of heavy traffic loads during the thaw period. The impacts seem to be important for the warm season with results suggesting an increase in rutting events. Furthermore, maintaining an effective drainage system and considering road runoff is crucial for future road maintenance in both warm and cold seasons.

4.1 Assumptions and limitations

As discussed, this is the first study to our knowledge that has investigated the capabilities of the road model in TEB. The road model has a simple three-layer configuration, with a top asphalt layer that is 8 centimeters thick and middle and base layers that are 20- and 100-centimeters thick, respectively.

This research employs offline simulations which rely on atmospheric forcing data, which encompasses various meteorological parameters, including specific humidity, wind speed, 2-meter air temperature, precipitation, incoming shortwave and longwave radiation, geopotential, and surface pressure coming from a lower resolution regional climate model. It is imperative to stress that using an offline simulation strategy highlights the importance of the driving data utilized. Offline simulations are highly dependent on the accuracy and completeness of the driving data and thus ensuring reliability of this data is a critical consideration. In this study the simulations were undertaken at 250 m resolution, and often times driving data at that resolution is not available. Driving data often comes from coarser resolution models, which may not have good representation of processes, including urban regions, leading to biases. This further signifies the need for coupled model simulations. A single year coupled simulation was undertaken with regional climate model GEM (Global Environmental Multiscale) and the results show significant differences in road surface temperature confirming once again the need for coupled simulation.

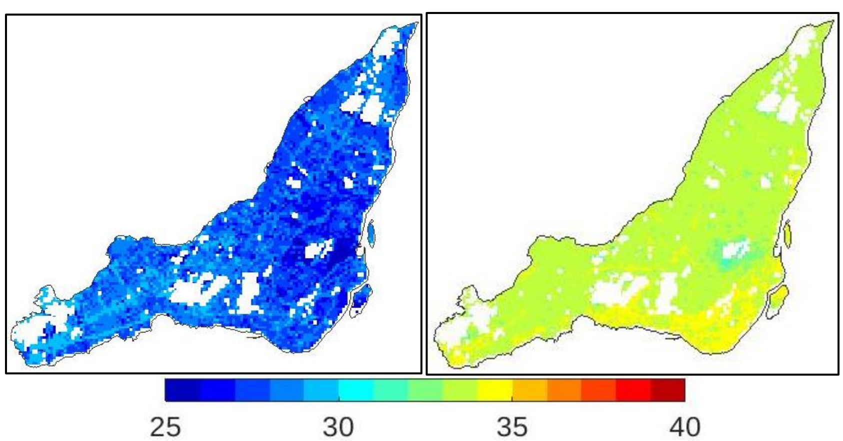

Figure 4.1 Road surface temperature for June from surface model (SPS- left) and coupled model (GEM- right).

Figure 4.1 shows the findings of road surface temperature for the month of June obtained from the

GEM model and the surface model used in this study and there is a noticeable variation of almost 5 to 6 ºC. This clearly indicates that the coupled simulations can help in avoiding errors that might result from the errors in the driving data in offline simulations. It is crucial to emphasize that variations in the driving data can have an impact on all other derived variables as well as the model's overall performance. But it is important to remember that these coupled simulations require a lot of resources and are expensive.

Enhancements can also be made to the model's structure and depiction of road attributes. Several parameters are essential for effectively predicting road temperatures, including albedo and thermal conductivity. Road albedo as represented by the model, derived from Canadian Vector Data (CanVec) version 9.0, shows only slight variations, as in Fig. 4.2. It is important to improve this through ground observations such as station measurements and utilizing remotely sensed observations like satellite data or aerial imagery.

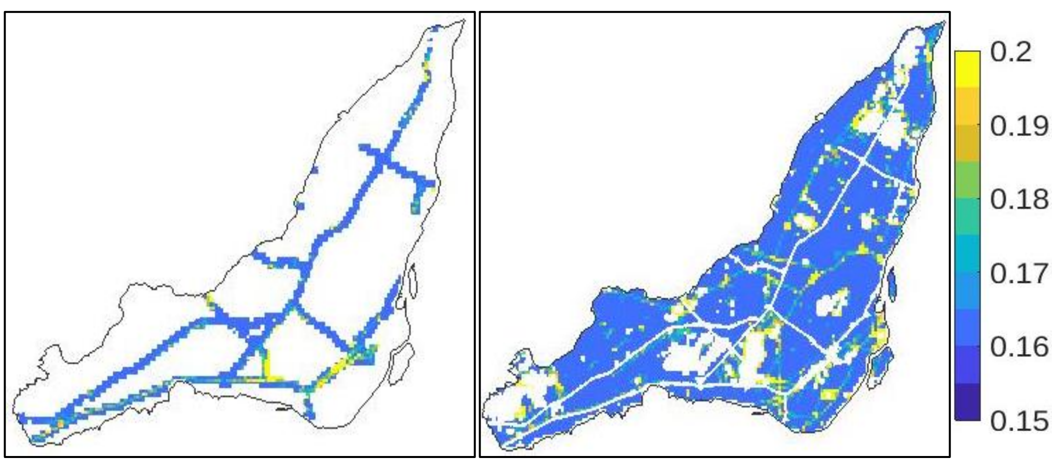

Figure 4.2: Albedo over road surface: Highways (first), local roads (last).

