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Effets des changements climatiques sur la santé et la sécurité des travailleurs au Québec

par

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Résumé

Les impacts des changements climatiques sur la population sont nombreux et ont été relativement bien documentés, ce qui n'est pas le cas de ces impacts sur la santé et la sécurité des travailleurs. L'objectif de cette thèse est de documenter les effets négatifs des changements climatiques sur la santé et la sécurité des travailleurs dans une région d'un pays industrialisé à climat tempéré, comme le Québec. Pour y arriver, deux approches ont été utilisées : a) les dangers et les effets sanitaires ont été identifiés par une revue de la littérature validée par des experts nationaux et internationaux, et des priorités de recherche ont été établies à l'aide d'une méthode de consultation itérative, b) des modèles statistiques, utiles à l'estimation des impacts sanitaires des changements climatiques, ont été développés pour apprécier les associations entre la survenue de lésions professionnelles et l'exposition des travailleurs aux chaleurs estivales et à l'ozone troposphérique, deux problématiques préoccupantes pour le Québec. Le bilan des connaissances a mis en évidence cinq catégories de dangers pouvant affecter directement ou indirectement la santé et la sécurité des travailleurs au Québec (vagues de chaleur, polluants de l'air, rayonnements ultraviolets, événements météorologiques extrêmes, maladies vectorielles transmissibles et zoonoses) et cinq conditions pouvant entraîner des modifications dans l'environnement de travail et pouvant ultimement affecter négativement la santé et la sécurité des travailleurs (changements dans les méthodes agricoles et d'élevage, altérations dans l'industrie de la pêche, perturbations de l'écosystème forestier, dégradation de l'environnement bâti et émergence de nouvelles industries vertes). Quant aux modélisations, elles suggèrent que les indemnisations quotidiennes pour des maladies liées à la chaleur et pour des accidents de travail augmentent avec les températures estivales, et que ces associations varient selon l'âge des travailleurs, le secteur industriel et la catégorie professionnelle (manuelle vs autre). Des associations positives statistiquement non significatives entre les indemnisations pour des atteintes respiratoires aiguës et les concentrations d'ozone troposphérique ont aussi été observées. Dans l'ensemble, cette thèse a permis de dégager douze pistes de recherche prioritaires pour le Québec se rapportant à l'acquisition de connaissances, à la surveillance épidémiologique et au développement de méthodes d'adaptation. Selon les résultats de cette recherche, les intervenants en santé au travail et les décideurs devraient déployer des efforts pour protéger la santé et la sécurité des travailleurs et mettre en place des actions préventives en vue des changements climatiques.

Mots-clés : Accidents de travail, Changements climatiques, Indemnisations, Maladies liées à la chaleur, Ozone, Pays nordique industrialisé, Pollution de l'air, Santé et sécurité du travail, Travailleurs, Température ambiante.

Abstract

The impacts of climate change on human health are multiple and have been extensively studied in the general population, whereas these impacts on the working population have received little attention. In this perspective, the objective of this research is to document the negative effects of climate change on Occupational health and safety (OHS) in northern industrialized countries with a temperate climate, such as in Quebec. To achieve this goal, two approaches were used: a) exposure/hazards and potential effects of climate change on OHS were identified using a narrative review of the scientific literature validated by a working group of international and national experts and Quebec's stakeholders, and research priorities applicable to the Quebec context were established by a consensus approach, b) statistical models, useful for quantifying the health impacts of climate change, were developed to estimate the associations between occupational illnesses, injuries and exposure to summer outdoor temperatures or tropospheric ozone, as these climate conditions are among the most preoccupying issues related to climate change in Quebec. The literature highlighted five categories of hazards that are likely to impact OHS in Quebec (heat waves/increased temperatures, air pollutants, UV radiation, extreme weather events, vector-borne/zoonotic diseases) and five conditions that could potentially affect the working environment and negatively impact the OHS (changes in agriculture/breeding methods, alterations in the fishing industry, disruptions of the forest ecosystem, deterioration of the built environment and emerging green industries). The modeled associations suggest that daily compensations for heat-related illnesses and work-related injury increase with ambient temperature, and that these relations vary according to workers age, industries and physical demand of the occupation (i.e. manual vs other type). Positive non-statistically significant associations were observed between acute respiratory problems compensations and levels of ozone. Overall, this work produced a list of twelve research topics for the Quebec context, all related to the knowledge acquisition, the surveillance of diseases or the development of adaptation strategies. According to this thesis, stakeholders and decision-makers should make effort to increase the protection of workers health and safety in the context of climate change.

Keywords: Ambient temperature, Air pollution, Climate change, Compensation data, Heat-related illnesses, Occupational health and safety, Ozone, Workers, Northern industrialized country, Work-related injuries.

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Liste des sigles et abréviations

En français

CC : Changements climatiques

CO_2: Gaz carbonique

CDC: Center for Disease Control and Prevention

EC: Environnement Canada

GIEC : Groupe d’experts intergouvernemental sur l’évolution du climat

INSPQ : Institut national de santé publique du Québec

IRSST : Institut de recherche Robert-Sauvé en santé et en sécurité du travail

O_3 : Ozone

OMS : Organisation mondiale de la santé

PNUE: Programme des Nations Unies pour l’environnement

RNC: Ressources Naturelles Canada

SC: Santé Canada

SST : Santé et sécurité du travail

En anglais

CC: Climate change

CCDO: Canadian Classification Dictionary of Occupations

CDC: Centers for Disease Control and Prevention (United States)

CI : Confidence Interval

CO2: Carbon dioxide

EC: Environment Canada

HC: Health Canada

IPCC: Intergovernmental Panel on Climate Change

IRR: Incidence Rate Ratio

NAICS: North American Industrial Classification System

NEC: Non else classified.

NHS: National Health Service (United Kingdom)

NRC: Natural Resources Canada

OHS: Occupational health and safety

OR: Odds ratio

UNEP: United Nations Environment Programme

UNS: Unspecified

USEPA: US Environmental Protection Agency

WCB: Workers' Compensation Board

WHO: World Health Organization

Je dédie cette thèse à mes parents Anne-Marie et Yves,

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CHAPITRE 1- Mise en contexte

1.1 Introduction générale

Il existe un consensus scientifique sur l'évolution rapide du climat depuis maintenant plus de deux décennies. Il est aujourd'hui établi par le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC), que le réchauffement climatique, c'est-à-dire la variation de l'état du climat que l'on peut déceler par des modifications de la moyenne sur de longues périodes de temps, est sans équivoque et est associé à une augmentation des concentrations de gaz carbonique (CO_2) dans l'atmosphère. Selon les conclusions du cinquième Rapport d'évaluation du GIEC, la température globale moyenne à la surface de la Terre subira des augmentations de l'ordre de 0,3 à 4,8°C pour la période de 2081-2100 comparativement à la période de 1986-2005 (IPCC, 2013).

1.1.1 Les changements climatiques et les conséquences sur l'environnement et sur la santé

Le réchauffement moyen à la surface du globe entraînera des changements de phénomènes météorologiques et climatiques et d'importantes modifications dans la structure des écosystèmes et dans les interactions écologiques, au détriment de la biodiversité et des biens et services fournis par l'environnement. Parmi les changements prévus, il faut souligner: 1) la variabilité de la température, des précipitations, de l'humidité et des vents, 2) l'augmentation significative du niveau des eaux dans les régions côtières, 3) l'altération des intensités et de la répartition géographique des événements météorologiques extrêmes, 4) l'augmentation des concentrations atmosphériques de certains polluants, 5) l'altération de la distribution de la faune et de la flore et 6) la détérioration des habitats naturels et de l'environnement bâti (IPCC, 2013).

Le Québec, tout comme les autres régions du monde, subira d'importantes variations météorologiques et environnementales associées aux changements climatiques (Desjarlais et al., 2010). Les modèles suggèrent, par exemple, des hausses de la fréquence et de la durée des vagues de chaleur en été ainsi que des augmentations globales de la température estivale variant entre 1,6 et 3,0 ^{o}C à l'horizon 2050 par rapport au climat de 1961-1990. Une dégradation de la qualité de l'air, causée par une augmentation des concentrations de pollens et des divers polluants, dont l'ozone troposphérique (O_3), est également envisagée. Ainsi, même dans une région industrialisée à climat tempéré comme au Québec, il est important d'étudier les changements climatiques, car ils entraineront des conséquences météorologiques et environnementales qui pourront à leur tour, influencer la santé des populations (Armstrong et al., 2012; Séguin, 2008). A titre d'exemple, il est connu que les chaleurs saisonnières et les périodes de chaleur accablantes posent un risque pour la santé des individus qui résident dans les régions tempérées. Considérant l'influence des changements climatiques sur la chaleur extérieure, il est possible que ceux-ci entrainent une augmentation des incidences de maladies et de décès liés à la chaleur (IPCC, 2013). Cette influence pourrait être d'autant plus importante étant donné le manque d'acclimatation de ces derniers. En effet, les individus qui habitent dans les endroits où les températures ambiantes sont élevées et les vagues de chaleur sont fréquentes sont moins affectés par la chaleur que ceux qui résident dans les endroits où les températures sont plus froides (Basu, 2009).

1.1.2. Les changements climatiques et les populations vulnérables

Certaines populations sont identifiées comme plus vulnérables aux effets des changements climatiques, en raison d'une sensibilité physiologique particulière, d'une capacité réduite à faire face aux risques liés au climat. Les personnes à santé précaire, les jeunes enfants et les personnes âgées ainsi que les individus à faibles revenus ou isolés socialement font partie des groupes communément identifiés comme potentiellement plus vulnérables aux effets sanitaires associés aux changements climatiques (IPCC, 2013). Par ailleurs, les travailleurs, bien que très peu étudiés, peuvent également être considérés comme potentiellement plus vulnérables aux effets des changements climatiques sur la santé, notamment en raison de l'augmentation de leur exposition face à certains dangers. Par exemple, les durées d'exposition aux chaleurs estivales peuvent être plus importantes chez les travailleurs extérieurs que chez les individus de la population générale, et ces travailleurs peuvent ainsi souffrir de l'exacerbation des effets de contraintes thermiques. D'autres travailleurs peuvent être exposés à des concentrations plus importantes de polluants atmosphériques lors de la pratique d'activités extérieures qui demandent un effort physique important et qui résulte en une augmentation du débit respiratoire (Schulte et Chun, 2009).

1.1.3 Les changements climatiques sur la santé et la sécurité des travailleurs

Les conséquences entraînées par les changements climatiques sur la santé et la sécurité des travailleurs n'ont été que très peu abordées dans la littérature scientifique et sont très peu connues pour une région tempérée comme le Québec. La plupart des publications à cet effet portent sur des enjeux retrouvés dans les pays en voie de développement et sont incomplètes ou inadaptées aux réalités climatiques, économiques et sociales du Québec (Bennett et McMichael, 2011; Kjellstrom et al., 2009).

Le seul article qui comporte des enjeux adaptés à une région à climat tempéré est une revue de la littérature publiée entre 1998 et 2008, dans lequel est présenté un cadre conceptuel qui recense les principaux dangers des changements climatiques à l'échelle mondiale (Schulte et Chun, 2009) et qui permet la visualisation des relations possibles entre les différents facteurs de risque et des problématiques de santé et de sécurité des travailleurs. Les principaux dangers associés aux changements climatiques identifiés dans ce cadre conceptuel sont classés en sept catégories : 1) l'augmentation de la température ambiante, 2) la pollution de l'air, 3) l'exposition aux rayons ultraviolets, 4) les événements météorologiques extrêmes, 5) les maladies vectorielles transmissibles et l'expansion des habitats des vecteurs, 6) les transitions industrielles et les industries émergentes et 7) les changements dans l'environnement bâti. De plus, les effets sur la santé et la sécurité des travailleurs suite aux expositions de chacun de ces dangers sont répertoriés dans le cadre conceptuel. Finalement, divers facteurs contextuels pouvant entraîner des augmentations dans l'ampleur et la sévérité des dangers énumérés ou encore, pouvant augmenter le nombre de travailleurs potentiellement exposés à ces dangers (augmentation des émissions de gaz à effet de serre, politiques énergétiques, conditions locales et circonstances socioéconomiques, urbanisation et déforestation) sont aussi présentés. Le cadre conceptuel traduit et adapté est présenté à la figure 1.

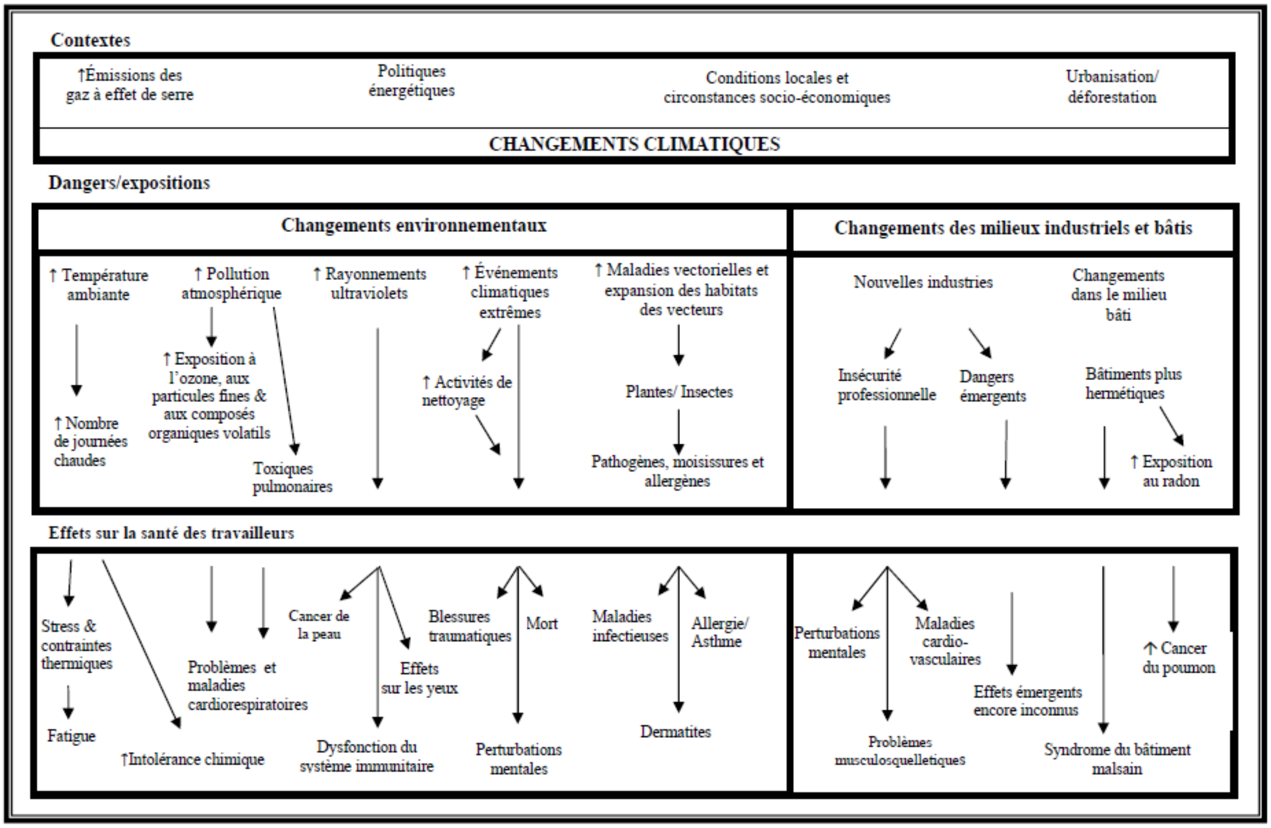

Figure 1 : Cadre conceptuel des relations entre les changements climatiques et la santé et la sécurité des travailleurs (traduit et adapté de Schulte et Chun, 2009). (Adam-Poupart et al., 2012).

1.1.4 Les changements climatiques et la quantification des impacts sanitaires chez la population générale et chez les travailleurs

Pour estimer les effets des changements climatiques sur la santé, il est nécessaire d'avoir des connaissances empiriques sur les relations entre des variables météorologiques associées aux modifications du climat, comme la température, et des indicateurs de santé (Baker et Nieuwenhuijsen, 2008). Lorsque ces associations sont suffisamment documentées pour permettre une inférence de la relation entre la cause et l'effet, elles peuvent ensuite être utilisées avec les estimations de températures prédites par les modèles climatiques pour quantifier les impacts sanitaires des futures températures, en estimant le nombre d'événements de santé attendus selon le climat. Par exemple, les publications sur les relations entre la température et la mortalité chez la population générale sont nombreuses et les évidences empiriques sont maintenant sans controverse (McMichael et al., 2006). Ainis, les mortalités futures associées à une exposition à la chaleur ont pu être estimées sous différents scénarios climatiques à l'aide de cette méthodologie (Huang et al., 2011). De la même façon, cette méthode a été utilisée pour quantifier les impacts sanitaires des augmentations de concentrations de polluants atmosphériques associées aux changements climatiques (Sujaritpong et al., 2012). Elle a notamment été utilisée aux États-Unis pour quantifier les futurs impacts de l'ozone troposphérique dans le contexte des changements climatiques, sur la mortalité toutes causes et sur la mortalité non accidentelle, deux effets sanitaires bien documentés par le USEPA (Post et al., 2012). Dans une perspective de santé publique, la quantification des risques sanitaires associés aux changements climatiques peut contribuer à prioriser les problèmes de santé et les populations vulnérables afin de développer des politiques et des stratégies appropriées (Sujaritpong et al., 2012).

Depuis maintenant plusieurs années au Québec, les connaissances évoluent sur les relations entre certaines variables météorologiques influencées par les changements climatiques et des indicateurs de santé de la population générale. La quantification des impacts de l'augmentation de chaleur associée aux changements climatiques sur la mortalité a notamment été estimée pour divers horizons temporels (Benmarhnia et al., 2014; Doyon et al., 2006). En ce qui concerne l'ozone, la quantification des impacts sanitaires futurs pour la population générale dans le contexte des changements climatiques n'a pas été réalisée, mais les relations entre l’ozone et la mortalité/morbidité sont bien documentées dans la littérature (Adam-Poupart et al., 2013; USEPA, 2006).

A l’inverse, la quantification des impacts sanitaires des changements climatiques chez les travailleurs des régions tempérées comme au Québec est une tâche difficile. En ce qui concerne les impacts l’augmentation future de la température, les relations entre cette variable et les indicateurs de santé/sécurité n’ont été que très peu explorées (manque d’évidence scientifique) et ne l’ont jamais été dans un contexte climatique similaire à celui du Québec. Bien que des études descriptives aient rapporté des augmentations de fréquences de décès par hyperthermie (Buisson, 2009, CDC, 2008; INRS, 2009), de maladies associées à une exposition à la chaleur (Bonauto et al., 2007; Donoghue et al., 2000; 2004; Fortune et al., 2013; Maeda et al., 2006) et d’accidents de travail (Nag et Nag, 2001) pendant les mois les plus chauds de l’année; les relations entre la température et l’un ou l’autre de ces indicateurs n’ont été estimées que dans sept études chez les travailleurs (Florida Department of Health, 2012; Fogleman et al., 2005; Knapik et al., 200; Mbanu et al., 2007; Mirabelli et Richardson, 2005; Morabito et al., 2006; Xiang et al., 2013). Ces associations n’ont d’ailleurs jamais été explorées pour une région à climat tempéré comme au Québec, là où les populations sont généralement moins acclimatées à la chaleur par rapport à celles des pays où le climat est plus chaud. Le même phénomène s’observe pour réaliser la quantification des impacts sanitaires futurs en lien avec l’ozone, car il n’existe que sept études qui ont tenté d’explorer la relation entre l’ozone et la diminution de fonctions respiratoires chez les travailleurs (Apte et al., 2007; Brauer et al., 1996 et 1997; Chang et Wu, 2005; Hoppe et al., 1995; Karakatsania et al., 2009;

Thaller et al., 2008). Parmi celles-ci, seulement deux ont été réalisées au Canada sur une seule et même population de travailleurs.

1.2 Objectifs de la recherche

1.2.1 Objectif général

L’objectif général de cette recherche est de documenter les effets négatifs des changements climatiques (CC) sur la santé et la sécurité des travailleurs (SST) dans une région d’un pays industrialisé à climat tempéré, comme le Québec.

1.2.2 Objectifs spécifiques

Le premier volet de cette recherche vise à décrire, à l’aide d’une revue de la littérature et de la validation subséquente par un groupe de travail constitué d’experts nationaux et internationaux et de représentants québécois des secteurs industriels, les relations qui existent entre les dangers des CC et la SST, en identifiant les secteurs d’activités économiques les plus susceptibles d’être affectés et en établissant des priorités de recherche pour le Québec.

Le second volet vise à estimer les relations entre la température extérieure estivale (variable météorologique influencée par les changements climatiques), et les indemnisations pour des lésions professionnelles reliées à une exposition excessive à la chaleur (insolations, syncopes, pertes de conscience, etc.) et les accidents de travail. Ce volet a aussi comme objectif l’identification des secteurs industriels et des professions les plus à risque de lésions professionnelles des suites d’une exposition à la chaleur extérieure.

Le troisième volet vise à estimer la relation entre l’ozone (variable environnementale influencée par les changements climatiques) et les indemnisations pour les atteintes respiratoires aiguës chez les travailleurs du Québec.

Tous les volets de cette recherche sont présentés sous la forme d'articles publiés ou soumis pour publication (chapitres 2, 3, 4 et 5).

ARTICLE 1 : Climate change and Occupational Health and Safety in a temperate climate: potential impacts and research priorities in Quebec, Canada; publié dans Industrial Health (2013) 51(1):68-78.

ARTICLE 2 : Summer outdoor temperature and occupational heat-related illnesses in Quebec (Canada); publié dans Environmental Research Journal (2014) 134 : 339-344.

ARTICLE 3 : Effect of summer outdoor temperatures on work-related injuries in Quebec (Canada), soumis à Occupational and Environmental Medicine Journal, en date du 25 juin 2014.

ARTICLE 4 : Association between outdoor ozone and compensated acute respiratory diseases among workers in Quebec (Canada), soumis sous la forme d'une courte publication (*short report*) à Industrial Health Journal, en date du 25 juin 2014.

À noter qu'un cinquième article est présenté à l'annexe 1. Celui porte sur le développement d'un modèle de prédiction spatiotemporelle des concentrations d'ozone troposphérique sur le territoire québécois, qui a été utilisé pour l'obtention des données d'exposition lors des analyses sur l'estimation de la relation entre ce polluant et les indemnisations pour les atteintes respiratoires aiguës chez les travailleurs (Article 4). Le développement de ce modèle est publié dans le journal Environmental Health Perspectives depuis le mois de mai 2014.

CHAPITRE 2- Climate change and Occupational Health and Safety in a temperate climate: potential impacts and research priorities in Quebec, Canada.

Climate Change and Occupational Health and Safety in a temperate climate: Potential impacts and Research priorities in Quebec, Canada

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2.1 Abstract

The potential impacts of climate change (CC) on Occupational Health and Safety (OHS) have been studied a little in tropical countries, while they received no attention in northern industrialized countries with a temperate climate. This work aimed to establish an overview of the potential links between CC and OHS in those countries and to determine research priorities for Quebec, Canada. A narrative review of the scientific literature (2005–2010) was presented to a working group of international and national experts and stakeholders during a workshop held in 2010. The working group was invited to identify knowledge gaps, and a modified Delphi method helped prioritize research avenues. This process highlighted five categories of hazards that are likely to impact OHS in northern industrialized countries: heat waves/increased temperatures, air pollutants, UV radiation, extreme weather events, vector-borne/zoonotic diseases. These hazards will affect working activities related to natural resources (i.e. agriculture, fishing and forestry) and may influence the socioeconomic context (built environment and green industries), thus indirectly modifying OHS. From this consensus approach, three categories of research were identified: 1) Knowledge acquisition on hazards, target populations and methods of adaptation; 2) Surveillance of diseases/accidents/occupational hazards; and 3) Development of new occupational adaptation strategies.

Key Words:

Climate change, Occupational health and safety, Research priorities, Northern industrialized country, Delphi method

2.2 Introduction

Over the last twenty years, most scientists have agreed regarding the rapid progression of climate change (CC). According to the conclusions of the fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), climate changes and global warming are unequivocal (IPCC, 2007a; Seguin, 2008). The IPCC predicts that the average warming of the earth's surface, associated with increased concentrations of CO_2 in the atmosphere, will lead to major changes in ecosystem structures and ecological interactions, with negative impacts on biodiversity and ecosystems' goods and services such as water and food supplies (IPCC, 2007a). Consequently, important environmental changes are expected all over the world: 1) variability of temperature, rainfall, humidity and winds, 2) alteration of intensity and geographic distribution of extreme climatic events, 3) significant rise of water levels in coastal areas, 4) alteration of wildlife distribution, 5) increased atmospheric concentrations of pollutants and 6) deterioration of natural habitats and of the built environment (D'amato and Cecchi, 2008; Desjarlais et al., 2010; IPCC, 2007a; Rosenthal and Jessup, 2009; UNEP/Sustainlabour, 2008).

The impacts of climate conditions on human health are multiple and have been extensively studied in the general population (Seguin, 2008). But to date, the working population has received little attention and no research has analyzed climate change impacts specifically in northern countries, despite evidences of impacts on the labor market (Lipsig-Mumme et al., 2010). For instance, new climate conditions may favor hydroelectricity and forestry production and increase agricultural crops such as maize and soy in northern countries. On the other hand, climate change may also affect negatively workers' health and safety because of thermal constraints exacerbation and modification of natural resources that are the basis of the economy (UNEP/Sustainlabour, 2008).

A most useful preliminary framework for identifying how climate change could affect occupational health and safety (OHS) worldwide was published in 2009 (Schulte and Chun, 2009). In addition to general research and practice considerations, this framework identified seven categories of hazards (increased ambient temperature, air pollution, UV radiation, extreme weather events, vector-borne and zoonotic- from animal to human being- diseases, changes in the built environment and emerging industries) and linked some health effects and types of work to them. Among the recommendations of the authors, two were targeting further development of the framework: the assessment of the relative magnitude and frequency of climate-related hazards on a regional basis and the development of a research and prevention agenda as well as a prioritization scheme.

In this perspective, the objectives of this work were to 1) establish an overview of the potential links between CC and OHS in northern industrialized countries with a temperate climate, and to 2) determine associated research priorities applicable to the Quebec (Canada) context.

2.3 Methods

A narrative review of the scientific literature was done and validated by a working group of international and national experts and Quebec's stakeholders. To determine associated research priorities, a modified Delphi method was carried out with the same working group (Harrington, 1994).

Review of the literature

Data sources, extraction and synthesis Research articles or reviews published in peer-reviewed scientific journals between January 2005 and December 2010 were retrieved from several bibliographic databases (Embase, Pubmed, Medline, Web of Science, Toxline, Chemical Abstracts). The following keywords were used: climate, climate change or global warming, with work or occupation. Ten articles published before 2005 and obtained by snowball literature search were also consulted.

