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Research Dissertation

Extreme temperatures in urban areas: assessment of inequalities looking at high-resolution climate data and vulnerabilities associated with socioeconomic factors and the built environment

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"One of the ironies of courage,

and the reason why we prize it so highly,

is that we find it easier to be brave for someone else than we do for ourselves alone"

- ***Shantaram***

Preface

The present PhD dissertation is based on three manuscripts submitted to peer-reviewed journals focusing on the relationship between extreme temperatures and health within the urban context, looking at social inequalities and built environment characteristics. The structure of the research is here represented in a consistent approach, allowing the replication of the applied methodology in other urban contexts. The first article consists of a systematic literature-review to understand the demographic, socio-economic and built environment variables nowadays considered in the temperature-health nexus in cities. The second and the third article involve the use of quantitative models, used to date in the field of environmental epidemiology. While the second paper is aimed at determining how risk is diversified by demographic and socio-economic groups looking at urban context as an aggregate unit, the third focuses on how these risks varied over time by social inequalities groups. Since the PhD candidate is the first author in all the papers here presented, she independently decided the preliminary structures of the papers, the design of each study, and – as such - she did the statistical analyses and wrote the manuscripts. *Chapter I* consists of the *Introduction*, which contextualizes the subject of the research as well as its objective. *Chapter II* contains the three scientific articles mentioned above in their entirety. Furthermore, *Chapter III* provides the *Conclusions*, with a specific focus on the *strengths and limits* as well as on the *future research and developments* to finalize the methodology here proposed.

Acknowledgments

As students before me informed me, the journey to complete this PhD has been extremely exciting, but also considerably arduous. Despite this, ever-present luck and constant personal determination have allowed me to start and complete a journey like this, which has offered me a unique opportunity to grow professionally and personally. My sincerest gratitude goes to those people who have been supportive all along the process, by helping me to believe in myself and enabling me to have such a fantastic experience.

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Most of all, I would like to express my deepest gratitude to my family and friends. To my old sister, Rachele, without whom I would never have embarked on the path that has led me to be who I am today. Thank you for giving me your tireless support, for being a constant source of inspiration and for guiding me through the most difficult times of our life. I will never stop being grateful to you in life. To all my family, without whom I would not have become the person I am today. To my mother, my pillar. Thank you for being a constant source of passion and strength to me, and for giving me the opportunity to follow my dreams in my own time and in my own way. To my father, for passing on rationality and the constant desire for knowledge. Without his spiritual support, I do not think I would have been able to achieve this goal. To Tanci and all my 'wonder women' who have always believed in me, to Marti for being an inexhaustible source of inspiration and sincerity, and to Livio, Tita and Oh Furini for the nicest moment I had in Venice. To Dario for allowing me to grow with him for part of our path, and to Giacomo who came to the end of this journey but has been extremely helpful with his way of living and thinking. Finally, I would like to thank all the people not explicitly mentioned here who, despite everything, believed in me and helped me to believe that I could do it.

I have grown in diligence, passion and confidence in both work and life, so thank you all.

Extreme temperatures in urban areas: assessment of inequalities looking at high-resolution climate data and vulnerabilities associated with socioeconomic factors and the built environment

ABSTRACT [EN]

Severe increases in temperature are projected in European regions, with more intense and prolonged extreme events for cities located in the Mediterranean Basin. Due to anthropogenic greenhouse emissions, the average annual temperature in Italy has increased by 1.1°C since 1980. The scope of this PhD thesis is to investigate trends in cold- and heat- mortality risk and burden by socio-economic factors, through the development of a flexible and reproducible methodology to apply in other urban contexts. The case study used in this research is based on a 37-year time-series of the city of Turin (Italy). Results demonstrated an increase in cold- and heat- attributable risk trends with heterogeneous associations across different factors influencing the population's vulnerability to extreme burden of temperatures. A better understanding on how the most vulnerable population sub-groups have adapted at the urban and sub- urban scale is essential to prevent risks using targeted public health responses to adapt to future extreme temperature events due to climate change impacts.

ABSTRACT [IT]

Le proiezioni climatiche evidenziano aumenti di temperatura nelle regioni europee, con eventi estremi più intensi e prolungati per le città nel bacino del Mediterraneo. A causa delle emissioni antropogeniche ad effetto serra, la temperatura media annuale in Italia è aumentata di 1,1°C dal 1980. Lo scopo principale di questa tesi è quello di indagare le tendenze del rischio di mortalità da freddo e da caldo in relazione ai fattori socioeconomici, attraverso lo sviluppo di una metodologia flessibile e riproducibile in altri contesti urbani. Il caso studio di questa ricerca è strutturato su una serie temporale di 37 anni della città di Torino (Italia). I risultati mostrano un aumento delle tendenze di rischio sia in condizioni di freddo sia di caldo con associazioni eterogenee tra i diversi fattori che influenzano la vulnerabilità della popolazione allo stress derivante dalle temperature. Una migliore comprensione di come i sottogruppi di popolazione più vulnerabili si siano adattati su scala urbana e sub-urbana è essenziale per prevenire i rischi attraverso l'uso di risposte di salute pubblica mirate in previsione dei futuri eventi di temperatura estrema.

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CHAPTER I

INTRODUCTION

This PhD dissertation explores the relationship between extreme temperatures and urban health by focusing on social inequalities and built environment characteristics, with the scope to develop a flexible and validated methodology reproducible to other urban contexts by using the city of Turin (north-west, Italy) as a case study. The following section provides the background of the thesis and emphasizes the need for further research on the nexus between temperature, health, and the built environment within the urban context. First, the relationship between extreme climate events, urbanization, and improvement in living conditions with respect to population health is analyzed to contextualize the historical changes. Second, a review on the epidemiology of temperature-related mortality under climate change conditions is conducted, with a specific focus on the variables which contribute to increase population vulnerability and, on the methods commonly used in the scientific studies. This is followed by an adequate distinction between climate and non-climate drivers of change, which constitute the base to plan effective policies to address public health challenges related to heat- and cold- temperatures impacts at the local scale. Finally, this section concludes with a detailed overview on the scope and the structure of the PhD research work.

Human Health, Climate Change and Extreme Temperatures

Human health and living conditions are better today than at any time in history. Life expectancy has risen considerably and mortality among children has declined substantially since the 1950s. At the same time, housing conditions as well as water and food accessibility experienced unprecedented improvements worldwide[1]. These quality improvements in public health have been associated with the progress of humanity, supported by the ecological and biophysical systems of the earth, such as the atmosphere, the oceans, and the diverse ecosystems. These components together with their interactions, help to maintain constant environmental conditions, providing essential ecosystem services such as clean air, water cycle equilibrium and nutrient recycling. These regulations provide humanity with clean drinking water, breathable air, adequate daily temperatures, and basic sanitation for the health and well-being of the population worldwide[2].

In pursuit of economic and social developments, human beings have prospered in an unprecedented and unsustainable manner by exploiting the natural resources, altering their balance and indirectly increasing the degradation of life support systems. This phenomenon, from pre-industrial times until present, has led to a series of threats such as loss of biodiversity, issues in water quality and quantity, land degradation and, finally, climate change and its associated impacts[2,3]. The deterioration of these environmental and natural conditions adversely affects citizens on a daily basis, in all the contexts in which people live, work and spend their free time. The degree of exposure to these hazards varies according to the geographical, demographic, and socio-economic conditions in which the individual resides. However, the aggravation of these impacts combined with other negative stressors, such as the urban sprawl or the rapid aging of the population, makes urban areas a "hotspot", especially when it concerns extreme weather events[4].

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) underlined how in the first two decades of the 21st century, global surface temperature was 0.99°C higher than in 1850-1900 (reference period), with a fraction attributable to human activities equal to 0.8°C. Therefore, hot extremes have become more frequent and more intense, while cold extremes have become less frequent and less severe[2]. Over European regions, a more significant increase has been observed, with average annual temperatures between 1.45-1.59°C[5]. In terms of climate projections, global warming of 1.5°C-2°C will be exceeded by mid-century, unless deep reduction in greenhouse gas emissions occur in the coming decades[2].

Under this scenario, the increase in the magnitude of warming is projected to be more drastic in the south-central part of Europe, whereas the longer extent of warm spells are projected to be more pronounced over the Mediterranean Basin[6]. Within these regions, Italy holds the upper-most heat-related effects on daily mortality considering hot temperatures[7], and these impacts are projected to increase consistently in the future. Among different Italian cities, those in the North of the country - such as Turin - are characterized by a greater excess of heat-related mortality than those in the South of the peninsula[8]. For these reasons, direct impacts of extreme temperatures on health have become a relevant field of research in environmental epidemiology.

Epidemiology of Temperature-related Mortality

Of all-natural disasters, extreme temperatures are the main cause of weather-related mortality in cities, and these events are expected to be the main phenomenon responsible for additional deaths due to climate change influence[9]. Heat and cold stress conditions are key drivers leading to direct health effects that result in increased hospitalizations or increased mortality rates[10]. These situations are closely dependent on meteorological variables, which in turn can be significantly influenced by climate change. In order to assess the perceived population thermal comfort within a specific environment, simple temperature variables (e.g., mean temperatures)[11,12,13] or meteorological indices (e.g., apparent temperatures)[14,15] are currently applied. Nevertheless, mean daily temperature is the most common variable used for predicting daily mortality, because of its simplicity and effectiveness in illustrating the impacts of temperature stresses on overall health for the entire reference day[16,17].

Environmental epidemiology models on temperature-related mortality reveal an asymmetric relationship between temperature and mortality, characterized by a *J*-, *U*-, or *V*-shape, which suggest increased risk under cold and warm conditions. De facto, findings from previous studies highlighted a marked seasonality of temperature-related mortality, with higher mortality attributable to winter months than in other seasons[17,18,19]. In that respect, some research suggested how the risk of death associated with cold has decreased in recent decades. However, cold-mortality associations of the urban population overtime have been poorly studied[20,21], reason why such evidence remains uncertain. Likewise, little is known about the temporal trends in the effect of cold and heat risks (i.e., relative risk (RR)) and impacts (i.e., cold- and heat- attributable fraction (AF)) among population subgroups and across time periods[22,23,24].

Worldwide, the overall attributable mortality risk to high and low temperatures is equal to 7.71% (95% CI: 7.43; 7.49), of which 7.29% (95% CI: 7.02; 7.49) is attributable to cold and 0.42% (95% CI: 0.39; 0.44) is attributable to heat. These subsets correspond to days with temperature lower or higher than the minimum mortality temperature (MMT), which is the temperature at which risk of overall mortality is at its minimum. According to the study, Italy results to be characterized by the highest attributable mortality in relation to ambient temperatures, which correspond respectively to 10.97% (95% CI: 8.03; 13.43) for the all year, 9.35% (95% CI: 6.59; 11.72) for cold, and 1.62% (95% CI: 1.24; 1.98) for heat[17]. Despite this, a general reduction in heat risk was seen from 1996 to 2010 in the peninsula, specifically after the implementation of the national prevention plan in 2004[25]. Therefore, health risk estimates and trends within different Italian urban contexts differ, due to the period considered within each specific analysis[14], but also to both climate[25] and non-climate[4,8] factors depending on each specific location.

Overall, to investigate population urban vulnerabilities to extreme temperatures, existing literature assesses the risks evaluating the all- or natural- causes mortality in relation to temperatures. While this nexus provides insightful results, it fails to take into consideration specific characteristics of the local population and of the urban context[4]. Population health risk is the result of a still undefined combination of sub-systems such as the spatial distribution of the hazard, the built environment, the land use, the infrastructures, the social, natural, and productive systems, the bio-geophysical factors as well as the socio-economic aspects. The main implication of this epidemiological approach is that many urban areas are still inadequately informed about where the most vulnerable people live as well as where to prioritize adaptation measures based on the most vulnerable areas[27].

Population Vulnerability and Adaptation Processes looking at Socio-Economic factors and Built Environment characteristics

In the thesis, the concept of "vulnerability" refers to the characteristics of the population as well as of the built environment which contribute to increase the citizens propensity or predisposition to be positively or negatively affected to extreme temperatures[4]. For the "exposure", the rationale is more complex due to the heterogeneity of uses based on the scientific context in which the analyses are conducted. For the stake of clarity, in the socio-economic research, the term "exposure" refers to the sample exposed to the hazard that in the thesis reflects the urban population that is likely to be adversely affected by extreme temperatures[4]. Whereas, in the epidemiological context, this term is applied to any factor that may be associated with an outcome of interest (i.e., the defined "climate hazard" from a socio-economic perspective)[22]. Finally, the concept of "risk" here refers to the mortality occurrences driven by a combination of sub-systems such as the local climate condition, the bio-geophysical factors, the socio-economic aspects as well as the built environment characteristics[22].

A distinction of temporal changes in these risks under a full range of temperatures can provide a more comprehensive characterization of the evolving contribution of the diverse mechanisms driven by extrinsic as well as intrinsic adaptation processes. However, an increase or a decrease of population vulnerability at the urban scale is strictly related to adaptation[10,11,28]. In the thesis, the concept of "intrinsic adaptation" refers to the natural physiological acclimation in response to changing temperatures. By contrast, "extrinsic adaptation" relates to the non-climate factors which are expected to influence the likelihood that extreme temperature events can have on health outcomes. The latter can be further categorized into those characteristics related to the individual-scale, which includes personal demographic and socioeconomic variables, and to those related to the urban-scale, which includes components of the indoor as well as outdoor built environment in the urban context[4,23].

In relation to the population vulnerability, four distinct categories of determinants have been identified in the literature state-of-the-art[29]: (i) mental and physical health, which refers to pre-existing individual health diseases; (ii) demographics, which includes basic individual characteristics of the person; (iii) social status, which refers to the conditions in which people born, live and work; and, finally, (iv) economic status, which includes information about individual economic conditions[4]. With regard to gender inequality, several studies revealed higher mortality rates in women than in men[4,30,31]. Differences by age and by education were observed in several cities with a common consensus that temperature-related mortality increases in the elderly and in the less educated, with variations by gender[11,20,32]. Furthermore, only few studies have focused on marital status and on the relationship between family structure characteristics (i.e., number of household occupants) and mortality risk, with no consistent evidence on how these social factors influence mortality under extreme temperature conditions[23].

With reference to the urban scale, the concept of "enhanced exposure" has been introduced in the thesis to reflect those aspects of the internal or external physical environment that can exacerbate temperature stresses within different places across cities. For example, air conditioning, thermal insulation or housing materials for the indoor environment, or number of floors, land cover type and traffic density for the outdoor environment[4]. Managing climate change hazards in cities is challenging, as it requires a deep understanding of the hazard distribution between sub-urban areas taking into account the built environment as well as the spatial distribution of the most vulnerable population[4,6,27].

To date, in environmental epidemiology, metropolitan fragmentation is underestimated due to the lack of data, standardized city indicators, and weak metric at the district-scale level. Until now, this research gap has been a barrier to prioritizing ad hoc adaptation measures[27,34]. Assessing quantitatively urban adaptation to extreme temperatures is therefore necessary to improve our understanding of urban risk and to evaluate the progress of urban adaptation strategies. This approach can be of value for policymakers, supporting them in comparing, evaluating, and undertaking actions, but can also be used as a retrospective method to assess implemented adaptation policies[4,23,35]. Higher-resolution data in relation to heat hazard and adaptation measures not only support policymakers and planners but can also facilitate the urban climate and health governance in understanding the patterns of projected human health risks in the future. For these reasons, further investigations on this subject are needed.

Scope and Structure of the PhD Research Work

This PhD research is composed by a macro-scale and a micro-scale objective. At the macro scale, the overall aim of this dissertation is to advance knowledge on risk evolution of temperature-mortality associations by focussing on social inequalities and built environment characteristics through the use of a flexible and validated methodology that can be applied to other urban contexts. In parallel, at the micro-scale, the aim is to explore and advance - qualitatively and quantitatively - the knowledge on the temporal changes of cold- and heat- attributable mortality risks by demographic and socio-economic variables and by built environment in a specific case study. Therefore, in order to do so, this methodology is here applied on the City of Turin (northwest of Italy), which constitute the urban case of the two empirical studies in this PhD thesis.

This dissertation is structured as follows; first, a literature review is developed to determine the social factors as well as the urban parameters most in evidence in the literature in connection with the risks under extreme temperatures. This is done to better capture the definition of the demographic, socio-economic and urban variables to be considered in the empirical studies, but also to more effectively define which types of adaptation measures to recommend based on the spatial diversification of emerging risks within the urban case (aspect explored in the last phase of this research project). Subsequently, an analysis on the cold- and heat- attributable mortality risks is conducted using data for a period of 37 years, to better understand the influence of the diverse demographic and socio-economic variables within the temperature-mortality relationship. Finally, a study of the evolution of temperature-mortality risks in relation to these variables is designed, so as to understand the process of adaptation of the population by each examined category. Through the use of the here presented methodology on Turin, this thesis has identified whether the population adaptation has occurred under cold and heat conditions, investigating differences by each demographic and socio-economic subgroup. These elements will then be considered as key factors on which to suggest the most appropriate adaptation measures based on the results achieved.

The research steps developed since the beginning of the PhD program – with respective research questions (**Q**) and objectives (**O**) - have been as follows:

- **Q_1:** Investigate the international state-of-the-art literature on hazard, sensitivity, adaptive capacity, and enhanced exposure factors to comprehensively understand the variables to consider within the nexus between extreme temperatures and health at the urban scale. {Paper I in Figure 1}

  O_1: *This step allowed the author to identify and justify the choices of the variables considered in the research articles presented in this thesis.*
- **Q_2**: Assess the associations between daily summer mean temperatures and all-causes mortality in the city of Turin among different demographic and social subgroups for the period 1982–2018. {Paper II in Figure 1}

  O_2: *This step allowed the author to identify and quantify the risks and attributable fraction of mortality under heat conditions by demographic and socio-economic subgroups looking at a city as an aggregate and highlighting subgroups differences which can be attributable to social inequalities.*
- **Q_3**: Explore trends in cold- and heat- attributable mortality risk and burden by demographic and social subgroups using subsets of time within the period 1982–2018. {Paper III in Figure 1}

  O_3: *This step allowed the author to evaluate the temporal changes of cold- and heat- attributable mortality risks by demographic and socio-economic variables, to identify the adaptation pattern over time by subgroups.*
- **Q_4**: Identify the cold- and heat- attributable mortality risks by districts and neighbourhoods for the period 1982–2018, by focussing on social inequalities as well as at the built environment characteristics that constitute each specific sub-urban area within the city. {Paper IV in Figure 1, under development}
- **O_4**: *This step allows the author to establish the cold- and heat- attributable mortality risks diversification within the city, and to consider these results in line with the characteristics of the built environment in each specific unit of the sub-urban area. In addition, it will be relevant to determine which adaptation measures to suggest on the basis of the results achieved.*

Based on the proposed structure, the climate-urban health-inequalities nexus is most visible in Paper I and will be re-evoked in Paper IV, to suggest contextual adaptation measures that incorporate all the elements at the basis of the analyses in this PhD thesis.

Figure 1 | PhD research work: paper structures and applied criteria and methods of analysis

Paper I, Paper II, and Paper III are included in *Chapter II* of this thesis, while for Paper IV an overview is included in the *Future research and Developments* section, within *Chapter III*.

CHAPTER II

RESEARCH ARTICLES

REASEARCH ARTICLE 1

Title
The heat-health nexus in the urban context: A systematic literature review exploring the socio-economic vulnerabilities and built environment characteristics

Authors
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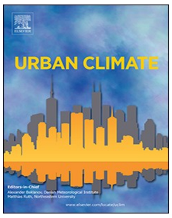

The heat-health nexus in the urban context: A systematic literature review exploring the socio-economic vulnerabilities and built environment characteristics

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ABSTRACT

Of all-natural disasters, extreme high temperatures events are the main cause of weather-related mortality. The compact urban settings of cities, the dependency on infrastructural systems as well as the larger concentration of people and economic activities make urban areas particularly vulnerable to health risks due to heat. To investigate vulnerabilities to heat, the study illustrates how vulnerability factors together with the hazard and the urban parameters determine the nexus between the heat and the health outcome, here called *heat-health nexus*. Peer-reviewed articles with no language limitations were searched from the first available record subjected to the imposed selection criteria. First, the information related to the study area were analysed, taking into consideration the level of resolution to investigate the scale of analysis. Then, the specific hazard parameters, divided in simple or combined weather indices, were evaluated. For sensitivity and adaptive capacity aspects, the study considered four distinct categories of determinants: mental and physical health, demographics, social and economic status. Finally, when looking at enhanced exposure, groups of determinants of vulnerability, divided between those describing indoor and outdoor environment conditions were analysed. Results demonstrated a heterogeneous spatial distribution of the identified case studies about heat and health in the urban context and highlighted different characteristics related to climate hazard, exposure, vulnerability and enhanced exposure factors in relation to the health of the population. This literature review demonstrate that a detailed identification of sensitivity, adaptive capacity and enhanced exposure elements is crucial in the implementation of effective adaptation measures in the health context.

1. Introduction

As is widely acknowledged, due to the large concentration of population, economic activity, transport and energy infrastructures, cities and metropolitan areas play an important role in contributing to climate change (Orimoloye et al., 2019; Khavarian-garmsir et al., 2019; Ropo et al., 2017). At the same time, they are the sites where the most pressing current challenges brought about by climate change are visible (Barber, 2017). Moreover, cities and metropolitan areas are the heart of today's world economy,

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increasingly concentrating political, economic, financial, cultural, technological and innovation capabilities. For this reason, climate change and the different local, regional and national capacity to address its effects, might also have important consequence on urban competitiveness and competition, at a variety of spatial scales (Kamal-Chaoui, 2008; Sharma, 2019). However, cities are not only part of the problem; yet they can also be regarded as a vital part of the global response to climate change and its impacts. As a point of fact, there is today growing evidence showing that many cities are becoming key players in shaping and implementing new initiatives aimed at dealing with the challenges brought about climate change, both at urban scale, through mitigation and adaptation measures (Carter, 2011; Carter et al., 2015; Leichenko, 2011) and at inter-urban scale, through the shaping and designing of new cooperation networks and efforts (Kern and Bulkeley, 2009; Gordon, 2013; Castán Broto and Bulkeley, 2013).

Against this background one of the more challenging issue cities and metropolitan areas need to address is the increasing magnitude and frequency of heatwaves. In fact, over the last half-century, the probability of heat extreme events has already changed by orders of magnitude in almost every region of the world, with occurrences that are now up to a hundred times more in respect to a century ago (Eckstein et al., 2019; WMO, 2019). As a result, the frequency and severity of extreme heat spells have become more visible for high- and low-income countries (Hintz et al., 2018). Because of these phenomena, heatwaves are one of the major cause of damages in the last years, especially in the Northern Hemisphere (Eckstein et al., 2019). Recent research has found that of all natural disasters, extreme high temperature events are the main cause of weather-related mortality (de' Donato et al., 2015; Petkova et al., 2014; Gabriel and Endlicher, 2011), and they are also expected to be the main factor responsible for additional deaths due to climate change in the coming years (WHO, 2018). In this context, to understand how cities and urban authorities plan to anticipate and cope with extreme high temperature events, in terms of monitoring and data organization, identification of main stressors and relationships between diverse and relevant factors and providing input for sound political responses is of paramount importance. As a point of fact, cities are hotspot locations, because they are characterized by an addition of several degrees warmer than their surroundings due to specific urban features and their albedo as well as urban waste heat and GHG emissions from infrastructure (Oppenheimer et al., n.d.; Rosenzweig et al., 2011). Therefore, the compact urban settings of cities - through the reduced evaporative cooling caused by lack of vegetation and the production of waste heat - bring to elevated surface and air temperature, generating the condition for the urban heat island (UHI) phenomenon (Rosenzweig et al., 2011; Oke, 1982; Breil et al., 2018). At a closer look it becomes evident that conditions within cities are not equal in all their parts, and identifying those areas which are particularly vulnerable to heat, either to their physical form or particular characteristics of their inhabitants, is particularly important. To date, more than 54% of the world's population live in urban areas and by 2050 this portion is projected to include two-thirds of the people around the globe (United Nations D of E and SA, 2014). Moreover, as mentioned above, cities are the heart of the contemporary economy, which means that heatwaves can hamper the economic structures of many regions and can promote budgetary problems and loss of competitiveness (Kamal-Chaoui, 2008). Climate projections (Representative Concentration Pathways, RCPs) as well as socio-economic scenarios (Shared Socio-Economic Pathways, SSPs), which describe respectively alternative climate pathways associated to emission levels (van Vuuren et al., 2011) and societal development trends (Jiang and O'Neill, 2017), estimate an increase of UHI effects due to changes related among others to urban density and urban land cover (Oke, 1982; Chapman et al., 2017).

The heat-related epidemiology literature emphasizes that population expansion under an increasing frequency, intensity, and duration of heatwaves is increasing the social vulnerability, exacerbating the temperature-mortality relationships (de' Donato et al., 2015; Petkova et al., 2014; Martinez et al., 2018; Michelozzi et al., 2008; McMichael et al., 2008). In order to investigate urban vulnerabilities to heat stress, many researchers assess the risks evaluating the mortality rates in relation to temperature trends. While this nexus provides insightful results, it fails to take into consideration specific heat stress conditions as well as specific characteristics of the local population and the physical environment (Lindley et al., 2018; Klein Rosenthal et al., 2014). In fact, the temperature-mortality relationship does not occur in a territorial vacuum. Rather, it is ‘embedded’ within the urban fabric, according to the context-specific way natural and socio-economic processes interact. Population health risk due to heat in cities is driven by a still undefined combination of sub-systems such as the spatial distribution of the UHI, the built environment characteristics, the land use, the infrastructures, the social, natural and productive systems, the bio-geophysical factors as well as the socio-economic aspects (Breil et al., 2018; Tapia et al., 2017; Kaźmierczak and Cavan, 2011; Georgi et al., 2016). A good understanding of the complexity of interactions between exposure, sensitivity and adaptive capacity and of relevant determinants of vulnerability is crucial for the informing interventions at local level and can contribute to developing instruments for diagnosis, as heat vulnerability indices (HVI). Such assessment studies translate the knowledge about determinants of heat vulnerability in composite indicators, while should be able to support local policy making in detecting potentially vulnerable areas and communities within their territory (Bao et al., 2015; Wolf et al., 2015).

