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Vulnérabilité à la chaleur dans le contexte des changements climatiques

par

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Résumé

Les changements climatiques constituent un enjeu important en santé publique. En effet, une hausse des températures provoquera une hausse de la mortalité attribuable à la chaleur. En outre, certaines populations et territoires sont particulièrement vulnérables aux effets de la chaleur. Il est donc nécessaire de les identifier clairement ainsi que les impacts futurs pour orienter avec équité les politiques publiques aujourd’hui et à l’avenir. L’objectif de cette thèse est de documenter les facteurs de vulnérabilité à la chaleur dans le présent et les éléments permettant leur prise en compte pour l’avenir dans le contexte des changements climatiques. Quatre étapes ont été menées pour répondre à cet objectif : a) Mener une revue systématique et une méta-analyse des facteurs de vulnérabilité face aux risques de mortalité en lien avec la chaleur ; b) Analyser si l’exposition chronique à la pollution atmosphérique modifie la relation entre la chaleur et la mortalité dans un contexte urbain (Paris) et explorer la double interaction avec la défaveur sociale ; c) Développer une méthode de quantification des impacts liés à la chaleur en lien avec les changements climatiques en intégrant une grande diversité de simulations climatiques ; d) Estimer les inégalités d’années de vies perdues attribuables à la chaleur et leurs projections futures dans deux contextes distincts (Montréal et Paris) et comparer ces inégalités. Cette thèse a permis de mettre en évidence sur la base de la littérature épidémiologique les groupes de population qui sont les plus vulnérables face aux effets de la chaleur et de montrer qu’il y a plusieurs divergences par rapport aux recommandations émises par les institutions de santé publique vis-à-vis de l’identification de populations vulnérables. Cette thèse a permis également d’identifier l’exposition chronique à la pollution atmosphérique comme nouveau facteur de vulnérabilité à la chaleur et que cette vulnérabilité était encore plus prononcée lorsqu’il s’agissait de populations défavorisées socialement. Puis, une méthode permettant de quantifier l'impact des changements climatiques sur les décès attribuables à la chaleur et ses sources d'incertitudes a été développée, et a permis de mettre en évidence que la probabilité que les changements climatiques conduisent à une augmentation de la mortalité en lien avec la chaleur est très forte. Cette méthode a ensuite été utilisée pour estimer que l'augmentation de la température conduira à une augmentation des inégalités sociales d'années de vie perdues à la fois à Montréal et à Paris, l'effet des changements climatiques sur l'accroissement de ces inégalités étant plus fort à Montréal qu'à Paris. Cette thèse, en se basant sur diverses méthodes épidémiologiques, a permis dans l'ensemble de clarifier quelles populations étaient particulièrement à risque face aux effets de la chaleur et de questionner les recommandations émises par les organismes tels que l'OMS. Elle a également permis de montrer l'effet des changements climatiques sur l'évolution de vulnérabilités face à la chaleur pour inciter dès aujourd'hui la mise en place de politiques publiques équitables et limiter l'impact des changements climatiques sur l'accroissement des inégalités de santé.

Mots-clés : Changements climatiques, Température ambiante, Vagues de chaleur, Vulnérabilité, Modification d'effet, Hétérogénéité, Analyses de séries temporelles, Inégalités sociales de santé, Meta-analyses, Modélisation climatique, Pollution de l'air.

Abstract

Climate change is an important public health threat. An increase in temperatures will lead to an increase in mortality attributable to temperature. In addition, some populations and territories are particularly vulnerable to the impact of increases in heat. It is thus necessary to identify these populations and territories as well as examine future heat-related health impacts in order to recommend equity-oriented policies today and in the future. The general objective of this thesis is to document current and future heat-related vulnerability factors in the context of climate change. In order to address this general objective, the thesis involved four components: a) to conduct a systematic review and a meta-analysis to assess the heterogeneity in the heat-mortality associations with respect to individual and contextual population characteristics; b) to identify whether and how the magnitude of mean temperature effects on all-cause mortality were modified by chronic air pollution exposure, social deprivation, and a combination of these two dimensions; c) to develop a method to quantify the climate change impacts on heat-related mortality using climate modeling; d) to assess historical and future social disparities in years of life lost caused by ambient temperature in Montreal and Paris, and compare these estimates as well as the impact of climate change on social disparities between the two cities. This thesis highlights which populations are more vulnerable to heat and shows that several differences exist with regard to guidelines from international public health institutions for the identification of vulnerable populations. This thesis also identified chronic air pollution exposure as a new vulnerability factor in heat-related mortality and that it has a double interaction with social deprivation. Furthermore, in this thesis a novel method to quantify future heat-related mortality was developed which emphasized the strong evidence of an increase in heat-related mortality under climate change. This method was then applied to estimate the increase in daily years of life lost social disparities in both

Montreal and Paris under climate change which showed that this increase would be greater in Montreal compared to Paris in the future. Thus, this thesis which used a variety of epidemiologic methods has clarified which populations are particularly vulnerable to heat impacts and challenges guidelines for the identification of vulnerable populations from international public health institutions. It has also highlighted the climate change impacts on health inequalities and aims to reorient equity-focused policies.

Key words: Climate Change, Ambient temperature, Heat waves, Vulnerability, Effect modification, Heterogeneity, Time-series analyses, Social health inequalities, Meta-analyses, Climate modeling, Air pollution.

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Liste des sigles et abréviations

En français

ADN : Acide Désoxyribonucléique

AASQA : Association Agréée de Surveillance de la Qualité de l'Air

CepiDc : Centre d'épidémiologie sur les causes médicales de décès

CERES : Comité d'Éthique de la Recherche En Santé

CESP : Comité d'Ethique de la Santé Publique du Québec

CNIL : Commission Nationale Informatique et Liberté

EC : Environnement Canada

GIEC : Groupe d'experts Intergouvernemental sur l'Evolution du Climat

INSEE : Institut National de la Statistique et des Etudes Economiques

INSERM : Institut National de la Santé Et de la Recherche Médicale

IRIS : Ilots Regroupés pour l'Information Statistique

MCG : Modèles Climatiques Globaux

MCR : Modèles Climatiques Régionaux

NO_2 : Dioxyde d'Azote

O_3 : Ozone troposphérique

OMS : Organisation Mondiale de la Santé

SASC : Systèmes d'Alerte de Santé en cas de Chaleur

En anglais

AC: Air Conditioning

AF: Attributable Fraction

AN: Attributable Number

ANCOVA: Analysis of Covariance

CI : Confidence Interval

CMIP: Coupled Model Intercomparison Project

CRCM: Canadian Regional Climate Model

DAGs: Directed Acyclic Graphs

DYLLD: Daily Years of Life Lost Disparities

DT: Daily Translation

ES: Effect Size

GCM: Global Climate Model

GHG: Greenhouse Gas

GLM: Generalized Linear Model

ICC: Impact of Climate Change

ICD: International Classification of Diseases

IPCC: Intergovernmental Panel on Climate Change

IQR: Inter Quartile Range

IRR: Incidence Rate Ratio

MPI: Max Planck Institute

MDC: Mean daily Death Count

ND: Number of Days

NO_x: Nitrogen oxides

NO_2: Nitrogen Dioxide

OR: Odds ratio

PCMDI: Program for Climate Model Diagnostic and Intercomparison

PM: Particulate matter

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RCM: Regional Climate Model

RR: Relative Risk

RRR: Ratios of Relative Risks

SD: Standard Deviation

SES: Socio Economic Status

SRES: Special Report on Emissions Scenarios

WHO: World Health Organisation

YLL: Years of Life Lost

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CHAPITRE 1. INTRODUCTION GÉNÉRALE

1. Facteurs de vulnérabilité dans la relation entre chaleur et mortalité

Parmi les nombreux déterminants environnementaux de la santé des populations, les déterminants climatiques ont fait l'objet de nombreuses recherches ces dernières années. Et pour cause, chaque année et partout dans le monde, de nombreuses personnes sont hospitalisées ou décèdent en lien avec une exposition à une température élevée. Parmi les raisons qui ont amené à la fois la communauté scientifique et les professionnels de la santé publique à étudier cette question de manière si soutenue, les vagues de chaleur ayant eu lieu dans les vingt dernières années ont sans aucun doute joué un rôle majeur. Une vague de chaleur appelée également canicule ou période de chaleur accablante peut se définir comme une série de jours exceptionnellement chauds (Robinson 2001; Tong, Wang, and Barnett 2010). Toutefois, il n'existe pas de définition unanime et chaque contexte (i.e. une ville) aura ses propres critères afin de déterminer quels jours constitueront des jours de vagues de chaleur. Par exemple, à Paris une vague de chaleur se définit par trois jours consécutifs où la température moyenne maximale atteint 31°C et la température moyenne minimale ne descend pas sous les 21 °C (Pascal et al. 2006). A Montréal, une vague de chaleur se définit par trois jours consécutifs où la température moyenne maximale atteint 33 °C et la température moyenne minimale ne descend pas sous les 20 °C, ou lorsque la température ne descend pas en bas de 25 °C durant deux nuits consécutives (Price et al. 2010).

Les vagues de chaleur ayant eu lieu à Chicago en 1995 (Semenza et al. 1996a; Whitman et al. 1997) et en Europe en 2003 (Fouillet et al. 2006; Garcia-Herrera et al. 2010; Johnson et al. 2005), et qui ont respectivement occasionné près de 750 et 23000 décès (dont 15000 uniquement en France), constituent les événements les plus mémorables. Plus récemment en 2010 à Montréal, une vague de chaleur de 5 jours a provoqué la mort de près de 110 personnes (Price, Perron, and King 2013). Ces épisodes constituent des événements extrêmes qui ne représentent pourtant qu'une part de l'ensemble des impacts totaux de la chaleur sur la mortalité (Hajat et al. 2006). En effet, les températures ambiantes durant l'été peuvent, indépendamment des jours considérés comme exceptionnellement chauds (i.e. vagues de chaleur), conduire à une augmentation de la mortalité dans la population (Armstrong 2006).

En plus de l'ampleur de ces événements d'un point de vue santé publique et de leurs impacts médiatiques, ceux-ci ont été particulièrement révélateurs de manques en termes de préparation, de programmes de prévention ou même de surveillance ad hoc, et surtout de connaissances épidémiologiques notamment en lien avec la vulnérabilité à la chaleur.

Dans cette section seront abordées les connaissances biologiques et épidémiologiques portant sur l'association entre la chaleur et la mortalité, ainsi que sur les facteurs de vulnérabilité et les interventions visant à réduire les impacts de la chaleur. Dans la section suivante, seront abordés les impacts liés aux changements climatiques. Dans cette thèse, nous n'aborderons pas les effets liés aux températures froides et aux vagues de froid qui impliquent des mécanismes biologiques, des mesures de prévention, et parfois des outils épidémiologiques différents.

1.1. Épidémiologie et mortalité en lien avec la chaleur

Les effets biologiques de la chaleur

L'été, la chaleur trop intense devient un stress pour le corps humain. En plus des symptômes associés au stress thermique (ex : crampes, évanouissements), la chaleur peut ainsi engendrer un processus morbide, tel que la déshydratation, l'hyperthermie, l'épuisement ou un coup de chaleur provoquant un décès (Kovats and Hajat 2008). La chaleur peut aussi agir indirectement en aggravant l'état d'une personne atteinte d'un problème de santé, en particulier si ce problème touche le système cardiovasculaire ou respiratoire (Basagana et al. 2011). En outre, les changements de température peuvent notamment induire des réactions inflammatoires à différents niveaux (Hampel et al. 2010), des changements de viscosité sanguine (Schauble et al. 2012) ou de pression sanguine (Halonen et al. 2011b; Hoffmann et al. 2012), une variabilité dans la fréquence cardiaque (Ren et al. 2011), ou modifier les taux de cholestérol (Halonen et al. 2011a; Keatinge et al. 1986). Récemment, une étude a également mis en évidence l'effet épigénetique des changements de températures sur des modifications de l'ADN des cellules sanguines (Bind et al. 2014).

Revue des études épidémiologiques portant sur l'association entre la chaleur et la mortalité

Dans la littérature épidémiologique s'intéressant à l'association entre la chaleur et la mortalité, deux catégories d'études se distinguent selon leur exposition : i) celles qui ont porté sur l'association entre la température ambiante et la mortalité et, ii) celles qui ont porté sur les impacts des vagues de chaleur sur la mortalité.

Une variété de types d'études épidémiologiques a été utilisée pour étudier les effets de la chaleur sur la mortalité. Sur l'ensemble des études ayant étudié la relation entre température ambiante et un événement de santé, les analyses de séries temporelles (régressions de Poisson) (Armstrong 2006) et les analyses cas croisés (Maclure 1991) sont les plus utilisées (Basu 2009). En ce qui concerne les effets des vagues de chaleur, des analyses de séries temporelles et cas croisés ont également été conduites, mais des études avec des approches plus simples comparant des taux de mortalité au sein d'une population entre des jours considérés comme vagues de chaleur et d'autres jours ont également été menées (Rooney et al. 1998; Semenza et al. 1996a). Enfin, des études cas-témoins ont aussi été conduites pour étudier le lien entre vagues de chaleur et mortalité (Bouchama et al. 2007).

Les résultats de ces études des effets de la chaleur sur la mortalité en population générale conduites dans des contextes divers et variés sont concordants. Premièrement, en ce qui concerne les études portant sur l'association entre température ambiante et mortalité, les études montrent une augmentation de la mortalité journalière en fonction de la température. Toutefois, la relation entre la température et la mortalité est une relation non linéaire (Armstrong 2006; Bhaskaran et al. 2013; Kovats and Hajat 2008). De plus, les seuils (à partir desquels la température a un effet) observés varient beaucoup de même que la forme de la relation selon le contexte d'étude (Baccini et al. 2008; Curriero et al. 2002). En outre, des études multicentriques mettent en évidence que l'ampleur des effets liés à la chaleur varie d'une ville à l'autre (Analitis et al. 2014; Baccini et al. 2008). Il est important de préciser l'aspect relatif de l'impact des températures. En effet, c'est l'augmentation relative aux températures d'un endroit donné qui sera importante vis-à-vis de la mortalité. Ainsi une température peut avoir un effet sur la mortalité dans une ville canadienne sans n'avoir aucun impact dans une ville brésilienne par exemple.

Deuxièmement, les études sur les vagues de chaleur et la mortalité montrent systématiquement des excès de mortalité au sein de la population exposée lors de ces vagues de chaleur (Basu 2009). Différentes définitions de vague de chaleur correspondant à des critères bien définis adaptés au contexte local (i.e. la ville) sont utilisées (Robinson 2001; Tong, Wang, and Barnett 2010). La définition des vagues de chaleur est un enjeu important lors de calculs d'excès de décès (Kent et al. 2014) car chaque contexte aura ses propres caractéristiques météorologiques qui permettront d'estimer le caractère exceptionnel de certains jours. Des études ayant comparé plusieurs définitions recommande l’utilisation de définitions spécifiques selon le contexte (Kent et al. 2014; Tong, Wang, and Barnett 2010; Wu et al. 2014).

La mesure de mortalité non accidentelle (toutes causes de décès sauf causes accidentelles) ou bien les causes spécifiques respiratoires et cardiovasculaires demeurent les plus étudiées que ce soit pour les effets de la température ambiante ou des vagues de chaleur (Basu 2009; Basu and Samet 2002). En ce qui concerne la mesure d’exposition, les mesures journalières de la température (moyenne, minimum, maximum, ou des indicateurs incluant l’humidité tels que la température apparente) au niveau écologique (i.e. au niveau d’une station météo) sont utilisées (Kovats and Hajat 2008).

Les facteurs de confusion considérés sont divers. Les niveaux journaliers d’humidité relative sont souvent inclus (Basu 2009; Basu and Samet 2002). De nombreuses études ont également considéré comme facteurs de confusion les niveaux journaliers de pollution atmosphérique (notamment l’ozone), mais les derniers travaux en inférence causale appliqués aux effets de la chaleur sur la santé remettent en cause cette pratique et recommandent de ne pas les inclure en tant que tels (Buckley, Samet, and Richardson 2014; Reid et al. 2012). Les facteurs temporels jouent un rôle primordial dans ce type d’étude. Il est en effet essentiel de contrôler l’effet de la variation temporelle des taux de mortalité. Les tendances à long terme et les variations saisonnières sont les principales tendances temporelles considérées (Armstrong 2006; Bhaskaran et al. 2013).

En parallèle de la compréhension de l’influence de la chaleur sur la mortalité afin de la prévenir, de nombreuses études se sont intéressées à des populations qui seraient plus à risque face aux effets de la chaleur. Ces populations sont usuellement appelées **populations vulnérables**.

1.2. Vulnérabilité dans la relation entre chaleur et mortalité

Comment définir la vulnérabilité à la chaleur

Lorsque l'on s'intéresse à la notion de vulnérabilité à la chaleur, il est crucial de définir clairement cette notion. En effet, il existe plusieurs manières de définir la vulnérabilité, qui varient plus ou moins sensiblement selon le domaine d'application (Alwang, Siegel, and Jorgensen 2001; Delor and Hubert 2000). Dans un contexte épidémiologique, la vulnérabilité se rapporte à la notion de modification d'effet (Knol and VanderWeele 2012). Ainsi, est considéré comme facteur de vulnérabilité, tout facteur qui modifie la relation entre la chaleur et la mortalité (Kuh et al. 2003). Il est important de préciser que cette notion peut se confondre la plupart du temps avec la notion d'interaction, mais pas systématiquement (VanderWeele 2009). Il est aussi à noter que les notions de susceptibilité et de vulnérabilité sont souvent imbriquées voire confondues. Ainsi, il est possible de trouver ces termes utilisés de manière interchangeable dans différents articles pour décrire le même phénomène (Kuh et al. 2003). Certains auteurs distinguent ces deux notions sur la base de caractéristiques qu'elles soient biologiques ou sociales (Brook et al. 2010). Ici nous proposons d'utiliser la notion de vulnérabilité indépendamment de ses origines biologiques ou sociales (qui sont souvent interdépendantes). La vulnérabilité peut se définir à une échelle individuelle et/ou communautaire. La définition de communauté est admise ici de manière similaire à la notion de territoire, ces deux termes étant utilisés dans la littérature et n'ayant pas de définition universellement acceptée (McMillan and Chavis 1986). Ainsi, la communauté est considérée ici comme l'ensemble de la population vivant dans un territoire donné avec une acceptation d'une hétérogénéité intra communautaire de différentes caractéristiques notamment sociales (Reid et al. 2009).

La littérature épidémiologique sur la vulnérabilité dans la relation entre chaleur et mortalité

Les études épidémiologiques qui évaluent quelles facteurs peuvent modifier la relation entre la chaleur et la mortalité ont été très abondantes les dix dernières années. Les facteurs de vulnérabilité qui ont été documentés sont variés. Ils incluent l'âge (en considérant les personnes âgées et les enfants et nourrissons) (Oudin Astom, Forsberg, and Rocklov 2011; Xu et al. 2012; Xu et al. 2013c), le sexe (Yu et al. 2010), et les conditions de maladies préexistantes avant le décès (cardiovasculaires, respiratoires etc…) (Zanobetti et al. 2012), les conditions sociales incluant le niveau d'éducation, le niveau de revenu, l'isolation sociale (prises en compte au niveau individuel ou communautaire), ou l'accès à l'air climatisé des individus (Medina-Ramon et al. 2006; O'Neill, Zanobetti, and Schwartz 2005). Des facteurs contextuels urbains ont également été étudiés incluant la faible densité d'espaces verts ou la présence de micro-îlots de chaleur (ce terme désigne des élévations localisées des températures au sein d'une même ville) (Smargiassi et al. 2009; Xu et al. 2013b), ou la densité de population (Chan et al. 2012).

Dans la quasi totalité de ces études, l'effet modificateur potentiel de ces facteurs sur la relation entre la chaleur et la mortalité a été évalué via la réalisation d'analyses stratifiées (Basu 2009; Chan et al. 2012; Xu et al. 2012; Xu et al. 2013c). De plus, il est important de noter que, majoritairement, tous ces facteurs de vulnérabilité ont été abordés indépendamment les uns des autres. Pourtant, il serait intéressant d'étudier la notion de **cumul de facteurs de vulnérabilité** afin d'affiner la priorisation dans les mesures prises lors d'interventions de santé publiques ad hoc.

Il existe une littérature abondante sur ces facteurs de vulnérabilité à la chaleur mais cette information n'a jamais été synthétisée. Pourtant, fournir des données probantes sur les facteurs de vulnérabilité à la chaleur permettrait de documenter efficacement les recommandations internationales et les différentes interventions au niveau local qui en découlent. Ainsi il est pertinent de mener une **analyse systématique de la littérature** sur les facteurs de vulnérabilité à la chaleur pour produire ce type de données probantes.

1.3. Interventions de santé publique visant à réduire les impacts sanitaires de la chaleur

De part la survenue des événements climatiques décrits précédemment et la documentation croissante en épidémiologie des effets de la chaleur et des facteurs de vulnérabilité, les pouvoirs publics ont mis en place depuis la dernière décennie plusieurs interventions de santé publique visant à réduire les impacts sanitaires de la chaleur. Plusieurs organismes tels que l'Organisation Mondiale de la santé (OMS) ou l'US EPA (Hajat et al. 2010; Lowe, Ebi, and Forsberg 2011; Pascal et al. 2006; WHO 2008a, b) ont proposé des lignes directrices sur la mise en place de telles interventions.

Dans un premier temps, il est possible de distinguer ces interventions selon qu'elles soient à court ou à long terme. Les interventions à court terme se retrouvent formalisées notamment dans le cadre de systèmes d'alerte de santé en cas de chaleur (SASC). Les SASC se définissent comme «*un système « qui s'appuie sur les prévisions météorologiques pour lancer des mesures d'intervention de santé publique énergiques dans le but de réduire les répercussions de la chaleur sur la santé humaine lorsque les températures sont anormalement élevées* » (Ebi and Schmier 2005; Kalkstein, Sheridan, and Kalkstein 2009). Ces types d'interventions sont décrits dans de nombreux documents (Kosatsky, King, and Henry 2005; Lowe, Ebi, and Forsberg 2011; Toloo et al. 2013; WHO 2008b) et incluent par exemple les messages dans les médias de masse, la distribution de documents de sensibilisation, ou l'alerte aux hôpitaux et aux services de soutien d'urgence. Les interventions à long terme quant à elles visent à réduire la charge thermique par des modifications de l'environnement. Par exemple, Chicago, Toronto et Shanghai comptent parmi les villes qui rafraîchissent leur environnement en mettant en œuvre des recommandations concernant la planification urbaine (e.g. réduction des micro-îlots de chaleur urbains par des mesures de verdissement) et la conception architecturale (Luber and McGeehin 2008).

Dans un second temps, il est possible de distinguer les interventions visant à réduire les impacts sanitaires de la chaleur selon qu'elles soient populationnelles ou ciblées. Les interventions populationnelles (Benach et al. 2011; Rose 1992) sont les plus courantes dans ce domaine (Toloo et al. 2013) et ciblent toute la population (d'une ville par exemple). Cela peut se formaliser par des messages médias sur les gestes de prévention à adopter en cas de période de vague de chaleur. Parallèlement à ces interventions populationnelles, les interventions ciblées visent des groupes d'individus ou territoires qui seraient plus particulièrement à risque ou nécessiteraient des actions adaptées et proportionnées (Marmot 2005; Marmot et al. 2008). Par exemple, ces interventions peuvent inclure des messages spécifiques à certaines populations telles que des personnes souffrant de troubles de santé mentale (Petkova, Morita, and Kinney 2014) ou des personnes immigrantes (Hansen et al. 2013). Elles peuvent aussi permettre de cibler des territoires dans lesquels la réduction des micro-îlots de chaleur urbains est prioritaire. Cela correspond aux populations et territoires **vulnérables**.

Ainsi, les lignes directrices qui guident la mise en place des interventions visant à réduire les impacts sanitaires de la chaleur se basent essentiellement sur les connaissances produites par les études épidémiologiques (Bassil and Cole 2010; Hajat et al. 2010; Kovats and Hajat 2008; Toloo et al. 2013). Ces lignes directrices, incluent systématiquement un volet central quant à la prise en compte des populations vulnérables (Hajat and Kosatky 2010; Toloo et al. 2013; WHO 2003, 2008b). Il est donc fondamental de documenter quels sont les facteurs de vulnérabilité à la chaleur afin d'orienter ces interventions de la manière la plus efficace.

Le cas particulier de la relation entre pollution atmosphérique et mortalité en lien avec la chaleur

L'effet de la pollution atmosphérique dans les études qui portent sur chaleur et santé a été la source de plusieurs articles ces dernières années. Ces interrelations ont été abordées de différentes manières. Premièrement, et tel que décrit plus haut, la pollution atmosphérique a été considérée comme un facteur de confusion dans la relation entre chaleur et mortalité (Buckley, Samet, and Richardson 2014). Pourtant en analysant les potentielles structures causales, il est peu plausible qu'un polluant atmosphérique (y compris l'ozone) puisse affecter directement les niveaux de température. La seule hypothèse qui soutiendrait une démarche analytique valide supposant un tel effet serait qu'il y ait une cause commune aux concentrations de polluants atmosphériques et aux niveaux de températures, hypothèse qui n'est à l'heure actuelle soutenue par aucune évidence. Ensuite, dans certaines études, la pollution atmosphérique a aussi été analysée comme potentiel modificateur d'effet dans la relation entre chaleur et mortalité (Analitis et al. 2014; Filleul et al. 2006; Katsouyanni et al. 1993; Ren et al. 2008b). Ces études ont inclus l'ozone, ou encore les particules fines et ont pu montrer un effet modificateur de ces polluants dans la relation entre chaleur et mortalité. Cependant, la pollution atmosphérique a été analysée dans ce cadre en considérant une exposition journalière seulement. Ceci suppose implicitement en termes d'interventions de santé publique en lien avec la chaleur, la mise en place de mesures renforcées ou spécifiques pendant des jours ou périodes particuliers (e.g. pics de pollution à l'ozone). Seulement, cela ne permet pas de cibler spatialement des populations et territoires qui seraient plus vulnérables aux effets de la chaleur du fait de leur plus forte exposition à la pollution atmosphérique à long terme. Ainsi, **l'étude de l'exposition à la pollution atmosphérique envisagée de manière chronique** (i.e. à long terme) permettrait de cibler des populations et territoires plus vulnérables aux effets de la chaleur et fournir des informations épidémiologiques permettant d’engager les interventions ciblées appropriées.

2. La prise en compte des facteurs de vulnérabilité dans la relation entre la chaleur et la mortalité dans le contexte des changements climatiques

Les effets de la chaleur constituent donc un enjeu très important pour la santé des populations d'aujourd'hui. Néanmoins, dans le contexte des changements climatiques et les modifications environnementales que cela va impliquer, les impacts sanitaires futurs attendus sont absolument importants à documenter afin d'influencer la prise de décision quant à la mise en place dès aujourd'hui des mesures qui limiteraient d'une part l'amplitude de ces changements climatiques (i.e. approches de mitigation) et d'autre part des mesures qui permettraient de prévenir les impacts sanitaires futurs. Dans cette section nous allons présenter les connaissances sur les projections de températures attendues, les impacts sanitaires auxquels il est possible de s'attendre, et la nécessité d'y considérer dès aujourd'hui la notion de vulnérabilité pour aller vers une adaptation aux changements climatiques équitable.

2.1. Changements climatiques et impacts sanitaires de la chaleur

Les changements climatiques

Les changements climatiques constituent l'un des plus importants enjeux contemporains. Il existe un quasi-unanime consensus scientifique sur le fait qu'il y a bel et bien des changements climatiques dont l'origine est largement attribuable aux émissions de gaz à effet de serre d'origine anthropique (Stocker et al. 2013). En France ou au Canada, comme dans bien d'autres pays dans le monde, cela signifie notamment pour la fin du XXI^{ème} siècle une augmentation de la température moyenne entre 2°C et 4°C par rapport à la deuxième moitié du XX^{ème} siècle, une plus grande fréquence et intensité d'événements extrêmes tels que les vagues de chaleur (Coumou and Rahmstorf 2012) ainsi que de nombreux autres impacts environnementaux tels que des changements dans les conditions de précipitation (Groisman et al. 2005) ou des changements de la distribution géographique de certains vecteurs de maladies infectieuses (McMichael, Woodruff, and Hales 2006). La science climatique a permis, via le développement très important ces dernières années de la modélisation climatique, de fournir des projections de température à différents horizons allant jusqu'à 2100. Ces projections de température sont estimées à l'aide de Modèles Climatiques Globaux (MCG) ou de Modèles Climatiques Régionaux (MCR) qui ont été développés dans plusieurs pays tels que le Canada (Flato et al. 2000), l'Allemagne (Jungclaus et al. 2006) ou l'Australie (Cai et al. 2005). Les résultats de ces projections sont synthétisés, analysés et discutés au sein du GIEC (Groupe d'experts Intergouvernemental sur l'Evolution du Climat) via le projet CMIP (*Coupled Model Intercomparison Project*). CMIP3 correspond à la synthèse du quatrième rapport du GIEC en 2007 et CMIP5 à la synthèse du cinquième et dernier rapport du GIEC en 2013. Ainsi, les changements climatiques avec les nombreuses conséquences sur l'environnement qu'ils impliquent influenceront la santé des populations.

Les impacts sanitaires des changements climatiques

Les impacts sanitaires potentiels liés aux changements climatiques sont nombreux (Patz et al. 2005). Parmi ceux-ci les impacts futurs liés à la chaleur sont parmi les plus préoccupants étant donné le fardeau sur la population qu'ils représentent (Armstrong et al. 2012; McMichael, Woodruff, and Hales 2006). Une augmentation des températures ambiantes d'une part et d'autre part une augmentation de l'intensité et de la durée des vagues de chaleur vont indéniablement contribuer à augmenter la mortalité attribuable à la chaleur. Il est ainsi possible en utilisant les projections de température de procéder à la quantification des impacts sanitaires de la chaleur dans le contexte des changements climatiques (Hayhoe et al. 2010; Huang et al. 2011a). Plusieurs études depuis les dernières années ont estimé les projections de mortalité en lien avec la chaleur en utilisant des simulations climatiques. Cependant, peu ont pris en compte une grande diversité de simulations climatiques (Gosling, McGregor, and Lowe 2012; Hajat et al. 2014; Li, Horton, and Kinney 2013). Pourtant, lorsqu'il s'agit d'estimer les projections de mortalité en lien avec la chaleur, le fait de fournir des informations qui tiennent compte de l'incertitude des projections climatiques en intégrant de nombreuses simulations apporte de la crédibilité aux données probantes pour influencer la prise de décision par les pouvoirs publics. Certaines études ont estimé les projections de mortalité attribuables spécifiquement aux vagues de chaleur en utilisant des simulations climatiques, mais leurs conclusions stipulent qu'il y a encore beaucoup d'erreur dans les simulations des extrêmes (Gosling, McGregor, and Lowe 2012). Ainsi dans cette thèse, nous nous intéresserons aux projections de mortalité attribuables à la température ambiante, sans aborder l'effet spécifique des vagues de chaleur.

Il parait donc essentiel de **quantifier les impacts futurs en lien avec les changements climatiques** en intégrant une grande diversité de simulations climatiques pour **considérer l'incertitude dans les projections de mortalité** en lien avec la chaleur.

2.2. De la quantification des impacts à une adaptation aux changements climatiques équitable

Les interventions de santé publique dans le contexte des changements climatiques se réfèrent aux mesures d'adaptation en santé publique (Huang et al. 2011b). Celles-ci comprennent l'ensemble des mesures visant à réduire les effets potentiels des changements climatiques sur la santé des populations (Hunt and Watkiss 2011; Paterson et al. 2012). La quantification des impacts sanitaires associés aux changements climatiques permet donc de supporter la prise de décision quant à la mise en place de ces mesures d'adaptation en santé publique. Cependant, afin de prioriser ces interventions, il est capital d'identifier quelles populations et territoires seront les plus touchées par les changements climatiques.

Une connaissance épidémiologique sur les facteurs de vulnérabilité actuels à la chaleur est certes indispensable pour cette priorisation, mais il est important aussi d'analyser l'évolution des facteurs de vulnérabilité à la chaleur. Plus précisemment, la notion de vulnérabilité à la chaleur renvoie à des inégalités de santé en termes de mortalité en lien avec la chaleur selon les différents facteurs de vulnérabilité (Hansen et al. 2013; Klinenberg 2003). Ceci étant dit, il est possible que les changements climatiques contribuent à accroitre ces inégalités de santé. Ainsi, une prise en compte des facteurs de vulnérabilité dans ce cadre viserait à produire des données probantes encourageant des interventions qui contriburaient à réduire les inégalités de santé en termes de mortalité en lien avec la chaleur en plus de réduire la mortalité attribuable à la chaleur en général. En outre, des inégalités de santé qui « *mettent systématiquement des groupes de personnes qui sont d'ores et déjà socialement désavantagés à des désavantages plus importants en lien avec leur santé* » constituent des inéquités en santé (Braveman and Gruskin 2003). Cette notion d'équité en santé renvoie à des principes de justice sociale (Dahlgren and Whitehead 1992; Marmot et al. 2008; Whitehead 1992). Si l'on applique la théorie de justice sociale proposée par John Rawls (Rawls 1971), deux aspects importants de cette théorie rejoignent la notion d'équité en santé dans les mesures d'adaptation aux changements climatiques, à savoir la notion de « plus grand bénéfice aux membres les plus désavantagés » et « l'obtention de conditions d'égalité équitable des chances ». Le potentiel de bénéfices justes des effets induits par les mesures d'adaptation par les populations vulnérables peut aussi être rapproché de la notion de *capabilité* (ou « *capacité de tirer bénéfice des opportunités »)* développée par Sen (Nussbaum 2003; Sen 1993; Sen, Chemla, and Laurent 2010) où les interventions ciblées et adaptées aux personnes vulnérables sont à relier à la notion de « facteurs de conversion » (liens entre la capacité et l'opportunité). Ainsi, c'est la raison pour laquelle il est décisif de **documenter l'évolution des inégalités d'effets de la chaleur en lien avec les changements climatiques** pour aller vers une adaptation aux changements climatiques équitable et atteindre des idéaux de justice sociale.

En parallèle, lorsqu'il s'agit de produire des données probantes pour orienter des politiques publiques équitables, la question de l'universalité est centrale (Lorenc et al. 2013). En effet, l'influence des changements climatiques sur l'évolution des inégalités d'effets de la chaleur peut vraisemblablement avoir des schémas différents selon le contexte étudié. Ainsi, il est **nécessaire d'analyser ces évolutions dans des contextes relativement distincts** pour questionner l'universalité de ces phénomènes.

CHAPITRE 2 : OBJECTIFS, MÉTHODES ET STRUCTURE DE LA THÈSE

1. Objectif Général :

L'objectif général de cette thèse est de documenter les facteurs de vulnérabilité à la chaleur dans le présent et les éléments permettant leur prise en compte pour l'avenir dans le contexte des changements climatiques.

2. Objectifs spécifiques :

O1 : Synthétiser la connaissance épidémiologique sur les facteurs de vulnérabilité à la chaleur de manière systématique.

O2 : Analyser si l'exposition chronique à la pollution atmosphérique modifie la relation entre la chaleur et la mortalité dans un contexte urbain (Paris) et explorer la double interaction avec la défaveur sociale.

O3 : Développer une méthode de quantification des impacts liés à la chaleur en lien avec les changements climatiques en intégrant une grande diversité de simulations climatiques. Un sous objectif sera d'estimer la contribution des différentes sources d'incertitudes dans les projections de mortalité.

O4 : Estimer les inégalités d'années de vies perdues attribuables à la chaleur et leurs projections futures dans deux contextes distincts (Montréal et Paris) et comparer ces inégalités.

3. Présentation des données utilisées

Cette section vise à présenter les différentes données utilisées dans l'ensemble de la thèse. Les variables et analyses utilisées dans chacun des articles de cette thèse ne sont présentées ici que succinctement puisque chacun des quatre articles scientifiques décrit précisément les approches utilisées dans les chapitres suivants. Les recherches dans le cadre de ce doctorat ont été menées sur l'île de Montréal (1 812 723 habitants en 2001)

(Institut Statistique Québec 2001) et sur la ville de Paris (2 234 105 habitants en 2006) (INSEE 2006).

4. Populations, sources de données à l'étude et devis des études menées.

Pour l'objectif **O1**, les sources de données sont les articles scientifiques publiés entre Janvier 1980 et Septembre 2013 au sujet des facteurs de vulnérabilité à la mortalité en lien avec la chaleur. Il s'agira d'une revue systématique incluant une méta analyse.

Pour l'objectif **O2**, la population d'étude est la population de Paris âgée de plus de 35 ans décédée en été entre 2004 et 2009. Il s'agira d'une étude écologique de type analyse de séries temporelles.

Pour l'objectif **O3**, la population d'étude est toute la population de Montréal décédée (hors cause accidentelle) en été entre 1990 et 2007. Il s'agira d'une étude écologique de type analyse de séries temporelles complétée avec une analyse quantitative de risque sanitaire pour estimer les mortalités futures.

Pour l'objectif **O4**, la population de Paris âgée de plus de 35 ans décédée en été entre 2004 et 2009 et toute la population de Montréal décédée (hors cause accidentelle) en été entre 1990 et 2007 sont utilisées. Il s'agira d'une étude écologique de type analyse de séries temporelles complétée avec une analyse quantitative de risque sanitaire pour estimer les mortalités futures.

5. Données utilisées

Données sanitaires :

Les données de mortalités journalières estivales géo-référencées (au code postal à six position du domicile) du Ministère de la santé (Québec) pour 1990-2007 sont utilisées pour la l'île de Montréal. Les données de mortalités journalières estivales géo-référencées (à l'IRIS du domicile) pour Paris sont auprès de l'INSERM (Institut National de la Santé Et de la Recherche Médicale) pour 2004-2009. Ces données contiennent l'âge et le sexe. Pour Montréal, les causes de décès excluant les causes accidentelles correspondant aux codes ICD-9 800–999 and ICD-10 S00– T98 de la classification internationale des maladies (ICD) sont incluses. Cela représente un total de 61356 décès pour la période 1990-2010 à Montréal et de 46056 pour la période 2004-2009 à Paris. Ces données sont utilisées pour les objectifs **O2, O3 et O4.**

Données environnementales :

Les données estivales de températures journalières (minimum maximum et moyenne) ainsi que les données d'humidité relative à Montréal (1990-2010) mesurées à la station météorologique d'Environnement Canada de l'Aéroport International Pierre Elliott Trudeau sont utilisées (O3 et O4). Pour Paris, les données estivales de température (minimum, maximum et moyenne) et d'humidité relative ont été obtenues auprès de Météo France pour la station du parc Montsouris. Ces données sont utilisées pour les objectifs **O2, O3 et O4.** En ce qui concerne les données de pollution atmosphérique, sont utilisées les concentrations de NO_2 obtenues auprès de L'AASQA (Association Agréée de Surveillance de la Qualité de l'Air) AirParif et modélisées à l'échelle des IRIS (Ilots Regroupés pour l'Information Statistique) à l'aide d'un modèle de dispersion (ESMERALDA) pour la période 2004-2009. Ces données sont utilisées pour l'objectif

O2. Pour Montréal, les mesures horaires d'ozone (O_3) provenant de toutes les stations fixes de mesure sur l'île de Montréal ont été obtenues auprès du réseau national de surveillance de pollution de l'air d'Environnement Canada (EC, 2012). Ces données ont été agrégées pour produire une valeur journalière d'exposition à l'ozone pour la période 1990-2007 à Montréal. Ces données sont utilisées pour l'objectif **O3**.