Commentaries, editorials and opinion letters were excluded, together with papers in other languages than English or French. The resulting documents were examined and only occupational studies that mentioned negative impacts of CC were retained; exceptionally, some articles pertaining to the general population were included when the information on workers was scarce and data on the general population could be inferred to workers (e.g. air pollution and workers' health). In addition, the documents had to address CC hazards, diseases, zoonoses and health effects already found or plausible in northern industrialized countries with a temperate climate. Papers on extreme cold weather were excluded because climatic predictions suggest warmer winters in Quebec. Reports and relevant information were accessed from governmental or scientific institutions, often through their web sites, such as the IPCC, the United Nations Environment Programme (UNEP), the World Health Organization

(WHO), the U.S. Environmental Protection Agency (US EPA), the Center for Disease Control and Prevention (CDC), the National Institute for Occupational Safety and Health (NIOSH) and the U.S. Army, the United Kingdom National Health Service (NHS), the Quebec consortium on climate change Ouranos, Health Canada (HC), Environment Canada (EC), and Natural Resources Canada (NRC).

Finally, exposure/hazards, potential effects on OHS and the types of industries potentially affected were extracted from the retained documents, synthesised and organized following the Schulte and Chun framework (Shulte and Chun, 2009).

Data verification

In order to verify the completeness of the review of literature, a summary of collected information was presented to a working group of national and international experts and some Quebec's stakeholders, during a two-day workshop held in November 2010 (n=19). Experts (n=7) were selected to ensure a broad expertise on CC hazards/ impacts and OHS, while stakeholders (n=12) were selected in order to represent the major industrial sectors potentially affected by CC in Quebec. Therefore, the experts' group was composed of two specialists in the OHS effects of ambient temperatures and thermal constraints, two in CC health and environment impacts/adaptation, one in general health and emergency medicine, one in zoonoses and one in UV radiation impacts on human health. Moreover, stakeholders from agriculture, construction, forestry, mining, municipal services, transportation, fisheries, wind power and public health took part in the working group.

Identification of the local research priorities

Establishment of research topics.

During the workshop, experts and stakeholders were asked to identify knowledge gaps on CC impacts identified in the literature review. Based on their expertise and interests, the literature review and the workshop discussions, the working group established a list of research topics that would address those gaps.

Prioritization of research topics

A modified Delphi approach was used to identify research priorities. The Delphi technique is based on sequential consultations in order to seek consensus on priority issues by a procedure of voting over a choice of topics. The process usually stops when consensus is reached or agreement on priorities is sufficiently advanced (Harrington, 1994).

This list of research topics was sent by e-mail to all members of the working group (n=19) and of the research team (n=7). Respondents were asked to complete and comment the list of research topics established during the workshop. Returned responses were examined and a revised list of research topics was produced and passed around to the same persons. In this instance, participants were asked to rank the ten most important research topics, and to add remarks at will. Votes were summed, providing a final list of research topics.

2.4 Results

Figure 1 presents a flow chart of the studies' selection for the literature review. The initial key words search yielded 15,097 papers. Applying the inclusion/exclusion criteria previously mentioned left 219 scientific articles for review.

The information on potential negative impacts of CC on OHS retrieved from the literature review, with the addition of the working group comments, is summarized in Fig. 2 and references are presented in Table 1. This information is essentially organized according to the framework provided by Schulte and Chun (2009), with the addition of the most concerned industries, which appeared to be the most appropriate way of presenting our findings. Three levels of impacts emerge from this information consolidation: impacts on workers, impacts on natural resources and impacts on the socio-economic context. Among the impacts on workers, five categories of direct and indirect hazards were identified: heat waves and increased temperatures, air pollutants, UV radiation, extreme weather events, vectorborne and zoonotic diseases. Impacts on natural resources are associated with changes in agriculture/breeding methods, alteration in the fishing industry and disruption of the forest ecosystem. In addition, two modifications on the socio-economic working context that could pose OHS threats were identified: deterioration of the built environment and emerging green industries.

Even in a temperate climate, the increased temperatures and the raised frequency and severity of heat waves over the coming decades is likely to increase the risk of cramps, fatigue and heatstroke, the absorption of chemicals, skin problems and possibly the risk of injuries and accidents related to a decrease in vigilance, manual dexterity and altered emotional state. Smog events are also likely to become more frequent and impact workers' health and safety by increasing the risk of cardiovascular and respiratory symptoms and diseases. Human exposure to UV radiation will also be more important, resulting in increased risks of eye and skin diseases from UV radiation, while extreme weather events are expected to be on the rise, increasing health problems and injuries. Moreover, vector-borne and zoonotic diseases may also increase and ‘new’ disorders, scarce or never seen in Quebec before, might also appear because of changes in geographic distribution of vectors and parasites. Impacts of CC on natural resources might affect OHS by influencing economic activities and work environments, resulting in an increase of health problems related to work insecurity in economic sectors where reduced productivity may happen. CC may also affect the effectiveness, service life and safety of infrastructures and buildings, increasing health and safety risks such as acci dents and injuries.

Finally, the development of new green industries in order to mitigate the impacts of CC by reducing greenhouse gas emissions might also bring new OHS issues. In addition to hazards and negative OHS effects of CC, the literature review also targeted types of industries that will potentially be affected by each category of hazard/ exposure, as identified in Fig. 2 (all specific references are presented in Table 1).

Most of these industries imply outdoor activities, such as construction, agriculture, forestry, mining, fishing, municipal services and transportation. However, some indoor activities were also identified, essentially in relation to heat waves (e.g. foundries or health care) and green jobs hazards (e.g. recycling or energy industries). Moreover, numerous factors may influence the intensity of OHS effects following an exposure to CC related hazards, such as the type and location of work and the length of exposure (Bennet and McMichael, 2010; CDC, 2010b; Jay and Kenny, 2010; Kjellstrom, 2009; Schulte and Chun, 2009; WHO, 2005) individual characteristics and physical conditions such as age, pregnancy, body weight or medication intake (CCOHS, 2011a; CCOHS 2011b; IPCC, 2007b; Marszalek et al., 2005; NOAA, 2010), the wearing of protective equipments (Bernard 1999; Park et al., 2009), exposure characteristics of the hazards such as pollutant concentrations (D'amato and Cecchi, 2008) and co-exposure to multiple environmental hazards (Walker et al., 2001).

A list of 30 research topics was first derived from exchanges during the workshop. Twelve research topics (Table 2) were prioritized using a modified Delphi method with 17 participants replying to two rounds of consultation. Six research topics were related to knowledge acquisition on hazards, target populations and methods of adaptation in the workplace, one research topic to surveillance of diseases, accidents and occupational hazards, and five topics to development of occupational adaptation strategies.

2.5 Discussion

The first objective of this project was to establish an overview of the negative impacts of CC on OHS in an industrialized country with a temperate climate such as Quebec (Canada). The literature review, completed by consulting a working group, identified the main exposure/hazards related to CC, their potential effects on workers' health and safety and the type of industries potentially affected. Our research led us to conclude that the regional assessment of this issue presented few differences compared to the global framework developed by Schulte and Chun (2009), and the study completed the framework by identifying a list of local industries likely to be negatively impacted by CC.

Our literature review contained the same five large hazards that could impact directly or indirectly OHS (heat waves and increased temperatures, air pollutants, UV radiation, extreme weather events, and vector-borne and zoonotic diseases). Two other impacts, which might potentially affect the socio-economic context, were also retained, as did Schulte and Chun (2009) in their framework; these are the deterioration of the built environment and emerging green industries with new OHS hazards. However, our review identified impacts that could affect the work environment changes in agriculture/breeding methods, alteration in the fishing industry, and disruption of the forest ecosystem; Schulte and Chun (2009) had considered these as part of the context influencing global CC instead of impacts of CC.

The regional assessment of CC impacts emphasizes that some aspects identified by Schulte and Chun (2009) were not important in the Quebec context. For example, the northern location of Quebec makes it unlikely that malaria or venomous snake bites ever become regional hazards.

The input of the working group has also brought to light potential regional OHS impacts and affected industries that were not found in the published literature or identified in Schulte and Chun's framework; for example, warmer winters are associated with permafrost changes that affect surface mining infrastructures and airport runways in the North. This was added as an OHS effect in the Built Environment category (Fig. 2).

According to Adisesh et al., (2011), the effects of climate change are likely to have relevance to occupational health and safety across all sectors of industry, such as emergency response, water supply, agriculture, energy, transportation, construction, etc. Our findings are in agreement with their conclusions, and suggest that CC in Quebec are likely to affect a large range of indoor and outdoor sectors. Moreover, OHS impacts might vary within the country due to regional micro-climates or local socio-economic characteristics which will play a role in how risks and hazards will impact on population groups (Adisesh et al., 2011).

The second objective of this project was to determine local research priorities in order to address potential negatives impacts of CC on OHS in Quebec. The consensual research agenda obtained through the Delphi approach, which suited both stakeholders' and scientists' perceptions, showed that the most important perceived area for future work was the acquisition of knowledge; this is coherent with the fact that the topic of CC impacts on OHS has never been studied in Quebec, or in a northern industrialized country with a temperate climate. Most stakeholders of the working group reported that they had never thought about this topic in the past, but became concerned during the workshop and actively participated in the identification of the hazards, OHS effects, potentially affected industries and research priorities. Interestingly, our regional assessment brought up research topics largely similar to what Schulte and Chun (2009) recommended in their conclusion. These are the improvement of epidemiologic surveillance with the development of health indicators, and also the general acquisition of knowledge on CC and OHS. A third topic recommended by Schulte and Chun (2009), namely the identification of occupational hazards related to new «green jobs», was listed among the initial research topics (increased health risks related to greener materials), but was not ranked among the top priorities after the second round of consultation.

This study presents limitations that need to be pointed out. First of all, this work has intentionally not gone very deep on CC impacts on the labor market and employment. Also, adaptation strategies were excluded from this analysis as we were not yet exploring solutions to the identified hazards (Lipsig-Mumme et al., 2010). Secondly, this work has only targeted negative effects of CC, although some CC effects on OHS will likely be positive; for example, with adequate insect pest control, some specific agricultural production and forestry activities might even be favored, increasing revenues and job numbers in these industries. Longer mild seasons may also favor some tourist activities, such as golf, hunting and fishing (Desjarlais et al., 2010). Thirdly, the working group selection, based on presently known CC impacts, has perhaps restricted identification of new hazards or industries during the workshop.

A delicate part of the Delphi procedure is the selection of a panel of participants that is representative of all bodies involved in the topic of interest (Iavicoli et al., 2006); it is very likely that a different set of stakeholders and scientists would have resulted in a different research agenda. Moreover, the retained sets of priorities were obtained after only two consultations and it is possible that additional consultations would have resulted in a slightly different consensus. Nevertheless, the degree of unanimity among the various responses was quite satisfactory, and the excluded items essentially targeted only one or two industries, likely having a low impact in the general issue of CC impacts on OHS.

The research priorities were established according to scientific knowledge available at a given time and in a given economic and political context. Changes in the economic and political environments will likely bring modifications that will affect climate change mitigation (Adisesh et al., 2011). For instance, international pressures on greener industries will lead to labor market changes, as already experienced in the Canadian energy, postal and automotive services sectors (Lipsig-Mumme et al., 2010). Thus research priorities have to be revised and updated over time, following important changes in the economy, but also if there are important modifications in climate predictions or CC impacts in Quebec.

Finally, the potential health threats to workers in areas of the world with hotter climates, where people from Quebec may work or where Quebec corporations have production activities with local staff, were not reviewed, but this issue would need to be considered in future research. The potential occupational health threats from climate conditions in hotter parts of the world have been analyzed in two series of papers, published in 2009 and 2010 in the journal Global Health Action (Kjellstrom et al., 2009; Nilsson and Kjellstrom, 2010).

In conclusion, the global context of CC in the upcoming decades is likely to impose major changes in some industries and occupations worldwide. This work highlighted five categories of hazards that are likely to impact OHS in northern industrialized countries: heat waves /increased temperatures, air pollutants, UV radiation, extreme weather events and vector-borne/ zoonotic diseases. These hazards will affect working activities related to natural resources (i.e. bring changes in production and harvesting methods in agriculture, fishing and forestry) and may influence the socioeconomic context (deterioration of the built environment and emergence of green industries), thus indirectly modifying OHS. Our study showed that the global framework developed by Schulte and Chun (2009) was relevant to address CC impacts on OHS in a temperate climate region. Bringing together regional and international experts and stakeholders proved useful to produce a consensual list of research topics. Regardless of the country considering the issue of CC impacts on OHS, it is likely that worldwide research priorities will fit into the large categories identified in our study. A concerted research effort is needed to increase our knowledge on hazards, target populations and methods of adaptation in the workplace; to ensure a proper surveillance of diseases, accidents and occupational hazards; and to develop new occupational adaptation strategies.

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2.7. Tables and figures

Table I. Main references reporting evidence on climate change hazards and their effects on occupational health and safety in northern industrialized countries with a temperate climate.

Hazards	Effects on health and safety	References
Impacts of CC on persons		
Heat waves and increased temperatures	• Cramps, fatigue and heatstroke	IPCC, 2007b ; Lo Vecchio et al., 2007; NOAA, 2010; Tanaka, 2007
	• Renal & cardiovascular problems	Kjellstrom et al., 2010
	• Increased absorption of chemicals	Gordon, 2005 a and b
	• Dehydration and decrease in cognitive performance	Grandjean and Granjean, 2007
	• Skin problems	Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010
	• Accidents related to	Ramsey, 1995 and Ramsey et al.,

	decrease in vigilance; decrease in manual dexterity	1983
	• Altered emotional states	Tawatsupa et al., 2010
	• Death	CDC, 2008; Létard et al., 2004; Statistics Canada, 2011; Tanaka, 2007
Air pollutants (Ozone, airborne particles, volatile organic compound and allergens)	• Cardiovascular/ Respiratory symptoms and diseases	Apte et al., 2008; Brauer et al., 1996; Chen et al., 2007; Cohen et al., 2005; Dominici et al., 2006; Goldberg et al., 2001; IPCC, 2007b; Rage et al., 2009
	• Atopic sensitization and increased allergic symptoms	D’amato and Cecchi, 2008; Peden and Reed, 2010
UV Radiation	• Skin diseases including cancer and eye diseases	CDC, 2010b; Gallager and Lee, 2006; Lucas et al., 2008; NASD, 2002
Extreme weather events	• Cardiovascular/ respiratory diseases	Desjarlais et al., 2010; IPCC, 2007b; Tak et al., 2007
	• Atopic sensitization	Apte et al., 2008; D’amato and

	(pollen and aeroallergens)	Cecchi, 2008
	• Vector borne diseases	Desjarlais et al., 2010; IPCC, 2007b
	• Falls, injuries & fatalities	Desjarlais et al., 2010; IPCC, 2007b; and Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010
	• Mental health disturbances	Bennet and McMichael, 2010; Tak et al., 2007
Vector-borne and zoonotic diseases	• Encephalitis caused by arthropods (St. Louis, La Crosse, Eastern Equine)	Desjarlais et al., 2010
	• Hantavirus Pulmonary Syndrome	Desjarlais et al., 2010
	• West Nile Virus	Desjarlais et al., 2010; NIOSH, 2005
	• Lyme Disease	CDC, 2010a; CPWR, 2002.; Desjarlais et al., 2010; Ogden et al., 2009

	• Brucellosis	Benett and McMichael, 2010
Impacts of CC on natural resources		
Changes in production, harvests, work methods in agriculture/breeding	• Insecurity and consequences on physical & mental health due to a decreased employment	Chakraborty et al., 2008; UNEP/Sustainlabour, 2008; Wheaton et al., 2007; WHO, 2012
	• Vector-borne and zoonotic diseases	Gale et al., 2009; Morgan and Wall, 2009; Slingenbergh et al., 2004
	• Variation in chemical exposure	Boxall et al., 2009
Changes in harvest, working methods in fishing	• Insecurity and consequences on mental health	UNEP/Sustainlabour, 2008.
	• Diseases related to marine toxins	Fleming et al., 2006 and Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010
	• Fishing under difficult conditions	Exchanges during Montreal CC and OHS workshops, Nov. 24-25,

		2010
Disruption of forest ecosystem and changes in distribution of toxic plants	• Allergies and lung irritation	Schulte and Chun, 2009.
	• Difficult logging conditions	UNEP/Sustainlabour, 2008; and Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010
Socio-economic context		
Deterioration of built environment infrastructures	• Insecurity and consequences on mental health	Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010
	• Environment creating new hazards	Baker et al., 2009; Infrastructure Canada, 2006
	• Accidents related to road infrastructure damages	Baker et al., 2009 ; Infrastructure Canada, 2006 and Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010
Increase in emerging «green» industries	• Exposure to chemical and biological agents, and radiation	CDC,2010c; Li et al., 2006; Rosenthal and Jessup, 2009; Schulte and Chun, 2009; Tanaka, 2007
	• Insecurity and	Exchanges during Montreal CC

	consequences on mental health due to a decreased employment	and OHS workshops, Nov. 24-25. 2010
	• Environment creating new hazards	CDC, 2010c; Madsen et al., 2006; Madsen, 2006; Madsen et al., 2009; OHS, 2009; UNEP/ILO/IOE/ITUC, 2008 and Exchanges during Montreal CC and OHS workshops, Nov. 24-25, 2010

Table II. Twelve research priorities applicable to the Quebec context and identified through the modified Delphi study.

Research priorities
Knowledge acquisition on hazards, target populations and methods of adaptation in the workplace
• Study past CC extreme events in order to identify type of work involved and develop mitigation strategies from this information.
• Evaluate new OHS hazards related to CC exposures and their potential impacts on infrastructures.
• Study the increased toxicity and health effects of different biological/chemical agents and materials during episodes of extreme heat, air pollution, drought or intense rainfall.
• Assess current and future risks related to aeroallergens and zoonoses.
• Study thermal and hydric stress due to wearing protective equipment during extreme heat episodes
• Identify categories of workers vulnerable to accidents and diseases associated with CC impacts, considering their working conditions and individual characteristics.
Surveillance of diseases, accidents and occupational hazards
• Define accident and disease indicators and gather information in order to enable surveillance of health effects attributable to the climate.
Development of occupational adaptation strategies
• Identify and evaluate adaptation methods established in other countries

- Develop training tools to prepare health care workers for the potential health effects of CC, in particular regarding heat strokes, zoonoses and vector-borne diseases.
- Develop suitable protective clothing and other equipments that are adequate for extreme climates in order to favor their actual wearing by workers.
- Explore CC adaptation methods using organization of work and work schedule management.
- Develop methods to heighten workplace (workers and employers) awareness of CC potential OHS risks, both short-term (e.g. violent storms and accidents) and long-term (e.g. skin cancer and UV radiation).

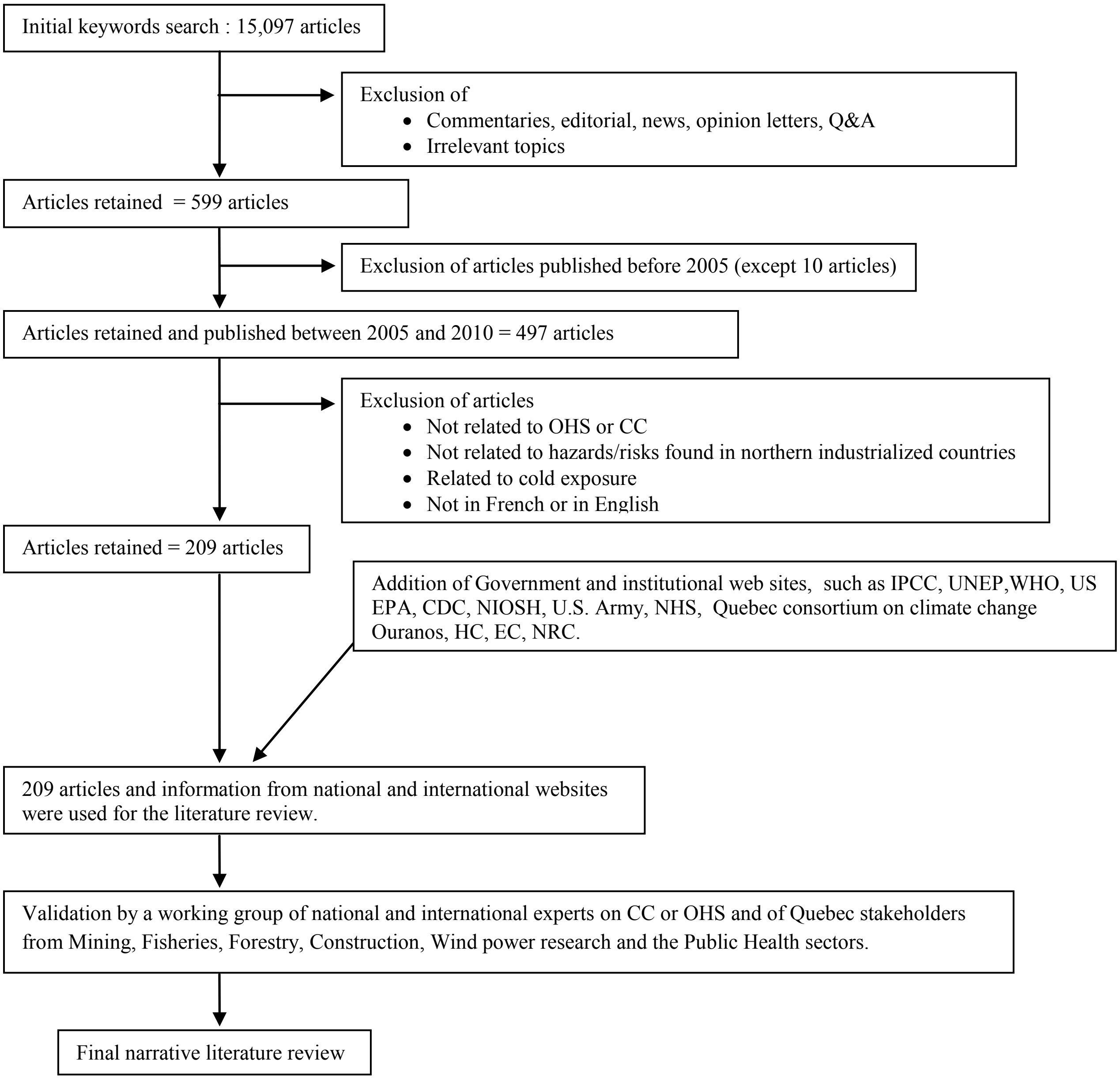

Figure 1. Flow chart representing the studies selection for the literature review and data validation.

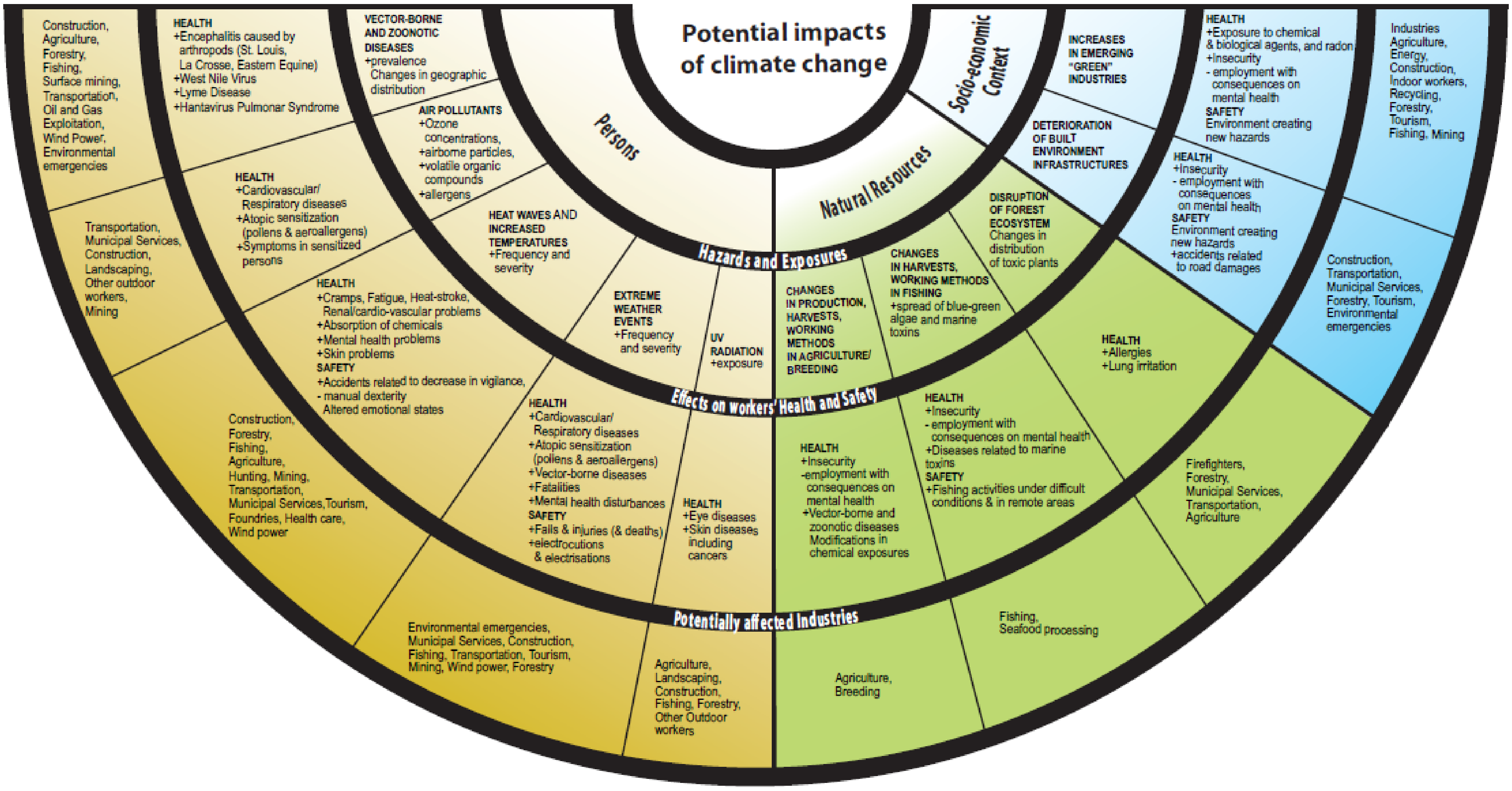

Figure 2. Main potential impacts of CC on OHS found in northern industrialized countries.

CHAPITRE 3 - Summer outdoor temperature and occupational heat-related illnesses in Quebec (Canada).

Summer outdoor temperature and occupational heat-related illnesses in Quebec (Canada).

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3.1 Abstract

Background: Predicted rise in global mean temperature and intensification of heat waves associated with climate change present an increasing challenge for occupational health and safety. Although important scientific knowledge has been gathered on the health effects of heat, very few studies have focused on quantifying the association between outdoor heat and mortality or morbidity among workers.

Objective: To quantify the association between occupational heat-related illnesses and exposure to summer outdoor temperatures.

Methods: We modeled 259 heat-related illnesses compensated by the Workers' Compensation Board of Quebec between May and September, from 1998 to 2010, with maximum daily summer outdoor temperatures in 16 health regions of Quebec (Canada) using generalized linear models with negative binomial distributions, and estimated the pooled effect sizes for all regions combined, by sex and age groups, and for different time lags with random-effect models for meta-analyses.

Results: The mean daily compensation count was 0.13 for all regions of Quebec combined. The relationship between daily counts of compensations and maximum daily temperatures was log-linear; the pooled incidence rate ratio (IRR) of daily heat-related compensations per 1°C increase in daily maximum temperatures was 1.419 (95% CI 1.326 to 1.520). Associations were similar for men and women and by age groups. Increases in daily maximum temperatures at lags 1 and 2 and for two and three-day lag averages were also associated with increases in daily counts of compensations (IRRs of 1.206 to 1.471 for every 1°C increase in temperature).