For this reason, in this review, the authors explore - together with the urban climate parameters – which vulnerability factors jointly with the exposure have been found to determine the nexus between the heat and the health outcome, here called *heat-health nexus*. Managing urban climate hazards and understanding the causes of intra-urban spatial heterogeneity is complex, as it requires a deep knowledge of how the hazard unfolds within urban areas and how it interacts with environmental circumstances and the spatial distribution of the most vulnerable population (Rosenzweig et al., 2011; Breil et al., 2018; Klein Rosenthal et al., 2014; Georgi et al., 2016; Araya-Muñoz et al., 2016; Urban et al., 2016).

Several studies have been conducted in order to assess the current and future hazard-exposure, but less effort has been spent in research to analyse environmental and social factors related to health issues (Lindley et al., 2018). In order to highlight the fundamental social and environmental characteristics, which have the potential to influence the heat-health outcomes within urban areas, this research focused on the three main pillars defining risk: *hazard* that here is defined as the potential occurrence of summer extreme temperatures amplified by urban conditions that can bring to heat stress status in the short and long term; *exposure* that reflects the urban population which could be adversely affected by extreme temperature conditions in urban areas, and *vulnerability* that describes the propensity or predisposition to be affected to extreme temperatures (Oppenheimer et al., n.d.). Among these factors the present review focusses on the concept of vulnerability. To facilitate the comprehension of the analysed material, vulnerability factors have been disaggregated into three main components that constitute the socio-spatial vulnerability index (Lindley et al., 2018): (i) *sensitivity*, that here represents the personal biophysical and social characteristics driving vulnerability, and (ii) *enhanced exposure*, which reflects aspects of the physical environment that can exacerbate (or mitigate) climate impacts within different places across cities. The aggregation of these indicators helps to explain which factors drive vulnerability at the intra-urban scale and which factors related to the characteristics of the built environment further enhance the exposure, taking into account the insights linked to each study location (Breil et al., 2018). In addition, all these dimensions are associated with (iii) *adaptive capacity* indices which reflects the ability of citizens, policy makers, local businesses and institutions within cities to respond to heat-stress conditions (Breil et al., 2018; Lindley et al., 2018). Understanding of these aspects - together with the level and distribution of health outcomes – and eventually their aggregation into heat vulnerability indices – could indeed be crucial to identify and implement efficient social and physical infrastructure measures through the use of ad hoc spatial planning considerations and urban governance decisions (Hintz et al., 2018; Wolf et al., 2015). In this context, higher-resolution data in relation to both heat hazard and health impacts and to determinants of vulnerability can facilitate the urban climate and the health governance in understanding the pattern of current and future human health risk in the next future in order to better shape adaptation measures at the local scale. Therefore, assessing the health risk due to heat in diversified intra-urban context is necessary to improve our understanding of the *heat-health nexus* and to evaluate the innovative progresses of urban adaptation strategies. In fact, while it is widely acknowledged that cities and metropolitan areas play a basic role in tackling climate change, both in terms of mitigation and adaptation policies, more research effort is needed to understand how management measures have to be differentiated at intra-urban scale, according to the specific local parameters and socio-economic vulnerabilities.

To this perspective, based on the available literature, 40 articles on health issues due to heat within urban contexts have been analysed to support the identification of enhanced exposure factors, sensitivity, adaptive capacity characteristics and health outcomes, highlighting common features and differences with emphasis on the urban parameters and the socio-economic vulnerabilities. This paper is organized as follows: *section 2* focusses on the methodology. It first refers to the systematic literature review approach; then it turns to the specific content of the 40 final articles. *Section 3* offers an insight into the achieved results of the analyses. In *section 3.1,* a discussion on the exposed sample to health impacts of heat stress in urban areas is proposed with the aim to analyse the urban geographical provenance of the case studies as well as the major causes of mortality due to heat. *Section 3.2* focussed on the parameters that the authors of the papers are using in order to evaluate the climate hazard. In *sections 3.3* and *3.4* the social dimensions of vulnerability (sensitivity and adaptive capacity) as well as the urban environment characteristics, which constitute the enhanced exposure, have been investigated in detail. Finally, some conclusive remarks are provided in *section 4* and *5.* In particular, the need for further investigation on the importance of social and economic parameters in affecting the evolution of the *heat-health nexus* is pointed out in *section 4.* A sound knowledge on the role played by these factors can support cities and urban authorities to tackle climate change impacts with more effective adaptation policies.

2. Methods

2.1. Literature review process

This paper is based on a systematic literature review approach to investigate the state-of-the-art literature on factors that link characteristics of the urban environment to vulnerability to heat during extreme temperature events. The review as well as the qualitative content analysis process was based on several known guidelines (Pullin and Stewart, 2006; Luederitz et al., 2016). The *PubMed* and *Scopus* database were used to identify and provide relevant literature through the developed research algorithm. The used search terms were selected through an initial screening process highlighting the most frequent keywords in almost 700 articles selected from the simple initial algorithm (see *Appendix A*). Peer-reviewed articles with no language limitations were searched from the first available record subjected to the imposed selection criteria until March 2019. The first step of the review returned in 1445 results for the selected time-period. For each record, title and abstract were filtered twice by the authors for inclusion in the list of potentially relevant papers (476). The remaining articles were then reviewed based on the set of criteria that have been imposed within the systemic review approach (see Fig. 1). First, the papers had to include at least one empirical case study together with the nexus between the heat and the health outcome, here defined *heat-health-nexus* (1st Set of Criteria). In fact, articles that focused solely on health sector were judged being beyond the scope of this study. Second, the papers had to describe connections with the built environment characteristics, which include the indoor conditions as well as the urban outdoor environment (2nd Set of Criteria). From the above sets of criteria, 31 papers were considered. Finally, a “snowballing method” was used to include in the list also those articles identified from the bibliographies of the previous selected papers (Pullin and Stewart, 2006). Although, at present, health impacts from extremely low temperatures are potentially more important in terms of morbidity and mortality (Hajat and Gasparrini, 2016), this study focuses on heat related impacts. In fact, only few studies inquire on factors related to enhanced exposure for the analysis of cold related health impacts, and including factors related to indoor conditions, generally related to energy poverty and poor building insulation. The selection process led to 40 papers and it is described in the following flowchart.

2.2. Content analysis

The analysis was performed following the most recent Intergovernmental Panel on Climate Change (IPCC) conceptual framework for risk that explicitly considers the presence of the elements exposed as an additional component (Oppenheimer et al., n.d.). As mentioned

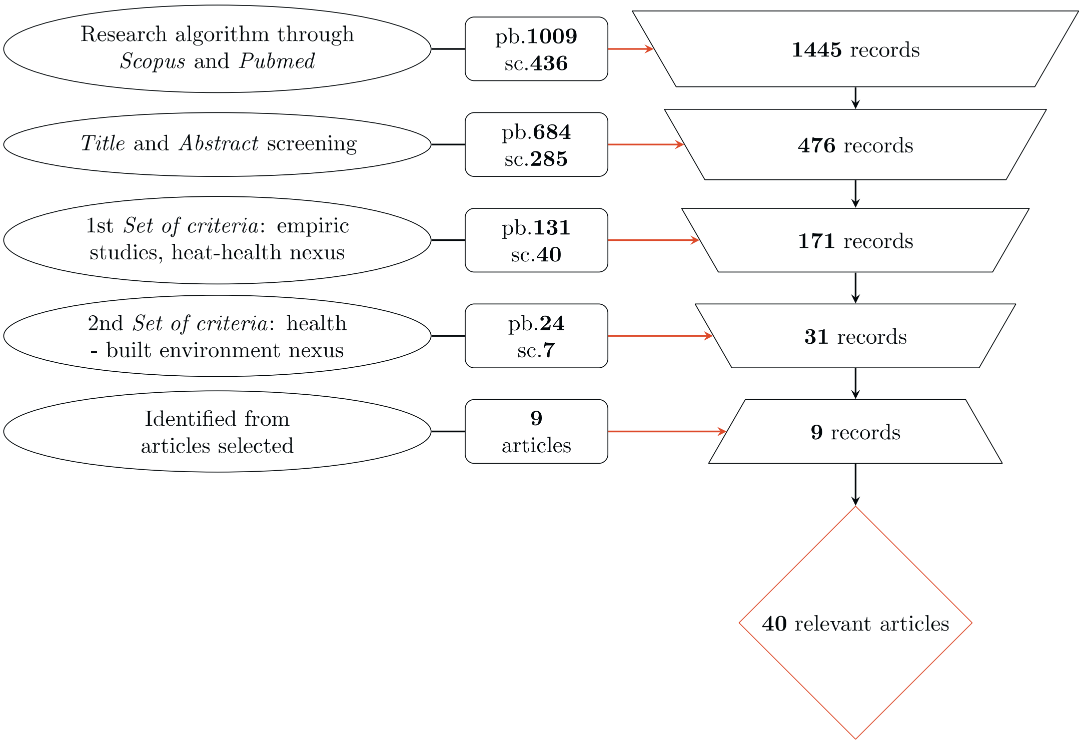

Fig. 1. Steps of the selection process.

in the previous chapter, in order to highlight the main variables related to the *heat-health nexus*, this study focused on the hazard-exposure relations (hazard and exposure), but also on the main components that constitute the socio-spatial vulnerability: sensitivity, adaptive capacity and enhances exposure. The content of the 40 final articles assessing variability in the impacts of heat through the analyses of health outcomes (when accessible) was investigated with the aim to identify relevant issues and common features. On this basis, the information was organized in this paper through the following classification method. Starting with the geographical dimension, information related to the area of study was collected, taking into consideration the level of resolution to investigate the scale of analysis. Then, the first step was to define the hazard parameters as well as the applied methodologies to collect and analyse the climatic data. Concerning enhanced exposure, the information was divided between *Indoor Environment* and *Outdoor Environment*. Under indoor environment, elements that influence the indoor heat stress were inserted, while under outdoor environment were included those variables that influence the outdoor urban heat stress. In order to investigate whether there were geographic differences in how single parameters are understood, due to different socio-economical contexts, the geographic environment in which the single studies are located have been considered. To differentiate all the information related to sensitivity and adaptive capacity, variables are here categorized into five different classes: physical and mental health, demographics, social and economic status. Finally, to investigate the main component of the research, the paper analysed if data related to the health sector (studies on heat morbidity or heat mortality) were available and, if any, which methodology each article decided to apply in the reference study.

3. Results

3.1. The health impacts of heat stress: the urban population (exposure)

Taking into account all variables that seem to influence the heat-exposure of urban population, the 40 papers was investigated looking at the geographical and spatial scale, focusing on the most prevalent health factors. A strong geographic bias within the analysed articles shows how most of the studies were conducted in USA, followed by Australia, UK and China. Diverse articles focused on single case studies within one European country, but only one refers to South America (Inostroza et al., 2016). In addition, it must be highlighted how, despite the heat stress risks faced by African cities, no comparable study dedicated to African urban areas was found, highlighting how the African continent is still underrepresented due to the lack of proper data (Eckstein et al., 2019).

Results show that the scale of application changes in respect to the analysed case: 27 articles reflect a city-scale analysis, 8 papers consist of a multi-cities analysis, 5 include entire metropolitan areas (all in USA), and one is considering a wider territorial area, consisting of urban and rural areas in the Yangtze River Delta (China). In a second moment, the paper focussed on the geographical resolution of urban exposure data to identify which units of analysis significantly elucidate intra-urban variations of risk. Yet, understanding differences at this scale is key for the definition of the spatial health risk distribution with respect to existing urban areas (see Table B.1 in *Appendix B* for further details). Of the 40 articles, just the half mentioned the analyses carried out to quantitatively determine how heat affects population health in a specific urban area. Research based on mortality generally contains geo-reference information and socio-demographic and -economic data for each death. On the other hand, morbidity case studies mostly refer to the investigation of the admissions to hospitals in the warmest periods of the year. At this stage, we found three cases based on survey data. Of those, one is focusing on self-reported perceived health effect (Bélanger et al., 2015), a second one on self-reported household thermal comfort (Loughnan et al., 2015) and the last one on self-reported perceived heat stress (see Table B.2 in *Appendix B*) (Henseke and Jürgen, 2014). Despite the qualitative approach, these perceived reported health effects contribute to identify a reliable and valid subjective measurement that reflect certain health aspects difficult to identify clinically (Bélanger et al., 2015). In addition, they also support policymakers in the identification of population groups most likely at-risk, promoting ad hoc services and preventive measures to mitigate the health consequences during very hot and humid conditions (Bélanger et al., 2015).

The majority of the case based on mortality indicate more clearly which diseases they took into consideration based on the International Classification of Diseases (specifically ICD-9 and ICD-10). In this context, if the ICD code was not explicit, it was derived from the classification provided by the World Health Organization (WHO) (WHO, 2016). By majority, *all-causes of death* (ICD 10: A00-Y89) together with *natural causes of death* (ICD 10: A00-R99) are the most common used classification methods. However, if a greater specification was available and the models allow to disrupt subdivide the population under analysis, a greater detail on causes of mortality contributes to enhance the quality of the analyses. For example, several case studies refer to ICD10 T67 and ICD10 X30 (Johnson and Wilson, 2009; Smoyer et al., 2000; Uejio et al., 2011; Gronlund et al., 2015; Nayak et al., 2018), which reflect specific diagnosis due to the effect of heat (e.g. heatstroke, heat syncope, heat cramp, etc.) as well as the exposure to natural heat as cause of sunstroke (e.g. ictus).

3.2. Climate parameters for heat (hazard)

Extreme temperatures significantly increase the risk of mortality and morbidity around the world. In order to evaluate the perceived thermal comfort of the population within a specific environment, several studies used simple temperature anomalies or combined weather indices (Barnett et al., 2010; Kim et al., 2014; Blazejczyk et al., 2012). In fact, some authors consider these measures to be efficient predictors for the heat-related health impacts assessment and were able to express an equivalent perceived temperature of the referent environment providing information on the physiological response of a reference population (Kim et al., 2014). In this context, the work of Barnett et al. is important (Barnett et al., 2010): they analysed the relationship between temperature related parameters and daily counts of deaths to identify the best predictor in the association between temperature and mortality. The results of the study proved how there is not a best climate parameter of mortality, but the choices must depend on practical concerns (e.g. data availability, missing data, etc.). However, due to its simplicity and efficacy to illustrate health impacts of heat, to date ambient temperature is still the most used variable in the heat risk assessment analyses (Barnett et al., 2010; Aubrecht and Özceylan, 2013). In addition to the climate parameters investigation, separate analyses by location (e.g. specific cities) or within the same location (e.g. districts) can increase the power of the study and can provide information on heterogeneity of environmental exposures (Bhaskaran et al., 2013).

In this chapter, the focus is on climate parameters used in the 40 papers to connect heat stress perceived in a specific location with the health effects. In fact, different climate factors contribute to heat stress, among these temperature variations, humidity and wind. Epidemiological studies frequently use observations from weather stations within the analysed city, emphasizing the relation between ambient heat and excess mortality (and morbidity) under extreme climate condition (Hu et al., 2019). Due to the limited number of parameters available from the stations, most of the research in the field used univariate heat measure and temperature-based heat-wave definitions (Aubrecht and Özceylan, 2013). The articles have been screened looking at the climate parameters (see Table B.3 in *Appendix* for climate indices description). From the analyses, it emerged that indicators were all based on daily parameters, and there was no difference in the use of specific patterns of climate indicators between countries under study. The identification of specific hot days within the hot season was based either on mean daily temperature (means of daily maximum temperatures or apparent temperature) or in some cases, specific definitions of heat wave duration were used for the selection of the period of investigation. With this term the state-of-the-art literature refers to a period of hot weather with a duration of at least two or three days in which days and nights reach high values of temperatures and humidity (Wolf and McGregor, 2013). Table 1 shows the studies that considered simple indicators related to temperature - such as ambient temperature, indoor temperature, maximum, mean and minimum daily temperature - as well as those who adopted more complex indices, such as maximum apparent temperature, relative humidity, heat stress and heat wave. Among these, land surface temperature represented the most frequently used parameter (almost 30% of the papers) since it is indeed particularly interesting for the analysis of urban heat distributions. In fact, the latter allow to overcome the limitations of single-station data provided by most of the meteorological stations and are able to represent intra-urban temperature differences at relatively small scales, which correspond to the spatial detail of information needed for the design of interventions in the urban space (Hu et al., 2019). Thermal data from remote sensing measurements provide a natural extension of the non-direct measurement of earth-based systems to investigate more in detail how environmental features can affect health for the study of UHI (Johnson et al., 2011). In addition, satellite images classification of surface temperature is being used for gaining insights into surface heat island morphology (e.g. MODIS image of land use cover) (Wolf and McGregor, 2013). However, remote sensing alone is considered insufficient to significantly elucidate intra-urban variations of health risk within an urban area and as results include higher level of uncertainty, due to the generally rare number of measurements. On the other hand side, remote sensing measurements represent an attractive source of information, due to their coverage and as short-term thermal imaginary is very often the only sensor available (Johnson and Wilson, 2009). In more data-rich situations, it is becoming increasingly common to use land surface as an integration to ambient air temperature as significant variables in modelling vulnerability from extreme temperature events in the urban environment (Johnson and Wilson, 2009; Hu et al., 2019; Wolf and McGregor, 2013).

Finally, this section focussed on studies related to indoor temperatures since people spend a lot of time indoors during extreme events. Therefore, it is essential to understand how they use the building to protect themselves (Loughnan et al., 2015). Some of the studies

Table 1
Climate indicators, case study location and temperature thresholds.

Climate Indicator	Respective thresholds	Case study	Time	Reference
Ambient temperature	30.0 °C 27.0 °C, 3 days	Australia	1999–2004	(Loughnan et al., 2010)
Ambient temperature Ground surface temperature	–	USA	2013	(Sharma et al., 2018)
Ambient temperature Relative humidity (RH)	26.6 °C 40%	USA	1997–2006	(Klein Rosenthal et al., 2014)
Apparent temperature Heat index (HI)	–	UK	2003, 2006	(Macintyre et al., 2018)
Daily excess heat factor (EHF)	–	Australia	1980–2010	(Hatvani-Kovacs et al., 2016a)
Heat index (HI) Human thermal comfort index (HTCI)	40.0 °C 200	USA	2003	(Harlan et al., 2006)
Heatwave Heat index	Tmax: 32.0 °C, 2 days 95 °F, 2 days	USA	2000–2011	(Madrigano et al., 2015)
Heatwave	Tmax: 30.0 °C, 3 days	USA	2010	(Aubrecht and Özceylan, 2013)
	–	Serbia	2015	(Savić et al., 2018)
	Tmax: 32.0 °C	USA	2003–2013	(Hu et al., 2019)
Heatwave	LST: 51 °C	USA	2006	(Jiang et al., 2015)
Heatwave Land surface temperature (LST)	Tmax: 27.0 °C, 2 days	Estonia	2014	(Sagris and Sepp, 2017)
Indoor temperature under extreme heat	Tmax: 37.0 °C, RH: 9% Tmax: 44.0 °C, RH: 2%	USA	Not specified	(Nahlik et al., 2017)
Indoor temperature	–	Australia	2012	(Loughnan et al., 2015)
Outdoor temperature	24.8 °C	UK	2006	(Taylor et al., 2015)
Land surface temperature (LST)	–	USA	1993	(Johnson and Wilson, 2009)
	55 °C	USA	1970–2000	(Jenerette et al., 2018)
	–	UK	1976	(Tomlinson et al., 2011)
	–	USA	1999, 2005	(Uejio et al., 2011)
	–	USA	2000	(Harlan et al., 2013)
	–	Netherlands	2006	(Van Der Hoeven and Wandl, 2015)
	–	Chile	2002–2010	(Inostroza et al., 2016)
	–	USA	2013–2014	(Méndez-Lázaro et al., 2018)
Maximum apparent temperature	32.0 °C	Canada	1980–1996	(Smoyer et al., 2000)
	–	USA	2008	(Hondula et al., 2012)
Maximum, mean and minimum temperature	95th percentiles for Tmax, Tmean, Tmin	UK	1990–2006	(Wolf and McGregor, 2013)
Maximum temperature	–	Australia	2007–2011	(Hondula and Barnett, 2014)
	40.0 °C	China	2013	(Chen et al., 2018)
Mean temperature Mean relative humidity (RH)	–	Australia	2004	(Yu et al., 2010)
Minimum temperature Maximum temperature Mean apparent temperature	97th and 99th percentiles	USA	1990–2007	(Gronlund et al., 2015)
N° of heat-wave days in a year (DH) N° of extremely high temperatures in a year (DE)	Tmax: 32.0 °C, 3 days Tmax: 35.0 °C, 3 days	China	2008–2011	(Dong et al., 2014)
Summer days Tropical nights	30.0 °C 20.0 °C	Germany	Not specified	(Blättner et al., 2010)

referred to indoor monitored data (e.g. portable data loggers) while some others reflected the personal evaluation by household members (e.g. householders' thermal comfort) (Loughnan et al., 2015; Van Der Hoeven and Wandl, 2015; Taylor et al., 2018; Nahlik et al., 2017). Studies based on indoor temperatures in dwellings is vitally important since several analyses proved how dwelling characteristics and occupant behaviour play a key role in the risk of mortality (Taylor et al., 2015). In addition, the duration of the exposure is also a crucial aspect that authors considered in order to explore the delayed ('lagged') associations between an outcome today (mortality) and an exposure (extreme heat) in previous days (Bhaskaran et al., 2013). This dimension represents a space over which the association within the *heat-health nexus* is defined, adding a backward (Gronlund et al., 2015; Hondula et al., 2012) or forward (Madrigano et al., 2015) lag-response relationship in addition to the usual exposure-response function (Hajat and Gasparrini, 2016). Between the peer-reviewed articles, just 3 considered the lag-delayed effect (Gronlund et al., 2015; Hondula et al., 2012; Madrigano et al., 2015), and all of them reported a short period lasting some days before/after the heat occurrences. As a matter of fact, this is in line with the state of art literature, which express how in case of investigation of health effects under heat, the relative risk of the outcome is often distributed over the nearest lags (from 0 to 7), depending on the population under analysis (Braga et al., 2020; Armstrong et al., 2018; Gasparrini, 2011).

3.3. The biophysical and social dimensions of vulnerability (sensitivity and adaptive capacity)

In this section, the paper focused on the biophysical and social dimensions of vulnerability to climate change that have been recognized within the 40 identified peer-reviewed articles. In fact, climate change impacts, as explained before, do not happen in isolation, but they are, inter alia, determined by the characteristics of the urban environment and socio-economic system often associated with a general concept of *vulnerability (*Lindley et al., *2018)*. Here, *vulnerability* is intended as the propensity or predisposition at which individuals (or communities) are affected by heat stress events driven by climate change (Oppenheimer et al., n.d.; Leal Filho et al., 2018). Since this concept is dynamic and context specific, it encompasses a variety of components such as sensitivity aspects of people that are determined by human behaviour and societal organization (Field et al., 2012; European Environment Agency, 2018). While most of the studies focussed on the analysis between current and future heat-mortality, less attention is paid to address personal factors that influence the social vulnerability of citizens (Klein Rosenthal et al., 2014); that is why this dimension of vulnerability is not sufficiently recognized in urban adaptation measures and policies (Lindley et al., 2018). For this reason, in this section the analyses focused on the social and biophysical personal characteristics that emerged from the 40 articles, which are expected to influence the likelihood that a heat stress event can have on the health outcomes in a specific urban context. To produce a representative overview from the studies analysed, Table 2 shows the subdivision that have been here applied to highlight the main social vulnerability components. Based on the WHO subdivision (WHO, 2019), four distinct categories of determinants have been chosen: (i) *mental and physical health*, that refers to the individual health status as well as access of services that prevent and treat disease influences health; (ii) *demographics*, which includes basic person's individual characteristics, such as age and gender; (iii) *social status*, that refers to the conditions in which people are born, grow up, live, and work, such as social support networks and education. And, finally, (iv) *economic status*, which includes information on the economic status, such as occupation and income.

3.3.1. Mental and physical health

Since "people in poor health are more prone to heat-related mortality and health impacts" (WHO, 2019), the first analysis focusses on the mental and physical health category that directly or indirectly refer to the pre-existing health factors. In this context, the first section of Table 2 highlights the main elements to understand the most common predisposing factors for heat-related illnesses in the analysed state-of-the-art-literature. To facilitate reading comprehension, three main groups have been developed to which the different variables belong to: health status, mobility-health status and mobility-health services. Factors related to previous medical status and to the use of substances that influence the temperature regulation – such as drugs or alcohol - were included in the first class. Physical disadvantages (e.g. handicap) as well as the degree of reliant on social services for home care were included in the second one, and finally, in the last class was included the elements relating to the accessibility of health services and their degree of efficiency.

3.3.2. Demographics

With regard to the demographic category, about the majority of the analysed paper (90%) introduced the concept of age differentiation and gender differences. By looking at gender, most of the case studies highlighted how females were found at higher risk in respect to males during heatwaves (Bélanger et al., 2015; Hatvani-Kovacs et al., 2016a; Yu et al., 2010). When dealing with the age groups, different approaches have been found. In fact, since age is one of the main personal factors that determine heat vulnerability (Yu et al., 2010; Seebaß, 2017), different age-thresholds for the increase of heat related mortality and morbidity have been considered. About 67% of the studies investigated the relation between elderly and health outcomes considering in general citizens over 65 years old as well as 75 years old (see Table 2 for detailed information). In addition, since there is some evidence of an increase of health issues among very young individuals (Leone et al., 2013), the analyses also took into account this variable ("People under 5 years old"). And, almost a quarter of the total of the studies considered individuals with less than 5 years old, without a common geographical pattern.