Données de projections climatiques :

En ce qui concerne l'objectif **O3**, 32 simulations climatiques futures établies à partir de différents modèles climatiques régionaux (MCR) et globaux (MCG) sont utilisées pour la ville de Montréal, pour la période 2020-2037. Ces 32 simulations sont issues du CMIP3 (Meehl et al 2007) dans le cadre du quatrième rapport du GIEC (Solomon 2007). Des processus de post traitement visant notamment à corriger la distribution des températures simulées grâce aux observations météorologiques historiques ont été menés. En ce qui concerne l'objectif **O4**, 30 simulations établies à partir de différents modèles climatiques globaux (MCG) issues du CMIP5 dans le cadre du cinquième rapport du GIEC sont utilisées (Stocker et al. 2013) pour la période 2021-2050. Ces 30 simulations sont les mêmes à Montréal et à Paris mais avec des processus de mise à l'échelle et de post traitement spécifiques à chaque contexte géographique. Ces données de projections climatiques sont toutes fournies par le Consortium Ouranos (www.ouranos.ca).

Données sociales attribués aux individus de l'étude :

Chaque individu décédé a comme attribution les caractéristiques sociales de son aire de diffusion (plus petite unité géographique du recensement canadien, code postal à six positions, avec 588 habitants en moyenne par unité) pour Montréal et IRIS (plus petite unité géographique du recensement français, avec 2199 habitants en moyenne par IRIS) pour Paris. Nous utilisons les caractéristiques sociales issues du recensement 2006 pour

Montréal (Institut Statistique Québec 2006) et Paris (INSEE 2006). Pour l'objectif **O2**, un indice de défaveur sociale composite construit pour Paris à l'échelle de l'IRIS est utilisé (Lalloué et al. 2013). Pour l'objectif **O4**, sont utilisés le pourcentage de personnes âgées de plus de 20 ans sans diplôme secondaire à Montréal et le pourcentage de populations sans diplôme à Paris, liées au lieu de résidence de chaque décès. Nous avons utilisé le niveau d'éducation car c'est la variable pour laquelle il y a le moins de données manquantes pour les deux villes.

6. Définition des variables utilisées

O1 : Nous utilisons pour cet objectif les mesures d'association entre la chaleur et la mortalité (sous la forme de risques relatifs) par strate de sous groupe potentiellement vulnérable (ex. pour le sexe : un sous groupe hommes et un sous groupe femmes), contenues dans les articles qui sont recensés via une revue systématique de littérature. Les facteurs de vulnérabilité considérés sont : le sexe, l'âge (moins de 5 ans, plus de 65 ans, plus de 75 ans et plus de 85 ans), le niveau socio-économique (individuel et communautaire), le design urbain, la présence d'air conditionné et l'isolation sociale. Les variables explicatives de l'hétérogénéité inter-études qui sont utilisées sont : le devis de l'étude (cas croisés ou étude de série temporelle), le continent (Europe, Amérique, Asie et Australie), la mesure d'association utilisée (comparaison entre deux percentiles de température ou augmentation du risque à partir d'un seuil), et la mesure de niveau socio-économique (à l'échelle individuelle ou communautaire).

O2 : Nous utilisons pour cet objectif la température moyenne journalière comme variable explicative. Le nombre de décès journalier constitue la variable à expliquer. Dans un premier temps, le nombre de décès par jour est stratifié selon le niveau de pollution atmosphérique chronique (3 strates) et selon le niveau de défaveur économique défini par un indice de défaveur sociale composite (3 strates). Les 3 strates sont définies par rapport aux terciles des distributions de la pollution atmosphérique chronique et de défaveur sociale. Dans un second temps, pour étudier la double interaction, le nombre de décès par jour est stratifié selon le niveau de pollution atmosphérique chronique (2 strates, par rapport à la médiane de la distribution) et selon le niveau de défaveur économique défini par un indice de défaveur sociale composite (3 strates). Les variables de confusion utilisées sont les niveaux journaliers d'humidité relative.

O3 : Nous utilisons pour cet objectif les niveaux de température moyenne, maximum et minimum journaliers (observées et simulées) comme variables explicatives. Le nombre de décès journalier constitue la variable à expliquer. Les variables de confusion utilisées sont les niveaux journaliers d'humidité relative et d'ozone.

O4 : Nous utilisons pour cet objectif la température moyenne journalière comme variable explicative. La variable à expliquer est un indice que nous avons crée, que nous avons appelé DYLLD (*Daily Years of Life Lost Disparities*). Cet indice correspond à la différence moyenne entre le nombre d'années de vie perdues journaliers de la strate de population vivant dans les quartiers avec le plus haut niveau d'éducation (défini par rapport aux terciles de la distribution) avec les deux autres strates de population avec des niveaux d'éducations plus faibles. Les variables de confusion utilisées sont les niveaux journaliers d'humidité relative.

7. Description succincte des analyses réalisées

O1 : Pour évaluer l'hétérogénéité entre deux sous groupes de population dans la relation entre la chaleur et la mortalité, deux approches sont menées. Premièrement, nous menons des tests d'hétérogénéité (*Cochran Q test*) entre les sous groupes de population pour chacune des études. Deuxièmement, nous menons une méta-analyse avec effets aléatoires des ratios de risques relatifs (RRR) de chacune des études pour les études portant sur la relation entre la température ambiante et la chaleur. Cette approche permet de comparer directement les études entre elles en ce qui concerne l'hétérogénéité de l'effet de la température sur la mortalité. Puis, pour évaluer les sources d'hétérogénéité inter-études, nous menons une méta-régression avec les RRR. Les biais de publication sont évalués avec un test Egger.

O2 : Nous menons des analyses de séries temporelles avec modèles de régressions de Poisson stratifiés pour évaluer l'association entre les niveaux de température et le nombre de décès journaliers. Des fonctions splines sont utilisées pour tenir compte des tendances naturelles dans les séries temporelles et également pour considérer la non-linéarité de la relation entre la température et la mortalité. La validité des modèles a été vérifiée en s'assurant qu'il ne restait pas d'auto corrélation dans les résidus en utilisant des graphiques d'auto-corrélation et des tests de bruit blanc. Nous estimons ensuite le nombre de décès attribuables à la chaleur dans chacune des strates et testons l'hétérogénéité entre les différentes strates.

O3 : Nous menons des analyses de séries temporelles avec modèles de régressions de Poisson pour évaluer l'association entre les niveaux de température (moyens, maximums et minimums) et le nombre de décès journaliers. Des fonctions splines sont utilisées pour tenir compte des tendances naturelles dans les séries temporelles et également pour considérer la non-linéarité de la relation entre la température et la mortalité. La validité des modèles a été vérifiée en s'assurant qu'il ne restait pas d'auto corrélation dans les résidus en utilisant des graphiques d'auto-corrélation et des tests de bruit blanc. Nous estimons ensuite le nombre de décès attribuables à la chaleur pour chacune des simulations climatiques (n=32). Afin d'estimer les nombres de décès attribuables aux températures futures nous utilisons les distributions des températures futures simulées (obtenues grâce aux modèles climatiques) et les fractions attribuables à l'aide des relations température-mortalité obtenues (sous forme de risques relatifs) à l'aide des modèles de Poisson. Pour estimer les sources d'incertitude dans les projections du nombre de décès attribuables à la chaleur, nous avons d'abord crée trois sets de risques relatifs (RRs) entre les niveaux de température et le nombre décès journaliers à l'aide de *bootstraping* (1000 échantillons). Dans la procédure de *bootstrap*, la structure temporelle a été maintenue en faisant des blocs par année. Le premier set de RRs correspond aux RRs obtenus avec les données observées et les deux autres sets de RRs correspondent aux percentiles 2,5 et 97,5 des nombres de décès attribuables obtenus à l'aide du *bootstraping*. Pour évaluer la contribution respective des différentes simulations, des années projetées et des trois sets de RRs, une analyse de covariance est conduite.

O4 : Nous menons des analyses de séries temporelles avec des modèles linéaires généralisés pour évaluer l'association entre les niveaux de température et les DYLLD séparément pour Montréal et Paris. Des fonctions splines sont utilisées pour tenir compte des tendances naturelles dans les séries temporelles et également pour considérer la non-linéarité de la relation entre la température et les DYLLD. La validité des modèles a été vérifiée en s'assurant qu'il ne restait pas d'auto corrélation dans les résidus en utilisant des graphiques d'auto-corrélation et des tests de bruit blanc. Nous estimons ensuite le nombre de DYLLD attribuables à la chaleur pour chacune simulations climatiques (n=30) séparément pour la période historique (1981-2010) et la période future (2021-2050). L'impact des changements climatiques (ICC) est défini par le ratio entre le nombre de DYLLD attribuables à la chaleur dans le futur et le nombre de DYLLD attribuables à la chaleur dans le passé. Nous menons ensuite une méta-analyse des ICC pour chacune des simulations pour obtenir un effet total de l'ICC par ville et conduisons une méta-régression avec comme variable explicative la ville (Montréal ou Paris) pour comparer l'effet des changements climatiques sur les DYLLD entre les deux villes.

8. Procédures d'éthique

Les approbations éthiques ont été obtenues par le Comité d'éthique de la recherche en santé (CERES) à l'Université de Montréal pour les données à Montréal et par la CNIL (Commission Nationale Informatique et Liberté) pour les données à Paris (voir annexe). En ce qui concerne les données de Montréal, Le projet a été mené dans le cadre du plan ministériel québécois de surveillance, qui a obtenu l'approbation éthique par le Comité d'Ethique de la Santé Publique (CESP) du Québec.

CHAPITRE 3 : VULNERABILITY TO HEAT-RELATED MORTALITY: A SYSTEMATIC REVIEW, META-ANALYSIS AND METAREGRESSION ANALYSIS

Vulnerability to heat-related mortality: a systematic review, meta-analysis and metaregression analysis

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1. Abstract

Background: Addressing vulnerability to heat-related mortality is a necessary step in the development of specific policies dictated by heat action plans. These policies should be based on international epidemiologic literature. The aim of this study was to provide a systematic assessment of the evidence regarding vulnerability to heat-related mortality.

Methods: Studies published between January 1980 and August 2013 were identified through MEDLINE and EMBASE. Studies assessing the association between high ambient temperature or heat-waves and mortality among different subgroups were selected. Estimates of association for all the included subgroups were extracted. We assessed the presence of heterogeneous effects between subgroups conducting Cochran Q tests. We then conducted random effect meta-analyses of Ratios of Relative Risks (RRR) for high ambient temperature studies. Finally, we performed random effects meta-regression analyses to investigate factors associated with the magnitude of the RRR.

Results: Overall 50 studies were included in the review. Using the Cochran Q test we consistently found evidence of vulnerability for the elderly aged more than 85 years. We found a pooled RRR of 0.98 (95% CI: 0.96, 0.99) for sex (RR_{men}/RR_{women}), 1.02 (95% CI: 1.01, 1.04) for age>65 years (RR_{65+}/RR_{15-64}), 1.05 (95% CI: 1.02, 1.07) for age>75 years (RR_{75+}/RR_{15-74}) and 1.02 (95% CI: 1.00, 1.03) for socioeconomic status (SES) ($RR_{lowSES}/RR_{highSES}$). We found association and SES measures to be determinants of heterogeneity in the pooled RRR.

Conclusions: We found evidence of heat-related vulnerability for women, the elderly aged more than 65 years and low SES groups. Further studies are needed to complete knowledge about heat-related vulnerable subgroups to inform public health programs.

2. Introduction

Rising temperatures, and their impact on human mortality, are a primary public health concern in the context of climate change. Studies of heat and mortality have increased during the last two decades, particularly with the documentation of prominent events including heat waves in Chicago in 1995 (Semenza et al. 1996) and in Western Europe in 2003 (Kovats and Kristie 2006). In the heat-related mortality literature, it is typical to distinguish two types of heat exposures: first, increases in ambient temperatures associated with mortality, and second, hot days (i.e. heat wave days) where population mortality is greater than on non-heat wave days. Many literature reviews (Basu 2009; Basu and Samet 2002; Gosling et al. 2009; Hajat and Kosatky 2010; Oudin Astrom, Bertil, and Joacim 2011; Romero-Lankao, Qin, and Dickinson 2012) have examined the evidence on mortality associated with elevated ambient temperatures, focusing on the variation of heat effect thresholds or heat slopes (as a measure of effect size) (Hajat and Kosatky 2010).

In epidemiological studies of heat-related mortality, various subgroups have been identified as being more severely impacted, and are therefore defined as “vulnerable” (McMichael et al. 2008; Stafoggia et al. 2006). Vulnerability is often used synonymously with susceptibility (Kuh et al. 2003), which can be defined as “the condition of having one or more interacting causes already and therefore being susceptible to the effect of the other” (Kuh et al. 2003) or as “a greater likelihood of an adverse outcome given a specific exposure, compared with the general population; including both host [individual] and environmental [contextual] factors” (Brook et al. 2010). Factors that mark greater vulnerability can be modifiers of the association between an exposure and mortality, whenever the causal effect of the exposure of interest differs across levels of the modifying factor. Thus, there would be greater vulnerability in some subgroup whenever the causal effect of heat on mortality across two or more strata is heterogeneous.

Several individual or contextual subgroup characteristics marking greater vulnerability have been documented in the past decade of epidemiologic research. Individual vulnerability factors include age (elderly, children) (Oudin Astrom, Bertil, and Joacim 2011; Xu et al. 2012), sex and socio economic factors (education, ethnicity, income, or social isolation). Contextual vulnerability factors include urban design (micro heat islands, population density), neighbourhood (or ecological) socioeconomic and community factors, and material conditions (air conditioning). These subgroups have mostly been identified in studies on the relationship between temperature, or heat waves, and mortality, using stratified analyses.

Addressing vulnerability to heat-related mortality is a necessary step in the development of heat action plans (WHO 2003), to orient specific actions towards sensible subgroups (Benach et al. 2011; Frohlich and Potvin 2008). While the need to consider vulnerable populations in heat action plans and other related policies is well-recognized (Bassil and Cole 2010; McMichael et al. 2008; Toloo et al. 2013), specific policies dictated by heat action plans should be based on best possible evidence.

No study to date has systematically assessed the evidence concerning the characterization of vulnerable subgroups in the peer-reviewed heat-related mortality literature. The aim of this review is thus to systematically assess the heterogeneity in the heat mortality associations with respect to individual and contextual population characteristics.

3. **Methods**

Search Strategy

We identified peer-reviewed epidemiological studies investigating potential heterogeneity in the associations between either high ambient temperature, or heat waves, and mortality, published between January 1980 and August 2013 in English. The strategy used to conduct this review, in accordance with the PRISMA guidelines (Moher et al. 2009), consisted of grouping keywords representing three categories: heat, mortality, and vulnerability (or heterogeneity). Keywords, titles, and abstracts were searched in PubMed and Elsevier Embase on the Ovid SP portal. No restriction was put on the geographical location. The keywords used for this review were: (Heat OR climate OR environmental change OR heat stress OR hot weather OR high temperature) AND (Mortality OR health OR risk OR deaths) AND (vulnerability OR modif* OR interaction OR susceptibility OR stratification OR differ* OR hetero*).

Selection of studies

First, the abstracts of all studies selected in the literature search were screened manually according to the following exclusion criteria:

- Studies without estimation of an association between mortality and heat.
- Studies reporting associations between mortality and heat only for the entire population and not for subgroups constituting vulnerability (as described in the introduction).
- Studies not performed on human populations.
- Commentaries, editorials or review articles.

Remaining articles from the previous step were examined in full. In this second step, studies or assessments within studies (i.e. by vulnerability subgroups) were further screened based on the following exclusion criteria:

- Studies or vulnerability subgroups (within a study) with either no comparison group or no reference group. If a study assessed only one of the strata for a given vulnerability factor, it was not possible to assess heterogeneity, thus such estimates were not considered (e.g. if a study assessed the association among individuals of 65 years and older, without giving the corresponding association for the 0-64 years age group). Studies not reporting a non-heat wave reference period (i.e. when the heat-exposure did not differ) were also excluded (e.g. case-control studies).
- When the vulnerability subgroups considered were assessed only once in all of the final set of selected papers (e.g. body mass index in Xu et al. (2013) (Xu et al. 2013a), depression in Stafoggia et al. (2006) (Stafoggia et al. 2006), smoking in Madrigano et al. (2013) (Madrigano et al. 2013), ozone exposure in Ren et al. 2008 (Ren et al. 2008)).
- When subcategories of outcomes (e.g. cause of death or place of death) were considered as vulnerability factors. We excluded these subgroups as they cannot modify the association between heat and mortality.

In addition, the reference sections of studies identified as described above were searched, and pertinent references not initially identified were thus added. Where published literature reviews on heat-related health effects were cited in these reference lists, we additionally searched their references: the reference lists of eight reviews on temperature effects in children (Xu et al. 2012; Xu et al. 2013c), the elderly (Oudin Astrom, Bertil, and Joacim 2011) and general population (Basu 2009; Basu and Samet 2002; Hajat and

Kosatky 2010; Hansen et al. 2013; Romero-Lankao, Qin, and Dickinson 2012) were thus searched by hand.

The articles finally selected were separated into two categories: 1) studies investigating the effect of high ambient temperature on mortality and 2) studies investigating the effect of heat waves on mortality.

Data extraction

From the selected studies, we extracted the estimates of association (i.e. RR, IRR or OR) for all the included subpopulations. We then documented the location of the studies, their time period, study design, the temperature exposure variable and the following vulnerability factors (see details in supplemental material: Table 1S): i) sex; ii) age: elderly and children; iii) individual and ecological socioeconomic status; iv) urban design and housing: intra-urban heat variations, air conditioning, and population density; v) social isolation.

Heterogeneity assessment using the Cochran Q test

To assess if there was a heterogeneous effect of high temperatures between subgroups, we conducted a Cochran Q test (see supplemental material: Appendix 1S for details). We considered the presence of heterogeneity at the 10% level of significance (Kaufman and MacLehose 2013; Shah et al. 2013). When estimates for all groups combined were not reported, we calculated them as described in the supplemental material (Appendix 1S) (for example, if a study presented estimates for men and women without presenting the estimate for both sexes combined). When analyses were conducted in the same study for different cities or for different time periods (e.g. different heat waves), we assessed the heterogeneity between different subgroups separately; for this reason, the number of strata comparisons is greater than the number of studies finally included. When more than two strata were presented, we compared only the two extreme groups. For example, if the heat effects were presented by quintiles of socioeconomic status (SES), we compared the less deprived group (first quintile) to the most deprived group (fifth quintile). For ethnic groups, we only compared White persons to Black persons or to Non-White persons and we did not include Hispanic persons in the comparisons (as this group was only assessed in Basu et al. 2008 (Basu and Ostro 2008)). When many employment status categories were presented (e.g. blue collar, white collar), we only compared unemployed to employed people.

Heterogeneity assessment using a meta-analysis

In parallel to the heterogeneity assessment described above, we conducted a meta-analysis. We included only high ambient temperature studies. We did not conduct a meta-analysis for heat wave studies since the study designs and methods were considerably different. Studies where no association between high temperature and mortality was found for the whole population were excluded for the meta-analysis. We considered sex, age (more than 65 and more than 75) and SES (individual and ecological definitions grouped together) subgroups. In order to compare subgroups within selected studies, we used the natural logarithm of the ratio of RR values (RRR) (or analogous estimates of association) for the two compared subgroups (e.g. RR_{men}/RR_{women}) as described by Altman et al. (2003) (Altman and Bland 2003) or Bassler et al. (2010) (Bassler et al. 2010). The formula used to calculate the standard errors of the ratios is presented in the Supplemental Material (Appendix 1S). As we estimated ln(RRR) values within studies, the fact that different association measures or study designs were used did not bias the pooled estimates. Moreover, for the studies that reported estimates of association by comparing two percentiles of temperature distributions, the highest percentile was always above the 95th percentile. We used random-effects models to account for heterogeneity between studies. To assess heterogeneity of the ln(RRR)s across individual studies, we used the I^2 statistic ($I^2 > 50\%$ was used as a threshold) (Higgins and Thompson 2002; Reid, Bolland, and Grey 2014). Publication bias was assessed with Funnel plots and Egger's regression model (Egger et al. 1997).

Meta-regression analysis

To investigate factors associated with the magnitude of the RRR, we performed random effects meta-regression analyses in which the dependent variable was the ln(RRR) and independent variables were: study design (i.e. case-crossover or time series), continent (i.e. Europe, America or Asia/Australia) and association measures (i.e. percentage increase comparing two percentiles of the temperature distribution or percent changes associated with degree units increases above a city specific threshold) for sex and age >65 years; the continent and the association measures for age >75 years; SES measure (i.e. individual measure or ecological measure), study design, continent and association measure for SES. A meta-regression was conducted for each variable separately. We estimated from these meta-regressions: the regression coefficients (Betas and 95% CI), the *P* Value, the R^2 statistic (which represents the proportion of between-study variance explained by the covariate), the residual I^2 (which represents after adjustment for the predictors, a measure of the percentage of the residual variation that is attributable to between-study heterogeneity) and the adjusted pooled RRR (and 95% CI).

4. Results

Selection of studies

Altogether the abstracts of 235 articles were assessed and 90 underwent in-depth review, with 50 studies fulfilling the inclusion criteria. **Figure 1** presents the inclusion and exclusion of studies. Among the 90 articles retained based on the first exclusion criteria (with an abstract screening), 38 studies were entirely excluded because they did not report a comparison group. Among them, 3 studies (Kosatsky, Henderson, and Pollock 2012; Medina-Ramon et al. 2006; Schwartz 2005) were excluded because they used a case only design which did not permit the comparison of different subgroups, and 7 studies were excluded because they only assessed the spatial variability of the heat-related mortality. Five studies were excluded they because showed variation only according to cities or regions. Among the 50 final studies, 7 were identified through reference searching.

Description of selected studies

The characteristics of the included studies are presented in **Table 1** and **Table 2**. All the studies were published between 1998 and 2013. Twenty one studies were conducted in Europe, 12 in America, 18 in Asia and Australia, and one in Africa (two studies assessed two regions).

Thirty-three retained studies assessed the effect of high ambient temperature (**Table 1**) on mortality. Among these studies, 27 used a time-series design and 6 used a case-crossover design. Various estimates of the association between mortality and high ambient temperature were reported: twenty-two studies assessed the relationship by reporting percent changes or RR (or IRR) associated with degree units increases (1°C, 3°C, 10°C, 10°F) above a city-specific threshold, and eleven reported percent increase or RR or odds ratios (OR) comparing two percentiles of temperature distributions.

Seventeen retained studies assessed the effect of heat waves (**Table 2**) on mortality. Among these studies, 10 used a descriptive design, 4 used a time-series design, and 3 used a case-crossover design (see **Table 2**). Various estimates of the association between mortality and heat waves were reported. Four studies reported this relationship by percent increase on heat wave days compared to non heat waves days, and 13 with RR, IRR or excess mortality rates for heat waves days compared with non heat-waves days.

Heterogeneity findings

We systematically compared all the included subgroup estimates (i.e. measures of association between heat and mortality) separately for high ambient temperature (**Table 3**) and for heat waves studies (**Table 4**). For studies on the association between high ambient temperature and mortality, we consistently found evidence of vulnerability for two subgroups: elderly persons above 85 years of age, and populations living in areas characterized by a low percentage of households having central air conditioning. For studies on the association between heat waves and mortality, we consistently found evidence of vulnerability for the following three subgroups: elderly persons above 85 years of age, populations living in hot places, and individuals who were not married (used as a proxy for social isolation). Heterogeneity was not always found for other subgroups studied, such as SES subgroups or children. Nonetheless when heterogeneity was found from studies on the association between temperature and mortality, the following subgroups were always identified as vulnerable: elderly persons more than 65 years and more than 75 years, low SES groups (measured at the individual level), populations living in high density areas, and unmarried individuals. The comparison of heterogeneity findings between high ambient temperature and heat waves studies is presented in the Supplemental material (**Table 2S**).

Meta-analysis results

We conducted meta-analyses of the ln(RRR) for sex, age (more than 65 and more than 75 years) and SES (individual and ecological grouped together) only on studies about high ambient temperature. We found that the pooled RRR according to sex (RR_{men}/RR_{women}) was 0.98 (95% CI: 0.96, 0.99) (**Figure 2**), suggesting that women were slightly more vulnerable to heat compared to men. We additionally found that the pooled ratio of RRs for individuals aged > 65 years, compared to adults aged between 15 and 64 years (RR_{65+}/RR_{15-64}) was 1.02 (95% CI: 1.01, 1.04) (**Figure 3**), and that the pooled ratio of RRs for those aged >75 years, compared to adults aged between 15 and 74 years (RR_{75+}/RR_{15-74}) was 1.05 (95% CI: 1.02, 1.07) (**Figure 4**). We found that the pooled RRR for low SES compared to high SES groups ($RR_{lowSES}/RR_{highSES}$) was 1.02 (95% CI: 1.00, 1.03) (**Figure 5**). Evidence of bias (assessed with Egger's test) was apparent for studies that assessed sex and age > 75 years as vulnerable factors, but not for age > 65 years and SES (see Supplemental Material: Figure 1S to Figure 4S).

Meta-regression results

The large heterogeneity (all $I^2 > 50\%$) found in the pooled RRR suggests the existence of study characteristics influencing this variability. We conducted meta-regression analyses to assess the influence of different study characteristics on meta-analysis heterogeneity. Of the study characteristics assessed for articles exploring age > 75 years, only the association measures were significantly related to the heterogeneity in the pooled RRR. The use of the percentage increase comparing two percentiles of the temperature distribution was associated with a higher vulnerability for elderly aged more than 75 years. For SES studies, both SES measures and association measures were significantly related to the heterogeneity in the pooled RRR. The use of the percentage increase comparing two percentiles of the temperature distribution as association measure, and the use of individual SES measures were associated with a higher vulnerability for low SES groups. The pooled estimate for the ratios for age > 75 years vs. younger age groups, adjusted for the association measure, was 1.11 (95% CI: 1.04, 1.19). The pooled ratio for low vs. high SES, adjusted for SES measures and measures of associations, were respectively 1.034 (95% CI: 1.01, 1.05) and 1.05 (95% CI: 1.03, 1.07). It is interesting to note that for SES, when adjusting for the association measure, the I^2 fell to 37.47%, which represents a low degree of heterogeneity in the pooled RRR. The meta-regression results for SES are presented in **Table 5** and other meta-regression results for sex, age > 65 years and > 75 years are presented in Supplemental Material (Table 3S to Table 5S).

5. Discussion

Summary of results

In this systematic review we assessed the evidence supporting the presence of subgroups vulnerable to heat-related mortality. Using the Cochran Q test we consistently found evidence of vulnerability for the elderly aged more than 85 years. Vulnerability was also noted, in heat waves studies, for populations living in hot places and for unmarried people, and in high ambient temperature studies, for people living in areas with a low percentage of households with central air conditioning, although very few assessments were available. On the other hand, results of the meta-analyses (focusing on high ambient temperature studies only) showed that women, elderly persons (of more than 65 and more than 75 years) and low SES groups were more vulnerable than their respective counterparts using the pooled estimate (RRR). It is difficult to entirely compare the two approaches. However our results suggest that even without concordance using the Cochran Q test, estimating an overall effect (i.e. considering variability between and within studies) will suggest heterogeneous effects for some subgroups. Yet some pooled estimates were close to homogeneous, varying from 0.98 (95% CI: 0.96, 0.99) for sex to 1.11 (95% CI: 1.04, 1.19) for age > 75 after meta-regression adjustment, suggesting that while statistical heterogeneity can be detected, effects between subgroups are nonetheless roughly comparable in policy terms.

Comparison of the results with actual knowledge

The results of the present study can be compared to factors of vulnerability reported in various institutional guidelines, aimed at guiding interventions for the prevention of heat-related mortality (e.g. the WHO heat action plan) (WHO 2008a, b). Heat action plans include heat warning systems during heat waves, plans for emergency measures, as well as actions aimed at reducing high ambient temperatures over the long term (e.g. greening activities).

In the European WHO heat health action plan (WHO 2008b), the vulnerable subgroups identified are the elderly, infants and children, people with chronic diseases, people taking particular medications, people with low SES, and people in specific occupations. The identification of elderly people and those from low SES subgroups as being of particular vulnerability is concordant with our results. Lowe et al. (2011) (Lowe, Ebi, and Forsberg 2011), in assessing the content of 12 European heat health action plans, also reported that in most of them (11/12), the elderly, children, the chronically ill, and those on medication were considered vulnerable subgroups. Thus, it appears that some subgroups identified as vulnerable in both the heat action plans and in guidelines for planning were not assessed, or not reported as having heterogeneous associations with mortality, in the present study. Other potential sources for their statements may include the grey literature (Brucker 2003), local community knowledge (Abrahamson et al. 2009), or epidemiologic studies not included in this review (e.g. case-control studies). For example, Bouchama et al. (2007) (Bouchama et al. 2007) conducted a meta-analysis of 6 case-control studies on heat waves-related mortality, and found that both not leaving home daily, and having a pre-existing illness, were associated with higher risk, while high social contact, and having air conditioning, were protective. However, even where action plans and guidelines are consistent with our results, the universality of the vulnerability findings has to be interpreted with caution for some subgroups (e.g. women), since the overall estimates we found were quite modest in magnitude on the relative scale.

Limits of the review

This review has some limitations. First, a number of studies were excluded given that the Cochran Q test could not be performed. Nonetheless, for most vulnerability factors (such as sex, age and SES), it was possible to calculate heterogeneity. In addition, the assessment of vulnerability was, for some subgroups, based only on one or two comparisons (e.g. social isolation), which provides limited evidence regarding these specific vulnerability factors. In addition, by excluding factors that have been assessed in the literature only once, it is possible that we omitted important and real effects in the review.

In epidemiologic studies addressing inequalities in the health effects of heat, such as those included in this review, the relative scale is used and the absolute scale is often ignored (King, Harper, and Young 2012). However, baseline risks can differ considerably across different subgroups, as for elderly compared to younger adults. Using absolute measures when addressing vulnerabilities reflects not only differences in health impacts across different subgroups, but can be a more useful public health strategy, as risk difference corresponds directly to attributable cases (Lynch et al. 2006; Yang et al. 2014). Moreover, absolute measures can highlight different patterns of inequalities between subgroups than relative measures (Harper et al. 2010; Lynch et al. 2006).

We conducted meta-analyses only for high ambient temperature studies to minimize the differences between study designs and methods of analysis. Still, we found a large heterogeneity between studies (all $I^2 > 50\%$), which makes the interpretation of an overall estimate difficult (Garg, Hackam, and Tonelli 2008; Lau, Ioannidis, and Schmid 1998). Hence, we conducted meta-regression analyses to investigate factors associated with the magnitude of the RRR, and found that only the inclusion of association measures reduced the I^2 estimate to below 50% for the SES meta-analysis. However, other study-related factors that were not assessed in this review, such as population structures (e.g. proportion of elderly, sex ratio), presence of local heat action plans, or latitude (Hajat and Kosatky 2010), could explain some of the residual heterogeneity.

We assessed socioeconomic vulnerability to heat, considering together income, education, immigration status, deprivation composite indexes, and other ecological or individual characteristics, assuming that they represent the same phenomenon. However, the various individual and/or ecological socioeconomic measures may not represent the same social dimension (Braveman et al. 2005; Galobardes, Lynch, and Smith 2007; Oakes and Rossi 2003; Shavers 2007). For example, education may influence the understanding of preventive messages, while income may limit access to air conditioning.

Finally, as many vulnerability definitions exist, the one adopted in our study could be disputed (Alwang, Siegel, and Jorgensen 2001; Delor and Hubert 2000). We chose an epidemiological definition (i.e. effect measure modification) to identify factors of vulnerability to heat, but vulnerability can encompass other dimensions beyond this definition (e.g. including the notion of social trajectory) (Delor and Hubert 2000). Also, in the literature reviewed in this paper, vulnerability factors were considered separately, but it is reasonable to think that several modifying factors might interact synergistically in the heat-related mortality relationship.

Recommendations for studies on the relationship between heat and death

We noted some limitations in the selected studies of our review, so here we present recommendations to guide further research on heat-related mortality vulnerability. As noted above, the absolute scale is rarely used in this context; therefore we encourage integrating risk differences in case-crossover designs. The use of novel inequality measures in time-series analyses is also encouraged, such as use of the Index of Disparity

(Pearcy and Keppel 2002), or simple measurement of differences in daily death counts between two subgroups as outcomes (Benmarhnia et al. 2014; Harper et al. 2010).

We excluded both cause of death and place of death as modifying factors as they are subcategories of the outcome (i.e. mortality). In the studies reviewed, causes of death for instance were used as proxies for existing cardiovascular or respiratory diseases. We argue that this is an inappropriate proxy as these factors are themselves due to heat (i.e. affected by exposure). Even if effect estimates across these strata can be heterogeneous, they do not constitute a modifying factor. This point should be further explored using appropriately designed studies with prospective data, in which the diagnosis of a pre-existing illness is used, as was undertaken in a recent paper on elderly persons (Zanobetti et al. 2012).

The causal pathways linking vulnerability factors (i.e. modifying factors) are complex and need further consideration. More efforts are needed in the inclusion of causal inference methods to properly consider the role of measured individual or contextual determinants in the heat-related mortality studies, and their synergic influence. Using directed acyclic graphs (DAGs) can be useful for identifying inappropriate practices in causal structures investigating vulnerable subgroups to heat-related mortality (Shrier and Platt 2008; VanderWeele and Robins 2007), as illustrated with respect to confounding in two recent papers (Buckley, Samet, and Richardson 2014; Reid et al. 2012). Methodological developments are also required since the distinction between individual and contextual factors remains unclear, and methods used to date do not permit one to elucidate the effect of place characteristics on individual outcomes while accounting for non-independence of observations (Greenland 2000; Naess et al. 2007).

Policy implications

While the link between excess heat and mortality is well established, the fundamental evidence on heat-vulnerable subgroups that is necessary for public health policy development remains incomplete. Knowledge about vulnerable subgroups is essential for the success of public health programs (Balbus and Malina 2009; Benach et al. 2011; Frohlich and Potvin 2008), and is necessary for the application of blended intervention strategies, such as proportionate universalism and targeting within universalism (Lawrence, Stoker, and Wolman 2013; Skocpol 1991). Where specific interventions are planned to reduce health impacts in vulnerable populations or territories – such as adapted campaigns or urban modifications – misclassification of vulnerability status may challenge intervention effectiveness and implementation success.

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8. Tables and Figures

Table 1: Characteristics of high ambient temperature studies included in the review (n=33)

Studies	**Location**	**Published**	**Period**	**Study Design**	**Ambient Temperature Measure**	**Vulnerability Subgroups Included**
Almeida et al. (Almeida, Casimiro, and Analitis 2013)	Portugal	2013	2000-2004	Time series	Daily maximum apparent T°	Age
Baccini et al. (Baccini et al. 2008)	12 countries in Europe	2008	1990–2000	Time series	Daily maximum apparent T° (except for the city of Barcelona where daily mean apparent T° was used)	Age
Basu et al. (Basu and Ostro 2008)	USA	2008	1999–2003	Case-crossover	Daily mean apparent T°	Age, Individual SES (ethnic group)
Bell et al. (Bell et al. 2008)	Brazil, Chile and Mexico	2008	1998-2002	Case-crossover	Daily mean apparent T°	Sex, Age, Individual SES (education)
Burkart et al. (Burkart et al. 2013)	Bangladesh	2013	2008	Time series	Universal thermal climate index (b)	Sex, Age (elderly and children), Population density, Ecological SES
Chan et al. (Chan et al. 2012)	China	2012	1998-2006	Time series	Daily mean T°	Sex, Age, Individual and ecological SES, Population density, Social isolation
Egondi et al. (Egondi et al. 2012)	Kenya	2012	2003-2008	Time series	Daily minimum and maximum T°	Sex
Goggins et al. (Goggins et al. 2012)	China	2012	2001-2009	Time series	Daily mean T°	Ecological SES, Intra-urban heat variations

Gomez-Alcebo et al. (Gomez-Acebo et al. 2012)	Spain	2012	2003-2006	Time series	Daily mean, maximum, and minimum T°	Sex, Age (elderly)
Gouveia et al. (Gouveia, Hajat, and Armstrong 2003)	Brazil	2003	1991-1994	Time series	Daily mean, maximum, and minimum T°	Age (elderly and children), Ecological SES
Hajat et al. (Hajat et al. 2005)	Brazil, England and India	2005	1991-2004	Time series	Daily minimum and maximum T°	Age (elderly and children)
Hajat et al. (Hajat, Kovats, and Lachowycz 2007)	England	2007	1993-2003	Time series	Daily minimum and maximum T°	Sex, Age, Ecological SES
Ishigami et al. (Ishigami et al. 2008)	England, Hungary and Italy	2008	1993-2004	Time series	Daily mean T°	Ecological SES
Kim et al. (Kim and Joh 2006)	South Korea	2006	2000-2002	Time series	Daily maximum T°	Individual SES (income)
Leone et al. (Leone et al. 2013)	7Mediterranean countries	2013	1991-2007	Time series	Daily maximum apparent T°	Age (elderly and children)
Ma et al. (Ma et al. 2012)	China	2012	2001-2004	Time series	Daily average T°	Sex, Age (elderly), Individual SES
Madrigano et al. (Madrigano et al. 2013)	USA	2013	1995-2003	Case-crossover	Daily apparent T°*	Sex, Age (elderly), Individual SES (ethnic group, income), Ecological SES (% poverty), Population density, Intra-urban heat variations
Medina-Ramon et al. (Medina-	USA	2007	1989-2000	Case-crossover	Daily maximum T°	Air conditioning, Population Density

Ramon and Schwartz 2007)						
Muggeo et al. (Muggeo and Hajat 2009)	Chile and Italy	2009	1989-1991; 1997-2001	Time series	Daily mean T°	Age (elderly)
O'Neill et al. (O'Neill, Zanobetti, and Schwartz 2003)	USA	2003	1986-1993	Time series	Daily mean apparent T°	Sex, Age (elderly), Individual SES (ethnic group, education)
O'Neill et al. (O'Neill, Zanobetti, and Schwartz 2005)	USA	2005	1986-1994	Time series	Daily mean apparent T°	Individual SES (ethnic group)
Rocklov et al. (Rocklov, Ebi, and Forsberg 2011)	Sweden	2011	1990-2002	Time series	Daily maximum apparent T°	Age (elderly)
Smargiassi et al. (Smargiassi et al. 2009)	Canada	2009	1990-2003	Case-crossover	Daily mean T°	Ecological SES (lodging value), Intra-urban heat variations
Son et al. (Son et al. 2011)	South Korea	2011	2000-2007	Time series	Daily mean T°	Sex, Age (elderly), Individual SES (education)
Stafoggia et al. (Stafoggia et al. 2006)	Italy	2006	1997-2003	Case-crossover	Daily mean apparent T°	Sex, Age (elderly), Individual SES (income), Social isolation
Stafoggia et al. (Stafoggia et al. 2008)	Italy	2008	1997-2004	Case-crossover	Daily mean apparent T°	Sex, Age (elderly), Individual SES (income), Social isolation
Urban et al. (Urban, Davídkovová, and Kysely 2013)	Czech Republic	2013	1994-2009	Time series	Daily mean T°	Sex

Vaneckova et al. (Vaneckova et al. 2008)	Australia	2008	1993-2004	Time series	Daily maximum T°	Age (elderly)
Wang et al. (Wang et al. 2013)	China	2013	2005-2008	Time series	Daily mean T°	Sex, Age (elderly), Individual SES (education)
Xu et al. (Xu et al. 2013a)	China	2013	1998-2009	Time series	Daily mean apparent T°	Sex
Yang et al. (Yang et al. 2012)	China	2012	2003-2007	Time series	Daily mean T°	Sex, Age (elderly), Individual SES (education, occupation)
Yu et al. (Yu et al. 2010)	Australia	2010	1996-2004	Time series	Daily mean T°	Sex, Age (elderly), Ecological SES)
Yu et al. (Yu et al. 2011)	Australia	2011	1996-2004	Time series	Daily mean T°	Age (elderly)

T°: Temperature

* Extreme temperature was also used in this study but we only included estimates for daily apparent temperature.