Conclusion: This study is the first to quantify the association between occupational heat-related illnesses and exposure to summer temperatures in Canada. The model (risk function) developed in this study could be useful to improve the assessment of future impacts of predicted summer outdoor temperatures on workers and vulnerable groups, particularly in colder temperate zones.

3.2 Introduction

Climate changes are undeniable and their potential impacts on human health are becoming increasingly important among scientific concerns and public health policies. Climate scenarios project an increase in global mean temperature and in the frequency and intensity of heat waves over most areas around the world in the near future (IPCC, 2013; 2014).

Several epidemiological studies have been conducted on the effects of heat on mortality and morbidity in the general population (Basu, 2009; Ye et al., 2012). These studies have usually shown a non-linear increase in mortality and morbidity, over a city-specific summer temperature threshold. With global warming, heat exposure may present an increasing challenge for public health.

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Heat exposure is also associated with health issues among workers. During the 2003 and 2006 heat waves in France, 15 and 8 deaths caused by hyperthermia were reported among workers respectively (Buisson, 2009; INRS, 2009), while in the United States, 423 deaths were attributed to heat stroke in the workplace between 1992 and 2006 (CDC, 2008). Industrial sectors with outdoor working activities, such as construction, agriculture, forestry, fishing, hunting and public services, present higher risks of death on hot days (Buisson, 2009; CDC, 2008; INRS, 2009). Descriptive morbidity studies, carried out on the working population of Washington State between 1995 and 2005 (Bonauto et al., 2007), and on working populations of the mining and the forestry sectors (Donoghue et al., 2000; Donoghue, 2004; Maeda et al., 2006), reported higher incidence of heat-related illnesses during the warmer months of the year and in specific occupations and/or sub-sectors.

Although important scientific knowledge has been gathered on the health effects of heat among workers (for a review, Jay and Kenny, 2010), very few studies have focused on quantifying the association between outdoor heat and heat illnesses. The risk function for the association between average summer temperatures and the number of occupational heat-related deaths was estimated in two studies; in the United States, the risk of on-duty coronary heart disease mortality among firefighters was not associated with increasing temperatures during months with average temperatures above 5 ^{o}C, between 1994 and 2004 (Mbanu et al., 2007), while in the whole working population of North Carolina between 1977 and 2001, the rate of heat-related death increased by 37% for each 1 °F increase (corresponding to approximately 77% per 1 ^{o}C increase) in average summer temperatures (Mirabelli and Richardson, 2005). In addition, only one pilot study, carried out by the Florida Department of Health (2012) between 2005 and 2009, reported a quantitative relationship between average summer temperatures and heat-related hospitalizations and emergency department visits, where cases were stratified in occupational and non-occupational groups. In this study, incidence rate ratios of 1.62 to 3.58 for every 5^{o}F increase (corresponding approximately to incidence rate ratios – IRRs - of 1.20 to 1.60 for every 1^{o}C increase) in daily maximum temperatures were calculated during the summer months in three different areas of the State.

Thus, there is evidence that outdoor heat may produce heat-related illnesses among workers, but theses associations are still little explored. The aims of this study are to quantify the association between occupational heat-related compensations and exposure to summer outdoor temperature in Quebec (Canada).

3.3 Methods

The study analyzed the relationship between daily counts of compensations for heat-related illnesses and daily temperatures for all regions of Quebec (Canada) from May 1st to September 30th of each year between 1998 and 2010. These months cover the period when hot days may happen in Quebec, and the years of study were chosen according to availability of data. The study period consisted in 1,989 days over the 13 years, and a total of 31,824 days-regions for analytical purposes (1,989 days*16 health regions).

Compensation data

Compensations for heat-related illnesses were identified from a database of the Workers' Compensation Board (WCB) of Quebec. The WCB is the exclusive provider of compensations for employment injuries and illnesses in Quebec for persons who do work for an employer for remuneration. A few exceptions to this mandatory insurance provision exist in certain circumstances when work is done for the federal government, or for self-employed independent operators. The WCB covers 93 % of the Quebec province workforce (AWCBC, 2013).

Study population

In the WCB database, all injuries are coded according to the nature of injury (i.e. physical characteristic of the injury) according to the Canadian Standards Association, Standard Z795. Compensations with any of the following nature codes were retained for the study period: 07200-Effects of heat or light, 07210-Heat stroke, 07220-Heat syncope, 07280-Multiple effects of heat or light, 07290-Effects of heat or light (not elsewhere classified) including heat-related fatigue and edema. Compensations for contact with hot objects or substances as events leading to the injury were excluded. To avoid misclassification, only compensations for acute heat exposure were retained for analyses. Case recurrence was verified and no claimant was compensated more than once for the same injury within 30 days.

Data obtained for each compensation included the claimant's date of birth and sex, the date of injury, the six-digit postal code of the employer establishment's location, the nature of injury, the North American Industrial Classification System (NAICS) code assigned to the employer's record, and the Canadian Classification Dictionary of Occupations (CCDO) code assigned to the claimant's occupation. When the postal code of the establishment's location was missing or erroneous (less than 7%), the postal code of the regional WCB office was used. The establishment's postal code was used to classify each claim within one of the 16 health regions of Quebec (see Figure 1 for health region names) and daily counts of heat-related injury compensations were calculated per health region, stratified by sex, age categories as found in the Labor Force Survey of Statistics Canada (15-24 years old, 25-44 years old, and 45 years old and more), and NAICS sector.

Meteorological data

Hourly meteorological data were obtained from the Environment Canada Data Access Integration Team (http://loki.qc.ec.gc.ca/DAI/DAI-e.html). One monitoring station, previously identified by Environment Canada as representative of the weather of each region (Martel et al., 2010), was chosen for each health region. The daily maximum hourly values in the 8-hour period between 9h00 and 17h00 were retained for dry bulb temperatures (°C), wet bulb temperatures (°C) and relative humidity (%). Wet bulb temperatures are obtained with a thermometer whose bulb is covered by a wet cloth and differ from the dry bulb temperatures by an amount that depends on the moisture content of the air (EC, 2013). The maximum daily temperature exposure was considered constant among the working population within each health region. For statistical analyses, days with less than 75 % of meteorological data (2.5 % of 31,824 days-regions) were excluded.

Statistical analyses

A risk function for the association between daily compensation counts and daily hourly maximum temperatures was developed using a generalized linear model with negative binomial regression for the health region with the highest compensation counts (i.e. Montreal, the largest urban area of the province). To control for temporal trends (i.e. seasonality, long term time trend), the model was adjusted for day of the week, month, year and for the two-week holiday of the construction sector (statutory in Quebec) and public holiday periods. Daily maximum relative humidity in the 8-hour period was also included in the model, since the increase in body temperature induced by heat exposure may be accelerated with high relative humidity (Parson, 2003; Tanaka, 2007).

In an attempt to find a compromise between providing adequate adjustments and leaving sufficient information from which to estimate the temperature effect, the impact of including the year, relative humidity and temperature as linear or cubic spline function variables was assessed with the likelihood ratio test. Additionally, the statistical interaction between temperature and relative humidity was verified. As an offset in the model, the monthly regional working population estimate obtained from the Labor Force Survey of Statistics Canada (table CANSIM 282-0001, http://www5.statcan.gc.ca/cansim/) was used. The model developed for the health region of Montreal is the following:

Ln [E(Yt)] = ln (Monthly working population estimates) + β_0 + $\beta_{1\text{-}6}$ Day of the week + $\beta_{7\text{-}10}$ Month + β_{11} Year + β_{12} Construction sector holiday + β_{13} Public holiday + β_{14} Daily maximum relative humidity over 8h + β_{15} Daily maximum temperature over 8h + ε

where E(Yt) is the expected daily counts of heat-related compensations.

This model (same variables with no spline function) was then applied to the other health regions of Quebec. Thus, IRRs per 1 ºC increase, and 95% confidence intervals (CI) per health region were obtained. In very few cases the negative binomial model did not converge and when data were not over-dispersed, Poisson regression was used instead. Pooled effect sizes for Quebec (all health regions combined) were estimated using a random effect model with the method of Dersimonian and Laird for meta-analysis.

The same analyses produced estimates after stratification by sex and age group. The pooled estimates were based on the regions where heat-related compensations were found in every sex/age groups and for which models converged with negative binomial or Poisson regressions using the same adjustment variables. For these analyses, the monthly working population estimates of each subgroup for the whole province were used as the offset, because this information was not available at a regional level. The Cochran Q test was used to assess differences of effect of temperatures between sex and age subgroups (Kaufman and MacLehose, 2013).

As the studied outcomes include health effects that could be related to longer term exposure, such as heat-related fatigue and edema, time-lag phenomena were explored by looking at the association between heat-related compensations and the weather conditions of the current day (lag 0), and also with weather conditions of the two previous days (lag 1 and lag 2). The cumulative effect of two-day (mean of lags 0-1) and three-day (mean of lags 0-1-2) averages of daily maximum temperatures was also estimated.

Finally, the effect of using another temperature metric (wet bulb temperature) in the model was assessed. All analyses were conducted with Stata version 12.1.

3.4 Results

Descriptive results

There were 259 heat-related illnesses (including 6 fatalities) compensated for acute heat exposure during the 1,989 days from 1998 to 2010 (May-Sept) in Quebec for an average annual population of 3.7 million workers (Figure 1). The heat-related illnesses that were compensated occurred in 15 out of the 16 health regions; 44% of these were in the greater area of Montreal with a working population of approximately 1.78 million. For the whole province of Quebec, the daily number of heat-related compensations ranged from 0 to 6 per region and the average daily number was 0.13 while the daily rates per million workers ranged from 0.01 to 0.09 with an overall rate of 0.04.

Meteorological data are summarized in Figure 1. The regional averages of daily maximum temperatures ranged from -7.8 to 37.3 ºC with an overall mean of 20.2 ºC. The regional averages of daily maxima had also large ranges for relative humidity (22 to 100%) and wet bulb temperatures (-8.8 to 29.4 ºC). As expected, May and September were the coldest months of the study period (average maxima of 15.9 ºC and 18.4 ºC), while July and August were the warmest months (average maxima of 23.3 ºC and 22.7 ºC).

The patterns of daily temperatures and of daily compensation counts over time, and characteristics of the compensations are presented as supplemental material (see Table S1 and Figure S1). Most compensated heat-related illnesses occurred on week days and during the months of July and August. Most compensated claimants were male (82.6%), aged 25-44 years old and working in the Manufacturing (29.8%), Public Administration (20.8%) or

Construction (10.7%) sectors, doing work as laborers (in material handling: 32% and metal processing: 4%), firefighters (11%) and truck drivers (4%). Overall, the "effects of heat or light (not elsewhere classified)" was the most frequent nature of injury, followed by heat syncopes. Six heat-related deaths (all men) occurred during the study period and were classified as one heat syncope and five deaths following effects of heat or light.

Exposure-response relationship

Over the study period, no heat-related outcome was compensated for days when the daily maximum temperature was below 10 °C, while 63.0 % of heat-related illnesses occurred on days when this temperature was between 10 and 30°C. More than a third of the illnesses occurred when the maximum temperature was higher than 30°C (3% of the 31,824 days-regions of the study period) and fatalities occurred on days when the daily maximum temperature was above 27°C. For the Montreal region, the linear model relating daily heat-related compensation counts and daily maximum temperatures and the model with spline functions were similar (likelihood ratio test : $\chi 2$(dl= 1): 0.91; p-value=0.339). Therefore, the relation between the daily heat-related compensation counts and daily maximum temperatures was modeled as linear for all regions.

There was a statistically significant effect of daily maximum temperatures on heat-related compensations in 14 of the 15 health regions where claims were accepted. For all regions combined, an increase of approximately 42% (pooled estimate) in daily heat-related compensations was observed with an increase of 1^{o}C in daily maximum temperatures (IRR 1.419, 95% CI 1.326-1.520; see Figure 1).

The incidence rate ratio of compensations per 1°C increase was higher among women than among men, but the 95% CIs overlapped considerably and the difference was not statistically significant (heterogeneity $\chi 2$(dl= 1) : 0.96; p = 0.327). The risk ratio was also slightly higher for workers aged 25-44 years old compared to other age groups, but again, the risk ratios were not statistically different between subgroups (heterogeneity $\chi 2$(dl= 2): 0.18; p = 0.916). Increases in daily maximum temperatures were associated with increases in daily heat-related compensations for lag 0, lag 1 and lag 2 and for two and three-day lag averages. Risks were similar across lags and multiple lag averages, with the strongest effects observed with two and three-day lag averages (Table 1). It was not possible to calculate specific IRRs per industrial sector due to the very low compensation counts in each health region.

When using a different temperature metric, the wet bulb temperature, the estimated IRR for all regions combined was 1.486 (95% CI 1.411-1.567), suggesting a stronger effect of temperature as measured with the wet bulb compared to the dry bulb metric adjusted for relative humidity.

3.5 Discussion

We observed a positive log-linear relationship between the daily maximum temperatures and heat-related compensations for 15 health regions of Quebec (one health region had no such compensation during the study period). With a mean daily count of 0.13 compensation, a 42% increase in daily heat-related compensations counts was observed with each increase of 1°C in daily maximum temperatures for all health regions combined.

These results cannot be directly compared to the risk functions developed to quantify the association between outdoor heat and mortality (Mbanu et al., 2007; Mirabelli and Richardson, 2005), because our model was developed essentially on non-fatal heat illnesses (6 fatalities for 259 heat illnesses). Comparison of our results with those of studies on morbidity performed in other latitudes may also be difficult, as hot temperature thresholds for morbidity appear to vary by location (Ye et al., 2012). Nonetheless, the influence of latitude may be limited and may not importantly limit the generalizability of our results as the latter are comparable to those of the Florida Department of Health (2012), located more than 10° latitude further south. In their pilot study using a similar approach to ours (i.e. generalized linear model, with a Poisson distribution and adjustments for temporal trends), the Florida Department reported incidence rate ratios for occupational heat-related hospitalizations or emergency department visits of 1.62 to 3.58 for every 5°F increase (corresponding approximately to IRRs of 1.20 to 1.60 for every 1°C increase) in daily maximum temperatures at lag 0 in three different areas of the State during the summer months. In comparison, we obtained an IRR of 1.42 per 1°C increase at lag 0.

Moreover, the Florida researchers calculated incidence rate ratios of 1.69 to 3.40 for every 5°F increase (corresponding approximately to IRRs of 1.21 to 1.57 for every 1°C increase) at lag 1 during the summer months. In this pilot study, authors did not model the temperature effect at lag 2, but reported that among models which included various numbers of lag days (lag 0; lags 0-1 to lag 0-5), the models that had the best fit were the ones including the temperature of the current and previous days (lags 0-1 and lags 0-2). In our study, daily maximum temperatures were associated with increases in IRRs on the day of the illness, on the following days (lags 1 and 2) and also with increase of two and three-day average temperatures; the temperature effects of those multiple lag days were even stronger compared to the model at lag 0 (Table 1). Overall, these findings suggest that heat-related illnesses may also develop over a number of days due to a delayed effect of heat exposure. In a recent review of epidemiological evidence on the relationship between ambient temperatures and morbidity (several nonspecific diagnoses), Ye et al. (2012) reported that the majority of studies on the relationship between ambient temperatures and nonspecific morbidity describe detrimental effects of temperatures on the same day or up to the following 3 days.

Regarding the effect of using several temperature metrics, we could not find a paper comparing risk estimates obtained from dry bulb and wet bulb temperatures. In the Florida pilot study (2012), the estimated incidence rate ratios were lower when modeled with the maximum heat index only (IRRs of 1.16 to 2.11 for every 5°F increase, corresponding approximately to IRRs of 1.06 to 1.32 for every 1°C) as opposed to maximum temperatures; the heat index is not directly comparable to the wet bulb temperature in that it is derived from both dry bulb temperature and relative humidity. Nonetheless and in contrast, we found that the effect of the wet bulb temperatures (IRR 1.486) was larger than the effect of the dry bulb temperatures adjusted for relative humidity (IRR 1.419). This difference may be, at least partially, explained by various assumptions. The relationship of the wet bulb temperatures in our study was modeled log-linearly and the effect of the dry bulb temperatures was adjusted for relative humidity, while the Florida department of Health modeled the heat index relationship as quadratic, and the effect of temperature was estimated without adjustment for relative humidity. In the literature, there is no consensus regarding the effect of the choice of temperature metrics on temperature-health associations (Ye et al., 2012) and recent studies reported that the metric selection for a specific health outcome should be based on data quality, completeness and coverage (Lippmann et al., 2013).

As did the Florida researchers (2012), we used a log-linear relationship (linear model with Poisson distribution) to estimate the association between daily counts of heat-related compensations and daily maximum temperatures. It is in agreement with findings by Ye et al., (2012), who reported that studies focusing separately on associations during hot or cold seasons usually show a linear association between temperatures and morbidity.

Vulnerable sub-groups

The risk ratio of compensation counts per 1°C increase in maximum daily temperatures was not statistically different between women and men or between age subgroups. In occupational studies, higher risk of heat-related illnesses and work-related injuries are often reported among young workers (Bonauto et al., 2007; CDC, 2010; Maeda et al., 2006; Xiang et al., 2013), which can be attributed to various factors such as the lack of experience, training and skills and their assignment to more strenuous tasks or to jobs with increased hazards (CDC, 2010; Xiang et al., 2013). Our findings are however based on very low compensation numbers obtained in the 15-24 age group (n=35), and this explains that not all regions contributed cases to calculate the age-specific IRRs (only 6 health regions). The relative lack of sensitivity of compensation data to capture heat-related illnesses could also have contributed to discrepancies between study findings, as well as a different distribution of age groups by industry. For the 8 years of study, six fatalities were compensated during the study period, all of them were male workers (5 out of 6 were less than 44 years old) who performed medium to heavy workload in outdoor activities (agriculture, n=1; forestry, n=2; landscaping, n=1; construction, n=2). Risk factors identified during the WCB inquests into these deaths (Commission de la santé et de la sécurité du travail du Québec, 2002a; 2002b; 2003a; 2003b; 2004; 2006), such as the lack of training and experience, obesity, use of medication, and incomplete knowledge of the main language used in the workplace, are commonly reported in the literature (CDC, 2008; Mirabelli and Richardson, 2005).

Methodological considerations

This study has some limitations. First, the daily counts of heat-related illnesses are probably underestimated: a large number of workers at risk for heat-related illnesses are employed in sectors that are well known for underreporting injuries, such as agriculture, forestry, fishing and construction (Fan et al., 2006). Second, the small numbers of regional daily counts of compensations dictate cautious interpretation of the results, especially in sex or age-stratified analyses. Third, misclassification of heat exposure is very likely. The employer's location (postal code) was used to link heat-related illnesses and temperatures and some workers may have suffered their heat-related illnesses at another location; this particularly concerns sectors where employees are on the road (e.g. transportation) or where the working activities take place far from the employer's location (e.g. forestry). Moreover, the database did not contain information on the working environment and some compensated injuries could have resulted from indoor heat exposure. Additional misclassification may have also resulted from the ecological nature of the temperature estimates: data from only one weather station was used to estimate the temperature per health region, instead of estimating local temperature at each employer's location. Even if these stations were previously identified by meteorological experts of Environment Canada as representative of the weather of a health region, and although they were used for health surveillance studies in Quebec (Lebel et al., 2011; Martel et al., 2010), they cannot capture conditions in microenvironments. Fourth, possible regional variations in the labor force during the study period may have influenced the results of the sex and age-stratified analyses, as the provincial monthly working population estimates of each group were used instead of region-specific estimates. Sensitivity analyses done without the offset gave very similar results, suggesting that the effect of the offset was negligible. Lastly, a limitation may arise from the fact that the models were developed based on data from an urban region. The adequacy of that model was verified by developing two additional models based on two rural health regions (i.e. with higher proportions of workers in agriculture and in forestry, fishing, mining, quarrying, oil and gas industries). One model was exactly the same as the urban one, while the other differed only by the modeling of the year variable (cubic spline provided a better fit according to the likelihood ratio test) and there was a significant interaction between temperature and humidity. Without the interaction term, the temperature effect remained the same, whereas with the interaction term, the temperature effect was negative and not statistically significant.

Despite some limitations, our study is the first in Canada that quantifies the association between occupational heat-related illnesses and exposure to summer ambient temperatures, using meteorological data linked to occupational compensation statistics. Results indicate a statistically significant increase in the number of heat-related illnesses with the increase of the maximum daily temperature. Recent evaluations for Quebec predict increases of average summer temperatures in the order of 1.6 to 3.0oC by year 2050 (Ouranos, 2010).The model (risk function) developed in this study could be useful to improve the assessment of future impacts of predicted summer outdoor temperatures on workers and vulnerable groups in temperate climates.

The model (risk function) developed in this study could be useful to improve the assessment of future impacts of predicted summer outdoor temperatures on workers and vulnerable groups, particularly in colder temperate zones.

If an health effects indicator as crude as compensation statistics can show measurable increments in risk with increasing maximum temperature, climate change effects will have to be closely monitored among workers.

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3.8. Tables and figures

Table I: Daily compensations and estimated incidence rate ratios associated with a 1oC increase by sex and age groups and for different time lags a,b. Quebec, Canada (May-September, 1998-2010).

Classification	Number of compensations n (%)	Mean daily count n (range)	IRR (95% CI)
Sex[c] and Age[d,e]			
Women	45 (17.4)	0.02 (0;4)	1.430 (1.210, 1.690)
Men	214 (82.6)	0.11 (0;7)	1.409 (1.250, 1.589)
15-24 years old	35 (13.5)	0.02 (0;4)	1.436 (1.163, 1.772)
25-44 years old	149 (57.5)	0.07 (0;6)	1.462 (1.284, 1.665)
45 years old and more	75 (29.0)	0.04 (0; 3)	1.395 (1.162, 1.677)
Lag effects			
Lag 0	259 (100.0)	0.130 (0;10)	1.419 (1.326, 1.520)
Lag 1	259	0.130	1.322

	(100.0)	(0;10)	(1.255, 1.392)
Lag 2	259 (100.0)	0.130 (0;10)	1.206 (1.161, 1.252)
2-day average (lag 0-lag 1)	259 (100.0)	0.130 (0;10)	1.471 (1.373, 1.576)
3-day average (lag0-lag1-lag2)	259 (100.0)	0.130 (0;10)	1.464 (1.376, 1.557)

IRR, incidence rate ratio; 95% CI: 95% confidence interval.

[a] Incidence rate ratios estimated for all health regions of Quebec combined (May-September, 1998-2010).

[b] Models estimated with binomial negative or Poisson regressions and adjusted for day of the week, month, year, public and construction sector holiday periods and relative humidity.

[c] Sex groups: IRRs estimated for 6 health regions (Saguenay, Estrie, Montréal, Chaudière-Appalaches, Laval, Montérégie) with heat-related compensations for men and women and in which models converged with negative binomial or Poisson regressions using the same adjustment variables.

[d] Age groups: IRRs estimated for 6 health regions (Saguenay, Estrie, Montréal, Lanaudiere, Laurentides, Montérégie) with heat-related compensations for every age group and in which models converged with negative binomial or Poisson regressions using the same adjustment variables.

[e] No statistically significant heterogeneity between sex or age groups.

	Mean daily maximum temperature °C (range)	Heat related compensations			
		Number of compensations (%)	Mean daily count (range)	Mean (range) daily rate per 1 000 000	IRR (95% CI)
Bas-Saint-Laurent	19.4 (0.7;34.3)	8 (3.1)	0.004 (0; 2)	0.04 (0.00; 20.88)	1.165 (0.885; 1.532)
Saguenay-Lac-Saint-Jean	20.1 (1.8;37.0)	21 (8.1)	0.011 (0; 1)	0.09 (0.00; 8.44)	1.171 (1.062; 1.291)
Capitale Nationale	21.1 (2.6;33.9)	14 (5.4)	0.007 (0; 2)	0.02 (0.00; 5.31)	1.428 (1.214; 1.680)
Mauricie et Centre du Québec	20.8 (4.4;33.4)	22 (8.5)	0.011 (0; 2)	0.05 (0.00; 8.88)	1.280 (1.099; 1.490)
Estrie	21.5 (4.0;33.8)	11 (4.2)	0.006 (0; 1)	0.04 (0.00; 7.39)	1.397 (1.131; 1.726)
Montréal	22.5 (4.8;35.1)	60 (23.2)	0,030 (0; 4)	0.03 (0.00; 4.32)	1.482 (1.360; 1.614)
Outaouais	21.3 (2.3;34.9)	5 (1.9)	0.003 (0; 1)	0.01 (0.00; 6.67)	1.751 (1.000; 3.065)
Abitibi- Témiscamingue	19.7 (-1,7;35.9)	4 (1.5)	0.002 (0; 1)	0.03 (0.00; 15.72)	1.348 (1.057; 1.720)
Côte-Nord	16.8 (1.3;30,1)	7 (2.7)	0.004 (0; 1)	0.06 (0.00; 18.73)	1.448 (1.152; 1.821)
Gaspésie-îles-de-la-Madeleine	15.0 (1,6; 29,7)	5 (1.9)	0.003 (0; 1)	0.07 (0.00; 28.41)	1.546 (1.091; 2.191)
Chaudière-Appalache	20.9 (2.2; 33.6)	18 (6.9)	0.009 (0; 2)	0.04 (0.00; 9.02)	1.413 (1.227; 1.627)
Laval	22.5 (4.8; 35,1)	15 (5.8)	0.008 (0; 2)	0.04 (0.00;10.69)	1.754 (1.419; 2.168)
Lanaudière	22.5 (3.8; 34,5)	21 (8.1)	0.011 (0; 6)	0.05 (0.00;33.20)	1.816 (1.450; (2.274)
Laurentides	21.5 (2.2; 35.6)	9 (3.5)	0.005 (0; 1)	0.02 (0.00;4.58)	1.313 (1.092; 1.579)
Montérégie	22.6 (4.2; 34,7)	39 (15.1)	0.020 (0; 2)	0.03 (0.00;2.91)	1.553 (1.394; 1.730)
Overall (16 health regions)[c]	20.2 (-7.8; 37.3)	259 (100)	0.130 (0; 10)	0.04 (0.00; 2.49)	1.419 (1.326-1.520)

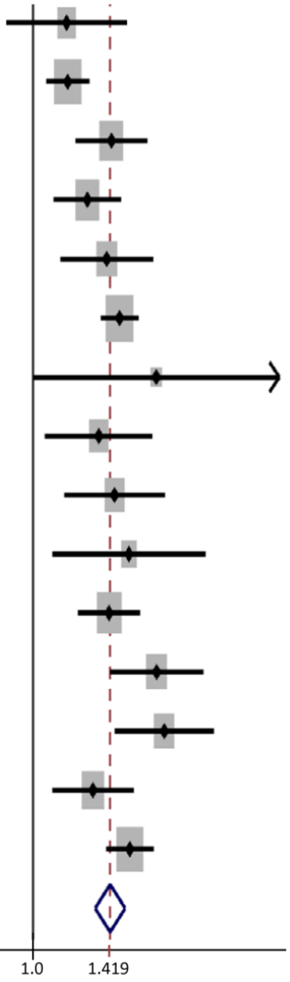

Figure 1. Daily maximum temperatures, heat-related compensations, estimated incidence rate ratios associated with a 1^{o}C increase in daily maximum temperatures, by health regions. Quebec, Canada (May-September, 1998-2010).