The road layer configuration also can be improved to increase the realism of the model. All roads are assumed to be at the ground surface, and future improvements can consider improving some of these assumptions.

The validation part in this paper still has some limitations, mainly due to the lack of road temperature data. Road observation data is still lacking or not publicly available.

It is critical to acknowledge that the model, given its simplicity, is good for preliminary analysis. It is a useful first step towards identifying possible hot spots in the road network. Thereafter specialized modeling tools like AASHTOWare can be utilized to fully comprehend these vulnerable road segments and to carry out more thorough research for design and failure studies.

Additionally, this study focuses on high-density urban areas and highways where a larger probability of road surface damage is expected, enhancing the significance and applicability of this research. Greater heat retention, high traffic, and environmental stressors are characteristics of high-density urban settings. Focusing the study efforts in these particular areas will help to understand how climate change affects road infrastructure in places where the effects are most noticeable and pertinent.

4.2 Implications and future research

Assessment of the co-benefits of high-resolution road surface temperature data goes beyond the scope of this project. Studying pedestrian comfort, a crucial component of urban planning and design, can be greatly aided by the data obtained from SPS. It makes it possible to comprehend how the thermal environment affects pedestrian comfort and safety on a deeper level. By improving the model, i.e., by incorporating urban vegetation and green infrastructure, the model can be effectively used in adaptation/mitigation studies by conducting carefully designed model experiments.

To sum up, the thorough modeling and analysis of the effects of climate change on Montreal island's road infrastructure used in this study makes a substantial contribution to the domains of engineering, urban planning, and adaptation strategies and policy. It emphasizes the need for immediate actions, including innovative drainage solutions, and monitoring to address the problems that a rising climate presents. The advancement of this study holds immense potential. Enhancing road characteristics, moving to coupled simulations, improving the modeling framework, and obtaining high-resolution driving data are all part of it. It also includes the model's possibility of incorporating green infrastructure. Essentially, this research establishes the foundation for additional investigations and improvements.

CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS

Even though Montreal's roads play a pivotal role in everyday life, the city faces serious problems as a result of the advanced deterioration of its aging road network. The increasing difficulties brought on by the widespread effects of climate change can exacerbate these problems. In order to strengthen the capacity to address these issues, it is essential to shift towards a more realistic representation of urban environments and road surface characteristics through interactive modeling of road surface conditions and temperatures.

This study looked at the potential impacts of a warmer climate on the road system of Montreal, for the future 2041-2060 period relative to the current climate 2001-2020. Unlike previous studies that relied on empirical relationships to estimate road temperatures from 2m air temperatures and related variables, this work employs an urban model TEB, with a simplistic representation of roads, combined with land surface model CLASS to provide a more detailed depiction of the urban environment. The study offers a direct assessment of selected thermal and hydrologic characteristics of roads, offering important insights into their variability for both local roads and highways. The main findings of this study are listed below:

- The model's ability to replicate road temperature characteristics appeared reasonable when compared with MODIS data for grid cells with a high percentage of pavement/road fraction. Pearson correlation coefficient values of 0.67 and 0.72 were obtained when comparing grid cells with greater than 50% and 80% road fractions, respectively.
- A potential decrease in thermal related road failure during the cold season is suggested for future climate compared to current climate. This decrease is attributed to relatively warmer temperatures, fewer daily freeze-thaw cycles, and partial thaws. The freeze-thaw events show a 12.5% decrease on local roads and highways, while partial thaws are projected to

decline by 1.5 to 2 events on local roads and roughly 1 to 1.5 events on highways, suggesting reduced distress than in current climate. On the other hand, the findings point to a possible rise in failure mechanisms associated with hydrologic features during cold season, particularly runoff, associated with higher rain to snow ratio during this season. Both road and land runoff are projected to increase in the 12 to 16% range for winter, underscoring the need to install efficient drainage systems.

- To prevent road deterioration from excessive traffic loads during the thaw season, load restriction period needs to be shifted earlier. Analysis suggests this shift to be of the order of two weeks in future climate, i.e., to the end of February.
- Thermal and hydrologic features suggest that road vulnerability will rise during the warmer season. The anticipated increase in the projected warm season mean daily RST in the 3.5 to 4°C range and mean daily maximum RST in 4 to 4.5°C range suggest a potential increase in road failures, specifically in the form of more rutting events (10 to 15 events), especially on highways, which can weaken and soften asphalt materials leading to transverse or longitudinal cracks. Similarly, an estimated 25% increase in warm-season land and road runoff, especially in core urban areas, highlights the critical requirement for a thorough evaluation of current drainage infrastructure.