Table 2: Characteristics of heat waves studies included in the review (n=17)

Studies	Location	Published	Period	Study Design	Heat Wave Definition	Vulnerabilty Subgroups Included
Anderson et al. (Anderson and Bell 2009)*	USA	2009	1987-2000	Time series	Two consecutive days with mean T° above the 99.5th percentile	Age (elderly)
Basagana et al. (Basagana et al. 2011)	Spain	2011	1983–2006	Case-crossover	Days with maximum T° above the 95th percentile	Age (children)
Borell et al. (Borrell et al. 2006)	Spain	2006	2003	Descriptive	NA	Individual SES (education)
Fouillet et al. (Fouillet et al. 2006)	France	2006	2003	Descriptive	NA	Sex, Age (elderly and children), Social isolation
Huang et al. (Huang, Kan, and Kovats 2010)	China	2010	2003	Descriptive	Three consecutive days with maximum T°>35 °C	Sex, Age (elderly and children)
Hutter et al. (Hutter et al. 2007)	Austria	2007	1998-2004	Time series	Three consecutive days with mean T°>30 °C	Sex
Kyseli et al. (Kysely and Kim 2009)	South Korea	2009	1991-2005	Descriptive	Three consecutive days with a daily heat index >33 °C	Sex, Age (elderly)
Lan et al. (Lan et al. 2012)	China	2012	2009-2010	Descriptive	Days with maximum T° above the 98th percentile	Sex, Age (elderly)
Medina- Ramon et al. (Medina-Ramon and Schwartz 2007)	USA	2007	1989-2000	Case-crossover	Days with maximum T° above the 99th percentile	Air Conditionning, Population Density

Nitschke et al. (Nitschke, Tucker, and Bi 2007)	Australia	2007	1993-2004	Descriptive	Three consecutive days with max T°>35 °C	Age (elderly and children)
Nitschke et al. (Nitschke et al. 2011)	Australia	2011	1993-2009	Descriptive	Three consecutive days with max T°>35 °C	Age (elderly and children)
Rey et al. (Rey et al. 2009)	France	2009	2000-2003	Descriptive	NA	Ecological SES (deprivation index)
Robine et al. (Robine, Michel, and Herrmann 2012)	16 european countries	2012	1998-2003	Descriptive	NA	Sex
Rooney et al. (Rooney et al. 1998)	England and Wales	1998	1995	Descriptive	NA	Sex, Age (elderly)
Schifano et al. (Schifano et al. 2009)	Italy	2009	2005-2007	Time series	A heat wave episode was defined when daily maximum T° rises above a monthly threshold	Sex, Ecological SES, Social isolation
Son et al. (Son et al. 2012)	South Korea	2012	2000-2007	Time series	Two consecutive days with mean T° above the 98th percentile	Sex, Age (elderly), Individual SES (education)
Xu et al. (Xu et al. 2013b)	Spain	2013	1999-2006	Case-crossover	Days with maximum T° above the 95th percentile	Age (elderly), Ecological SES, Intra-urban heat variations, Air conditioning

NA: not available; T°: Temperature

* The study by Anderson et al. 2009 was retained only for heat waves studies. For the high ambient temperature effects, the results they present do not meet our inclusion criterion.

Table 3: Heterogeneity findings for high ambient temperature studies (n=33)

Vulnerability Factor	**Subcategories**	**Studies**	**Number of Estimations Found Heterogeneous**^{a}
Sex	**Men vs. Women**	**17:** Bell 2008, Burkart 2013, Chan 2012, Egondi 2012, Gomez Acebo 2012, Hajat 2007, Ma 2012, Madrigano 2013, O'Neill 2003, Son 2011, Stafoggia 2006, Stafoggia 2008, Urban 2013, Wang 2013, Xu 2013, Yang 2012, Yu 2010.	Men (1/21), Women (6/21)
Elderly^{b}	**More than 65 (b)**: Elderly (>=65 yrs pooled) vs. Non elderly (<64 yrs)	**22:** Almeida 2013, Baccini 2008, Basu 2008, Bell 2008, Burkart 2013, Chan 2012, Gomez Acebo 2012, Hajat 2005, Hajat 2007, Leone 2013, Ma 2012, Madrigano 2013, Muggeo 2009, O'Neill 2003, Rocklov 2011, Son 2011, Stafoggia 2006, Vaneckova 2008, Wang 2013, Yang 2012, Yu 2010, Yu 2011.	Elderly (30/49), Non-elderly (0/49)
	More than 75 (b): Elderly (>=75 yrs pooled) vs. Non elderly (<74 yrs)	**9:** Anderson 2009, Baccini 2008, Chan 2012, Gomez Acebo 2012, Hajat 2007, Leone 2013, Stafoggia 2006, Yang 2012, Yu 2010.	Elderly (17/19), Non-elderly (0/19)
	More than 85 (b): Elderly (>=85 yrs) vs. Non elderly (<84 yrs)	**6:** Gomez Acebo 2012, Hajat 2007, Stafoggia 2006, Yang 2012, Yu 2010, Yu 2011.	Elderly (8/8), Non-elderly (0/8)
Children	**Less than 5 (b):** children (<= 5 yrs) vs. All adults non elderly (<65 yrs)	**4:** Basu 2008, Burkart 2013, Gouveia 2003, Hajat 2005	Children (3/7), Adults non-elderly (2/7)

SES	**All SES measures:** Low SES vs. High SES	**19:** Basu 2008, Bell 2008, Chan 2012, Goggins 2012, Gouveia 2003, Hajat 2007, Ishigami 2008, Kim 2006, Ma 2012, Madrigano 2013, O'Neill 2003, O'Neill 2005, Smargiassi 2009, Son 2011, Stafoggia 2006, Stafoggia 2008, Wang 2013, Yang 2012, Yu 2010.	Low SES (13/29), High SES (3/29)
	All individual SES measures: Low SES vs. High SES	**11:** Basu 2008, Bell 2008, Chan 2012, Kim 2006, Ma 2012, Madrigano 2013, O'Neill 2003, O'Neill 2005, Son 2011, Wang 2013, Yang 2012.	Low SES (7/15), High SES (0/15)
	All ecological SES measures: Low SES vs. High SES	**10:** Chan 2012, Goggins 2012, Gouveia 2003, Hajat 2007, Ishigami 2008, Madrigano 2013, Smargiassi 2009, Stafoggia 2006, Stafoggia 2008, Yu 2010.	Low SES (6/14), High SES (2/14)
Urban Design and Housing	**Intra-urban heat variations**: hot places vs. Cool places	**3:** Goggins 2012, Madrigano 2013, Smargiassi 2009.	Hot places (2/7), Cool places (1/7)
	Air Conditioning: Low AC vs. High AC	**1:** Medina Ramon 2007	Low AC (1/1), High AC (0/1)
	Population density: High Density places vs. Low Density places	**4:** Burkart 2013, Chan 2012, Madrigano 2013, Medina Ramon 2007.	High density places (3/6), Low density places (0/6)
Social isolation	Not married vs. Married	**3:** Chan 2012, Stafoggia 2006, Stafoggia 2008.	Not Married (2/3), Married (0/3)

a: When multiple analyses were conducted in the same study, for different cities or for different time periods, we assessed the heterogeneity between different strata separately. That is why there are more strata comparisons than the number of studies finally included. b: For elderly, we gathered the age groups equal to or more 65 years and compared them to the age groups under 65 years, we gathered the age groups equal to or more 75 years and compared them to the age groups under 75 years, and we gathered the age groups equal to or more 85 years and compared them to the age groups under 85 years. For children, we gathered the age groups under 5 years and compared them to adult groups under 65.

Table 4: Heterogeneity findings for heat waves studies (n=17)

Vulnerability Factor	**Subcategories**	**Studies**	**Number of Estimations Found Heterogeneous**[a]
Sex	**Men vs. Women**	**8:** Fouillet 2006, Huang 2010, Hutter 2007, Lan 2012, Robine 2012, Rooney 1998, Schifano 2009, Son 2012.	Men (1/9), Women (4/9)
Elderly[b]	**More than 65 (b)**: Elderly (>=65 yrs pooled) vs. Non elderly (<64 yrs)	**9:** Fouillet 2006, Huang 2010, Kysely 2009, Lan 2012, Nitschke 2007, Nitschke 2011, Rooney 1998, Son 2012, Xu 2013.	Elderly (6/16), Non-elderly (3/16)
	More than 75 (b): Elderly (>=75 yrs pooled) vs. Non elderly (<74 yrs)	**7:** Fouillet 2006, Kysely 2009, Lan 2012, Nitschke 2007, Nitschke 2011, Rooney 1998, Son 2012.	Elderly (5/9), Non-elderly (1/9)
	More than 85 (b): Elderly (>=85 yrs) vs. Non elderly (<84 yrs)	**1:** Rooney 1998.	Elderly (2/2), Non-elderly (0/2)
Children	**Less than 5 (b):** children (<= 5 yrs) vs. All adults non elderly (<65 yrs)	**5:** Fouillet 2006, Huang 2010, Nitschke 2007, Nitschke 2011, Rooney 1998.	Children (2/7), Adults non-elderly (3/7)
SES	**All SES measures**: Low SES vs. High SES	**5:** Borell 2006, Rey 2009, Schifano 2009, Son 2012, Xu 2013.	Low SES (3/8), High SES (1/8)
Urban Design and Housing	**Intra-urban heat variations**: hot places vs. Cool places	**1:** Xu 2013.	Hot places (2/2), Cool places (0/2)
	Air Conditioning: Low AC vs. High AC	**1:** Xu 2013.	Low AC (0/1), High AC (0/1)
Social isolation	Not married vs. Married	**2:** Fouillet 2006, Schifano 2009.	Not Married (2/2), Married (0/2)

a: When multiple analyses were conducted in the same study, for different cities or for different time periods, we assessed the heterogeneity between different strata separately. That is why there are more strata comparisons than the number of studies finally included. b: For elderly, we gathered the age groups equal to or more 65 years and compared them to the age groups under 65 years, we gathered the age groups equal to or more 75 years and compared them to the age groups under 75 years, and we gathered the age groups equal to or more 85 years and compared them to the age groups under 85 years. For children, we gathered the age groups under 5 years and compared them to adult groups under 65.

Table 5: Meta-regression model investigating the predictors of the log [ratio of relative risks] for SES [a]

Independent Variable [b]		**Beta (95% CI)**	***P* Value**	**R^2** [c]	**Residual I^2** [d]	**Adjusted Pooled Ratio (95% CI)**
SES measure		-0.03 (-0.06 to -0.00)	**0.04**	0.31	56.55%	1.03 (1.01 to 1.05)
Study design		-0.01 (-0.05 to 0.03)	0.78	-0.08	66.86%	1.02 (0.99 to 1.06)
Continent	Europe	reference	0.08*	0.65	50.33%	1.03 (1.00 to 1.05)
	America	0.03 (-0.00 to 0.07)				
	Asia/Australia	0.03 (-0.01 to 0.07)				
Association measure		-0.04 (-0.07 to -0.02)	**0.00**	0.83	37.47%	1.05 (1.03 to 1.07)

[a] Model with the log[ratio of relative risks] as dependent variable. The meta-regression analysis was performed using data from 23 studies.

b Independent variables represent a) for SES measure: individual measure or ecological measure; b) for study design: case-crossover or time series; c) for continent: Europe or America or Asia/Australia; d) for association measure: percentage increase comparing two percentiles of the temperature distribution or percentage changes associated with degree units increases above a city-specific threshold.

[c] Reflects the proportion of the variability in the log[ratio of relative risks] explained by the statistical model.

[d] Reflects the percentage of the residual variation that is attributable to between-study heterogeneity. The initial I^2 was 67.6%

* The *P* value corresponds to a joint test for all covariates with Knapp-Hartung modification.

CI: Confidence Interval

Figure Legends

Figure 1: Flowchart outlining study selection

Figure 2: Meta-analysis of the ratio of the RRs according to sex (RR_{men}/RR_{women}); ES: Effect Size

Figure 3: Meta-analysis of the ratio of the RRs according to age65 (individuals aged > 65 years, compared to adults aged between 15 and 64 years) (RR_{65+}/RR_{15-64}); ES: Effect Size

Figure 4: Meta-analysis of the ratio of the RRs according to age75 (individuals aged > 75 years, compared to adults aged between 15 and 74 years) (RR_{75+}/RR_{15-74}); ES: Effect Size

Figure 5: Meta-analysis of the ratio of the RRs according to SES ($RR_{lowSES}/RR_{highSES}$); ES: Effect Size

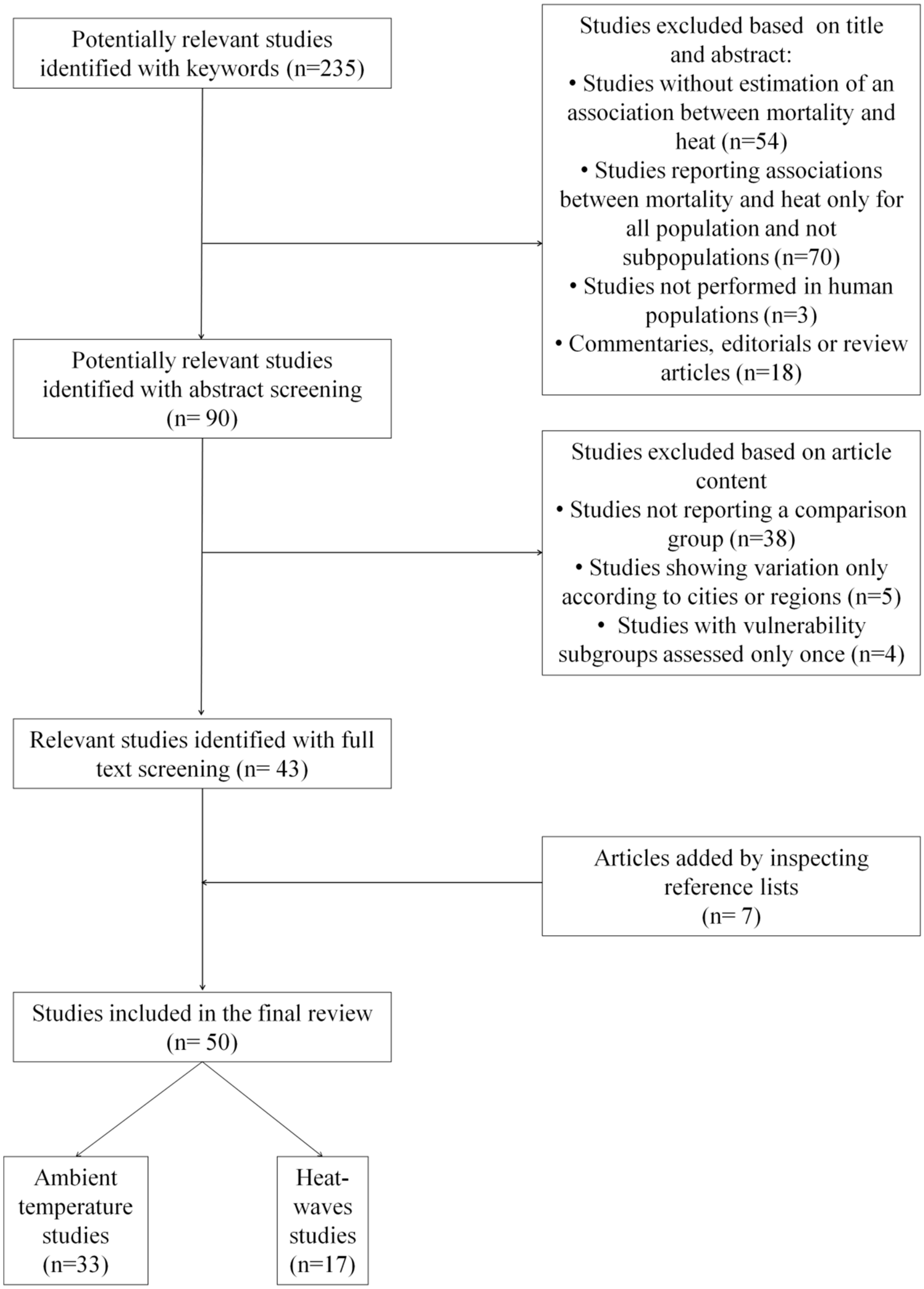

Potentially relevant studies identified with keywords (n=235)
Studies excluded based on title and abstract:
• Studies without estimation of an association between mortality and heat (n=54)
• Studies reporting associations between mortality and heat only for all population and not subpopulations (n=70)
• Studies not performed in human populations (n=3)
• Commentaries, editorials or review articles (n=18)
Potentially relevant studies identified with abstract screening (n= 90)
Studies excluded based on article content
• Studies not reporting a comparison group (n=38)
• Studies showing variation only according to cities or regions (n=5)
• Studies with vulnerability subgroups assessed only once (n=4)
Relevant studies identified with full text screening (n= 43)
Articles added by inspecting reference lists (n= 7)
Studies included in the final review (n= 50)
Ambient temperature studies (n=33)
Heat-waves studies (n=17)

Figure 1

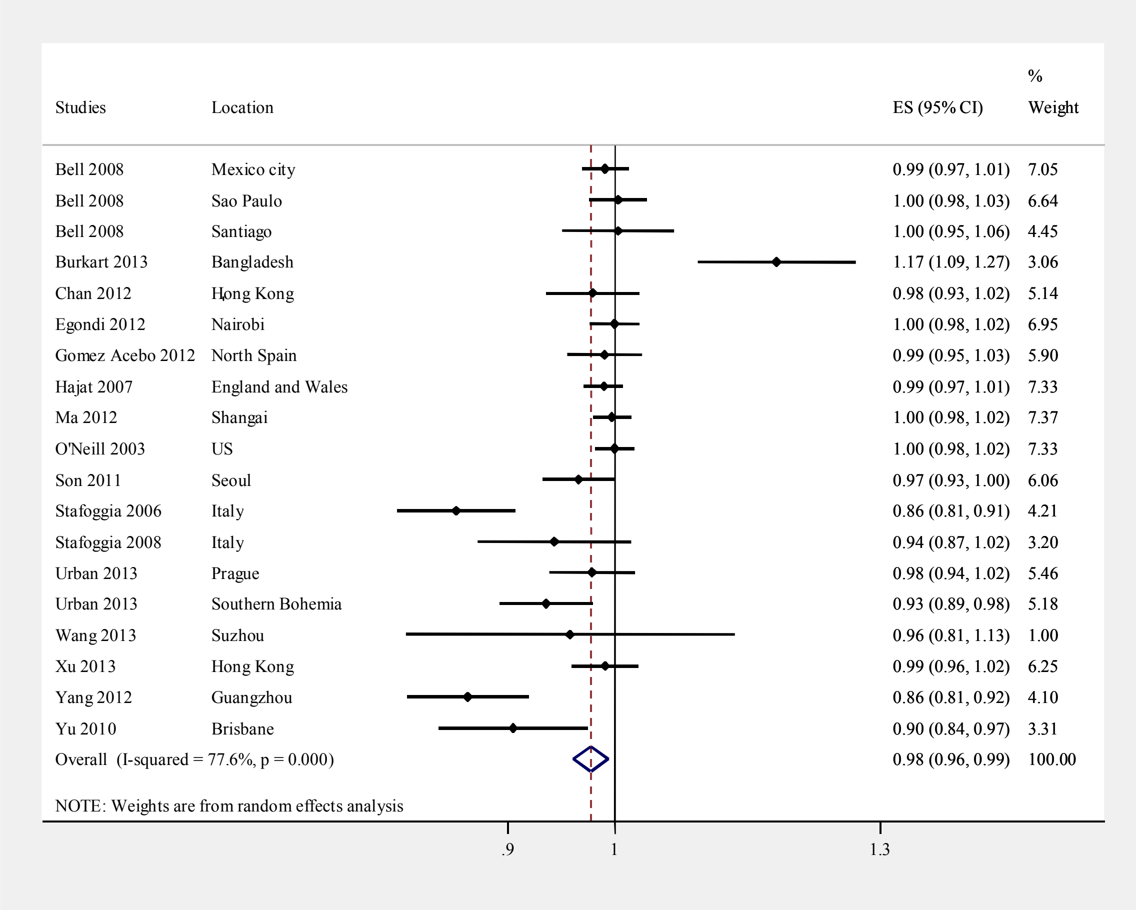

Studies Location ES (95% CI) % Weight
Bell 2008 Mexico city 0.99 (0.97, 1.01) 7.05
Bell 2008 Sao Paulo 1.00 (0.98, 1.03) 6.64
Bell 2008 Santiago 1.00 (0.95, 1.06) 4.45
Burkart 2013 Bangladesh 1.17 (1.09, 1.27) 3.06
Chan 2012 Hong Kong 0.98 (0.93, 1.02) 5.14
Egondi 2012 Nairobi 1.00 (0.98, 1.02) 6.95
Gomez Acebo 2012 North Spain 0.99 (0.95, 1.03) 5.90
Hajat 2007 England and Wales 0.99 (0.97, 1.01) 7.33
Ma 2012 Shangai 1.00 (0.98, 1.02) 7.37
O'Neill 2003 US 1.00 (0.98, 1.02) 7.33
Son 2011 Seoul 0.97 (0.93, 1.00) 6.06
Stafoggia 2006 Italy 0.86 (0.81, 0.91) 4.21
Stafoggia 2008 Italy 0.94 (0.87, 1.02) 3.20
Urban 2013 Prague 0.98 (0.94, 1.02) 5.46
Urban 2013 Southern Bohemia 0.93 (0.89, 0.98) 5.18
Wang 2013 Suzhou 0.96 (0.81, 1.13) 1.00
Xu 2013 Hong Kong 0.99 (0.96, 1.02) 6.25
Yang 2012 Guangzhou 0.86 (0.81, 0.92) 4.10
Yu 2010 Brisbane 0.90 (0.84, 0.97) 3.31
Overall (I-squared = 77.6%, p = 0.000) 0.98 (0.96, 0.99) 100.00
NOTE: Weights are from random effects analysis
.9
1
1.3

Figure 2

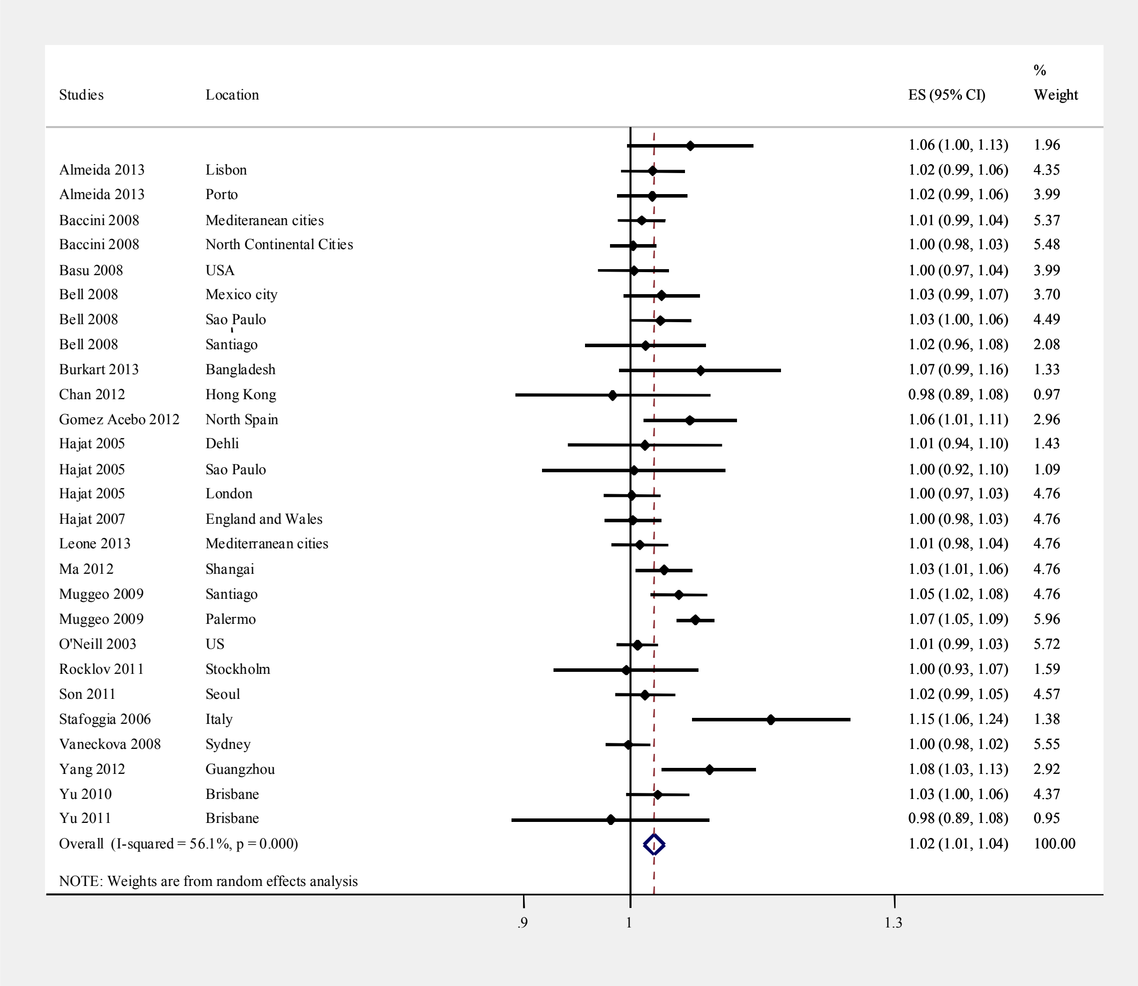

Studies
Location
ES (95% CI)
% Weight
1.06 (1.00, 1.13) 1.96
Almeida 2013 Lisbon 1.02 (0.99, 1.06) 4.35
Almeida 2013 Porto 1.02 (0.99, 1.06) 3.99
Baccini 2008 Mediteranean cities 1.01 (0.99, 1.04) 5.37
Baccini 2008 North Continental Cities 1.00 (0.98, 1.03) 5.48
Basu 2008 USA 1.00 (0.97, 1.04) 3.99
Bell 2008 Mexico city 1.03 (0.99, 1.07) 3.70
Bell 2008 Sao Paulo 1.03 (1.00, 1.06) 4.49
Bell 2008 Santiago 1.02 (0.96, 1.08) 2.08
Burkart 2013 Bangladesh 1.07 (0.99, 1.16) 1.33
Chan 2012 Hong Kong 0.98 (0.89, 1.08) 0.97
Gomez Acebo 2012 North Spain 1.06 (1.01, 1.11) 2.96
Hajat 2005 Dehli 1.01 (0.94, 1.10) 1.43
Hajat 2005 Sao Paulo 1.00 (0.92, 1.10) 1.09
Hajat 2005 London 1.00 (0.97, 1.03) 4.76
Hajat 2007 England and Wales 1.00 (0.98, 1.03) 4.76
Leone 2013 Mediterranean cities 1.01 (0.98, 1.04) 4.76
Ma 2012 Shangai 1.03 (1.01, 1.06) 4.76
Muggeo 2009 Santiago 1.05 (1.02, 1.08) 4.76
Muggeo 2009 Palermo 1.07 (1.05, 1.09) 5.96
O'Neill 2003 US 1.01 (0.99, 1.03) 5.72
Rocklov 2011 Stockholm 1.00 (0.93, 1.07) 1.59
Son 2011 Seoul 1.02 (0.99, 1.05) 4.57
Stafoggia 2006 Italy 1.15 (1.06, 1.24) 1.38
Vaneckova 2008 Sydney 1.00 (0.98, 1.02) 5.55
Yang 2012 Guangzhou 1.08 (1.03, 1.13) 2.92
Yu 2010 Brisbane 1.03 (1.00, 1.06) 4.37
Yu 2011 Brisbane 0.98 (0.89, 1.08) 0.95
Overall (I-squared = 56.1%, p = 0.000) 1.02 (1.01, 1.04) 100.00
NOTE: Weights are from random effects analysis
.9
1
1.3

Figure 3

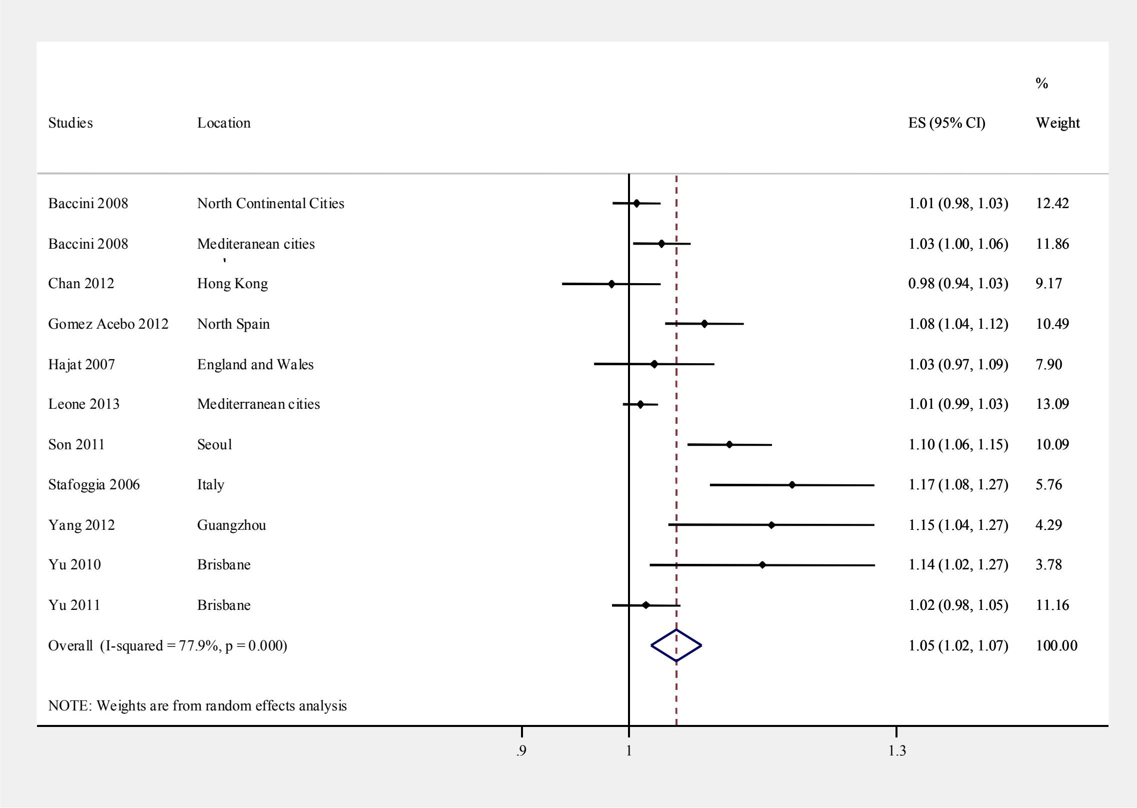

Studies
Location
ES (95% CI)
%
Weight
Baccini 2008
North Continental Cities
1.01 (0.98, 1.03)
12.42
Baccini 2008
Mediteranean cities
1.03 (1.00, 1.06)
11.86
Chan 2012
Hong Kong
0.98 (0.94, 1.03)
9.17
Gomez Acebo 2012
North Spain
1.08 (1.04, 1.12)
10.49
Hajat 2007
England and Wales
1.03 (0.97, 1.09)
7.90
Leone 2013
Mediterranean cities
1.01 (0.99, 1.03)
13.09
Son 2011
Seoul
1.10 (1.06, 1.15)
10.09
Stafoggia 2006
Italy
1.17 (1.08, 1.27)
5.76
Yang 2012
Guangzhou
1.15 (1.04, 1.27)
4.29
Yu 2010
Brisbane
1.14 (1.02, 1.27)
3.78
Yu 2011
Brisbane
1.02 (0.98, 1.05)
11.16
Overall (I-squared = 77.9%, p = 0.000)
1.05 (1.02, 1.07)
100.00
NOTE: Weights are from random effects analysis
.9
1
1.3

Figure 4

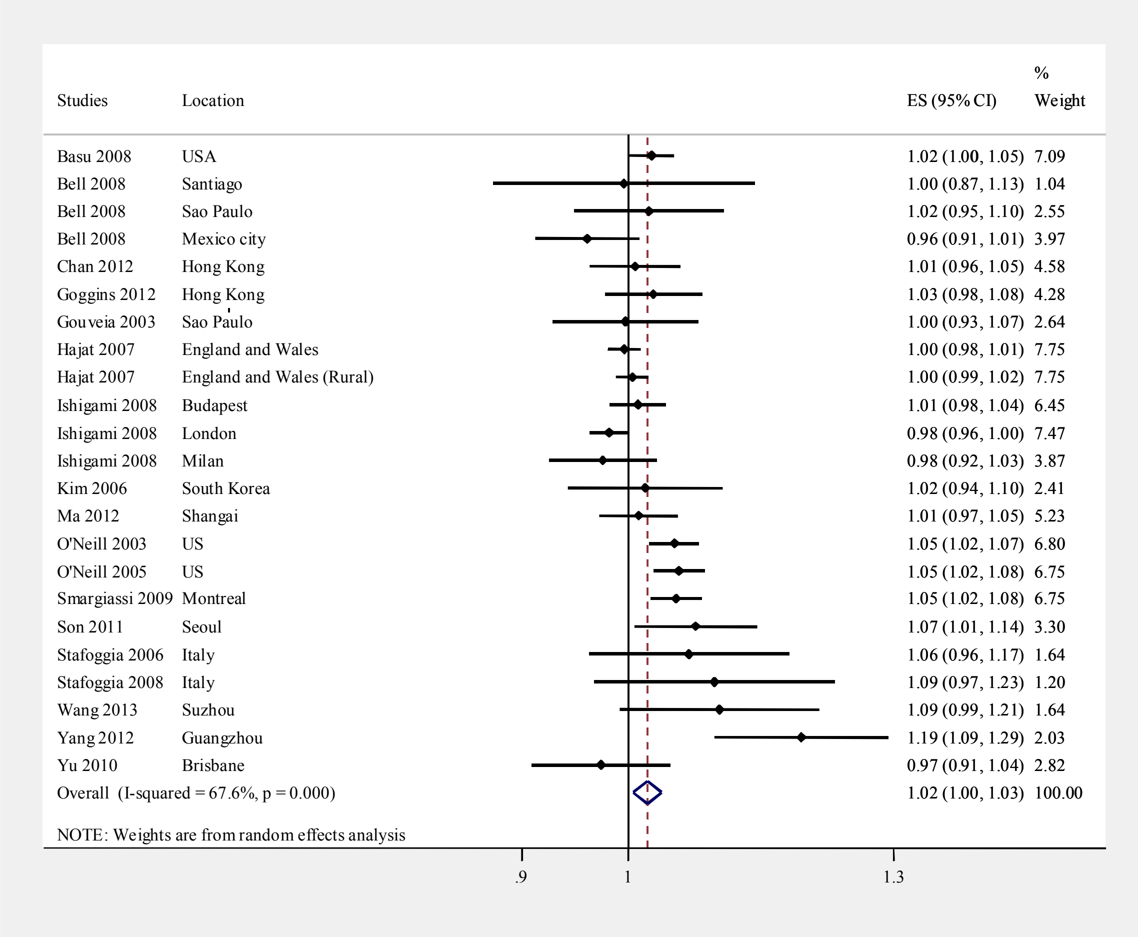

Studies
Location
ES (95% CI)
% Weight
Basu 2008 USA 1.02 (1.00, 1.05) 7.09
Bell 2008 Santiago 1.00 (0.87, 1.13) 1.04
Bell 2008 Sao Paulo 1.02 (0.95, 1.10) 2.55
Bell 2008 Mexico city 0.96 (0.91, 1.01) 3.97
Chan 2012 Hong Kong 1.01 (0.96, 1.05) 4.58
Goggins 2012 Hong Kong 1.03 (0.98, 1.08) 4.28
Gouveia 2003 Sao Paulo 1.00 (0.93, 1.07) 2.64
Hajat 2007 England and Wales 1.00 (0.98, 1.01) 7.75
Hajat 2007 England and Wales (Rural) 1.00 (0.99, 1.02) 7.75
Ishigami 2008 Budapest 1.01 (0.98, 1.04) 6.45
Ishigami 2008 London 0.98 (0.96, 1.00) 7.47
Ishigami 2008 Milan 0.98 (0.92, 1.03) 3.87
Kim 2006 South Korea 1.02 (0.94, 1.10) 2.41
Ma 2012 Shangai 1.01 (0.97, 1.05) 5.23
O'Neill 2003 US 1.05 (1.02, 1.07) 6.80
O'Neill 2005 US 1.05 (1.02, 1.08) 6.75
Smargiassi 2009 Montreal 1.05 (1.02, 1.08) 6.75
Son 2011 Seoul 1.07 (1.01, 1.14) 3.30
Stafoggia 2006 Italy 1.06 (0.96, 1.17) 1.64
Stafoggia 2008 Italy 1.09 (0.97, 1.23) 1.20
Wang 2013 Suzhou 1.09 (0.99, 1.21) 1.64
Yang 2012 Guangzhou 1.19 (1.09, 1.29) 2.03
Yu 2010 Brisbane 0.97 (0.91, 1.04) 2.82
Overall (I-squared = 67.6%, p = 0.000) 1.02 (1.00, 1.03) 100.00
NOTE: Weights are from random effects analysis
.9
1
1.3

Figure 5

9. Supplemental Material

Table 1S: Description of vulnerability indicators used

Individual SES	Ethnic group i) white, black; ii) white, non white; Education i) none, <=12 years, >12 years; ii) none, primary, secondary, University; iii) illiterate and primary school, middle school and above; iv) high school or less, more than high school; Income i) < median household income, > median household income; Employment status i) unemployed, employed; Migration status i) native born, migrant;
Ecological SES	Deprivation indexes stratified according to the median, terciles or quintiles; Neighbourhood median income stratified according to the median or terciles; Neighbourhood % poverty i) < median % household in poverty, > median % household in poverty; Neighbourhood lodging value < 25th percentile, >25th percentile; Neighbourhood % low education stratified into quintiles; Neighbourhood % manual workers stratified into quintiles; Neighbourhood % unemployment stratified into quintiles; Neighbourhood % old buildings stratified into quintiles; Neighbourhood % manual workers stratified into quintiles; Neighbourhood % old buildings stratified into quintiles;
Urban design and housing: intra-urban heat variations	Quartiles and quintiles of the neighbourhood's area proportion of micro heat islands, green spaces or water bodies, perception of little greenness;
Air conditioning	Quartiles of the percentage of households with central air conditioning; Quintiles of houses without air conditioning;
Population density	< median of the population density, > median of the population density;
Social isolation	Unmarried vs. married

Appendix 1S: Formula used for the heterogeneity assessment

<u>Cochran Q Test</u> (from ***Kaufman and MacLehose 2013***) (26)

$$Cochran's\ Q = \left[\frac{(\beta_1 - \beta_P)^2}{VAR(\beta_1)} + \frac{(\beta_2 - \beta_P)^2}{VAR(\beta_2)}\right]$$

Where β_1 *= ln (RRstrata*$_1$*);* β_2 *= ln (RRstrata*$_2$*); VAR is the variance*

For the Cochran Q estimation we just have to conduct a χ^2 *test statistic (with degrees of freedom equal to the number of strata minus 1)*

<u>Pooled estimates calculation</u> (from ***Kaufman and MacLehose 2013***) (26)

$$pooled = \frac{\frac{\beta_1}{Var(\beta_1)} + \frac{\beta_2}{Var(\beta_2)}}{\frac{1}{Var(\beta_1)} + \frac{1}{Var(\beta_2)}}$$

Where β *= ln RR;* β_1 *= ln (RR*$_1$*);* β_2 *= ln (RR*$_2$*); VAR is the variance*

Formula used to calculate the standard errors of the ratios

$$SD(ratio) = ratio \times \sqrt{\left(\frac{SD\ RR1^2}{RR1}\right) + \left(\frac{SD\ RR2^2}{RR2}\right)}$$

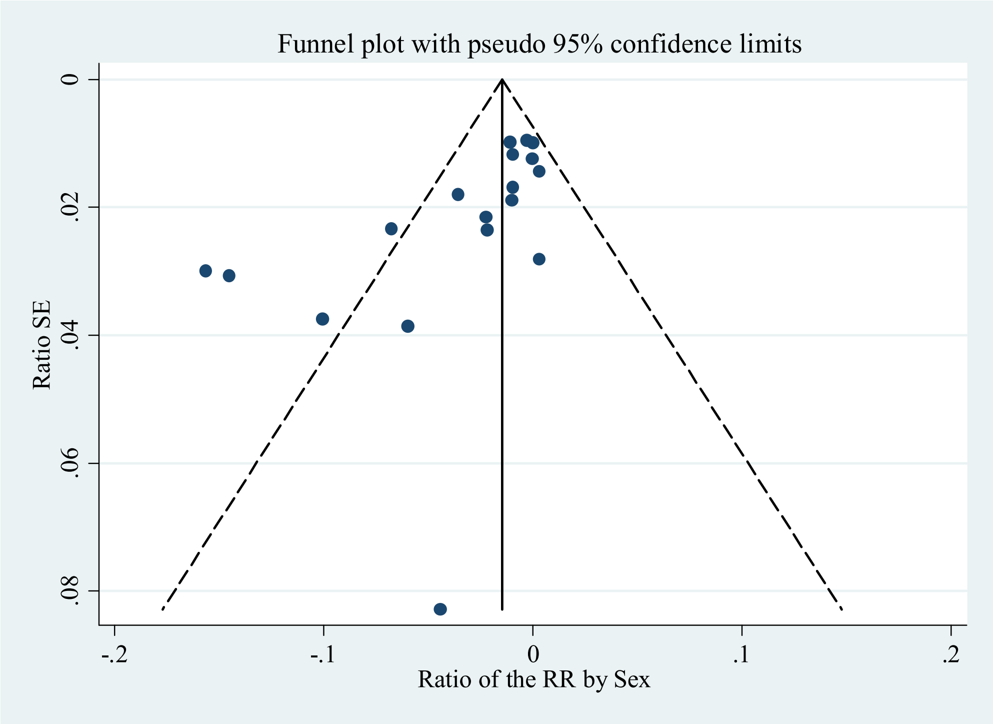
Where SD is Standard Deviation; RR1 represents the Relative Risk for the strata 1 and RR2 represents the Relative Risk for the strata 2.