3.9. Supplemental material

Table S1: Characteristics of the heat-related compensations. All health regions of Quebec (May-September, 1998-2010).

	Days-regions **Number (%)**
Number of daily compensations	
0	31,594 (99.0)
1	211 (0.7)
2	14 (0.04)
3	2 (<0.01)
4	2 (<0.01)
5 and more	1 (<0.01)
	Compensations
	Number (%)
Week Day	
Monday	46 (17.8)
Tuesday	68 (26.3)
Wednesday	65 (25.1)
Thursday	34 (13.1)
Friday	32 (12.4)

	Saturday	5 (1.9)
	Sunday	9 (3.5)
Month		
	May	14 (5.4)
	June	58 (22.4)
	July	101 (39.0)
	August	71 (27.4)
	September	15 (5.8)
Year		
	1998	10 (3.9)
	1999	9 (3.5)
	2000	4 (1.5)
	2001	28 (10.8)
	2002	30 (11.6)
	2003	25 (9.7)
	2004	16 (6.2)
	2005	42 (16.2)
	2006	16 (6.2)
	2007	17 (6.6)
	2008	10 (3.9)
	2009	8 (3.1)
	2010	44 (17.0)

Public holidays		
	Yes	3 (1.2)
	No	256 (98.8)
Construction holidays		
	Yes	35 (13.5)
	No	224 (86.5)
Nature of injury		
	Effects of heat or light	7 (2.7)
	Heat stroke	14 (5.4)
	Heat syncope	38[a] (14.7)
	Multiple effects of heat or light	4[a] (1.5)
	Effects of heat or light (not elsewhere classified)	196[b] (75.7)
Industrial Sectors (only for years 2003-2010; n=178)[c]		
	Agriculture	4 (2.2)
	Forestry	8 (4.5)
	Mining, quarrying, and oil and gas extraction	3 (1.7)
	Construction	19 (10.7)
	Manufacturing	53 (29.8)
	Wholesale and Retail trade	8 (4.5)
	Transport and warehousing	6 (3.4)
	Information and cultural industries; Arts, entertainment and recreation	4 (2.2)

Professional, scientific and technical services	3 (1.7)
Management of companies and enterprises; Administrative and support, waste management and remediation	12 (6.7)
Health care and social assistance	7 (3.9)
Accommodation and food services	1 (0.6)
Other services (except public administration)	4 (2.2)
Public administration	37 (20.8)
Unknown sectors	9 (5.1)

[a] Including one death

[b] Including four deaths

[c]The NAISC classification was only available after 2003; therefore the number of compensations per sector are illnesses that occurred between 2003-2010 (n=178).

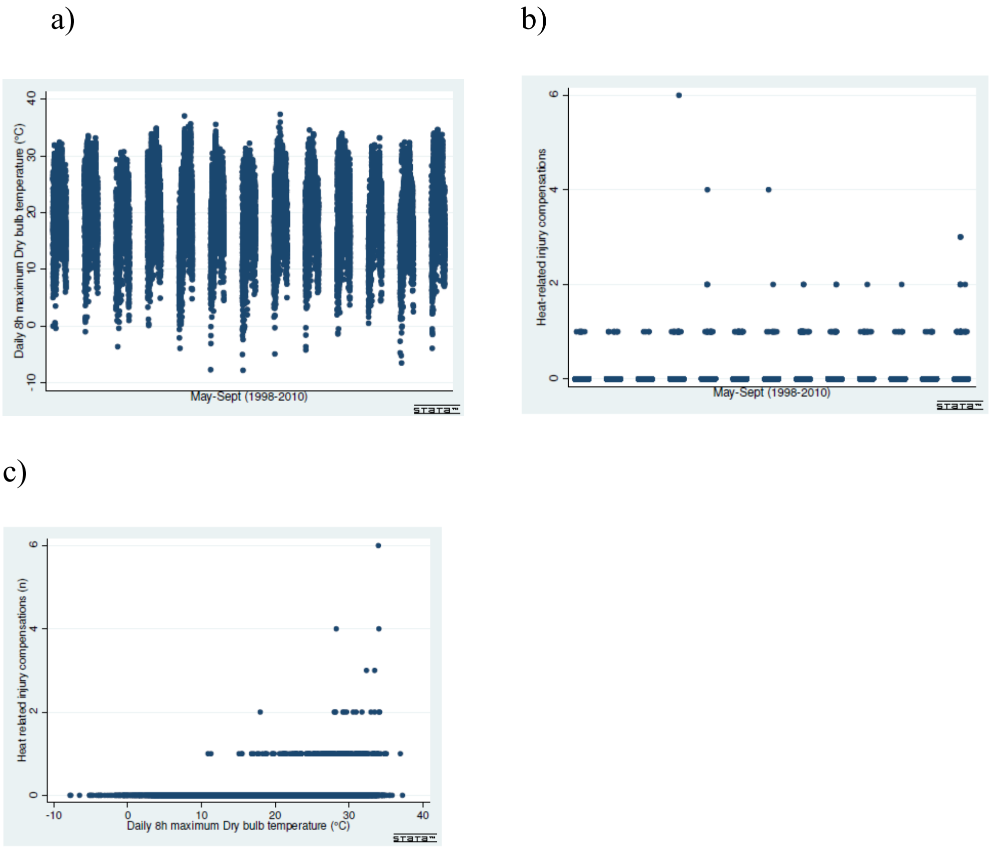

Figure S1: Patterns of a) daily maximum temperatures over time, b) heat-related compensations over time and c) relation between the two variables (All health regions of Quebec, May-September, 1998-2010).

CHAPITRE 4- Effect of summer outdoor temperatures on work-related injuries in Quebec (Canada).

Effect of summer outdoor temperatures on work-related injuries in Quebec (Canada).

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4.1 Abstract

Objective: To quantify the associations between occupational injury compensations and exposure to summer outdoor temperatures in Quebec (Canada).

Methods: The relationship between 374 078 injuries compensated by the Workers' Compensation Board (between May and September, 2003-2010) and maximum daily outdoor temperatures was modelled using generalized linear models with negative binomial distributions. Pooled effect sizes for all 16 health regions of Quebec were estimated with random-effect models for meta-analyses, for all compensations, and by sex, age group, mechanism of injury, industrial sector and occupations (manual *vs*. other) within each sector. Time lags and cumulative effect of temperatures were also explored.

Results: The relationship between daily counts of compensations and maximum daily temperatures reached statistical significance for 3 health regions. The incidence rate ratio (IRR) of daily compensations per 1ºC increase was 1.002 (95% CI 1.002 to 1.003) for all health regions combined. Statistically significant positive associations were observed for men, workers aged less than 45 years old, various industrial sectors with both indoor and outdoor activities, and for slips/trips/falls, contact with object/equipment and exposure to harmful substances/environment. Manual occupations were not systematically at higher risk than non-manual and mixed ones.

Conclusion: This study is the first to quantify the association between work-related injury compensations and exposure to summer temperatures according to physical demands of the occupation and this warrants further investigations. In the context of global warming, results can be used to estimate future impacts of summer outdoor temperatures on workers, as well as to plan preventive interventions.

4.2 Introduction

Direct effects of heat on occupational health have been recognized for some time. Several studies showed that both indoor and outdoor temperatures were associated with morbidity and mortality in the workplace (Bonauto et al., 2007; Buisson, 2009; Donoghue, 2004; Donoghue et al., 2000; INRS, 2009; Jay and Kenny, 2010; Maeda et al., 2006; Mbanu et al., 2007; Mirabelli and Richardson, 2005).

Heat exposure has also been shown to produce other effects on workers, such as physical discomfort, reduced vigilance and increased fatigue, which could lead to accidents and injuries (Basagaña, 2014; Grandjean and Granjean, 2007; Ramsey, 1995; Tawatsupa et al., 2010; Xiang et al., 2014a). The effect of heat on activities, performance and productivity is known to be complex. Working in hot temperatures may cause sweating, which may affect activities requiring grip and influence manual performance. In contrast, increased blood flow to muscles and arousal level due to heat stress may enhance attention and facilitate movements (Parsons, 2003).

Little research has been conducted on the association between outdoor heat exposure and these consequences. High outdoor temperature was associated with increase in injuries in the mining sector (Fogleman et al., 2005), during army combat training (Knapik et al., 2002) and in the textile manufacturing industry in India (Nag and Nag, 2001) as well as with increase in hospital admissions due to work-related accidents in Italy (Morabito et al., 2006). Very recently, the relationship between daily average summer temperatures and daily work-related injuries was quantified in South Australia (Xiang et al., 2013) where it was observed that daily occupational injury compensations increased with temperature up to 37.7°C and declined above this threshold.

Thus, the association between outdoor temperature and work-related injuries has been little studied and was not explored in Canada. The aims of this study were to quantify the associations between occupational injury compensations and exposure to summer outdoor temperatures in Quebec (Canada), and to identify vulnerable subgroups of workers and industrial sectors.

4.3 Methods

The study was conducted in Quebec, Canada. The relationships between daily counts of compensations for work-related injuries and daily summer temperatures were quantified for all health regions of Quebec, from May 1st to September 30th 2003 to 2010.

Workers' compensation data

Workers' compensation data were obtained from the Workers' Compensation Board (WCB) of Quebec, which is the major provider of compensation for employment injuries in the province (AWCBC, 2013).

Study population

In the WCB database, each accepted compensation claim includes information on the claimant (i.e. identification number, date of birth and sex, Canadian Classification Dictionary of Occupations (CCDO) code assigned to the occupation), on the employer (i.e. six digit postal code of the establishment's location, North American Industrial Classification System (NAICS) code assigned to the employer's record) and on the injury (i.e. date, nature, mechanism of injury, exposure and sources, as classified by the Canadian Standards Association - Standard Z795).

For this study, compensations for accidental injuries that occurred between May 1st and September 31st - the warmest months in Quebec - were retained between 2003 and 2010 due to data availability. Only acute occupational injuries were retained for analysis. When the same identification number appeared more than once in a 31-day period with the same information (claimant, employer and injury), only the first compensation was retained in the database to avoid double-counting of recurrent cases (less than 0.02% of compensations were excluded). Daily counts of work-related injury compensations were calculated for the 16 health regions of Quebec, using the employer's establishment postal code to classify each claim within one of the regions (see Table 1 for health region names). Stratification by sex, age categories as reported in the Labour Force Survey of Statistics Canada (15-24 years old, 25-44 years old, and 45 years old and more), mechanism of injury (see Table 1 for categories) and by NAICS industrial sectors (see Tables 2 and 3 for sector names) was applied to the regional daily counts of compensations.

In order to take into account physical demands of occupations, a rough indicator developed by the Institut de recherche Robert-Sauvé en santé et en sécurité du travail was used to stratify regional daily compensation counts per industrial sector. The indicator groups standard occupational codes into one of three categories of physical demands, i.e. manual, non-manual and mixed demands, described as follows. Manual occupations require handling heavy or average loads on a regular basis, handling lighter loads in static postures, or continuous repetitive work. Mixed occupations entail occasional handling of heavy or average loads or handling light loads, but not in continuous static postures. Finally, non-manual occupations rarely involve strenuous physical activities or handling loads (Hébert et al., 1997).

Meteorological data

One monitoring station was selected per health region and meteorological data for each station was obtained from the Environment Canada Data Access Integration Team (http://loki.qc.ec.gc.ca/DAI/DAI-e.html). These monitoring stations were previously identified by experts from Environment Canada as representative of the weather of each region (Martel et al., 2010; Lebel et al., 2010). For each station, the highest hourly value in the 8-hour period between 9h00 and 17h00 was retained for dry bulb temperatures (°C) and relative humidity (%). Days with less than 75% of meteorological data (less than 2.5% of days in the study period) were excluded from statistical analysis.

Statistical analyses

The association between the daily counts of compensations for work-related injuries and daily hourly maximum dry bulb temperatures was assessed for the Montreal health region, and the characteristics of this model (i.e. same adjustment) were then used to estimate the risks in the other health regions. Montreal, the largest urban area of the province, was chosen as this region had the highest compensation counts during the period of study. The risk function was developed using a generalized linear model with negative binomial regression. The model was adjusted for day, month, year, two-week holiday of the construction sector and public holiday periods to control for temporal trends, and for relative humidity, as high relative humidity may accelerate the increase of body temperature during heat exposure (Parsons, 2003; Tanaka, 2007). The likelihood ratio test was used to assess the effect of including the year, relative humidity and temperature as linear or cubic spline function variables with 3 knots located at 10, 50 and 90 percentiles of the temperature variable, according to Harrell (2001). The statistical interaction between temperature and relative humidity was verified. As an offset in the model, the monthly regional working population estimates obtained from the Labor Force

Survey of Statistics Canada (table CANSIM 282-0001, http://www5.statcan.gc.ca/cansim/) were used.

The developed model is as follows:

Ln [E(Yt)] = ln (Monthly working population estimates) + β_0 + $\beta_{1\text{-}6}$ Day of the week + $\beta_{7\text{-}10}$ Month + $\beta_{11\text{-}13}$ Year $_{\text{(cubic spline 3 knots)}}$ + β_{14} Construction sector holiday + β_{15} Public holiday + β_{16} Daily maximum relative humidity over 8h + β_{17} Daily maximum temperature over 8h + ε

where E(Yt) is the expected daily count of work-related compensations.

As mentioned earlier, this model was used to estimate the risks in the other 15 health regions. In very few cases, the negative binomial model did not converge and when data were not over-dispersed, Poisson regression was used instead. Incidence rate ratios (IRR) per 1ºC increase, and 95% confidence intervals (CI) were obtained per health region, and pooled effect sizes for all health regions combined were estimated using the DerSimonian and Laird random-effects model for meta-analysis (Borenstein et al., 2010).

The same analyses were conducted to assess the potential delayed effect of temperature on work-related injuries. The associations between daily compensation counts and the weather conditions for each of the two previous days (lags 1 and 2) and of the cumulative two-day (mean of lags 0-1) and three-day (mean of lags 0-1-2) moving averages were assessed.

Additional analyses were performed on stratified data. Provincial pooled estimates by sex and age subgroups were obtained, and differences of temperature effects between subgroups were verified with Cochran Q test (Kaufman and MacLehose, 2013). For these analyses, the provincial monthly working population estimates of each subgroup were used as offset term, because this information was not available at a regional level. Provincial pooled estimates were also obtained for each mechanism of injury, as well as for each group of industrial sectors. For the forestry/logging, fishing/hunting/trapping and mining/quarrying/oil and gas extraction sectors, the monthly working population estimate for the three groups combined was used as offset term, because this information was not available separately in the Labour Force Survey. Lastly, provincial pooled estimates were calculated for manual and other occupations (mixed and non-manual) for each industrial sector and Cochran Q test was used to compare the effect of outdoor temperatures between these subgroups of occupations. All analyses were performed with Stata version 12.1.

4.4 Results

Overall, 374 078 work-related injury compensations were allocated during the 1 224 days of the eight years under study. Almost half of these occurred in the greater area of Montreal (working population of approximately 1.78 million during the period of study), on week days. Claimants were predominantly men aged between 25 and 44 years old. The average daily number of compensations per region was 19.10, ranging from 0.46 to 85.48. Meteorological data and various characteristics of the work-related injury compensations are summarized in the online supplementary material (Tables A-1 and A-2 and Figure 1A).

Exposure-response relationship

For the Montreal health region, including the temperature as a spline variable (3 knots) did not provide a better fit compared to the linear term (likelihood ratio test for the comparison of models: $\chi 2$(dl= 1): 0.81; p-value=0.39). Therefore, the relation between daily injury compensation counts and daily maximum temperatures was included as linear in the risk function.

Total and delayed effects of temperature

For all regions combined, a 0.2% increase in daily compensation counts was observed with each increase of 1^{o}C in the daily maximum temperature (Table 1; supplementary Table A-2 for IRRs per region). IRRs were similar at lags 1 and 2 and stronger effects of temperatures were observed with two and three-day moving averages (Table 1).

Sex and age stratification

A 0.3% increase in daily injury compensations counts was observed with each increase of 1^{o}C in the daily maximum temperatures for men, whose risk ratio was significantly higher than that for women (heterogeneity chi-square test, $\chi 2$(dl= 1): 14.35; p<0.001). A significant difference in the effect of temperatures between age subgroups was found (chi-square test, $\chi 2$(dl= 1): 41.37; p<0.001) and the IRR was higher for younger workers (Table 1).

Mechanism of injury

Most compensated injuries occurred as a result of exertion/repetitive motion/bodily reaction, contact with object/equipment or slips, trips and falls. Statistically significant positive associations between daily maximum temperature and daily injury compensations were observed for slips, trips and falls, contact with object/equipment and exposure to harmful substances/environment, regardless of whether the workplace was mostly outside or not (Table 1).

Industrial sectors and physical demands of the occupation

Statistically significant effects of temperatures were not consistently found in sectors with mostly outside work (Table 2), but were also observed for some sectors where activities are mostly inside (Table 3). When stratified according to physical demands of the occupation, statistically significant increased risks were observed, but not similarly across industrial sectors, and manual occupations were not systematically at higher risk (Tables 2 and 3).

4.5 Discussion

In this study, a 0.2% increase in daily work-related injury compensations was observed with each increase of 1^{o}C in daily maximum temperatures for all regions combined. This significant effect of temperature is in agreement with results from the few studies published on the subject. For instance, Fogleman et al., (2005) reported a significant relationship between categories of an outdoor heat index combining outdoor temperature (from -18 to 43°C) and relative humidity and acute injury in an aluminium smelter of the Midwest of the United States between 1997 and 1998. Authors observed significantly elevated odds ratios (OR) for categories of outdoor temperatures between 33 and 38°C (OR 2.28; 95% CI 1.49-3.49) and over 38°C (OR 3.52; 95% CI 1.86-6.67) when compared to temperatures between 11 to 16°C. In a study conducted in Florida between 1997 and 1998 on army basic combat training, Knapik et al., (2002) observed higher risks of injury in summer (temperatures from 30.8 to 36.1°C) compared to fall (temperatures from 14.5 to 26.1°C) for men (relative $\text{risk}_{\text{summer/fall}}$ of 2.0; 95% CI 1.7-2.3) and for women (relative $\text{risk}_{\text{summer/fall}}$ of 1.4; 95% CI 1.3-1.6). Hot weather conditions were also associated with increases in hospital admissions due to work-related accidents in Tuscany between the summer seasons of 1998 to 2003 (Morabito et al., 2006). In this study, the peak of work accidents occurred on days characterized by a mean apparent temperature ranging from 24.8 to 27.5°C.

Our findings are also similar to those of Xiang et al., (2013) who quantified the relationship between ambient temperatures and work-related injury compensations during the warm season in Adelaide (South Australia; 2001-2010). For all injuries combined, they calculated an incidence rate ratio of 1.002 (95% CI 1.001-1.004) for every 1^{o}C increase in maximum temperatures between 14.2°C and 37.7°C on the day of the injury, and a decrease by 1.4% per °C above this threshold. They reported no delayed effect of temperatures above the threshold of 37.7°C and did not explore delayed effects below it, whereas we observed similar effects of temperatures at lags 1 and 2 with a slightly stronger effect with two and three-day moving averages compared to lag 0.

We observed a statistically significant positive association for men only and no effect for women. For the same range of temperatures, Xiang et al., (2013) reported comparable findings. This possibly reflects gender differences in the industrial sector of employment in Quebec, where men constitute more than 70% of the workforce in Agriculture, Forestry, Fishing, Mining and oil and gas extraction, and Construction (CCHALW, 2009). We also found higher IRRs for young workers (less than 25 years old), as observed in other studies (Fogleman et al., 2005; Xiang et al., 2013; Xiang et al., 2014a) and this could be trigger by more strenuous tasks and physical activity experienced by workers in this age groups (Xiang et al., 2014a).

Statistically significant effect of temperatures were observed in our study for accidents resulting from slips, trips and falls, contact with object/equipment and exposure to harmful substances/environment, regardless of whether the industrial sectors included mostly outside work or not. The only paper that reported on mechanisms of injury in association with outdoor heat compared injuries occurring during heat wave periods to those during non-heatwave periods, reporting that moving objects, contact with chemicals, and injuries related to environmental factors were significantly associated with heatwaves (Xiang et al., 2014b). In the USA between 1985 and 1990, Hassi et al., (2000) observed increases in mining accident caused by handling materials, machinery, powered haulage and hand tools with increases of ambient temperatures (ranging from 3 to 89°F or approximately -16.1 to 31.7°C).

In contrast with Xiang et al., (2013), who found statistically significant effects only in industrial sectors with mostly outside work, we also found statistically significant IRRs for sectors where activities are mostly inside. This suggests that outdoor heat may add to the temperature burden resulting from heat-generating industrial processes, intense physical work and absence of heat-mitigating devices or policies on hot days. The effect of outdoor temperature also appears to vary with physical demands of the occupation, but not similarly across industrial sectors. For example, the only risk estimates that reached statistical significance in the industrial sectors with outdoor activities concerned the category that includes mixed and non-manual occupations. We could not find published data on the subject, but it is possible that these last types of occupations require more complex perceptual motor tasks which seem to be more influenced during heat exposure than simple motor task, and which could potentially increase the risk of accidents (Jay and Kenny, 2010). The complex relation of heat on activities, performance and productivity, which could vary among subjects and according to the task, has been highlighted (Parsons, 2003) and the intricate role of physical workload in detrimental effects of heat exposure warrants further study.

Methodological considerations

This study has limitations. First, the effect of temperatures is likely to be underestimated as a large number of workers who mostly work outdoors are employed in sectors that are well known for underreporting injuries, such as agriculture, forestry, fishing and construction (Fan et al., 2006). Second, some exposure misclassification may have resulted from the selection of only one weather station per health region, even if these stations were previously identified as representative of the weather for each region (Lebel et al., 2011; Martel et al., 2010;. Moreover, the fact that the employer's location (postal code) was used to link injuries and temperatures might have also introduced additional exposure misclassification for employees who are on the road or at remote worksites from their employer's location. Third, the use of less specific offsets may have influenced the results found for the sex and age analyses and for some industrial sectors. However, we conducted sensitivity analyses with the regional monthly working population estimates (all workers per health region) and obtained similar results. Fourth, some IRRs were not estimated with all 16 health regions due to small numbers of regional daily counts of compensations or because the fully-adjusted models did not converge with binomial negative or Poisson regressions. This dictates cautious interpretation of the results, especially for data stratified by type of occupation according to physical demands. Lastly, the adequacy of the risk function may be questioned because the model was developed with data from the largest urban region of Quebec and then applied for each of the other regions. Nevertheless, additional risk models were developed based on data from two rural health regions. The risk functions were the same (cubic spline function with 3 knots on the year variable, linear functions for temperature and relative humidity) with the only exception of an interaction term between temperature and humidity being significant in one of the two models.

4.6 Conclusion

This study is the first of its kind to quantify the impact of summer outdoor temperatures on work-related injuries in Canada. In the context of climate change, increases in global temperatures and in frequency and intensity of heat waves are expected, and the results of this study could be helpful to estimate future impacts of global warming on workers, as well as to plan preventive interventions.

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4.9 Tables and figures

Table I : Daily work-related injury compensations counts, incidence rate ratios and 95% confidence intervals associated with a 1°C increase in daily maximum temperatures by sex, age groups, mechanism of injury, and for different time lags (all health regions of Quebec combined, May-September 2003-2010)[a, b.]

Classification		**Number of compensations (%)**	**Mean daily count per region (range)**	**Pooled IRR per 1°C increase[c] (95% CI)**
All accidents		374 078 (100)	19.10 (0;175)‡	1.002 (1.002 to 1.003)
Sex and Age				
	Women	110 844 (29.6)	5.66 (0;58)	1.000 (0.998 to 1.003)
	Men	263 234 (70.4)	13.44 (0;130)	1.003 (1.002 to1.005)
	15-24 years old	59 668 (16.0)	3.05 (0;37)	1.008 (1.005 to 1.010)
	25-44 years old	178 441 (47.7)	9.11 (0;100)	1.003 (1.001 to 1.004)
	45 years old and more	135 969 (36.3)	6.94 (0;83)	1.000 (0.999 to1.001)

Lag effects			
Lag 1	374 078 (100)	19.10 (0;175)	1.001 (1.000 to1.002)
Lag 2	374 078 (100)	19.10 (0;175)	1.001 (1.000 to 1.002)
2-day average (lag 0-lag 1)	374 078 (100)	19.10 (0;175)	1.002 (1.001 to1.003)
3-day average (lag0-lag1-lag2)	374 078 (100)	19.10 (0;175)	1.003 (1.001 to 1.004)
Mechanism of injury			
Transportation accidents	5 848 (1.6)	4.8 (0;21)	1.003 (0.996 to1.010)
Slips, trips and falls	57 709 (15.4)	47.1 (6;103)	1.003 (1.001 to 1.006)
Contact with object/equipment	114 472 (30.6)	93.5 (10;212)	1.004 (1.002 to1.006)
Exposure to harmful substances/environment	18 748 (5.0)	15.3 (2;45)	1.009 (1.003 to 1.015)
Exertion /repetitive motion/bodily reaction	138 496 (37.0)	113.2 (17;274)	0.999 (0.997 to1.001)
Other events/exposures and unknown	38 805 (10.4)	31.7 (2;76)	1.009 (1.003 to 1.015)

[a] IRR, incidence rate ratio; 95% CI: 95% confidence intervals. Models were estimated with binomial negative or Poisson regression and were adjusted for day, month, year, public and construction sector holiday periods and relative humidity.

[b] Statistically significant heterogeneity was found between sex and age groups.

[c] The provincial mean daily number of compensations was 306 ranging from 54 to 641.

Table II : Daily work-related injury compensations counts, pooled incidence rate ratios and 95% confidence intervals associated with a 1°C increase in daily maximum temperatures by industrial sector with mostly outdoor work[a] and stratified by type of occupation (manual and others). All health regions of Quebec combined, May-September 2003-2010)[b, c]

Classification	**All occupations**			**Manual**		**Others**	
	Number of compensations (%)	**Mean daily count (range)**	**Pooled IRR per 1°C increase (95% CI)**	**Mean daily count (range)**	**Pooled IRR per 1°C increase (95% CI)**	**Mean daily count (range)**	**Pooled IRR per 1°C increase 95% CI**
Agriculture							
	4 054 (1.1)	3.3 (0;12)	1.005 (0.993 to1.016)	2.72 (0;11)	1.002 (0.987 to 1.017)	0.13 (0;2)	1.041 (0.988 to 1.096)
Construction							
	29 784 (8.0)	24.3 (0;73)	1.003 (1.000 to 1.006)	19.36 (0;57)	1.003 (0.999 to 1.007)	1.19 (0;7)	0.992 (0.980 to 1.005)

Fishing, hunting and trapping							
	222 (0.06)	0.2 (0;3)	1.001 (0.927 to 1.082)	0.16 (0;3)	0.997 (0.929 to 1.069)	0.01 (0;2)	-
Forestry, logging and supporting activities							
	3 504 (0.9)	2.9 (0;15)	1.011 (1.001 to 1.020)	1.80 (0;13)	1.004 (0.989 to 1.019)	0.48 (0;4)	1.025 (1.004 to 1.048)
Mining, quarrying and oil and gas extraction							
	3 751 (1.0)	3.1 (0;12)	0.995 (0.984 to 1.006)	2.37 (0;10)	0.996 (0.988 to 1.005)	0.29 (0;3)	0.980 (0.955 to 1.006)
Transportation and warehousing							
	20 603 (5.5)	16.8 (0;46)	1.005 (1.001 to 1.009)	10.47 (0;29)	1.002 (0.995 to 1.009)	3.82 (0;14)	1.007 (1.003 to 1.011)

[a] Excluding 14 066 injury compensations (3.8%) with unspecified industrial sector

[b] IRR, incidence rate ratios; 95% CI: 95% confidence intervals. Models were estimated with Binomial negative or Poisson regression and adjusted for day, month, year, public and construction sector holiday periods and relative humidity.