Lack of observed road surface temperature and runoff limited the validation of the model. Future research projects should prioritize filling in this data gap. Despite this, the SPS simulations undertaken have important ramifications for engineering design and urban planning since they provide a more thorough and realistic representation of the road network within the urban environment. This research can be advanced by making the models more refined, switching to coupled atmosphere-land/urban simulations, and improving road properties within the model as discussed in Chapter 4.

In conclusion, this thorough investigation into how climate change affects the road system on Montreal Island makes a major contribution to the domains of engineering and urban planning. It emphasizes the seasonal differences in climate change impacts on the Montreal road network, which indicate adaptive strategies to be developed to improve climate resiliency. This research not only establishes a foundation for further investigation, but also marks the beginning of a continuous endeavor to understand and tackle the complex problems associated with climate change on urban infrastructure.

REFERENCES

Adugna, D., Lemma, B., Jensen, M. B., & Gebrie, G. S. (2019). Evaluating the hydraulic capacity of existing drain systems and the management challenges of stormwater in Addis Ababa, Ethiopia. *Journal of Hydrology: Regional Studies*, *25*, 100626.

Adwan, I., Milad, A., Memon, Z. A., Widyatmoko, I., Ahmat Zanuri, N., Memon, N. A., & Yusoff, N. I. M. (2021). Asphalt pavement temperature prediction models: A review. *Applied Sciences*, *11*(9), 3794.

Al-adili, A., Abdulamir, R., & Abbas, H. (2018). Drainage investigation of surface runoff for highway pavement. MATEC Web of Conferences,

Andersson, A., & Chapman, L. (2011). The use of a temporal analogue to predict future traffic accidents and winter road conditions in Sweden. *Meteorological Applications*, *18*(2), 125-136.

Andersson, A. K., & Chapman, L. (2011). The impact of climate change on winter road maintenance and traffic accidents in West Midlands, UK. *Accident Analysis & Prevention*, *43*(1), 284-289.

Asefzadeh, A., Hashemian, L., & Bayat, A. (2017). Development of statistical temperature prediction models for a test road in Edmonton, Alberta, Canada. *International Journal of Pavement Research and Technology*, *10*(5), 369-382.

Barber, E. S. (1957). Calculation of maximum pavement temperatures from weather reports. *Highway Research Board Bulletin*(168).

Belair, S., Leroyer, S., Seino, N., Spacek, L., SOUVANLASSY, V., & Paquin-Ricard, D. (2018). Role and impact of the urban environment in a numerical forecast of an intense summertime precipitation event over Tokyo. *Journal of the Meteorological Society of Japan. Ser. II*.

Bilodeau, J.-P., Drolet, F. P., Doré, G., & Sottile, M.-F. (2015). Effect of climate changes expected during winter on pavement performance. In *Cold Regions Engineering 2015* (pp. 617-628).

Bilodeau, J., & Doré, G. (2020). *Assessment of Pavement Response during Spring Thaw Using Heavy Vehicle Simulator Testing*. ASTM International.

Bosscher, P. J., Bahia, H. U., Thomas, S., & Russell, J. S. (1998). Relationship between pavement temperature and weather data: Wisconsin field study to verify superpave algorithm. *Transportation research record*, *1609*(1), 1-11.

Byrne, M., & Aguiar, G. (2010). *Impact of climate change on road performance: updating climate information for Australia* (1921709162).

Chen, J., Wang, H., & Xie, P. (2019). Pavement temperature prediction: Theoretical models and critical affecting factors. *Applied thermal engineering*, *158*, 113755.

Chinowsky, P., & Arndt, C. (2012). Climate change and roads: A dynamic stressor–response model. *Review of Development Economics*, *16*(3), 448-462.

de Abreu, V. H. S., Santos, A. S., & Monteiro, T. G. M. (2022). Climate change impacts on the road transport infrastructure: A systematic review on adaptation measures. *Sustainability*, *14*(14), 8864.

Di Mascio, P., Piccolo, I., & Cera, L. (2007). Automated Distress Evaluation. Proceedings of 4th International SIIV Congress, Palermo, Italy,

Diefenderfer, B. K., Al-Qadi, I. L., & Diefenderfer, S. D. (2006). Model to predict pavement temperature profile: development and validation. *Journal of Transportation Engineering*, *132*(2), 162-167.

Diro, G., & Sushama, L. (2017). The role of soil moisture–atmosphere interaction on future hot spells over North America as simulated by the canadian regional climate model (CRCM5). *Journal of Climate*, *30*(13), 5041-5058.