3.3.3. Social status

Among the social drivers relevant for increased heat vulnerability, all the relevant variables related to this category can be subdivided into five groups: education, social status, household structures, social interaction and service dependency. Starting from education, several studies highlighted how an individual's educational background may also influence the respective health outcomes (Urban et al., 2016; Török, 2017), because it is assumed that higher degree of education can bring to more appropriate reactions during experience of subjective heat stress (Aubrecht and Özceylan, 2013; Loughnan et al., 2010; Seebaß, 2017). Differentiation between the degree of education as well as the geographical area of the case studies have been investigated. Of the 16 case studies that include the variable education, more than a half refer to the threshold corresponding to high school diploma for people with more than 25 years old, and all took place in American urban areas. Finally, the remaining variables refer to a more general categorization of the urban population, such as the number of enrolled population in public school (Méndez-Lázaro et al., 2018), the total years of study from zero to elementary school (Inostroza et al., 2016), the illiteracy or the semi-illiteracy rates of population (Chen et al., 2018), respectively related to USA, Chile and Yangtze River Delta urban areas.

When dealing with *social status* variables, the focus of the studies is on ethnic minorities. In fact, while there is no evidence on racial differences to heat-stress mortality (Harlan et al., 2006), some studies found a positive association between ethnicity and intra-urban variability of temperatures due to social, cultural and economic inequalities (Klein Rosenthal et al., 2014; Johnson and Wilson, 2009; Hondula et al., 2012), while some others found no significant mortality difference using races as an indicator (Kalkstein and Davis, 2010; Green et al., 2010). That is why ethnic minority was considered in the research, which – in the sampled studies – is often differentiated in African-, Hispanic-, Asian-, and Native-American communities and individuals (Uejio et al., 2011; Sharma et al., 2018; Harlan et al., 2006). Less frequent but still important under this category was the association between mortality and social indicators like female-headed household (Harlan et al., 2013) (as a *proxy* for household income) and rate of property tax delinquencies (Klein Rosenthal et al., 2014). In fact, while female-headed households imply low access to resources, education and income (VMK, 2011) as well as a limited access to protective social network (Flatø et al., 2017), the rate of property tax delinquencies corresponds to housing violations, and deteriorating and dilapidated buildings, suggesting that the quality of seniors' housing is a

Table 2
Sensitivity and adaptive capacity determinants by categories, groups and referent variables.

Categories	Groups	Variables	Reference
Mental and Physical Heath	Health status	Asthma (> 18 years old)	(Oppenheimer et al., n.d.; Hondula et al., 2012)
		Cardiovascular disease: - Chronic obstructive disease (> 18 years old) - Coronary heart disease (> 18 years old) - High blood pressure (> 18 years old) - High cholesterol (> 18 years old)	(Hondula et al., 2012; Gasparrini, 2011; Loughnan et al., 2010)
		Diabetes (> 65 years old)	(Oppenheimer et al., n.d.; Chen et al., 2018; Field et al., 2012)
		Pre-existing illness	(Blazejczyk et al., 2012; Loughnan et al., 2010; Tomlinson et al., 2011)
		Hypertension diagnosis (> 65 years old)	(Klein Rosenthal et al., 2014)
		Kidney disease (> 18 years old)	(Sharma et al., 2018)
		Long absence from work (*proxy* for health status)	(Bélanger et al., 2015)
		Mental health and illness (> 18 years old): - Psychiatric conditions	(Oppenheimer et al., n.d.; Blazejczyk et al., 2012; Hondula et al., 2012; Gasparrini, 2011)
		Obesity (> 18 years old)	(Oppenheimer et al., n.d.; Hondula et al., 2012)
		Physical health status (and self-reported)	(Oppenheimer et al., n.d.; Méndez-Lázaro et al., 2018)
		Renal disease	(Jiang et al., 2015)
		Respiratory disease: - Pulmonary disease (> 18 years old)	(Hondula et al., 2012; Gasparrini, 2011)
		Use of drugs (e.g. diuretic)	(Luederitz et al., 2016; Madrigano et al., 2015)
	Mobility and health status	Disability/ies (handicap, blindness, deafness, muteness, paralysis, mental illness and multiple physical disabilities)	(Jiang et al., 2015)
		Requirement of public assistance	(Hondula and Barnett, 2014)
	Mobility and health services	Accessibility to emergency services	(Loughnan et al., 2015)
		Bed confinement	(Jiang et al., 2015)
Demographic	Age	Age thresholds	(Madrigano et al., 2015; Sagris and Sepp, 2017; Méndez-Lázaro et al., 2018)
		Elderly	(Loughnan et al., 2010; Hatvani-Kovacs et al., 2016a)
		People under 5 years old	(Hajat and Gasparrini, 2016; Inostroza et al., 2016; Loughnan et al., 2015; Bhaskaran et al., 2013; Hondula et al., 2012; Armstrong et al., 2018; Gasparrini, 2011; Sharma et al., 2018)
		People over 60 years old	(Pullin and Stewart, 2006; Inostroza et al., 2016)
		People over 65 years old	(Araya-Muñoz et al., 2016; Urban et al., 2016; Armstrong et al., 2018; Gasparrini, 2011; Sharma et al., 2018) (Harlan et al., 2006; Savić et al., 2018; Jiang et al., 2015)
			(Hajat and Gasparrini, 2016; Jenerette et al., 2018; Chen et al., 2018; Field et al., 2012) (Loughnan et al., 2015; Henseke and Jürgen, 2014; WHO, 2016; Johnson and Wilson, 2009) (Blazejczyk et al., 2012; Bhaskaran et al., 2013; Van Der Hoeven and Wandl, 2015)
		People over 75 years old	(Johnson and Wilson, 2009; Tomlinson et al., 2011)
	Gender	Male and female	(Luederitz et al., 2016; Hajat and Gasparrini, 2016; Johnson and Wilson, 2009; Johnson et al., 2011; Braga et al., 2020; Sagris and Sepp, 2017; Méndez-Lázaro et al., 2018; Chen et al., 2018)

(*continued on next page*)

Table 2 (*continued*)

Categories	Groups	Variables	Reference
Social	Education	Education, in general	(Nayak et al., 2018; Hondula et al., 2012; Madrigano et al., 2015; Gasparrini, 2011; Savić et al., 2018; Méndez-Lázaro et al., 2018)
		Without education	(Chen et al., 2018)
		Primary education	(Inostroza et al., 2016)
		High school education	(Oppenheimer et al., n.d.; Urban et al., 2016; Hajat and Gasparrini, 2016; Loughnan et al., 2015; Johnson and Wilson, 2009; Van Der Hoeven and Wandl, 2015; Armstrong et al., 2018; Harlan et al., 2006; Chen et al., 2018)
	Social status	Ethnic minorities	(Oppenheimer et al., n.d.; Loughnan et al., 2015; WHO, 2016; Johnson and Wilson, 2009; Blazejczyk et al., 2012; Van Der Hoeven and Wandl, 2015; Hondula et al., 2012; Armstrong et al., 2018; Harlan et al., 2006; Chen et al., 2018)
		Female-headed household	(Harlan et al., 2013)
		Overcrowding renters (*proxy* for social isolation)	(Jiang et al., 2015)
		Rate of property tax delinquencies	(Klein Rosenthal et al., 2014)
	Household structures	Household size	(WHO, 2016; Méndez-Lázaro et al., 2018)
		Marital status (e.g. married, widower, etc.) (*proxy* for family structure)	(Pullin and Stewart, 2006; Hajat and Gasparrini, 2016; Johnson and Wilson, 2009)
		Single pensioner households	(Wolf and McGregor, 2013)
	Social interaction	Linguistic isolation	(Araya-Muñoz et al., 2016; WHO, 2016; Taylor et al., 2018; Hondula et al., 2012)
		Marital status: living alone (*proxy* for social isolation)	(Pullin and Stewart, 2006; WHO, 2016; Johnson and Wilson, 2009; Van Der Hoeven and Wandl, 2015; Loughnan et al., 2010; Harlan et al., 2006; Savić et al., 2018; Chen et al., 2018; Field et al., 2012)
		Living alone + older ages	(Oppenheimer et al., n.d.; Araya-Muñoz et al., 2016; Hajat and Gasparrini, 2016; Loughnan et al., 2015; Johnson and Wilson, 2009; Nayak et al., 2018; Van Der Hoeven and Wandl, 2015; Chen et al., 2018; Field et al., 2012) (Hondula et al., 2012; Harlan et al., 2006; Jiang et al., 2015)
		Occupation (*proxy* per social isolation)	(Jiang et al., 2015)
	Service dependency	Accessibility to health services	(Loughnan et al., 2015)
Economic	Access to communication	Household with mobile phone, internet connection, vehicle availability	(Pullin and Stewart, 2006; Gasparrini, 2011)
	Income	“Gold” retirement	(Tomlinson et al., 2011)
		Families receiving public assistance	(Urban et al., 2016; Taylor et al., 2018)
		Health insurance (y/n)	(Gasparrini, 2011; Savić et al., 2018)
		Home ownership	(Oppenheimer et al., n.d.; WHO, 2016; Hondula et al., 2012; Hatvani-Kovacs et al., 2016a)
		Income	(Oppenheimer et al., n.d.; Araya-Muñoz et al., 2016; Van Der Hoeven and Wandl, 2015) (Hondula et al., 2012; Madrigano et al., 2015; Braga et al., 2020; Armstrong et al., 2018) (Macintyre et al., 2018; Harlan et al., 2006; Jenerette et al., 2018) (Tomlinson et al., 2011; Méndez-Lázaro et al., 2018) (Urban et al., 2016; Luederitz et al., 2016; Hajat and Gasparrini, 2016; Loughnan et al., 2015; WHO, 2016; Johnson and Wilson, 2009; Nayak et al., 2018; Blazejczyk et al., 2012; Chen et al., 2018; Field et al., 2012)
		Pro-capite GDP	(Chen et al., 2018)
	Professional condition	Employment (y/n)	(Araya-Muñoz et al., 2016; Pullin and Stewart, 2006; Hajat and Gasparrini, 2016; Van Der Hoeven and Wandl, 2015; Madrigano et al., 2015; Braga et al., 2020; Savić et al., 2018; Méndez-Lázaro et al., 2018)
		Occupation qualification	(Wolf et al., 2015; Braga et al., 2020)

population-level risk factor for heat-associated mortality (Klein Rosenthal et al., 2014).

Subsequently, all the socio economic household variables (Inostroza et al., 2016; Loughnan et al., 2015; Hu et al., 2019) have been categorized as *household structure*. Often, this factor corresponded to a census variable called marital status, that is sub-divided in single, married, unmarried, divorced, separated or widower (Inostroza et al., 2016). And, while some studies used the marital status as a proxy for the family structure (Inostroza et al., 2016; Gronlund et al., 2015) or to evaluate the number of people living in the same dwelling (Loughnan et al., 2015), some others used this variable as a proxy for social isolation (e.g. single-person households) (Inostroza et al., 2016). The latter is also one of the principal variables classified in the following category: the *social interaction*. In fact, among the socio-economic drivers relevant for increased heat vulnerability, most case studies took into account the degree at which an individual is integrated into networks and social relationships (Breil et al., 2018; Harlan et al., 2006; Blättner et al., 2010), because "the more social interactions a person has, the lower their perception of heat stress is" (Seebaß, 2017). Since the access to this type of information is very limited, the analyses rely frequently on proxies such as household structure data, as mentioned before. In particular, "living alone" is often used as a proxy for social isolation (Uejio et al., 2011; Gronlund et al., 2015; Wolf and McGregor, 2013; Savić et al., 2018; Tomlinson et al., 2011; Harlan et al., 2013; Méndez-Lázaro et al., 2018; Reid et al., 2009; Bradford et al., 2015), and – when available - it usually associated with the age of the individual (see Table 2 for referent studies). Then, the remaining studies included information targeting citizens in regard to the linguistic isolation of the households where they live (Loughnan et al., 2015; Uejio et al., 2011; Nayak et al., 2018; Madrigano et al., 2015; Sharma et al., 2018; Bradford et al., 2015), their availability of phone services (Klein Rosenthal et al., 2014; Inostroza et al., 2016) as well as their availability of vehicles (Jiang and O'Neill, 2017) as further proxies for social isolation and for access to services that can strengthen social interactions. Neighbourhood stability have been also included in the *social interaction* group (e.g. vacant households, quality of life of the neighbourhood, etc.), because there were evidence that social interaction with neighbours can strengthen the ability to master periods of high temperatures (Jiang and O'Neill, 2017; Uejio et al., 2011; Van Der Hoeven and Wandl, 2015).

The last group of the social determinants is here defined as *service dependency*. Under this category, included studies that use the indicators for the existence and accessibility of health services have been included, given the importance of these services for supporting vulnerable populations during the occurrence of extreme heat events (Garbutt et al., 2015). Therefore, studies using variables such as services on wheels (Tomlinson et al., 2011) and number of aged care facilities (Loughnan et al., 2015) have been inserted within this class.

3.3.4. Economic status

In conclusion, economic drivers of sensitivity considered in heat-health related studies are usually built on indicators that refer to economic status and disadvantages (Breil et al., 2018; Smoyer et al., 2000; Sagris and Sepp, 2017; Seebaß, 2017). At first, the majority of the studies were found to agree on relates to the professional condition, in particular related to the position on the labour market, so being employed or not and the type of qualification (Wolf et al., 2015; Pullin and Stewart, 2006; Barnett et al., 2010), followed by home ownership (Klein Rosenthal et al., 2014; Uejio et al., 2011; Sharma et al., 2018; Tomlinson et al., 2011), all proxies to represent the income. On the other hand, some more studies considered isolated factors, such as the percent of families receiving public assistance (Madrigano et al., 2015), the availability of health insurance coverage (Jiang et al., 2015) or the access to a "golden" retirement (Tomlinson et al., 2011). Finally, in cases in which limited high-resolution data has been used, e.g. some aggregated indices such as GDP per capita (Chen et al., 2018) and average income per district (Jenerette et al., 2018; Dong et al., 2014; Seebaß, 2017) have been found as further indicators.

3.4. The neighbourhood environmental contribution on heat stress (enhanced exposure)

Urban residents are particularly exposed to heat and heatwaves due to UHI effects, which is owed to the fact that built up areas have a higher capacity for storing energy from sunlight and release it in form of higher temperatures than vegetated areas. Intensity of the UHI and resulting air temperatures can vary not only between urban and rural areas, but also within urban areas, creating different heat conditions at relatively small scales (Grimmond et al., 2010). Such differences create further disadvantages for parts of the urban population, which are directly related to features of urban morphology, in terms of density of urban fabric and activity, quality and typologies of buildings and presence of intra-urban green areas. As the analysis by Klinenberg on the Chicago heatwave of 1995 shows, there are furthermore causal links between levels of mortality and socio economic conditions and quality of urban life in the neighbourhood leading to different mortality rates despite similar urban morphology features (Klinenberg, 1999). Such conditions include levels of crime, urban decay and concentration of socially disadvantaged groups, for instance ethnic minorities (e.g. African Americans in the case of Chicago, the city studied by Klinenberg, during the heatwave in 1995). According to this seminal analysis, socio-economic conditions within the neighbourhoods determined differences in rates of mortality between neighbourhoods with similar physical conditions (Klinenberg, 1999). Epidemiological studies following up on these findings, need to join data from different sources regarding the physical elements characterizing the urban environment as well as those regarding the elements "enhancing" exposure, consisting of precarious living conditions, decaying urban environments, poverty or low incomes. Such investigations encounter again some limits in the possibility of combining a sufficiently big amount of health data with the sufficient spatial detail of urban living conditions, aiming at identifying those urban areas with physical and socio-economic conditions, which favour high ambient and/or surface temperatures.

3.4.1. Outdoor environment

On the side of physical conditions, one of the most frequently used proxy that we found for urban environments favouring uncomfortable conditions during days with extreme high temperatures are high rates of impervious surfaces or, on the contrary, high rates of green or vegetated surfaces. These two proxies are used in most studies for describing neighbourhood environmental qualities (see Table 3 for further details) (Araya-Muñoz et al., 2016; Johnson and Wilson, 2009; European Environment Agency, 2018). In some of the case studies, also population densities are used as a proxy for urban density (Henseke and Jürgen, 2014; Smoyer et al., 2000; Hondula and Barnett, 2014), while only in few cases building densities have been used. For instance, Kim et al. (Kim et al., 2014) compare temperatures and mortality for historic and new settlement patterns for Seoul, finding that, compared to traditional forms of high-density inner-city morphologies, newly developed areas with high rise buildings demonstrated a reduction of heat-stress related mortality by about a half despite similar population density. Impacts of urban and building morphologies on urban outdoor temperatures and comfort is investigated by several studies, yet, without the possibility of direct comparison such an investigation requires more detailed observations for characterizing elements of urban morphology. For example, orientation and symmetry of buildings (Loughnan et al., 2015; Harlan et al., 2006), size and shading options of windows (Blättner et al., 2010) and building and roofing materials (Sharma et al., 2018; Hatvani-Kovacs et al., 2016a), which rarely are feasible for larger urban areas. Only few articles were found which go beyond these physical characteristics, attempting to capture also aspects of socio-economic disadvantages as determinants for negative health outcomes, like for instance Sharma et al. (Sharma et al., 2018). In fact, in their investigation, the authors combine the analysis of physical outdoor characteristics, as roof surface temperatures, with socio economic indicators, using intensity of the use of air conditioning as a proxy for economic status of residents and focus on building characteristics, quality of housing and indoor conditions as an indicator for exposure to heat. Despite focussing on outdoor conditions, most studies rely on statistics on mortality cases that are registered with the residential address, rather than with working places or other outdoor places where people eventually stayed before feeling bad. Referring to residential conditions might not have interfered with the heat stress if this was related to outdoor or working place conditions.

3.4.2. Indoor environment

On the other hand side, indoor qualities have been explored for their relevance for heat outcomes for a series of buildings characteristics focussing mainly on energy efficiency (Van Der Hoeven and Wandl, 2015), and using in many cases proxies such as building age for insulation efficiency (Hajat and Gasparrini, 2016; Hu et al., 2019; Tomlinson et al., 2011). Only rarely, indoor conditions are actually estimated or measured in order to obtain more precise information of exposure to heat (Taylor et al., 2015), while building characteristics are used more frequently as an indicator for the socio-economic status of residents and neighbourhoods such as building conservation or need for repair (Oppenheimer et al., n.d.; Luederitz et al., 2016; Braga et al., 2020; Armstrong et al., 2018; Gasparrini, 2011) or living in public or low-rent housing (Bélanger et al., 2015; Wolf and McGregor, 2013). Other indicators for

Table 3
Enhanced Exposure determinants by categories, groups and referent variables [(*) refers to variables used as a proxy].

Categories	Groups	Variables	Reference
Indoor Environment	Building standard	Aeration capacity in summer	(Bélanger et al., 2015)
		Air Conditioning	(Oppenheimer et al., n.d.; Luederitz et al., 2016; Hajat and Gasparrini, 2016; Smoyer et al., 2000; Kim et al., 2014; Aubrecht and Özceylan, 2013; Armstrong et al., 2018; Jiang et al., 2015; Yu et al., 2010)
		Blinds	(Loughnan et al., 2015)
		Cooling energy for workplaces	(Van Der Hoeven and Wandl, 2015)
		Double-glazed windows	(Hatvani-Kovacs et al., 2016a)
		Fans	(Loughnan et al., 2015)
		Lack central air conditioning	(Bradford et al., 2015)
		Lack of air conditioning of any kind	
		Not having working air conditioning	(Wolf and McGregor, 2013)
		Type of cooling system	(Harlan et al., 2006)
		Housing types	(Hatvani-Kovacs et al., 2016a)
		Indoor temperature (good/bad)	(Bélanger et al., 2015)
		Insulated roofs and walls	(Hajat and Gasparrini, 2016; Yu et al., 2010)
		Thermal insulation	(Luederitz et al., 2016; Hajat and Gasparrini, 2016)
		Need for maintenance/repairs on the dwelling*	(Bélanger et al., 2015)
		Solar panels on roof	(Loughnan et al., 2015)
	Building/Housing standard	Elevator in building*	(Bélanger et al., 2015)
		Thermo isolation of home	(Wolf and McGregor, 2013)
	Housing standard	Access to water supply	(Inostroza et al., 2016)
		Balcony Downsizers	(Tomlinson et al., 2011)
		Expansion of top floor flats	(Blättner et al., 2010)
		Housing materials (wall/floor types and material)	(Loughnan et al., 2015)
		Living on a high floor of multi storey buildings*	(Savić et al., 2018; McGeehin and Mirabelli, 2001)
		Living in communal establishment*	(Wolf and McGregor, 2013)
		Low-rent housing*	(Bélanger et al., 2015)
		Pergolas/outdoor living areas	(Loughnan et al., 2015)
		Presence or absence of swimming pool (private)	(Harlan et al., 2006)
		Roofing construction (e.g. form and material)	(Loughnan et al., 2015)
		Type of building (dwelling type,floor level)	(Savić et al., 2018)
		Walls and ceiling	(Loughnan et al., 2015)

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Table 3 (*continued*)

Categories	Groups	Variables	Reference
Outdoor Environment	Building standard	Building status*	(Blättner et al., 2010)
		Direction of the window front	
		Need for maintenance/repairs*	
		Reflectivity of roofing material	(Harlan et al., 2006)
		Size and shading options for windows	(Blättner et al., 2010)
	Urban morphology & Building standard	Green Roofs	(Sharma et al., 2018)
		Material Index: n° of houses per hectare with light materials in external walls	(Inostroza et al., 2016)
	Residential standard	Building age*	(Hajat and Gasparrini, 2016) (Henseke and Jürgen, 2014; WHO, 2016; Johnson and Wilson, 2009) (Johnson et al., 2011; Nahlik et al., 2017; Taylor et al., 2015; Harlan et al., 2006; Yu et al., 2010)
		Built up surfaces and open spaces	(Inostroza et al., 2016)
		Dwelling age	(Hatvani-Kovacs et al., 2016a)
		Housing materials (wall/floor types and material)	(Klein Rosenthal et al., 2014)
		Neighbourhood rating (good or excellent)*	
		Roofing construction (tiles, colorbond, flat vs pitched)	(Loughnan et al., 2015)
		Structure n° of floors	(Hondula and Barnett, 2014)
	Residential standard & Urban morphology	Population and residential density*	(Oppenheimer et al., n.d.; Urban et al., 2016; Inostroza et al., 2016; Henseke and Jürgen, 2014; Smoyer et al., 2000; Madrigano et al., 2015; Hatvani-Kovacs et al., 2016a)
		Building density (building volume per unit area)*	(Kim et al., 2014)
	Urban morphology	Amount of open space (%)	(Harlan et al., 2006)
		Building types (geometries)	(Taylor et al., 2015)
		Distance from river area	(Hsu et al., 2017)
		Enhanced vegetation index (EVI)	(Chen et al., 2018)
		Environment index: land surface temperature from infrared remote sensing data	(Dong et al., 2014)
		Heat stress resistant features (e.g. insulation, garden vegetation)	(Hatvani-Kovacs et al., 2016a)
		Land cover (impervious surface: stone, asphalt, concrete or sand)	(Araya-Muñoz et al., 2016; Johnson and Wilson, 2009; Nayak et al., 2018; Kim et al., 2014; Bhaskaran et al., 2013; Gasparrini, 2011)
		Land Use	(Nayak et al., 2018; Aubrecht and Özceylan, 2013; Bhaskaran et al., 2013; Braga et al., 2020; Hatvani-Kovacs et al., 2016a; Harlan et al., 2006)
		Lack of (nearby) green spaces (NDVI)	(Pullin and Stewart, 2006; Smoyer et al., 2000; Uejio et al., 2011; Sharma et al., 2018)
		Roads: km/km2 of roads per census tract	(Inostroza et al., 2016)
	Outdoor & Environmental qualities	Shadows by trees	(Blättner et al., 2010)
		Shady plants	(Oppenheimer et al., n.d.; Nayak et al., 2018; Johnson et al., 2011; Braga et al., 2020)
		Stone mulch in garden	(Loughnan et al., 2015)
		Type of landscaping	(Harlan et al., 2006)
		Urban vegetation (%)	(WHO, 2016; Kim et al., 2014)
		Vegetation density (SAVI)	(Harlan et al., 2006)
	Environmental qualities	Access to indoor public swimming pools	(Bélanger et al., 2015)
		Access to outdoor public swimming pools	
		Lack of benches on the main streets	
		Need for maintenance/repairs	(Blättner et al., 2010)
		Traffic density	(Madrigano et al., 2015)
	Services	Access to medical services (distance of the centroid of the built-up area in the census block to the nearest health care centre)	(Inostroza et al., 2016)
		Cooling Centers (and public buildings)	(Bradford et al., 2015)
		Distance from the city center (km)	(Harlan et al., 2006)
		Total beds of health institutions	(Chen et al., 2018)
	Sensible population	Locations of sensible receptors (e.g. hospitals, care homes, schools, prisons, etc.)	(Macintyre et al., 2018)

the impact of housing conditions on heat mortality refer to technical installations. This group of indicators refers to measures which, while mitigating heat conditions inside buildings, might not be available in all cases in low cost housing or not accessible for low income groups or for renters with limited possibilities in changing installations, such as air conditioning (Wolf and McGregor, 2013; Van Der Hoeven and Wandl, 2015; Hatvani-Kovacs et al., 2016a; Bradford et al., 2015), fans (Loughnan et al., 2015), shading facilities for windows (Blättner et al., 2010) or elevators (Bélanger et al., 2015). The lack of elevators might limit the possibility of leaving overheated dwellings and search for cooling outside for elderly or physically impaired persons.