Table 2S: Comparison of heterogeneity findings between ambient temperature and heat waves studies

Vulnerability Factor	Percentage of heterogeneity findings by vulnerability factor*	
	Ambient Temperature	Heat Waves
Sex	33%	56%
Elderly more than 65	61%	38%
Elderly more than 75	89%	56%
Elderly more than 85	100%	100%
Children	43%	29%
SES (individual and ecological measures)	26%	38%
Intra-urban heat variations	29%	100%
Social Isolation	67%	100%

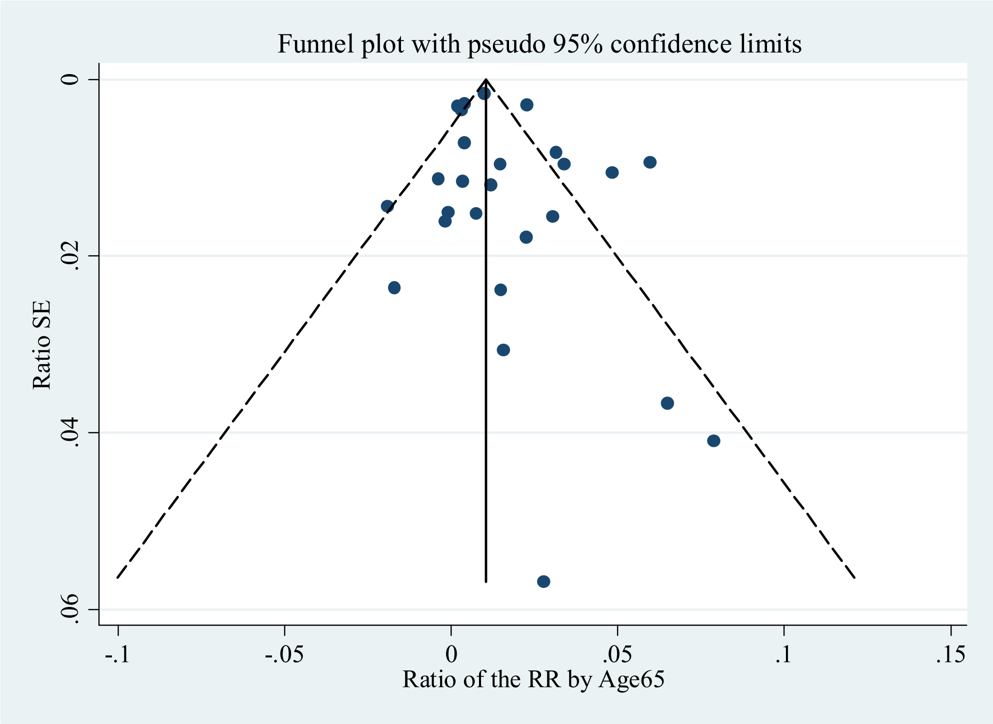
* These results are obtained from table 3 and table 4

Figure 1S: Publication bias assessment: ratio between men and women



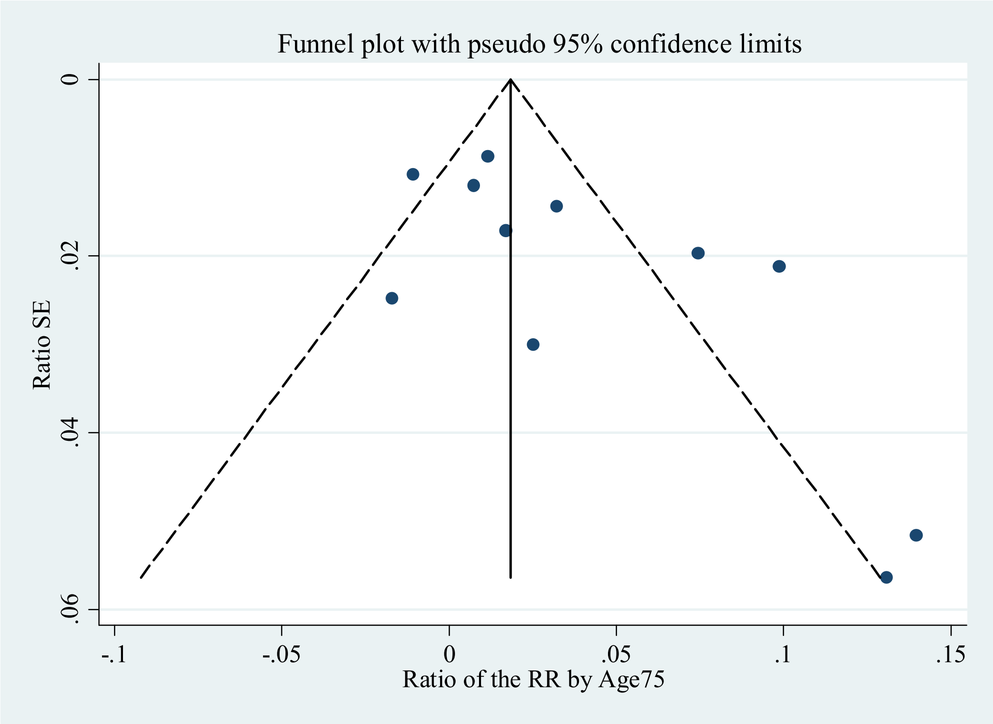
Egger's test p=0.002

Figure 2S: Publication bias assessment: ratio between group 65+ and 65 and less



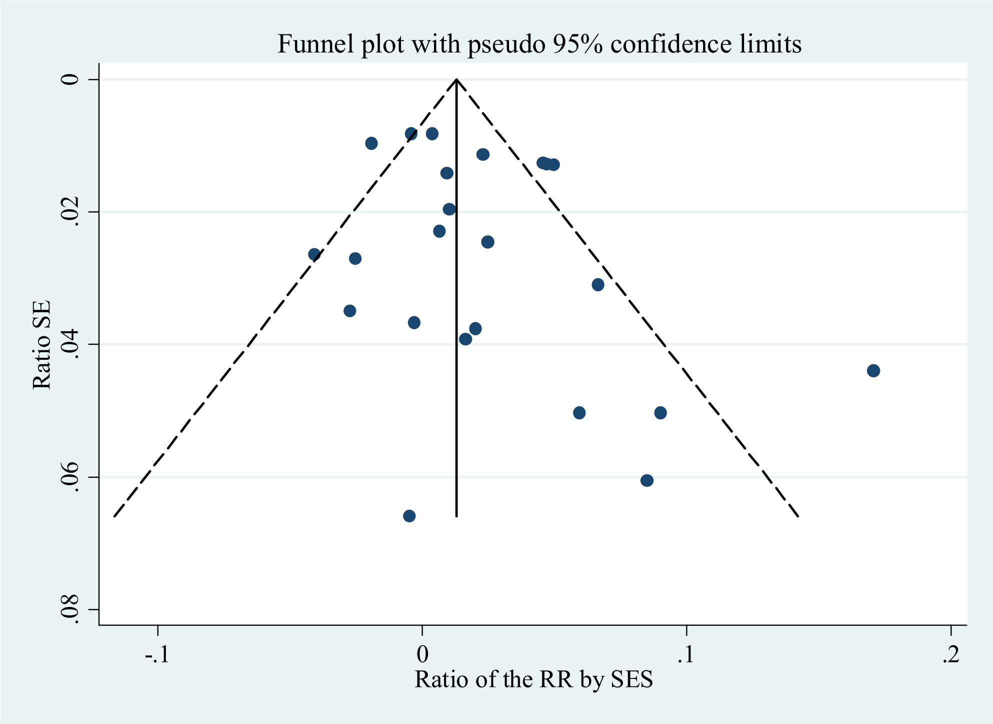
Egger's test p= 0. 244

Figure 3S: Publication bias assessment: ratio between group 75+ and 75 and less



Egger's test p= 0.039

Figure 4S: Publication bias assessment: ratio between low SES and high SES



Egger's test p= 0.172

Table 3S: Meta-regression Model Investigating the Predictors of the Log [ratio of relative risks] for Sex [a]

Independent Variable [b]		Beta (95% CI)	P Value	R^2 [c]	Residual I^2 [d]	Adjusted Pooled Ratio (95% CI)
Study design		0.01 (-0.05, 0.06)	0.79	-0.11	73.91%	0.96 (0.92,1.01)
Continent	Europe	reference	0.25*	0.04	72.42%	0.95 (0.92,0.99)
	America	0.04 (-0.01,0.10)				
	Asia/Australia	0.01 (-0.04,0.06)				
Association measure		0.03 (-0.02, 0.07)	0.27	0.02	72.79%	0.96 (0.93,0.99)

[a] Model with the log[ratio of relative risks] as dependent variable. The meta-regression analysis was performed using data from 18 studies.

b Independent variables represent a) for study design: case-crossover or time series; b) for association measure: percentage increase comparing two percentiles of the temperature distribution or percentage changes associated with degree units increases above a city-specific threshold.

[c] Reflects the proportion of the variability in the log[ratio of relative risks] explained by the statistical model.

[d] Reflects the percentage of the residual variation that is attributable to between-study heterogeneity. The initial I^2 was 77.6%

* The *P* value corresponds to a joint test for all covariates with Knapp-Hartung modification.

CI: Confidence Interval

Table 4S: Meta-regression Model Investigating the Predictors of the Log [ratio of relative risks] for Age65 [a]

Independent Variable [b]		Beta (95% CI)	P Value	R^{2} [c]	Residual I^{2} [d]	Adjusted Pooled Ratio (95% CI)
Study design		-0.00 (-0.03,0.02)	0.86	-0.08	53.23%	1.02 (0.99,1.05)
Continent	Europe	reference	0.99*	-0.16	56.06%	1.02 (1.01,1.04)
	America	0.00 (-0.02,0.03)				
	Asia/Australia	0.00 (-0.02,0.03)				
Association measure		-0.00 (-0.02,0.02)	0.85	-0.09	53.31%	1.02 (1.00,1.04)

[a] Model with the log[ratio of relative risks] as dependent variable. The meta-regression analysis was performed using data from 25 studies.

b Independent variables represent a) for study design: case-crossover or time series; b) b for association measure: percentage increase comparing two percentiles of the temperature distribution or percentage changes associated with degree units increases above a city-specific threshold.

[c] Reflects the proportion of the variability in the log[ratio of relative risks] explained by the statistical model.

[d] Reflects the percentage of the residual variation that is attributable to between-study heterogeneity. The initial I^{2} was 56.1%

* The *P* value corresponds to a joint test for all covariates with Knapp-Hartung modification.

CI: Confidence Interval

Table 5S: Meta-regression Model Investigating the Predictors of the Log [ratio of relative risks] for Age75 [a]

Independent Variable [b]		**Beta (95% CI)**	**P Value**	**R^2 [c]**	**Residual I^2 [d]**	**Adjusted Pooled Ratio (95% CI)**
Continent	Europe	referent				
	Asia/Australia	0.03 (-0.03,0.10)	0.26	-0.03	76.19%	1.05 (1.00,1.11)
Association measure		-0.09 (-0.16,-0.02)	**0.02**	0.67	61.22%	1.11 (1.04,1.19)

[a] Model with the log[ratio of relative risks] as dependent variable. The meta-regression analysis was performed using data from 11 studies.

b Independent variables represent a) for association measure: percentage increase comparing two percentiles of the temperature distribution or percentage changes associated with degree units increases above a city-specific threshold. Study design was not assessed because all included studies used a time series design.

[c] Reflects the proportion of the variability in the log[ratio of relative risks] explained by the statistical model.

[d] Reflects the percentage of the residual variation that is attributable to between-study heterogeneity. The initial I^2 was 77.9%

CI: Confidence Interval

CHAPITRE 4 : CHRONIC AIR POLLUTION AND DEPRIVATION AS MODIFIERS OF THE ASSOCIATION BETWEEN HIGH TEMPERATURE AND DAILY MORTALITY

Chronic air pollution and social deprivation as modifiers of the association between high temperature and daily mortality

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1. Abstract

Background: Heat and air pollution are both associated with increases in mortality. However, the interactive effect of temperature and air pollution on mortality remains unsettled. Similarly, the relationship between air pollution, air temperature, and deprivation has never been explored.

Methods: We used daily mortality data from 2004 to 2009, daily mean temperature variables and relative humidity, for Paris, France. Estimates of chronic exposure to air pollution and deprivation at a small spatial scale were calculated and split into three strata. We developed a stratified Poisson regression models to assess daily temperature and mortality associations, and tested the heterogeneity of the regression coefficients of the different strata. Deaths due to ambient temperature were calculated from attributable fractions and mortality rates were estimated.

Results: We found that chronic air pollution exposure and deprivation are effect modifiers of the association between daily temperature and mortality. We found a potential interactive effect between deprivation and chronic exposure with regards to air pollution in the mortality-temperature relationship.

Conclusion: Our results may have implications in considering chronically polluted areas as vulnerable in heat actions plans and in the long-term measures to reduce the burden of heat stress especially in the context of climate change.

2. Introduction

Among environmental determinants of health, climatic effects are of high concern, especially given the growing body of literature concerning the impacts of climate change. Ambient temperature has long been recognized as a physical hazard, and is associated with a wide range of adverse health effects (Basu and Samet 2002). Increases in summer ambient temperatures are associated with increases in mortalities over a city specific threshold. Consequently, future heat-related mortality is likely to increase in the context of climate change (Armstrong et al. 2012; McMichael 2013).

Identification of factors that increase vulnerability to hot temperature in human populations has become a growing public health concern (Basu 2009; Yu et al. 2010). Some studies have explored different aspects of heat-related mortality or morbidity heterogeneity across different level. These heterogeneity factors or effect modifiers in relation to temperature and mortality represent the heat vulnerability factors which can be observed at the individual or at the community level. At the scale of the individual, many studies have reported increased vulnerability of elderly individuals to hot temperatures (Anderson and Bell 2009; Astrom, Forsberg, and Rocklov 2011; Baccini et al. 2008; Hajat, Kovats, and Lachowycz 2007; Ishigami et al. 2008; Stafoggia et al. 2006). The effects of gender on temperature impacts have seen mixed evidence. At the community level, vulnerability of populations has been shown to be influenced by factors such as low density of green spaces (Reid et al. 2009), poor urban design and planning (Stone Jr and Rodgers 2001), urban heat islands (Smargiassi et al. 2009), and the modification effect by air pollutants (Analitis et al. 2014; Ye et al. 2012a). Ozone in particular has been studied as an effect modifier in the mortality-temperature relationship (Filleul et al. 2006; Ren et al. 2008a), while the link between temperature and particulate matter (PM) (Ren, Williams, and Tong 2006), sulfur oxides (SOx) (Katsouyanni et al. 1993) or Nitrogen oxides (NOx) (Peel et al. 2012) has been less explored. Furthermore, urban air pollution has never been studied from a chronic exposure perspective but only using daily levels. Some studies have also focused on community-based social characteristics may influence mortality and morbidity outcomes through effects of community organisation(Romero-Lankao, Qin, and Dickinson 2012b), social cohesion and social networks (Klinenberg 2003), deprivation, using an aggregated index (Rey et al. 2009b).

The interaction between ambient temperature and air pollution has been studied in air pollution mortality time series studies and, to a lesser extent, in temperature mortality time series analyses (Roberts 2004). To our knowledge, no data are available on the relationship between temperature and mortality effect modified by chronic air pollution exposure and socio-economic factors (or ecological deprivation) assessed jointly.

The objective of the study is to identify whether and how the magnitude of the effects of mean temperature on all-cause mortality were modified by chronic air pollution exposure (here nitrogen dioxide (NO2) representing urban traffic), deprivation, and a combination of these two dimensions. For this purpose, we studied the city of Paris (France) where NO2 long-term average concentrations vary substantially across the city according to traffic density(i.e. the main source of NO2 emissions), and where the different city neighbourhoods host populations with contrasted socio-economic profiles. We hypothesized that a better understanding of these vulnerability factors should provide relevant information for developing public health programs targeting the most vulnerable populations and territories.

3. Methods

Study setting and small-area level

Paris, the capital city of France, has a population of roughly 2.25 million inhabitants. The spatial scale used was the French census block (i.e. IRIS - a French acronym for “blocks for incorporating statistical information”), which constitute the smallest census unit areas in

France, designed by the National Census Bureau (INSEE), for which aggregate data is available. The city of Paris is subdivided into 992 census blocks with a mean population of 2,199 inhabitants (range = 0–5,456 inhabitants) and a mean area of 0.11 km2 (range = 0.009-5.4 km2).

Mortality and population data

We considered all deaths occurring in the city of Paris (excluding woods of Boulogne and Vincennes) for residents older than 35 years old from May to August for the years 2004-2009 included. All-cause mortality data were provided by the death registry of the city of Paris. Individual information on age, sex, date of death, and census block of residence was available for each case of death. For confidentiality issues it was not possible to distinguish causes of mortality, thus external causes of deaths could not be excluded. The analysis included only subjects older than 35 years old at the time of death to minimize this bias because accidental causes of death are dominant in subjects under 35 years old (Meslé and Vallin 1996). We obtained the number of population in each stratum was taken from the INSEE.

Ethical approval was obtained from the French commission on data privacy and public liberties (CNIL - Commission Nationale Informatique et Liberté).

Climate data

Daily mean outdoor temperatures and relative humidity were obtained from Météo-France, as measured at the Montsouris station in Paris and were computed using data of the corresponding period (summers from 2004 to 2009).

Air pollution data

Annual N02 concentrations were modeled at a grid scale of 25x25m throughout the period 2004–2009 (only summers) by the local association for the monitoring and the study of air quality (AirParif). We used a dispersion model (ESMERALDA) to produce annual NO2 concentrations at a fine spatial resolution. A description of the methods used to produce NO2 levels at the French census block is provided in Supplemental Material. Chronic NO2 exposure at the census block scale was defined as the average of annual NO2 concentrations from 2004 to 2009. We did not include other air pollutants such as ozone due to the lack of data at this spatial scale.

Community based socio-economic characteristics: deprivation

To characterize the socio-economic characteristics at a community level, we computed an aggregated, multidimensional deprivation index, fitted at the census block scale (Lalloué et al. 2013). We provided a summary description of the deprivation index and its categorization in Supplemental Material.

Statistical analyses

Deprivation was defined and stratified according to the 3-classes deprivation index described above. NO2 chronic exposure was categorized into three groups according to the terciles of its distribution. To create a double stratification with sufficient statistical power, we stratified the chronic NO2 exposure into two strata according to the median of NO2 chronic concentrations (i.e. we obtained a total of 6 strata for this double stratification). We also assessed area-related vulnerability (i.e. number of daily deaths for the ≥65 years people compared to the number of daily deaths for the <65 years) and sex-related vulnerability (number of daily deaths for men versus the number of daily deaths women).

First, in a crude model, we developed stratified Poisson regression models to assess daily temperature-related mortality associations with daily mean temperatures daily death count (Armstrong 2006). We used cubic B-splines to control for secular trends in the mortality series (5 knots) (Hajat, Kovats, and Lachowycz 2007). Seasonal patterns of mortality were controlled by including a quadratic function represented by the day of the season (1 to 123) (Fouillet et al. 2007). Sensitivity analyses were performed by using a cubic polynomial for seasonality. We used natural cubic splines to consider the non-linearity of the temperature-mortality relationship (with 2 knots). Daily levels of humidity were incorporated into out regression models as possible confounding variables based on evidence in the literature (Basu and Samet 2002; Buckley, Samet, and Richardson 2014; Hajat, Kovats, and Lachowycz 2007). Then, we developed stratified models for each category (Chan et al. 2012). The threshold for statistical significance was set at $p \leq 0.05$ and all the tests were two-sided. Model assumptions and validity were verified graphically (i.e. with quintile-quintile and partial autocorrelation function plots). A white noise test was also used to ensure that no auto-correlation remained in the residuals. Estimates of exposure (daily temperature) – response (mortality) functions - were expressed as Relative Risks (RR) and their confidence intervals (CI) at 95% for each temperature degree. Relative Risks for the relation between mortality and temperature were estimated relative to the daily mean number of deaths for the entire period (Hajat, Kovats, and Lachowycz 2007). We assessed the heterogeneity of temperature–mortality associations across different strata using methods developed by Payton et al. (Payton, Greenstone, and Schenker 2003) to compare the regressions' coefficients between different strata. This test was conducted on all regression coefficients across the strata.

Calculation of deaths attributable to temperature

We calculated deaths attributable to ambient temperatures for each stratum. Attributable deaths were calculated from attributable fractions (AF), using heat-related mortality relationships (RR) described in the previous section (Baccini et al. 2011; Hajat et al. 2006). We considered only days with daily mean temperature related to a RR strictly greater than 1 for any temperature value (corresponding to 280 days in total). AF were calculated for each temperature degree (Ti°: represents a temperature unit) and using the equation [(RR(Ti°)-1)/RR(Ti°)].

The Attributable Number of deaths (AN) for the period 2004-2009 (months of May, June, July, and August), for a given temperature variable, was then estimated from the following equation:

$$\mathrm{AN} = \sum_{i=min}^{max} \mathrm{AF}(T_i) \times \mathrm{MDC} \times \mathrm{ND}(T_i)$$

In this equation, i is the temperature degree Celsius, AF(T_i) is attributable fraction for temperature degree (Ti), MDC is the mean observed daily death count, and ND(T_i) is the number of days for which temperature was i (°C). We then divided the total number of attributable deaths for the period 2004-2009 by 6 to obtain an average attributable number of deaths by summer. We used the RR estimated within the strata of interest to estimate the AR in those strata. We calculated confidence intervals at 95% of attributable number of deaths. Then we compared the number of deaths attributable to temperature in each of the groups stratified by chronic air pollution exposure (3strata), deprivation (3 strata) and the two simultaneously (6 strata). We made sure that there was no homogeneity in the temperature–mortality associations across different strata, like described in the last section. Finally we calculated attributable mortality rates, by dividing the total number of deaths attributable to temperature in each stratum (by summer) by the total population in each of these strata. The final results were mapped to visualize heat vulnerability according to deprivation and chronic air pollution exposure.

4. Results

46,056 deaths were registered during the study period, and the mean age at death was 68 years (SD=10.21). As presented in **Table 1**, daily death count ranged from 3 to 93 (mean, 33.3, IQR: 27 to 42). Mean temperatures ranged from 7°C to 26°C (mean: 17.3°C, IQR: 14°C to 20°C), while atmospheric pollution assessed by daily NO2 ranged from 16 to 121 µg/m3 (mean: 48.9 µg/m3, IQR: 38 µg/m3 to 58 µg/m3) (**Table 1**). Chronic NO2 exposure ranged from 39 µg/m3 to 81 µg/m3 (mean: 52.8 µg/m3, IQR: 48 µg/m3 to 56 µg/m3). From the 992 census blocks in our study, we had 54 census blocks with missing data concerning deprivation which corresponded to 160 deaths. These census blocks are non-residential (activity and miscellaneous) and with few residents. Descriptive statistics of the deprivation index and chronic air pollution are presented in Supplemental Material (Table 1S). As shown in Figure 1S, chronic NO2 concentrations were slightly higher in the most favoured census blocks. In the crude model (for the whole population), mortality was significantly associated with daily mean temperature (RR for each temperature unit and for all strata are not shown). The association between temperature and mortality was U-shaped. Applying the central point estimate of the temperature-mortality relationships to the observed mean temperatures, an average number of 121 attributable deaths by summer (May to August) was estimated. Deaths attributable to mean temperature are presented with their 95% confidence intervals in **Table 1S**.

As presented in the **Figure 1**, we observed a gradient in the raw deaths attributable to temperature according to deprivation: the higher the degree deprivation, the higher the number of deaths attributable to mean temperature. Likewise, higher chronic air pollution exposure as assessed by NO2 levels was also identified as a vulnerability factor in the relationship between temperature and mortality. We observed a significant difference in regression coefficients (between strata) separately according to deprivation and chronic air pollution ($p<0.05$).

Finally, we calculated mortality rates (**Table 2**), including the population living in each strata to consider the differences in population density across strata. We found some heterogeneity ($p<0.10$) between ambient temperature and mortality according to age, deprivation and chronic air pollution exposure. Sex was not an effect modifier in the relationship between heat and temperature ($p=0.51$). For the double stratification, we found that, in the low chronic exposure group, deprivation did not significantly modify the relation between heat and mortality ($p=0.14$), while we found that deprivation may have modified this relation in the high chronic exposure group ($p=0.07$). We also conducted heterogeneity tests across the two chronic exposure groups. We found a heterogenic effect (data not shown) only between the strata low chronic exposure/ high deprivation and the strata high chronic exposure/ high deprivation.

Figure 2 presents the spatial distribution of deprivation and chronic air pollution exposure. The spatial variation of both social characteristics are related to deaths attributable to temperature as presented in Table 2.

5. Discussion

In this study, we assessed the effects of mean temperature and chronic air pollution (with NO2 representing urban traffic) on all-cause mortality with additional attention paid to the interactive effects of deprivation. To do this we conducted stratified time-series analyses. We found that chronic air pollution exposure modifies the association between daily temperature and mortality. We also found that deprivation is a heat vulnerability factor. Finally we found that there is a potential combined modification effect of deprivation and chronic exposure to NO2 with regards to heat-related mortality.

Our results for the temperature-mortality relationship are comparable to other studies conducted in Paris (Baccini et al. 2008; Fouillet et al. 2007). Concerning social vulnerability to heat-related mortality, our results are consistent with other studies, using time series analyses (Yu et al. 2010) or using different methods, such as a case crossover design (Stafoggia et al. 2006).

Ecological social vulnerability can be explained by an accumulation of differing types of vulnerabilities for individuals within a census block (e.g., social isolation (Semenza et al. 1996a), material conditions (Rogot, Sorlie, and Backlund 1992), poor urban design including micro heat islands (Smargiassi et al. 2009) or poorer health (Bell et al. 2008). In the same way, social mobility may also partly explain the social gradient we observed, similar to previous studies looking at socio-economic scales (Perchoux et al. 2013). Thus, populations with low socio-economic levels will be inclined to stay in their neighbourhoods, with a low daily mobility, accumulating other heat vulnerability factors and with other consequences on certain determinants of health as physical activity.

We found that air pollution modifies the relation between ambient temperature and daily mortality as found in previous studies using daily exposure (Filleul et al. 2006; Katsouyanni et al. 1993; Ren et al. 2008a; Ren, Williams, and Tong 2006; Roberts 2004). It is possible that chronic NO2 levels modify the effects of temperature on mortality. A range of studies have shown that NO2 is consistently associated with many health outcomes such as cardiovascular effects (Hart et al. 2011; Latza, Gerdes, and Baur 2009), which can explain how the NO2 chronic effects can make vulnerable some populations to heat impacts.

Our results suggest that ambient temperature has a greater impact on daily mortality on chronically polluted areas, especially if these areas are socially deprived. However our results only suggest this double effect modifier and further studies may confirm this result.

Methods for estimating the heat related mortality relationships inevitably rely on some assumptions. In our study, we chose to not take into account lag effects to simplify the interpretation of deaths attributable to temperature. We considered that contribution of lag effects compared to the day of death was not differential according to the different strata characteristics. We did not take into account harvesting effect or mortality displacement. We also did not consider intra urban variations of temperatures. Future studies should consider these aspects. We considered the deprivation at the ecological level, and we did not explore social inequalities in mortality at the individual level, because of the lack of data. The use of a synthetic index rather than using independent ecological socio-economic measures allows us to represent an accumulation of social and material disadvantages (Townsend 1987) and these kinds of indexes are more useful to lead population interventions (Rey et al. 2009b). The division of neighbourhoods into census blocks aims to maximize their homogeneity in terms of population size, socioeconomic characteristics, land use and zoning. In Paris, the area of a block census is quite small so the ecologic bias is likely to be small. Finally, we did not consider the spatial auto-correlation in our analysis which is a result of the correlation between the spatial unit and the adjacent geographical areas. Variables observed at small area level are interdependent because proximity and linkages between neighbouring areas. This issue could influence the effect of deprivation and chronic air pollution (Deguen et al. 2010), and further studies could consider it by conducting spatial analyses such as a hierarchical Bayesian modeling approach.

Conclusion

In this study, we showed areas which are chronically polluted by air pollution can be characterized as vulnerable to heat in the sense that they have more deaths attributable to heat than less exposed areas. We also presented a potential combined vulnerability of deprivation and chronic exposure to air pollution in the mortality-temperature relationship. Our results may have important implications considering chronically polluted areas as vulnerable in heat actions plans (especially including adapted surveillance and warning systems) and in the long-term measures to reduce the burden of heat stress (as building regulations, urban planning or land-use changes), especially in the context of climate change. However, further studies are necessary to determine whether similar results could be found in other settings.

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Competing interests: None

Ethics approval: French commission on data privacy and public liberties (CNIL - Commission Nationale Informatique et Liberté)

8. **Tables and figures**

Table 1: Summary statistics for health outcomes, climate and air pollutants data (Paris, 2004-2009)

Variable	Mean	Minimum	25th Percentile	Median	75th Percentile	Maximum	Standard Deviation
Daily death count (n)	33.3	3	27	33	42	93	4.5
Minimum Temperature (°C)*	12.5	0	9	13	16	21	4.2
Mean Temperature (°C)*	17.3	7	14	17	20	26	4.4
Maximum Temperature (°C)*	20.9	8	17	21	24	35	5.2
Relative Humidity (%)*	68.4	37	61	69	76	94	10.7
Daily NO2 (µg/m^3)	48.9	16	38	47	58	121	14.3
Chronic NO2 (µg/m^3)	52.5	38.7	47.88	51.8	56.1	81.1	6.8

* Summary statistics for weather variables (minimum, mean and maximum temperatures as well as relative humidity) are based on daily data.

Table 2: Mortality rates attributable to summer temperatures (per 100 000) by strata

Strata	*Population*	*Mortality rates (per 100 000)*[a]	*p for heterogeneity*[b]
Total	2234105	5.37 [5.01;5.73]	
Age			
Under 65 years	1921330	0.78 [0.62;0.88]	0.001
More than 65 years	312774	33.57 [31.65;35. 81]	
Sex			
Female	1161734	5.51 [4.99;5.85]	0.51
Male	1072370	5.22 [4.76;5.67]	
Deprivation			
Low Deprivation	692572	4.33 [3.31;5.23]	0.08
Medium Deprivation	781936	4.60 [3.59;5.41]	
High Deprivation	743956	7.26 [6.74;7.85]	
Chronic air pollution exposure			
Low Chronic NO2 Exposure ≤ 50.6 µg/m^3	737254	4.75 [4.13;5.22]	0.03
Medium Chronic NO2 Exposure 50.6-55.8 µg/m^3	795341	5.97 [5.36;6.32]	
High Chronic NO2 Exposure > 55.8 µg/m^3	670231	7.89 [7.28;8.14]	
Double stratification **Low Chronic Exposure Group**			
Low Deprivation	370567	3.78 [2.87;5.03]	0.14
Medium Deprivation	381190	4.19 [3.34;5.25]	
High Deprivation	375341	6.92 [5.11;8.12]	
Double stratification **High Chronic Exposure Group**			
Low Deprivation	389872	3.59 [2.29;5.07]	0.07
Medium Deprivation	391432	5.36 [4.22;6.41]	
High Deprivation	325701	9.82 [7.79;10.93]	

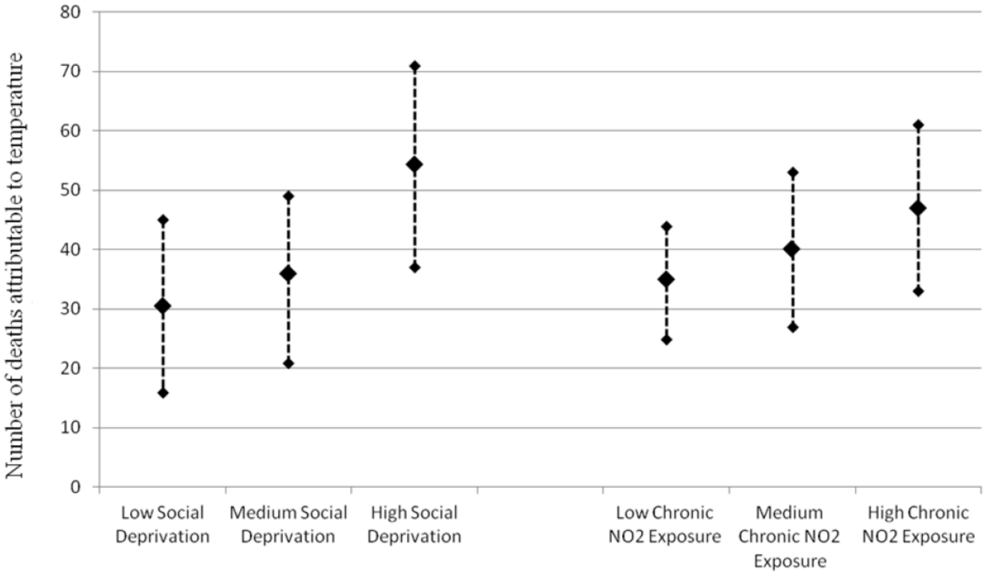
[a]: For deprivation and chronic air pollution strata, mortality rates were standardized for age and sex.

[b]: Homogeneity test of Chi- square Pearson, for central estimates.

Legend for figures

Figure 1: Number of deaths attributable to mean temperature by deprivation (3 strata) and chronic air pollution exposure (3strata).