[c] IRRs per NAICS sector (all occupations) and for manual and other occupations within each sector were mostly estimated with 16 health regions. Exceptions are presented in online supplementary material (Table A-3).

Table III: Daily work-related injury compensations counts, pooled incidence rate ratios and 95% confidence intervals associated with a 1°C increase in daily maximum temperatures by industrial sector with mostly inside activities[a] and stratified by type of occupation (manual and others). All health regions of Quebec combined, May-September 2003-2010)[b, c]

Classification	**All occupations**			**Manual**		**Others**	
	Number of compensations (%)	**Mean daily count (range)**	**Pooled IRR per 1°C increase (95% CI)**	**Mean daily count (range)**	**Pooled IRR per 1°C increase (95% CI)**	**Mean daily count (range)**	**Pooled IRR per 1°C increase 95% CI**
Accommodation and food services							
	17 543 (4.7)	14.3 (2;29)	1.007 (1.003 to 1.010)	4.85 (0;15)	1.005 (0.999 to 1.012)	7.36 (0;18)	1.006 (1.001 to 1.012)
Educational services							
	9 360 (2.5)	7.6 (0;37)	0.994 (0.989 to 0.999)	1.98 (0;12)	1.008 (0.998 to 1.018)	4.44 (0;21)	0.988 (0.981 to 0.994)

Finance and insurance							
	4 615 (1.2)	3.8 (0;13)	1.009 (0.999 to 1.019)	1.71 (0;8)	1.013 (0.999 to 1.027)	1.35 (0;7)	0.999 (0.987 to 1.011)
Health care and social assistance							
	48 576 (13.0)	39.7 (9;73)	0.999 (0.997 to 1.002)	17.98 (2;39)	1.001 (0.998 to 1.004)	16.90 (2;38)	0.997 (0.991 to 1.002)
Information/culture; Arts/entertainment and recreation							
	6 988 (1.9)	5.7 (0;17)	1.004 (0.998 to 1.010)	2.29 (0;9)	1.002 (0.987 to 1.017)	2.25 (0;8)	1.007 (0.997 to 1.016)
Waste management/ remediation services; Administrative/ support services							
	15 732 (4.2)	12.9 (0;43)	1.007 (1.003 to 1.011)	8.23 (0;26)	1.008 (1.003 to 1.013)	2.52 (0;21)	1.008 (0.997 to 1.019)

Manufacturing							
	107 940 (28.9)	88.2 (3;234)	1.002 (1.000 to 1.004)	67.84 (1;189)	1.001 (1.000 to 1.003)	5.22 (0;19)	1.005 (0.999 to 1.011)
Other services including Repair and maintenance (not public administration)							
	11 959 (3.2)	9.8 (0;27)	1.005 (1.001 to 1.010)	7.20 (0;22)	1.010 (1.002 to 1.017)	1.77 (0;9)	0.990 (0.979 to 1.002)
Professional. scientific and technical services							
	2 652 (0.7)	2.2 (0;11)	1.002 (0.992 to 1.011)	0.53 (0;5)	1.002 (0.982 to 1.021)	1.10 (0;6)	0.999 (0.986 to 1.012)
Public administration							
	21 152 (5.7)	17.3 (1;43)	1.008 (1.004 to 1.011)	6.94 (0;26)	1.003 (0.996 to 1.010)	7.18 (0;22)	1.008 (1.003 to 1.014)

Utilities							
	1 418 (0.4)	1.2 (0;7)	0.987 (0.972 to 1.003)	0.70 (0;5)	0.979 (0.959 to 1.000)	0.21 (0;3)	0.998 (0.938 to 1.062)
Wholesale and Retail trade							
	50 159 (13.4)	41.0 (1;99)	1.001 (0.999 to 1.004)	20.87 (0;62)	1.003 (1.000 to 1.006)	13.00 (1;33)	1.000 (0.997 to 1.004)

[a] Excluding 14 066 injury compensations (3.8%) with unspecified industrial sector

[b] IRR, incidence rate ratios; 95% CI: 95% confidence intervals. Models were estimated with Binomial negative or Poisson regression and adjusted for day, month, year, public and construction sector holiday periods and relative humidity.

[c] IRRs per NAICS sector (all occupations) and for manual and other occupations within each sector were mostly estimated with 16 health regions. Exceptions are presented in online supplementary material (Table A-3).

4.10 Supplemental material

Table S1 Characteristics of the work-related injury compensations (All health regions of Quebec, May-September 2003-2010).

	Number	(%)
Days		
Monday	73 475	19.6
Tuesday	74 988	20.0
Wednesday	71 126	19.0
Thursday	66 038	17.7
Friday	52 236	14.0
Saturday	19 885	5.3
Sunday	16 330	4.4
Months		
May	74 617	19.9
June	72 142	19.3
July	69 225	18.5
August	79 542	21.3
September	78 552	21.0
Years		
2003	54 901	14.7
2004	53 612	14.3
2005	51 424	13.7

	2006	49 552	13.2
	2007	45 757	12.2
	2008	43 004	11.5
	2009	38 120	10.2
	2010	37 708	10.1
Public holidays			
	Yes	4603	1.2
	No	369 475	98.8
Construction holidays			
	Yes	27 859	7.4
	No	346 219	92.6
Total		374 078	100.0

Table S2: Regional daily maximum temperatures, work-related injury compensations, and estimated incidence rate ratios and 95% confidence intervals associated with a 1°C increase in daily maximum temperatures (All health regions of Quebec, May-September 2003-2010)[a].

		Work-related injury compensations			
Name of region	**Daily maximum temperature (°C) Mean (range)**	**Total (%)**	**Daily count Mean (range)**	**Daily rate per 100,000 workers Mean (range)**	**IRR** per 1°C increase[b] **(95% CI)**
Bas-Saint-Laurent	19.01 (1.8; 34.3)	10 332 (2.8)	8.44 (0; 25)	8.8 (0.0; 26.6)	1.000 (0.996;1.005)
Saguenay-Lac-Saint-Jean	19.90 (1.8; 35.5)	14 112 (3.8)	11.53 (0;37)	9.2 (0.0; 28.4)	1.001 (0.997-1.005)
Capitale Nationale	20.88 (4.8; 33.9)	36 902 (9.9)	30.15 (3;69)	8.5 (0.8; 20.4)	1.002 (0.999-1.005)
Mauricie et Centre du Québec	20.53 (6.5; 31.2)	23 070 (6.2)	18.85 (0; 53)	8.2 (0.0; 24.0)	1.007 (1.003-1.011)
Estrie	21.35 (5.3; 32.4)	14 952 (4.0)	12.22 (0;37)	8.2 (0.0; 24.7)	1.005 (1.000-1.009)
Montréal	22.30 (4.9; 33.9)	104 633 (28.0)	85.48 (14;175)	9.2 (1.5; 19.4)	1.002 (1.001-1.004)

		Work-related injury compensations			
Name of region	**Daily maximum temperature (°C) Mean (range)**	**Total (%)**	**Daily count Mean (range)**	**Daily rate per 100,000 workers Mean (range)**	**IRR** per 1^{o}C increase[b] **(95% CI)**
Outaouais	21.33 (2.3; 33.9)	9189 (2.5)	7.51 (0;24)	4.1 (0.0; 13.6)	1.003 (0.998-1.008)
Abitibi-Témiscamingue	19.57 (-1.7; 35.9)	7570 (2.0)	6.18 (0;19)	9.3 (0.0; 29.8)	1.004 (0.999-1.009)
Côte-Nord	16.75 (1.9; 30.1)	5647 (1.5)	4.61 (0;14)	8.7 (0.0; 26.8)	1.004 (0.996-1.011)
Nord-du-Québec	15.43 (-7.8; 37.3)	562 (0.2)	0.46 (0;5)	0.9 (0.0; 8.9)	0.999 (0.982-1.017)
Gaspésie-Îles-de-la-Madeleine	14.90 (1.6; 29.7)	4118 (1.1)	3.36 (0;13)	9.0 (0.0; 34.9)	0.991 (0.980-1.002)
Chaudière-Appalaches	20.68 (2.2; 33.2)	25 131 (6.7)	20.53 (0;55)	9.7 (0.0; 26.1)	1.002 (0.999-1.005)
Laval	22.30 (4.9; 33.9)	17 914 (4.8)	14.64 (0;40)	7.6 (0.0; 21.1)	1.005 (1.001-1.009)

Name of region	Daily maximum temperature (°C) Mean (range)	Work-related injury compensations Total (%)	Daily count Mean (range)	Daily rate per 100,000 workers Mean (range)	**IRR** per 1°C increase[b] (95% CI)
Lanaudière	22.37 (5.7; 34.5)	16 923 (4.5)	13.83 (0;37)	6.2 (0.0; 16.6)	1.000 (0.996-1.003)
Laurentides	21.49 (2.2; 34.6)	21 989 (5.9)	17.96 (0;46)	6.8 (0.0; 19.1)	1.003 (1.000-1.006)
Montérégie	22.43 (4.2; 34.4)	61 034 (16.3)	49.86 (3;113)	7.1 (0.4; 16.9)	1.002 (1.000-1.004)
Mean for all health regions (n=16)	20.08 (-7.8; 37.3)	374 078 (100.0)	306 (54;641)	8.0 (1.4; 17.5)	1.002 (1.002-1.003)

[a] IRR, incidence rate ratio; 95% CI: 95% confidence intervals. Models were estimated with binomial negative regression and were adjusted for day, month, year, public and construction sector holiday periods and relative humidity.

[b] per 1ºC increase in daily maximum temperature.

Table S3: Number of regions used to estimate pooled incidence rate ratios and 95% confidence intervals associated with a 1°C increase in daily maximum temperatures per industrial sector (all occupations) and for manual and other occupations within each sector.[a]

	Number of regions		
Industrial sectors	**All occupations**	**Manual**	**Others**
Mostly outdoor work			
Agriculture	13	13	8
Construction	16	16	16
Fishing. hunting and trapping	3	3	-
Forestry, logging and supporting activities	13	13	11
Mining. quarrying and oil and gas extraction	13	12	9
Transportation and warehousing	16	14	13
Other sectors			
Accommodation and food services	16	16	16
Educational services	16	16	16
Finance and insurance	16	14	14
Health care and social assistance	16	15	15
Information and cultural industries; Arts, entertainment and recreation	15	14	14

Waste management and remediation services; Management of companies and enterprises; Administrative and support services	15	15	14
Manufacturing	16	16	16
Other services including Repair and maintenance (except public administration)	16	16	16
Professional. scientific and technical services	15	13	14
Public administration	16	16	16
Utilities	14	12	8
Wholesale and Retail trade	16	16	16

[a] Regions where work-related injuries were compensated in the reported industrial sector (all occupations, manual or other) and for which models converged with binomial negative or Poisson regressions using the same adjustment variables.

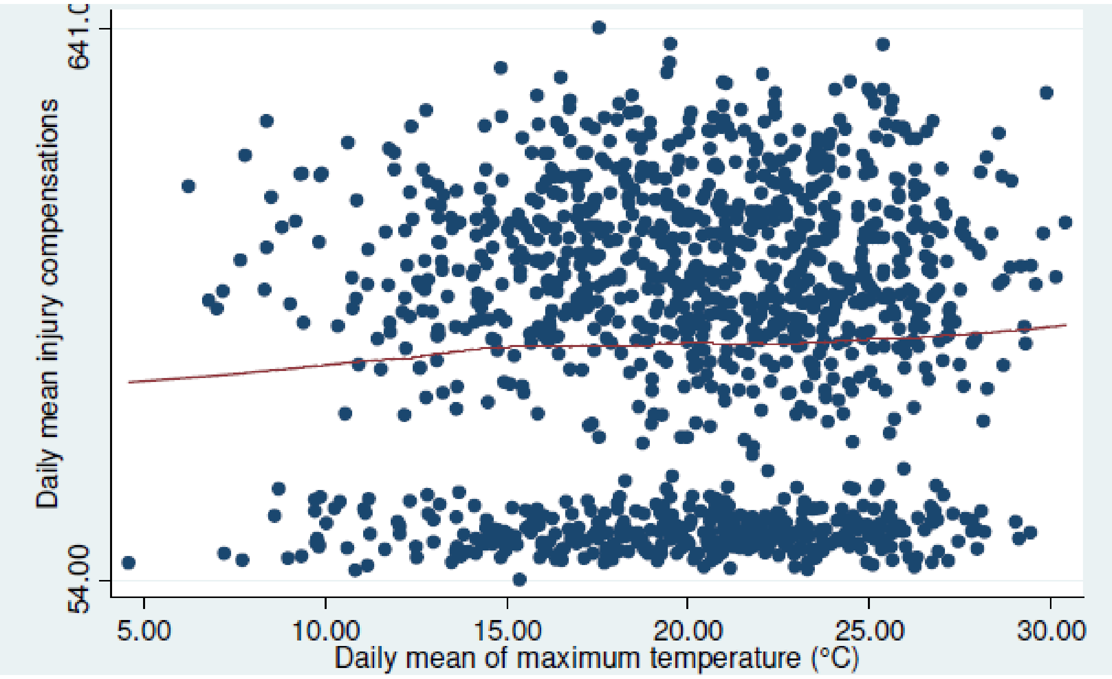

Figure S1: Exposure-response relationship between daily mean of maximum temperature and daily work-related injury compensations for Quebec (all regions combined). Data were smoothed using LOWESS (locally weighted scatter plot smoothing), bandwitdth=0.8.

CHAPITRE 5 - Association between outdoor ozone and compensated acute respiratory diseases among workers in Quebec (Canada).

Association between outdoor ozone and compensated acute respiratory diseases among workers in Quebec (Canada).

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5.1. Abstract

The respiratory effect of ozone in the workplace has not been extensively studied. Our aim was to explore the relationship between daily average ozone levels and compensated acute respiratory problems among workers in Quebec between 2003 and 2010 using a time-stratified case–crossover design. Health data on compensations came from the Workers' Compensation Board. Daily concentrations of ozone were estimated using a published spatiotemporal model. Conditional logistic regressions, with and without adjustment for temperature, were used to estimate odds ratios (ORs, per 1 ppb increase of ozone), and lag effects were assessed. Relationships with respiratory compensations in all industrial sectors were essentially null. Positive non-statistically significant associations were observed for outdoor sectors (ORs 1.02 to 1.06), and results also suggested a delayed effect of ozone. Considering the predicted increase of air pollutant concentrations in the context of climate change, closer investigation should be carried out on outdoor workers.

5.2. Introduction

Ozone is a major air pollutant responsible for acute and chronic damages to the respiratory system (Seguin, 2008), and there are increasing evidences suggesting that outdoor workers are at risk of ozone-related respiratory effects (Vinikoor-Imler et al., 2014). In the context of climate change, predicted increases in surface temperature and greenhouse gases emissions could result in the rising of background surface ozone (IPCC, 2013). Workers could be exposed to higher concentrations of this pollutant in the future, specially on warm days when ozone levels are known to be high (US EPA, 2013). Our aim was to explore the relationship between daily average ozone levels and compensated acute respiratory diseases among workers in Quebec (Canada).

5.3. Methods

Compensation data came from the Workers' Compensation Board (WCB) of Quebec, the exclusive provider of compensations for employment injuries and illnesses for persons who do remunerated work for an employer in Quebec. The period of study was from May 1st to September 30th of each year between 2003 and 2010. These months cover the period when outdoor ozone levels are higher, as concentrations during the winter are almost null in Quebec (Adam-Poupart et al., 2014), while the years of study were chosen according to availability of data. In the WCB database, all injuries coded for Respiratory system diseases according to the Canadian Standards Association (Standard Z795) were retained, except those resulting from stings of wasps, bees and hornets, and from the ingestion of substances.

The study area was restricted to the territory where daily ozone levels were available (see Figure 1). Daily average levels of ozone (9h-17h) were obtained from a Bayesian Maximum Entropy spatiotemporal model, developed over Quebec ($R^2 = 0.653$; Root mean square error = 7.06 ppb). Details on the model can be found in Adam-Poupart et al., 2014 (or in appendix 1; p. xvii).

We assessed the relation between daily ozone levels and compensated acute respiratory problems using a case–crossover design (Maclure 1991). In this design, temporal trends are controlled by selecting control days for each day in which one or more acute respiratory problem was compensated (case day). This design partially controls for potential confounders by making within-subject (i.e. workers) comparisons. Using a time-stratified approach in which the study period is divided into monthly strata, we selected control days for each case as the same days of the other weeks in the same month. Thus, if a compensated respiratory problem occurred on Tuesday 10 March 2009, the selected control days were other Tuesdays of the same month (3, 17, 24 and 31 March 2009). Daily mean ozone concentrations were estimated for six-digit postal code of each employer establishment's location on case and control days.

Conditional logistic regressions were used to compare daily mean ozone levels for cases with their matched control days. Case days with less then three control dates were discarded. Odds ratios (ORs) and their 95% confidence intervals (CIs) were expressed per 1ppb increase of ozone levels. Models were adjusted for daily mean temperature (9h-17h), estimated from hourly meteorological data available from the Environment Canada Data Access Integration Team (http://loki.qc.ec.gc.ca/DAI/DAI-e.html). Additionally, the statistical interaction between ozone and temperature was verified by adding a product term to the model.

Analyses were conducted for all industrial sectors and then restricted to industries with mostly outside work (i.e. agriculture, construction, fishing/hunting/trapping, forestry/logging/supporting activities, mining/quarrying/oil/gas extraction, and transport/warehousing). We assessed possible time-lag effects by looking at the association between compensations and ozone levels of the current day (lag 0), and of the two previous days (lag 1 and lag 2). The cumulative effect of two-day (mean of lags 0-1) and three-day (mean of lags 0-1-2) moving averages of daily levels of ozone was also estimated. All analyses were conducted with Stata version 12.1.

5.4. Results

Overall, 328 respiratory diseases were compensated in Quebec from 2003 to 2010 (May-Sept). Of these compensations, 252 were retained for analysis, as they occurred in areas for which we could estimate ozone concentrations on case and control days. Only 26 compensations occurred in industrial sectors with mostly outdoor work. The number of compensations per type of acute respiratory problems and industrial sector are presented in Table 1. For the period of study, estimations of daily average concentrations of ozone on case and controls days ranged from 6.9 to 61.4 ppb (mean of 28.0 ppb) and daily mean temperature from 0.3 to 31.8°C (mean of 18.7°C).

Associations between ozone estimates and compensated acute respiratory problems are detailed in Table 2. Crude relationships with respiratory compensations in all industrial sectors were essentially null, the adjustment for temperature increased the effect of ozone and the interactions between daily ozone and daily mean temperature were significant at almost all lags and moving averages (p-values varied from <0.01 to 0.40). Crude associations for compensations in sectors with mostly outdoor work were all positive (all lags and moving averages), however a large statistical variability was noted and adjusting for temperature reduced the effect of ozone. For these sectors, no statistical interaction was found between ozone and temperature (p-values varied from 0.24 to 0.75).

5.5. Discussion

The positive trend noted only for outdoor workers could be attributed to higher exposure of outdoor workers to ambient air pollution compared to indoor workers. Outdoor workers are classified as one of the most common categories of people at increased risk of ozone-related respiratory health effects because they are exposed to ambient O_3 concentrations for a greater period of time than individuals who spend their days indoors (Vinikoor-Imler et al., 2014). Moreover, some occupations in these sectors are physically demanding (i.e. roofers) and workers of these occupations could possibly inhaled higher dose of pollutant because of the increase in minute ventilation associated with physical activity (US EPA, 2013). Delayed respiratory effect of ozone on outdoor workers, which was previously reported on mail carriers in Taiwan (Chan and Wu, 2005) and on berry pickers in Canada (Brauer et al., 1996; Brauer and Brook, 1997), is also suggested by the positive trend of associations noted for outdoor workers.

This study presents several limitations that could potentially explain the inconclusive results. Firstly, the statistical variability observed for the crude positive associations between ozone levels and respiratory compensations for outdoor workers may be explained, at least partially, by the small number of cases (n= 26 case days). Secondly, we analyzed compensation data which is known to reflect only part of actual work-related injuries and illnesses (Shannon and Lowe, 2002). It is likely that our analysis estimates the actual risks with larger error, as several industrial sectors with outdoor activities are well known for underreporting injuries, such as agriculture, forestry, fishing and construction (Fan et al., 2006). Between 2003 and 2010, 17 compensations occurred in these sectors compared to 26 for sectors with mostly outdoor work.

Moreover, the lack of precision of both the health indicator and the exposure assessment could also be responsible for the inconclusive results. In the few studies where statistically significant associations between ozone and respiratory health effects were observed among workers, lung functions were evaluated more precisely using spirometry (Brauer et al., 1996; Brauer and Brook, 1997; Chang and Wu 2005; Thaller et al., 2008), or the exposure was assessed individually with portable sampling devices (Karakatsani et al., 2009).

Lastly, the adjustment for temperature had various influence on the effect on ozone; it increased the magnitude of the association between ozone levels and respiratory compensations for all sectors and reduced this association for sectors with mostly outdoor work. Therefore, it is unclear if the observed trends for outdoor workers are due to ozone levels, to high temperatures or to other unmeasured parameters that are associated with them. Moreover, the statistical interaction between daily ozone and daily mean temperature did not vary systematically among the analysis. In the literature, the respiratory effect of a co-exposure to heat and ozone has never been explored in the workplace and conclusions on the role of ozone in health studies of heat exposure in the general population are inconsistent (Reid et al., 2012). In a recent review of the scientific epidemiological evidences on the respiratory effects of the climate events (such as heat) combined to air quality (such as ozone) in the context of climate change, De Sario et al., (2013) reported that the temperature-air pollution interactions can not be easily considered in temperature or air pollution respiratory studies, because the true magnitude of the association may be underrestimated.

However, several studies provided consistent evidence of a synergy between the ozone and heat exposure, and from a toxicological perspective, interactions could occur during co-exposure : heat triggers a series of compensatory physiological responses such as respiratory rate increases, which could simultaneously increase the volume of inhaled air and the ozone dose reaching the respiratory system (De Sario et al., 2013).

In conclusion, a positive non-statistically significant associations between exposure to ozone and acute respiratory problems among outdoor workers in Québec was observed in this study. Considering the predicted increase of ozone concentrations in the context of climate change (IPCC, 2013), closer investigation should be carried out on the potential respiratory impact of this pollutant, as well as others that may have acute respiratory effects, such as fine particulates and nitrogen oxides (Chang and Wu, 2005; Karakatsani et al., 2009;), on workers who spend most of their workday outside.

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Conflicts of Interest: The authors declare they have no competing financial interests.

5.8 Tables and figures

Table I : Number of compensations per type of respiratory problems and industrial sectors (Quebec, May-September 2003-2010).

	Number of compensations	**(%)**
Natures		
Extrinsic asthma	70	27.8
Reactive airway dysfunction syndrome	28	11.1
Acute respiratory infections	25	9.9
Other respiratory system diseases. NEC	23	9.1
Influenza	15	6.0
Bronchitis	13	5.2
Respiratory system diseases. UNS	10	4.0
Pneumonia. influenza. NEC	10	4.0
Chronic obstructive pulmonary diseases and allied conditions. NEC	9	3.6
Pneumonitis. NEC	8	3.2
Allergic rhinitis	7	2.8
Pneumonia	6	2.4
Chronic conditions of upper respiratory tract	5	2.0
Diseases of upper respiratory tract. UNS	3	1.2
diseases of upper respiratory tract. NEC	3	1.2
Asbestosis	3	1.2

Pulmonary edema	3	1.9
Chronic obstructive pulmonary diseases and allied conditions. UNS	2	0.8
Chronic obstructive lung disease	2	0.8
Pneumonia. influenza. UNS	1	0.4
Legionnaires' disease	1	0.4
Extrinsic allergic alveolitis and pneumonitis Includes: farmers' lung. bagassosis	1	0.4
Silicosis	1	0.4
Berylliosis	1	0.2
Byssinosis. mill fever	1	0.4
Pneumonopathy. NEC	1	0.4
Pulmonary fibrosis. NEC	1	0.4
Industrial Sectors		
Manufacturing	78	31.0
Health care and social assistance	62	24.6
Wholesale and Retail trade	26	10.3
Construction	11	4.4
Educational services	11	4.4
Waste management and remediation services; Management of companies and enterprises; Administrative and support services	10	4.0

Unclassified	10	4.0
Public administration	8	3.2
Agriculture	7	2.8
Transportation and warehousing	7	2.8
Professional. scientific and technical services	5	2.0
Accommodation and food services	5	2.0
Other services including Repair and maintenance (except public administration)	4	1.6
Finance and insurance	3	1.2
Utilities	2	0.8
Information and cultural industries; Arts. entertainment and recreation	2	0.8
Mining. quarrying. oil and gas extraction	1	0.4
Forestry. logging and supporting activities	0	0.0
Fishing. hunting and trapping	0	0.0

UNS: Unspecified; NEC; Non else classified.

Table II : Associations between ozone estimates and compensated acute respiratory problems among workers, for each 1 ppb increment of average ozone levels, in Quebec, May-September 2003-2010.[a]

Type of daily ozone mean estimates	**All compensations (2003-2010)**				**Compensations for sectors with mostly outdoor work (2003-2010)[b]**			
	Days with compensations (n)	**OR per 1 ppb increase in daily average ozone concentration (95%CI)**		**Interaction between ozone and temperature**	**Days with compensations (n)**	**OR per 1 ppb increase in daily average ozone concentration (95%CI)**		**Interaction between ozone and temperature**
		Not adjusted	**Adjusted [c]**	**P value**		**Not adjusted**	**Adjusted [c]**	**P value**
Lag 0	252	1.01 (0.98; 1.03)	1.01 (0.98; 1.05)	<0.01	26	1.02 (0.95; 1.10)	0.98 (0.88; 1.09)	0.75
Lag 1	250	1.00 (0.97; 1.02)	1.01 (0.98; 1.05)	0.05	26	1.04 (0.96; 1.12)	1.01 (0.91; 1.12)	0.73
Lag 2	243	1.00	1.01	0.40	23	1.06	1.05	0.66

		(0.97; 1.03)	(0.98; 1.05)			(0.98; 1.13)	(0.93; 1.18)	
Lags 0-1[d]	244	1.00 (0.98; 1.03)	1.01 (0.98; 1.05)	<0.01	25	1.03 (0.95; 1.12)	0.98 (0.87; 1.10)	0.70
Lags 0-2[e]	230	1.00 (0.97; 1.03)	1.01 (0.97;1.06)	0.02	22	1.05 (0.95;1.16)	0.98 (0.84; 1.15)	0.24

[a] Compensations occurring in areas for which we could estimate ozone concentrations with the model on case and control days, and for which we had 3 or 4 control days per case day (106 case days out of 358 were excluded).

[b] Sectors with mostly outdoor work : agriculture, construction, fishing/hunting/trapping, forestry/logging/supporting activities, mining/quarrying/oil and gas extraction, transport/warehousing.

[c] Ajusted for mean daily temperature, evaluated on the same day as ozone estimates.