Further to the fact that high outdoor temperatures directly influence indoor temperatures, some qualities of the outdoor spaces influence furthermore the conditions of livelihoods in urban areas, as the presence of shady green areas where to cool down (Bélanger et al., 2015), or the availability of services in the neighbourhood where to find medical assistance or cooling spaces (Harlan et al., 2006; Chen et al., 2018; Bradford et al., 2015). Many authors find overlaps between qualities of the physical environment and socio-economic characteristics to favour higher rates of heat related mortalities. For instance, Dong et al. (Dong et al., 2014), who surveyed surface temperatures for particular land use types and imperviousness rates and associated average temperatures per type of land, found heat health risk more effectively described by these environmental factors than only by the hazard (surface temperatures) and vulnerability related indices (population densities, age and income) (Dong et al., 2014). Potentially, high levels of enhanced exposure to overheating exist also in other urban areas, such as for the State of New York (Nayak et al., 2018). In this case, Nayak et al. (Nayak et al., 2018) found not only indicators for heat related sensitivity (as age and social isolation), but also spatial characteristics (such as the low availability of green areas and shading to be concentrated in some parts of the state), especially in the metropolitan areas. Klein Rosenthal et al. (Klein Rosenthal et al., 2014) confirm that indicators characterizing the socio-economic position of citizens (e.g. poverty rates and income levels) together with those describing housing quality like rates of serious housing violations, property tax delinquencies, and deteriorating and dilapidated buildings were significantly correlated with the mortality rate ratios of elderly above 65 in New York (Klein Rosenthal et al., 2014). Relationships between income levels and sensitivity to heat were found also by Harlan et al. (Harlan et al., 2006), with the amount of un-vegetated (impervious) area as factor able to predict, alongside with indicators describing socio economic characteristics, heat related vulnerabilities in the Maricopa County (Arizona), for the period between 2000 and 2008 (Harlan et al., 2006). They found evidence for lower mortality rates in less dense, greener and wealthier areas. A direct relationship between low income and spatial disadvantages was found to increase mortality only in the very specific case of homeless people, who were more frequently found dead in central urban areas. This brings to the conclusion that the relationship between place based characteristics (which account for “exposure” and mortality) together with indicators for vulnerability, such as health, wealth and age, should be used as complements and not substitutes for person-level risk variables (Harlan et al., 2013). There is evidence from the analysed studies that some of the conclusions and indicators used for the description of enhanced exposure to heat are very much dictated by the situation of US metropolitan areas. In these cases, some cautious translations is needed before being applied to other contexts, as have been found for instance for London (Taylor et al., 2015) or for the small city of Kassel (Blättner et al., 2010). For instance, both studies found that elderly do not live predominantly in densely built city centres, but may suffer from overheating in poorly isolated houses in the peripheries, places where crime might not play the same dominant role for social isolation of elderlies, but lack of services and lack of awareness alongside with poor housing quality may nevertheless increase the impact from heat despite relatively high levels of vegetation..

4. Discussion

Climate scenarios reveal how over the next 30 years there will be a consistent global warming shifts in the climate of major cities around the world, with the most direct health risk due to heat (Oppenheimer et al., n.d.; Bastin et al., 2019). Therefore, urban administrations need a deep knowledge and awareness on the context specific aspects of socio-spatial vulnerability with respect to heat, so to be able to understand the structure and the distribution of the heat related vulnerability (Hintz et al., 2018; Breil et al., 2018; O'Neill et al., 2009; Lindley et al., 2018). Based on this international literature review, results confirm not only on the role of urban morphologies, green spaces and urban transformation processes (context specific physical characteristics), but also the relevance of interactions between socio-economic status and heat related impacts (context specific socio-economic characteristics) on the urban population have been recognized as essential drivers to understand the *heat-health nexus* at the intra-urban scale. While high outdoor temperatures in urban areas can be exacerbated by urban morphologies, with a predominance of sealed surfaces and some building characteristics all contributing to the so called UHI effect, socio-economic and health conditions can make it more difficult for vulnerable persons to seek for help and receiving appropriate assistance. Yet, both realities are represented by indicators characterizing the urban environment as well as by those synthesizing processes and social status. Such indicators can change in accordance to the geographic and socio-economic context in which they are used (Lindley et al., 2018) since they describe factors which in a certain places may have different meanings than in others. For example, in the Santiago de Chile case study proposed by Inostroza et al. (Inostroza et al., 2016), kilometers of roads per census tract was considered as a measure of adaptive capacity, because roads play a central role to determining social responses to heat hazards (e.g. providing access to the hospital), especially in a context with a low density of infrastructures. In contrast, Dong et al. (Dong et al., 2014) found, for Beijing, a positive correlation between the amount of road surfaces as part of the overall impervious surfaces and mean hazard, leading to a significant increase in the UHI effects (Dong et al., 2014).

Several studies in USA and Australia have identified drivers of vulnerability that have been translated into indicators that are hardly reflected in European urban policies. For instance, a study on the 1995 heatwave in Chicago, highlighted how the original provenance of ethnic minorities groups could be used as a proxy for low social status and qualities of social networks (Klinenberg, 1999). In fact, Klinenberg stresses differences between Hispanic and Afro-American communities in coping with heat impacts, underlining that the former have much stronger social networks in their neighbourhood which has a positive impact on the health outcomes during the heatwave, although the quality of the urban environment for both communities was comparable (Klinenberg, 1999). In the European context, some studies might attempt to transfer such indicators based on the findings made for Chicago in a period of urban decay, but this requires further to an accurate knowledge about socio-economic inequalities in urban cities and their consequences, the availability of data which would be able to describe such disadvantages. In some cases, ethnic minority was used as a proxy for linguistic isolation (Wolf and McGregor, 2013), while in some others a positive association between ethnicity and intra-urban variability of temperatures was related to economic inequalities (Klein Rosenthal et al., 2014; Johnson and Wilson, 2009; Hondula et al., 2012). Another example is the rate of property tax delinquencies (Harlan et al., 2013; Flatø et al., 2017), a statistical indicator for economic decline of households, again specific to the US (Török, 2017), and indicates the economic decline of the a neighborhood (Klein Rosenthal et al., 2014) rather than rising levels of delinquency tout court. In contrast, within the European context, there was no evidence of the use of this indicator.

When dealing with future scenarios, there are some important critical aspects to be highlighted. While the modelling of future scenarios for the heat risk at the national, regional or local scale has become a relatively common exercise which is based on physical drivers (Solomon et al., 2007), modelling future socio-economic developments in such a detail is far more difficult (Breil et al., 2018). Scenarios on future heat conditions are based on numerical models, while the socio-economic systems, such as cities, are more complex (O'Neill et al., 2014) and evolve following different political and social dynamics and trajectories of development. Therefore, discovering the interactions among variables within those systems is extremely difficult due to their complex nature, where the related elements and dynamics are characterized by non-physical returns and feedback mechanisms (Vasileiadou and Safarzyńska, 2010). While climate scenarios indicate that climate change will increase risks for the urban population (Leary et al., 2013) in the world, which are expected to increase the number of potentially vulnerable persons due to age related sensitivities. Nevertheless, social dynamics as climate induced increase of migration as well as the growing proportion of single households are trends which will contribute to further shaping vulnerabilities of urban population in addition to climate stressors (European Environment Agency, 2018).

The above arguments are crucial for a wider discussion on the changing systems of climate governance, and the role that cities and metropolitan areas play in this regard. In this perspective, in addressing the challenges brought about climate change, represented by the *heat-health nexus*, cities are today laboratories in which new systems of multi-level governance are being experimented, with the aim of exploring new ideas and initiatives in a context of increasing uncertainty. Greater coordination of policy responses, more efforts for integrating urban and regional plans, and new public-private cooperation efforts aimed at implementing 'economic convergence' scenarios are basic elements in this respect (Bulkeley and Betsill, 2004; Hughes and Chu, 2018; Giddens, 2015). However, it is clear that a deeper understanding of the role that social and economic characteristics plays in affecting the vulnerability of urban population is imperative for increasing the local awareness and preparedness to natural hazards as well as for designing and implementing effective adaptation policies. For defining the *heat-health nexus* at urban scale the availability of data representing factors which determine socio-economic disadvantages and physical exposure to heat are crucial, and needed not only for Europe and North America, where most of the studies included in this review are concentrated, but also for African and Asian cities.

5. Conclusion

Due to climate change, extreme temperature events in cities and urban centers are expected to become a global concern in the near future. This is a global concern with local implications and differences. The impacts of extreme heat events on cities differ very much according to geographical, institutional, social and economic features. The *heat-health nexus* is 'embedded' in the context-specific combination of physical and socio-economic characteristics. Vulnerability is not the simple outcome of temperature, but it is produced in and by society. This review study has demonstrated that despite several efforts have been done in order to understand the dynamics beyond the heat exposure and the health outcome relationship, more research is still required to connect these aspects together with the built environment characteristics. Such evidence could be used for informing the creation of "ready to use indicator sets" or tools which can support local adaptation policies with indication for risk analysis, design of strategies (Wolf et al., 2015) and monitoring of implementation in a meaningful way, if necessary local specificities are respected and suitable data for indicators is available. A detailed identification of elements influencing sensitivity as well as the consideration of conditions of enhanced exposure is indeed essential to facilitate the comprehension of the context-specific form of the *heat-health nexus*, which is crucial in the implementation of effective adaptation measures. The identification of these locally relevant variables within each specific urban system are the first step to determine drivers of inequalities with regards to exposure and sensitivity of urban populations both across and within urban areas. Such a diagnosis would represent a fundamental step towards the design of policies for adaptation which are best tailored for addressing effectively specific challenges presented of the *heat-health nexus* in the local context and can help identify the appropriate combination of forms of intervention and levels of governance which should compose such local adaptation policies regarding the challenge represented by rising temperatures and increasing frequencies of heatwaves. Adaptation policies aimed at copying with extreme high temperature events, particularly at urban level must therefore be grounded on a sound understanding of how the various elements of the socio-economic system interact with the physical environment in territorializing and socializing climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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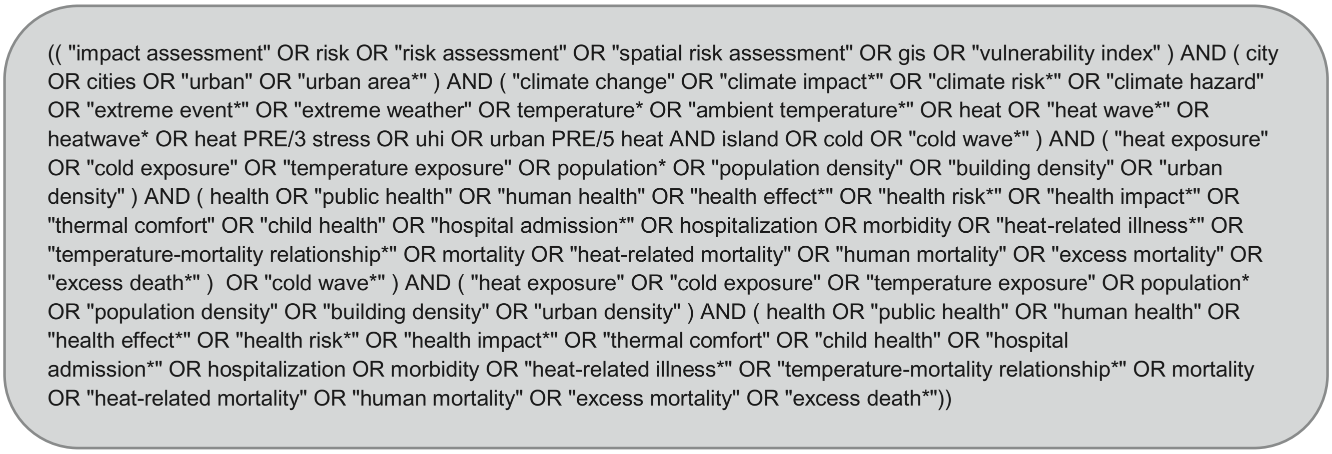
Appendix A. Appendix

A.1. The research algorithm

The final search string that authors decide to apply on *Scopus* and *Pubmed* search platform to identify the desired articles was developed through a start screening process highlighting the most frequent keywords in almost 700 articles selected from the following initial algorithm on *Scopus:*

```
TITLE-ABS-KEY ("extreme temperature*" AND "climate change" AND ( mortality OR morbidity ) AND ( urban OR city OR cities ) )
```