Figure 2: Spatial distribution of deprivation and chronic air pollution.



80
70
60
50
40
30
20
10
0
Number of deaths attributable to temperature
Low Social Deprivation
Medium Social Deprivation
High Social Deprivation
Low Chronic NO2 Exposure
Medium Chronic NO2 Exposure
High Chronic NO2 Exposure

Figure 1


N
Legend
Chronic air pollution
Low
Medium
High
0
5
10
Kilometers
N
Legend
Social Deprivation Index
No Data
Low
Medium
High
0
5
10
Kilometers

Figure 2

9. Supplemental Material

Description of the methods used to produce daily NO2 levels

First, annual NO2 concentrations were modelled from a grid of 25x25m resolution throughout the period 2002–2009 by the local association for the monitoring and the study of air quality (AirParif: http://www.airparif.asso.fr/). They used the ESMERALDA dispersion model (ESMERALDA 2012) for background pollution and the STREET dispersion model (Oxalys Scop SA, Broissieux, France) for pollution related to traffic proximity. To compute annual NO2 concentrations at a fine spatial resolution (25x25m), these models incorporated several types of input data: emission inventories, meteorological data and background pollution measurements, supplied respectively by industry and environment regional administration, Météo-France (French meteorological agency) and monitoring stations of the regional network. Air pollutant concentrations were then aggregated at the census block scale in order to obtain the annual mean of NO2 concentration for each census block. The aggregation technique was a population-weighted average.

Summary description of the Deprivation Index

To characterize the socioeconomic status, we used an index developed at the census block scale for Paris. Briefly, a principal component analysis was used to select variables among 41 socioeconomic and demographic variables provided by the 2006 national census at the census block scale. Following the results of this principal component analysis, 15 variables were best correlated (based on the contribution) with the first component: median income, percentage of people with basic or intermediate general or vocational qualifications, people with a higher educational degree, unemployed, self-employed, non-graduates, non-owners, housing with floor area more than 100 m², subsidized housings, foreign immigrants, artisans, managers, employees, blue-collar workers, and single-parent families. These 15 variables were selected to carry out a final principal component analysis where the reduced first component was used to calculate the socioeconomic index. Finally, an ascendant hierarchical analysis was performed to gather census blocks in 3 homogenous socioeconomic categories numbered from 1 (the most privileged) to 3 (the most deprived). About 13% (n = 126) of census blocks were not classified in a socioeconomic category because they corresponded to non-residential census blocks (activity and miscellaneous) with few residents. Category 1 is characterized by census blocks with high median incomes and high percentages of housings with area greater than 100 m², self-employed, artisans, managers, and people with a higher educational degree. Only two variables positively characterized the census blocks of category 2: percentage of managers and people with a higher educational degree are over-represented, while the census blocks with the other variables are under-represented. The most deprived category (category 3) is represented by a high percentage of non-graduates, blue-collar workers, employees, subsidized housings, single-parent families, unemployed, people with basic or intermediate general or vocational qualifications, non-owners, and foreign immigrants.

Table 1S: Summary statistics for Deprivation and Chronic Air Pollution (Paris, 2004-2009)

Variable	Mean	Minimum	25th Percentile	Median	75th Percentile	Maximum	Standard Deviation
Deprivation	-0.06	-6.25	-2.39	-0.81	1.62	9.70	3.05
Chronic NO2 (µg/m^3)	52.5	38.7	47.88	51.8	56.1	81.1	6.8

Figure 1S: Distribution of NO2 levels by quintile of deprivation

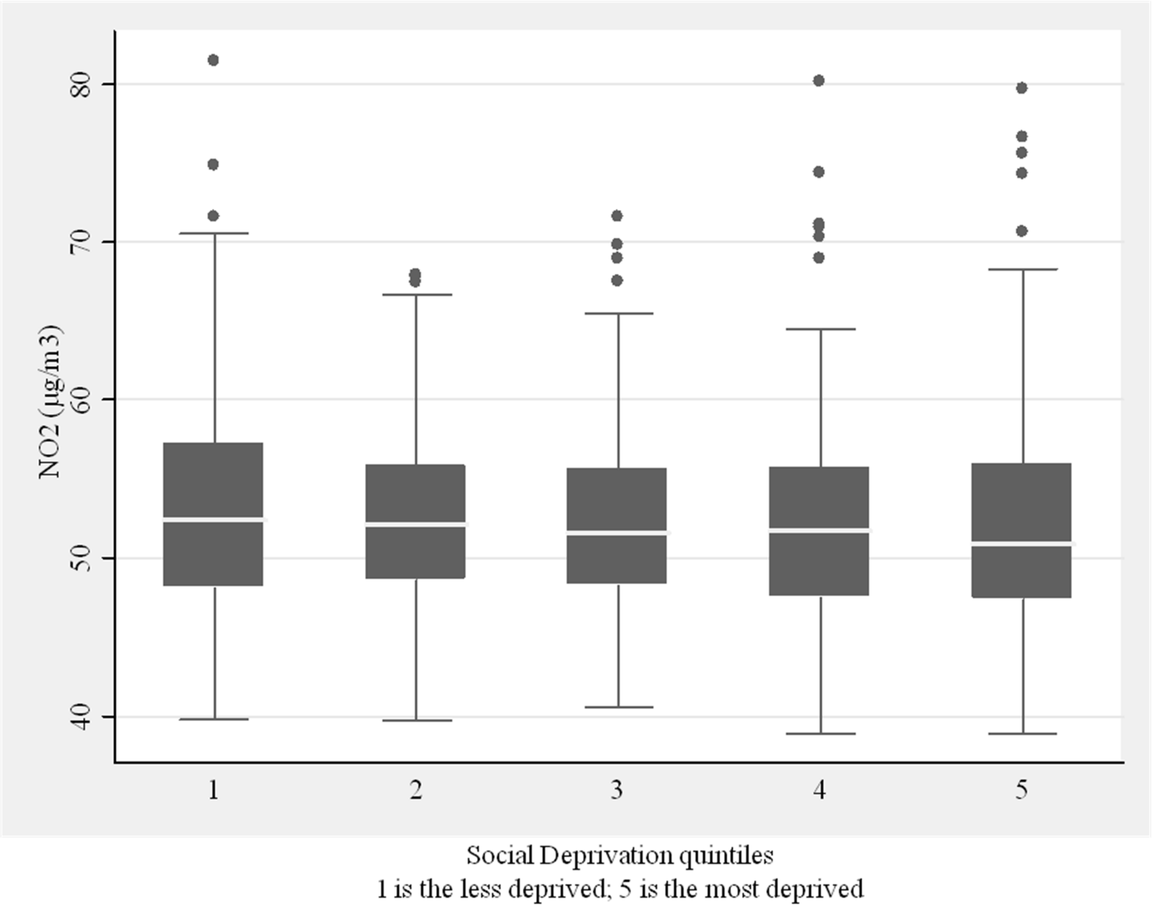


Table 2S: RR estimates for Deprivation strata

	Low Deprivation			**Medium Deprivation**			**High Deprivation**		
Mean Temperature (°C)	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
7	1.020	0.895	1.162	1.024	0.900	1.165	1.027	0.903	1.168
8	1.007	0.899	1.128	1.011	0.904	1.131	1.014	0.907	1.134
9	0.994	0.903	1.095	0.998	0.908	1.098	1.001	0.910	1.102
10	0.982	0.906	1.064	0.986	0.911	1.067	0.989	0.914	1.070
11	0.970	0.910	1.034	0.974	0.914	1.038	0.977	0.917	1.041
12	0.959	0.913	1.007	0.963	0.917	1.011	0.966	0.920	1.014
13	0.949	0.915	0.986	0.954	0.919	0.990	0.957	0.922	0.993
14	0.942	0.916	0.970	0.947	0.921	0.974	0.950	0.923	0.977
15	0.938	0.916	0.960	0.945	0.924	0.968	0.948	0.926	0.971
16	0.937	0.917	0.957	0.944	0.924	0.965	0.947	0.927	0.968
17	0.940	0.921	0.959	0.947	0.928	0.967	0.950	0.931	0.969
18	0.947	0.930	0.965	0.955	0.938	0.972	0.973	0.956	0.990
19	0.960	0.944	0.976	0.967	0.952	0.983	1.000	0.985	1.016
20	0.975	0.958	0.993	0.992	0.975	1.010	1.025	1.008	1.043
21	0.988	0.971	1.006	1.005	0.988	1.023	1.038	1.021	1.056
22	1.009	1.001	1.017	1.017	1.006	1.031	1.050	1.034	1.067
23	1.016	1.004	1.029	1.033	1.015	1.052	1.067	1.048	1.085
24	1.041	1.024	1.058	1.058	1.038	1.074	1.091	1.071	1.112
25	1.074	1.053	1.096	1.091	1.070	1.112	1.124	1.103	1.145
26	1.114	1.088	1.141	1.130	1.104	1.157	1.164	1.137	1.190

LCI: Lower Confidence Intervals; UCI: Upper Confidence Intervals

Table 3S: RR estimates for Chronic NO2 exposure strata

	Low NO2 exposure			**Medium NO2 exposure**			**High NO2 exposure**		
Mean Temperature (°C)	RR	LCI	UCI	RR	LCI	UCI	RR	LCI	UCI
7	1.047	0.922	1.188	1.050	0.925	1.192	1.058	0.933	1.201
8	1.034	0.926	1.155	1.037	0.929	1.158	1.045	0.937	1.167
9	1.021	0.930	1.122	1.024	0.933	1.125	1.033	0.941	1.134
10	1.009	0.934	1.090	1.012	0.937	1.094	1.020	0.944	1.102
11	0.997	0.937	1.061	1.000	0.940	1.064	1.008	0.947	1.073
12	0.996	0.950	1.044	0.990	0.953	1.048	1.007	0.960	1.056
13	0.987	0.952	1.023	0.974	0.955	1.022	0.998	0.963	1.034
14	0.979	0.953	1.007	0.973	0.954	1.021	0.990	0.964	1.018
15	0.975	0.953	0.998	0.978	0.958	1.024	0.987	0.965	1.010
16	0.974	0.954	0.995	0.977	0.957	0.998	0.986	0.966	1.007
17	0.977	0.958	0.996	0.980	0.961	0.999	0.989	0.970	1.008
18	0.980	0.937	1.002	0.982	0.970	1.005	0.991	0.979	1.014
19	0.983	0.951	1.013	0.985	0.994	1.026	1.002	1.000	1.035
20	0.987	0.957	1.030	1.009	1.001	1.014	1.018	1.003	1.029
21	1.000	0.991	1.043	1.022	1.011	1.030	1.031	1.020	1.042
22	1.012	1.001	1.053	1.034	1.021	1.047	1.043	1.032	1.056
23	1.028	1.015	1.072	1.051	1.039	1.067	1.060	1.047	1.081
24	1.053	1.038	1.099	1.075	1.059	1.097	1.085	1.069	1.105
25	1.086	1.062	1.122	1.108	1.078	1.135	1.118	1.098	1.132
26	1.126	1.096	1.177	1.148	1.111	1.200	1.158	1.115	1.211

LCI: Lower Confidence Intervals; UCI: Upper Confidence Intervals

Table 4S: Summer deaths attributable to mean temperature presented with their 95% CI.

		Deaths attributable to T° and percentage attributable to temperature*	LCI	UCI
Deprivation	Low Deprivation	30 (9%)	16	45
	Medium Deprivation	36 (10%)	21	49
	High Deprivation	54 (14%)	37	71
Chronic Air Pollution	Low Chronic NO2 Exposure	35 (10%)	25	44
	Medium Chronic NO2 Exposure	40 (11%)	27	53
	High Chronic NO2 Exposure	47 (13%)	33	61
Double Stratification				
Low Chronic NO2 Exposure	Low Deprivation	13 (9%)	4	21
	Medium Deprivation	17 (11%)	9	27
	High Deprivation	26 (13%)	17	34
High Chronic NO2 Exposure	Low Deprivation	14 (9%)	6	23
	Medium Deprivation	20 (12%)	12	29
	High Deprivation	32 (14%)	23	39

T°: Temperature

LCI: Lower Confidence Interval

UCI: Upper Confidence Interval

*: percentages attributable to temperature are rounded up to the whole number and are obtained from the average attributable fraction by strata weighted by the number of days by temperature value.

Figure 2S: Descriptive map for mortality rates in Paris by census block

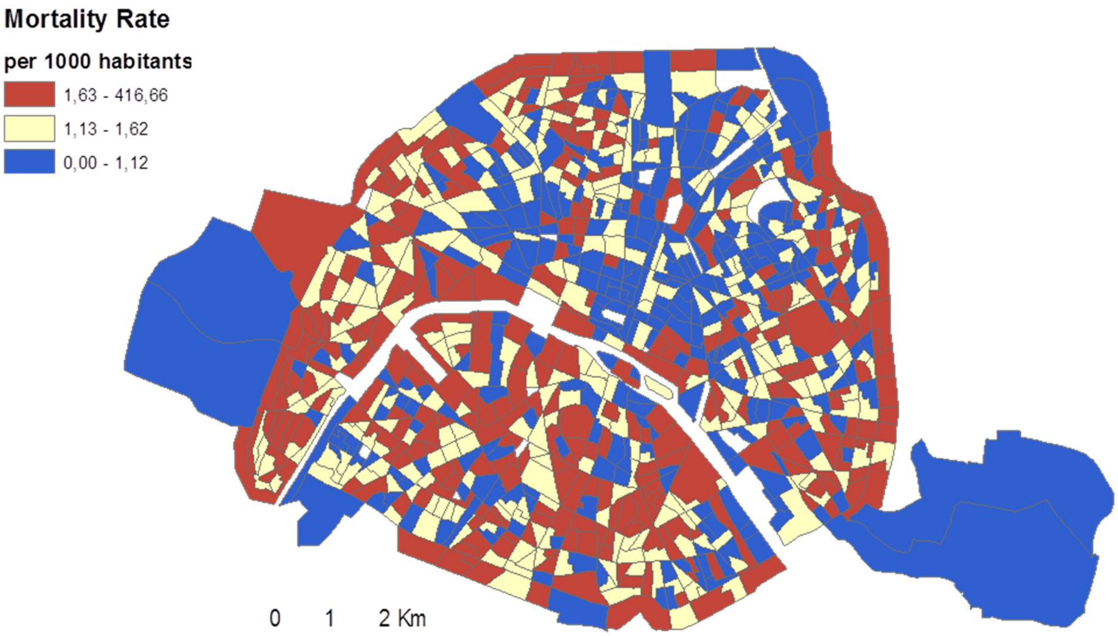


Figure 3S: Daily time series plot for the death in Paris.

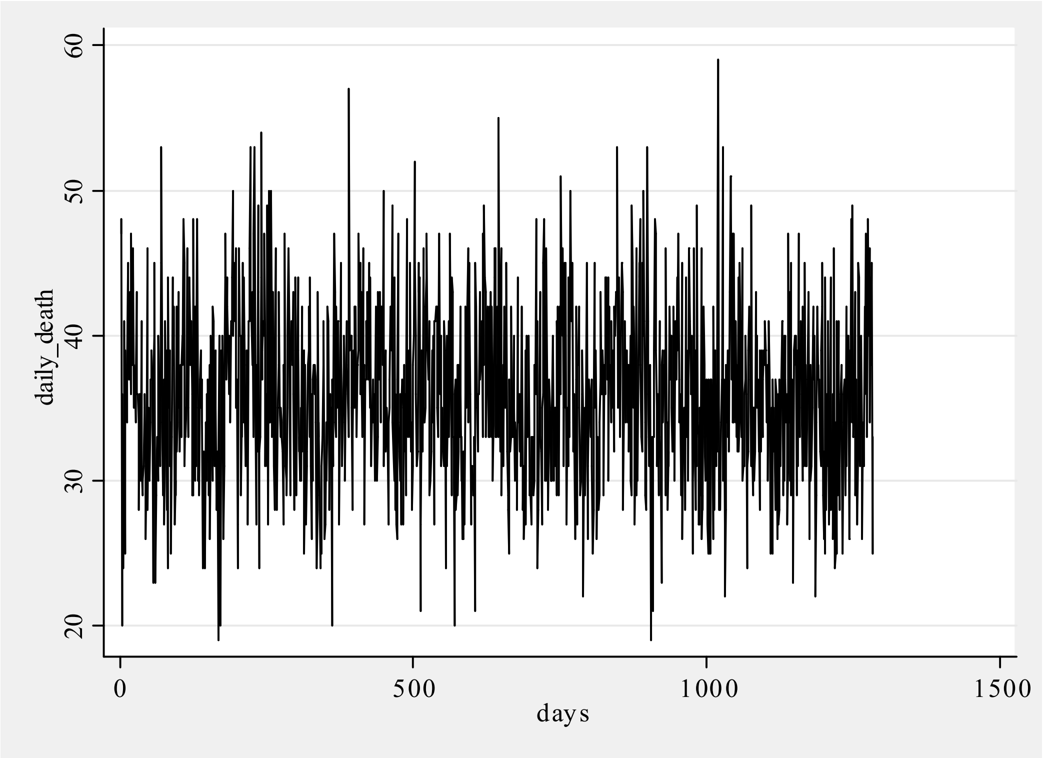


Figure 4S: Daily time series plot for the mean temperature in Paris.

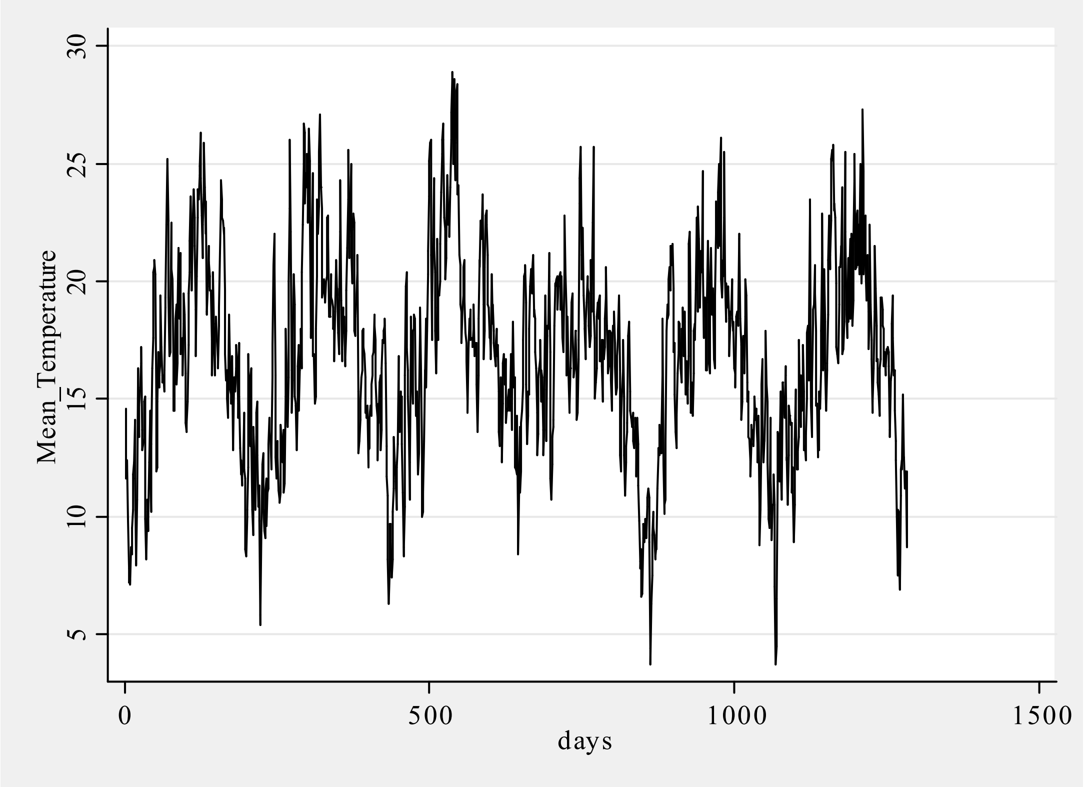
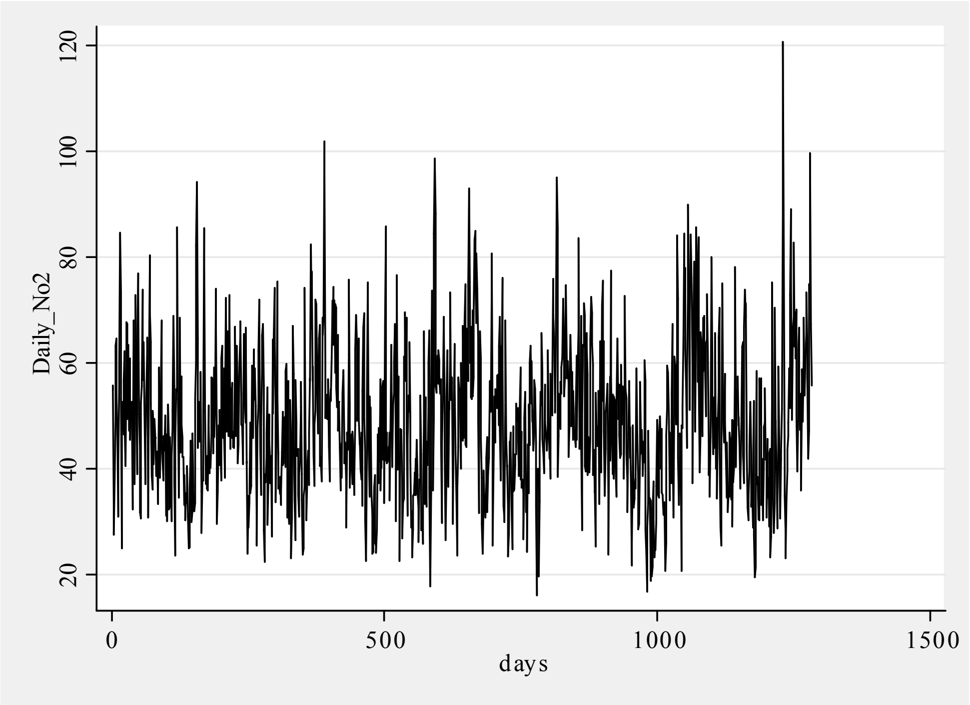


Figure 5S: Daily time series plot for the NO2 in Paris.



CHAPITRE 5 : VARIABILITY IN TEMPERATURE-RELATED MORTALITY PROJECTIONS UNDER CLIMATE CHANGE

Variability in Temperature-Related Mortality Projections under Climate Change

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1. Abstract

Background: Most studies that have assessed impacts on mortality of future temperature increases have relied on a small number of simulations and have not addressed the variability and sources of uncertainty in their mortality projections. We assessed the variability of temperature projections and dependent future mortality distributions, using a large panel of temperature simulations based on different climate models and emission scenarios.

Methods: We used historical data from 1990 through 2007 for Montreal, Quebec, Canada and Poisson regression models to estimate relative risks (RR) for daily non-accidental mortality in association with three different daily temperature metrics (mean, minimum, and maximum temperature) during June–August. To estimate future numbers of deaths attributable to ambient temperatures and its uncertainty, we used 32 different simulations of daily temperatures for June-August 2020-2037 derived from 3 global climate models (GCMs) and a Canadian regional climate model with three sets of RRs (one based on the observed historical data, and two on bootstrap samples that generated the 95% confidence interval of the attributable number of deaths), We then used an analysis of covariance (ANCOVA) to evaluate the influence of the simulation, the projected year, and the sets of RRs used to derive the attributable numbers of death (ANs).

Results: We found that <1% of the variability in the distributions of simulated temperature for June-August of 2020-2037 was explained by differences among the simulations. Estimated ANs for 2020–2037 ranged from 34 to 174 per summer (i.e. June-August). Most of the variability in mortality projections (38%) was related to the temperature-mortality RR used to estimate the ANs.

Conclusions: The choice of the RR estimate for the association between temperature and mortality may be important to reduce uncertainty in mortality projections.

2. Introduction

Among environmental determinants of health, weather and climate have received increasing attention related to awareness of climate change and the documentation of both usual and catastrophic heat-related mortality (Campbell-Lendrum and Woodruff 2007; Ebi 2008; Kovats and Hajat 2008; O'Neill and Ebi 2009; Patz et al. 2005).

Increases in ambient summer temperatures over city-specific thresholds have been associated with an increase in mortality (Hajat and Kosatsky 2010; IPCC 2007; Parry et al. 2007). Although present-day health effects of summer temperatures have been well characterized (Armstrong 2006), the extent to which future changes in summer temperatures will affect human health has received relatively little attention (Campbell-Lendrum and Woodruff 2007; Costello et al. 2009; Ebi and Gamble 2005; Huang et al. 2011; McMichael et al. 2006; Peng et al. 2011). Global average ambient temperatures are projected to increase under any scenario of increasing greenhouse gas (GHG) concentrations (IPCC 2001; Parry et al. 2007). Various models have been developed in climate science (Caya et al. 1995; McFarlane et al. 1992) to estimate future temperatures according to different GHG emission scenario (SRES, Special Report on Emissions Scenarios) (Nakicenovic et al. 2000).

Studies published since 2008 that have estimated the impacts of future temperatures on mortality, have mainly been conducted in Europe and North America, and the time periods used for baseline data and projections have varied among them. Most studies have evaluated projected temperatures based on only a small number of climate change simulations, with the exception of Li et al. (2013). For a review of most studies, also see Huang et al. (2011) and Gosling et al. (2009).

Divergences in temperature projections, due for example to model structure and GHG emissions scenarios, may occur; to capture the maximal range of possible future temperatures and health impacts, it may thus be important to consider a large number of simulations when assessing health impacts.

We assessed the variability of temperature projections and future mortality distributions, using a large panel of temperature simulations based on climate models and emission scenarios for the period 2020-2037 in Montreal, the most populous city of the province of Quebec, Canada.

3. Methods

To predict mortality attributable to past (1990-2007) and future temperatures (2020–2037) in Montreal, we first used historical data for 1990–2007 to estimate three sets of relative risks (RRs) for associations between mortality and temperatures during June–August in the city of Montreal (Quebec, Canada) with Poisson models. We refer to «set» of RRs given that there is one RR per degree temperature due to the non-linear relation between temperature and mortality. One set of RRs was based on the observed historical data, and two on individual bootstrap samples constructed from the observed historical data that generated the 95% confidence interval of attributable number of deaths. We then used the three sets of RRs to predict mortality attributable to past (1990-2007) and future temperatures (2020–2037), with observed historical temperatures, and with 32 different temperature simulations (for 1990-2007 and 2020-2037) based on three General Circulation Models (GCM) and the Canadian Regional Climate Model (RCM) (Caya et al. 1995). Predicted temperature distributions were corrected by applying the Daily Translation method (Mpelasoka and Chiew 2009) based on observed versus simulated temperatures for 1990–2007. Finally we studied with an analysis of covariance (ANCOVA), factors that influence the variability in future attributable numbers of deaths (ANs), including the three sets of RRs, and the 32 temperature simulations used to estimate future ANs (2020-2037). The project was carried out in the context of the Quebec ministerial health surveillance plan, which obtained ethics approval from the Quebec Public Health Ethical Health Surveillance Committee.

Observations

Mortality data

The mortality file comprises residents of the city of Montreal who died in the city during June, July, and August of 1990 through 2007. We included all underlying non-accidental causes of death and excluded deaths for the following codes of the International Classification of Diseases, ICD: ICD-9 800–999 (Injury and poisoning) and ICD-10 S00– T98 (WHO 2004) (Injury, poisoning and other consequences of external causes).

Observed temperatures and ozone levels

We computed daily (from 00:00 to 23:00) mean, minimum, and maximum outdoor temperatures using data for June-August 1990–2007 obtained from the Environment Canada meteorological observation station at the Montréal Pierre Elliott Trudeau International Airport (EC, 2012), located about 20 km from the city core (see Doyon et al. 2008). We obtained hourly measurements of ozone (O_3) at seven fixed-site monitoring stations from the Environment Canada National Air Pollution Surveillance Network (EC, 2012). We averaged hourly concentrations over all stations and we computed daily mean concentrations of O_3 (from 00:00 to 23:00) from these values for June-August 1990-2007.

Projection of temperatures and methods applied to correct simulated temperatures

Models and simulations

The 32 simulations used for the present study provided climate data for 1990-2007 (to allow for correction of simulated temperatures: see below) and 2020–2037, and daily temperature estimates (Table 1). We selected the near future period 2020-2037 for projections to provide a climate change signal out of the climate natural variability that still corresponds to a near future for public health consideration. For each climate model, we considered the temperature time series for the grid-point nearest to Montréal. Twenty-two of the simulations used in this study were based on the GCM simulations of the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007), which use the three B1, A1B and A2 SRES GHG emissions scenarios representing mild, medium, and strong future emissions of greenhouse gases and aerosols, respectively (Nakicenovic et al. 2000). GCMs have a resolution of 200 to 300 km and RCM have a resolution of approximately 50 km. The ensemble of the CMIP3 climate models is the multi-model dataset used for the fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The CMIP3 simulations are available from the Program for Climate Model Diagnostic and Intercomparison (PCMDI) archive (www-pcmdi.llnl.gov). Most of the CMIP3 GCMs cover three time discrete periods (1961-2000, 2046-2065, 2081-2100), whereas the time periods selected for the present study (1990–2007 and 2020–2037) limited our choices to three GCMs with continuous simulations. Therefore, we used fifteen simulations (with varying initial conditions) of the Canadian Global Circulation Model version 3.1 (CGCM3.1/ T47; Flato et al. 2000), developed at the Canadian Centre for Climate Modeling & Analysis (CCCMA) and three simulations of the same model truncated at a finer resolution (CGCM3.1/T63); three simulations of the Mark 3.5 (Mk3.5) climate model developed at the CSIRO Atmospheric Research, Australia (Cai et al, 2003); and one simulation of the German Coupled Global Climate Model (ECHAM5; Junglaus et al. 2006) developed at the Max Planck Institute (MPI) of Meteorology (Germany). Grids representing the GCM models are shown in Supplemental Material, Figure S1.

In addition to the GCM simulations, we used ten simulations of the Canadian Regional Climate Model (CRCM; Caya et al. 1995; Plummer et al. 2006; Laprise 2008), version 4.1 and 4.2 (de Elía and Côté 2010; Paquin 2010) that mirror the recent CRCM evolution (within version 4), and include some minor modifications in parameters associated with surface processes and ozone data. RCMs use GCMs to produce climate projections at a higher resolution on a regional (usually continental) scale (see Christensen et al 2007, and references therein). CRCM simulations over two domains were considered: a domain covering North America (200x192 grid points), and a domain centered over Quebec (111x87 grid points), both with a horizontal grid-size mesh of 45 km (true at 60° N). Grids representing the RCM models are shown in Supplemental Material, Figure S2.

There are different sources of uncertainty that affect temperature projections (Déqué et al. 2007; de Elía and Côté 2010). These include the effects introduced by the RCM downscaling on temperature projections (called here resolution), the GHG emission scenarios (SRES) based on different states of future human activities, the climate model (GCM) itself (each model is conceived with a different structural design, numerical scheme, and physical parameterizations), the initial conditions, which generate (due to the chaotic nature of the climate system) an intrinsic "natural variability" in the climate model response, and the domain (area covered by the RCM simulation). We assessed in the present study the influence of different simulations on the variability of temperature projections and thus, on the variability of future mortality distributions.

To ensure that the 32 simulations covered most of the range of possible future temperature (minimum, maximum and mean) simulations, we computed the differences between the average of future (2046–2065) and historical simulated temperature distributions (1971–2000) for the three temperature metrics (daily mean, minimum, and maximum temperature) based on the 32 simulations versus all simulations available at the Ouranos consortium on climate change (http://www.ouranos.ca/) (n=127 simulations for mean temperatures, n=111 for maximum and minimum temperatures). This analysis confirmed that the 32 simulations included in the present analysis covered most of the temperature variability distribution from all simulations available (see Supplemental Material, Figure S3).

Method applied to correct simulated temperatures

GCM and RCM project future temperatures at specific locations with errors related to the scale of the model predictions and other factors (Mpelasoka and Chiew 2009). Correction methods originally developed for hydro-climatology studies (Teng et al. 2011) include notably Constant Scaling, Daily Scaling, and Daily Translation (DT) methods (Mpelasoka and Chiew 2009). For the present analysis we used the DT method to derive correction factors based on differences between observed historical data for 1990–2007 from a local meteorological station and simulated data for the same location and time period, thereby accounting for errors related to scaling as well as other sources of error.

Deaths attributable to historical and future temperatures

Relationships between observed historical temperatures and mortality

We used separate generalized linear Poisson models to estimate associations between daily death counts [relative risks (RR) compared with the daily mean death count over the entire period] and daily mean, maximum, and minimum observed temperatures during June, July, and August of 1990–2007 (Armstrong 2006). We used cubic B-splines of time with 5 degrees of freedom (splines R package) to control for secular trends in the mortality series (Hajat et al. 2007) and modeled the day of the season (1 to 92) using a spline with three knots (percentiles 10, 50, 90) to control for seasonal patterns. To account for the non-linear relationship between mortality and temperature, we modeled each temperature variable as a cubic spline with 5 knots (corresponding to 0, 25, 50, 75 and 100 percentiles). Thus a different RR was estimated for each degree temperature (i.e. set of RRs based on observed historical data). We also included daily mean levels of O_3 in the regression as a simple continuous variable. To ensure that no auto-correlation remained in the residuals we visually inspected partial autocorrelation plots and used the white noise statistical test (null hypothesis not rejected at $p>0.05$, Lobato and Velasco 2004). We also inspected visually the plots of modelled Pearson residuals against the predicted values, to verify that there was no important over dispersion.

Sets of RRs that generated the 95% confidence intervals of the attributable numbers (ANs)

There is no standard analytical way to estimate the 95% confidence interval bounds of the distribution of a set of RRs (i.e. when there is one RR per degree temperature due to the non-linear relation). We thus estimated the statistical uncertainty of the ANs calculated with the observed historical temperatures (see calculation explained below) with one thousand bootstrap samples, from which we selected the 2.5% and the 97.5% of the ANs based on the observed data, and the corresponding sets of RRs that produced them (i.e. corresponding point estimates per degree temperature produced with the same parameters as the Poisson model developed with the historical data).

The bootstrap samples were developed from the observed daily data as follows. For each of the thousand samples, we drew with replacement 18 times from the day ones, the day twos, etc. (bootstrap samples stratified by day of “summer”). Thus each of the one thousand samples contained 1656 days (92 days x 18 years).

Calculation of deaths attributable to temperatures

We first calculated the attributable fraction of daily deaths (AF) for each daily temperature metric value T_i (mean, maximum or minimum), using the three sets of RRs described above (i.e. one based on the observed historical data, and two based on individual bootstrap samples). We calculated AFs with equation [1] only for RR greater than 1, above the following daily minimum, mean and maximum temperatures: 15°C, 20°C, 20°C:

$$\mathrm{AF}(T_i) = [\mathrm{RR}(T_i)-1]/\mathrm{RR}(T_i) \qquad [1]$$

The total number of attributable deaths (AN) per year for the 1990-2007 and 2020-2037 periods, for a given temperature metric (mean, maximum or minimum), was then estimated from the following equation [2]:

$$\mathrm{AN} = \Sigma\ [\mathrm{AF}(T_i)\times\mathrm{MDC}\times\mathrm{ND}(T_i)] \qquad [2]$$

where MDC is the mean observed daily death count for the period 1990-2007 and $\mathrm{ND}(T_i)$ is the number of days with the value of the temperature (observed or simulated) metric = T_i, and values are summed from the minimum value of T_i (i.e. 15°C, 20°C, 20°C for daily minimum, mean and maximum temperatures) for which the estimated RR for the temperature metric and mortality based on historical data was >1 to the maximum value of T_i.

In our calculation of deaths attributable to future temperatures, we assumed that there would be no change in the mean daily death count in the future, no demographical change, no change in ozone levels and no adaptation to heat from populations.

Variability analysis

We studied the influence of the different simulations on the future temperature and mortality distributions (2020-2037) focussing on daily mean temperature (not daily maximum or minimum).

Temperature projections variability

We performed an analysis of covariance (ANCOVA) where the variable to be explained was the simulated daily mean temperature and the predictors were the simulation (n=32) and the year modelled (n=18).

Attributable numbers variability

We also used an ANCOVA to evaluate the influence of the set of RRs used to represent the temperature-mortality association, the simulation used to project future temperatures, and the year of the simulation on the estimated number of deaths attributable to temperature during each future year of 2020-2037. The three sets of RR used included the set based on the observed historical data, and the two sets of RRs based on the bootstrap data samples that generated the 95% confidence interval of ANs.

4. Results

Observations

For the 18-year period 1990–2007 in Montreal, 61,356 non-accidental deaths occurred during June–August, 79.9% among people older than 65 years of age. The average observed temperature values for daily mean, maximum and minimum temperatures were 20.4°C, 24.9°C and 15.6°C for June-August of 1990-2007. Table 1S, in Supplemental Material, presents the distributions of observed daily temperatures and ozone levels for the summers (i.e. June-August) 1990 to 2007. The average daily ozone concentration for the same period was 25.3 μg/m^3 (range 0.83–76.1 μg/m^3) (Supplemental Material, Table S1).

Simulated temperatures

Simulated historical June-August temperatures

Average values of simulated daily mean temperatures for 1990–2007 over the 32 simulations were lower than observed values before the DT correction was applied (16.6 compared with 20.4 °C), while simulated mean daily temperatures were closer to the observed values after correction (e.g., mean 20.1 °C) (Table 2). We found similar results with daily maximum and minimum temperatures (data not shown).

Simulated future June-August temperatures

All simulations (corrected with the DT method) for June–August 2020–2037 suggested an increase in daily mean temperatures in Montreal, compared to observed temperatures (Table 2). The average of the daily mean temperatures from the 32 future simulations was 20.9°C (range: 20.3°C - 21.3°C), compared with 20.4°C for the observed temperatures for the 1990-2007 summers (i.e. June-August). We observed notable differences between the 32 DT-corrected and uncorrected values (uncorrected average daily mean of 17.6°C). However, the effect of the correction was not constant at all percentiles: greater differences in the ranges were noted at higher and lower percentiles. For example the average (range) of the corrected and uncorrected simulated daily mean temperatures for the lowest percentile were 8.2°C (5.2– 10.5°C) and 5.5 °C (3.8–8.7°C), respectively, and for the 50th percentile were 21.1°C (20.3–21.6°C) and 17.7 (17.1–18.1), respectively. Results were similar for daily maximum and minimum temperatures (data not shown).

Variability in temperature projections

Table 3 presents the percent of variance in daily temperature projections explained by the simulation and the year. Less than one percent of the daily temperature variation was explained by the choice of simulation model and year simulated.