Fifer Bizjak, K., Dawson, A., Hoff, I., Makkonen, L., Ylhäisi, J. S., & Carrera, A. (2017). The impact of climate change on the European road network. Proceedings of the Institution of Civil Engineers-Transport,

Freistetter, N.-C., Médus, E., Hippi, M., Kangas, M., Dobler, A., Belušić, D., Käyhkö, J., & Partanen, A.-I. (2022). Climate change impacts on future driving and walking conditions in Finland, Norway and Sweden. *Regional Environmental Change*, *22*(2), 1-13.

Fujimoto, A., Saida, A., & Fukuhara, T. (2012). A new approach to modeling vehicle-induced heat and its thermal effects on road surface temperature. *Journal of Applied Meteorology and Climatology*, *51*(11), 1980-1993.

Gedafa, D. S., Hossain, M., & Romanoschi, S. A. (2014). Perpetual pavement temperature prediction model. *Road Materials and Pavement Design*, *15*(1), 55-65.

Hambly, D., Andrey, J., Mills, B., & Fletcher, C. (2013). Projected implications of climate change for road safety in Greater Vancouver, Canada. *Climatic change*, *116*(3), 613-629.

Hamdi, R., Degrauwe, D., & Termonia, P. (2012). Coupling the Town Energy Balance (TEB) scheme to an operational limited-area NWP model: evaluation for a highly urbanized area in Belgium. *Weather and Forecasting*, *27*(2), 323-344.

Hamdi, R., Giot, O., De Troch, R., Deckmyn, A., & Termonia, P. (2015). Future climate of Brussels and Paris for the 2050s under the A1B scenario. *Urban Climate*, *12*, 160-182.

Hori, Y., Cheng, V., Gough, W. A., Jien, J. Y., & Tsuji, L. J. (2018a). Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic change*, *148*(1), 109-122.

Hori, Y., Cheng, V. Y., Gough, W. A., Jien, J. Y., & Tsuji, L. J. (2018b). Implications of projected climate change on winter road systems in Ontario's Far North, Canada. *Climatic change*, *148*, 109-122.

Islam, M. R., Ahsan, S., & Tarefder, R. A. (2015). Modeling temperature profile of hot-mix asphalt in flexible pavement. *International Journal of Pavement Research and Technology*, *8*(1), 47.

Juga, I., Nurmi, P., & Hippi, M. (2013). Statistical modelling of wintertime road surface friction. *Meteorological Applications*, *20*(3), 318-329.

Kangas, M., Heikinheimo, M., & Hippi, M. (2015). RoadSurf: a modelling system for predicting road weather and road surface conditions. *Meteorological Applications*, *22*(3), 544-553.

Khadrawi, A., Al-Shyyab, A., & Abo-Qudais, S. A. (2012). Transient thermal behavior of hot–mix asphalt pavement. *Applied Mechanics and Materials*, *110*, 400-407.

Kouroshnejad, K., Sushama, L., Sandanayake, H., Cooke, R., & Ziya, O. (2023). Pluvial flash flood-traffic interactions in current and future climates for the City of Ottawa. *Safety in extreme environments*, *5*(3), 161-176.

Kršmanc, R., Slak, A. Š., & Demšar, J. (2013). Statistical approach for forecasting road surface temperature. *Meteorological Applications*, *20*(4), 439-446.

Kwiatkowski, K. P., Stipanovic Oslakovic, I., Ter Maat, H., Hartmann, A., Chinowsky, P., & Dewulf, G. P. (2020). Modeling cost impacts and adaptation of freeze–thaw climate change on a porous asphalt road network. *Journal of Infrastructure Systems*, *26*(3), 04020022.

Lemonsu, A., Viguie, V., Daniel, M., & Masson, V. (2015). Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France). *Urban Climate, 14,* 586-605.

Leong, P., Tighe, S., & Doré, G. (2005). Using LTPP data to develop spring load restrictions: A pilot study. Proc., 84th Annual Meeting,

Li, Y., Liu, L., & Sun, L. (2018). Temperature predictions for asphalt pavement with thick asphalt layer. *Construction and building materials*, *160*, 802-809.

Lukanen, E. O., Stubstad, R., Briggs, R. C., & Intertec, B. (2000). *Temperature predictions and adjustment factors for asphalt pavement*.

Maadani, O., Shafiee, M., & Egorov, I. (2021). Climate change challenges for flexible pavement in Canada: an overview. *Journal of Cold Regions Engineering*, *35*(4), 03121002.

Makkonen, L., Ylhäisi, J., Törnqvist, J., Dawson, A., & Räisänen, J. (2014). Climate change projections for variables affecting road networks in Europe. *Transportation Planning and Technology*, *37*(8), 678-694.

Masson, V. (2000a). A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-layer meteorology*, *94*, 357-397.

Masson, V. (2000b). A physically-based scheme for the urban energy budget in atmospheric models. *Boundary-layer meteorology*, *94*(3), 357-397.