.



```
(( "impact assessment" OR risk OR "risk assessment" OR "spatial risk assessment" OR gis OR "vulnerability index" ) AND ( city OR cities OR "urban" OR "urban area*" ) AND ( "climate change" OR "climate impact*" OR "climate risk*" OR "climate hazard" OR "extreme event*" OR "extreme weather" OR temperature* OR "ambient temperature*" OR heat OR "heat wave*" OR heatwave* OR heat PRE/3 stress OR uhi OR urban PRE/5 heat AND island OR cold OR "cold wave*" ) AND ( "heat exposure" OR "cold exposure" OR "temperature exposure" OR population* OR "population density" OR "building density" OR "urban density" ) AND ( health OR "public health" OR "human health" OR "health effect*" OR "health risk*" OR "health impact*" OR "thermal comfort" OR "child health" OR "hospital admission*" OR hospitalization OR morbidity OR "heat-related illness*" OR "temperature-mortality relationship*" OR mortality OR "heat-related mortality" OR "human mortality" OR "excess mortality" OR "excess death*" )  OR "cold wave*" ) AND ( "heat exposure" OR "cold exposure" OR "temperature exposure" OR population* OR "population density" OR "building density" OR "urban density" ) AND ( health OR "public health" OR "human health" OR "health effect*" OR "health risk*" OR "health impact*" OR "thermal comfort" OR "child health" OR "hospital admission*" OR hospitalization OR morbidity OR "heat-related illness*" OR "temperature-mortality relationship*" OR mortality OR "heat-related mortality" OR "human mortality" OR "excess mortality" OR "excess death*"))
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The pre-screening process was useful to identify the main keywords to include in the final research algorithm, related to the factor of interest: risk assessment terms, urban spatial scale, hazard parameters, exposure groups, enhanced exposure, sensitivity and adaptive capacity characteristics, and, finally, health impact terms.

The latter one, applied on *Scopus* and on *PubMed* platform, allowed the desired articles to be identified, as specified in the section *2.1 Literature review process*.

Appendix B. Appendix

B.1. In-depth descriptive tables

Table B.1
The geo-spatial details of the case studies by scale of resolution, country and urban areas.

Exposed sample	Resolution	Country	Urban area/s	Reference
Urban area	Census Block groups	United States of America	Philadelphia	(Johnson and Wilson, 2009)
	Census Block groups	United States of America	Phoenix	(Harlan et al., 2006)
	Census Block groups	United States of America	Pittsburgh	(Bradford et al., 2015)
	Census tracts	Chile	Santiago	(Inostroza et al., 2016)
	Census tracts	United States of America	Chicago	(Sharma et al., 2018)
	Census tracts	United States of America	New York	(Nayak et al., 2018)
	Census tracts	United States of America	New York City	(Madrigano et al., 2015)
	Census tracts	United States of America	San Juan	(Méndez-Lázaro et al., 2018)
	Census tracts	United States of America	(not specified)	(Reid et al., 2009)
	Community Districts (CDs) United Hospital Fund (UHF)	United States of America	New York City	(Klein Rosenthal et al., 2014)
	Household levels	Australia	(not specified)	(Loughnan et al., 2015)
	Household levels	Austria	Linz	(Henseke and Jürgen, 2014)
	Household level	Germany	Nuremberg	(Seebaß, 2017)
	Local Climate Zones	Serbia	Novi Sad	(Savić et al., 2018)
	Municipal personal records	Netherlands	Amsterdam	(Van Der Hoeven and Wandl, 2015)
	Statistical Local Areas	Australia	Brisbane	(Hondula and Barnett, 2014)
	Statistical Local Areas	Australia	Brisbane	(Yu et al., 2010)
	Statistical Local Areas	Australia	Melbourne	(Loughnan et al., 2010)
	Statistical Units	Estonia	Tallin	(Sagris and Sepp, 2017)
	Statistical Units	Germany	Kassel	(Blättner et al., 2010)
	Super Output Lower levels	United Kingdom	Birmingham	(Tomlinson et al., 2011)
	Super Output Lower levels	United Kingdom	London	(Wolf and McGregor, 2013)
	Ward units	United Kingdom	London	(Taylor et al., 2015)
	Zip Code Tabulation areas	United States of America	Los Angeles	(Jiang et al., 2015)
	–	Australia	Adelaide	(Hatvani-Kovacs et al., 2016b)
	–	China	Taipei	(Hsu et al., 2017)
	–	Korea	Seoul	(Kim et al., 2014)
Metropolitan area	Census Block groups	United States of America	Arizona	(Harlan et al., 2013)
	Census Block groups	United States of America	Washington	(Aubrecht and Özceylan, 2013)
	Census tracts	United States of America	Los Angeles & Phoenix	(Nahlik et al., 2017)
	Census tracts	United States of America	Phoenix	(Jenerette et al., 2018)
	Census Transportation Products	United States of America	Chicago	(Hu et al., 2019)
Multiple urban areas	Census Block groups	China	Beijing	(Dong et al., 2014)
	Census Block groups	United States of America	Philadelphia & Phoenix	(Uejio et al., 2011)
	Census subdivision	Canada	Toronto, Windsor, London, Kitchener, Waterloo, Cambridge, Hamilton	(Smoyer et al., 2000)
	Household level	Canada	Québec	(Bélanger et al., 2015)
	Zip Code Tabulation areas	United States of America	Michigan	(Gronlund et al., 2015)
	Zip Code Tabulation areas	United States of America	Philadelphia	(Hondula et al., 2012)
	–	United Kingdom	West Midlands	(Macintyre et al., 2018)
Sub-national area	–	China	Yangtze River Delta	(Chen et al., 2018)

Table B.2
Health data and methodologies to assess the health risk of population in urban areas.

Health Data	Causes of death: ICD (10)	Methodologies	Reference
Morbidity			
Heat stress emergency dataset by: - georeferenced data	Heat-related causes: T67, X30	Principal Component Analysis	(Nayak et al., 2018)
Hospital admissions dataset by: - georeferenced data	All-natural causes: A00-R99	Local regression smoother	(Hondula and Barnett, 2014)
Hospital admissions dataset by: - social-demographic data: age - georeferenced data	Myocardial infarction: I21	General linear model multiple analysis of Variance	(Loughnan et al., 2010)
Mortality dataset by:			
● causes of death	Heat-related causes: T67, X30	Spatial Generalized Linear and Mixed Models	(Uejio et al., 2011)
(heat related diseases)	Endocrine, nutritional and metabolic: E00-E99 Mental and behavioural: F00–99 Nervous system: G00–99 Circulatory system: I00–99 Respiratory system: J00–99 Not elsewhere classified: R00–99	Klima-Michel Model	(Kim et al., 2014)
● georeferenced data	Heat-related causes: T67, X30	Spatial analysis using the standard deviation ellipse	(Johnson and Wilson, 2009)
	All causes: A00-Y89	Excess mortality method	(Dong et al., 2014)
	All causes: A00-Y89	–	(Savić et al., 2018)
● georeferenced data ● socio-economic data: ● age, gender, race, place of death	Non-external mortality: A00-R99 (Cardiovascular disease: I00–I99) (Myocardial infarction: I21) (Congestive heart failure: I50) (Respiratory diseases: J40–J47)	Multinomial logistic regression	(Madrigano et al., 2015)
● georeferenced data ● social-demographic data: ● age, gender, education, ● marital status and race	All-natural causes: A00-R99, T67, X30 Heat-related causes: T67, X30 Cardiovascular causes: I0-I52 Respiratory causes: J9:J18, J40:J44, J47	Time-stratified case-crossover design	(Gronlund et al., 2015)
● georeferenced data	All causes: A00-Y89	Principal Component Analysis	(Hondula et al., 2012)
● socio-economic data: age	–	Binary logistic regression	(Harlan et al., 2013)
● georeferenced data ● social-economic data: ● income and race	These records included date of death, ZIP code of residence, marital status, race, age, sex and educational level.	Outdoor Human Thermal Comfort Index	(Harlan et al., 2006)
● social-economic data: age	Heat-related causes: T67, X30	Excess mortality method	(Smoyer et al., 2000)
	All-natural causes: A00-R99, T67, X30	Multivariate linear regression	(Klein Rosenthal et al., 2014)
● social-economic data: ● age, gender	All causes: A00-Y89	Time series regression with linear post-threshold	(Taylor et al., 2015)
● social-economic data: ● age, gender, socio-economic index for area (SES)	All-natural causes: A00-R99	Generalize Additive Model	(Yu et al., 2010)
Survey			
Self-reported perceived health effect			(Bélanger et al., 2015)
Self-reported household thermal comfort			(Loughnan et al., 2015)
Self-reported perceived heat stress			(Henseke and Jürgen, 2014)

Table B.3
Climate indicators description.

Type	Name	Description
Simple indicators	Indoor temperature	Temperature of the air in a given indoor place
	Maximum temperature	Highest temperature recorded in 24 h
	Mean temperature	Mean temperature recorded in 24 h
	Minimum temperature	Minimum temperature recorded during in 24 h
	Night air temperature	Minimal night temperature recorded during night-time
	Relative humidity	Amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature
Complex indicators	Apparent maximum temperature	Measure that incorporate temperature and dew point temperature (humidity)
	Excess heat factor	Calculated from the deviation of the daily mean temperatures of the recent 3 days from the recent 30 days and the 95th percentile of the recent 30 days
	Heat stress index	Measure that incorporate ambient temperature and relative humidity
	Heatwave	Consecutive period of at least x days during which the daily maximum temperature is higher than or equal to a certain given threshold

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REASEARCH ARTICLE 2

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Social inequalities in heat-attributable mortality in the city of Turin, northwest of Italy: a time series analysis from 1982 to 2018.

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RESEARCH Open Access

Social inequalities in heat-attributable mortality in the city of Turin, northwest of Italy: a time series analysis from 1982 to 2018

Marta Ellena[1,2*], Joan Ballester[3], Paola Mercogliano[2], Elisa Ferracin[4], Giuliana Barbato[2], Giuseppe Costa[4] and Vijendra Ingole[3]

Abstract

Background: Understanding context specific heat-health risks in urban areas is important, especially given anticipated severe increases in summer temperatures due to climate change effects. We investigate social inequalities in the association between daily temperatures and mortality in summer in the city of Turin for the period 1982–2018 among different social and demographic groups such as sex, age, educational level, marital status and household occupants.

Methods: Mortality data are represented by individual all-cause mortality counts for the summer months between 1982 and 2018. Socioeconomic level and daily mean temperature were assigned to each deceased. A time series Poisson regression with distributed lag non-linear models was fitted to capture the complex nonlinear dependency between daily mortality and temperature in summer. The mortality risk due to heat is represented by the Relative Risk (RR) at the 99th percentile of daily summer temperatures for each population subgroup.

Results: All-cause mortality risk is higher among women (1.88; 95% CI = 1.77, 2.00) and the elderly (2.13; 95% CI = 1.94, 2.33). With regard to education, the highest significant effects for men is observed among higher education levels (1.66; 95% CI = 1.38, 1.99), while risks for women is higher for the lower educational level (1.93; 95% CI = 1.79, 2.08). Results on marital status highlighted a stronger association for widower in men (1.66; 95% CI = 1.38, 2.00) and for separated and divorced in women (2.11; 95% CI = 1.51, 2.94). The risk ratio of household occupants reveals a stronger association for men who lived alone (1.61; 95% CI = 1.39, 1.86), while for women results are almost equivalent between alone and not alone groups.

Conclusions: The associations between heat and mortality is unequal across different aspects of social vulnerability, and, inter alia, factors influencing the population vulnerability to temperatures can be related to demographic, social, and economic aspects. A number of issues are identified and recommendations for the prioritisation of further research are provided. A better knowledge of these effect modifiers is needed to identify the axes of social inequality across the most vulnerable population sub-groups.

Keywords: Climate change, Italy, Social inequalities, Summer temperature-attributable mortality, Urban Heat Island

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Background

Climate change and heat stress

In a scenario of no or limited adaptation to climate change, extreme temperatures are expected to be one of the main adverse events responsible for additional deaths [1]. Temperature rises already revealed profound heat stress impacts experienced by human populations, with prolonged and more frequent heatwaves and new emerging threats to public health [2, 3]. In 2018, over 220 million persons over the age of 65 were additionally exposed to heatwaves compared to a climatological baseline, and of those the majority lived in urban areas [4]. In fact, cities experience twice as many heat days than surrounding areas and by the end of the twenty-first century this number is projected to increase 10-fold [5]. The effects around the globe are not evenly distributed [6] and the impacts can differ by city and between suburban areas since the conditions within cities are not equal in all their parts [1, 7, 8]. Overall, severe increases in temperature are projected in Europe, with the highest levels of warming expected in Mediterranean regions during summer seasons [3, 9–11]. Of those, Italy is the country with the highest heat-related effects on daily mortality considering summer temperatures [12]. In particular, studies over urban areas located in the northern regions of Italy highlighted how these specific areas reached the greatest excess in mortality due to heat in the past [13–15] and they are characterised by a strong positive association between the number of daily emergency visits [16] and daily mean air temperatures.

Urban population susceptibility

Associations between heat and mortality are generally unequal across different aspects of society, and several studies have documented the importance of the context specific risks, which can vary by spatial, climatological and population characteristics [17–19]. Inter alia, factors influencing the population vulnerability to temperature are related to demographic, social, and economic aspects [20]. According to the World Health Organization (WHO), a better knowledge of these effect modifiers is needed to identify the axes of inequality across the most vulnerable population groups [2, 21]. Nowadays, in regard to gender inequality, some studies have identified higher mortality rates in women compared to men [4, 22–24] across different ages [25, 26], while some others observed men to be more at risk under heat stress conditions [27, 28]. Evidence about the relevance of age to the increase of heat related mortality have been observed in different cities [4, 21, 29]. Qualitative [30] as well as quantitative studies [31–34] on heat stress agree that the temperature-related mortality risk increases in the elderly. Moreover, according to an investigation by Leone et al. [29] that considered different age-group thresholds in different Mediterranean cities, none of the studies provide evidence of direct health effects among young persons [29].

The importance of socio-economic inequalities

Regarding the socio-economic factors, statistical associations have been found between mortality and socio-economic drivers in the case of vulnerability to heat, such as education [34–38], marital status [39, 40], employment status [41–43], as well as household structure factors [30, 44]. An adequate health adaptation response requires an assessment of the vulnerability of populations as a baseline analysis, but most of the environmental epidemiological studies rely exclusively on the available statistical data and do not have access to more precise information [4]. To the extent of our knowledge, while some studies have identified the effect modification of education in the heat-mortality relationship in a European urban context [21], just a few focussed on marital status and on the relationship between the household structure characteristics and the mortality risk, with no insight into how these socio-economic factors influence mortality under heat stress conditions. Therefore, in this study, the first objective was to develop a distributed lag non-linear model (DLNM) to estimate the non-linear and delayed effects of summer temperatures on mortality in the city of Turin for the period 1982–2018, looking at social inequality factors such as education, marital status and number of household occupants as well as to linkages between variables. Second, the research defines the attributable risk due to heat for the entire 37-year observational study, through the calculation of attributable fractions and attributable numbers differentiated by summer months, sex and socio-economic groups.

Methods and materials

Study area

Turin (45°6′ 58″ N and 7°44′ 33″ E) is located in the north-west part of Italy and it is the fourth largest Italian urban area with a population of 875698 inhabitants [45]. The city is located 800 ft above sea level and despite the climate predominantly being characterised by dry summers and mild wet winters (Mediterranean), the presence of the Alpine mountain range and the Superga hills favours a limited circulation of the foehn winds, conferring to Turin a complex mosaic of microclimates.

Data sources

With the aim of defining the relationship between summer temperatures and mortality, individual mortality records and individual-specific socioeconomic status for the period of 1982–2018 were collected. Following the Guidelines on Warning-System Development [2], a long time frame have been selected in order to track the changes of heat occurrences into the historical context over the study area. Only summer deaths (15th of May until the 15th of September) were considered in this analysis (according to the local heat wave bulletin). Data on individual all-cause mortality and socio-economic status were obtained from a dynamic population-based database, called Turin Longitudinal Study (TLS) [45]. As a measure of individual socio-economic position, the educational level, the marital status and the number of household occupants of the deceased were used [46]. Following the original structure of the dataset [45], the educational level was categorized into three groups ("no more than primary education", "secondary education", "high school or more") and the marital status were categorised into four groups ("un-married", "married", "widower", "separated and divorced"). The household occupant's variable into two main groups ("alone" and "not alone"). For practical reasons, the "separated and divorced" category of the marital status variable were merged into one singular group, and the age variable was divided into four groups ("0–64", "65–74", "75–84" and "85+"). Therefore, the social inequalities were analysed diversifying the analysis by sex and by sub-groups (see Table 1), looking at cross-linkages between variables.

Exposures to daily mean temperature in summer were assigned to each deceased case based on a temperature time series built through an arithmetic mean of mean temperature values related to each of the nine grid cells within the boundaries of the city. Climate data were obtained from the MESCAN-SURFEX system (5.5 km resolution), which consists of a surface re-analysis dataset using an optimal interpolation algorithm for 2 m ambient temperature, available for each day at 00 (H), 06, 12 and 18 UTC [47].

Table 1 Number of deaths, MMT (CI 95%) and 99th RR (CI 95%) per socio-economic variables

Categories	Sub-categories	N° of deaths	MMT (°C)	95% CI	RR at P99	95% CI
Mortality by	**Men**	53909	16.2	(12.1, 18.0)	1.56	(1.45, 1.67)
Age-group	0–64 years old	12151	14.7	(9.0, 20.4)	1.32	(1.13, 1.55)
	65–74 years old	13006	14.5	(9.0, 19.2)	1.44	(1.23, 1.69)
	75–84 years old	17677	18.0	(11.2, 20.0)	1.53	(1.37, 1.71)
	85+ years old	11075	15.5	(15.0, 18.2)	2.04	(1.76, 2.38)
Education	No more than primary school	28417	15.8	(9.0, 18.2)	1.64	(1.49, 1.80)
	Secondary school	14564	18.8	(9.0, 21.1)	1.36	(1.20, 1.54)
	High school or more	10624	13.9	(9.0, 18.4)	1.66	(1.38, 1.99)
Marital status	Married	38704	16.3	(11.1, 18.3)	1.54	(1.41, 1.67)
	Separated and divorced	2479	20.6	(9.0, 26.2)	1.39	(1.07, 1.81)
	Unmarried	6062	11.7	(9.0, 19.7)	1.63	(1.20, 2.23)
	Widower	6630	16.0	(9.0, 19.8)	1.66	(1.38, 2.00)
Household occupants	Alone	9489	17.9	(9.0, 21.4)	1.61	(1.39, 1.86)
	Not alone	44187	15.7	(9.8, 17.9)	1.53	(1.42, 1.66)
Mortality by	**Women**	56046	17.2	(15.6, 18.3)	1.88	(1.77, 2.00)
Age-group	0–64 years old	6799	14.4	(9.0, 32.1)	1.26	(1.00, 1.58)
	65–74 years old	8422	16.7	(9.0, 19.1)	1.69	(1.43, 1.99)
	75–84 years old	18277	17.1	(11.4, 19.0)	1.90	(1.71, 2.11)
	85+ years old	22548	17.9	(16.3, 19.0)	2.13	(1.94, 2.33)
Education	No more than primary school	36827	17.2	(15.4, 18.3)	1.93	(1.79, 2.08)
	Secondary school	12698	18.3	(13.8, 20.1)	1.83	(1.62, 2.07)
	High school or more	6252	16.1	(9.0, 19.7)	1.69	(1.39, 2.05)
Marital status	Married	17892	16.4	(9.0, 18.9)	1.71	(1.52, 1.92)
	Separated and divorced	2069	16.9	(9.0, 32.1)	2.11	(1.51, 2.94)
	Unmarried	7777	17.4	(9.0, 19.8)	1.87	(1.60, 2.20)
	Widower	28267	17.5	(15.7, 18.7)	1.97	(1.81, 2.14)
Household occupants	Alone	24055	17.9	(15.9, 19.1)	1.88	(1.72, 2.05)
	Not alone	31451	16.3	(12.6, 18.0)	1.89	(1.74, 2.06)

Statistical analysis

The statistical analysis was performed in 2 stages. In the first stage, a generalised linear model with standard quasi-Poisson regression was used to estimate the association between heat and mortality, reported as Relative Risks (RR). In the second stage, a DLNM model was applied to examine the complex non-linear and delayed dependencies between daily summer temperature and mortality values. The analyses were stratified by sex, age-group, education, marital-status and household occupants of the deceased.

Firstly, the short-term association of daily summer temperatures and all-cause mortality was investigated. A time series Poisson regression were fitted for modelling seasonality and long-time trends through a standard quasi-Poisson model to account for the over-dispersion of daily death records. With reference to prior research, seasonal trends were controlled by using a natural cubic B-spline of the day-of-the-season with 2 degree of freedom per year [23]. The latter parameter was permitted to vary from 1 year to another through the inclusion of an interaction between the applied natural cubic spline and the year. A natural cubic B-spline of time with 1 degree of freedom per decade was included to control for the long-term pattern [48]. Finally, the day-of-the-week factor was inserted in the time series quasi-Poisson regression as an indicator variable.

The key feature of the second-stage analysis is the investigation of the non-linear and delayed effect which specifies the temporal dependency between summer temperature and mortality on the scale of lag, here defined as exposure-lag-response association. To capture this complex non-linear dependency, a DLNM was included through the definition of a cross-basis, obtained by the combination of two functions describing respectively the exposure-response and the lag-response association [49–51]. The exposure–response curve was modelled consisting of a quadratic B-spline with 1 internal knot placed at the 90th percentile of the temperature distribution. For the lag-response curve, a natural cubic spline with 2 equally spaced knots on the log scale was applied. The effect of daily summer temperatures on mortality up to 7 days of lag to capture the overall temperature effect and adjusting for any potential harvesting [52] was assessed. The model choices were based on the quasi-Akaike Information Criterion (qAIC) and on modelling choices from previous works [23, 50, 53, 54]. The final algebraic representation of the model is:

$$Log(\mu_t) = \alpha + cb + dow_t + ns(dos_t\, df = 2) : factor(year_t) + ns(date_t, df = 1\, per\, decade_t) \tag{1}$$