Deaths attributable to historical and future temperatures

The three sets RRs, for each temperature unit, used to calculate deaths attributable to temperature, are presented in Table S2 in Supplemental Material. Applying the RR (>1) of the temperature-mortality relationships, we estimated a mean of 62 (95% CI: 32-86) attributable deaths per summer (i.e. June-August), for the years 1990 to 2007. For maximum and minimum historical daily temperatures, we estimated 55 (95% CI: 32-79) and 38 (95% CI: 9-61) deaths respectively. Table S3 in Supplemental Material also presents deaths attributable to temperatures and their confidence intervals calculated by bootstrapping.

The estimated numbers of deaths attributable to daily mean, maximum, and minimum temperatures during June–August 2020–2037 based on the 32 DT-corrected simulations are presented in Figure 1, along with estimated numbers of deaths attributable to temperatures during 1990–2007 based on observed and DT-corrected simulated temperatures. Average numbers of deaths attributable to daily mean temperature during each year for 2020–2037, were higher based on all 32 simulations than the average number based on observed mean daily temperatures for 1990–2007 (i.e. symbols on the figure represent the attributable numbers based the RRs derived from the observed data). For maximum and minimum daily temperatures, 100% and 72% of the projections, respectively, produced estimated attributable numbers of daily deaths above the average estimated for observed daily temperatures in 1990–2007. Average attributable numbers of deaths based on simulated daily mean temperature during each year for 1990–2007 were similar to the average numbers based on observed mean daily temperatures for 1990–2007. However, differences were noted for simulated daily minimum and maximum temperatures between attributable numbers based on simulated and observed temperatures for this period.

Variability in mortality projections

We noted a high degree of variability in summer (i.e. June-August) deaths attributable to daily temperatures (see Table S3 in Supplemental Material), using the RR based on the observed historical data, for the period 2020-2037, between the 32 simulations (range: 65-129 summer deaths for mean temperatures, 78-161 for maximum temperatures and 30-53 for minimum temperatures).

Table 4 presents the percentage of the variance in future yearly deaths attributable to temperature projections that is explained by the simulation, the year, and the set of RRs used to calculate the ANs. A higher part of the variability in mortality projections, than in temperature projections, was explained by the simulation: six percent of the yearly variation of deaths attributable to future temperatures was explained by the choice of the simulation, compared to less than 1% for the projections of temperatures. Nonetheless, most of the variability in mortality projections (38%) was related to the temperature-mortality RRs used to estimate the attributable fraction of heat-related deaths.

In Figure 2 we show the yearly average estimated number of attributable deaths associated with each daily mean temperature value with RR>1, such that the numbers for each distribution shown in the figure will sum to the average total estimated number of attributable deaths. The majority of estimated attributable deaths occur on days with daily mean temperatures between 24°C and 28°C. This reflects the number of days with temperatures in this range.

5. Discussion

In this study, we estimated the variability in future death projections during June–August 2020–2037 attributable to temperatures in Montreal, Quebec. To do this, we used 32 RCM and GCM temperature simulations (with different climate models, SRES, domains, versions, and members). We found, using DT-corrected simulated summer (i.e. June-August) temperatures, an increase in estimated numbers of deaths attributable to daily mean ambient temperatures during 2020–2037, with a large variability ranging from 34 to 174 deaths per summer (i.e. June-August), compared to 62 deaths attributable to daily observed mean temperatures in 1990 to 2007. We found that a small portion of the estimated variability in mortality projections was due to the different simulations (i.e. variability due to characteristics of the simulations): most of the variability was associated with the RR used to calculate deaths attributable to temperature.

The uncertainty related to the temperature-mortality relationship had much more impact on heat-related mortality projections than that due to climate models. This may be due to the chosen temperature simulations. While the simulations chosen covered an important part of the temperature variability from all simulations available, extreme simulations were not included in our study (see Figure S3 in Supplemental Material). This may thus contribute to underestimating the contribution of the climate model projections. Furthermore, the uncertainty related to the temperature-mortality relationship may be large due to the propagation of the errors associated with the repeated use of the same mortality risk for a given temperature occurring frequently; small changes in the risk function are magnified when applied repeatedly over numerous summer days. Future work is thus needed to better assess the uncertainty of the temperature-mortality relationship and of climate model projections. Finally, we used a crude way to apportion the variation in the future ANs to different sources of variations, by only using the sets of RRs that generated the lower and the upper bounds of the 95% confidence interval of the ANs, and not the shape of the distribution of probable RRs. The explained variance by the sets of RRs thus represents an upper estimate.

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To study the variability in mortality projections we corrected the simulated temperatures with the DT method, as uncorrected simulated values of historical temperatures were quite different from the observed data. We used the DT method because it permits a validation confronting historical simulations with observations. Future work should deepen the contribution of the use of different methods to correct simulated temperatures in mortality projections, as in hydro-climatology studies (Teng et al. 2011).

Studies published on the near future impact of summer temperatures on mortality in Montreal to date report an increase in deaths attributable to heat relative to current numbers of deaths in the summer (Cheng et al. 2008; Doyon et al. 2008; Martin et al. 2011). While such studies used different methods to estimate future mortality, comparisons with our results are still possible. Martin et al. 2011 calculated a predicted change in annual heat-related mortality rate per 100,000 population; they estimated an increase of 152 heat-related attributable deaths per summer for the period 2031-2050, compared to 1981-2000 (Martin et al. 2011). Doyon et al. (2008) calculated the equivalent of 79 summer heat-related deaths for 2020 (2% increase), and 81 deaths, for 2050 (6% increase). Cheng et al. 2008 estimated 96.3 summer heat-related deaths per year in the time window 2040–2059. These results correspond to the range of our results. In line with our results on factors affecting the variability in mortality projections, some differences are likely due to RRs used to estimate the attributable numbers of heat-related deaths. Lower numbers of summer heat-related deaths are likely in southern countries as heat thresholds are generally higher in communities closer to the equator (Hajat and Kosatsky 2010).

Methods for estimating mortality projections inevitably rely on assumptions. First these assumptions concern heat-related mortality relationships. In our study, we chose to not take into account lag effects (Goldberg et al. 2011), harvesting, or mortality displacement (Zanobetti et al. 2002). We did not consider intra urban variations of temperatures and risks (Smargiassi et al. 2009). Future studies should consider these aspects. We also chose to estimate only non-accidental causes of death, and did not conduct specific analyses for cardiovascular or respiratory causes of death (Goldberg et al. 2011; Halonen et al. 2011), while the distribution of specific causes of death may vary in the future. Thus, further work should also address these aspects. Furthermore, other limits remain in our work: we assumed the same mean daily death count in the future, no demographic changes, and no population adaptation to heat, such as through access to air conditioning (Rogot et al. 1992). It is difficult to conclude what the impacts of these assumptions might be. On one hand, with demographic changes there will be more vulnerable populations (elderly populations in particular) and on the other hand, adaptations and mitigation measures may reduce climate impacts (Patz et al. 2008). New climate change impact studies taking into account these specific adaptation and mitigation measures should be performed. We also did not consider other future climate factors like future humidity or air pollution. This could be done with future air pollution (Zhao et al. 2011) and humidity or dew point simulations (Lenderink et al. 2011).

Effects of climate change on health will affect most populations in the next decades, and put the lives and wellbeing of billions of people at increased risk. Our results suggest that the choice of the RR estimate for the association between temperature and mortality may be important to reduce uncertainty in mortality projection.

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7. Acknowledgments and Conflicts of Interest

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

8. Tables and figures

Table 1: Simulations of temperatures and climate models used

Simulation Name	Climatic model	Pilot [a]	Member [b]	SRES	Domain	T° variables [c]
RCM						
RCM1	MRCC 4.2.3	cccma_cgcm3_1	run5	sresA2	North America	All
RCM2	MRCC 4.2.3	cccma_cgcm3_1	run4	sresA2	North America	All
RCM3	MRCC 4.2.3	echam5	run1	sresA2	North America	All
RCM4	MRCC 4.1.1	cccma_cgcm3_1	run4	sresA2	Quebec	All
RCM5	MRCC 4.1.1	cccma_cgcm3_1	run5	sresA2	Quebec	All
RCM6	MRCC 4.2.3	cccma_cgcm3_1	run4	sresA2	Quebec	All
RCM7	MRCC 4.2.0	cccma_cgcm3_1	run4	sresA2	North America	All
RCM8	MRCC 4.2.0	cccma_cgcm3_1	run5	sresA2	North America	All
RCM9	MRCC 4.2.3	cccma_cgcm3_1	run5	sresA2	Quebec	All
RCM10	MRCC 4.2.3	echam5	run1	sresA2	Quebec	All
GCM						
GCM1	cccma_cgcm3_1	NA[d]	run1	sresa1b	NA	All
GCM2	cccma_cgcm3_1	NA	run1	sresa2	NA	All
GCM3	cccma_cgcm3_1	NA	run1	sresb1	NA	All
GCM4	cccma_cgcm3_1	NA	run2	sresa1b	NA	All
GCM5	cccma_cgcm3_1	NA	run2	sresa2	NA	All
GCM6	cccma_cgcm3_1	NA	run2	sresb1	NA	All
GCM7	cccma_cgcm3_1	NA	run3	sresa1b	NA	All
GCM8	cccma_cgcm3_1	NA	run3	sresa2	NA	All
GCM9	cccma_cgcm3_1	NA	run3	sresb1	NA	All
GCM10	cccma_cgcm3_1	NA	run4	sresa1b	NA	All
GCM11	cccma_cgcm3_1	NA	run4	sresa2	NA	All
GCM12	cccma_cgcm3_1	NA	run4	sresb1	NA	All
GCM13	cccma_cgcm3_1	NA	run5	sresa1b	NA	All

GCM14	cccma_cgcm3_1	NA	run5	sresa2	NA	All
GCM15	cccma_cgcm3_1	NA	run5	sresb1	NA	All
GCM16	cccma_cgcm3_1_t63	NA	run1	sresa1b	NA	Only Mean T°
GCM17	cccma_cgcm3_1_t63	NA	run1	sresa2	NA	Only Mean T°
GCM18	cccma_cgcm3_1_t63	NA	run1	sresb1	NA	Only Mean T°
GCM19	csiro_mk3_5	NA	run1	sresa1b	NA	All
GCM20	csiro_mk3_5	NA	run1	sresa2	NA	All
GCM21	csiro_mk3_5	NA	run1	sresb1	NA	All
GCM22	mpi_echam5	NA	run4	sresa1b	NA	All

[a] Pilot corresponds to the GCM used to drive the RCM; [b] Member corresponds to a set of initial conditions; [c] T°: Temperature; [d] NA means not applicable;

Table 2: Observed (1990-2007), future simulated (2020-2037) and historical simulated (1990-2007) daily mean temperature distributions (n=1656 days)

Time period, Quantile	**Observed**	**Simulated, uncorrected** [a]	**Simulated, DT-corrected** [a]
1990–2007			
Minimum	9.6	4.55 (3.96-8.08)	7.62 (5.75-9.23)
1%	12.5	7.41 (6.94-7.99)	11.46 (10.58-12.36)
5%	15.0	9.80 (8.94-10.22)	14.02 (13.61-14.66)
25%	18.3	13.57 (13.17-13.89)	17.68 (17.33-18.03)
50%	20.5	16.56 (16.01-17.03	20.22 (19.91-20.54)
75%	22.7	19.32 (18.79-20.06)	22.59 (22.42-22.89)
95%	24.5	23.71 (23.10-24.13)	25.62 (25.04-26.13)
99%	27.4	26.27 (25.44-27.82)	27.72 (26.84-28.83)
Maximum	29.2	28.77 (27.74-30.09)	31.37 (28.81-37.29)
Mean	20.4	16.57 (16.02-16.97)	20.06 (19.85-20.34)
Standard deviation	3.24	4.21 (4.08-4.36)	3.56 (3.33-3.76)
2020–2037			
Minimum	NA [b]	5.50 (3.78-8.65)	8.15 (5.24-10.48)
1%	NA	8.43 (8.08-8.86)	12.07 (11.31-12.92)
5%	NA	10.55 (10.16-11.02)	14.69 (13.91-15.38)
25%	NA	14.38 (13.78-14.90)	18.47 (17.92-18.92)
50%	NA	17.68 (17.12-18.09)	21.10 (20.30-21.59)
75%	NA	20.70 (20.14-21.05)	23.57 (22.74-24.22)
95%	NA	24.80 (23.87-25.44)	26.58 (25.48-27.18)
99%	NA	29.27 (28.32-30.65)	28.76 (27.37-29.89)
Maximum	NA	29.71 (28.12-32.18)	32.21 (29.39-35.75)
Mean	NA	17.62 (17.27-17.89)	20.94 (20.31-21.32)
Standard deviation	NA	4.33 (4.25-4.39)	3.66 (3.39-3.89)

[a] Average of the 32 simulations and the range

[b] NA: Not Applicable

Table 3: Effect of simulation and year on daily mean temperature projections from an ANCOVA model (n=52992).

Variable	**Partial Sum of Squares**	**df**	**Mean Squares**	**F**	**p**	**η^2**
Year (n=18, 2020-2037)	1476	1	1476	110.4	<0.001	0.2%
Simulations (n=32)	3269	31	105	7.9	<0.001	0.5%
Residuals	708380	52991	13	-	-	-

Eta squared = variance explained by the variable

Table 4: Effect of simulation, year and set of RRs on death attributable to future temperatures by season from an ANCOVA model (n=1,728)

Variable	**Partial Sum of Squares**	**df**	**Mean Squares**	**F**	**p**	**η^2**
Set of RRs (n=3)	2143137	2	1071568	607.3	<0.001	38.0%
Year (n=18, 2020-2037)	163979	1	163979	92.9	<0.001	2.9%
Simulations (n=32)	342493	31	11048	6.3	<0.001	6.1%
Residuals	2987066	1693	1764	-	-	-

Eta squared = variance explained by the variable

Figure legends

Figure 1: Estimated average annual deaths attributable to temperature (daily mean, daily maximum, or daily minimum) during June–August based on observed data for 1990–2007, and simulated data for 1990–2007, and 2020–2037. Simulated data are based on 32 simulations from Regional Climate Models (RCM) and Global Climate Models (GCM) corrected with the daily translation method. Deaths attributable to simulated temperatures were estimated with a set of RRs based on the observed historical data; the upper lines represent the attributable numbers calculated with the set of RRs that generated the upper 95% confidence interval bound of the ANs for the highest attributable number of deaths, while the lower lines represent the attributable numbers calculated with the set of RRs that generated the lower 95% confidence interval bound of the ANs for the lowest attributable number of deaths. The three sets of RRs were also used to generate the attributable numbers for the observed data.

Figure 2: Yearly estimates of minimum, maximum, and average numbers of deaths during June–August attributable to observed temperatures in 1990–2007 and predicted temperatures in 2020–2037 based on 32 simulations (corrected using the daily translation method) according to mean daily temperature (°C).

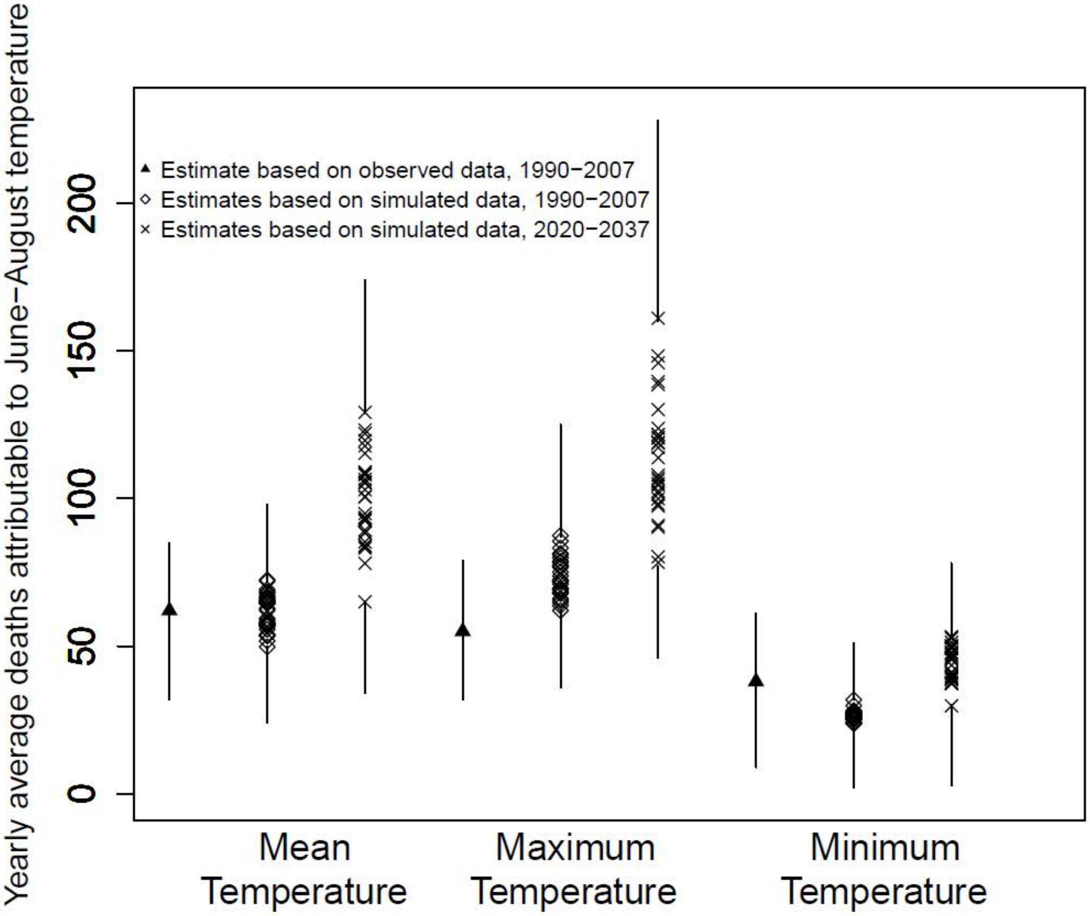
Yearly average deaths attributable to June–August temperature
0
50
100
150
200
▲ Estimate based on observed data, 1990−2007
◇ Estimates based on simulated data, 1990−2007
× Estimates based on simulated data, 2020−2037
Mean Temperature
Maximum Temperature
Minimum Temperature

Figure 1

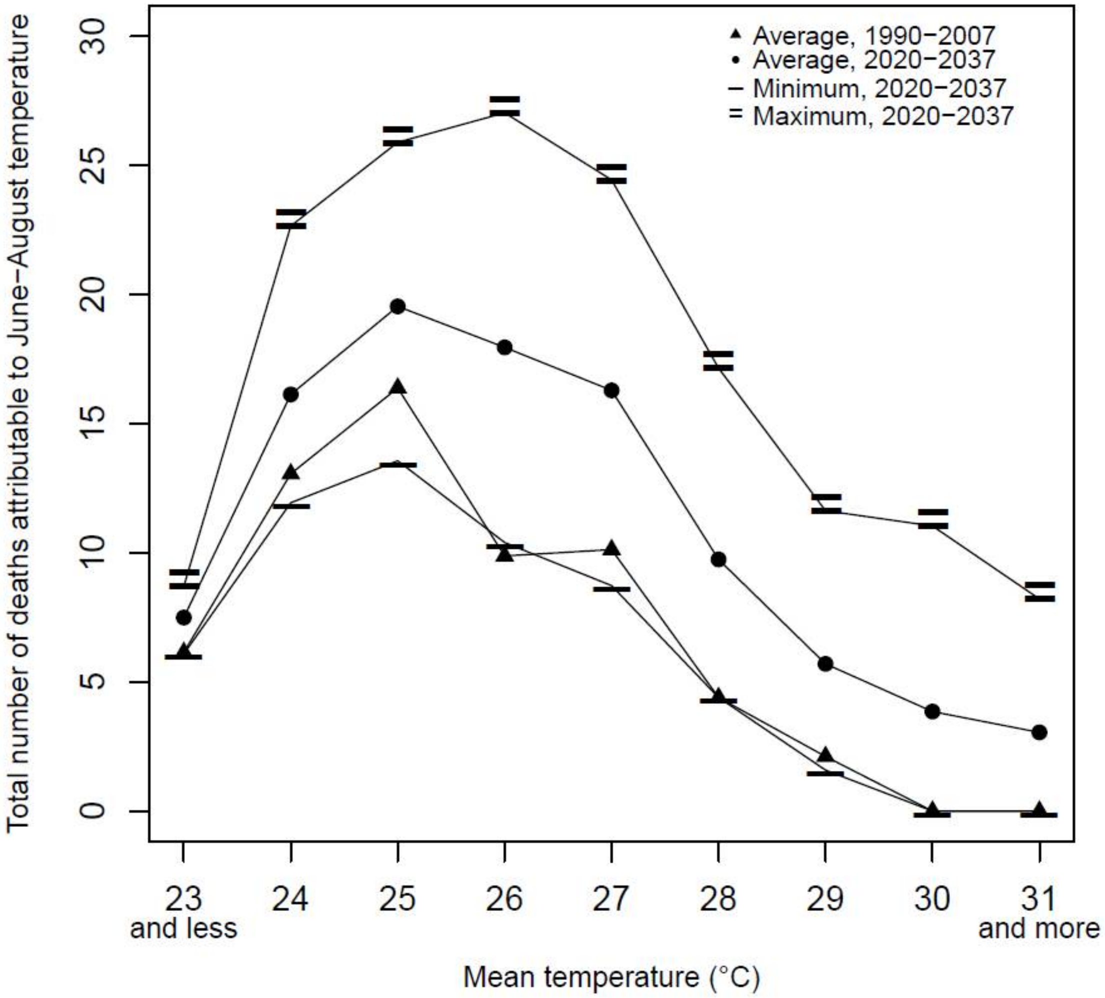
▲ Average, 1990−2007
● Average, 2020−2037
− Minimum, 2020−2037
= Maximum, 2020−2037
Total number of deaths attributable to June−August temperature
0
5
10
15
20
25
30
23
and less
24
25
26
27
28
29
30
31
and more
Mean temperature (°C)

Figure 2

9. Supplemental Material

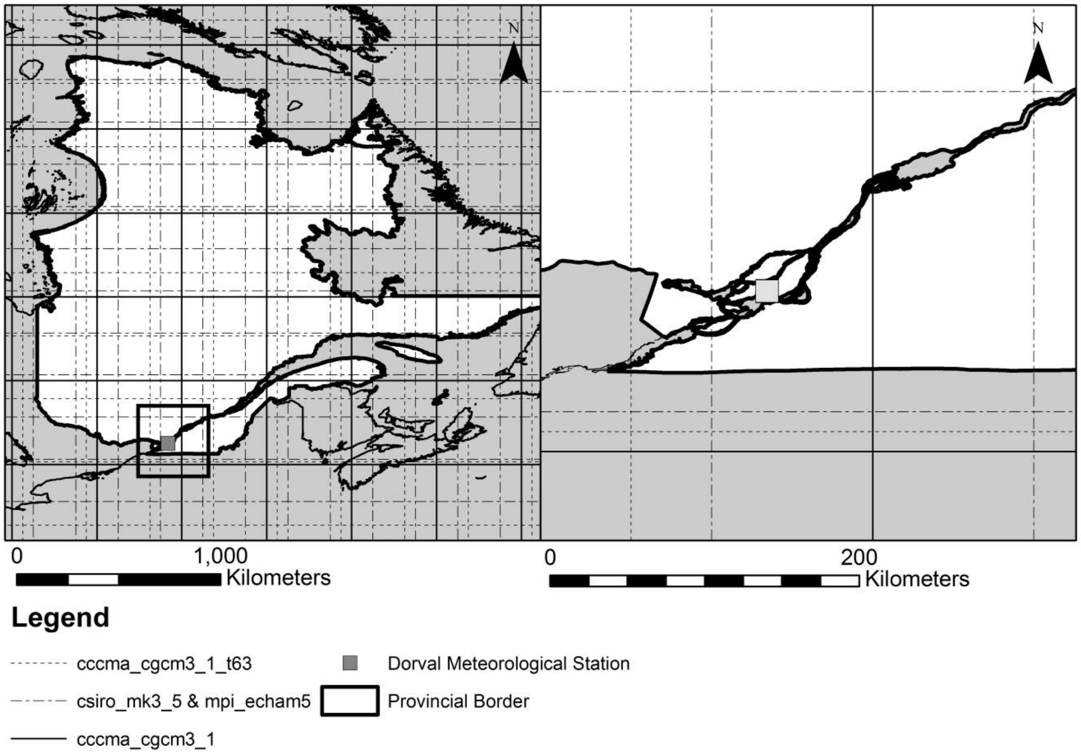

Figure S1: GCM models grid

NB: the lines represent the different GCM used (see Table 2). The area shown represents the Province of Quebec (left) and the city of Montreal (right).

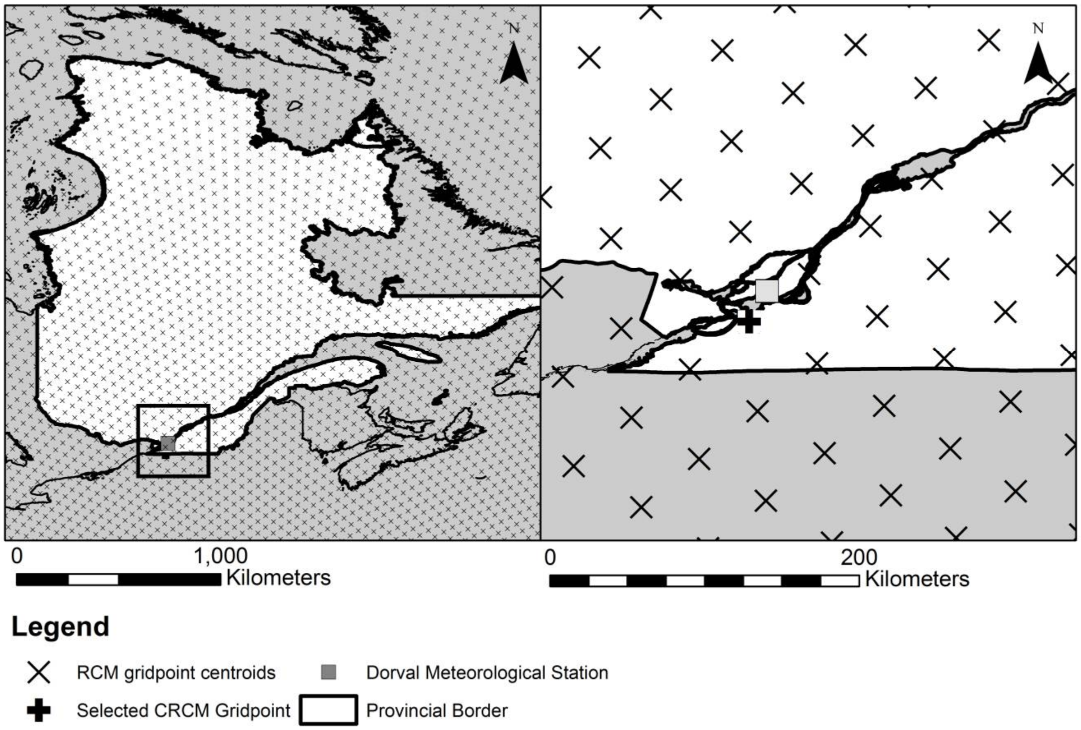

Figure S2: RCM models grid
The area shown represents the Province of Quebec (left) and the city of Montreal (right).

Figure S3: Comparison between the 32 temperatures simulations used with 127 simulations available at Ouranos Consortium.

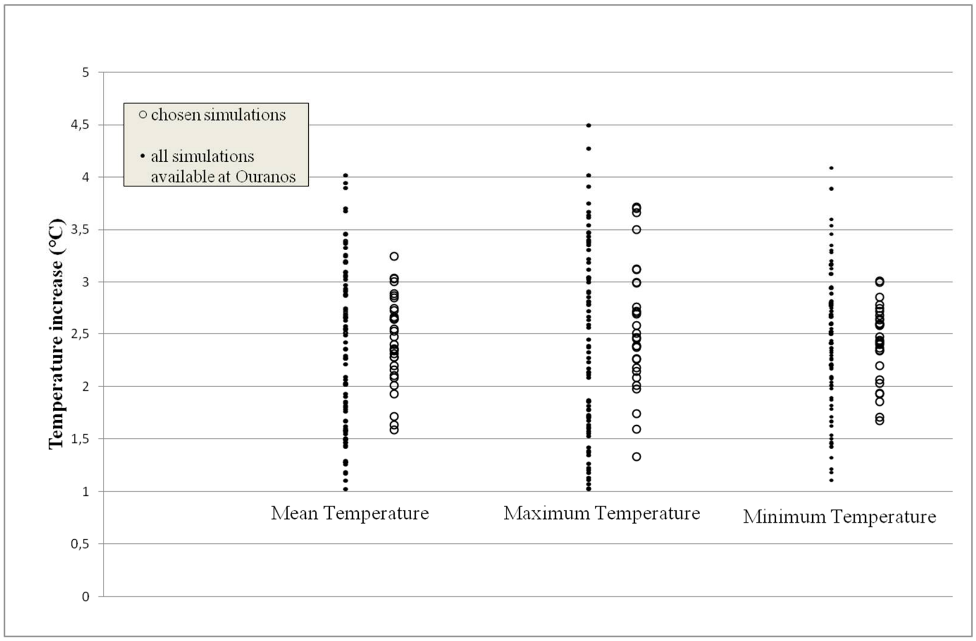

Figure S3: Differences between the mean of the future (2046-2065) and of the historical simulated temperature distributions (1971-2000) (deltas of the mean of the three temperature variables, i.e. daily mean. minimum and maximum temperatures) for the simulations chosen and for all available simulations at the Ouranos consortium on climate change (n=127 simulations for mean temperatures, n=111 for maximum and minimum temperatures).

Table 1S: Observed temperatures (T°), relative humidity, ozone levels for the period 1990-2007 (n=1656 days).

Quantile	Mean T° (C°)	Maximum T° (C°)	Minimum T° (C°)	O3 (µg/m3)
Minimum	9.6	12.0	3.1	0.83
1%	12.5	15.4	7.0	5.4
5%	15.0	18.6	9.5	9.8
25%	18.3	22.5	13.3	17.1
50%	20.5	25.0	15.8	23.5
75%	22.7	27.5	18.2	31.3
95%	24.5	30.7	21.2	47.7
99%	27.4	32.5	23.1	
Maximum	29.2	35.4	25.8	76.1
Mean	20.4	24.9	15.6	25.3
Standard Deviation	3.24	3.70	3.57	1

Table S2: RR from the three sets for each temperature unit (in °C) in Montreal, for daily mean, maximum and minimum temperatures.

Mean Temperatures	RR based on the observed historical data	RR 2.5% of bootstrap estimates	RR 97.5% of bootstrap estimates	Maximum Temperatures	RR based on the observed historical data	RR 2.5% of bootstrap estimates	RR 97.5% of bootstrap estimates	Minimum Temperatures	RR based on the observed historical data	RR 2.5% of bootstrap estimates	RR 97.5% of bootstrap estimates
5	0.95	0.85	0.95					5	0.93	0.91	0.83
6	0.95	0.85	0.95					6	0.93	0.91	0.86
7	0.95	0.86	0.94					7	0.94	0.92	0.88
8	0.95	0.87	0.94					8	0.94	0.93	0.90
9	0.95	0.87	0.93	9	1.01	1.02	1.12	9	0.94	0.93	0.92
10	0.94	0.88	0.92	10	1.00	1.02	1.10	10	0.95	0.94	0.94
11	0.94	0.89	0.92	11	0.99	1.01	1.09	11	0.96	0.95	0.95
12	0.94	0.90	0.92	12	0.99	1.00	1.07	12	0.96	0.96	0.96
13	0.94	0.90	0.91	13	0.98	0.99	1.05	13	0.97	0.97	0.97
14	0.95	0.91	0.91	14	0.97	0.99	1.04	14	0.98	0.98	0.98
15	0.95	0.92	0.91	15	0.97	0.98	1.02	15	0.99	0.99	0.98

16	0.95	0.93	0.92	16	0.96	0.97	1.01	16	0.99	0.99	0.99
17	0.95	0.94	0.93	17	0.96	0.97	1.00	17	1.00	0.99	1.00
18	0.96	0.95	0.95	18	0.96	0.96	0.99	18	1.01	0.99	1.02
19	0.97	0.96	0.97	19	0.96	0.96	0.98	19	1.02	1.00	1.04
20	0.98	0.98	0.99	20	0.96	0.96	0.97	20	1.04	1.01	1.07
21	0.99	0.98	1.01	21	0.96	0.96	0.97	21	1.06	1.03	1.09
22	1.00	0.98	1.01	22	0.96	0.96	0.97	22	1.09	1.05	1.12
23	1.02	1.00	1.03	23	0.97	0.97	0.97	23	1.12	1.08	1.16
24	1.05	1.02	1.07	24	0.98	0.97	0.97	24	1.16	1.11	1.19
25	1.09	1.06	1.12	25	0.98	0.98	0.98	25	1.20	1.14	1.23
26	1.14	1.12	1.19	26	0.99	0.99	0.99	26	1.24	1.17	1.26
27	1.20	1.18	1.28	27	1.00	1.00	1.00	27	1.28	1.21	1.30
28	1.27	1.25	1.38	28	1.02	1.01	1.03	28	1.32	1.24	1.34
29	1.35	1.33	1.50	29	1.05	1.03	1.07	29	1.37	1.28	1.38
30	1.42	1.42	1.63	30	1.08	1.05	1.12				
31	1.51	1.51	1.76	31	1.12	1.07	1.19				

32	1.60	1.60	1.91	32	1.17	1.09	1.27				
33	1.69	1.70	2.08	33	1.23	1.12	1.36				
34	1.79	1.81	2.25	34	1.29	1.14	1.46				
35	1.89	1.93	2.44	35	1.35	1.17	1.57				
36	2.01	2.05	2.65	36	1.42	1.20	1.70				
37	2.12	2.18	2.88	37	1.50	1.23	1.83				
				38	1.58	1.26	1.97				
				39	1.66	1.29	2.13				
				40	1.74	1.32	2.29				
				41	1.83	1.35	2.47				
				42	1.93	1.38	2.67				
				43	2.03	1.42	2.88				

Table 3S: Estimated annual number of deaths (with 95% CI[a]) attributable to observed mean, minimum, or maximum daily temperature of June–August 1990-2007, and minimum, and maximum numbers of annual deaths attributable to projected temperature data for 2020–2037 from 32 simulations.

Daily temperature metrics	**AN based on observed temperatures (1990-2007) with 95% CIa**	**Minimum AN based on simulated temperature (2020-2037) with 95% CIa**	**Maximum AN based on simulated temperature (2020-2037) with 95% CIa**
Mean daily temperature	62 (32, 86)	65 (34, 89)	129 (67, 174)
Maximum daily temperature	55 (32, 79)	78 (46, 109)	161 (95, 228)
Minimum daily temperature	38 (9, 61)	30 (3, 46)	53 (15, 78)

[a] CI bounds for estimates based on simulated data represent the 2.5th and 97.5th percentiles of 1,000 bootstrap samples.

CHAPITRE 6 : SOCIAL DISPARITIES IN YEARS OF LIFE LOST ATTRIBUTABLE TO HEAT UNDER CLIMATE CHANGE IN PARIS AND MONTREAL

Social disparities in years of life lost attributable to heat under climate change in Paris and Montreal

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1. Abstract

Background: Heat related mortality is not equally distributed across populations according to their socioeconomic status. The aim of this study is to assess historical and future social disparities in years of life lost caused by ambient temperature in Montreal, Canada and Paris, France, and to compare these estimates as well as the impact of climate change on social disparities between the two cities.

Methods: We used summer historical data from 1990 through 2007 for Montreal and from 2004 through 2009 for Paris to estimate daily years of life lost social disparities (DYLLD) summarizing social inequalities across groups. We used a Generalized Linear Model to separately estimate relative risks (RR) for DYLLD in association with daily mean temperatures in both cities. To estimate future temperature distributions, we used 30 climate scenarios of daily mean temperature (from the last IPCC report). We calculated rates of DYLLD attributable to temperature for both historical and future periods and for each city and we calculated the impact of climate change (defined as the ratio between future and historical estimates) on DYLLD attributable to temperature. We performed random effect meta-analyses for the impact of climate change by climate scenario to produce a pooled ICC for each city and compared the impact of climate change for the 2 cities using a meta-regression analysis.

Results: The summer rate of DYLLD attributable to temperature for the historical period was 34.70 years per 100 000 persons (95% CI: 16.22, 47.44) in Montreal and 13.34 years per 100 000 persons (95% CI: 7.97, 18.26) in Paris. For the future period, rates of DYLLD attributable to future temperatures ranged from 22.40 years per 100 000 persons (95% CI: 14.01, 32.77) to 100.24 years per 100 000 persons (95% CI: 80.54, 121.75) in Montreal and from 9.98 years per 100 000 persons (95% CI: 6.00, 17.23) to 35.23 years per 100 000 persons (95% CI: 26.50, 41.18) in Paris. The impact of climate change on DYLLD attributable to temperature was of 2.06 (95% CI: 1.90, 2.25) in Montreal and 1.77 (95% CI: 1.61, 1.94) in

Paris. The city explained a difference of 0.31 (95% CI: 0.14, 0.49) on the impact of climate change.

Conclusion: An increase in ambient temperature can lead to an increase in daily years of life lost social disparities. Our results support evidence suggesting that adaptation measures should be oriented toward reducing health disparities in the context of climate change, as we showed that health disparities related to heat impacts exist today and will increase in the future.

2. Introduction

It is well known that increasing ambient temperatures is associated with increased heat related health impacts, namely to increases in mortality (Armstrong et al. 2012; Huang et al. 2011). Yet, heat related mortality is not equally distributed across populations or territories. Populations or territories which are more impacted by heat are considered as vulnerable, where vulnerability is related to a factor that modifies the effect of heat on mortality (Kuh et al. 2003). One such factor is the socioeconomic status of populations (Chan et al. 2012; O'Neill, Zanobetti, and Schwartz 2003; Stafoggia et al. 2006). Mortality projections associated with heat, for vulnerable populations can be useful to orient the allocation of resources towards those that are most in need to reach health equity, and to orient the implementation of policies to reach social justice ideals in the context of climate change.

So far no study has assessed how social health disparities (defined as inequalities in health status associated with different levels of social deprivation) related to heat will vary in the context of climate change. Besides, social health disparities associated with heat can vary between countries and social contexts (Popham, Dibben, and Bambra 2013; Van Doorslaer et al. 1997; Parks and Roberts 2010). Thus, it seems important to compare different settings to explore if future climate conditions will influence in a different way social health disparities.

Objectives

Our aim is to assess historical and future social disparities in years of life lost caused by ambient temperature in Montreal, Canada and Paris, France, and to compare these estimates as well as the impact of climate change on these social disparities between the two cities.