Masson, V., Grimmond, C. S. B., & Oke, T. R. (2002). Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *Journal of applied meteorology*, *41*(10), 1011-1026.

Matulla, C., Hollósi, B., Andre, K., Gringinger, J., Chimani, B., Namyslo, J., Fuchs, T., Auerbach, M., Herrmann, C., & Sladek, B. (2018). Climate Change driven evolution of hazards to Europe's transport infrastructure throughout the twenty-first century. *Theoretical and Applied Climatology*, *133*, 227-242.

Mills, B. N., Tighe, S. L., Andrey, J., Smith, J. T., & Huen, K. (2009). Climate change implications for flexible pavement design and performance in southern Canada. *Journal of Transportation Engineering*, *135*(10), 773-782.

Minhoto, M. J., Pais, J. C., Pereira, P. A., & Picado-Santos, L. G. (2005). Predicting asphalt pavement temperature with a three-dimensional finite element method. *Transportation research record*, *1919*(1), 96-110.

Mokoena, R., Mturi, G., Maritz, J., Mateyisi, M., & Klein, P. (2022). African case studies: Developing pavement temperature maps for performance-graded asphalt bitumen selection. *Sustainability*, *14*(3), 1048.

Moretti, L., & Loprencipe, G. (2018). Climate change and transport infrastructures: State of the art. *Sustainability*, *10*(11), 4098.

Mukherjee, D. (2014). Highway surface drainage system & problems of water logging in road section. *Int. J. Eng. Sci*, *3*, 44-51.

Oh, S.-G., & Sushama, L. (2021). Urban-climate interactions during summer over eastern North America. *Climate Dynamics*, *57*(11-12), 3015-3028.

Palko, K., & Lemmen, D. S. (2017). Climate risks and adaptation practices for the Canadian transportation sector 2016.

Pang, X., Gu, Y., Launiainen, S., & Guan, M. (2022). Urban hydrological responses to climate change and urbanization in cold climates. *Science of The Total Environment*, *817*, 153066.

Park, D.-Y., Buch, N., & Chatti, K. (2001). Effective layer temperature prediction model and temperature correction via falling weight deflectometer deflections. *Transportation research record*, *1764*(1), 97-111.

Park, J. J., Shin, E. C., & Yoon, B. J. (2016). Development of frost penetration depth prediction model using field temperature data of asphalt pavement. *International Journal of Offshore and Polar Engineering*, *26*(04), 341-347.

Pregnolato, M., Ford, A., Wilkinson, S. M., & Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment*, *55*, 67-81.

Prein, A. F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., Keller, M., Tölle, M., Gutjahr, O., & Feser, F. (2015). A review on regional convection‐permitting climate modeling: Demonstrations, prospects, and challenges. *Reviews of geophysics*, *53*(2), 323-361.

Qiao, Y., Santos, J., Stoner, A. M., & Flinstch, G. (2020). Climate change impacts on asphalt road pavement construction and maintenance: An economic life cycle assessment of adaptation measures in the State of Virginia, United States. *Journal of Industrial Ecology*, *24*(2), 342-355.

Qin, Y., & Hiller, J. E. (2011). Modeling temperature distribution in rigid pavement slabs: impact of air temperature. *Construction and building materials*, *25*(9), 3753-3761.

Roberge, F., & Sushama, L. (2018). Urban heat island in current and future climates for the island of Montreal. *Sustainable Cities and Society*, *40*, 501-512.

Shah, Y. U., Jain, S., Tiwari, D., & Jain, M. (2013). Development of overall pavement condition index for urban road network. *Procedia-Social and Behavioral Sciences*, *104*, 332-341.

Shao, Z., Jenkins, G., & Oh, E. (2017). Assessing the impacts of climate change on road infrastructure. *GEOMATE Journal*, *13*(38), 120-128.

Shi, X., Zollinger, D. G., & Mukhopadhyay, A. K. (2020). Punchout study for continuously reinforced concrete pavement containing reclaimed asphalt pavement using pavement ME models. *International Journal of Pavement Engineering*, *21*(10), 1199-1212.

Singh, S., Ransinchung, G., Debbarma, S., & Kumar, P. (2018). Utilization of reclaimed asphalt pavement aggregates containing waste from Sugarcane Mill for production of concrete mixes. *Journal of Cleaner Production*, *174*, 42-52.

Southgate, H. F. (1968). An evaluation of temperature distribution within asphalt pavements and its relationship to pavement deflection.

Teltayev, B., & Radovskiy, B. (2018). Predicting thermal cracking of asphalt pavements from bitumen and mix properties. *Road Materials and Pavement Design*, *19*(8), 1832-1847.

Teufel, B., Carmo, F., Sushama, L., Sun, L., Khaliq, M., Bélair, S., Shamseldin, A., Kumar, D. N., & Vaze, J. (2023). Physics-informed deep learning framework to model intense precipitation events at super resolution. *Geoscience Letters*, *10*(1), 19.