where μ_t is the expected number of deaths at the day of observation *t*, *cb* is the cross-basis matrix produced by DLNM, *dow* is the categorical variable for the day of the week and *ns* specifies the natural cubic B-spline for day-of-the-season and for the year/summer respectively. At this stage of the analysis, the temperature at which risk of overall mortality is at minimum was identified, here called minimum mortality temperature (MMT). This value was calculated with its confidence intervals (95% CI) through the use of a parametric bootstrap method proposed by Tobías et al. [55]. MMT values for all mortality counts and by socio-economic categories were calculated to capture the social inequality differences in the temperature-mortality associations. The mortality risk due to heat was represented by the RR at the 99th percentile of daily summer temperatures. Then, the attributable fraction (AF) and the attributable number (AN) of deaths by summer months, considering the "total heat" (for all days exceeding the MMT), the "moderate heat" (between the MMT and the 97th percentile of daily summer temperatures) and the "extreme heat" period (exceeding the 97th percentile) were calculated. These estimates provided the relative excess measure and the absolute excess measure due to the exposure to different levels of summer temperatures [56]. For the attributable values, we only showed results for the June, July and August (JJA) months.

All statistical analyses were performed with *R software (version 3.6.0)* through the use of the *dlnm* package, developed by Gasparrini [51].

Results

In the 37-year observational study, the mean daily temperature range was between 10° and 32 °C, with the 50th, 95th and the 99th percentile respectively equal to 22°, 26.9° and 28.5 °C. The daily average mortality count was 24, with a minimum number of deaths per day equal to 8 and a maximum number of deaths per day equal to 83. Figure 1 depicts the effect of daily summer temperatures on all-cause mortality by sex. From the contour plot (Fig. 1(a)) it emerges that the risks decrease with increasing lead times, with higher RR under hot temperature conditions. On the other hand, the cumulative exposure-response association differentiated by sex (Fig. 1(b)) shows how the overall association between daily mean temperatures and mortality during summer months follow a U-shaped curve in both sexes, with representative MMT and RR values.

The dataset contained 109955 deaths, of which 53909 men (49%) and 56046 women (51%). In Table 1 a summary of the characteristics of the study population was presented. As mentioned in the previous section, a representative MMT and a corresponding 99th RR for each sub-group differentiated by sex was detected. 95%

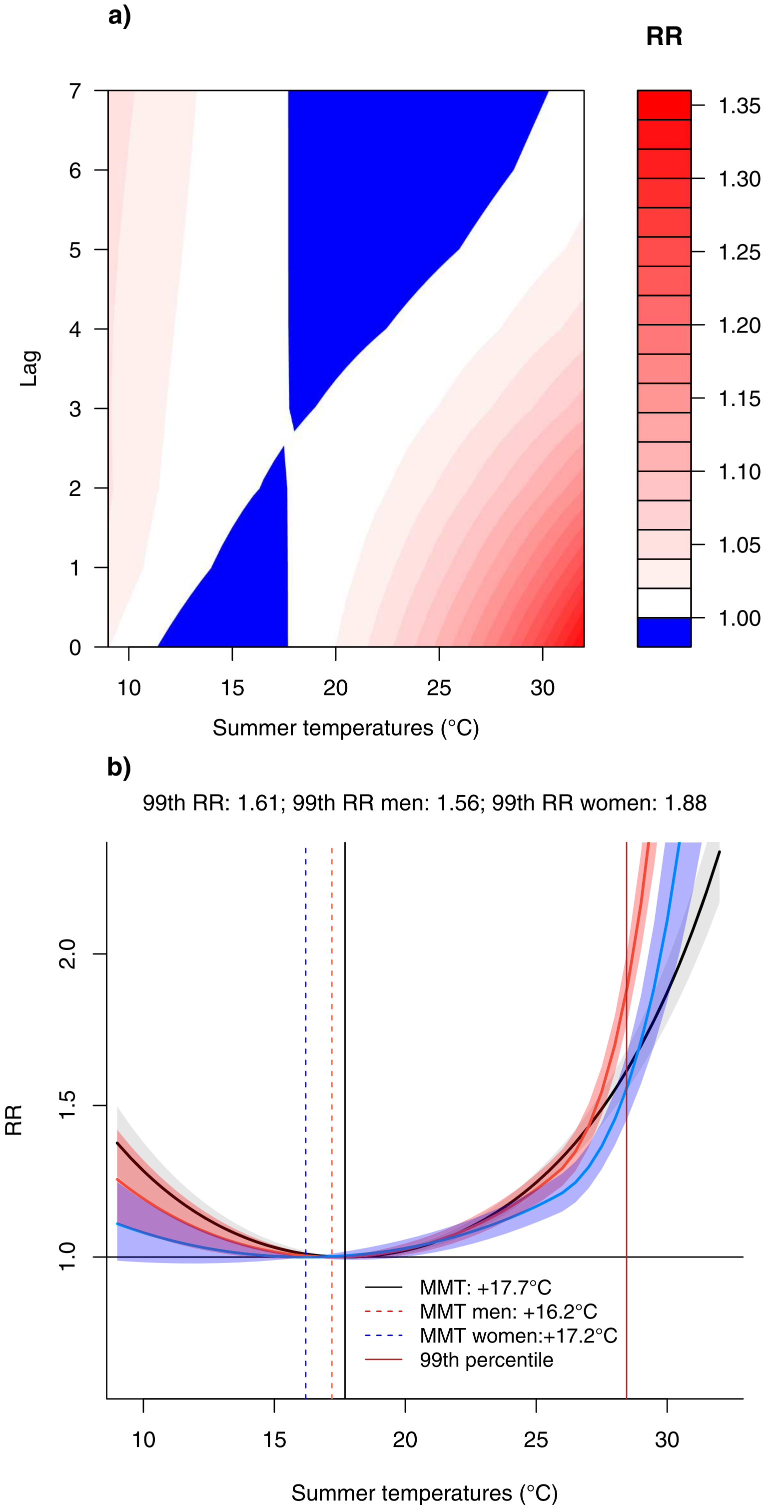

Fig. 1 The exposure-response relationship between summer temperatures and all-cause mortality. **a** Contour plot with reference at the 99th percentile Relative Risk (RR). **b** Overall cumulative temperature-mortality association between summer temperatures and mortality in the city of Turin by sex (RRs in solid lines and 95% CI in shaded colours)

confidence intervals (CI) are also provided. The temperature-mortality relationship through the visualization of the overall cumulative plots, which highlights a non-linear "U shaped association for all the available socio-economic categories, was summarised (see A1.1-A1.4 Figs in Additional file 1 for overall cumulative plots by sex and socioeconomic sub-group).

Age

Mortality records were divided into four categories based on the age of the deceased person at the time of death: "0–64", "65–74", "75–84", and "85+" years old. In the youngest groups ("0–64" and "65–74" years), the number of women was slightly lower (15221) than the number of men (25157), while at the oldest groups ("75–84" and "85+") the number was higher in women (40825) than in men (28752). In fact, women live longer and die older than men [57, 58], therefore gender and age are here interlinked. The RR at the 99th percentile grows with age in both sexes, with a RR in the age group "85+" equal to 2.04 (95% CI: 1.76–2.38) in men and 2.13 (95% CI:1.94–2.33) in women. In all the sub-groups the RRs were positive and significant, with higher RRs in women compared to men.

Education

When considering education, we classified the groups into "no more than primary school", "secondary school" and "high school or more". The "no more than primary school" was the sub-group with the highest number of observations (28417 for men, 36827 for women), while "high school or more" was the most restricted one (10624 for men, 6252 for women). Results in Table 1 display a significant effect of summer temperatures in all the sub-groups, with a significantly higher effect for women in respect to men. The most significant effects of heat for men was found in the "high school or more" and in the "no more than primary school" sub-groups, with a RR equal to 1.66 (95% CI: 1.38, 1.99) and to 1.64 (95% CI: 1.49, 1.80) respectively. On the other hand, in women a higher effect was found in the "no more than primary school", with a RR equal to 1.93 (95% CI: 1.79–2.08). Furthermore, while for women the most significant effect reflects the lowest level of education and decreases with increasing education, in men it became less straightforward. Therefore, cross-linkages between education, gender and age seem to play an important role in the latter sub-category.

Marital status

The marital status categorisation was divided into the following sub-groups: "un-married", "married", "separated and divorced" and "widower". The most substantial sub-category of observations for men corresponded to "married" (38704), while for women it was to "widower" (28267). In addition, the sex gap was also visible under this socio-economic driver, which implies an interconnection with the above variable and the age category. The RRs show a higher effect on women than men. In men, it was found that the most significant effects are in the "widower" and in the "unmarried" sub-groups, with a RR equal to 1.66 (95% CI: 1.38, 2.00) and to 1.63 (95% CI: 1.20, 2.23) respectively. On the other hand, in women a higher effect it was found in the "separated and divorced" sub-group as well as in the "widower" sub-groups, which corresponded to a RR of 2.11 (95% CI: 1.51, 2.94) and to 1.97 (95% CI: 1.81, 2.14). In general, all the RR estimates were significant.

Household occupants

Under this categorisation, all results were diversified by sex and significant. In particular, the most significant effect for men was the one that refers to people who lived "alone", that corresponded to a RR equal to 1.61 (95% CI: 1.39, 1.86). On the contrary, in women, the RRs between the two sub-categories were almost the same, with the most significant effect in the "not alone" group, which is equal to 1.89 (95% CI: 1.74, 2.06). Moreover, people living "not alone" were the most prevalent under this category, with 44187 records in men and 31451 records in women.

Results of AFs and ANs were analysed by sex, looking at the most significant estimates for "moderate heat", "extreme heat" and "total heat" conditions. Comparing the hottest 3 months of the time series (June, July and August), the highest AFs and ANs were obtained for "total heat" temperatures in July (AN tables provided in A2.1 Table, Additional file 2). Table 2 shows how AF estimates were higher for women compared to men. In fact, the total AF for men was 13% (95% CI: 10, 17) with AN equal to 1836 (95% CI: 1365, 2349), while the total AF for women was 17% (95% CI: 15–20) with AN equal to 2544 (95% CI: 2113, 2946). The highest AFs and ANs were obtained among the "85+" age-groups, with AF equal to 23%(95% CI: 15, 31) in men and to 21% (95% CI: 16, 24) in women. When considering education, the highest AFs were related to the "high school or more" sub-groups for men (18% (95% CI: 7, 30)), while for women was related to the "no more than primary school" (18% (95% CI: 15, 22)), in accordance with the RRs. On the contrary, when considering ANs, it was found that the highest values was in the category "no more than primary school", which corresponded to 1070 (95% CI: 681, 1429) in men and to 1821 (95% CI: 1478, 2157) in women.

In accordance with the 99th RR estimates, the highest AFs for the marital status category were the "widower" group (AF: 17% (95% CI: 8, 23)) for men, while for women it was the "divorced and separated" group (28% (11, 42)).

Table 2 Mortality attributable fraction due to moderate, extreme and all temperatures by sex, with 95% confidence intervals (CI)

Attributable fraction of deaths (AF) with CI 95%		JUNE			JULY			AUGUST		
		Moderate	Extreme	Total heat	Moderate	Extreme	Total heat	Moderate	Extreme	Total heat
Mortality by:	**Men**	7.0% (4.0, 9.0)	1.0% (0.0, 1.0)	8.0% (4.0, 10.0)	11.0% (8.0, 15.0)	2.0% (2.0, 2.0)	13.0% (10.0, 17.0)	9.0% (6.0, 12.0)	3.0% (2.0, 3.0)	12.0% (9.0, 15.0)
Age-groups	0–64 y	5.0% (−4.0, 13.0)	0% (0, 0)	5.0% (−4.0, 13.0)	9.0% (−3.0, 17.0)	1.0% (0, 2.0)	10.0% (−3.0, 19.0)	8.0% (− 1.0, 17.0)	1.0% (0, 2.0)	9.0% (−1.0, 19.0)
	65–74 y	7.0% (−2.0, 15.0)	0% (0, 1.0)	7.0% (−2.0, 16.0)	11.0% (− 2.0, 19.0)	2.0% (1.0, 2.0)	13.0% (−1.0, 21.0)	9.0% (−1.0, 17.0)	2.0% (1.0, 3.0)	11.0% (0, 20.0)
	75–84 y	5.0% (2.0, 8.0)	1.0% (1.0, 1.0)	6.0% (3.0, 9.0)	9.0% (4.0, 13.0)	2.0% (2.0, 2.0)	11.0% (6.0, 15.0)	7.0% (2.0, 11.0)	3.0% (2.0, 3.0)	10% (4.0, 14.0)
	85+ y	13.0% (6.0, 19.0)	1.0% (1.0, 1.0)	14.0% (7.0, 20.0)	20.0% (12.0, 27.0)	3.0% (3.0, 4.0)	23.0% (15.0, 31.0)	17.0% (9.0, 24.0)	5.0% (4.0, 5.0)	22.0% (13.0, 29.0)
Education	No more than primary school	8.0% (4.0, 11.0)	1.0% (0, 1.0)	9.0% (4.0, 12.0)	12.0% (7.0, 17.0)	2.0% (2.0, 3.0)	14.0% (9.0, 20.0)	10.0% (6.0, 15.0)	3.0% (2.0, 3.0)	13.0% (8.0, 18.0)
	Secondary school	4.0% (1.0, 6.0)	0% (0, 1.0)	4.0% (1.0, 7.0)	6.0% (1.0, 11.0)	1.0% (1.0, 2.0)	7.0% (2.0, 13.0)	4.0% (0, 8.0)	2.0% (1.0, 3.0)	6.0% (1.0, 11.0)
	High school or more	11.0% (−1.0, 21.0)	1.0% (1.0, 1.0)	12.0% (0, 22.0)	16.0% (5.0, 27.0)	2.0% (2.0, 3.0)	18.0% (7.0, 30.0)	14.0% (3.0, 24.0)	3.0% (2.0, 4.0)	17.0% (5.0, 28.0)
Marital status	Married	7.0% (5.0, 10.0)	0% (0, 0)	7.0% (5.0, 10.0)	13.0% (9.0, 16.0)	2.0% (1.0, 2.0)	15.0% (10.0, 18.0)	11.0% (7.0, 14.0)	2.0% (2.0, 2.0)	13.0% (9.0, 16.0)
	Separated and divorced	4.0% (0, 8.0)	1.0% (0, 1.0)	5.0% (0, 9.0)	7.0% (−1.0, 14.0)	1.0% (−1.0, 2.0)	8.0% (−2.0, 16.0)	5.0% (−3.0, 12.0)	1.0% (−3.0, 3.0)	6.0% (−6.0, 15.0)
	Unmarried	8.0% (1.0, 14.0)	0% (0, 1.0)	8.0% (1.0, 15.0)	13.0% (4.0, 21.0)	2.0% (1.0, 3.0)	15.0% (5.0, 24.0)	11.0% (2.0, 20.0)	2.0% (1.0, 3.0)	13.0% (3.0, 23.0)
	Widower	8.0% (4.0, 12.0)	1.0% (1.0, 1.0)	9.0% (5.0, 13.0)	14.0% (6.0, 20.0)	3.0% (2.0, 3.0)	17.0% (8.0, 23.0)	11.0% (5.0, 17.0)	3.0% (2.0, 4.0)	14.0% (7.0, 21.0)
Household occupants	Alone	4.0% (1.0, 8.0)	1.0% (0, 1.0)	5.0% (1.0, 9.0)	7.0% (1.0, 13.0)	2.0% (2.0, 3.0)	9.0% (3.0, 16.0)	6.0% (−1.0, 11.0)	3.0% (2.0, 4.0)	9.0% (1.0, 15.0)
	Not alone	8.0% (5.0, 11.0)	1.0% (0, 1.0)	9.0% (5.0, 12.0)	12.0% (8.0, 16.0)	2.0% (2.0, 2.0)	14.0% (10.0, 18.0)	10.0% (6.0, 14.0)	2.0% (2.0, 3.0)	12.0% (8.0, 17.0)
Mortality by:	**Women**	8.0% (7.0, 10.0)	1.0% (1.0, 1.0)	9.0% (8.0, 11.0)	14.0% (12.0, 17.0)	3.0% (3.0, 3.0)	17.0% (15.0, 20.0)	12.0% (9.0, 14.0)	4.0% (4.0, 5.0)	16.0% (13.0, 19.0)
Age-groups	0–64 y	8.0% (−4.0, 18.0)	0% (0, 0)	8.0% (−4.0, 18.0)	12.0% (−2.0, 23.0)	1.0% (0, 2.0)	13.0% (−2.0, 25.0)	10.0% (−4.0, 22.0)	1.0% (−1.0, 2.0)	11.0% (−5.0, 24.0)
	65–74 y	10.0% (4.0, 15.0)	1.0% (0, 1.0)	11.0% (4.0, 16.0)	15.0% (8.0, 22.0)	3.0% (2.0, 3.0)	18.0% (10.0, 25.0)	13.0% (6.0, 20.0)	3.0% (2.0, 4.0)	16.0% (8.0, 24.0)
	75–84 y	7.0% (4.0, 10.0)	1.0% (1.0, 1.0)	8.0% (5.0, 11.0)	12.0% (8.0, 17.0)	3.0% (3.0, 4.0)	15.0% (11.0, 20.0)	10.0% (5.0, 14.0)	4.0% (4.0, 5.0)	14.0% (9.0, 18.0)
	85+ y	10.0% (7.0, 12.0)	1.0% (1.0, 1.0)	11.0% (8.0, 13.0)	17.0% (13.0, 20.0)	4.0% (3.0, 4.0)	21.0% (16.0, 24.0)	13.0% (10.0, 17.0)	6.0% (5.0, 6.0)	19.0% (15.0, 23.0)
Education	No more than primary school	9.0% (7.0, 11.0)	1.0% (1.0, 1.0)	10.0% (8.0, 12.0)	15.0% (12.0, 18.0)	3.0% (3.0, 4.0)	18.0% (15.0, 22.0)	13.0% (10.0, 16.0)	4.0% (4.0, 4.0)	17.0% (14.0, 20.0)
	Secondary school	6.0% (3.0, 9.0)	1.0% (1.0, 1.0)	7.0% (4.0, 10.0)	10.0% (6.0, 15.0)	3.0% (2.0, 3.0)	13.0% (8.0, 18.0)	8.0% (3.0, 13.0)	5.0% (4.0, 5.0)	13.0% (7.0, 18.0)
	High school or more	9.0% (1.0, 17.0)	1.0% (0.0, 1.0)	10.0% (1.0, 18.0)	14.0% (3.0, 23.0)	2.0% (2.0, 3.0)	16.0% (5.0, 26.0)	11.0% (0, 20.0)	4.0% (3.0, 5.0)	15.0% (5.0, 25.0)

Table 2 Mortality attributable fraction due to moderate, extreme and all temperatures by sex, with 95% confidence intervals (CI) *(Continued)*

Attributable fraction of deaths (AF) with CI 95%		**JUNE**			**JULY**			**AUGUST**		
		Moderate	**Extreme**	**Total heat**	**Moderate**	**Extreme**	**Total heat**	**Moderate**	**Extreme**	**Total heat**
Marital status	Married	8.0% (6.0, 11.0)	0% (0, 1.0)	9.0% (6.0, 12.0)	14.0% (10.0, 18.0)	2.0% (2.0, 2.0)	16.0% (12.0, 20.0)	12.0% (8.0, 15.0)	3.0% (2.0, 3.0)	15.0% (10.0, 18.0)
	Separated and divorced	16.0% (3.0, 27.0)	1.0% (0, 1.0)	17.0% (3.0, 28.0)	25.0% (9.0, 38.0)	3.0% (2.0, 4.0)	28.0% (11.0, 42.0)	21.0% (6.0, 35.0)	5.0% (3.0, 7.0)	26.0% (9.0, 42.0)
	Unmarried	9.0% (5.0, 12.0)	1.0% (1.0, 1.0)	10.0% (6.0, 13.0)	16.0% (11.0, 22.0)	3.0% (2.0, 4.0)	19.0% (13.0, 26.0)	14.0% (9.0, 18.0)	4.0% (3.0, 4.0)	18.0% (12.0, 22.0)
	Widower	10.0% (8.0, 12.0)	1.0% (1.0, 1.0)	11.0% (9.0, 13.0)	18.0% (15.0, 21.0)	3.0% (3.0, 4.0)	21.0% (18.0, 25.0)	15.0% (12.0, 17.0)	4.0% (4.0, 4.0)	19.0% (16.0, 21.0)
Household occupants	Alone	8.0% (6.0, 10.0)	1.0% (1.0, 1.0)	9.0% (7.0, 11.0)	14.0% (11.0, 17.0)	3.0% (3.0, 3.0)	17.0% (14.0, 20.0)	11.0% (8.0, 14.0)	4.0% (4.0, 5.0)	15.0% (12.0, 19.0)
	Not alone	9.0% (6.0, 12.0)	1.0% (1.0, 1.0)	10.0% (7.0, 13.0)	15.0% (11.0, 19.0)	3.0% (3.0, 4.0)	18.0% (14.0, 22.0)	13.0% (8.0, 16.0)	4.0% (4.0, 4.0)	17.0% (12.0, 20.0)

In regard to AN, it was found to be the “widower” group that had the highest significant value (AN: 1581 (95% CI: 1332, 1801)), which is the largest class within this category for women. When dealing with the household occupants’ category, the highest statistically significant AFs obtained was obtained for the “not alone” groups in both sexes, which corresponded to 14% (95% CI: 10, 18) in men and to 18% (95% CI: 14, 22) in women. Finally, the statistically significant highest ANs for the prominent sub-groups (“not alone”) ((men: 1611 (95% CI: 1151, 2067), (women: 1492 (95% CI: 1119, 1831)).

Multiple sensitivity analyses were performed, changing key modelling decisions in order to check the consistency of the results and to investigate whether day-to-day changes in the number of deaths are explained by changes in summer ambient temperatures. Starting with the full-year analysis, focusing on the summer period only, since our objectives were on summer heat. For the standard quasi-Poisson model analyses, first the type of function of time to capture the long-time trend and seasonality of the mortality data was analysed, based on Bhaskaran [48]. Having defined the spline function to capture seasonal patterns in a way that is allowed to vary from 1 year to the next, the number of knots was modified in order to identify the best spline to use. Later, in the specification of the cross-basis functions to define the DLNM, a consistent amount of analyses was applied to understand (i) the exposure response function to use (ns or bs), (ii) the percentile of temperature to focus on and the related number of knots to use, and, finally, (iii) the lag number to use in order to take into account the short-term effect of heat as well as the harvesting effect. To better focus the final choice, the qAIC from different models was compared (see A3.1-A3.3 Figs in Additional file 3).

Consequently, it is believed that the parameters used in the final model of this study can adequately capture the main effect of summer temperatures on mortality.

Discussion

Results of our study contribute to the overall cumulative associations of summer temperatures and mortality comprehension for the city of Turin over the 37-year observational study, reporting results stratified by demographic and socio-economic drivers. In particular, to the best of knowledge of those involved in this study, this is the first investigation to assess comprehensively social inequalities in relation to the heat-health nexus, looking at sex, age, educational level, marital status and household occupants at the same time. This allow to provide a more specific overview on how different drivers can affect heat stress in a South-European urban context. The achieved results strongly support the hypothesis that the different sub-categories that refer to each social variable can negatively or positively affect the risk of heat mortality, contributing significantly to the variation of the mortality fraction attributable to heat. In general, results suggested that the effect of heat on mortality largely varied by each analysed category with higher RRs for women compared to men for each sub-category of interest. Moreover, cross-linkages between demographic and socio-economic drivers were also visible. According to the state-of-the-art literature, the mortality risk grows with age in both sexes, and the study found a statistically significant association for all the ages. With regards to education, significant effects of heat in all the groups was found and, contrary to prior expectations, while for women risk values were higher for lower educational level and decreased as education increased, in men the stronger effects corresponded to those with higher “formal” education as well as to those with lower educational levels. Mortality risk ratios by marital status were higher for those who lived alone (e.g. unmarried, separated and divorced and widower) than for married people, in both sexes. Results on household occupants consistently indicate a strong association among men who lived alone, while for women results were equivalent for the two analysed groups.

Sex

All-causes mortality was assessed by sex, and it was found that women were systematically more at risk than men under heat stress conditions. These results are in line with many studies, which identify higher mortality rates for women compared to men [4, 22, 57, 58], specifically in the European context [21, 23, 25, 26]. This discrepancy may arise from differences in response to thermal stress due to physiological characteristics in body temperature regulation [59, 60] as well as pre-existing socio-demographic characteristics in the inhabited society [11, 26], such as the lower social condition that characterises elderly women, which often live alone due to longer life expectancy compared to men.

Age

Age is one of the main personal factors that determines heat vulnerability [22], and is the reason for having investigated this factor by sub-groups and sex. In all the age-groups a positive significant association between summer temperatures and mortality was found. The RRs at the 99th percentile increased with age and RRs were consistently higher in women than men. In fact, women live longer and die older, while men die younger [58, 61]. Therefore, the relationship between the age and the sex variable here is consistent. These results extended previous hypothesis based on the evidence that heat stress increases the susceptibility of the elderly to hot temperatures with advancing age [27, 30, 41, 58].

Intrinsic changes in the thermoregulatory system, the presence of pre-existing diseases, the use of certain medication together with the social conditions that characterise older people (e.g. single occupancy) makes this category more susceptible to heat events than other sub-groups [2].

Education

With regard to education, a significant effect of heat on mortality in all the educational groups was observed, with higher RRs for women compared to men. In men the highest significant effects were seen in the higher level of education ("high school or more") as well as in the lower once ("no more than primary school"). In contrast, risk values for women were higher for lower educational level and decreased as education increased. In this context, several studies underline how an individual's educational background may influence the health outcomes [21, 62, 63]. Very often, it is assumed that the higher the educational level, the more appropriate individual adaptation measures are applied during periods of heat stress [35, 61]. These hypotheses are in line with the results achieved for women, but it is not the case for men. Some evidence from Turin suggested that the achieved results in this study are a combination of two phenomena. The first one is related to the mortality conditions observable among sexes in the City of Turin. Costa et al. [45, 57] highlighted how men characterized by low socio-economic conditions corresponded to high rates of premature deaths. In fact, men die younger, particularly if less educated [64–66]. This imply that individuals with lower levels of education are associated to a higher risk of mortality in younger ages, reason why the "no more than primary school" corresponded to a high RR. On the other side, following the same reasoning, deaths attributable among older men can be associated to higher levels of education, reason why the "high school or more" sub-group present a high RR for men. The second phenomenon is the value attributed to education in different social careers of men and women over the last 40 years. The northern cities of Italy have had many experiences of migration, especially from the regions of the south, that not only affects the life of migrants, but more generally changes the life horizons of all Turin citizens [67, 68]. Therefore, to understand the social and employment structure of Turin, it is important to take into account the phenomena of social stratification created by the different waves of migration. Men from the south are often associated with very low education, condition that make them suitable for a premature mortality. In addition, the remaining male population from the south with higher educational qualifications were discriminated from the native population of Turin, implying fewer career opportunities [45]. To the best of knowledge of those involved in this study, the novel results presented here partly contrast those of previous works; instead suggesting that for the population of Turin the association of mortality risk with heat is stronger in higher levels of education ("high school or more") as well as in lower level of education ("no more than primary school") for men, while for women stronger association have been found in lower levels of education ("no more than primary school").

Marital status