[d] Two-day lag average

[e] Three-day lag average

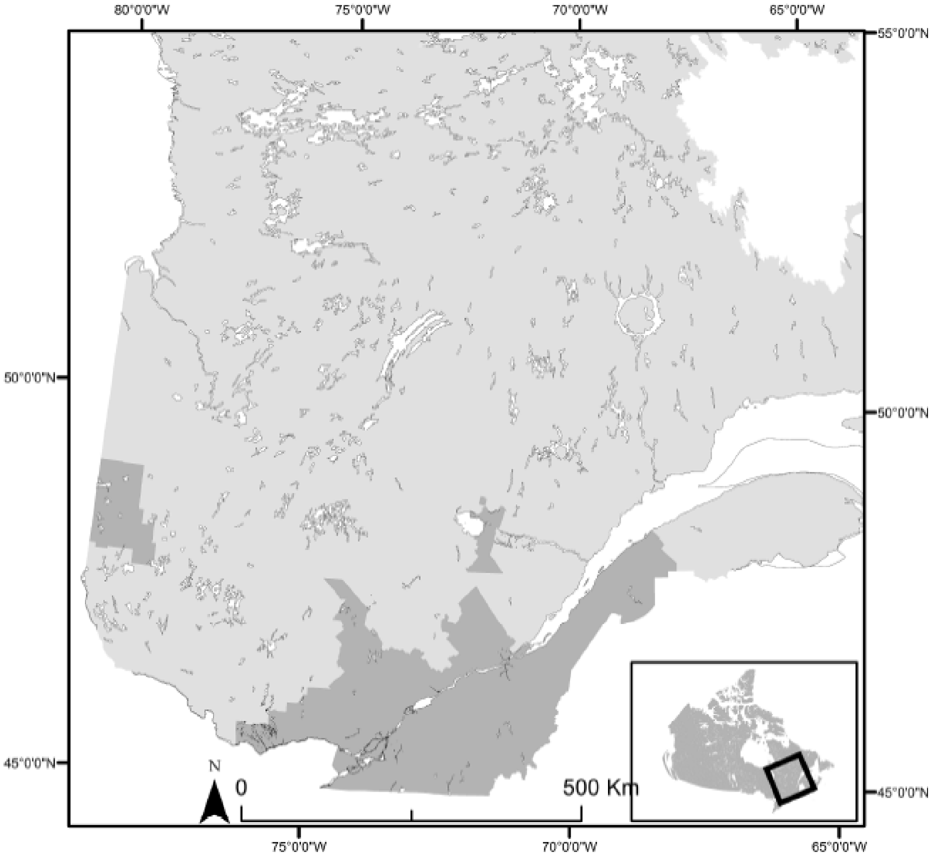

Figure 1: Geographical location the territory (dark grey) where daily ozone levels were available in Quebec (Canada).

CHAPITRE 6- Discussion et conclusion

L'objectif de cette thèse était de documenter les effets négatifs des CC sur la SST dans une région d'un pays industrialisé à climat tempéré, comme au Québec. Cette recherche permettait notamment de répondre à des lacunes dans la littérature scientifique puisqu'il n'existait, au début des travaux, qu'un seul cadre de référence détaillé qui traitait de ces enjeux dans un contexte mondial et que les autres documents publiés portaient généralement sur les pays en voie de développement et étaient inadaptés aux réalités climatiques, économiques et sociales de ces pays (Bennett et McMichael, 2011; Kjellstrom et al., 2009).

Tout récemment, le GIEC publiait son cinquième Rapport d'évaluation et ses conclusions mettaient en évidence que la plupart des recherches scientifiques qui ont été publiées sur les enjeux en SST depuis 2007 portaient essentiellement sur les effets sanitaires de la chaleur et sur la diminution de la productivité des travailleurs dans les pays tropicaux sous-développés (IPCC, 2013; 2014). Dans ce contexte, cette thèse contribuera sans doute à ajouter un nouveau pan à la littérature scientifique actuelle.

Les travaux réalisés au cours du premier volet (chapitre 2) ont permis d'identifier les principaux effets négatifs des CC sur la SST au Québec. À l'aide d'une revue de la littérature et d'une démarche de consultation d'experts et de représentants québécois des secteurs industriels, cinq catégories de dangers pouvant affecter directement ou indirectement la SST au Québec (vagues de chaleur, polluants de l'air, rayonnements ultraviolets, événements météorologiques extrêmes, maladies vectorielles transmissibles et zoonoses) et cinq autres conditions pouvant entraîner des modifications dans l'environnement de travail ou du contexte socioéconomique (changements dans les méthodes agricoles et d'élevage, altérations dans l'industrie de la pêche, perturbations de l'écosystème forestier, dégradation de l'environnement bâti et émergence de nouvelles industries vertes) ont été identifiées.

Les dangers, les effets négatifs sur la SST et les industries potentiellement affectées par les CC ont été mises en commun dans un cadre d'analyse, qui constitue aujourd'hui la base des connaissances sur cette problématique au Québec. Ce cadre d'analyse pourrait devenir un document de référence pour développer des projets de recherche et établir des priorités d'action. Il serait toutefois judicieux de l'actualiser de façon périodique afin de tenir compte des importants changements du marché du travail, par exemple de l'augmentation importante du nombre de travailleurs dans les industries vertes (ECO Canada, 2010), ou encore, des modifications dans les prédictions climatiques au Québec. Cette démarche de mise à jour, qui permettrait de maintenir une vision globale et actuelle de la problématique et d'identifier des dangers émergents, pourrait s'inspirer de la méthodologie utilisée lors de la première évaluation, et se faire via une consultation d'experts et de représentants des secteurs industriels.

Par ailleurs, les effets des CC au Québec ne seront pas uniquement négatifs sur la SST. En effet, les prédictions rapportent une diminution de la fréquence des vagues de froid et une augmentation de la température globale en hiver (Desjarlais et al., 2010), ce qui pourrait contribuer à une diminution des risques de blessures, d'engelures et même de décès par hypothermie. De plus, certaines activités de tourisme, telles que le golf, la chasse et la pêche, pourraient voir leurs saisons de pratique prolongées (Desjarlais et al., 2010), ce qui pourrait être bénéfique à la SST via l'augmentation des revenus et le nombre d'emplois dans cette industrie. Dans ce contexte, il serait intéressant d'ajouter à la présente réflexion, les enjeux liés aux effets potentiellement positifs du climat sur les travailleurs.

Le cadre d'analyse développé dans cette thèse est le premier qui porte de façon détaillée sur les effets des CC sur la SST dans une région d'un pays industrialisé à climat tempéré. Bien que développé dans un contexte spécifiquement québécois, ce cadre constitue le fondement d'une réflexion qui pourrait être adapté à d'autres situations économiques et sociales. Une consultation réalisée auprès d'un groupe d'acteurs multidisciplinaires permettrait notamment l'adaptation locale du cadre d'analyse par l'intégration d'informations spécifiques à de nouveaux contextes.

Par exemple, les maladies à transmission vectorielles retrouvées en Europe ne sont pas toutes les mêmes que celles documentées pour le Québec. Certaines régions de l'Europe présentent aujourd'hui des conditions climatiques adéquates pour *Ae. Albopictus*, un des principaux vecteurs de la dengue (IPCC, 2014) et des cas de transmissions locales ont été rapportés en France et en Croatie (OMS, 2014). Cette maladie n'a pas été documentée dans le contexte québécois, et l'ajout de celle-ci dans les risques associés à l'augmentation de la prévalence des maladies vectorielles constituerait une adaptation régionale du cadre d'analyse.

Les travaux réalisés dans les deuxième et troisième volets (chapitre 3, 4 et 5) ont permis de documenter les risques sur la SST de deux problématiques préoccupantes pour le Québec, soit l'augmentation de chaleur estivale et des vagues de chaleur, et la dégradation de la qualité de l'air en été. Ces recherches constituent les premières à explorer les associations statistiques entre les indemnisations des travailleurs, la chaleur et l'ozone troposphérique dans une région d'un pays industrialisé à climat tempéré.

Les modélisations réalisées dans le second volet (chapitres 3 et 4) suggèrent que les indemnisations quotidiennes pour des maladies liées à la chaleur et pour des accidents de travail augmentent avec les températures extérieures en été au Québec. Plus précisément, des hausses des indemnisations de 42% pour les problèmes de santé en lien avec une exposition excessive à la chaleur et de 0,2% pour les accidents de travail ont été observées par augmentation de 1°C de température maximale journalière. En appliquant le modèle développé pour les maladies liées à la chaleur, on estime que 4,3 indemnisations seraient dues à la chaleur, si l'on considère un compte journalier moyen de 0,13 indemnisation par jour pour une journée d'été où la température maximale est de 30,2°C. Pour cette même journée d'été, un total de 19,5 indemnisations seraient dues à la chaleur si l'on applique le modèle pour les accidents de travail et que l'on considère un compte journalier moyen de 19,10 indemnisations par jour. Les analyses réalisées dans ce volet ont également mis en évidence que les relations statistiques entre la température et les indemnisations pour les accidents de travail pouvaient varier selon l'âge, le secteur industriel et la catégorie professionnelle (manuelles vs autres).

Les associations rapportées aux chapitres 3 et 4 ont été estimées malgré les limites inhérentes aux devis de recherche et à l'utilisation de fichiers administratifs qui ne contiennent que des lésions professionnelles déclarées et indemnisées par la CSST et qui ne représentent qu'un sous-ensemble du nombre de lésions professionnelles survenues au Québec (Duguay et al., 2003). Dans une étude canadienne (Shannon et Lowe, 2002), la sous-déclaration des lésions admissibles aux commissions provinciales d'indemnisation professionnelle a été estimée à près de 40%, ce qui laisse à penser que le nombre d'indemnisations retenues pour le développement des modèles pour les maladies liées à la chaleur et les accidents est inférieur au nombre réel de lésions professionnelles. Il faut également souligner que les lésions indemnisées pour la chaleur ne représentent que les problèmes de santé dont les symptômes sont les plus sévères et que leur utilisation comme indicateur d'un problème de santé associé à la chaleur sous-estime vraisemblablement le fardeau réel de la chaleur sur la santé et la sécurité des travailleurs, car des problèmes mineurs comme un œdème à la chaleur (enflure), des réactions cutanées ou des crampes n'ont possiblement pas été déclarés à la CSST.

Par ailleurs, les associations estimées dans le second volet (chapitres 3 et 4) présentent des caractéristiques qui suggèrent leur robustesse, malgré les limites méthodologiques des études. D'une part, les associations des deux effets sanitaires étudiés présentent une constance, car elles ont été observées à plusieurs reprises dans les différentes régions sociosanitaires. Un effet positif et statistiquement significatif de la température sur les problèmes de santé liés à la chaleur a été mis en évidence pour 14 des 15 régions sociosanitaires où des lésions professionnelles avaient été indemnisées (chapitre 3) alors qu'un effet positif de la température sur les indemnisations pour les accidents de travail a aussi été observé pour 14 des 16 régions sociosanitaires où des lésions professionnelles avaient été indemnisées; cet effet était statistiquement significatif pour 3 d'entre elles (chapitre 4). Outre cette constance entre les régions, les analyses de sensibilité qui ont porté sur le développement de fonctions de risque sur des régions rurales plutôt que sur Montréal (région urbaine) ont démontré la justesse des modèles, car ces nouvelles fonctions de risques étaient très similaires à celles initialement développées (chapitres 3 et 4).

De plus, les associations estimées sont cohérentes avec les observations des études en SST qui ont été réalisées dans des pays ayant des climats différents de celui du Québec. Les fonctions de risque observées dans notre étude au chapitre 3 sont semblables à celles qui ont été rapportées pour les maladies associées à une exposition à la chaleur par le Département de la santé de la Floride (2012), avec une augmentation quotidienne du risque de lésions de 20 à 60 % par augmentation de 1 °C de la température maximale. La force d'association observée dans notre étude dans le chapitre 4 pour l'ensemble des indemnisations est identique à celle rapportée par Xiang et al. (2014) pour les accidents du travail indemnisés en Australie, avec une augmentation quotidienne de 0,2 % des accidents pour chaque 1°C d'augmentation de température maximale journalière. Cette association était similaire malgré le fait que l'étude australienne ait porté sur un intervalle de températures maximales situées entre 14,2 et 37,7 °C, alors que l'intervalle de températures de notre étude était de -7,8 à 37,3 °C. Toujours en termes de cohérence avec les autres études en SST, il faut souligner que les sous-populations et les industries identifiées comme des groupes plus vulnérables à la chaleur ont aussi été observées dans d'autres études, tel que discuté dans les chapitres 3 et 4. Finalement, nos résultats sont également cohérents avec les observations des études réalisées sur la population générale et qui rapportent, par exemple, des associations entre la température ambiante et la morbidité pour plusieurs diagnostics non spécifiques (Ye et al., 2012) ou avec des risques pour des chutes, des lésions et des accidents de la circulation routière (Basagana, 2014).

Dans la littérature scientifique, il n'existe que très peu d'études ayant documenté les relations entre la chaleur extérieure et les effets sur la SST et la cohérence entre les fonctions de risques développées aux chapitres 3 et 4 et celles du Département de la santé en Floride (Florida Department of Health, 2012) et de Xiang et al. (2014), soulève l'intérêt de développer des modèles similaires dans d'autres contextes climatiques, économiques et sociaux afin de mieux documenter ces relations à l'échelle mondiale.

De plus, les fonctions de risques développées aux chapitres 3 et 4 pourraient maintenant permettre d'estimer l'augmentation des risques sur la SST associée aux hausses prévues des températures dans un contexte de changements climatiques pour le Québec. Cette méthodologie, brièvement présentée en introduction, et qui repose sur le jumelage des associations statistiques avec des projections climatiques à long terme, a été utilisée à quelques reprises au Québec pour estimer la mortalité future à différents horizons (Benmarhnia et al., 2014; Doyon et al., 2006). Considérant le fait que les augmentations de température prédites pour le Québec sont assez différentes entre le Nord et le Sud (Desjarlais et al., 2010), et que les associations entre la température et les indemnisations varient selon certaines caractéristiques, il serait intéressant d'estimer la charge morbide attribuable au climat futur par région et par groupe de travailleurs, afin d'orienter l'établissement des mesures de prévention.
Il serait également judicieux de documenter davantage les vulnérabilités chez les jeunes travailleurs et dans les secteurs industriels où les risques estimés sont les plus importants. Ces analyses pourraient être accompagnées d'une approche participative de communication des risques, qui permettrait à la fois de sensibiliser divers intervenants, de mieux comprendre les vulnérabilités et d'identifier, le cas échéant, des options de prévention ou d'adaptation.

Le troisième volet de cette thèse (chapitre 5) constitue la première recherche à avoir exploré les risques d'atteintes respiratoires aiguës chez les travailleurs exposés à des concentrations d'ozone troposphérique à l'aide de données d'indemnisations. Bien que les résultats de cette étude exploratoire ne soient pas concluants, la mise en évidence d'associations positives, mais non significatives chez les travailleurs extérieurs, malgré les importantes limites de cette étude, pourrait justifier l'initiation de nouvelles recherches.

Il faut souligner que la pollution de l'air est une problématique de santé publique qui ne repose pas uniquement sur l'ozone troposphérique, mais sur la présence de plusieurs autres polluants dont les particules en suspension (incluant les particules fines), les composés organiques volatils, les pollens et autres aéroallergènes (moisissures, spores et mycotoxines) (INSPQ, 2012). La pollution atmosphérique est déjà connue pour augmenter les risques d'un large éventail de maladies, comme les maladies respiratoires et cardiaques et tout récemment, le Centre international de Recherche sur le Cancer a classé la pollution de l'air extérieur comme cancérogène pour l'homme (Groupe 1), notamment pour les cancers des poumons et de la vessie (OMS, 2013).

Certains travailleurs sont parmi les individus les plus exposés à la pollution de l'air, notamment ceux qui occupent des emplois qui se pratiquent à l'extérieur sur de longues périodes de temps et qui demandent un effort physique important. En effet, ces travailleurs voient leur débit respiratoire et la durée de leur exposition augmenter de façon notable (US EPA, 2013; Vinikoor-Imler et al., 2014). De plus, les prédictions climatiques suggèrent que la qualité de l’air pourrait se dégrader dans les prochaines décennies au Québec, tout comme ailleurs dans le monde (Desjarlais et al., 2010; IPCC, 2014).

Il semble donc nécessaire de poursuivre les recherches sur cette problématique et d’initier une réflexion sur des mesures de prévention et d’adaptation. Des exemples d’adaptation sont déjà instaurés ailleurs dans le monde, notamment à Hong Kong, où le ministère du Travail a récemment publié des lignes directrices pour assister les employeurs dans la réalisation d’analyses de risques et dans la prise de mesures appropriées pour protéger la santé des employés dans les situations où les niveaux de pollution de l’air sont élevés (Occupational Safety and Health Branch of the Labour Department of Hong Kong, 2013).

Les travaux de cette thèse auront contribué au développement des connaissances générales en santé publique et aussi sur le plan méthodologique. En termes de connaissances en santé publique, les travaux du premier volet auront permis de mettre en évidence l’existence d’effets négatifs des CC sur la SST dans une région d’un pays industrialisé à climat tempéré et à établir des pistes de recherche pertinentes pour aborder cette problématique (chapitre 2). Ce volet aura aussi permis de constituer un groupe de recherche international dans le domaine des changements climatiques en lien avec la santé et la sécurité du travail.

Les travaux du second volet auront contribué à l’identification d’associations statistiques entre la chaleur ambiante et la SST dans une région d’un pays industrialisé à climat tempéré et à définir des sous-groupes d’individus et des industries potentiellement plus vulnérables à la chaleur et ultimement aux effets des changements climatiques (chapitres 3 et 4).

L'identification de la survenue de maladies liées à la chaleur ou d'accidents de travail à des températures qui ne sont pas extrêmement chaudes fait également partie de nouvelles connaissances développées. Sur le plan méthodologique, le second volet aura démontré que les données d'indemnisation peuvent être utilisées pour évaluer les associations entre la température et les risques de lésions professionnelles et aura identifié plusieurs limites méthodologiques associées à leur utilisation. La mise en évidence de risques malgré ces limites aura aussi fait valoir l'importance de poursuivre des recherches sur cette problématique, à l'aide de données différentes, comme l'utilisation de fichiers sur les visites à l'urgence ou encore, des données spécifiquement obtenues sur le terrain dans des groupes de travailleurs identifiés comme vulnérables.

Il est souhaitable que les connaissances développées dans cette thèse soient largement diffusées et intégrées dans des processus décisionnels existants. En effet, les études sur l'adaptation associée aux CC mettent en évidence qu'il est avantageux d'intégrer les considérations en matière de CC dans des activités actuelles de gestion des risques (Séguin, 2008). Ceci s'explique notamment par le fait que la plupart des mesures d'adaptation ne seront pas entreprises uniquement pour répondre à des préoccupations concernant les CC, mais le seront pour répondre à des problématiques actuelles qui s'intensifieront avec les CC. Dans le contexte de la SST, ceci pourrait se traduire par l'intégration des informations relatives aux dangers et aux vulnérabilités associées aux CC (comme la chaleur) dans des politiques ou des mesures actuelles de prévention des accidents du travail et des maladies professionnelles. En réalisant cette intégration d'informations, l'adaptation aux CC devrait se réaliser de façon cohérente avec les programmes et les actions de prévention déjà bien établis.

En conclusion, cette thèse a permis de mettre en évidence l’existence d’effets négatifs des CC sur la SST dans une région d’un pays industrialisé à climat tempéré et plus spécifiquement pour le Québec. Les connaissances à ce sujet sont encore limitées et dans ce contexte, l’apport de cette thèse est appréciable, car elle constitue un point de départ important au chapitre des efforts à déployer pour protéger la santé et la sécurité des travailleurs dans le futur.

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ANNEXE 1- Spatiotemporal Modeling of Ozone Levels in Quebec (Canada): A Comparison of Kriging, Land Use Regression (LUR), and Combined Bayesian Maximum Entropy-LUR Approaches.

Spatiotemporal Modeling of Ozone Levels in Quebec (Canada): A Comparison of Kriging, Land Use Regression (LUR), and Combined Bayesian Maximum Entropy-LUR Approaches.

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1. Abstract

Background: Ambient air ozone is a pulmonary irritant that has been associated with respiratory health effects including increased lung inflammation and permeability, airway hyper-reactivity, respiratory symptoms, and decreased lung function. Ozone exposure estimation is a complex task because the pollutant exhibits complex spatiotemporal patterns. To refine the quality of exposure estimation, various spatiotemporal methods have been developed worldwide.

Objectives: The objective of this work was to compare the accuracy of three spatiotemporal models to predict summer ground-level ozone in Quebec, Canada.

Methods: We developed a land use mixed effects regression (LUR) model based on readily available data (air quality and meteorological monitoring data, road networks information, latitude), a Bayesian Maximum Entropy model incorporating both ozone monitoring station data and the land use mixed model outputs (BME-LUR), and a kriging method model based only on available ozone monitoring station data (BME kriging). We performed leave-one station out cross-validation and visually assessed the predictive capability of each model by examining the mean temporal and spatial distributions of the average estimated errors.

Results: The BME-LUR was the best predictive model (R^2= 0.653) with the lowest RMSE (7.06 ppb), followed by the LUR model (R^2= 0.466, RMSE= 8.747) and the BME kriging model (R^2= 0.414, RMSE= 9.164).

Conclusions: Our findings suggest that errors of estimation in the interpolation of ozone concentrations with BME can be greatly reduced by incorporating outputs from a LUR model developed with readily available data.

2. Introduction

Tropospheric ozone (O_3) is a photochemical pollutant that has increased globally in concentration since the 19th century (Bogaert et al., 2009). Short and long-term exposure to ambient ozone has been associated with a variety of adverse health outcomes, including respiratory, cardiovascular, neurological conditions, and possibly increased mortality (Chen et al., 2007; EPA 2006; INRS 1997; Jerrett et al., 2009).

Large population studies designed to assess the health risks of ozone exposure need accurate exposure estimates. The assessment of the exposure of a population is a complex task because ozone exposure exhibits complex spatiotemporal patterns, which present considerable modeling challenges. Modeling methods have been developed worldwide to improve exposure assessment of population studies and to capture small spatiotemporal variations in pollutant levels like ozone (Briggs 2005; Jerrett et al., 2005; Zou et al., 2009). For instance, land use regression (LUR) models are used to predict pollutant concentrations at unmonitored sites based on regression models of geo-referenced covariates that predict observed (i.e. measured) data from monitored sites (Beelen et al., 2009; Jerrett et al., 2005). Kriging and the Bayesian Maximum Entropy (BME) framework are interpolation methods that assign a series of weights to observed monitoring station data to compute interpolated values of pollutants at unmonitored sites (Bell 2006; Bogaert et al., 2009; Christakos and Vyas 1998; de Nazelle et al., 2010).

The main objective of this work was to compare the accuracy of three spatiotemporal models to predict ground-level ozone in Quebec (Canada). The models were: a land use mixed effects regression model (LUR) developed with readily available data (air quality and meteorological monitoring data, road networks information, latitude) and two spatiotemporal interpolation models: a combined land use Bayesian Maximum Entropy model incorporating both ozone monitoring station data and the land use mixed model outputs (BME-LUR), and a kriging method based only on available data from ozone monitoring stations (BME kriging).

3. **Methods**

Data used for the study

Ozone monitoring data

We retrieved hourly ground level ozone observations for 1990 through 2009 from the National Air Pollutant Surveillance (NAPS) program (Environment Canada, 2012) (Figure 1). We only calculated 8-hour midday (9am – 5pm) ozone concentrations during summer months (May through September) because ozone concentrations during the winter and at night are almost null in Quebec, and included data for all available days with less than 25% missing data (i.e., days with hourly data for at least six of the eight hours).

In Quebec, the number of ozone monitoring stations increased from two stations in 1990 to a total of 50 stations available at the end of 2009. Up to 51 stations were available at some point in time during the period, resulting in 156,060 total observations (station days). All stations had a limit of detection (LOD) of 1ppb by 1995, and most stations had a LOD of 10 ppb before 1995. Measured 8-hour daily ozone levels were recorded as 0 ppb for 373 observations (station days) during the study period, of which 355 observations were recorded before 1995 when less sensitive instruments were in use. However, these data were retained in analyses as they represented only 0.02% of the observations used to develop the three models

Road density data

We extracted road density data from the Digital Mapping Technology inc. (DMTI) Road Layer Dataset (2010) and retained major roads, primary and secondary highways, and freeways from all road layers. We measured the total kilometers of such roads within a 1 km buffer around the ozone stations and the road density was expressed in km/πkm^2.

Meteorological data

We obtained meteorological data from the National Climatic Data and Information Archive of Environment Canada for the period of 1990-2009 (National Climatic Data and Information Archive, 2011), between May and September. We extracted mean 8-hour temperature (from 9am to 5pm for days with at least 75% of the data available) and daily precipitation records for all weather stations in Quebec. Locations of all available meteorological stations are presented in Figure 1.

Development of models

The following section describes the three models developed to predict exposure to ground-level ozone concentrations (8-hour average) in Quebec and the method used for comparing their predictive ability.

Land use regression mixed effects model

We developed a linear mixed effects regression (LUR) model to predict ozone concentrations measured at monitoring sites with the R software (2010). Temperature, precipitation, day of year, year, road density in a one km buffer, and latitude were the variables used in the model. Temperature and precipitation data were from the closest weather station to each ozone-monitoring site. We shifted and rescaled these variables to produce coefficients of a similar range and to render the intercept interpretable. Specifically, we subtracted 121 from the numeric day of the year to shift its range from 121–274 to 0–153, subtracted 1990 from the year to convert its range from 1990–2009 to 0–19, and subtracted 4,995.9 (the minimum value) from the latitude variable to standardize its range to 0–583.3 km (such that a latitude of 0 represents that latitude of the southerly most ozone monitoring station.)

We used linear splines to model temperature (one knot at 18 ºC), road density (one knot at $15\text{km}/\pi\text{km}^2$), and latitude (one knot at 50 km) because their relationships with ozone were not linear. We determined the number and location of the knots by visual inspection, and selected linear splines over cubic splines to increase simplicity, as the results were nearly as good (i.e. the root mean square difference between the prediction of the two models was <0.81 ppb). Therefore, associations with ozone were represented by two model coefficients (one for each linear segment) for each of these variables.

We nested values within stations, which were treated as a random intercept. Thus, we estimated average 8-hour daily ozone concentrations for each observed station-day as follows:

$$O_3 = \beta_0 + \beta_1 X_{low\_temperature} + \beta_2 X_{high\_temperature} + \beta_3 X_{precipitation} + \beta_4 X_{dayofyear} + \beta_5 X_{year} + \beta_6 X_{low\_road} + \beta_7 X_{high\_road} + \beta_8 X_{low\_latitude} + \beta_9 X_{high\_latitude} + u_{station} + \varepsilon , \qquad [1]$$

BME-LUR and BME kriging analysis

We developed both BME kriging and BME-LUR models for a territory involving census districts of population density greater than 5 people per square km in 2006 (Statistics Canada 2007). This was to ensure that a large proportion of the Quebec population would be covered by the study area, without including areas with very low population. We created a buffer of 50 km around our study area to avoid any edge effects caused by lack of data just outside a census district. Therefore, the selected study region was situated between approximately 42 to 50 decimal degrees North latitude and 65 to 80 degrees East longitude encompassing a total area of 103,110 km^2 (Figure 1).