To do that, we propose an innovative approach relating daily social disparity in Years of Life Lost (YLL) to temperature in times series analyses, using a large panel of climate scenarios (n=30) from the last IPCC report from the global climate modeling centers. We estimated YLL instead of mortality, because YLL is an indicator of premature mortality giving larger burden to younger deaths (Burnet et al. 2005; Huang et al. 2012a, b; Romeder and McWhinnie 1977) , which is particularly relevant when studying social disparities (Crimmins and Saito 2001; Franzini and Spears 2003; Jagger et al. 2009; Kalediene and Petrauskiene 2000).

3. Methods

Mortality data

The study population includes all residents of the island of Montreal, Canada who died in the city in the summers of 1990 to 2007 and the residents of the city of Paris, France in the summers of 2004-2009. We defined "summers" as the months June, July and August. For Montreal, we included all underlying non-accidental causes of death (WHO 2004). It was not possible to exclude accidental causes of death in Paris, because we did not have access to underlying causes of mortality. Therefore we only included Paris subjects older than 35 years old at the time of death to minimize this bias because accidental causes of death are dominant in subjects under 35 years old (Meslé and Vallin 1996). We also used this approach with the Montreal data for a sensitivity analysis.

Years of life lost estimation

To calculate the life expectancy at birth for each death, we used the Quebec life table for Montreal for the years 2000 to 2002 (Statistiques Canada 2002) and the French life table for Paris for the years 2004 to 2006 (INSEE 2006), matching by age and sex. To obtain an individual number of years of life lost (YLL) (which can be positive or negative), we estimated for each death, the difference between the life expectancy and the factual age of death. We then summed all the YLL individual estimates by day to obtain the total daily YLL. YLL were estimated separately for men and women but were then grouped together in the total daily YLL.

Socioeconomic data

We attributed the following community level social vulnerability indicators to each death at the smallest census unit area available for both Montreal and Paris. For Montreal we used the percentage of the population of a dissemination area aged >20 years without a high school diploma from the 2006 census (Institut Statistique Québec 2006), and for Paris we used the percentage of the population without diploma (corresponding to high school) at the IRIS French census division (group of blocks for statistical information) from the 2006 national census (INSEE 2006). We also used a social vulnerability indicator as a composite deprivation index for Paris (Lalloué et al. 2013) for a sensitivity analysis. The mean population level for the dissemination areas of Montreal was 588, while it was 2199 inhabitants for the IRIS of Paris. We then stratified the total daily YLL by terciles of the indicator of social vulnerability. Figure S1 and Figure S2 present the spatial distribution of education levels in Montreal and Paris respectively.

Meteorological data

Daily mean outdoor temperatures (°C) and daily relative humidity (%) were obtained for the period 1981-2010 at the Montréal Pierre Elliott Trudeau International Airport from Environment Canada (EC, 2014) and at the Montsouris station from Météo-France (REF) for Paris.

Climate scenarios of historical and future temperatures

Thirty climate scenarios of daily mean temperature were used. A climate scenario is here defined as a time series with statistical properties judged plausible over a period of time. Each climate scenario is based on a climate simulation from a numerical Earth System Model (ESM) used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012). The post-processing of each model's raw simulation is performed for maximizing agreement of temperature distributions with observations during the historical period, following a method akin to that of Themeßl et al. (2011).The same 30 climate simulations are used for Montreal and Paris, but post-processing steps are conducted separately, using each city's meteorological data. No single scenario should be seen as a prediction, but as an ensemble they aim to cover the real future climate trajectory. The simulations selection covers 4 different emission scenarios and 7 different ESMs (see the list in **Table 1**). Periods investigated are 1981-2010 (historical) and 2021-2050 (future).

Estimating daily YLL social disparities

In order to represent daily social disparities (i.e. inequalities in health status associated with different levels of education measured by day) in terms of YLL, we used a modified "Index of Disparity" (Pearcy and Keppel 2002), for summarizing inequalities across groups by day. In this way, the outcome is the inequality.

We calculated daily YLL social disparities (DYLLD) with formula [1]:

$$DYLLD = \left[\, \textstyle\sum_{j=1}^{J}\left(YLL_j - YLL_{ref}\right) / J \,\right]_{\text{day}} \qquad [1]$$

where YLL is the total daily years of life lost, j indexes each of the J social groups (here J=2), and YLL_{ref} is the daily total YLL estimate for the highest socioeconomic group (the reference group). Formula calculated for all deaths occurring each day. Consequently, we obtain a DYLLD for each day of the observed period. Using this index allowed us to obtain a single daily estimate of YLL social disparities between the different social strata. This index thus represents a daily average difference between all groups with the most advantaged social group.

Estimating the historical association between DYLLD and temperature

A Generalized Linear Model (GLM) was used to estimate the association between DYLLD and daily mean temperatures in both cities separately. We used cubic B-splines of time (7 degrees of freedom) to control for secular trends in the DYLLD series. To consider the non-linear relationship between DYLLD and temperature, we modeled the temperature variable as a cubic spline with 3 knots (corresponding to 25th, 50th and 75th percentiles). Models were adjusted or not (for sensitivity analyses), for daily relative humidity. Sensitivity analyses were carried out by changing the degrees of freedom for secular trends. The adequacy of the models was checked by verifying that the residuals were independent over time (with visual inspection of partial autocorrelation plots and using white noise statistical test). We calculated Relative Risks (RR) for the relation between DYLLD and daily temperature relative to the average DYLLD for the entire period (Hajat, Kovats, and Lachowycz 2007). Thus RRs were computed by a comparison with the averaged DYLLD over the entire period. We estimated RRs by each temperature unit.

Calculation of DYLLD attributable to temperature

Assuming that the estimated associations were causal, we calculated DYLLD attributable to temperature for both historical and future periods and for each city. Attributable DYLLD were calculated using attributable fractions (AF) with the specific RRs by temperature, calculated with the historical data. We included in the calculation only days with daily temperature related to a RR >1. To calculate the total DYLLD attributable to temperature we used the formula [2]:

$$\text{Total DYLLD}_{\text{att}} = \Sigma\ [\text{AF}(T_i) \times \text{Mean}_{\text{DYLLD}} \times \text{ND}(T_i)] \qquad [2]$$

where $\text{Mean}_{\text{DYLLD}}$ is the mean observed DYLLD for the observed periods and $\text{ND}(T_i)$ is the number of days with the value of the temperature (observed or simulated) unit = T_i, and values are summed from the minimum value of T_i (for which the estimated RR was >1) to the maximum value of T_i.

We used the observed temperature distribution for the period 1981-2010 to estimate historical total DYLLD attributable to temperatures in Paris and in Montreal (n=1 x 2). We used simulated temperature distributions in both cities (n=30 x 2) for the period 2021-2050 to estimate future total DYLLD attributable to temperatures. We chose to present annual June-August estimates (referred to as summer estimates) by dividing the total DYLLD attributable to temperature by 30 (years) for both the historical and future periods. We used bootstrapping to construct the 95% confidence intervals for summer attributable number of DYLLD. We estimated percentile bootstrap 95% confidence intervals for the total attributable number of DYLLD with one thousand bootstrap samples based on the observed data, from which we selected the 2.5% and the 97.5% of the number of total DYLLD. We created bootstrap samples by choosing DYLLD randomly in each year among the whole periods.

Calculation of the impact of Climate Change on DYLLD attributable to temperature

We defined the impact of climate change (ICC) on DYLLD attributable to temperature as the ratio between future and historical summer estimates. We then performed random effect meta-analyses of ICC by climate scenario to produce a pooled ICC (and its 95% CI) for each city separately. The formula used to calculate the standard errors of the ratios is presented in the Supplemental Material. We assumed no acclimatization to heat, and no changes in population size, age structure or life expectancy.

Comparison of the two cities

We first compared the impact of climate change on temperatures between the two cities. We conducted random effect meta-analyses of averaged difference between observed historical and future daily mean temperatures by climate scenario (n=30). We computed pooled estimates for each city and compared them (with a t test).

To compare historical summer DYLLD attributable to observed historical temperature between Montreal and Paris, we first calculated rates of DYLLD attributable to temperature, by dividing the total number of DYLLD attributable to temperature by the total population in each city on year 2001 for Montreal and year 2006 in Paris, based on census data (Institut Statistique Québec 2001; INSEE 2006). We compared the two estimates by conducting a t test.

We also compared future summer DYLLD attributable to simulated temperature between Montreal and Paris. As for historical estimates, we calculated rates using the 2001 and 2006 populations. We then conducted a meta regression analysis on the 60 future rates (30 for Montreal and 30 for Paris) where the dependent variable was the ln(DYLLD rates) and the independent variable was the city. We finally compared the pooled ICC between Montreal and Paris by conducting a meta-regression analysis on the 60 ICC estimates (30 for Montreal and 30 for Paris) in which the dependent variable was the ln(ICC) and the independent variable was the city.

4. Results

All together, 3408 and 3235 deaths by summer (June-August) respectively occurred in Montreal and Paris for the study periods. The average summer daily mean observed temperatures were 20.4°C (SD = 3.24°C) for Montreal and 19.63°C (SD = 3.21°C) for Paris for the study periods. The daily YLL ranged from 1076 years to 6739 years in Montreal (mean = 2660 years) and from 633 years to 2991 years in Paris (mean = 1483 years). The percentage of the population without a high school diploma in the census division of decedents ranged from 0% to 73.47% in Montreal (mean = 20.97%) and from 0% to 100% in Paris (mean = 33.67%) (see details in supplemental material: Table S1). Table S2 presents daily estimates of DYLLD in Montreal and Paris. The mean daily estimates of DYLLD were 339.35 years (SD = 326.21 years) for Montreal and 187.32 years (SD = 169.11 years) for Paris.

Table S3 and S4 present the descriptive statistics for daily mean temperatures from the 30 climate scenarios respectively in Montreal and Paris, for the periods 1981-2010 and 2021-2050.

The pooled estimate of averaged difference between simulated historical and future daily mean temperatures was 1.35°C (95% CI: 1.13°C, 1.60°C) for Montreal and 1.12°C (95% CI: 0.93°C, 1.36°C) for Paris suggesting that the impact of climate change on daily mean temperature will be larger ($P < 0.01$) in Montreal than in Paris according to the climate scenarios included in our analysis.

Heat YLL disparities relationships

The RRs for each temperature unit are presented in Table S5 and Table S6. We present and used RRs from regression analyses that did not adjust for relative humidity as it had minimal influence on the RRs (data not shown). Changing the degrees of freedom for secular trends had a minimal influence on RRs as well (data not shown). The relations between daily temperatures and DYLLD in Paris and Montreal were J-shaped. The effect of temperature started to increase at 23°C in Montreal and 22°C in Paris. We found no effect of temperatures on DYLLD below these respective thresholds.

DYLLD attributable to historical temperatures

The summer rates of DYLLD attributable to temperature in historical period was 34.70 years per 100 000 persons (95% CI: 16.22, 47.44) in Montreal and 13.34 years per 100 000 persons (95% CI: 7.97, 18.26) in Paris. We found that historical summer DYLLD rates attributable to temperature were higher in Montreal compared to Paris ($P < 0.01$).

DYLLD attributable to future temperatures

For the future period, rates of DYLLD attributable to future temperatures ranged from 22.40 years per 100 000 persons (95% CI: 14.01, 32.77) to 100.24 years per 100 000 persons (95% CI: 80.54, 121.75) in Montreal and from 9.98 years per 100 000 persons (95% CI: 6.00, 17.23) to 35.23 years per 100 000 persons (95% CI: 26.50, 41.18) in Paris.

Coefficients of meta-regressions for the comparison of the rates of future DYLLD attributable to temperatures in Montreal and Paris are presented in **Table 2**. Future summer rates of DYLLD attributable to temperature were higher in Montreal than in Paris. The city explained a difference of rates of DYLLD attributable to temperature between Montreal and Paris of 45.13 years per 100 000 persons (95% CI: 37.17, 53.54) for future summer periods.

Impact of climate change on DYLLD attributable to temperature

Using a meta-analysis we estimated the overall ratio (according to the 30 different climate scenarios) between future and historical DYLLD for each city to represent the impact of climate change. We found an overall ratio of 2.06 (95% CI: 1.90, 2.25) in Montreal (Figure 1) and 1.77 (95% CI: 1.61, 1.94) in Paris (Figure 2). The impact of climate change on DYLLD attributable to temperature was higher in Montreal compared to Paris. The city explained a difference of ICC (i.e. ratio between historical and future summer estimates) of 0.31 (95% CI: 0.14, 0.49) (Table 1).

5. Discussion

In this paper, we showed that an increase in ambient temperature can lead to an increase in daily years of life lost disparities (according to the education level as a social community level indicator) in both Montreal and Paris. We also found these heat-related social disparities to be larger in Montreal than in Paris in both historical (1981-2010) and future (2021-2050) periods. Lastly, we estimated that the increasing years of life lost social disparities associated with climate change will be higher in Montreal than in Paris. This last result can be partly explained by the fact that the impact of climate change on daily mean temperature will be larger in Montreal than in Paris according to the climate scenarios included in our analysis.

In this study, we offer various methodological innovations which can be used in further studies. We present a pioneering approach relating daily social disparity in years of life lost (using an index of disparity) to temperature in times series analyses to measure health disparities as an alternative to stratified analyses which are commonly used in this context (O'Neill, Zanobetti, and Schwartz 2003; Schifano et al. 2009; Stafoggia et al. 2006; Yu et al. 2010). We believe that this approach is more effective for orienting equity-based interventions because it directly reveals the impact of this environmental determinant of health on disparities (King, Harper, and Young 2012). This approach can be reproduced for any modifying effect question when using time series analyses. We calculated future health impacts, for the first time to our knowledge, using a large panel of climate scenarios from the most recent IPCC report from the global climate modeling centers with modern post-processing analyses (i.e. quantile-quantile methods). The use of climate scenarios in health impact studies has recently been performed (Benmarhnia et al. 2014; Huang et al. 2011; Li, Horton, and Kinney 2013) and offers a more suitable approach, given the uncertainty and complexity of climate projections, than simply adding 1°C or more to the observed historical temperatures (Bennett et al. 2014; Huang et al. 2012b). Indeed, the use of numerous climate scenarios is essential to represent the uncertainty in future mortality impacts (Benmarhnia et al. 2014). We also proposed a way to compare the heat-related health impacts of climate change in different cities by conducting meta-regressions.

We attempted to conduct equivalent analytical approaches between the two cities to keep the comparison plausible, yet there are several limitations to our comparison analysis. First, the urban configurations and social heritages are quite different between Montreal and Paris. Indeed, in the Montreal Metropolitan Area (Greater Montreal) which represents the reach of commuter movement to and from the island of Montreal and its surrounding suburbs, the most socially disadvantaged communities are situated within the island of Montreal (Auger et al. 2011; Pampalon and Raymond 2000) whereas in the Paris Metropolitan Area, the city of Paris (except few North East neighborhoods) over represents the less socially disadvantaged communities of the Paris Metropolitan Area (Gobillon, Magnac, and Selod 2011; Pinçon and Pinçon-Charlot 2008; Tovar and Bourdeau-Lepage 2013). This could explain why we found more heat-related social disparities in Montreal than in Paris. Unfortunately, we did not have access to mortality data for the whole Paris Metropolitan Area to fully explore this issue.

Second, although we tried to employ the same social and environmental measures for the two cities, some differences remain. The size of the census division at which the social vulnerability indicator was available was larger in Paris (mean population of 588 in Montreal vs. 2199 in Paris). This can lead to a larger misclassification bias for the attribution of community level social vulnerability characteristics in Paris. Then, baseline age distributions and mortality rates are quite different between the two cities. These points could have an influence on the DYLLD attributable to historical and future temperatures comparison. However, they will most likely not affect our results about the impact of climate change on health disparities, because these estimates are relative to each city.

Third, the difference in analytical approach with mortality data (i.e. including only subjects older than 35 years in Paris) and the choice of community level social vulnerability indicators could have also influenced our findings. Yet, in sensitivity analyses, our results remained unaltered by modifications of the population (using individuals >35 years of age for Montreal), and of the social indicators used (i.e. composite deprivation index for Paris) (see Table S7).

Other limitations of this study deserve mention and might be addressed in further studies. First, we did not consider the effect of heat waves (Hajat et al. 2006), which can possibly result in our health impact projections being underestimated. Second, we only considered the heat effects on DYLLD at current day's temperature (i.e. lag0), which possibly also underestimate our estimates. However, according to previous studies the strongest heat effects are from the current day's temperature (Goldberg et al. 2011; Huang et al. 2012b), thus this underestimation is likely slight. Third, we applied the historical associations between ambient temperature and DYLLD to future populations, and by doing this, we disregarded the repercussion of demographic or health changes (increase in life expectancy, changes in age pyramid…) and adaptation measures which could influence population's vulnerability (Petkova, Morita, and Kinney 2014; Petkova, Gasparrini, and Kinney 2014).

Despite these limitations, our results should orient adaptation measures to help reduce heat-related mortality as well as health disparities in the context of climate change, as we show that health disparities related to heat impacts exist today and will increase in the future.

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7. Acknowledgments and conflict of interest

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Conflict of interest: None declared.

8. Tables and figures

Table 1: Simulations of temperatures and climate models used

Simulation ID	Climate Model	Emission Scenarios	Member*
1	BCC-CSM1.1	rcp26	r1i1p1
2	CanESM2	rcp26	r1i1p
3	CanESM2	rcp26	r2i1p1
4	CanESM2	rcp26	r3i1p1
5	CanESM2	rcp26	r4i1p1
6	CanESM2	rcp26	r5i1p1
7	MPI-ESM-LR	rcp26	r1i1p1
8	NorESM1-M	rcp26	r1i1p1
9	BCC-CSM1.1	rcp45	r1i1p1
10	CanESM2	rcp45	r1i1p1
11	CanESM2	rcp45	r2i1p1
12	CanESM2	rcp45	r3i1p1
13	CanESM2	rcp45	r4i1p1
14	CanESM2	rcp45	r5i1p1
15	INM-CM4	rcp45	r1i1p1
16	IPSL-CM5A-LR	rcp45	r1i1p1
17	MPI-ESM-LR	rcp45	r1i1p1
18	MRI-CGCM3	rcp45	r1i1p1
19	NorESM1-M	rcp45	r1i1p1
20	BCC-CSM1.1	rcp60	r1i1p1
21	IPSL-CM5A-LR	rcp60	r1i1p1
22	NorESM1-M	rcp60	r1i1p1
23	BCC-CSM1.1	rcp85	r1i1p1

24	CanESM2	rcp85	r1i1p1
25	CanESM2	rcp85	r2i1p1
26	CanESM2	rcp85	r3i1p1
27	INM-CM4	rcp85	r1i1p1
28	MPI-ESM-LR	rcp85	r1i1p1
29	MRI-CGCM3	rcp85	r1i1p1
30	NorESM1-M	rcp85	r1i1p1

* members represent different initial conditions of the simulation

Table 2: Meta-regression models investigating the influence of the city on future rates of summer DYLLD and on the impact of climate change.

	Influence of the City*	
Dependent Variable	**Beta (95% CI)**	***P* Value**
Future summer rates of DYLLD** (2021-2050)	45.13*** (37.17 to 53.54)	**< 0.001**
Impact of Climate Change (ICC) on summer DYLLD	0.31 (0.14 to 0.49)	**< 0.001**

* Montreal was coded as 1 and Paris as 0.

** The total population used was 1 812 723 (year 2001) for Montreal and 2 234 105 (year 2006) for Paris.

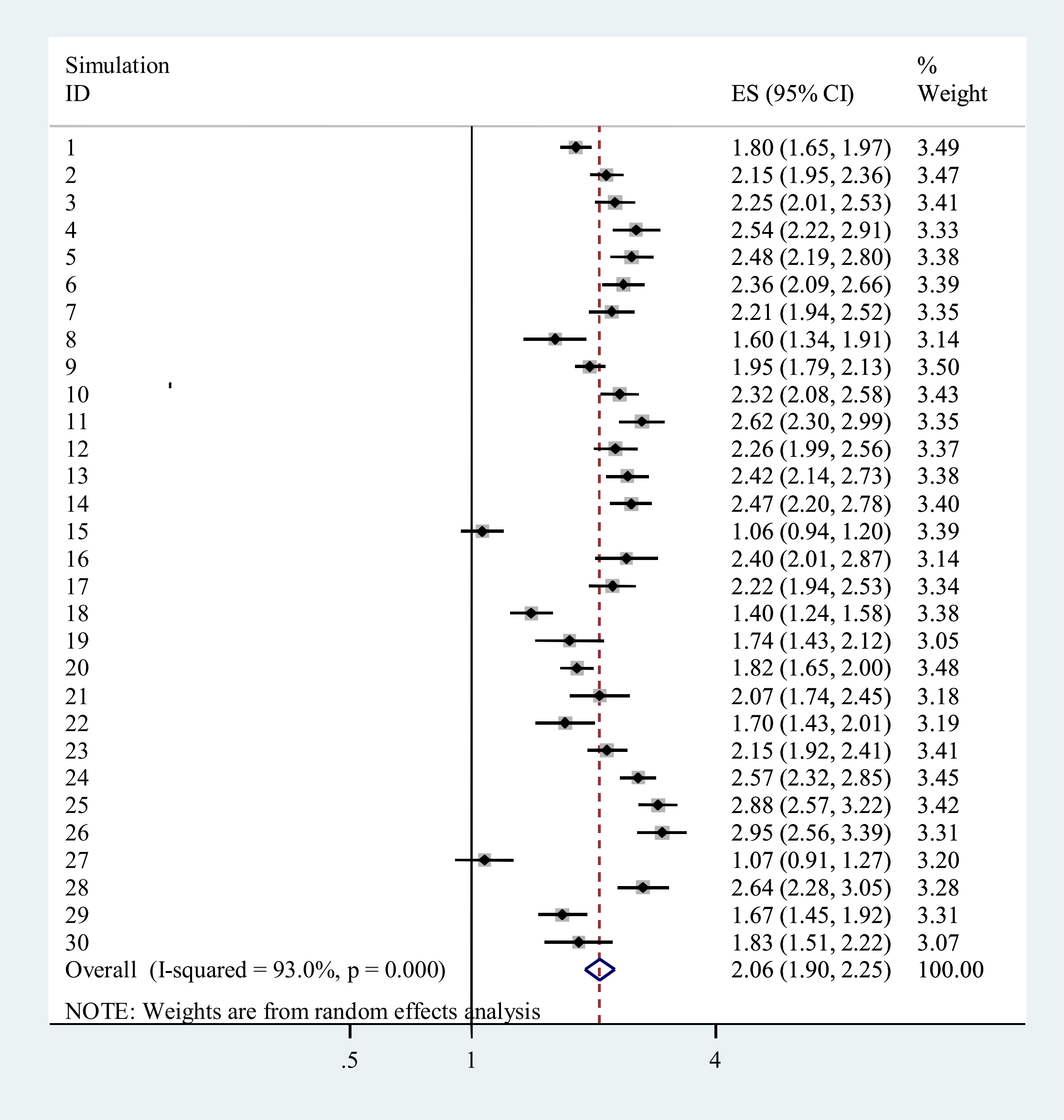
*** Summer rates of DYLLD are expressed per 100 000 persons.

CI: Confidence Interval.

Figure legends

Figure 1: Meta-analysis of the impact of climate change on summer YLL disparities attributable to temperatures in Montreal; ES: Effect Size

Figure 2: Meta-analysis of the impact of climate change on summer YLL disparities attributable to temperatures in Paris; ES: Effect Size



Simulation ID	ES (95% CI)	% Weight
1	1.80 (1.65, 1.97)	3.49
2	2.15 (1.95, 2.36)	3.47
3	2.25 (2.01, 2.53)	3.41
4	2.54 (2.22, 2.91)	3.33
5	2.48 (2.19, 2.80)	3.38
6	2.36 (2.09, 2.66)	3.39
7	2.21 (1.94, 2.52)	3.35
8	1.60 (1.34, 1.91)	3.14
9	1.95 (1.79, 2.13)	3.50
10	2.32 (2.08, 2.58)	3.43
11	2.62 (2.30, 2.99)	3.35
12	2.26 (1.99, 2.56)	3.37
13	2.42 (2.14, 2.73)	3.38
14	2.47 (2.20, 2.78)	3.40
15	1.06 (0.94, 1.20)	3.39
16	2.40 (2.01, 2.87)	3.14
17	2.22 (1.94, 2.53)	3.34
18	1.40 (1.24, 1.58)	3.38
19	1.74 (1.43, 2.12)	3.05
20	1.82 (1.65, 2.00)	3.48
21	2.07 (1.74, 2.45)	3.18
22	1.70 (1.43, 2.01)	3.19
23	2.15 (1.92, 2.41)	3.41
24	2.57 (2.32, 2.85)	3.45
25	2.88 (2.57, 3.22)	3.42
26	2.95 (2.56, 3.39)	3.31
27	1.07 (0.91, 1.27)	3.20
28	2.64 (2.28, 3.05)	3.28
29	1.67 (1.45, 1.92)	3.31
30	1.83 (1.51, 2.22)	3.07
Overall (I-squared = 93.0%, p = 0.000)	2.06 (1.90, 2.25)	100.00

NOTE: Weights are from random effects analysis

Figure 1: Meta-analysis of the impact of climate change on summer YLL disparities attributable to temperatures in Montreal; ES: Effect Size

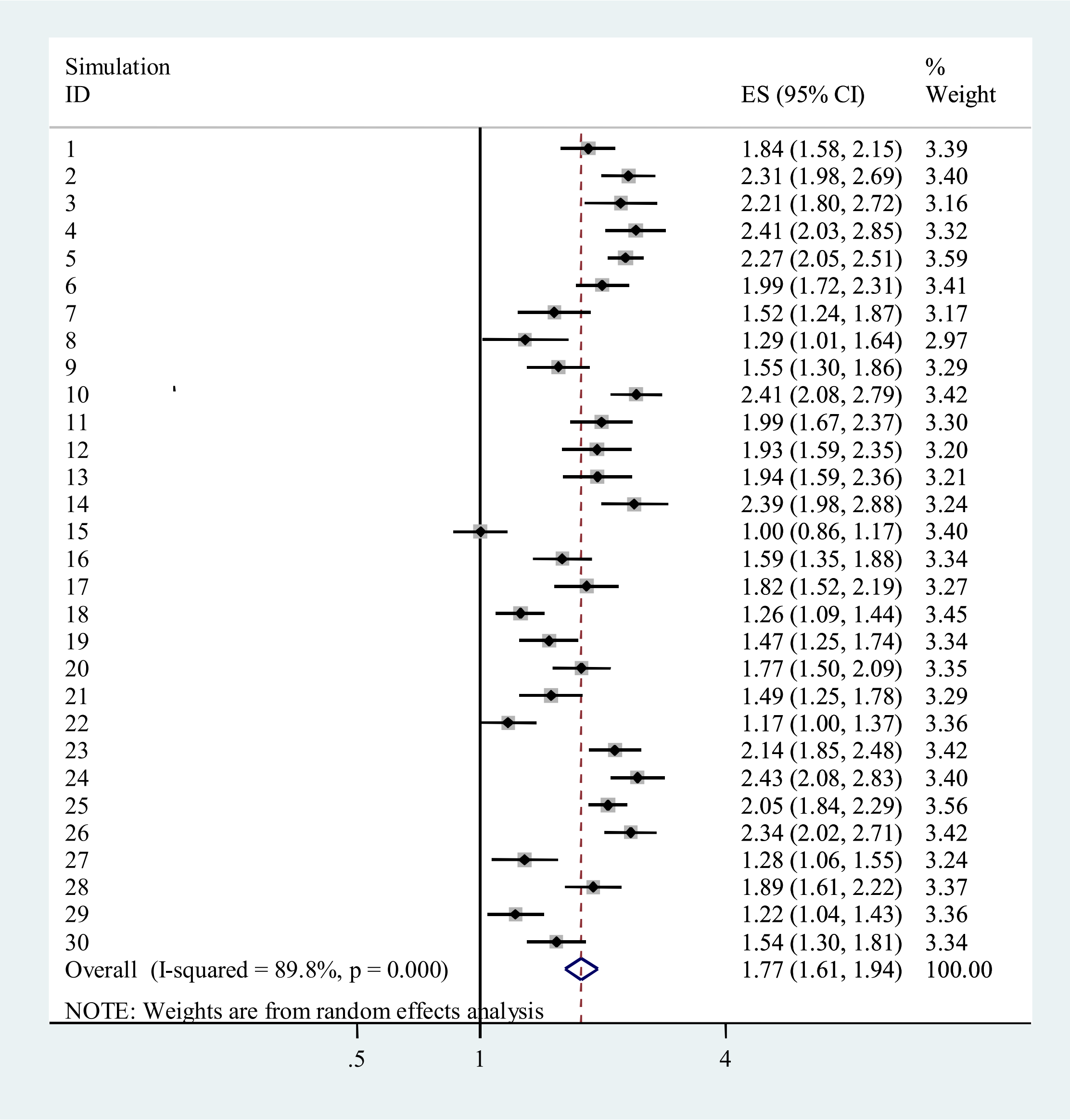


Figure 2: Meta-analysis of the impact of climate change on summer YLL disparities attributable to temperatures in Paris; ES: Effect Size

9. Supplemental Material

Table S1: Summary statistics for education level in Montreal and the composite deprivation index in Paris

Variable	Mean	Minimum	25th Percentile	Median	75th Percentile	Maximum	Standard Deviation
Education Level (%) in Montreal	20.97	0	13.27	20.21	27.62	73.47	10.26
Education Level (%) in Paris	33.67	0	26.94	36.29	42.10	100	11.59

Figure S1: Spatial distribution of education level in Montreal

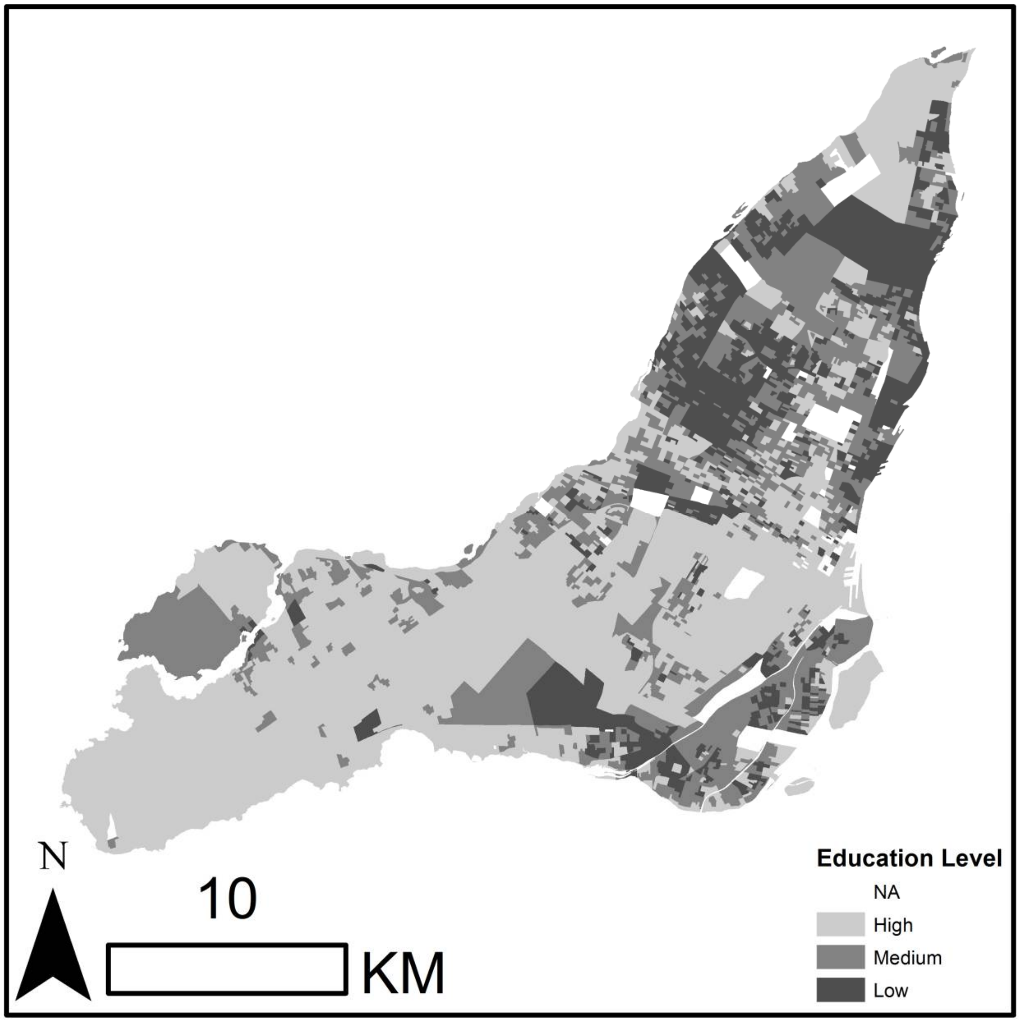
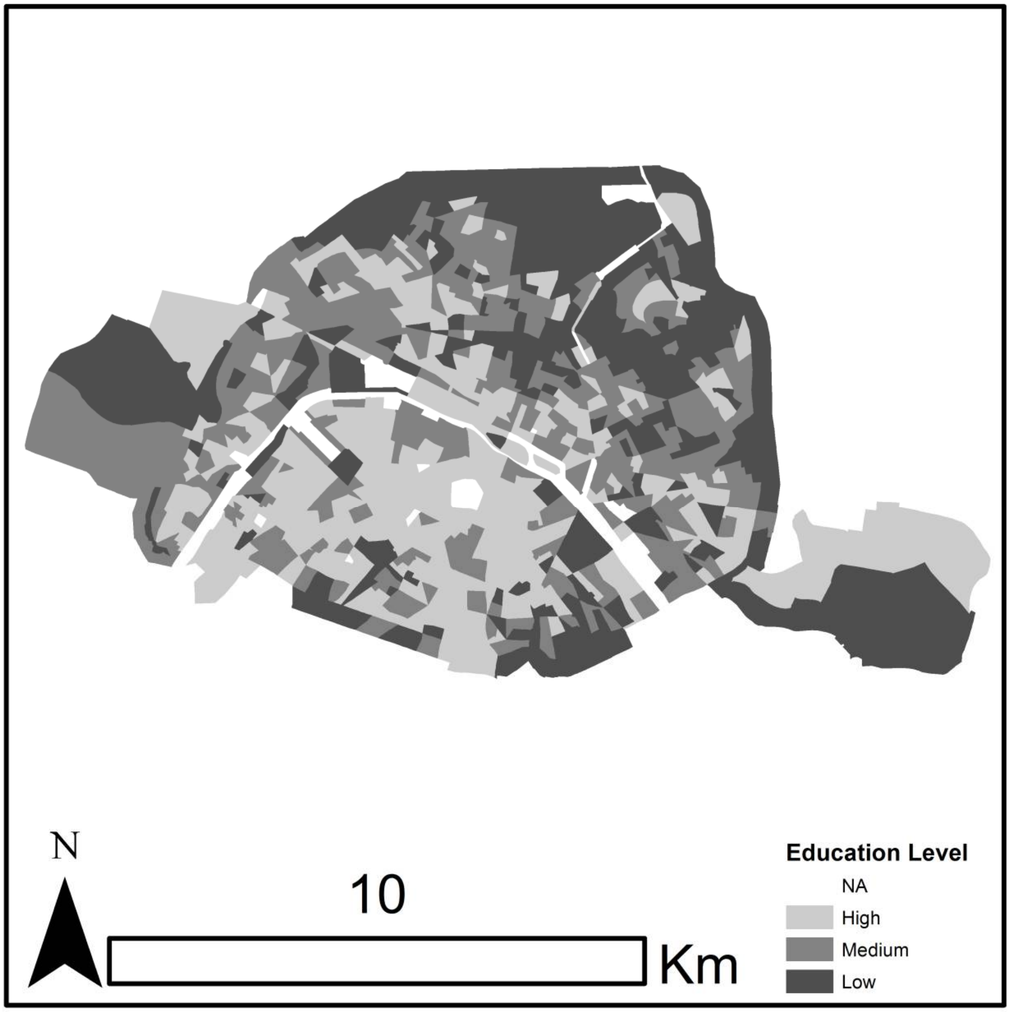


Figure S2: Spatial distribution of education level in Paris



Formula used to calculate the standard errors of the ratios

$$SD(ratio) = ratio \times \sqrt{\left(\frac{SD\ Future^2}{Future}\right) + \left(\frac{SD\ Historical^2}{Historical}\right)}$$

Where SD is Standard Deviation; Future represents the YLL disparities attributable to temperature for the future period (2021-2050) and Historical represents the YLL disparities attributable to temperature for the historical period (1981-2010).

Table S2: Descriptive statistics of daily estimates of YLL social disparities in Montreal and Paris

Variable	Mean	Minimum	Maximum	Std. Dev
YLL disparities in Montreal	339.35	-527.41	1649.34	326.21
YLL disparities in Paris	187.32	-300.56	829.25	169.11

Table S3: Descriptive statistics of daily mean temperatures from the 30 simulations in Montreal, for the periods 1981-2010 and 2021-2050, corrected with the quantile mapping method.

	Montreal (1981-2010)				Montreal (2021-2050)			
Simulation ID	Mean	Minimum	Maximum	Std. Dev	Mean	Minimum	Maximum	Std. Dev
1	20.07	8	31	3.60	21.20	7	34	3.45
2	20.49	9	31	3.44	21.72	10	33	3.31
3	19.97	9	30	3.28	21.81	9	32	3.28
4	19.94	8	32	3.33	22.02	10	33	3.40
5	19.98	9	30	3.42	21.94	10	32	3.45
6	20.08	6	30	3.40	21.72	10	33	3.50
7	20.07	8	29	3.49	21.30	10	33	3.79
8	20.10	9	29	2.86	21.05	10	30	2.91
9	20.08	8	32	3.56	20.85	9	34	3.60
10	20.26	9	31	3.36	21.79	10	33	3.41
11	20.06	8	33	3.36	22.01	9	34	3.58
12	19.99	8	29	3.30	21.77	11	35	3.46
13	20.08	9	30	3.41	21.91	10	32	3.37
14	20.10	6	31	3.41	21.81	7	36	3.63
15	20.10	11	28	2.63	20.40	11	31	2.74
16	20.14	8	28	3.10	22.01	11	29	3.16
17	20.11	8	29	3.45	21.58	9	32	3.52
18	20.15	9	31	3.20	20.94	10	33	3.11
19	20.12	10	29	2.82	21.61	11	30	2.88
20	20.07	8	31	3.59	21.17	9	33	3.48
21	20.15	8	28	3.08	21.66	6	30	3.21
22	20.12	10	29	2.84	21.15	10	30	2.94
23	20.08	9	31	3.61	21.52	9	36	3.69

24	20.38	9	31	3.44	22.07	10	35	3.46
25	20.06	8	31	3.42	22.42	10	34	3.45
26	19.83	8	29	3.33	22.44	10	34	3.49
27	20.07	11	29	2.63	20.76	10	30	2.74
28	20.10	8	29	3.44	22.10	7	33	3.50
29	20.17	10	31	3.17	21.15	10	30	3.19
30	20.10	10	29	2.86	21.61	10	30	3.06

Table S4: Descriptive statistics of daily mean temperatures from the 30 simulations in Paris, for the periods 1981-2010 and 2021-2050, corrected with the quantile mapping method.