Results of RR by marital status highlighted a significant effect in all groups. Overall, RR were higher for the "unmarried", "separated and divorced" and "widowed", than for those "married" in both sexes with higher RRs for women than men. Over the years, several studies analysed the statistical association between marital status and mortality [64, 65, 69–71], however, very few studies focused on the relationship between marital status and mortality under heat stress events [39, 66, 72], due to limited data availability. Of those studies, the marital status is often used as a proxy for the family structure [39, 73] or as a proxy for social isolation [40, 74]. The most recent epidemiological and demographic research shows a beneficial effect of marriage on the health of the spouses [75–78]. In fact, in accordance with a study over French related to the 2003 heat wave [66], results generally suggested higher impacts for unmarried, widowed, separated and divorced people rather than those who were married. Marriage offers a 'protective effect' for health; it encourages healthier lifestyle [69], it discourages risk taking behaviour, it increases more favourable societal attitudes [79] and it may increase material well-being [64]. Therefore, 'protective effect' of the family on health manifests itself through lower risk of death, lower likelihood of experiencing phases of depression or anxiety, lower health problems, benefits that are often more pronounced for men. From the analyses, AF values for men were higher among the "widowed" group. The consequences of the stress of losing a spouse through divorce or widowhood can have long-term consequences for both men and women's mental and physical health [45]. This effect was evident among women, who were found to have a higher AF values in the "widowed" as well as in the "separated and divorced" category. Previous studies suggested how the death of the spouse for widowers [80, 81], or the dissolution of the marriage for the separated and divorced [19, 66, 82, 83], can be a dramatic and stressful event, with considerable health consequences [45]. In fact, benefits of married life also seem to accumulate during the marriage, with a long-term beneficial effect that could come from the mutual support. Moreover, in contrast with the literature state-of-the-art which recognises that "single" men are more at risk than women [65, 69], the study's findings show higher mortality risks for women. This result could be attributable to the fact that women live longer than men in our case study, and therefore the probability of being alone in advanced age for women is higher [57]. This is a novel in the literature, since it is the first time that these results have been found in studies related to mortality and temperature association during summer periods.

Number of household occupants

With regard to the number of household occupants, in men the results indicate a stronger evidence in individuals who lived alone at the time of death (in accordance with the conclusions found for the previous category). On the other hand, in women the RR differences between the two sub-categories were minimal. Among socio-economic drivers relevant for increased heat vulnerability, the "number of household occupants" (also called household structure in the literature) is relevant to take into account the degree at which an individual is integrated into networks and social relationships [17, 80, 84]. In fact, as Seebaß [30] highlighted, "the more social interactions a person has, the lower their perception of heat stress is". As the analysis by Aubrecht and Özceylan [35] shows, living alone can be a significant indicator that possibly resulting in fewer contacts with family and friends, increasing vulnerability and eventually mortality under heat stress condition [35]. In contrast, some other studies found a not significant correlation of living alone with increasing mortality [37, 44], highlighting how the type of social contacts a person has as well as the frequency of interacting with these contacts are more important in subjective heat stress [30]. Costa et al. [45] pointed out how generally differences in social inequalities decreases with age. Therefore, considering that women live longer than men, it can be assumed that the discrepancies between living "alone" and "not alone" decrease with age in women, aspect that emerged from the analyses.

Hence, the two categories mentioned above (marital status and household occupants) are logically interlinked [85]. In fact, some case studies used the marital status as a proxy for the family structure [39, 40] while some others used the household structure variable as a proxy for social isolation [31, 36, 39, 44]. In this research, both were used to see the differences of RRs by sub-categories and sex. In men the RR was higher for single-person households, in accordance with the marital status results, while for women RRs between "alone" and "not alone" were almost equivalent, demonstrating a minimum deviation from the previous analysed variables. Therefore, the fact that being socially integrated reduces mortality risk due to heat can be partially confirmed in this study.

The key strength of this study is the extension of results seen in previous investigations on temperature and mortality association (37 years observational study), by looking at age-groups, education, marital status and household occupants, stratified by sex, which were previous knowledge gaps in the literature. It was possible to run these analyses thanks to the availability of a continuous record linkage between the mortality register and the municipal census. Another strength of the study is that in order to have mean temperature values for the whole study period, an evaluation of the uncertainty comparing the mean temperature time series of the used dataset with other two climate datasets was provided [84]. This comparison highlighted that the selected dataset reproduces well the climatology obtained from the local meteorological station for the city of Turin. These processes allowed for the largest daily time series - of 37 years in the European urban context - to be developed. The main limitations of the study are related to two different aspects. First, information on specific causes of deaths were not available for the whole study period, reason why the present research did consider all-causes mortality. However, datasets on all-causes mortality are often employed in the heat-health nexus research due to both the lack of available data and to the absence of a uniform definition for heat-related death [31, 54, 85, 86]. Second, the range of possibilities and studies with ozone (O_3) or particular matter ($PM_{2.5-10}$) has not been fully sampled or explored, due to the lack of data for the reference period. In addition, the spatial distributions of vulnerabilities were not taken into account, which could have helped the understanding as to how sensitive populations are distributed within the sub-urban area under study. This issue will be further assessed in future research, through the adoption of a time-stratified case-crossover design followed by the application of geostatistical models using geo-coded mortality and environmental data. This will allow policymakers to better understand the district- and neighbourhood-level vulnerability within the urban environment. Finally, it was decided to not include the possibility of potential temporal changes in effect estimates due to adaptation of the population (or action taken). This aspect is crucial to understand more precisely if there are any dynamic impacts (such as adaptation) in the data over the entire time-frame and if there is a relative contribution of interannual temperature anomalies and year-to-year climate variability to the evolution of each attributable fractions related to every socio-economic driver. In fact, the significance of each considered variable in relation to the health of the population could have changed over the time. Therefore, in order to be able to locate the precise steps of the changes of predictive capacity for each analysed variable and to analyse the relative risk variations of cause-specific mortality across the whole range of summer temperatures, a dedicated scientific study with the use of time-varying DLNMs is under development. This evidence can give greater detail and aid in the understanding of how population risks change over time, and how external policies influence these adaptation processes.

Conclusions

This study proposes a distributed lag non-linear model for characterising the non-linear and delayed effects of summer temperatures on mortality in the city of Turin for the period 1982–2018. The study shows that demographic, social and economic drivers such as sex, age, education, marital status and household occupants play an important role in determining the most vulnerable groups within a population, also looking at cross-linkages between variables. This is important since having better knowledge of these effect modifiers is necessary to identify the axes of inequalities across the most vulnerable population subgroups and to therefore contribute towards relevant policy risk mitigation suggestions.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s12940-020-00667-x.

Additional file 1. Overall cumulative plots by sex and socioeconomic sub-group.

Additional file 2. Attributable number of deaths by demographic and socio-economic drivers.

Additional file 3. Sensitivity analyses for modelling choices.

Abbreviations

CI: confidence intervals; DLNM: distributed lag nonlinear model; MMT: minimum mortality temperatures; RR: relative risk

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Authors' contributions

ME, VJ and JB contributed to the conceptualization of the paper. ME, EF and GB contributed to the data curation. ME and VJ contributed to the formal analyses and investigation section. PM and GB performed the historical evaluation on climate data. GC performed the review on the discussion related to the achieved results. All the authors contributed to the Writing – Review & Editing section. The author(s) read and approved the final manuscript.

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Availability of data and materials

The climate dataset analysed during the current study is available in the Copernicus data store repository [https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-uerra-europe-single- levels?tab = form]. The mortality and socio-economic datasets that support the findings of this study are available from the Regional Epidemiology Unit of ASL TO3, but restrictions apply to the availability of these data, which were used under license for the current study and so are not publicly available. Data are however available from the authors upon reasonable request and with permission from the Regional Epidemiology Unit of ASL TO3.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Additional file 1

Overall cumulative plots by sex and socioeconomic subgroups

- **Overall cumulative plots by sex and age-groups**

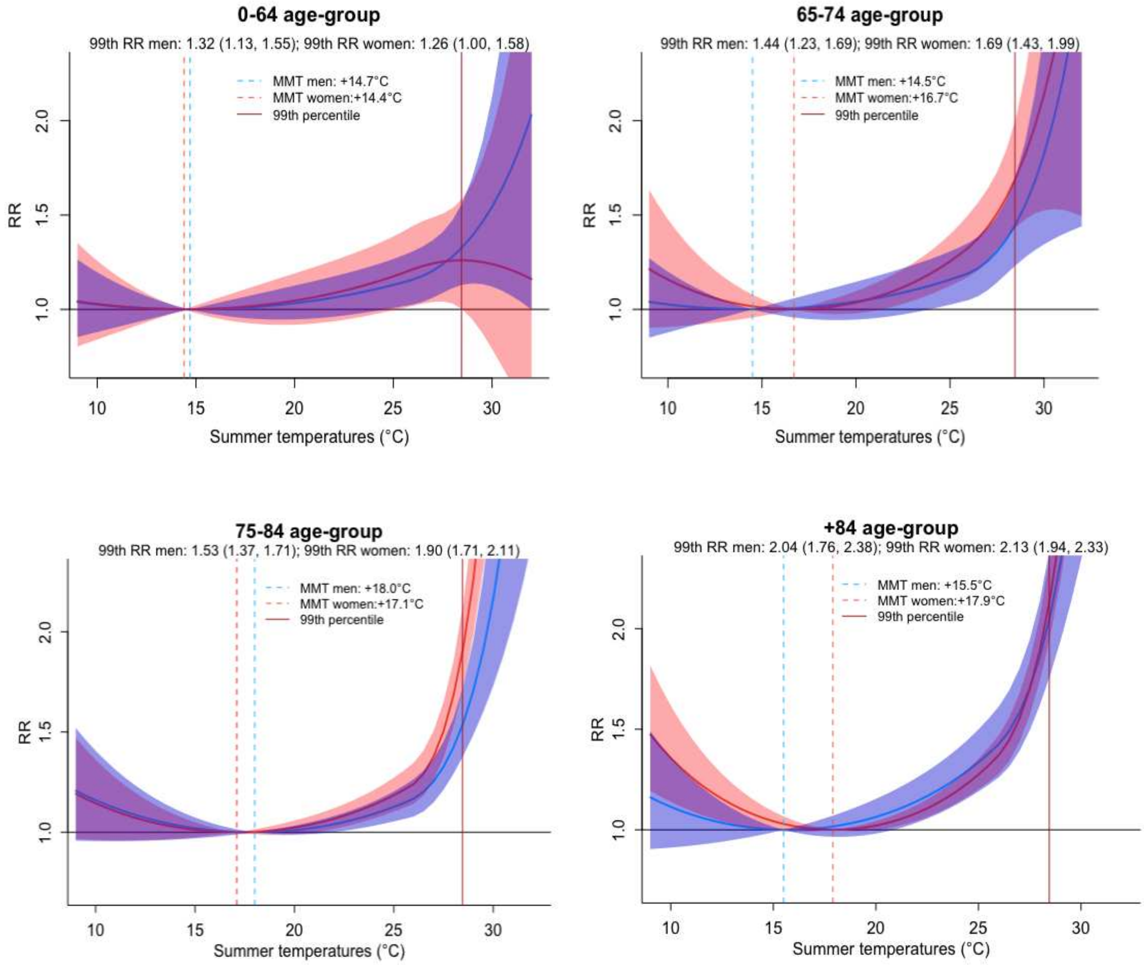

Fig. A1.1 | Age-group by sex
Overall cumulative plots showing RR curves for age-groups by sex: men (blue) and women (red) (RRs in solid lines, MMT in dotted lines and 95% CI in shaded colours)

- **Overall cumulative plots by sex and education**

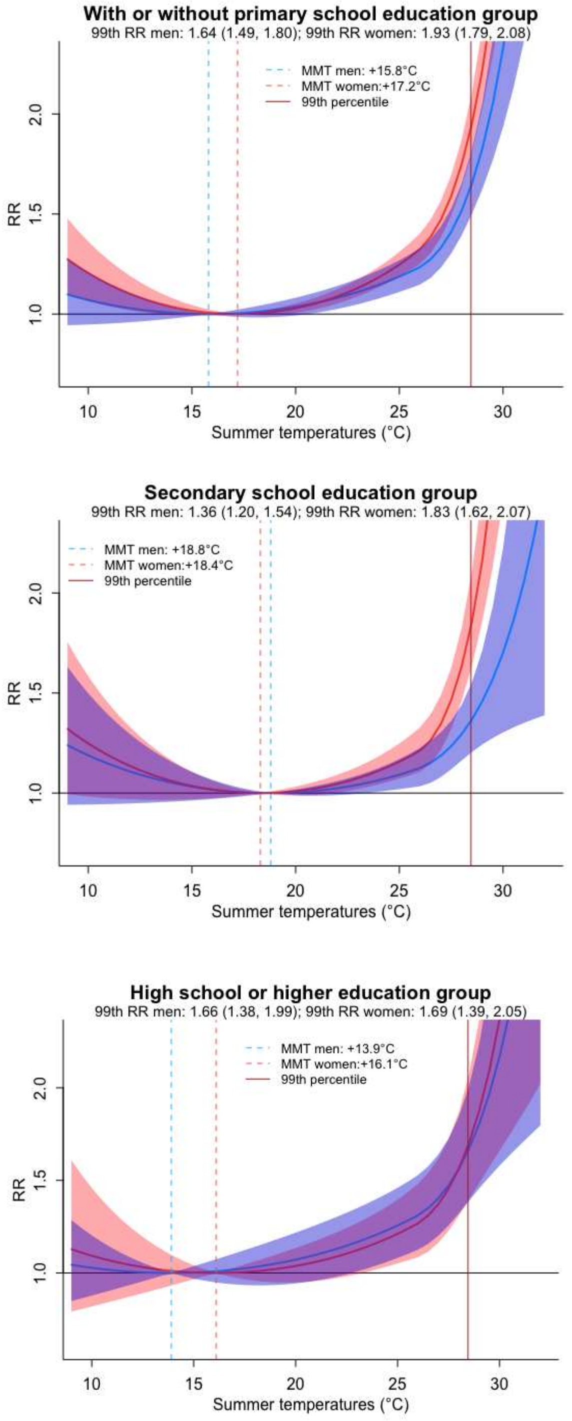

Fig. A1.2 | Education by sex

Overall cumulative plots showing RR curves for education by sex: men (blue) and women (red) (RRs in solid lines, MMT in dotted lines and 95% CI in shaded colours)

- **Overall cumulative plots by sex and marital status**

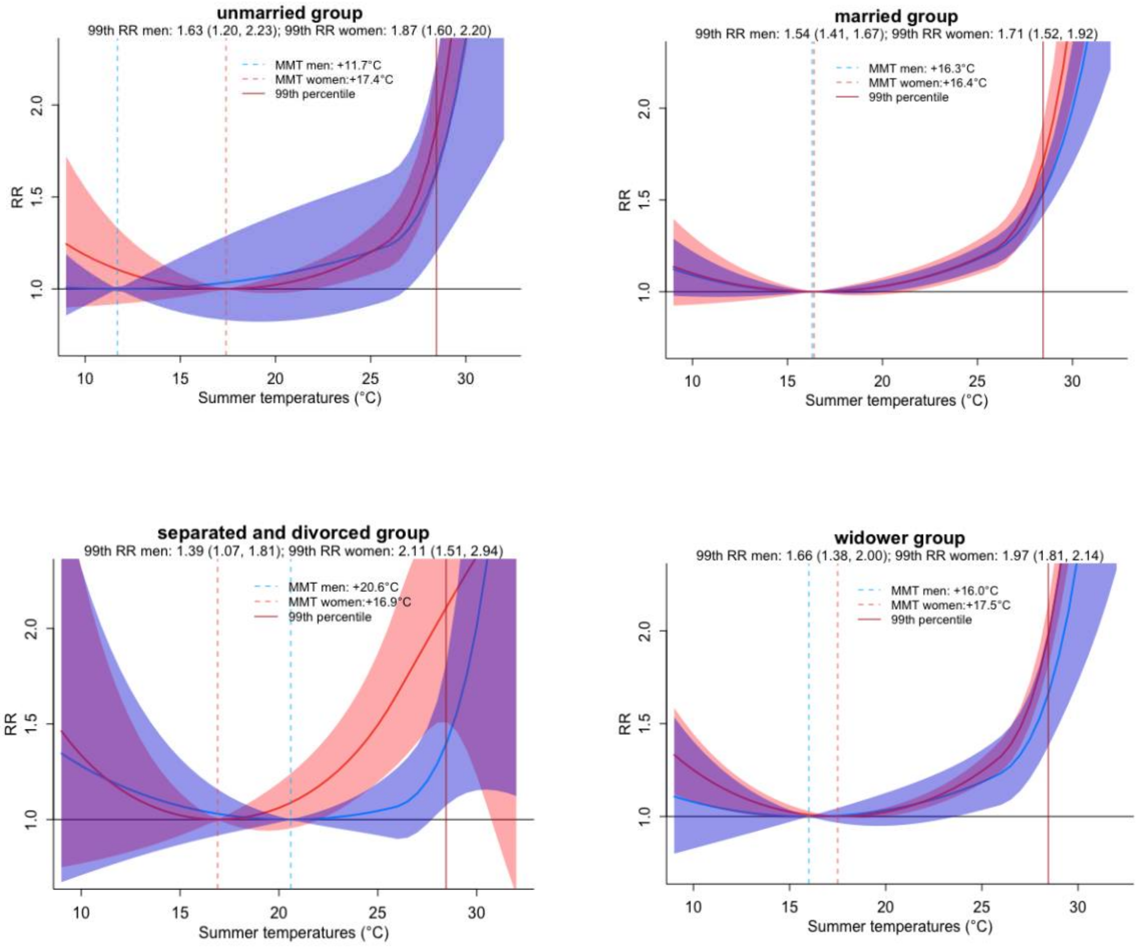

Fig. A1.3 | Marital status by sex

Overall cumulative plots showing RR curves for marital status by sex: men (blue) and women (red) (RRs in solid lines, MMT in dotted lines and 95% CI in shaded colours)

- **Overall Cumulative Plots by sex and household occupants**

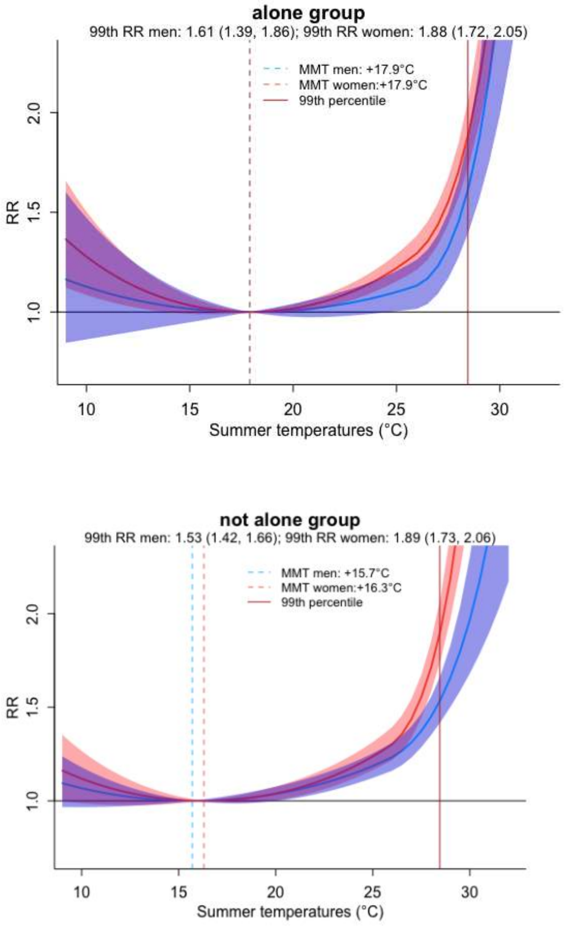

Fig. A1.4 | Household occupants by sex

Overall plots showing RR curves for household occupants by sex: men (blue) and women (red) (RRs in solid lines, MMT in dotted lines and 95% CI in shaded colours)

Additional file 2

Attributable number of deaths by demographic and socio-economic drivers

Attributable number of deaths (AN) with CI 95%		JUNE			JULY			AUGUST		
		Moderate	Extreme	Total heat	Moderate	Extreme	Total heat	Moderate	Extreme	Total heat
Mortality by:	**Men**	886 (527, 1214)	74 (65, 83)	960 (592, 1297)	1547 (1114, 2021)	289 (251, 328)	1836 (1365, 2349)	1245 (823, 1714)	348 (296, 397)	1593 (1119, 1711)
Age-groups	0 – 64 y	142 (-78, 355)	6 (2, 10)	148 (-76, 365)	278 (-10, 530)	42 (16, 61)	320 (-6, 591)	252 (-48, 532)	39 (12, 60)	290 (-36, 592)
	65 – 74 y	224 (-41, 457)	15 (9, 20)	238 (-32, 477)	369 (57, 673)	54 (30, 74)	421 (87, 747)	290 (-37, 577)	66 (36, 89)	353 (-1, 666)
	75 – 84 y	219 (98, 329)	28 (22, 33)	247 (120, 362)	392 (177, 585)	96 (75, 115)	489 (252, 700)	291 (94, 479)	118 (84, 148)	409 (178, 627)
	85+ y	361 (170, 526)	26 (21, 31)	393 (191, 560)	556 (348, 758)	93 (75, 111)	649 (423, 869)	479 (271, 677)	136 (107, 160)	604 (378, 837)
Education	No more than primary school	531 (274, 789)	41 (34, 46)	572 (308, 835)	896 (536, 1229)	174 (145, 200)	1070 (681, 1429)	734 (360, 1054)	191 (151, 227)	925 (511, 1281)
	Secondary school	129 (35, 207)	14 (10, 18)	143 (45, 225)	247 (70, 412)	53 (34, 71)	300 (104, 483)	163 (10, 298)	72 (40, 100)	235 (50, 398)
	High school or more	273 (-18, 528)	20 (13, 26)	293 (-5, 554)	441 (118, 703)	64 (41, 83)	505 (159-786)	395 (68, 689)	85 (56, 111)	480 (124, 800)
Marital status	Married	683 (455, 888)	46 (39, 53)	729 (494, 941)	1252 (911, 1559)	173 (142, 199)	1425 (1053, 1758)	1046 (735, 1336)	186 (149, 221)	1232 (884, 1557)
	Separated and divorced	23 (-3, 45)	2 (-0, 4)	25 (-3, 49)	43 (-12, 88)	9 (0, 16)	52 (-12, 104)	30 (-17, 68)	9 (-5, 19)	39 (-22, 87)
	Unmarried	115 (12, 206)	7 (3, 10)	122 (15, 216)	208 (62, 333)	28 (14, 40)	236 (76, 373)	170 (33, 283)	33 (18, 46)	203 (51, 329)
	Widower	128 (57, 190)	14 (10, 17)	142 (67, 207)	250 (135, 355)	50 (34, 62)	300 (169, 417)	187 (71, 290)	47 (29, 62)	234 (100, 353)
Household occupants	Alone	93 (-3, 174)	16 (11, 20)	109 (8, 194)	177 (2, 319)	62 (44, 77)	239 (46, 396)	135 (-10, 270)	83 (59, 104)	218 (49, 374)
	Not alone	815 (468, 1163)	58 (50, 66)	873 (518, 1229)	1386 (962, 1809)	225 (189, 258)	1611 (1151, 2067)	1134 (717, 1527)	259 (208, 298)	1393 (925, 1825)
Mortality by:	**Women**	1120 (863, 1390)	111 (102, 119)	1331 (965, 1509)	2079 (1687, 2442)	465 (426, 504)	2544 (2113, 2946)	1621 (1254, 1965)	591 (541, 639)	2212 (1795, 2604)
Age-groups	0 – 64 y	127 (-50, 287)	4 (0, 7)	131 (-50, 294)	208 (-34, 419)	21 (3, 35)	239 (-31, 454)	164 (-60, 368)	15 (-10, 34)	179 (-70, 402)
	65 – 74 y	194 (80, 289)	12 (9, 15)	206 (89, 304)	340 (178, 499)	59 (41, 73)	399 (219, 572)	274 (123, 413)	58 (37, 74)	332 (160, 487)
	75 – 84 y	305 (158, 435)	32 (28, 37)	337 (186, 472)	598 (372, 818)	160 (137, 180)	758 (509, 998)	455 (263, 655)	199 (174, 221)	645 (437, 876)
	85+ y	528 (387, 660)	64 (58, 70)	592 (438, 730)	969 (769, 1175)	224 (200, 247)	1,193 (914, 1422)	765 (576, 950)	324 (290, 355)	1089 (847, 1305)
Education	No more than primary school	784 (576, 969)	74 (68, 80)	848 (644, 1049)	1488 (1175, 1792)	333 (303, 365)	1821 (1478, 2157)	1175 (894, 1464)	382 (339, 416)	1557 (1233, 1880)
	Secondary school	189 (99, 283)	24 (20, 28)	213 (119, 311)	341 (180, 493)	91 (74, 106)	432 (254, 599)	259 (110, 393)	148 (121, 168)	407 (231, 561)
	High school or more	132 (4, 241)	11 (7, 14)	143 (11, 255)	230 (52, 39)	42 (27, 54)	272 (79, 450)	170 (17, 301)	61 (39, 79)	231 (56, 380)
Marital status	Married	353 (230, 469)	23 (18, 27)	376 (248, 496)	667 (461, 861)	99 (78, 116)	766 (539, 977)	522 (344, 684)	114 (85, 138)	636 (419, 822)
	Separated and divorced	75 (18, 124)	3 (2, 4)	78 (20, 128)	137 (60, 199)	17 (10, 23)	154 (70, 222)	117 (32, 176)	28 (15, 38)	145 (47, 214)
	Unmarried	162 (98, 224)	17 (13, 20)	179 (101, 244)	337 (223, 445)	65 (50, 77)	402 (273, 522)	273 (170, 374)	72 (54, 86)	345 (224, 460)
	Widower	685 (551, 808)	64 (58, 70)	749 (609, 878)	1332 (1109, 1526)	249 (223, 275)	1581 (1332, 1801)	1036 (864, 1224)	283 (251, 312)	1319 (1115, 1536)
Household occupants	Alone	457 (322, 581)	50 (44, 55)	507 (366, 636)	891 (649, 1229)	199 (175, 223)	1090 (824, 1352)	670 (475, 876)	270 (237, 297)	940 (712, 1173)
	Not alone	700 (466, 937)	61 (54, 67)	761 (520, 1004)	1227 (884, 1537)	265 (235, 294)	1492 (1119, 1831)	992 (665, 1288)	316 (276, 351)	1308 (941, 1639)

Table A2.1 | Attributable number of deaths per month

Additional file 3

Sensitivity analyses for modelling choices

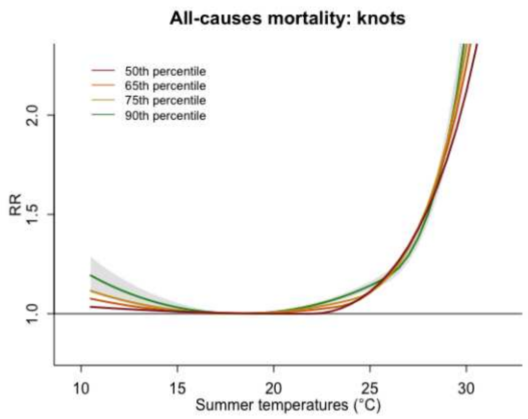

Fig A3.1 | Knots for exponse-response

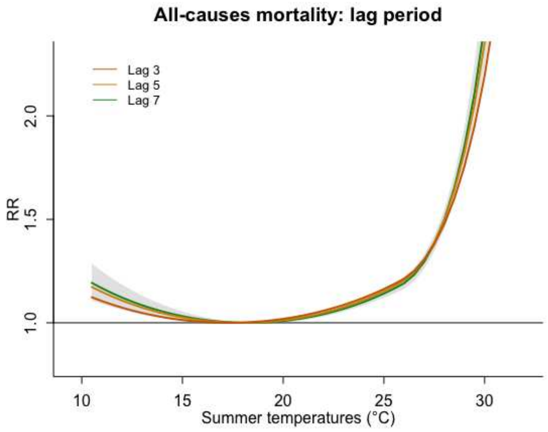

Fig A3.2 | Lag period

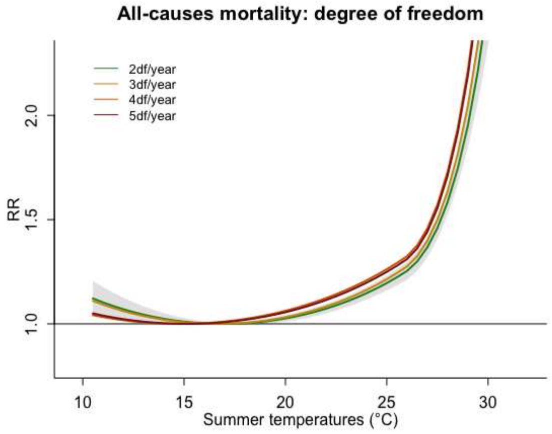

Fig A3.3 | Degrees of freedom for seasonal trend

REASEARCH ARTICLE 3

Title
Evolution of temperature-attributable mortality trends looking at social inequalities: an observational case study of urban maladaptation to cold and heat over time

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Marta Ellena, Joan Ballester, Giuseppe Costa, Hicham Achebak

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Evolution of temperature-attributable mortality trends looking at social inequalities: an observational case study of urban maladaptation to cold and heat over time

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ABSTRACT

Background To date, little is known about the temporal variation of the temperature-mortality association among different demographic and socio-economic groups. The aim of this work is to investigate trends in cold- and heat-attributable mortality risk and burden by sex, age, education, marital status, and household occupancy in the city of Turin, Italy.

Methods We collected daily time-series of temperature and mortality counts classified by demographic and socio-economic groups for the period 1982-2018 in Turin. We applied standard quasi-Poisson regression models to data subsets of 25-year moving subperiods, and we estimated the temperature-mortality association over time with distributed lag non-linear models (DLNM). We provided cross-linkages between the evolution of minimum mortality temperatures, relative risks of mortality and temperature-attributable deaths under cold and hot temperatures.

Results Our findings highlighted an overall increase in risk trends under cold and heat conditions. All-cause mortality at the 1st percentile increased over time from 1.15 (95% CI: 1.04; 1.28) in 1982-2006 to 1.24 (95% CI: 1.11; 1.38) in 1994-2018, while at the 99th percentile the risk shifted from 1.51 (95% CI: 1.41; 1.61) to 1.59 (95% CI: 1.49; 1.71). In relation to social differences, women were characterized by greater values in respect to men, and similar estimates were observed among the elderly in respect to the youngest subgroup. Risk trends by educational subgroups were mixed, according to the reference temperature condition. Finally, individuals living in conditions of isolation were characterized by higher risks, with an increasing vulnerability throughout time.

Conclusions The overall increase in cold- and heat-related mortality risk and burden suggests a maladaptation to ambient temperatures in Turin. Despite alert systems now in place increase public awareness and improve the efficiency of existing health services at the local level, they do not necessarily prevent risks in a homogeneous way. Targeted public health responses to cold and heat in Turin are urgently needed to adapt to extreme temperatures due to climate change.

Introduction

The changing health risks under the influence of temperature variations, driven by human-induced climate change, by urbanization growth as well as by the influence of social determinants of health are known to be a major concern - among others - for public health policy makers and scientists (1). In fact, as global warming has become more evident, negative health impacts linked to the increase in the frequency, intensity and duration of extreme weather events are exacerbating human health conditions, bringing to a general rise in mortality and morbidity (2). By 2050, at 1.5°C of global warming, the population exposed to deadly heat in the world's most populous cities is estimated to be around 350 million, considering a midrange population growth scenario (3). The strongest extreme hot temperatures are projected to occur within Mediterranean region (2,4). In this context, Italy holds the uppermost heat-related effects on daily mortality considering hot temperatures (5). In fact, in the country, in particular near by the Alpine regions, it is expected an increase of temperatures up to 2°C in the period 2021-2050 and up to 5°C by 2100 (compared to 1981-2010) under the RCP 8.5 scenario (6). At the present, Italian citizens are more sensitive to uncomfortable conditions due to extreme events compared to other countries (7). Nonetheless, there are spatial differences between and within Italian urban areas (8) due to physical variables (such as urban land cover) (9) as well as the spatial distribution of social inequalities (10). It is well-established that the health risks related to temperatures depend on pure adaptation processes - such as individual behavioural changes and acclimatisation, but also on non-climate factors - such as the built environment, population characteristics and the available health care services (11). An adequate distinction between these drivers of change is crucial to plan effective policies to address public health challenges related to heat- and cold- temperatures impacts at the urban scale (12). A comprehensive risk assessment requires detailed analyses with respect to potential changes in population susceptibility over time, considering the full temperature range, from cold to heat (13). In fact, despite it is undeniable that a growing risk to health is due to heat under climate change (1), it is unquestionable how cold events are responsible for a significant higher proportion of the overall health burden associated to temperatures (2,11). Disentangling the temporal changes of the risks under a complete range of temperatures can provide a more complete description of the evolution of the contribution of different adaptive mechanisms driven by: (i) non-climate factors such as socioeconomic development (i.e., extrinsic adaptation) (14,15), or (ii) physiological acclimatisation in response to changing temperatures (i.e., intrinsic adaptation) (16).

To date, despite several studies have already mentioned how the health effects of cold often exceed those of heat (17,18), cold-mortality associations over time have been poorly studied, showing controversial results (2,19). Over the years, a growing number of studies tried to assess the temporal variation in population vulnerability (10,13), expressed as minimum mortality temperatures (MMTs), relative risks (RRs) and attributable fraction (AFs). For example, in Spain, evidence of a reduction in mortality from respiratory and cardiovascular diseases have been found during the coldest and hottest months of the year (1980-2016)(16,20). Results from a multi-country study over the period 1985-2012 revealed an increase in population vulnerability under cold temperatures in Japan and South Korea, with a decline of RRs under hotter conditions. Similar trends were observed for the US (21). In Sweden, an increase in MMTs over the course of the 20th century, suggested an adaptation pattern to increasing temperatures (15), as found similarly by Hajat et al. (22) in the UK.

Understanding the evolution of MMT, RR and AF over time, it is necessary to support health policymakers in the comprehension of the potential drivers of change, managing and preventing risks from the temperature-related health nexus under present and climate change scenario conditions (11). Therefore, adequate public health planning in urban areas should be based on quantitative evaluation – such as the one provided in this study – to prevent cold- and heat- mortality and morbidity (13,19,23). The present paper assesses the temporal changes in temperature-mortality associations by sex, age, education, marital status, and household's occupancy in the city of Turin, Italy. In doing so, the study provides cross-linkages between the evolution of MMT, RR of mortality and temperature-AF of death under a broad range of temperatures along the whole year period.

Methods

Data sources

We collected daily time series of mortality counts and temperatures from the 1st of January 1982 to the 31st of December 2018 in the city of Turin, the biggest urban area in the northwest of Italy. The Regional Epidemiology Unit of the local health authority (ASL TO3) provided daily mortality data from all causes, disaggregated by sex, age, education, marital status and number of household occupants (24). Daily mean temperature was selected as the main exposure variable (25).