‘‘Hard” data used to develop the BME kriging and BME-LUR models were the measured ozone concentration data provided by the ozone monitoring stations for all eligible station-days during 1990 to 2009. “Soft” data refers to information that can be used to improve estimates by compensating for the limited amount of measured data. Usually, soft information is based on some a priori knowledge of the physical processes that affect the spatiotemporal distribution of the pollutant. For our analysis, the soft data were ozone levels (and their respective normal errors) estimated from the land use mixed effects regression model for 1km x 1km grid cells within the study area for May – Sept, 2005, the year used as the reference year for cross-validation (see below).

Soft data from the LUR model was composed of an ozone estimate for each location as well as an associated error estimate. The error estimated for each modeled point (each center of the 1 km x 1 km grid cell) was the sum of squares of the standard errors from the fixed effects and the square of the standard deviation of the soft random intercept. For the ozone estimate itself (soft data), only the fixed portion of the LUR model was used to create a value, since the mean random effect was 0. There were a total of 278,633 possible grid points per day (~ 42 million spatio-temporal points were possible overall), with the ozone levels estimated using data from the closest meteorological station. Soft data were estimated only when all predictors were available. It was impossible for a large portion (~99%) of points to be estimated due to missing precipitation or temperature data at the closest monitor (mainly in the inhabited northern regions of our study area). However, this did not influence the cross-validation analysis because the analysis was limited to the location of the ozone monitors that had sufficient soft data.

We treated kriging as a special case of the BME in which we used only hard data (i.e. station days with ozone monitoring station data) without including soft data estimates from the LUR model, and thus refer to this model as BME kriging. Because of the spatiotemporal nature of the model used, kriging in this instance refers to a spatiotemporal interpolation of ozone, and not merely a spatial estimate. We implemented the BME-LUR and BME kriging analysis to estimate daily 8-hour average ozone levels at a 1 km^2 grid using Matlab software (2007) and the SEKS-GUI v. 0.69.5 program (Yu et al., 2007).

To account for short-term and small-scale patterns in the ozone data and to remove any spatio-temporal autocorrelative patterns, we used a Gaussian de-trending model (Yu et al., 2007) at a distance of 25 km and a temporal trend of 2 days. This detrending is used to facilitate the interpolation of the remaining stochastic structure of the data. Such detrending algorithms are common in spatial estimation techniques such as kriging. While several detrending methods do exist, the SEKS-GUI provides the Gaussian detrending algorithm as its only detrending option. From visual inspection of time series of ozone levels at monitoring stations, and of spatial distributions of daily ozone levels across all stations, Gaussian detrending appeared to be a sufficient function to remove spatiotemporal trends. The detrended data was then used as our stochastic spatiotemporal dataset for BME kriging and BME-LUR modeling.

Ozone soft and hard data was not normally distributed. We thus corrected soft and hard data using n-scores normalization prior to analysis, as a normal distribution is a necessary condition for accurate estimation by the BME (Yu et al., 2007). We constructed a spatiotemporal covariance model to describe the stochastic processes affecting ozone levels after localized de-trending. We used the resulting model for estimation of the ozone values, followed by de-normalization and re-trending of the estimated value.

Cross-validation

We performed cross-validation to test the predictive ability of the different models and to find the best predictive model. Cross-validation was performed using data from 2005 as a sample year. We did cross-validation for summer days at each monitoring station for which a LUR model estimate could be created (n= 3,986 station days points among 30 stations). In BME-kriging and BME-LUR, we removed all hard data up to one year prior to each cross-validation date at each monitoring station, for the cross-validation at that station. This was done to eliminate the effects of temporally near data. This approach allows for the assessment of the estimation accuracy in different space-time domains, while avoiding the potentially biased interpretation of the estimation results induced by purely temporal autocorrelation (Yu et al., 2009). To perform our cross-validation, we removed a given station day's hard data and estimated it using the remainder of the data (leave-one-out validation). The soft data used for the cross-validation did contain the information from all stations (i.e. the station was not removed during the construction of the LUR), since removing individual stations from the leave-one-out analysis would have had a marginal effect on the construction of the LUR model and subsequent soft data, as each station represents approximately 2% of the data (1/50 stations).

We compared estimation errors (estimated values minus observations) across methods for each station day versus the ozone values for that monitoring station at that time. We used root mean-square errors (RMSE) to estimate the total magnitude of error. We also defined a percent change in mean square error (PCMSE) as used in de Nazelle et al., (2010), where the results correspond to the percent increased or decreased estimation accuracy of the ozone concentration prediction based on the LUR or BME kriging models compared with corresponding predictions based on the BME-LUR. We assessed visually for unusual spatial or temporal patterns in the distributions of the average estimated errors (estimated versus observed data).

Lastly, we compared observed exceedances of the 8-hour Canadian Ambient Air Quality Standard (i.e., 65 ppb) identified using monitoring station data to exceedances identified using model estimates. To do so, we first transformed monitored and estimated ozone data variables into binary variables (0 = no exceedance, 1 = exceedance) and compared the estimated exceedances to the observed exceedances using Cohen’s kappa measure of agreement.

4. **Results**

Table 1 presents the description of the data used for the development of the LUR model for the years 1990–2009. Predictors and ozone data were available at 39 ozone monitoring stations on 2,441 days. Since information was not available concurrently at all stations and all days, we used 29 685 spatiotemporal points (station days) out of 118,560 possibilities (152 days × 20 years × 39 stations) to develop the model. These 29,685 points are spatiotemporal moments where we concurrently had information on ozone levels, temperature, and precipitation. Eight-hour ozone concentrations varied from 0 to 104 ppb, eight-hour temperatures varied from -3.5 to 33.9 ºC, daily precipitation varied from 0 to 123.8 mm/day, and road density from 0 to 25.4 km/πkm2. The range of latitude values was between 0 and 583.3 km.

The LUR model is found in Table 2. Considering the estimated effect size (see footnote of Table 2 for clarification on the calculation) of each variable, temperature, day of the year, and road density were the main predictors. In this model, coefficients for linear spline functions of temperature (≤18ºC and >18ºC) were positively associated with ozone concentrations while precipitation, day of the year, year, and coefficients for linear spline functions of low and high road density and of low latitude (<50km) were negatively associated with ozone levels. Overall, all predictors had a significant association, except the coefficient of the linear spline function for high latitude. To better visualize the fixed effects, LOESS plots of bivariate relationships of these predictor variables are presented in the Supplemental Material, Figure S1. Every coefficient of the LUR model was in agreement with the LOESS plots, and with known processes of the formation and the destruction of ozone, except for cold temperature.

Based on the LOESS plot, we expected temperatures between -3.5 and 18°C to have no relation with ozone, or the relation to be slightly negative, while in the LUR model, after controlling for latitude, year and day of the year, the relation between ozone and the lowest temperatures was slightly positive.

Table 3 describes hard and soft data used to build BME-LUR and BME kriging models. Hard data were observations at monitoring sites for 1990–2009 (n=103,669 out of 156,060 station days with ozone data), while predicted soft data estimates were derived from the fixed effect portion of the LUR model and errors estimated from the fixed and random effects of the same model for the year 2005 only (152 days). Therefore, we could estimate 90,847 spatiotemporal points from the LUR model, considering the availability of temperature and precipitation information concurrently, out of around 42 million maximum possible spatiotemporal points (152 days × 278,633 possible grids points per day in our study area). For BME kriging and BME-LUR, we used the same de-trending and covariance structures to describe the spatiotemporal covariance pattern in the data. The covariance model used to fit the measured spatiotemporal covariance of the data consisted of two components: a short-term (2-day exponential) long-distance (100-km exponential) trend that described the majority of the variability (covariance = 0.9), and a second component (covariance = 0.1) describing the weekly (3-day cosinusoidal) trend in covariance in time with a small spatial (i.e. local 12.5 km exponential) scale due to the cyclic nature of ozone in urban stations in Quebec, where ozone tends to be lower on the weekends and rises during week days. Modeled covariances as derived from the information above are presented in the Supplemental Material, Figure S2.

Table 4 describes the cross-validation results for the three models, for the year 2005 at the 30 stations available to produce the soft data with all mixed model predictors (n = 3,980). For the BME-LUR, on June 25th, estimates at 6 stations, all located in the southeastern portion of the study area could not be estimated with the BME-LUR. On that day, all measurements at these stations were high (hard data) (75-78 ppb) when compared to the range of values of the calculated soft data (28-48 ± 6.6 ppb) for that day. Overall, the BME-LUR was the most predictive model (R^2= 0.653), and had the lowest RMSE (7.06 ppb). The LUR model performed better and with greater precision (R^2= 0.466, RMSE= 8.747) than the BME kriging model (R^2= 0.414, RMSE= 9.164). The BME-LUR outperformed the LUR model and BME kriging by 19.9% and 23.0% using PCMSE, respectively. Finally, the Cohen's kappa of the BME-LUR (n: 18 predicted exceedances; kappa=0.525, 95%CI: 0.495-0.555) obtained from the comparison of 8-hour Canadian Ambient Air Quality Standard (65 ppb) monitored (n: 34 observed exceedances) and estimated concentrations suggests moderately good agreement between the model and the measurements. The BME-LUR outperformed both BME-kriging (n: 39 predicted exceedances; kappa=0.169, 95%CI: 0.138-0.200) and the LUR model (kappa=0 as no predicted value above 65ppb).

A graph of the distribution of errors in the ozone concentration estimates generated by each model (i.e., the difference between estimated and observed values) based on the leave-one-out analysis also demonstrated that the BME-LUR was the more accurate model (Figure 2). As can be observed in Figures 3, the RMSE of the three models appears stochastic in time. Figure 4 also shows that the RMSE of the BME-LUR in space (at all stations) was closest to zero in comparison to BME-kriging and the LUR. Figure 5 represents a map of predicted mean daily ozone levels (9h00-17h00) and standard errors (SE) at one km grid across the greater Montreal region for the summers 2006–2009. Levels of ozone are higher around the suburbs of Montreal compared to downtown metropolitan areas and concentrations are also greater in places far from highways (Figure 5a). Moreover, greater difference between observed and estimated ozone concentrations may be found in the northeast of the greater Montreal (Figure 5b).

5. Discussion

Overall, our findings suggest that error of estimation in the interpolation of ozone concentrations using the BME method may be improved with the inclusion of a LUR model developed with readily available database.

We found that the estimation of ozone across monitoring sites was more accurate with the BME-LUR model compared with other models; this difference was close to 20% in R^2 and around 2 ppb in RMSE. These results are consistent with previous work. For instance, Yu et al., (2009), which modeled air pollutant concentrations in North and South Carolina (USA), found that the integration of soft information by the BME method effectively increased the estimation accuracy for ozone predictions compared with estimates derived using BME kriging. Yu et al., (2009) used measurements from monitoring stations as soft data, whereas we created soft data from outputs of a LUR model. In Yu et al., (2009), the R^2 and RMSE values were not reported, but the mean and standard deviation of their estimation errors for daily estimates were similar to ours (Yu: kriging= 0.483 ± 7.035 and BME= 0.177 ± 6.845 ppm; present study: kriging= 0.414 $\pm$ 9.164 and BME-LUR= 0.653 $\pm$ 7.057). de Nazelle et al., (2010) also found better predictive accuracy for the representation of space-time ozone distribution in North Carolina with a BME model based on observed (hard) and modeled (soft) data from a stochastic analysis of an urban-intercontinental-scale atmospheric chemistry transport model, compared with kriging method estimates based on hard data only. We found that, similar to de Nazelle et al., (2010), ozone estimates further away from monitoring stations were more accurate when soft data was used in the BME versus kriging alone. As in our work, their PCMSE values were always negative (between -1.486 and -27.699 depending on the cross-validation radii of exclusion points), indicating that the integration of observed and modeled prediction was consistently more accurate than relying solely on observations. Furthermore, agreement between modeled and observed Canadian Ambient Air Quality Standard exceedances was highest for estimates based on the BME-LUR.

We found that error estimates from the BME-LUR model were more accurate where monitoring stations were clustered in the region of the study, such as in the southern (i.e. more urban) part of Quebec (Figure 4). This result is consistent with Yu et al. (2009), which indicated that the locations where the estimates exhibit higher discrepancies from the data values were mostly close to regions of data scarcity.

We showed that the LUR model was slightly more accurate (lower RMSE) than the BME kriging model (Table 4). Coefficients of the LUR model indicated that linear spline functions of temperature were positively associated with ozone concentrations, while precipitation, day of the year, year, and coefficients for linear spline functions of low and high road density and of low latitude were negatively associated with ozone levels (Table 2). The LUR model coefficients for the spline temperature variable are in line with the expected trend (EPA, 2006) and suggest an increase of ozone with temperature, which is more pronounced at higher temperatures. With regards to road density, both coefficients for linear spline functions of low and high density were negative, and this may be explained by the fact that at regional scale, low traffic represents lower concentrations of ozone precursors (traffic related pollutant such as NOx), while at the local scale, low traffic represents lower destruction of ozone. The other fixed effects of the LUR model are also in agreement with the known atmospheric processes of ozone and highlight that its formation rely on various factors such as sunlight. Ozone concentrations are also greater with altitude and show diurnal and weekly variations with higher levels during weekdays (EPA, 2006; Finlayson-Pitts and Pitts, 1997). Lastly, the negative coefficient found for day of the year variable highlight the small intra-annual decrease in ozone levels from May to September in Quebec.

Nevertheless, the fact that the LUR model was slightly more accurate than BME kriging is inconsistent with what was found by Beelen et al., (2009) who developed maps of ozone levels across the European Union using a regression model with altitude, distance to sea, major roads, high-density residential areas and a combination of meteorological data as predictors. They obtained values of R^2= 0.54/0.38 and RMSE= 8.63/8.74 ppb respectively for the regression and kriging models at rural scale. At urban locations, kriging was more accurate than the regression model with only the high-density residential predictor (regression/kriging: R^2= 0.38/0.61 and RMSE= 7.32/5.84). Kriging methods predict well when a dense and representative monitoring network is available (Briggs, 2006; Jerrett et al., 2005; Laslett, 1994). In our study, BME-LUR was more accurate in estimating ozone levels than LUR and BME kriging at urban and suburban scales (i.e., island of Montreal and its surrounding area), and LUR was more accurate than BME kriging in urban areas only (Figure 4). In Quebec, the monitoring station network is relatively sparse and the good correlations between the predictors used in the LUR model and the measured ozone concentrations at monitoring stations may at least partially explain the relatively weak performance of BME kriging.

We created maps representing mean ozone levels (9h-17h) and standard error predictions from the BME-LUR at one km grid for summers 2006-2009 to visualize how the model would estimate ozone in urban and suburban areas of the greater Montreal region. As observed in Figure 5, levels of ozone are higher around Montreal Island (suburban areas) compared to downtown metropolitan (center of Island) areas and concentrations are also greater in areas far from highways. This may be explained by the fact that the efficiency of ozone production depends on NOx concentrations. In areas with low NOx concentrations (e.g. in rural areas), ozone production increases with higher levels of NOx. In downtown metropolitan areas where the highest NOx concentrations may be found, there is net destruction of ozone by reaction with NO (EPA, 2006). Also, we found greater difference between observed and estimated ozone concentrations in the northeast of the greater Montreal as indicated by figure 5b, and this may be explained by the possible incongruity between soft and hard data points, hard data points themselves, or by a possible lack of ozone stations outside the Montreal area.

As mentioned previously, 6 stations could not be computed with the BME-LUR on June 25th. In-depth analysis reveals that all these stations had high monitored values (hard data) when compared to the range of values of the calculated soft data for that day. To our knowledge, this issue has not been reported elsewhere in the literature and investigations of BME estimation failure should be realized in future studies.

The developed BME-LUR model presents other limitations. For instance, the meteorological variables (temperature and precipitation) used to estimate soft data do not represent the complete atmospheric processes of ozone. This would have been more correctly assessed with the use of some integrated meteorology models like the Community Multiscale Air Quality (CMAQ) modeling system. However, such models do not capture small area estimations such as our LUR model predictions (USEPA, 2012). Another limitation is that the LUR model predictions were only estimated for each one km grid of the territory due to computational constraints, as adding soft data at 100m resolution would have dramatically increase the amount of time needed to run the BME-LUR. Computational time required to create maps is another limitation. In this study, 90 days were needed to create maps of ozone levels for an area of 103,110 km^2 at a resolution of 1km while running multiple processors on a high-powered computer (2.93 GHz 4-core processor and eight concurrent threads with 6gb RAM). This computational time can be improved by reducing the resolution of the study area or the number of soft data points, as well as by estimating only points of interest (e.g. residential addresses of interest vs 1km grid).

Despite the computational demands, the BME-LUR adds value to the ozone exposure estimation because it generates the complete probability distribution of exposure at each point in space and time (Yu et al., 2007) and it reduces the estimation errors. This may lead to less biased effect measures and greater statistical power in health studies (Baker and Nieuwenhuijsen 2008; Briggs 2005; Goldman et al., 2012).

For implementation in future health studies, the BME-LUR might be improved by including additional predictors in the LUR model, such as population density, land use, topography, and industrial sources of precursors (Hoek et al., 2008). As noted by Beelen et al., (2009), stratification of the study area (e.g. separating urban and rural areas) could also improve model predictions.

6. Conclusions

We aimed at comparing the ability of three spatiotemporal models to predict ground-level ozone in Quebec (Canada) to improve ozone health risks assessment. The BME-LUR model appeared to be the best model for exposure prediction. This work illustrated the accuracy of the BME-LUR models to predict air pollutants such as ozone across space and time over LUR and BME kriging methods and that error of estimation in the interpolation of ozone concentrations can be greatly reduced using outputs from a LUR model that can be developed with readily available data.

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The authors also appreciated the advice of Alexander Kolovos for his assistance in the usage and modification of the SEKS-GUI BME program.

9. Tables and figures

Table 1. Descriptive statistics of variables used for the development of the LUR model for years 1990-2009.

Variables	Number of spatiotemporal points[a]	Mean ± SD	Min	Max
8h ozone concentration (ppb)	29,685	31.2 ± 13.1	0.0	104.0
8h temperature (ºC)	29,685	19.1± 5.3	-3.5	33.9
Precipitation (mm/day)	29,685	3.0 ± 7.1	0.0	123.8
Road density (km/πkm^2)	39	6.4 ± 7.9	0.0	25.4
Rescaled latitude (km)	39	114.6 ± 134.6	0	583.3

Abbreviations: SD: standard deviation; Min: Minimum; Max: Maximum.

[a] 29,685 station days out of 118,560 possible station days (limited by temperature and precipitation variables) were used for the development of the LUR model.

Table 2. Summary of the LUR model for ozone concentrations in the region of study (1990-2009)[a].

Fixed effects	Coefficients	SE	Effect size[c]
Constant	39.530	1.577	-
Temperature ≤18ºC[b]	0.218	0.021	39.461
Temperature >18ºC[b]	2.139	0.019	-
Precipitation	-0.010	0.001	-1.238
Day of the year	-0.107	0.001	16.371
Year	-0.165	0.018	3.315
Road Density ≤15km/ πkm^{2}[b]	-0.255	0.098	-14.995
Road Density >15km/ πkm^{2}[b]	-1.074	0.219	-
Latitude ≤ 50km[b]	-0.123	0.038	1.687
Latitude >50km[b]	0.003	0.003	-

Abbreviations: SE: Standard error.

[a] For the random effect, the standard deviation of intercept is 2.464 (95%CI: 1.915-3.170); the standard deviation of residuals of mixed model is 8.904.

[b] Variables modeled as linear spline functions to account for nonlinear relations with ozone.

[c] The effect size was calculated by $\beta_i V_{iMax} - \beta_i V_{iMin}$ for non-splined variables, and by $\beta_{iLower} V_{iSpline} - \beta_{iLower} V_{iMin} + \beta_{iUpper}(V_{iMax} - V_{iSpline})$ where $V_{iSpline}$ is the value of the knot of the variable of interest, β_{iLower} the coefficient for values lower than the knot value, and β_{iUpper} the coefficient for values greater than the knot value.

Table 3: Statistics for measured (hard) ozone data (1990–2009) and predicted and error “soft” data from the LUR (year 2005) used for BME-LUR and BME kriging models.

Variables	Number of spatiotemporal points	Mean ± SD (ppb)	Min (ppb)	Max (ppb)
Hard data (n=51)	103,669[a]	30.6 ± 12.5	0.0	110
Soft data at a 1 km grid (predicted)	90,847[b]	46.3 ± 9.3	12.1	76.4
Soft data (error)	90,847[b]	6.9 ± 1.8	5.5	63.9

Abbreviations: SD: standard deviation; Min: Minimum; Max: Maximum.

[a] 103,669 out of 156,060 station days with ozone data (limited by ozone data availability only) were used as hard data for BME-LUR and BME kriging models.

[b] 90,847 spatiotemporal points with data for temperature and precipitation were estimated as soft data for 2005 out of approximately 42 million maximum possible spatiotemporal points (152 days × 278,633 possible grid points per day in our study area).

Table 4: LUR, BME kriging, and BME-LUR models leave-one-station-out cross-validation results for year 2005, n=30 ozone monitoring stations (estimated points: 3,980).

Methods	**R^2**	**RMSE (ppb)**	**PCMSE**
LUR	0.466	8.747	-19.9%
BME kriging	0.414	9.164	-23.0%
BME-LUR	0.653	7.057	-

Abbreviations: RMSE: Root mean-square errors; PCMSE: percent change in mean square error

Figure 1.

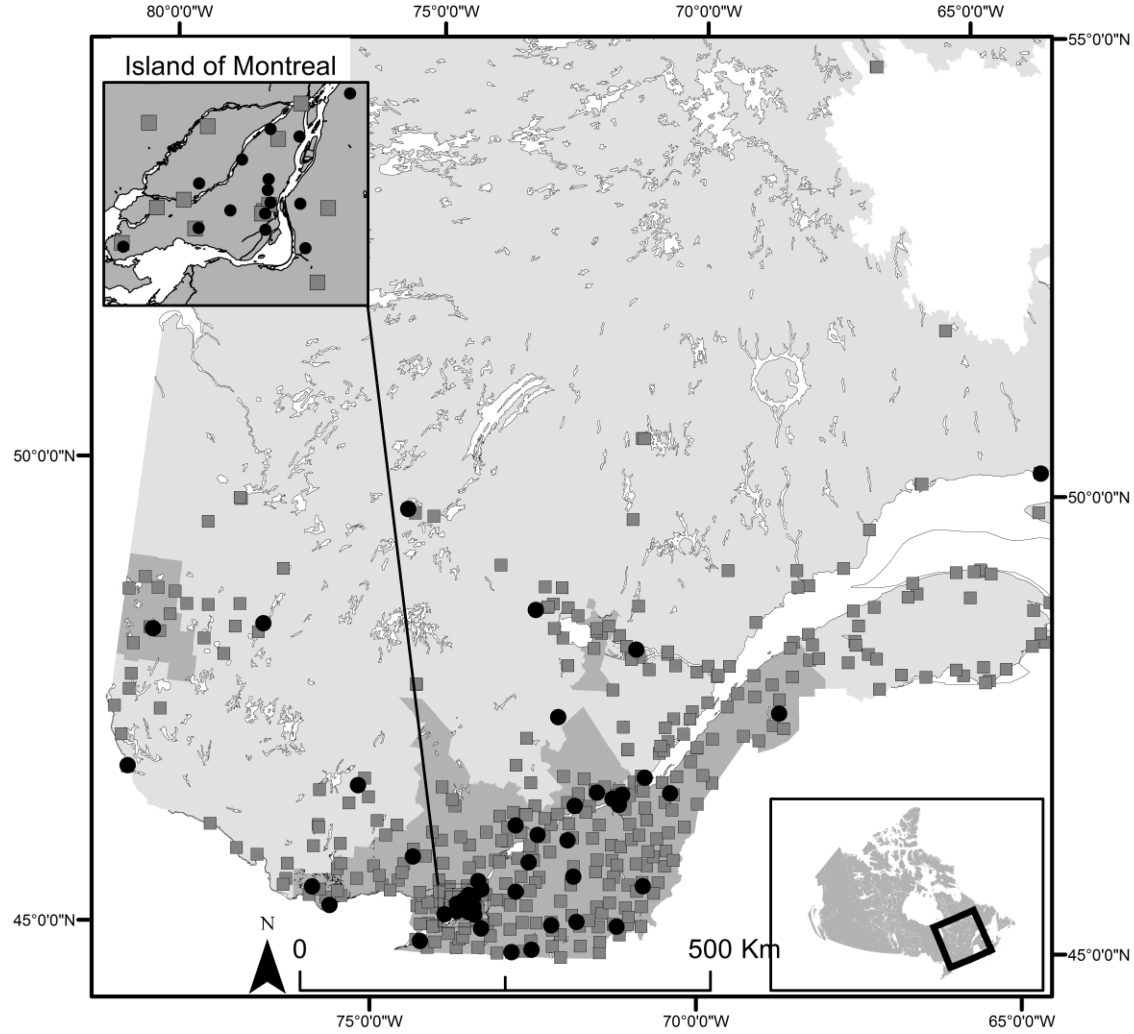


Figure 1. Geographical location of ozone monitoring (black circles) and meteorological stations (grey squares) in the study region (dark grey). Locations are for monitor used at any time during the study period.

Figure 2.

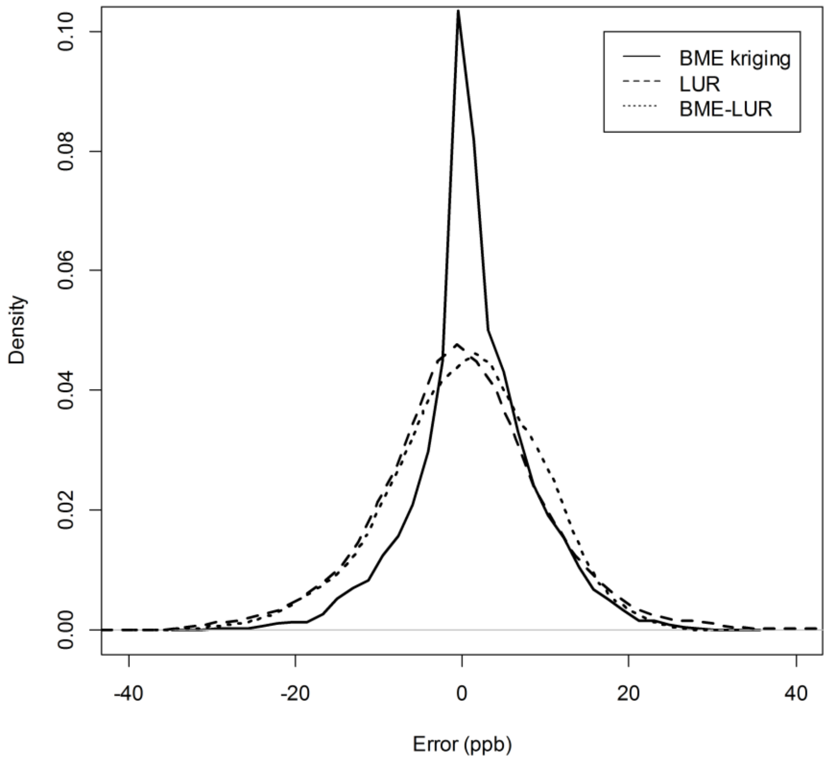


Figure 2. Ozone mapping error estimates from the leave-one-station-out cross-validation [where error = estimated – measured (observed) ozone concentration (in ppb) at each monitoring station] based on the LUR (long dashes, mean ± standard deviation = 0.282 ± 8.93 ppb), BME kriging (short dashes, 0.130 ± 9.804 ppb), and BME-LUR (solid line, 1.339 ± 7.086 ppb) models for the year 2005.