Teufel, B., & Sushama, L. (2021). 2° C vs. High Warming: Transitions to Flood-Generating Mechanisms across Canada. *Water*, *13*(11), 1494.

Teufel, B., & Sushama, L. (2022). High-resolution modelling of climatic hazards relevant for Canada's northern transportation sector. *Climate Dynamics*, *59*(9-10), 3135-3151.

Teufel, B., Sushama, L., Poitras, V., Dukhan, T., Bélair, S., Miranda-Moreno, L., Sun, L., Sasmito, A. P., & Bitsuamlak, G. (2021). Impact of COVID-19-related traffic slowdown on urban heat characteristics. *Atmosphere*, *12*(2), 243.

Toivonen, E., Hippi, M., Korhonen, H., Laaksonen, A., Kangas, M., & Pietikäinen, J.-P. (2019). The road weather model RoadSurf (v6. 60b) driven by the regional climate model HCLIM38: evaluation over Finland. *Geoscientific Model Development*, *12*(8), 3481-3501.

Tu, W., Zhu, T., Zhong, C., Zhang, X., Xu, Y., & Li, Q. (2022). Exploring metro vibrancy and its relationship with built environment: a cross-city comparison using multi-source urban data. *Geo-spatial Information Science*, *25*(2), 182-196.

Vaillancourt, C., Duchesne, S., & Pelletier, G. (2019). Hydrologic performance of permeable pavement as an adaptive measure in urban areas: case studies near Montreal, Canada. *Journal of Hydrologic Engineering*, *24*(8), 05019020.

Van Deusen, D., Schrader, C., Bullock, D., & Worel, B. (1998). Springtime thaw weakening and load restrictions in Minnesota. *Transportation research record*, *1615*(1), 21-28.

Verseghy, D. L. (1991). CLASS—A Canadian land surface scheme for GCMs. I. Soil model. *International Journal of Climatology*, *11*(2), 111-133.

Wada, S. A. (2016). Bituminous pavement failures. *Journal of Engineering Research and Applications*, *6*(2), 94-100.

Wang, K. C., Li, Q. J., Yang, G., Zhan, Y., & Qiu, Y. (2015). Network level pavement evaluation with 1 mm 3D survey system. *Journal of traffic and transportation engineering (English edition)*, *2*(6), 391-398.

Wang, T., Qu, Z., Yang, Z., Nichol, T., Dimitriu, D., Clarke, G., & Bowden, D. (2019). How can the UK road system be adapted to the impacts posed by climate change? By creating a climate adaptation framework. *Transportation Research Part D: Transport and Environment*, *77*, 403-424.

Wu, H., Zhong, Y., Xu, W., Shi, W., Shi, X., & Liu, T. (2020). Experimental investigation of ground and air temperature fields of a cold-region road tunnel in NW China. *Advances in Civil Engineering*, *2020*, 1-13.

Yang, B., Qin, Z., Zhou, Q., Li, H., Li, L., & Yang, X. (2020). Pavement damage behaviour of urban roads in seasonally frozen saline ground regions. *Cold Regions Science and Technology*, *174*, 103035.

Zsebeházi, G., & Szépszó, G. (2020). Modeling the urban climate of Budapest using the SURFEX land surface model driven by the ALADIN-Climate regional climate model results. *Időjárás/quarterly journal of the hungarian meteorological service*, *124*(2), 191-207.

Appendix A: Supplementary material for Chapter 3

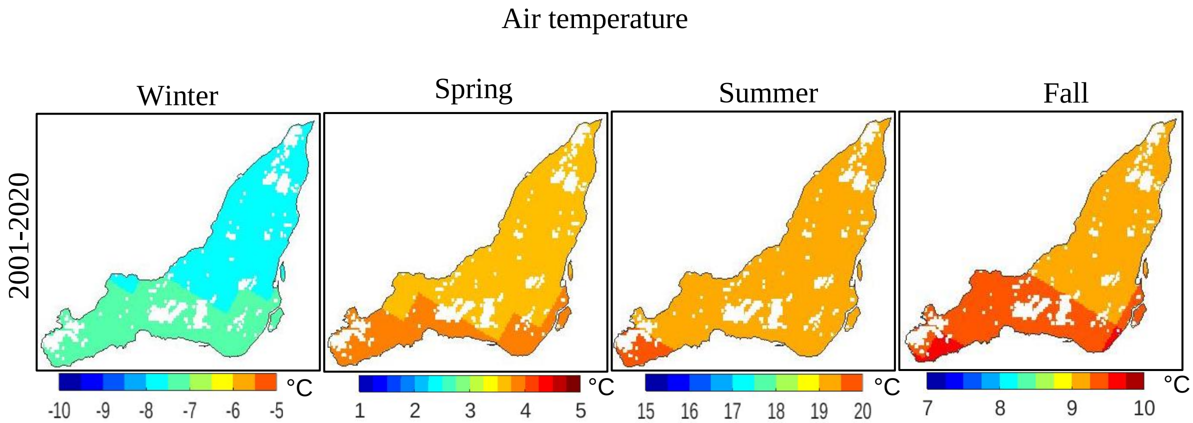

Figure A.1: Mean seasonal temperature values (in °C) derived from the hourly driving data used for SPS_ERA5 simulation for the 2001–2020 period for winter, spring, summer, and fall.