	Paris (1981-2010)				Paris(2021-2050)			
Simulation ID	Mean	Minimum	Maximum	Std. Dev	Mean	Minimum	Maximum	Std. Dev
1	19.74	12	31	3.36	20.74	12	33	3.45
2	20.05	11	31	3.16	21.54	11	33	3.47
3	19.89	11	30	3.24	21.43	11	37	3.51
4	19.74	11	32	3.16	21.54	11	33	3.51
5	19.51	10	31	3.15	21.46	10	35	3.52
6	19.52	11	32	3.13	21.18	11	32	3.39
7	19.73	11	31	3.26	20.36	12	31	3.43
8	19.77	12	30	2.92	20.46	13	30	2.96
9	19.72	12	32	3.32	20.33	12	31	3.40
10	20.03	11	32	3.16	21.51	11	34	3.57
11	19.84	11	31	3.15	21.70	12	36	3.64
12	19.61	11	32	3.20	21.22	12	32	3.30
13	19.69	10	30	3.19	21.22	11	32	3.34
14	19.54	11	32	3.17	21.51	11	34	3.53
15	19.70	11	31	2.56	20.13	12	35	2.80
16	19.81	9	31	3.03	21.11	11	33	3.36
17	19.72	11	31	3.20	20.63	12	32	3.58
18	19.71	11	30	3.11	20.17	12	31	3.12
19	19.75	12	30	2.89	21.22	12	32	3.11
20	19.71	12	31	3.34	20.66	11	32	3.43
21	19.83	9	30	3.07	21.05	11	31	3.20
22	19.78	12	29	2.89	20.47	12	30	2.89
23	19.71	12	31	3.38	21.08	12	34	3.57

24	19.99	11	31	3.19	21.55	12	35	3.53
25	19.79	11	32	3.22	22.01	12	34	3.62
26	19.45	11	32	3.13	21.60	12	32	3.38
27	19.71	11	31	2.53	20.11	11	33	2.84
28	19.71	11	31	3.27	20.89	11	32	3.53
29	19.73	11	30	3.10	20.30	11	30	2.90
30	19.78	12	30	2.88	21.25	13	32	3.11

Table S5: RR for each temperature unit in Montreal

Temperature Unit	**RR**	**95% CI**
10	0.97	0.94, 1.01
11	0.99	0.94, 1.03
12	0.92	0.89, 0.95
13	0.94	0.92, 0.96
14	0.91	0.90, 0.93
15	0.92	0.91, 0.93
16	0.98	0.97, 1.00
17	0.97	0.97, 0.98
18	0.98	0.96, 1.00
19	0.95	0.95, 0.96
20	0.95	0.95, 0.96
21	0.97	0.96, 0.98
22	0.99	0.98, 0.99
23	1.02	1.01, 1.03
24	1.05	1.05, 1.06
25	1.10	1.09, 1.10
26	1.13	1.12, 1.14
27	1.18	1.17, 1.19
28	1.21	1.20, 1.22
29	1.24	1.21, 1.29

Table S6: RR for each temperature unit in Paris

Temperature Unit	RR	95% CI
12	0.98	0.96, 1.01
13	0.97	0.95, 0.99
14	0.97	0.96, 0.99
15	0.99	0.98, 0.99
16	0.98	0.98. 1.00
17	0.97	0.96, 0.99
18	0.97	0.96, 0.98
19	0.97	0.96, 0.99
20	0.98	0.97, 1.01
21	0.99	0.97, 1.03
22	1.04	1.02, 1.06
23	1.06	1.03, 1.08
24	1.09	1.06, 1.11
25	1.12	1.08, 1.15
26	1.15	1.11, 1.19
27	1.18	1.14, 1.23
28	1.22	1.14, 1.27
29	1.23	1.13, 1.31

Table S7: Sensitivity analyses results

	Estimates	**Using individuals >35 years of age ***	**Using a composite deprivation index**
Montreal	Mean daily estimates of DYLLD	363.21 years (SD = 333.62 years)	NA
	Summer rates of DYLLD attributable to temperature in historical period	36.11 years per 100 000 persons (95% CI: 16.56, 48.01)	NA
	Summer rates of DYLLD attributable to temperature in future period	23.56 years per 100 000 persons (95% CI: 15.56, 34.10) to 102.31 years per 100 000 persons (95% CI: 83.34, 123.18)	NA
	ICC overall Ratio	2.06 (95% CI: 1.92, 2.29)	NA
Paris	Mean daily estimates of DYLLD	NA	203.12 (SD = 206.69)
	Summer rates of DYLLD attributable to temperature in historical period	NA	15.13 years per 100 000 persons (95% CI: 8.63, 19.06)
	Summer rates of DYLLD attributable to temperature in future period	NA	11.52 years per 100 000 persons (95% CI: 7.85, 20.11) to 37.20 years per 100 000 persons (95% CI: 27.13, 44.31)
	ICC overall Ratio	NA	1.82 (95% CI: 1.66, 1.99)

* 8008 cases of death were excluded for the whole period (1990-2007)

NA: Not Applicable

CHAPITRE 7 : DISCUSSION GÉNÉRALE

L'objectif de cette thèse était de documenter les facteurs de vulnérabilité à la chaleur aujourd'hui et les éléments permettant leur prise en compte pour l'avenir dans le contexte des changements climatiques. Cette recherche à la croisée de plusieurs disciplines incluant l'épidémiologie environnementale, l'épidémiologie sociale, et la science du climat s'inscrit dans des préoccupations de santé publique contemporaines à savoir la reconnaissance et la prise en compte des populations vulnérables dans les politiques publiques visant à réduire les inégalités de santé et la considération au sein de ces dernières des effets sanitaires des changements climatiques. En effet, si l'on considère les événements climatiques extrêmes survenus ces dernières années tels que l'ouragan *Sandy* en 2012 à New York ou *Katrina* en Louisiane ou la vague de chaleur au Royaume Uni en 2013, il a été bien documenté à quel point toutes les populations n'ont pas subi les impacts avec la même ampleur (Greene et al. 2013; McDougall 2007; Zaidi and Pelling 2013) et n'ont pas eu les mêmes ressources pour revenir à une situation de stabilité rapidement (ce que l'on appelle par ailleurs la résilience) (Alwang, Siegel, and Jorgensen 2001) . Bien qu'il soit difficile d'attribuer les effets des changements climatiques à des événements précis, il est certain que la fréquence et l'intensité de ces événements extrêmes comprenant les vagues de chaleur augmentera de même que l'on observera une augmentation des températures moyennes, quels que soient les mesures prises aujourd'hui et pour les prochaines décennies (Huang et al. 2011b). Ainsi, la préparation des pouvoirs publics par la mise en place de mesures d'adaptation avec d'ores et déjà une préoccupation vis-à-vis de l'équité via la prise en compte des populations vulnérables parait donc cruciale.

Les résultats de cette thèse qui sont appliqués à un déterminant fatal de la santé, à savoir la chaleur, qui est fortement influencé par les changements climatiques, viennent compléter les connaissances documentées dans la littérature scientifique actuelle et mettre en lumière des enjeux qui doivent être pris en compte pour atteindre l'équité à l'aide de politiques publiques.

1. Rappel des principaux résultats

Dans le premier article (chapitre 3) de cette thèse portant sur les facteurs de vulnérabilité à la chaleur, nous avons trouvé une preuve quant à la vulnérabilité à chaleur seulement pour les personnes âgées de plus de 85 ans. Nous avons aussi trouvé que les personnes vivant dans des micro-îlots de chaleur, les personnes non mariées (proxy pour l'isolation sociale), les personnes vivant dans des territoires avec peu d'accès à l'air climatisé étaient plus vulnérables, bien que ces résultats aient été basés sur très peu d'études (i.e. 1 ou 2 études). Nous avons aussi montré que les femmes, les personnes âgées de plus de 65 ans et 75 ans, ainsi que les personnes de faible niveau socio-économique étaient plus vulnérables à la chaleur que leurs homologues. Cependant, les estimés globaux (« *pooled estimates* ») étaient très proches d'un effet homogène (i.e. un ratio égal à 1).

Dans le deuxième article (chapitre 4), nous avons trouvé que les populations qui sont exposées à des niveaux chroniques de pollution atmosphérique issue du trafic routier plus élevés sont plus vulnérables à la chaleur, de même que les populations les plus défavorisées. Nous avons aussi trouvé un double effet modificateur de la pollution chronique et la défaveur car par exemple, la mortalité en lien avec la chaleur chez les personnes les plus défavorisées était plus élevée chez ceux qui vivaient en plus dans les quartiers les plus pollués chroniquement par les polluants issus du trafic routier. Par ailleurs, nous avons montré dans cet article que les personnes âgées de plus de 65 ans étaient plus vulnérables à la chaleur que les personnes âgées de moins de 65 ans, et qu'il n'y avait pas de différence selon le sexe.

Suite au développement des approches permettant de quantifier la mortalité attribuable à la chaleur dans le futur (troisième article, chapitre 5), nous avons estimé les inégalités sociales d'années de vie perdues attribuables à la température ambiante dans le présent et dans le futur à Montréal et à Paris (quatrième article, chapitre 6). Nous avons montré que l'augmentation de la température conduit à une augmentation des inégalités sociales d'années de vie perdues à la fois à Montréal et à Paris. Ensuite nous avons montré que ces inégalités sont plus importantes à Montréal qu'à Paris que ce soit dans le présent ou le futur. Enfin nous avons montré que les changements climatiques auront plus d'impact sur l'accroissement de ces inégalités à Montréal qu'à Paris.

2. Contributions

Les travaux réalisés dans le cadre de cette thèse ont permis plusieurs contributions qu'elles soient d'une part vis-à-vis des connaissances générales visant à orienter les interventions de santé publique et d'autre part d'un point de vue méthodologique.

Connaissances générales en santé publique

Les résultats issus de l'article de revue (article 1, chapitre 3) soutenant une évidence épidémiologique pour certains sous groupes de populations, pourront être utilisés par l'ensemble des acteurs internationaux mettant en œuvre des interventions visant à réduire les impacts sanitaires de la chaleur, de même que par les chercheurs en épidémiologie afin de produire de nouvelles connaissances pour les sous groupes de population où il y a peu d'évidence.

Les résultats du chapitre 4 (article 2), ont permis de mettre en évidence un facteur de vulnérabilité à la chaleur qui n'avait jusque-là jamais été étudié, à savoir l'exposition à long terme à des niveaux de polluants atmosphériques élevés. Cette vulnérabilité peut s'expliquer notamment par l'effet de l'exposition à long terme des polluants tels que les dioxydes d'azote (NO_2) sur plusieurs maladies cardiovasculaires (Hart et al. 2011; Latza, Gerdes, and Baur 2009), qui viendront rendre les populations plus exposées au NO_2 plus fragiles face aux effets de la chaleur. Ceci permettra possiblement dans le futur de développer des interventions ciblées en considérant certains territoires vis-à-vis de leurs niveaux d'exposition chronique à la pollution de l'air. De plus, dans la même étude nous avons montré que cette vulnérabilité était encore plus prononcée lorsqu'il s'agissait de populations défavorisées ce qui dans la même veine encourage davantage à la mise en place d'interventions ciblées permettant de réduire ces inégalités de santé.

Les résultats du chapitre 5 (article 3) ont permis de quantifier l'impact des changements climatiques sur les décès attribuables à la chaleur et ses sources d'incertitudes. Ces résultats constituent une information importante car ils montrent que la probabilité que les changements climatiques conduisent à une augmentation de la mortalité en lien avec la chaleur est très forte. Ceci est donc un argument robuste pour les pouvoirs publics afin de considérer dès aujourd'hui des mesures d'adaptation avec un certain degré de certitude sur le bien-fondé de celles-ci. Nous avons également montré que de nombreux développements épidémiologiques sont encore nécessaires pour réduire les erreurs dans la manière dont on modélise la relation entre la chaleur et la mortalité, car ces erreurs sont les sources principales de la variabilité des projections de mortalité.

Enfin, les résultats du chapitre 6 (article 4) ont permis de mettre en avant la contribution des changements climatiques dans l'augmentation des inégalités sociales de mortalité. Ceci permet de placer l'équité à une place centrale dans les développements des mesures d'adaptation aux changements climatiques. Dans ce chapitre, nous avons aussi montré que les inégalités sociales de mortalité en lien avec la chaleur avaient des schémas distincts entre Montréal et Paris. Ces résultats, joints aux résultats du chapitre 3, attirent l'attention sur le fait que la notion de vulnérabilité (spécialement vis-à-vis de facteurs socio-économiques) peut être difficile à généraliser, et qu'il faut être vigilant lorsque des recommandations à ce sujet sont émises, notamment au niveau international tel qu'actuellement fait dans les documents émis par l'OMS.

Connaissances méthodologiques

Dans le cadre des travaux de cette thèse, plusieurs développements méthodologiques ont été réalisés pour répondre aux différents objectifs et qui peuvent être utilisés dans des travaux futurs en épidémiologie y compris appliqués à d'autres déterminants que ceux étudiés ici.

Afin de produire une évidence épidémiologique sur les facteurs de vulnérabilité, nous avons développé une méthode innovante visant à effectuer une méta-analyse des ratios de risques relatifs pour produire directement un effet global de la vulnérabilité selon un facteur donné (ici la température). Cette méthode a plusieurs avantages incluant le fait qu'on peut y assembler des devis épidémiologiques relativement différents, des mesures d'associations ou de l'exposition différentes car comme les ratios sont estimés intrinsèquement à chaque étude, ils n'influencent pas l'effet global estimé. Cette méthode s'inscrit donc dans l'exigence contemporaine de fournir des recommandations de santé publique basées sur les preuves (Petticrew et al. 2004).

Nous avons aussi développé une approche analytique, alternative aux analyses stratifiées, permettant de mesurer les inégalités dans les analyses de séries temporelles. Pour cela nous avons mesuré l'association entre la température et une mesure des inégalités de santé entre les groupes (via l'indicateur « *Index of Disparity* »), plutôt que de mesurer une association entre la température et l'événement de santé sur plusieurs strates et comparer entre eux les résultats des strates. Cette approche présente comme avantages de fournir un impact direct d'une exposition donnée sur l'accroissement des inégalités de santé au sein d'une population ce qui permet de donner une information directe en termes de santé publique sur les bénéfices potentiels d'interventions sur la réduction des inégalités, et d'obtenir un seul estimé permettant ainsi une analyse multi-villes directement.

Enfin, en ce qui concerne la quantification des impacts futurs en lien avec les changements climatiques, nous avons proposé une nouvelle méthode que nous avons appliquée à la mortalité (Chapitre 5, article 3) et aux années de vies perdues (Chapitre 6, article 4).

3. Limites

Outre les limites inhérentes à chacune des études composant cette thèse, il y a des limites d'ordre général qui méritent d'être discutées.

Comme décrit dans le chapitre 1, les effets de la chaleur incluent à la fois les effets de la température ambiante et ceux des vagues de chaleur. Tout au long de cette thèse, nous avons fait la distinction entre ces deux effets, mais pourtant n'avons traité les effets des vagues de chaleur qu'au chapitre 3 (article 1). Les analyses conduites dans les chapitres 4, 5 et 6 (articles 2, 3 et 4) ne concernent que les effets de la température ambiante. Ceci étant dit, il est important de préciser que lorsque l'on étudie les effets de la température ambiante sur la santé sur une période donnée, les jours qui pourraient être considérés (tout dépendant de la définition donnée selon le contexte) comme jours de vagues de chaleur, y sont inclus. Cependant, cela faisant nous ne considérons pas l'effet spécifique sur plusieurs jours très chauds consécutifs, ce qui au final contribue à sous-estimer les impacts liés à la température que nous obtenons. Cet effet spécifique, notamment lorsqu'on étudie les effets de la chaleur sur plusieurs années, ne représente cependant qu'une faible part comparativement à l'effet de la température sur tous les autres jours (Hajat et al. 2006). En ce qui concerne les projections de mortalité, nous avons choisi de ne pas étudier spécifiquement les effets des vagues de chaleur (Gosling, McGregor, and Lowe 2012), d'une part car d'après la littérature en climatologie il demeure encore beaucoup d'erreurs dans la simulation future des extrêmes, et d'autre part comme les définitions actuelles des vagues de chaleur que ce soit à Montréal ou à Paris, concernent plusieurs jours consécutifs avec une température donnée, il est pour le moment impossible d'obtenir des projections de températures de cette nature (Huang et al. 2011; Taylor et al. 2012). De plus, nous n'avons pas étudié spécifiquement les effets moisson (« harversting effect ») (Basu 2009). Il est possible que ces effets soient différents selon la population et de ce fait qu'ils aient un impact sur la compréhension des vulnérabilités à la chaleur.

Puis, cette thèse s'est intéressée aux effets de la chaleur sur la mortalité (ou aux années de vie perdues). Certes, la mortalité comme effet de santé représente un enjeu fondamental en termes de santé publique et constitue l'effet pour lequel il y a le plus d'évidence épidémiologique aujourd'hui (Basu 2009). Cependant la chaleur peut être responsable d'autres issues de santé qui amèneraient à des considérations différentes que ce soit vis-à-vis de la notion de vulnérabilité ou par rapport aux recommandations formulées. D'après la littérature épidémiologique, les indicateurs de santé sur lesquelles la chaleur aurait un effet documenté sont notamment les admissions à l'hôpital (Ye et al. 2012b), les accidents de travail et maladies professionnelles (Adam-Poupart et al. 2014a, b), ou les issues de grossesse (Auger et al. 2014). Ces autres issues de santé, bien qu'ils constituent des enjeux différents de ceux en lien avec la mortalité, peuvent toutefois parfaitement s'intégrer comme source d'information pour ce que l'on a appelé les interventions ciblées.

Nous nous sommes, dans cette thèse, intéressés aux inégalités sociales de mortalité en lien avec la chaleur (chapitres 3, 4 et 6). Dans le chapitre 3 (article 1), nous avons vu que dans la littérature, le niveau socio-économique pour les populations incluses dans les études a été mesuré soit au niveau individuel soit au niveau écologique (ou communautaire). Dans les chapitres 4 et 6, nous avons mesuré le statut socio-économique des individus inclus dans notre population avec des mesures écologiques, avec un indicateur composite de défaveur sociale dans le chapitre 4, et avec le niveau d'éducation du quartier dans le chapitre 6. Ces indicateurs écologiques ont été utilisés comme des proxys du niveau socio-économique des individus, car nous n'avions pas accès aux données individuelles. Cela représente ainsi un potentiel biais de classification dans le sens où par exemple certains individus qui habitent dans des quartiers avec un niveau d'éducation bas, pourront avoir un niveau d'éducation plus élevé et vice-versa. Cependant, d'un point de vue de santé publique, l'utilisation d'indicateurs écologiques qui représentent la distribution territoriale de la défaveur sociale peut permettre de faciliter la priorisation des politiques publiques en ciblant les territoires qui subissent le fardeau le plus important. De plus, l'unité spatiale considérée était la plus fine disponible à la fois à Montréal et à Paris. Enfin, dans le chapitre 4 nous avons procédé à des analyses stratifiées, et avons dû considérer seulement deux ou trois strates pour avoir un nombre d'évènements suffisants pour conserver une puissance statistique dans les régressions de Poisson. Cela mène à une perte d'information, en ne considérant pas toute la distribution de la défaveur ou des niveaux de pollution atmosphérique.

Nous avons dans le chapitre 6 (article 4) comparé l'effet de la chaleur sur l'augmentation des inégalités sociales de santé entre Montréal et Paris. Nous avons trouvé que ces inégalités étaient d'ampleurs différentes mettant en évidence la difficulté de statuer de manière globale sur des facteurs de vulnérabilité. Cependant, en menant cette étude sur seulement deux villes, toute interprétation d'ordre général devrait être sujette à caution. Il serait ainsi intéressant que dans études futures, une comparaison similaire soit faite sur davantage de villes. Enfin, il est important de préciser que ces deux villes, qui ont des climats tempérés ne seront pas les plus touchées dans le monde par les augmentations de température et par les impacts sanitaires associés. De plus, étant donné qu'il s'agit de deux villes économiquement développées, les capacités d'adaptation seront plus importantes que dans d'autres contextes (Petkova et al. 2014).

4. Articulation avec les recommandations internationales sur la vulnérabilité dans les interventions visant à réduire les impacts de la chaleur

Les résultats de cette thèse constituent donc une contribution vis-à-vis des connaissances des facteurs de vulnérabilité à la chaleur. Néanmoins, un certain décalage a pu être mis en évidence entre les recommandations internationales fournies par différents organismes tels que l'OMS ou l'US EPA sur la définition des populations vulnérables et nos résultats. En effet, dans ces recommandations, les populations définies comme vulnérables semblent l'être sans aucune ambigüité. Cependant, d'après nos résultats, il y a au final très peu de sous groupes de populations pour lesquels il y a une évidence épidémiologique robuste. Pour illustrer ce point, nous pouvons prendre l'exemple des enfants comme population potentiellement vulnérable. Lorsque l'on explore les recommandations de l'OMS Europe, ou même le contenu des plans d'actions chaleur de plusieurs pays européens (Lowe, Ebi, and Forsberg 2011), les enfants y sont définis comme vulnérables à la chaleur et cela est appuyé par quelques références épidémiologiques. Cependant, bien que les articles cités (Basu and Ostro 2008; Gouveia, Hajat, and Armstrong 2003; Nitschke et al. 2011) puissent montrer que les enfants sont bel et bien vulnérables à la chaleur, nous avons trouvé, en effectuant une recherche systématique, autant d'articles avec des conclusions opposées (Basagana et al. 2011; Fouillet et al. 2006; Nitschke, Tucker, and Bi 2007). Ces résultats devraient conduire à de futures recherches pour clarifier ces incertitudes.

De plus, ces recommandations et plans d'actions chaleur peuvent également juger comme vulnérables des populations qui n'ont pas fait l'objet d'études épidémiologiques. Cette approche, qui met sur le même plan des résultats issus d'études épidémiologiques, des ressentis du terrain et des jugements de valeur, peut limiter la capacité à mettre en place des actions de santé publique opérationnelles et efficaces. Elle peut rapidement aboutir à des listes très hétéroclites. Par exemple, dans le plan canicule français, les personnes citées comme « vulnérables » sont (Ministère de la santé et des sports 2012; Ministère des affaires sociales et de la santé et al. 2013) : les personnes âgées, les enfants, les personnes souffrant de pathologies cardio-vasculaires, endocriniennes, uro-néphrologique, de drépanocytose homozygote, de mucoviscidose, de troubles mentaux, d'obésités, de handicap, d'alcoolisme, de toxicomanie, de fièvre, les femmes enceintes, les personnes isolées, les sans-abris, les travailleurs extérieurs, les sportifs et les personnes incarcérées. D'autres plans prennent également en compte les femmes, les musulmans, les touristes, les personnes à faibles revenus (Lowe, Ebi, and Forsberg 2011).

Avec une telle diversité, le concept de personnes vulnérables peut devenir très difficile à appréhender. De même, dans l'évaluation du plan canicule anglais, des entretiens avec des parties prenantes du plan ont montré que leur compréhension de la vulnérabilité à la chaleur était très personne-dépendante, malgré les informations données dans les documents de référence du plan (Health Protection Agency 2012).

Des conséquences peuvent découler de ces confusions sémantique et méthodologique. Définir des personnes ou territoires comme vulnérables de manière trop englobante ou imprécise peut conduire à une dispersion des moyens à mettre en œuvre se traduisant par l'impossibilité d'avoir des actions réellement ciblées et proportionnées, pourtant fondamentales dans la lutte contre les inégalités de santé (Marmot 2005) et donc au final à des actions de santé publique inefficaces contribuant à maintenir voire accroitre ces inégalités de santé (Frohlich and Potvin 2008).

Deux raisons pourraient expliquer cette diversité quant à la définition des populations vulnérables.

Premièrement, il est possible que cela vienne d'une confusion dans la définition même de la vulnérabilité. En effet, la notion de vulnérabilité peut être définie de plusieurs manières différentes (Adger 2006) et dans le contexte des changements climatiques et des impacts sanitaires il est possible de retrouver, parmi toutes les définitions recensées, au moins deux sens distincts à la notion de vulnérabilité (Benmarhnia and Pascal 2014). Le premier, qui correspond notamment à la définition donnée par le GIEC de la vulnérabilité (Parry 2007), renvoie au fait que certaines populations ou territoires soient exposés à des dangers tandis que d'autres ne le sont pas. Le second correspond quant à lui à une définition similaire à la définition épidémiologique de modification d'effet, telle qu'incluse dans cette thèse. Ainsi, proposer une définition qui rassemblerait l'ensemble des sens prêtés à la vulnérabilité pour une application aux effets de la chaleur sur la santé dans le contexte des changements climatiques permettrait de faciliter grandement la mise en œuvre et la compréhension de cette notion par les différents acteurs impliqués (Benmarhnia and Pascal 2014).

Deuxièmement, il est possible que cette diversité provienne en partie de différences épistémologiques entre, d'une part les acteurs en santé publique qui mettent en place les politiques publiques et y définissent quelles populations sont vulnérables, et d'autre part les chercheurs qui mènent les études épidémiologiques ou évaluent les effets de ces politiques publiques. Il existe au moins quatre approches épistémologiques distinctes en santé publique (Bhaskar 2009; Hedstrom and Swedberg 1998; Hedstrom and Ylikoski 2010; Ng and Muntaner 2014): i) l'empirisme (ou positivisme : tout savoir provient de l'expérimentation basée sur une hypothèse à priori), ii) le pragmatisme (la connaissance d'un concept ou d'une proposition dépend de ces effets pratiques), iii) le rationalisme (le raisonnement déductif est l'ultime manière d'examiner un savoir) et iv) et le réalisme (la réalité est ontologiquement indépendante d'effets pratiques, d'expériences sensorielles ou de croyances rationnelles). Le positionnement épistémologique majoritaire, bien que souvent implicite (Baum 1995; Harper et al. 2010; King, Harper, and Young 2012), dans la recherche quantitative en santé publique correspond à une approche empirique tandis que dans la pratique de la santé publique vue plus largement, la production de la connaissance (Piaget 1967), en l'occurrence vis-à-vis de la définition des populations vulnérables, peut être de nature différente (Ng and Muntaner 2014). Cette distinction peut vraisemblablement expliquer pourquoi un décalage existe entre la manière dont les populations vulnérables sont définies dans les politiques publiques et la manière dont les hypothèses sur l'existence des vulnérabilités à la chaleur sont formulées en épidémiologie.

5. Recommandations et travaux futurs

En lien avec l'ensemble des éléments rapportés dans cette thèse qu'il s'agisse des résultats, de leur articulation avec les recommandations internationales ou des limites exprimées, plusieurs recommandations pour des recherches futures sur la vulnérabilité et la température peuvent être formulées.

Premièrement, des travaux empiriques sont encore nécessaires pour produire de l'évidence sur la connaissance des facteurs de vulnérabilité à la température. Certains sous groupes de la population méritent d'être davantage étudiés car l'évidence actuelle ne permet pas la formulation de recommandations claires. Cela concerne notamment les enfants et nourrissons, les personnes qui souffrent de maladies chroniques préexistantes, les personnes qui souffrent de troubles de santé mentale (e.g. schizophrénie, maladie d'Alzheimer…), les personnes qui souffrent de troubles additifs (e.g. alcool, psychostimulants, opiacés), ou encore l'isolement social. Vis-à-vis des facteurs socio-économiques, déterminer précisément, et ce dans plusieurs contextes (i.e. villes) distincts, quels facteurs influencent le plus la vulnérabilité à la chaleur serait incontestablement enrichissant pour la formulation de recommandations sur des interventions ciblées. Ensuite, tel que nous l'avons fait pour l'exposition chronique à la pollution atmosphérique, des futures recherches pourraient investiguer le potentiel effet modificateur de la relation entre la chaleur et la mortalité pour des facteurs, avec un cadre causal plausible, qui n'ont jamais été documentés jusqu'alors comme les personnes fortement exposées au bruit environnemental (Ising and Kruppa 2004; Tetreault, Perron, and Smargiassi 2013) par exemple.

Un deuxième axe qui mériterait grandement d'être investigué à l'avenir concerne l'évaluation des interventions visant à réduire l'impact de la chaleur (Bassil and Cole 2010; Toloo et al. 2013) et spécifiquement vis-à-vis des populations définies comme vulnérables. Ces dernières années, quelques études ont évalué l'impact des interventions mises en place pour réduire les effets de la chaleur sur la santé. Elles ont évalué soit des changements de comportements et de niveaux de connaissances des risques et actions de prévention en lien avec l'intervention (Abrahamson et al. 2009) soit la réduction de la mortalité et de la morbidité « attribuable » à l'implantation d'interventions spécifiques (Fouillet et al. 2008). Cependant ces études demeurent rares (Bassil and Cole 2010; Bittner et al. 2014; Petkova, Morita, and Kinney 2014; Toloo et al. 2013) et n'abordent que très peu la problématique des populations vulnérables (Bittner et al. 2014). Ainsi, le développement du champ de la recherche évaluative, que ce soit pour l'analyse des effets ou de l'implantation, appliqué aux interventions en lien avec la chaleur parait essentiel aujourd'hui. La prise en compte d'outils provenant du champ de l'évaluation de programmes tels que les modèles logiques (Brousselle, Champagne, and Contandriopoulos 2006; Champagne et al. 2009; Kaplan and Garrett 2005; Renger and Titcomb 2002) ou les analyses de contributions (Mayne 2008) constitue une perspective intéressante notamment lorsqu'ils sont appliqués dans un cadre de d'Etudes Impact Santé (Kemm, Parry, and Palmer 2004), comme réalisé récemment pour les interventions visant à réduire les effets de la pollution de l'air en milieu urbain (Cartier, Benmarhnia, and Brousselle 2014). En parallèle, il parait nécessaire de développer, pour l'analyse des effets des interventions, des méthodes quantitatives qui sont appliquées dans le cas d'expérimentations naturelles tels que les méthodes de différence dans les différences (*difference-in-differences*) (Bertrand, Duflo, and Mullainathan 2002; Donald and Lang 2007), de discontinuité dans les régressions (*regression discontinuity*) (Bor et al. 2014; Cook 2008) et divers méthodes d'appariement (e.g. scores de propension) (Oakes and Johnson 2006; Weitzen et al. 2004) qui permettent de constituer des devis quasi-expérimentaux. Enfin, pour évaluer l'implantation des interventions et ceci spécifiquement pour des groupes de populations définies comme vulnérables, et renseigner les freins et leviers dans la réussite de la mise en place d'une intervention, le déploiement de méthodes qualitatives telles que des focus groupes ou des entretiens semi-dirigés semblent offrir des opportunités attrayantes en termes de santé publique (Abrahamson et al. 2009).

Un troisième axe pour les recherches futures concerne les développements méthodologiques et notamment en inférence causale. L'inférence causale en épidémiologie vis-à-vis des études observationnelles s’est énormément développée ces dernières années (Dumas et al. 2014; Hernan and Robins 2014; Rothman and Greenland 2005). De nombreuses méthodes d’analyses causales ont ainsi été proposées. Parmi elles, nous pouvons mentionner les Graphiques Acycliques Orientés (*Direct Acyclic Graphs* : DAGs), support qualitatif à l’étude des relations causales (Foraita, Spallek, and Zeeb 2014; Shrier and Platt 2008). Les DAGs ont été utilisés pour différentes questions de recherche, à savoir : i) représenter les relations causales entre différentes variables (Greenland and Brumback 2002; Greenland, Pearl, and Robins 1999; Pearl 1995); ii) déterminer quels variables sont effectivement des facteurs de confusion qu’il faut contrôler (Hernan et al. 2002); iii) déterminer via une classification, quelles relations causales peuvent donner lieu à des biais de sélection (Hernan, Hernandez-Diaz, and Robins 2004). Une démarche de classification basée sur les DAGs a été également conduite (VanderWeele and Robins 2007) et complétée (Weinberg 2007) pour déterminer quatre types de modification d’effets : i) la modification d’effet directe ; ii) la modification d’effet indirecte ; iii) la modification d’effet par un proxy ; iv) la modification d’effet par une cause commune. Les auteurs y proposent également un cadre d’analyse pour considérer la modification d’effet multiple. Dans l’ensemble de cette thèse et au final dans toute la littérature qui y est citée, la seule modification d’effet considérée est la modification d’effet de type directe. S’approprier ces différentes démarches analytiques et développer leur application à la vulnérabilité à la chaleur parait ainsi prometteur. D’autres méthodes d’analyses causales méritent d’être citées comme les modèles à équations structurelles (Ullman and Bentler 2003) qui permettent de considérer des relations causales complexes, et les modèles développés dans le « cadre contrefactuel » qui incluent notamment des techniques telles que les modèles marginaux structuraux (Robins, Hernan, and Brumback 2000), la pondération par l’inverse de la probabilité (Naimi et al. 2014b) ou les les G-estimations (Naimi et al. 2014a). De nouveaux concepts épidémiologiques, qui appliqués aux facteurs de vulnérabilité à la chaleur seraient très pertinents, ont également été proposés très récemment comme le concept de proportion éliminée (*proportion eliminated*) (Suzuki et al. 2014; VanderWeele 2013) qui permettraient de davantage prendre en compte les effets médiateurs dans la relation la chaleur et la mortalité.

La prise en compte des derniers développements en inférence causale en est aux balbutiements en épidémiologie environnementale (Buckley, Samet, and Richardson 2014; Reid et al. 2012) et leur prise en compte semble prometteuse pour examiner les situations complexes telles que la présence de multiples facteurs de vulnérabilité ou leurs variations dans le temps par exemple.

Conclusion

Les changements climatiques constituent sans aucun doute un enjeu important du XXIème siècle. De part l'augmentation des impacts sanitaires prévus, il est fondamental que les pouvoirs publics mettent en place dès aujourd'hui des mesures d'adaptation qui limiteront l'ampleur de ces impacts. Les résultats de cette thèse mettent en avant l'importance de la prise en compte de la vulnérabilité de certaines populations face à ce défi majeur. En outre, la vulnérabilité des populations face aux changements climatiques est à relier aux autres enjeux majeurs de ce siècle que sont la croissance de la population mondiale, la transition démographique, ainsi que la croissance économique (Stephenson et al. 2013) et l'augmentation des inégalités socio-économiques (Piketty 2014). Entre 2000 et 2050, la proportion de la population mondiale de plus de 60 ans doublera pour passer d'environ 11% à 22% et cette évolution démographique sera particulièrement rapide et importante dans les pays à revenu faible et intermédiaire (Lee 2003). De plus, en 2008, a eu lieu une crise économique d'une ampleur considérable ayant eu des effets en termes de santé publique de plus en plus documentés (Stuckler et al. 2011) notamment en Europe. Les effets en termes de santé publique de cette crise, et spécifiquement des mesures d'austérité mises en place pour y répondre, ont des impacts plus marqués chez les populations déjà fragilisées comme les populations isolées socialement ou les populations âgées (Escolar-Pujolar et al. 2014 ; Benmarhnia et al. 2014b).

Ainsi, étant donné la croissance démographique attendue et les impacts potentiels des crises économiques sur les populations déjà fragiles, la question de la vulnérabilité des populations face aux changements climatiques se trouve au carrefour de plusieurs enjeux contemporains majeurs et sa prise en compte est essentielle.

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ANNEXES

Annexe 1 Valorisation scientifique durant la thèse

Articles dans revues à comité de lecture

Benmarhnia T, Sottile MF, Plante C, Brand A, Casati B, Fournier M, Smargiassi A. *Variability in temperature-related mortality projections under Climate Change*. Environmental Health Perspectives, 2014 [Advance Publication]

Benmarhnia T, Oulhote Y, Petit C, Lapostolle A, Chauvin P, Zmirou-Navier D, Deguen S. *Chronic air pollution and social deprivation as modifiers of the association between high temperature and daily mortality*. 2014 Environmental Health, 13(1), 53.

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Benmarhnia T, Rey L, Cartier Y, Clary CM, Deguen S, Brousselle A. *Equity in interventions to reduce air pollution in urban areas: a systematic review.* International Journal of Public Health. [Accepted]

Benmarhnia T, Deguen S, Kaufman JS, Smargiassi A. *Vulnerability to heat-related mortality: a systematic review, meta-analysis and metaregression analysis*. [To be submitted]

Benmarhnia T, Pascal M. Bringing together epidemiology and adaptation to climate change, the relevance of the "vulnerability" approach. [To be submitted]

Benmarhnia T, Grenier P, Brand A, Fournier M, Deguen S, Smargiassi A. *Social disparities in years of life lost attributable to heat under climate change in Paris and Montreal.* [To be submitted]

Dionne PA, **Benmarhnia T**, Tchouaket E, Fansi A, Brousselle A. *An economic evaluation of the Strategy for Actions Promoting Healthy Habits in Quebec: do the benefits overcome the costs?* [To be submitted]

Cartier Y, **Benmarhnia T**, Brousselle A. *Framework for assessing health impact of interventions modifying air quality in urban environments: a proposition*. [To be submitted]

Benmarhnia T, Léon C, & Beck F. *Exposure to indoor tanning in France: A population based study.* BMC Dermatology, 2013. 13(1), 6.

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Benmarhnia T, Mathlouthi F, Smargiassi A. *Health Impacts of Particles from Forest Fires*. INSPQ. 2014

Présentations orales en congrès internationaux

Assessing the link between policies or interventions aiming to reduce urban air pollution and health outcomes: equity integration and evaluation methods. 21st IUHPE World Conference. August 28th 2013 Pattaya, Thailand.

A health promotion framework to help develop equity-focused climate change adaptation strategies: extreme heat events as a case study. 21st IUHPE World Conference. August 26th 2013 Pattaya, Thailand. (Co- author)

Climate change and heat related mortality: an environmental inequality perspective, Environmentela Health Conference. March 6th 2013 Boston, USA.

Predicting future temperature related Mortality in climate change context using global and regional climate models: Methodological considerations in climatic change epidemiologic studies and application in Quebec, Canada. European Doctoral College on Environment and Health (EDCEH). June 4th 2012 Rennes, France.

Mesurer la multi-exposition dans un contexte d'injustice environnementale. 80e du Congrès de l'ACFAS « Colloque 419 - Droits humains et justice environnementale : enjeux et perspectives » May 10th 2012 Montréal, Canada.

Présentations affichées en congrès internationaux

Chronic air pollution and social deprivation as modifiers of the association between high temperature and daily mortality. ISEE 2013 August 23th 2013 Basel, Switzerland.