Figure 3.

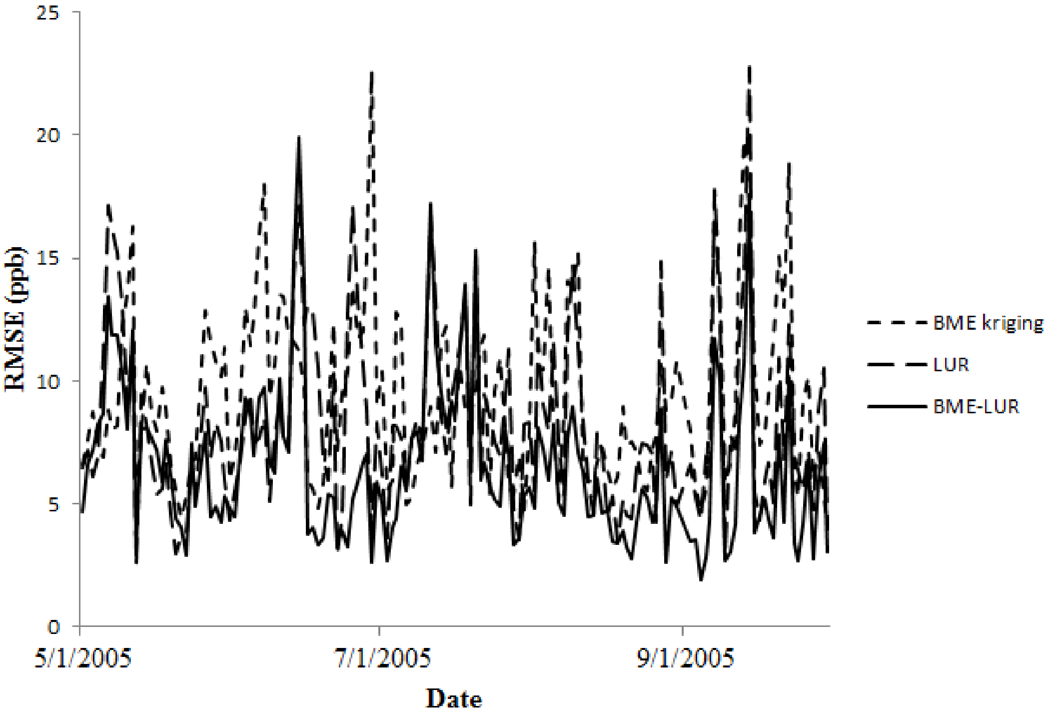


Figure 3. Mean temporal ozone error estimates (RMSE) based on the leave-one-station-out cross-validation for LUR (long dashes), BME kriging (short dashes), and BME-LUR (solid line) models for the year 2005.

Figure 4.

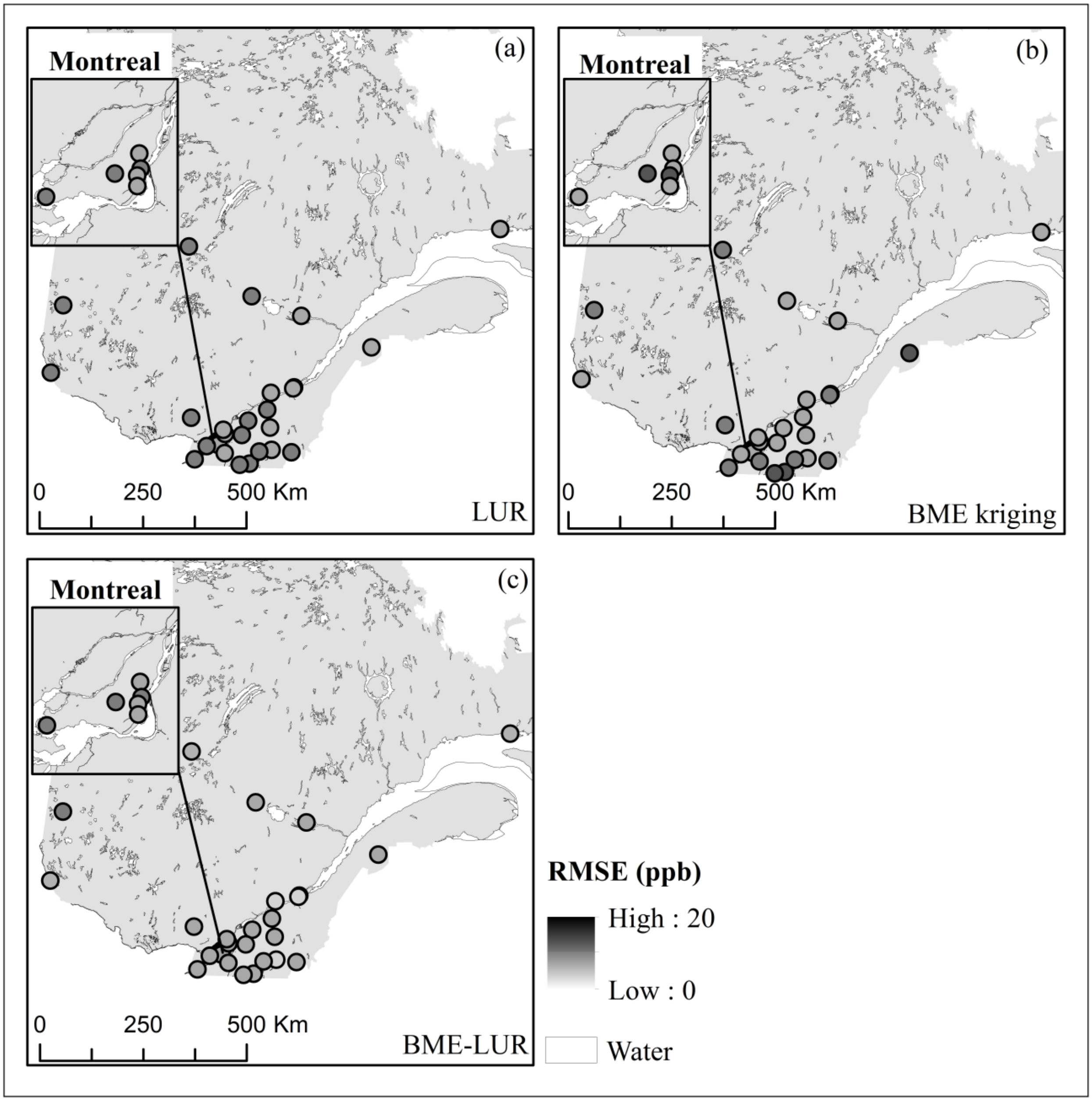
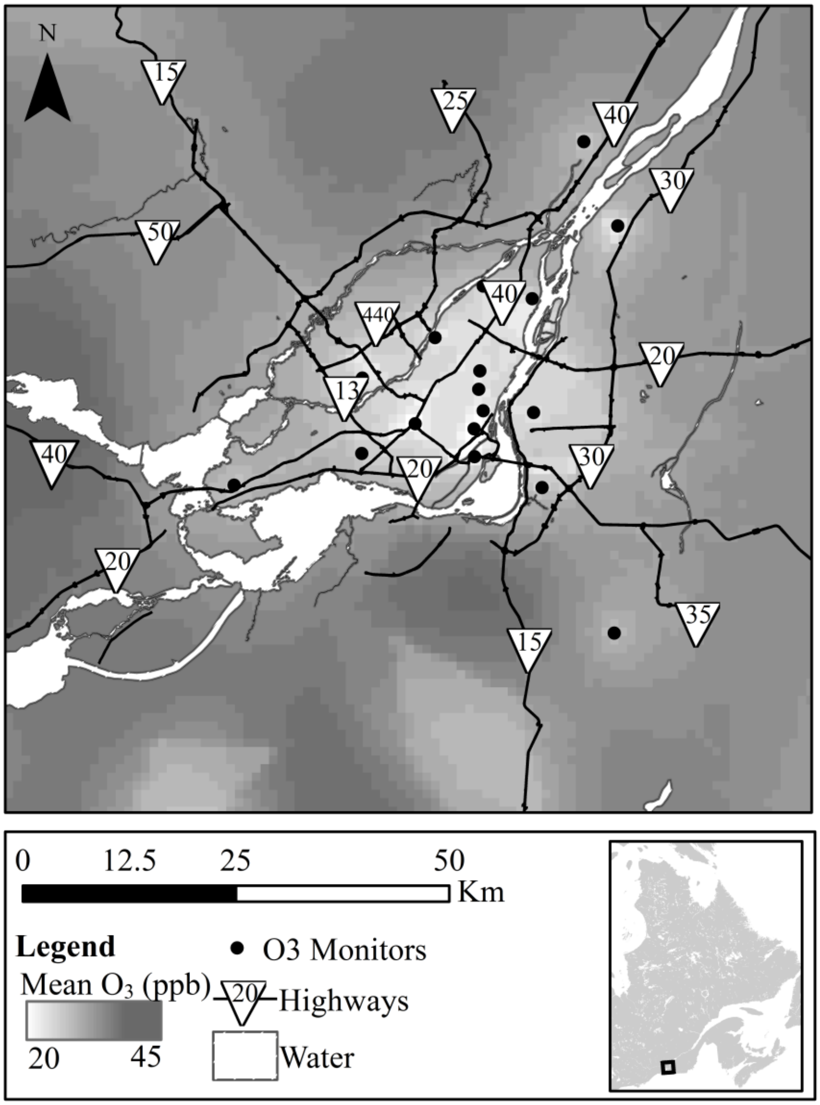


Figure 4. Spatial distribution of mean ozone error estimates (RMSE) in the study area (year 2005) based on the leave-one-station-out cross-validation for LUR, BME kriging, and BME-LUR models.

Figure 5a.


N
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Km
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O3 Monitors
Mean O$_3$ (ppb)
20
Highways
20
45
Water

Figure 5b.

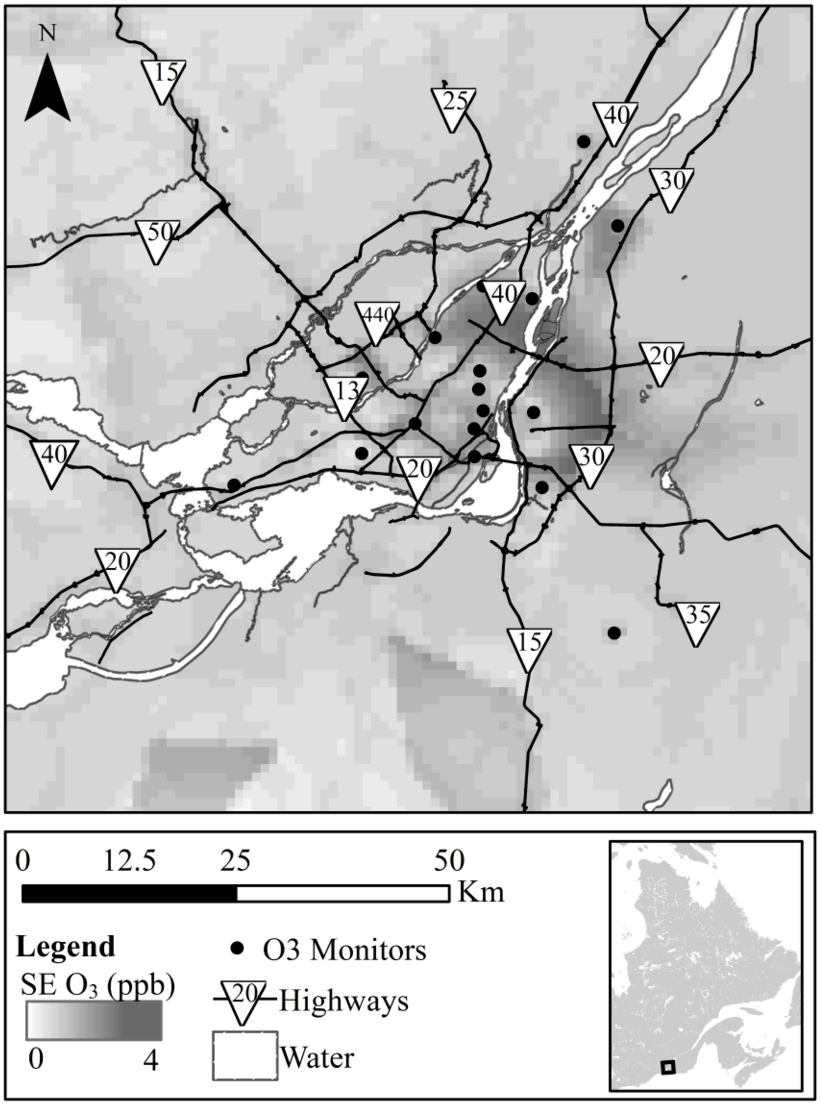
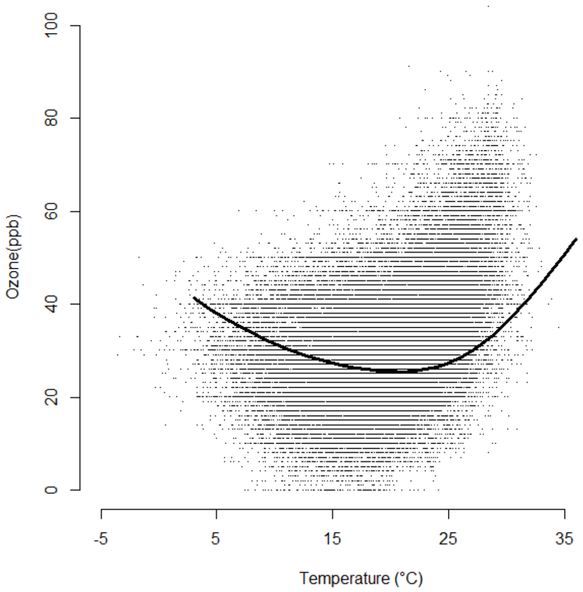


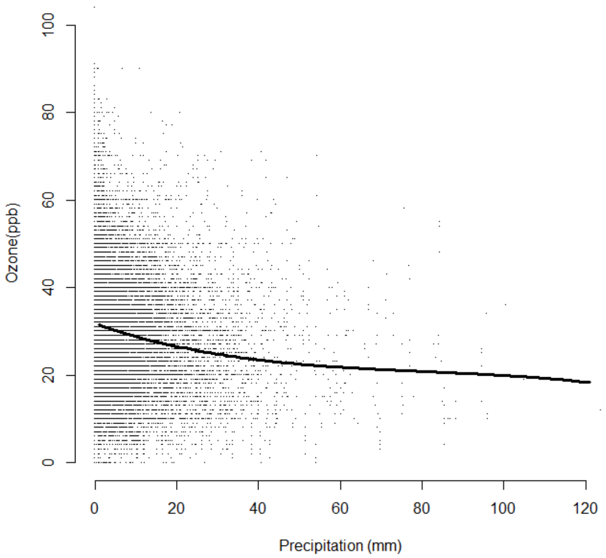
Figure 5. Mean ozone levels (9h00-17h00) (a) and standard errors (SE) (b) predicted from the BME-LUR at one km grid across the greater Montreal region in Quebec (Canada) for the summers 2006-2009.

10. Supplemental material

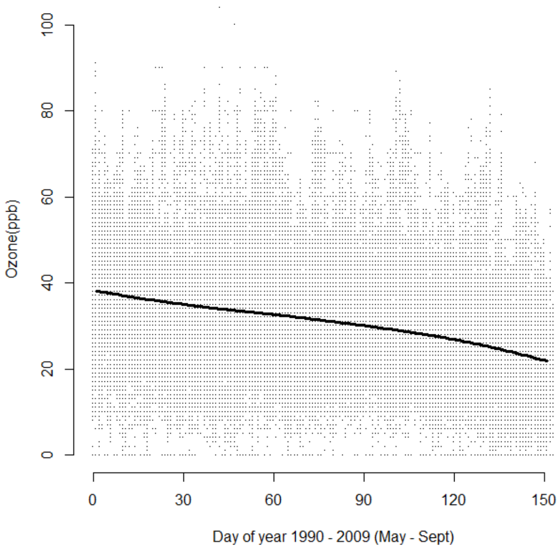
Temperature VS Ozone



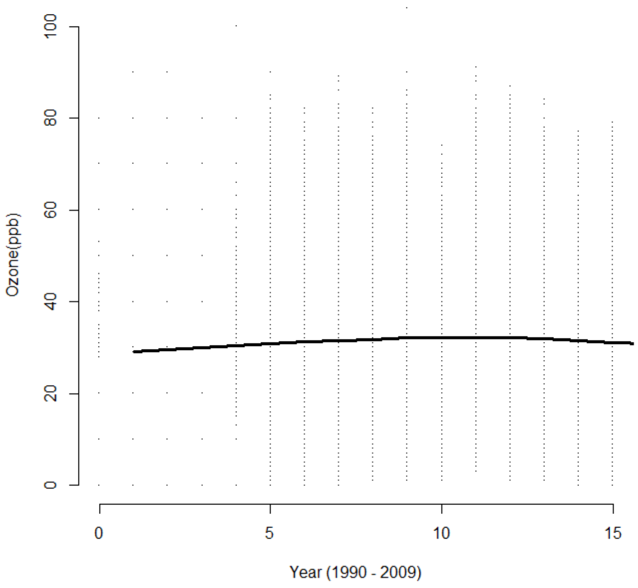
Precipitation VS Ozone


Ozone(ppb)
0
20
40
60
80
100
Precipitation (mm)
0
20
40
60
80
100
120

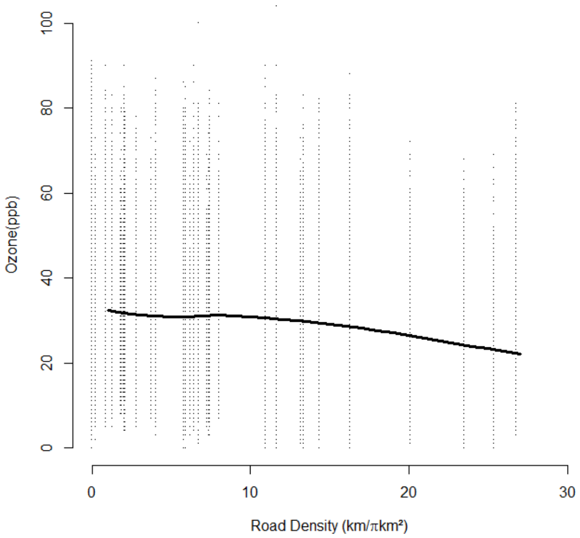
Day of year VS Ozone



Year VS Ozone



Road density VS Ozone



Latitude VS Ozone

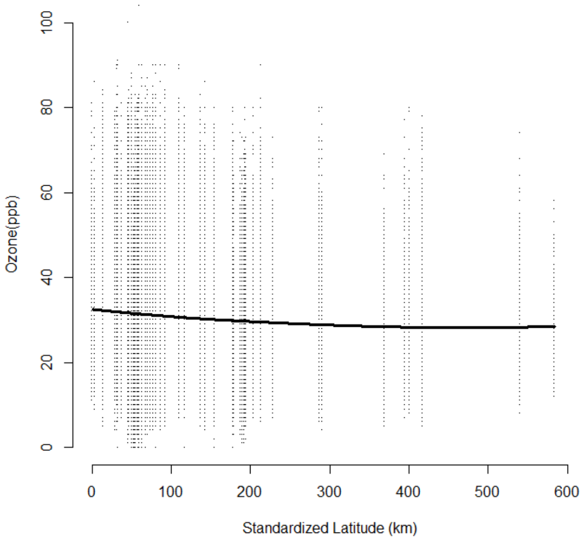


Figure S1: LOESS plots for each bivariate relations between predictors variables of the LUR model and ozone levels.

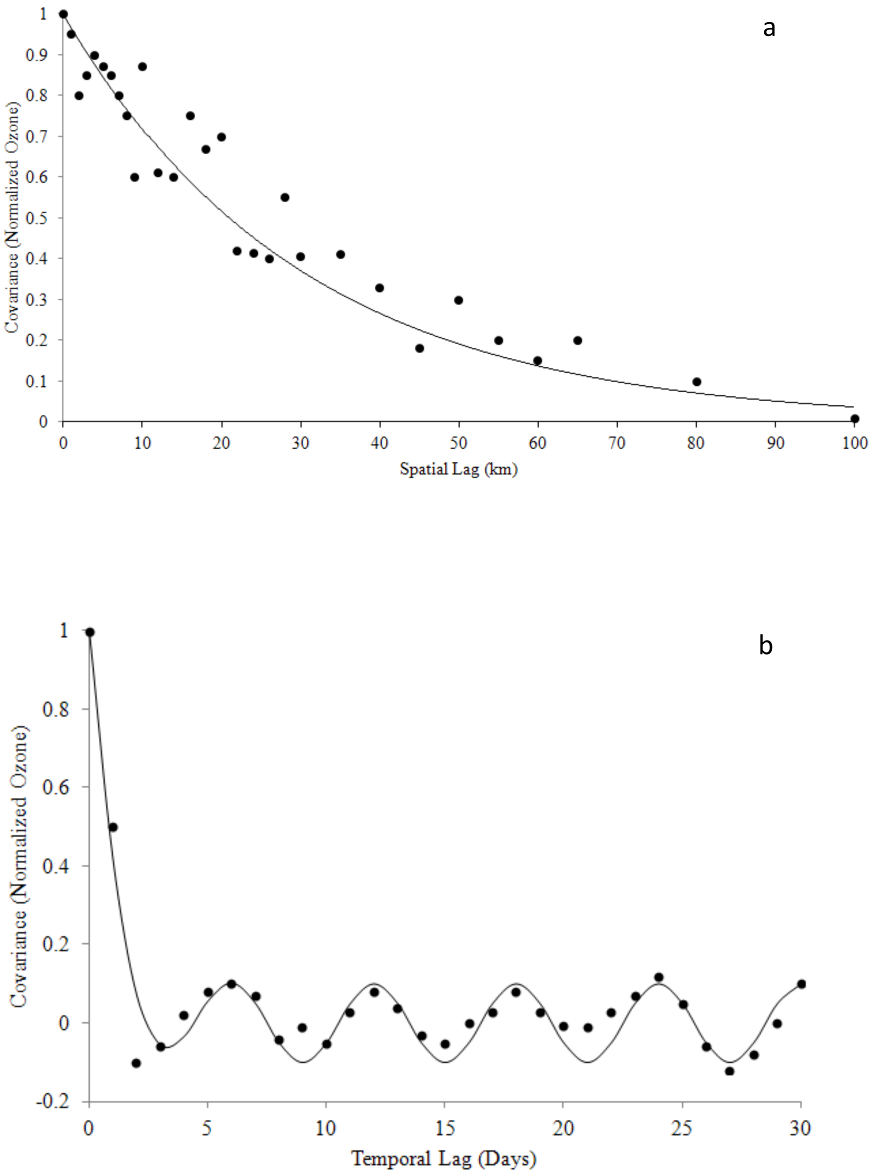


Figure S2. Spatial (a; at temporal lag = 0 days) and temporal (b; at spatial lag = 0 km) covariance plots of de-trended normalized ozone data from the BME kriging model used by the BME kriging and BME-LUR models.

ANNEXE 2- Autres contributions en lien avec les travaux de cette thèse

Rapports de recherche ou rapports produits pour le gouvernement

2014 Adam-Poupart A, Smargiassi A, Busque M-A, Fournier M, Duguay P, Fournier M, Zayed J, et Labrèche F. Associations entre la température estivale, les concentrations d'ozone et les indemnisations professionnelles au Québec. Institut de recherche Robert-Sauvé en santé et en sécurité du travail IRSST. (En révision).

2013 Adam-Poupart, Brand A, Fournier M, Smargiassi A. Estimation de l'exposition environnementale à l'ozone troposphérique : un exemple de modélisation pour la population québécoise. Institut national de santé publique du Québec. INSPQ. N° de publication : 1680. ISBN : 978-2-550-68444-2

2013 Adam-Poupart A, Labrèche F, Smargiassi A, Duguay P, Busque M-A, Gagné C, Rintamaki H, Kjellstrom T, Zayed J. Climate Change and Occupational Health and Safety in a temperate climate: Potential impacts and Research priorities in Quebec, Canada. GOHNET Newsletter Number 20 - WHO.

2013 Adam-Poupart A, Labrèche F, Smargiassi A, Duguay P, Busque M-A, Gagné C, Zayed J. Impacts of Climate Change on Occupational Health ans Safety. Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST). Rapport-775.

2012 Adam-Poupart A, Labrèche F, Smargiassi A, Duguay P, Busque M-A, Gagné C, Zayed J. Impacts des changements climatiques sur la santé et la sécurité des travailleurs. Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST). Rapport-733.

Exposés lors de congrès, symposiums, conférences

2014 Adam-Poupart A, Labrèche F, Zayed J, Busque M-A, Fournier M, Duguay P Smargiassi A. The associations between work-related injuries and summer outdoor temperatures in Québec, Canada. XXe Congrès Mondial sur la Sécurité et la Santé au travail. Août 2014. Frankfurt, Allemagne.

2014 Labrèche F, Adam-Poupart A, Busque M-A, Duguay P, Fournier M, Zayed J, Smargiassi A. The usefulness of compensation statistics to detect heat-related health outcomes in a temperate climate: the experience of Quebec. 24th International Conference on Epidemiology in Occupational Health. Juin 2014. Chicago, Illinois.

2013 Adam-Poupart A, Smargiassi A, Zayed J, Busque M-A, Duguay P, Fournier M, Labrèche F. Relationships between summer outdoor temperatures and occupational compensation statistics- Preliminary results in Quebec (Canada). 23rd International Conference on Epidemiology in Occupational Health. Juin 2013. Utrecht, Pays-Bas.

2013 Brand A, Adam-Poupart A, Fournier M, Benmarhnia T et Smargiassi A. Associations between neighbourhoods deprivation and ambient ozone levels in Montréal (Canada). Environmental Health Conference. Mars 2013. Boston. États-Unis.

2012 Labrèche F, Smargiassi A, Adam-Poupart A, Duguay P, Busque M-A, Zayed J. Issues related to climate change impacts in the workplace. 30th Congress of the International Commission on Occupational Health (ICOH). Mars 2012, Cancun, Mexique.

2012 Adam-Poupart A, Labrèche F, Smargiassi A , Duguay P, Busque M-A, Zayed J. Research Priorities for the Assessment of the Impacts of Climate Change on Occupational Health and Safety in Quebec, Canada. VIIe Colloque annuel des étudiants en santé publique de l'Université de Montréal. Février 2012, Montréal, Canada.

2011 Adam-Poupart A, Smargiassi A, Labrèche F, Duguay P, Busque M-A, Zayed J. Évaluation des impacts potentiels des changements climatiques sur la santé et la sécurité (SST) des travailleurs du Québec. 79e Congrès de l'ACFAS. Mai 2011, Sherbrooke, Canada.

2011 Adam-Poupart A, Smargiassi A, Labrèche F, Duguay P, Busque M-A, Zayed J. Impacts of Climate Change on Occupational Health and Safety: Assessment for a country with a continental climate. The XIX World Congress on Safety and Health at Work. Septembre 2011, Istanbul, Turquie.