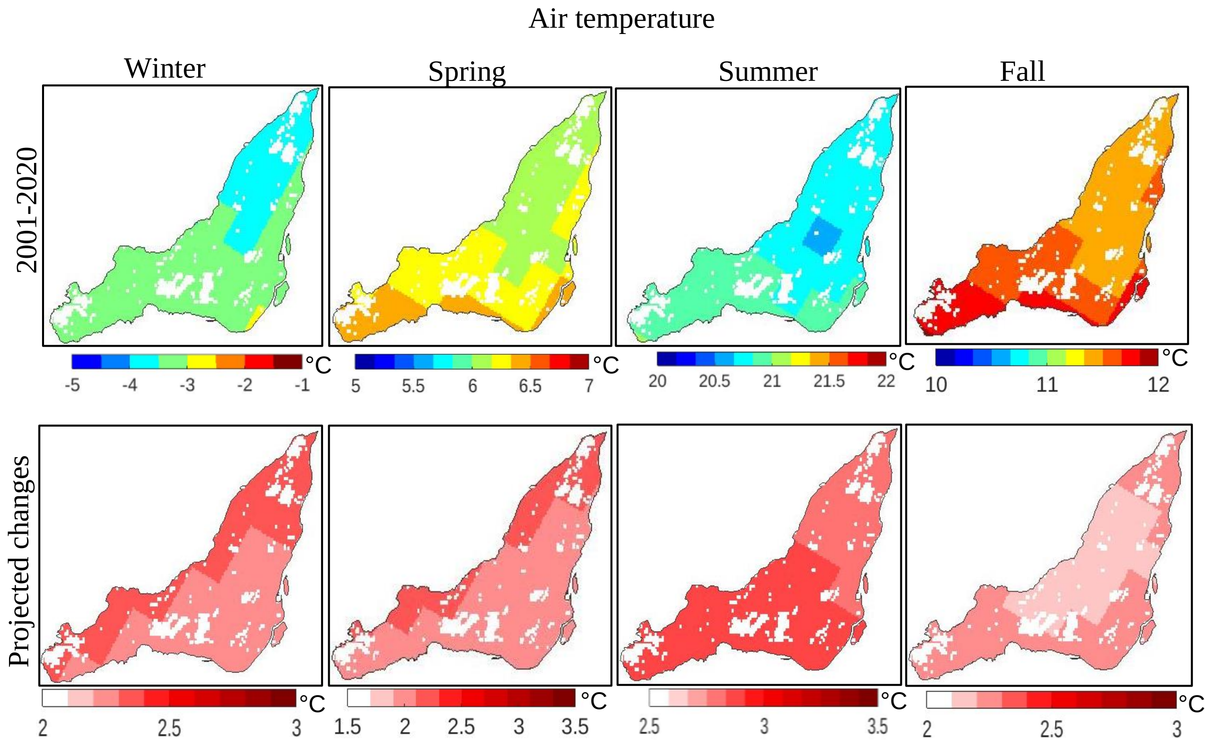

Figure A.2: Mean seasonal temperature values (in °C) derived from the hourly driving data used for SPS_CanESM2 simulation for the 2001–2020 period (top panel) and its projected changes for the 2041–2060 future period (bottom panel) for winter, spring, summer, and fall.

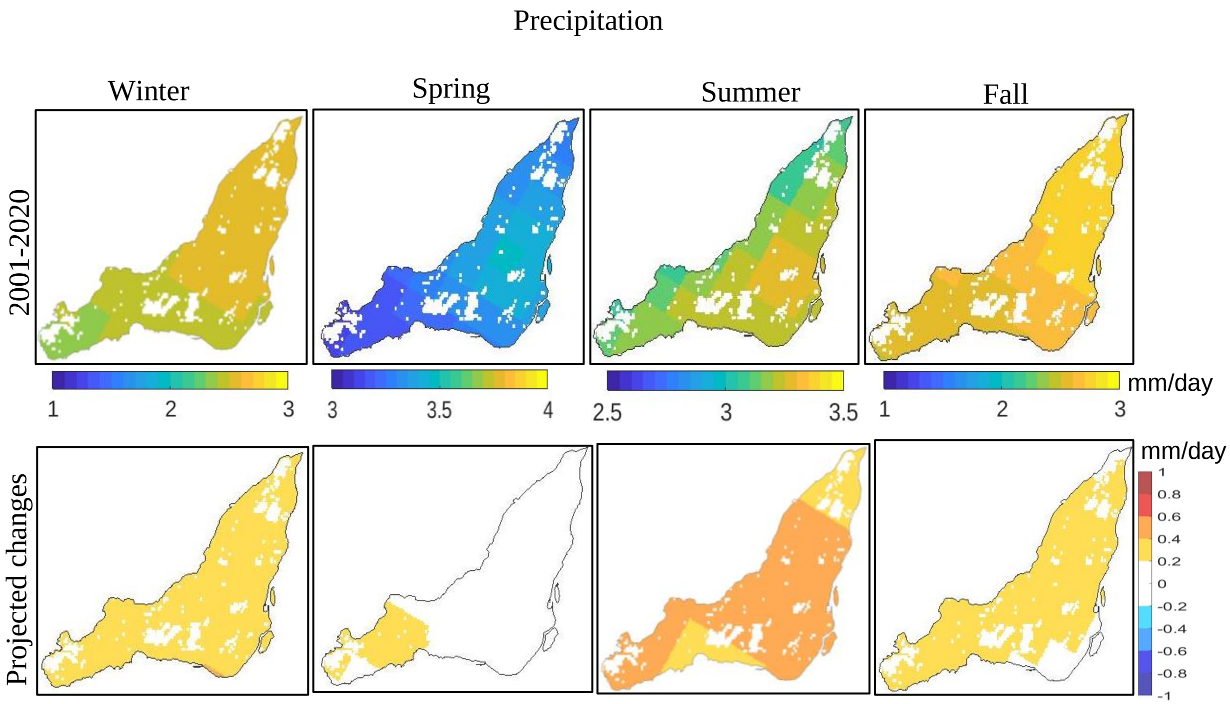

Figure A.3: Mean seasonal precipitation values (in mm/day) derived from the hourly driving data used for SPS_CanESM2 simulation for the 2001–2020 period (top panel) and their projected changes for the 2041–2060 future period (bottom panel) for winter, spring, summer, and fall.

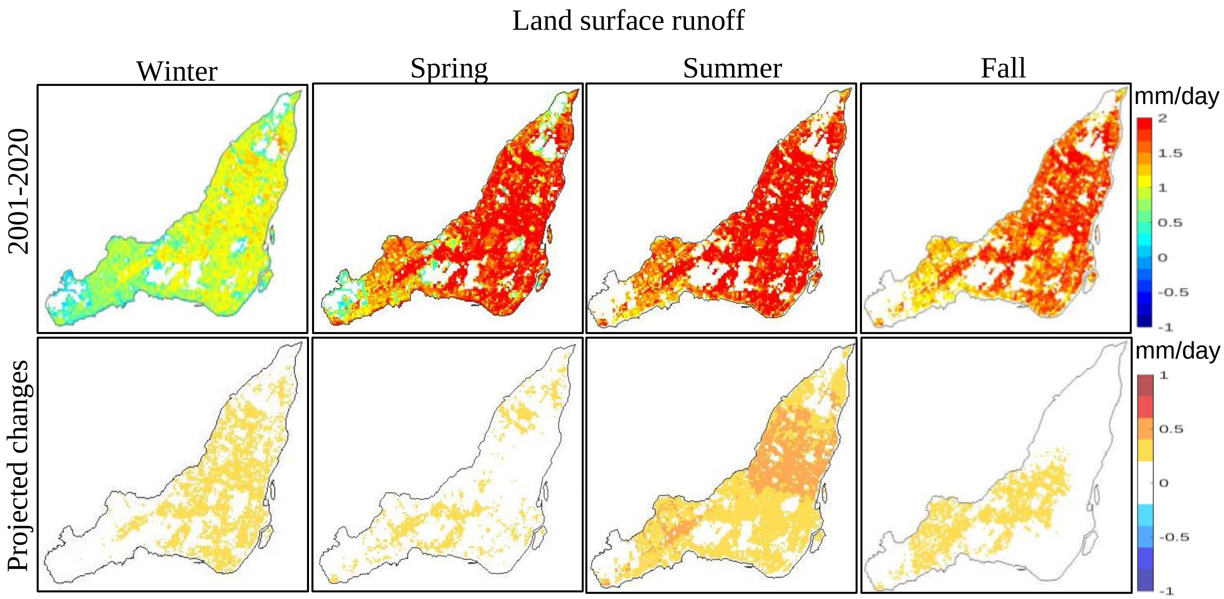

Figure A.4: Mean land runoff from SPS_CanESM2 (in mm/day) for the 2001–2020 period (top panel) and their projected changes for the 2041–2060 future period (bottom panel) for winter, spring, summer, and fall.