High-resolution gridded data (~5.5 km) was derived from the UERRA Regional reanalysis Dataset (26) using an optimal interpolation algorithm. Both mortality and temperature datasets had no missing values. These data have been used and described in a previous analysis (27).

Statistical analysis

We performed a time-series quasi-Poisson regression model to derive estimates of temperature-mortality associations by population subgroups and data subsets of 25-year moving periods, summarised as RR values. The sub-periods analysed were 1982-2006, 1983-2007, and so forth, up until 1994-2018. In accordance with previous studies (16,28), the former model included a natural cubic spline of time with 8 degrees of freedom (df) per year to control for seasonality and long-term trend, and a categorical indicator of day of the week (dow). We estimated the complex non-linear relationship between temperatures and mortality through a distributed lag non-linear model (DLNM), which is based on a definition of a cross-basis function defining the conventional exposure-response association and the additional lag-response association for a given time interval (29). Specifically, the exposure–response curve was modelled through a natural cubic B-spline with three internal knots placed at the 10th, 75th and 90th percentile of the temperature distribution (16,30,31). On the other hand, the lag-response function was modelled with a natural cubic spline with an intercept and three internal knots placed at equally spaced values in the log scale (32). To capture the potential short-term harvesting (heat) as well as the long-lagged associations (cold), we extended the lag period up to 21 days (20,31).

These modelling choices were thoroughly tested in sensitivity analyses by varying the number of knots to include, the degrees of freedom to consider and, the number of lags to examine. Furthermore, a variety of analyses were conducted to select the model to use (i.e., time-varying or moving period), as well as the range of years to be considered in the time sub-periods (i.e., 15-, 20-, or 25-years moving period). Based on the quasi-Akaike criteria (Q-AIC), we chose the model which furnished the lowest score compared to other choices (29,33).

The temperature-mortality RR curves obtained in each of the 13 subperiods of 25 consecutive years were centred at the MMT of the specific subperiod - which is the temperature at which the RR of death is at its minimum or lowest value - and used to compute the mortality burden (i.e., AF) attributable to temperatures during the all-year period, to understand the AF changes over time during the hottest (i.e., June-August) and the coldest (i.e., December-February) months of the year. To do so, we used a method described in Gasparrini and Leone (34). R *software* (version 4.0.3) was used to create data sets and to develop statistical models and outputs using functions from *splines* and *dlnm* packages.

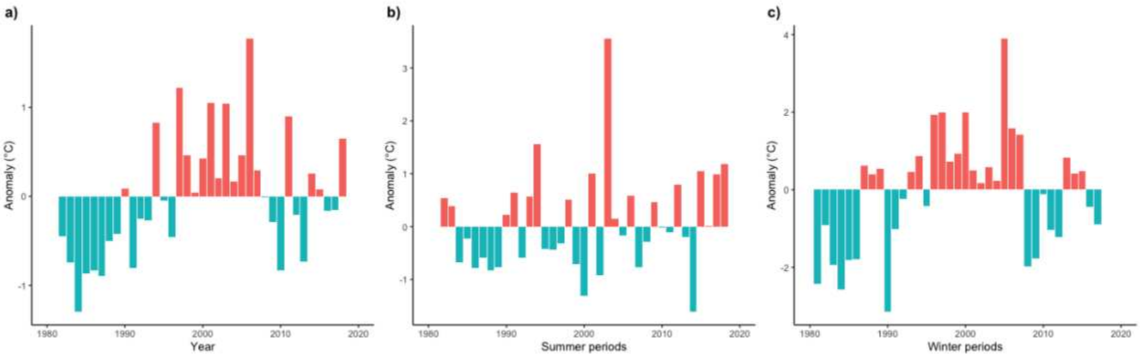

Figure 1 | Evolution of annual mean temperatures for (a) all, (b) summer and (c) winter months, 1982–2018
Summer is represented by the hottest months of the year (June, July and August) and winter is represented by the coldest months of the year (December, January and February). The anomalies reflect the difference relative to the average of the 1982-2011 period in Turin (Italy).

Results

Evolution of mortality and temperatures in Turin

The dataset included 364,755 deaths covering a period of 37 years, from the 1st January 1982 to the 31st December 2018. Analyses and results here presented were stratified by sex ("women" [51.4%] and "men" [48.6%]), age ("65-84 years" [51.62%] and "over 84 years" [31.18%]), education ("until primary school" [56.9%] and "over primary school" [37.49%]), marital status ("married" [47.94%], "unmarried" [15.82%] and "widower" [31.06%]) and number of household occupants ("alone" [29.58%] and "not alone" [64.58%]). Analyses by individuals younger than 65 years were not computed, because of the small number of daily deaths counts recorded for those age ranges, which did not guarantee model convergence and optimal fitting. Overall, the evolution of all mortality and number of deaths by sex over time remained more or less constant over the study period (see Fig.S1 in Supplementary Materials). In relation to the age, the two subgroups displayed opposite trends of mortality. The "65-84 years" visibly decreased, while the "over 84 years" increased over time. Fig.1 shows the evolution of annual, summer (JJA) and winter (DJF) mean temperature anomalies over the period 1982-2018. As expected, these temperatures have been increasing, on average, at a rate of 0.26°C, 0.16°C and 0.43°C per decade, respectively.

Trends in the minimum mortality temperature and in the risk of death

The temporal evolution of MMT by population subgroups and subperiods is provided in Fig.2 (with MMT Confidence Intervals visible in Fig.S2 in Supplementary Materials). In relation to "all-causes mortality", MMT evolution increased over the 13 sub-periods (by 0.5°C from 1982 to 2018); increase correlated with the rise in mean temperatures observed for the same time period. Between the 1990-2014 and the 1994-2018, MMT values progressively increased in "women" and "men", with a more visible increase tendency in the first subgroup. In fact, the "men" pooled overall MMT corresponded to 22.5°C in 1982 and 2018, while in "women" the MMT values increased from 21.3°C to 22.4°C. When considering age, results differed. Specifically, MMTs initially declined for the "65-84 years" subgroup and then considerably increased towards the end of the period, while for "over 84 years" remained rather stable. In the case of education, MMTs evolution for the "until-primary school" increased over time from 22.1°C in 1982 to 22.4°C in 2018. In the "over-primary school", MMT values increased with a significant shift from 21.6°C in the 1986-2010 subperiod to 22.4°C in 1987-2011. Within the marital status category, MMTs were generally higher for the "married" and "widower" subgroups. Specifically, in the case of "married", MMTs evolution increased from 22.3°C to 22.7°C, while for the "widower" remained around 22.4°C for the whole period. The "unmarried" subgroup - although some visible fluctuations – was the one with the most visible increasing trend, from 18.1°C in 1982-06 to 21.9°C in 2006-18. Finally, in relation to the household occupancy group, MMTs increased significantly over time both for the "alone" (from 21.7°C to 22.4°C), but also for the "not alone" (from 22.2°C to 22.5°C) subgroup.

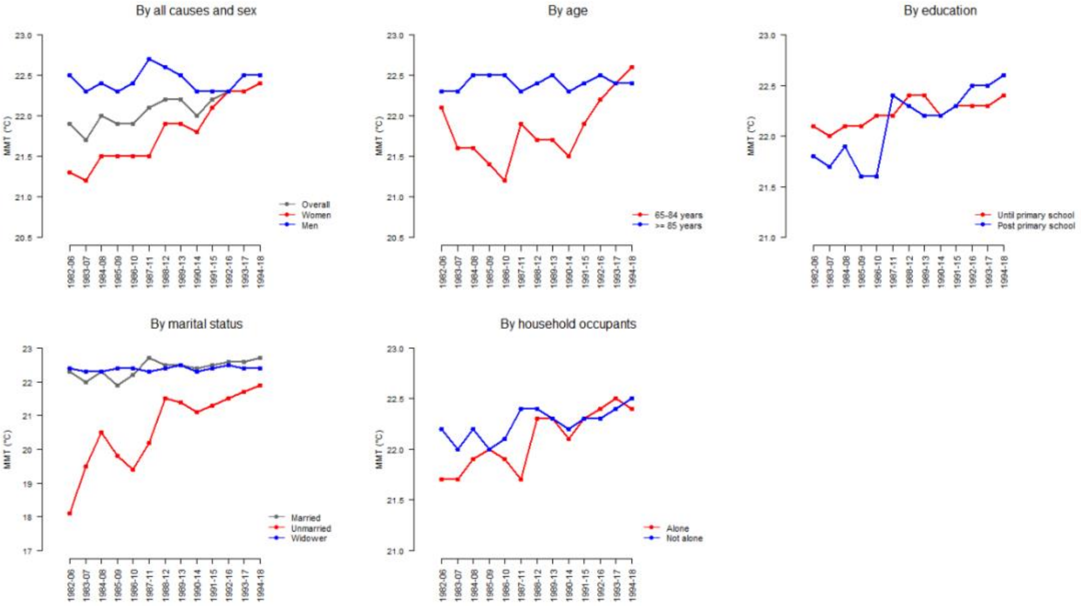

Figure 2 | Minimum mortality temperature (°C) by subgroup
MMT = Minimum Mortality Temperature

RR estimates were extracted from the RR curves computed from the 13 subperiods of 25 consecutive years, which are provided in Fig.3, for the 1982-2006 (initial) and the 1994-2018 (final) subperiod. Pooled overall RR estimates indicated that both cold- and hot-temperatures were associated with a general increased risks in mortality, looking at the most extreme temperature percentiles. Overall, the slope of the RR curves under hotter conditions was steeper than under the colder ones, and the values varied consistently by subgroups. The RR at the 1st percentile increased from 1.15 (95% CI: 1.04; 1.28) in 1982-2001 to 1.24 (95% CI: 1.11; 1.38) in 1999-2018 for "all-causes mortality", from 1.11 (95% CI: 0.96; 1.29) to 1.23 (95% CI: 1.05; 1.43) in "men", and from 1.19 (95% CI: 1.03; 1.37) to 1.25 (95% CI: 1.08; 1.44) "in women". In parallel, for the 99th percentile, the RR increased from 1.51 (95% CI: 1.41; 1.61) to 1.59 (95% CI: 1.49; 1.71), from 1.34 (95% CI: 1.27; 1.47) to 1.45 (95% CI: 1.31; 1.60), and from 1.68 (95% CI: 1.54; 1.84) to 1.74 (95% CI: 1.58; 1.91) respectively. Overall RR curve for "65-84 years" in the 1999-2018 sub-period highlighted a rise under both cold and hot conditions in respect to the initial period. On the contrary, the "over 84 years" exhibited a slight decrease in RR values under both cold and hot conditions. In fact, the RR at the 1st percentile increased from 1.15 (95% CI: 1.00; 1.33) to 1.18 (95% CI: 1.02; 1.38) for the "65-84 years" and decreased from 1.39 (95% CI: 1.26; 1.71) to 1.35 (95% CI: 1.14; 1.61) in the "over 84 years". Under the 99th percentile, the RR increased from 1.43 (95% CI: 1.31; 1.57) to 1.50 (95% CI: 1.36; 1.66) in the youngest group and decreased from 1.84 (95% CI: 1.62; 2.09) to 1.79 (95% CI: 1.60; 2.00) in the oldest one. In relation to education, RR curves highlighted an increase under cold and hot conditions. In fact, RRs at the 1st percentile increased from 1.18 (95% CI: 1.03; 1.34) to 1.26 (95% CI: 1.09; 1.45) for the "until primary school", and from 1.09 (95% CI: 0.91; 1.30) to 1.23 (95% CI: 1. 05; 1.45) in the "over primary school". In parallel, the RR at the 99th percentile increased from 1.55 (95% CI: 1.43; 1.69) to 1.57 (95% CI: 1.43; 1.73) in the less educated subgroup, and from 1.40 (95% CI: 1.25; 1.56) to 1.59 (95% CI: 1.43; 1.76) in the most educated ones.

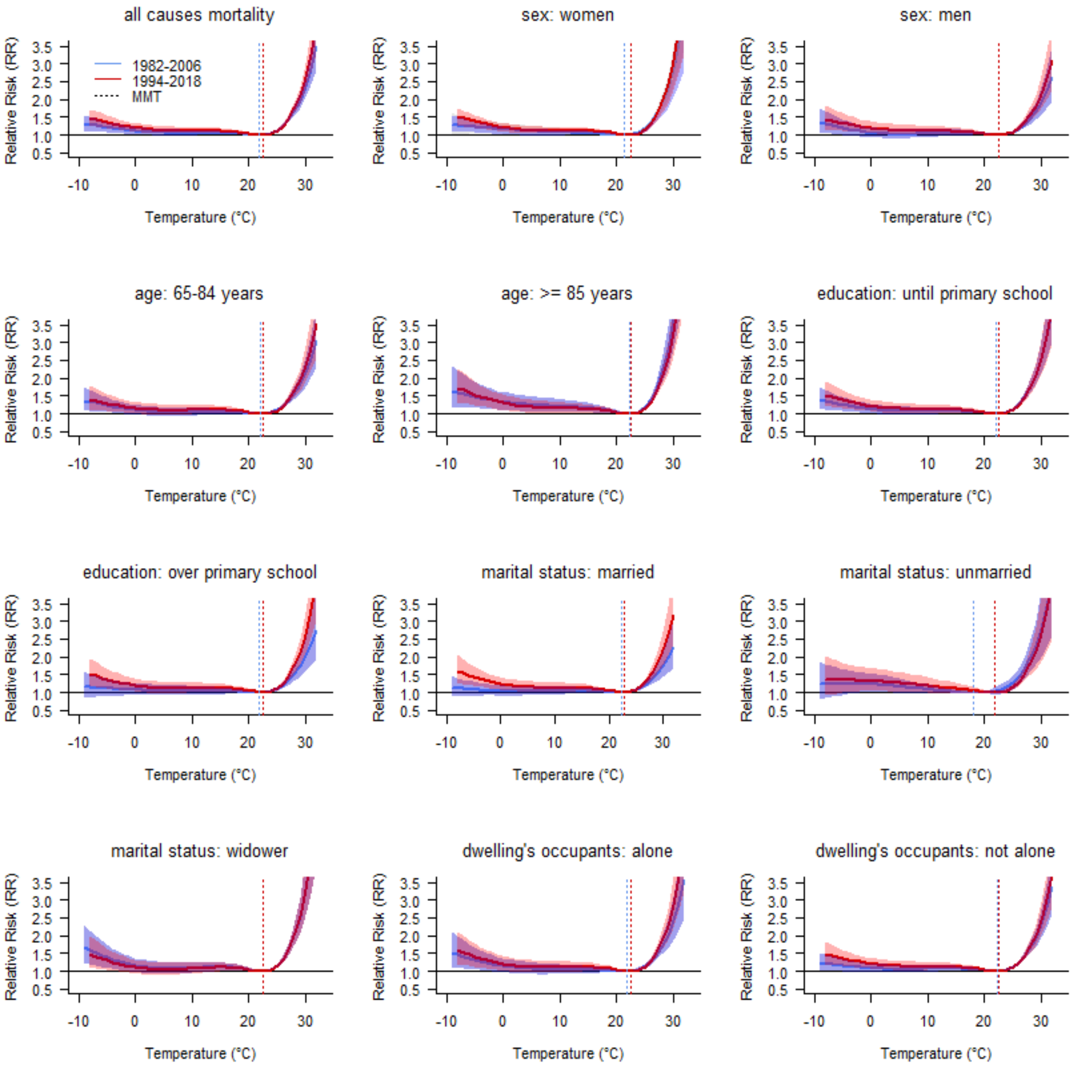

Figure 3 | Overall cumulative temperature-mortality relationships by subgroup, 1982-2006 *vs* 1994-2018
1982-2006 (in blue) and 1994-2018 (in red)

Within the marital status category, similar RR trends have been observed, apart from the “unmarried” subgroup which showed a different trend, probably because the model did not adequately converge for the limited number of observations. RRs showed more positive and significant curves and estimates for the “unmarried” and “widower” subgroups, despite the “married” ones. Finally, in relation to RRs estimates for the household occupants group, increased RR trends have been found in respect to the “alone” and the “not alone” subgroups. In fact, the RR at the 1st percentile slightly increased from 1.21 (95% CI: 1.00; 1.47) to 1.25 (95% CI: 1.04; 1.50) in the first subgroup, and from 1.11 (95% CI: 0.97; 1.26) to 1.24 (95% CI: 1.09; 1.42) in the second. Under the 99th percentile, RRs increased from 1.53 (95% CI: 1.36; 1.73) to 1.66 (95% CI: 1.48; 1.87) and from 1.48 (95% CI: 1.36; 1.60) to 1.53 (95% CI: 1.40; 1.67) respectively. To illustrate more specifically the trends over each of the 13 analysed subperiods, Fig.4 shows the RRs evolution over time at the 1st and 99th temperature percentiles, with 95% empirical confidence intervals (CI).

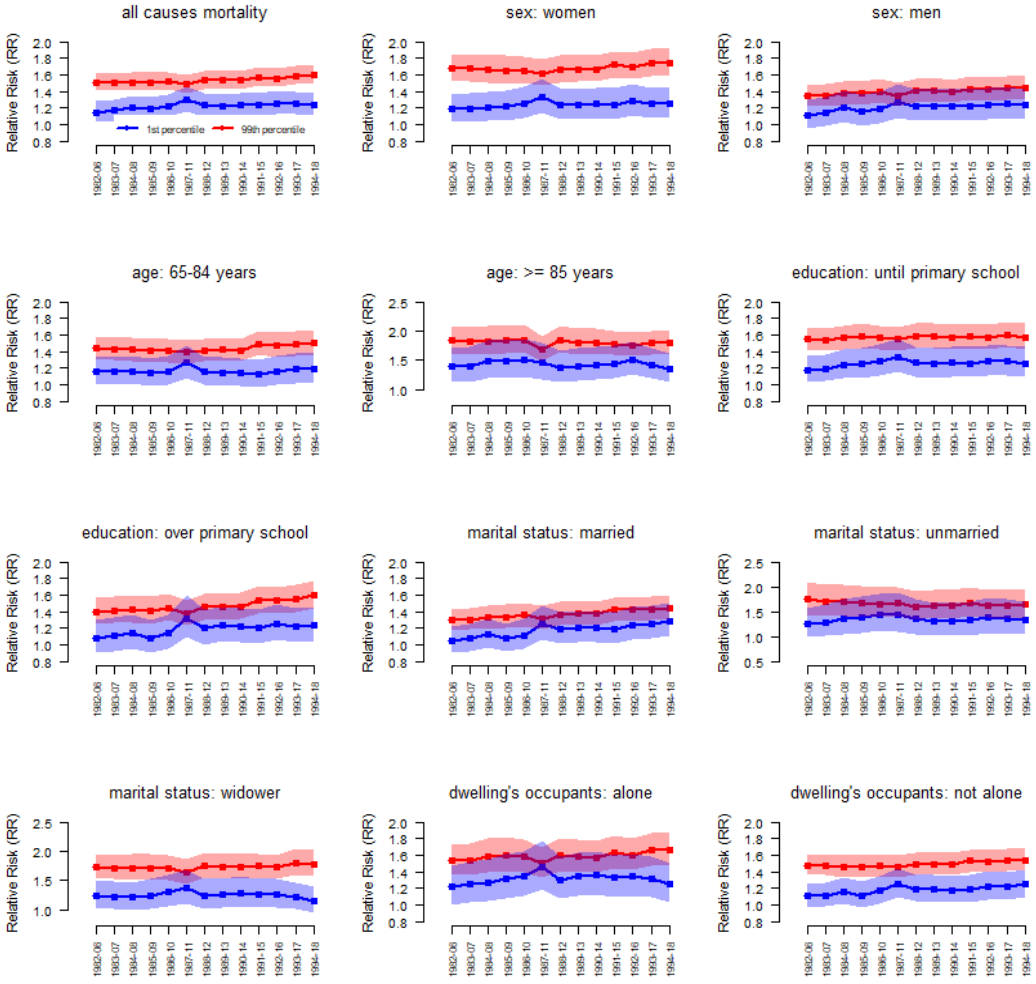

Figure 4 | Temporal evolution of relative risk by subgroup by 25-years subperiods.
1st percentile (in blue) and 99th percentile of temperatures (in red)

Monthly attributable mortality over time: focus on cold- and heat- AF

Fig.5 summarizes the evolution of the AF by months and by subgroups between the first and the last subperiods. The overall trend highlighted AF differences between the coldest ("Dec", "Jan" and "Feb") and the hottest months ("Jun", "Jul" and "Aug") of the year, here defined as cold- and heat- AF. In agreement with previous findings, results revealed (apart from few specific cases) a general increase in AFs from 1982-2006 to 1994-2018, with more visible rises in cold-AFs and a less noticeable increase in heat-AFs. This is the case for "all-causes mortality", "men", "65-84 years", "until-" and "over primary school", "married" and "unmarried" subgroups, and – finally – the "alone" and the "not alone". On contrary, "women" revealed very similar cold- and heat- AFs between subperiods, which assumed a stable trend over time under the most extreme percentile of temperatures. In the "over 85 years" subgroup, cold-AFs of the initial period exceeded the ones corresponded to the last one, implying a slight adaptation of this category to cold temperatures over time. Finally, in the case of "widower", it emerged a decrease of cold-AFs and an increase of heat-AFs.

Multiple sensitivity analyses were performed using Akaike Information Criterion (AIC) to identify the most explicative model to use and the appropriate parameters to adopt, with the aim to capture the main effects related to cold- and heat- events. All sensitivity examinations suggested that the reported results were not dependent on modelling choices (see Fig.S3.1-S3.2) and modelling assumptions (see Fig.S4.1-S4.2 in Supplementary Materials). Please, note that, since the RR curves are centred at different MMT values in each subperiod, the RR and AF values are not perfectly comparable between the different subperiods.

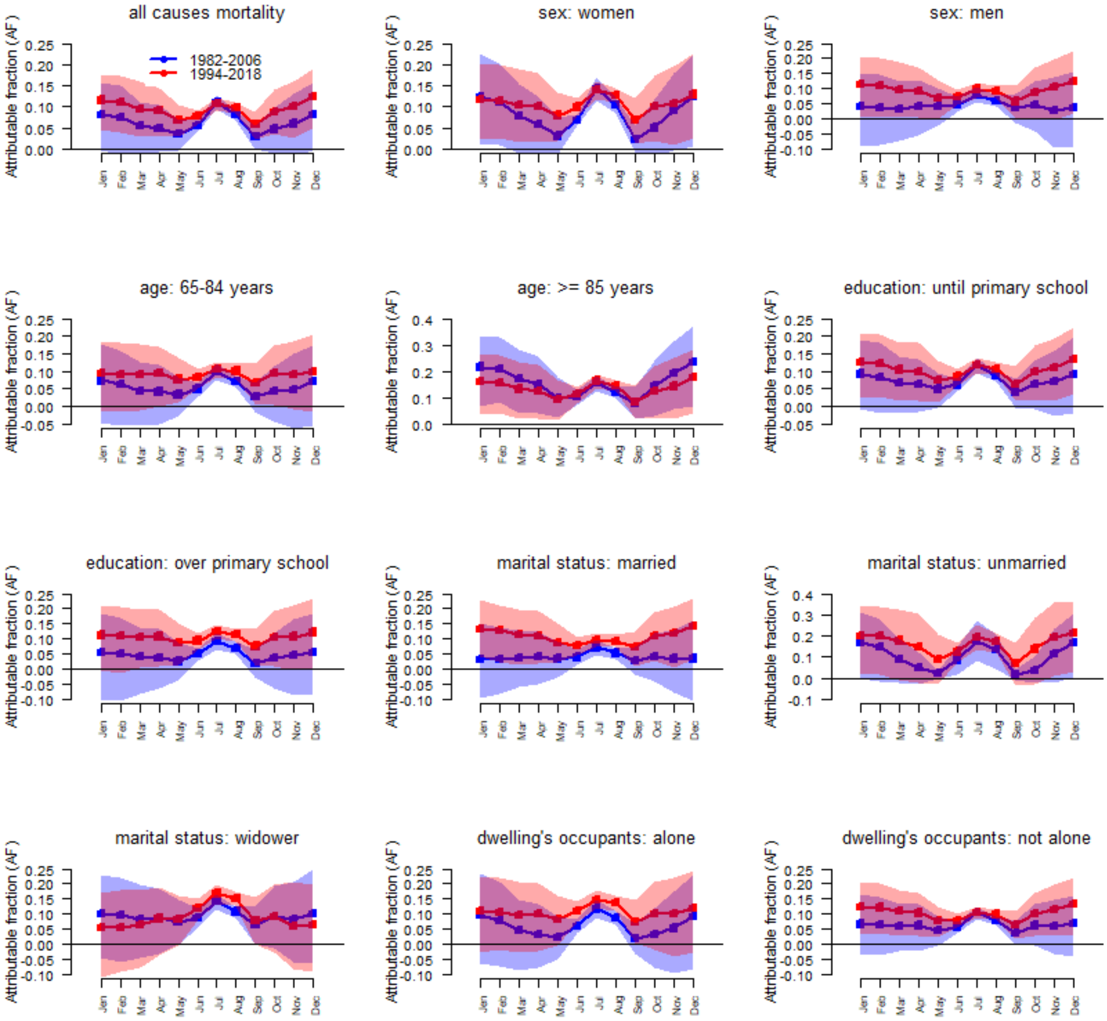

Figure 5 | Evolution of monthly attributable fraction of mortality by subgroup, 1982-2006 *vs* 1994-2018
1982-2006 (in blue) and 1994-2018 (in red)

Discussion

To the best of our knowledge, this is the first study in which the evolution of the impacts of temperature on mortality is investigated among population categorized by sex, age, education, marital status, and household's occupants. Results of this investigation contributes to comprehensively understand the overall temperature-mortality trends, reporting evolution of risks in relation to social inequalities across the last decades, under cold and hot conditions. This allowed us to provide a more specific overview on how different drivers affect the temperature-mortality relationships. Results suggested that the effects of cold and heat varied differently by subperiods and subgroups. In fact, our analysis demonstrated how - despite the considered subperiod - women are characterized by greater risks under hot and cold conditions in respect to men. Similar consideration can be derived for the elderly in respect to the youngest subgroup, who, however, demonstrated a light decreasing trend in risks. More difficult to interpret are the risk trends related to education, since - despite the increasing risk – the more educated were found to be more vulnerable under hot conditions, while those less educated were more vulnerable under cold temperatures. Finally, as previously found in another study conducted by the authors (27), individuals living in conditions of isolation (e.g., widowers) were characterized by higher risks, with an increasing vulnerability throughout time. Moreover, cross-linkages between groups were visible. In fact, the profile of women, the elderly, the less educated, and the most isolated shared more similarities between them than the others subgroups, probably due to the fact that aging is very feminine in Italy as well as in Europe (10,24). In this regard, since the death records referred to the past decades, it is reasonable to assume that women have been generally characterized by lower level of education and higher level of isolation, given the more advanced age at which they died. Contrary to the existing literature (14,19), our analyses showed a general increase in the risks due to cold and hot conditions, findings which have substantial implications for climate change health adaptation policies.

In the analyses, MMTs increased in parallel with the rise in mean temperature along the study period, for all the subgroups. This warming is consistent with findings of previous studies across Europe (15,16,35). For instance, in Spain the overall MMT increased by 0.7°C from the 1980-94 to the 2002-16 subperiods (16), while in France it increased by 0.4°C in winter and by 0.6°C in summer between the 1982-95 and the 1996-2009 subperiods (35). While some of these studies support the hypothesis that increased MMT is concomitant with increased temperatures through human adaptation over time (15,35), our analyses demonstrated what was expressed by Achebak et al. (16). In particular, the simultaneous timing of increases in MMTs and mean temperatures, suggested that the temporal evolution of risks (and therefore of AFs) is closely associated to changes in the shape and slopes of exposure-response curves, instead of on MMTs evolutions and temperature warming.

Results on RRs and AFs under hot temperatures, revealed an increasing trend that has not been found in other investigations over Italian urban areas (14,36). These could be attributed to the fact that the periods under analysis were different and there was not such temporal continuity in these studies. In parallel, results related to cold temperatures highlighted also an increasing trend, confirming the theory by which “countries with mildest winter climates exhibit the highest variations in seasonal cold mortality” (28,38). Based on these findings, two considerations necessitate further explanations. Firstly, the maladaptation to heat over time might be attributed to the fact that approximately half of Turin residents born in the south of Italy and immigrated in the city during the 1950s/1960s (24). By origin, this population was genetically and phenotypically more heat-adapted than the natives, due to more extreme heat conditions in the South of the peninsula. Over time, due to the acclimation processes, there may have been a loss of this resilience against heat for these population groups. Inversely for cold, the rationale is not so intuitive. Secondly, Turin - like many cities in other European regions - has a low proportion of institutionalized elderly, due to a lack of supply on the one hand (e.g., long waiting lists), and to a cultural attitude towards home care of the elderly from family members on the other (24). This may have been especially impactful in relation to heat, since the health care residences were all air conditioned only after the 2003 heat wave.

Mortality risks by sex revealed an enhanced vulnerability over time to heat for women, while risk trends due to cold were similar among the two sex subgroups. To date, many studies confirmed how risks and AF due to heat is often higher in women (10,16), while risks due to cold is generally higher in men (20,39). This heterogeneity within sex subgroups might be related to socio-economic, cultural and health factors (16), which can differ between women and men, but also between age classes (20). In fact, in relation to age, we observed a decrease in vulnerability to heat in the oldest group, which is often the most vulnerable to extreme temperature conditions (27). However, this decrease in risk was not observed in individuals aged 65 to 85 years. Findings on previous studies by age differences were mixed (13,40). In accordance with these analyses, a decrease in AFs have been found in de'Donato et al. (40) for the 85+ age group under hot conditions, while Almendra et al. (19) highlighted higher cold-related mortality for the elderly, trend which increased with ageing. In this context, several aspects need further explanations. First, in 37 years of time series the change of birth generations is a critical point. Thanks to more advantageous living conditions, the entry into old age of new post-II war baby boomers led to a steady increase in the longevity of Turin's elderly (24). Nevertheless, this aspect will be more visible in individuals who are now around 65-84 years. Secondly, a flow that could influence the risk trends over the last subperiods could be attributable to the enlargement of the first post-I war baby boomers, which nowadays are over-90s (24). Another important phenomenon is the "frailty bias": premature mortality (i.e., under 70 years) reaps the frailest in some vulnerable categories, while letting them survive in more advantaged social categories (41). This could cause the less educated and lonely to be more resilient, since the frailest have been already subjected to premature mortality. Therefore, as a consequence, the strongest ones survived (42). In support of this reasoning, our results highlighted higher RRs for subgroup characterized by lower education, with a stronger increase for the most educated under hot conditions. Similar RR values and trends have been observed for the "most isolated", which exhibited an increase of vulnerability over time. In this context, a low income (indirectly related to single person salary/pension) (43) together with the stress due to loneliness may contribute to degrade even more the state of health (44,45). In contrast, different trends have been observed under cold, which highlighted a decreasing trend in RR especially from the central subperiods onwards. About relatively warm countries, literature explained how the elderly often fail to wear protective clothing and often do not remain indoors (46), which implies a lack of knowledge and awareness of safe temperatures (47). This could bring this population more exposed to cold weather conditions. But, over the years, the school reform in Italy seems to have improved the average level of education, while also providing more opportunities for the most vulnerable groups (24). This may have increased the level of education of the elderly population as well as the degree of awareness, resulting in a decreasing trend under cold temperatures over time.

To the best of our knowledge, this is the first time in which cold- and heat- trends in sex, age, education, marital status, and household occupants have been analysed within a Southern European urban context.

Strength and limitations of this work

Through the application of a flexible modelling framework which estimated the cold- and heat- mortality associations over time, our study provided an original contribution able to capture the evolution of mortality under extreme percentile of temperatures within an Italian urban context over the last decades. In the state-of-the-art literature, most analyses compare the absolute number of deaths occurring during heatwave or cold-spell events (48) or estimate aggregated RRs and/or AFs at an aggregate level, aspect which might mask within-country/urban trends (11,49). In this sense, our results could support policymakers in understanding how these temperature impacts can evolve within different population subgroups. Further, to our knowledge, our study covers the longest period in which changes in education, marital status and household occupants have been investigated. However, some limitations must be acknowledged. Despite the importance of seasonal influenza and air pollution – which could affect the estimates on effects of cold on population susceptibility - we did not disentangle these confounding factors due to the lack of data. Nevertheless, these factors should not confound the outcomes of these analysis since the aim was related to the long-term trend that is not collinear with any known phenomenon of change in the prevalence of influenza infections between years. Moreover, their confounding role is currently under debate in research (11,19,22). In addition, we did not include the causes of death due to the limitation of available years during the study. Finally, the inclusion of urban design parameters as well as the evaluations of specific adaptive measures to recommend based on these results (such as the use of heating and cooling systems, the greenery of a city or priority actions depending on the most deprived neighbourhoods), which could contribute to mitigate the risks under heat- and cold- conditions, were not considered. Notwithstanding, subsequent comprehensive spatiotemporal analyses, inclusive of all these aspects (i.e., climate-urban health-inequalities elements) is under development in a further dedicated scientific study.

Conclusions

Understanding how populations have adapted locally to cold and heat in each specific urban context in the last decades, is important for determining future city planning. In this context, findings from our study indicated that although extreme temperature events are arising over time in Turin, increases of mortality due to both cold- and heat- temperatures has been observed over the last decades. After the 2003 heat wave in Europe, it has been shown that health consequences may be avoided or partly reduced through the activation of local alarm systems, such as national heat plans (14,52) or winter seasonal health plans (51,52). Although these alert systems increase public awareness and improve the efficiency of existing health services, they do not necessarily prevent risks in a homogeneous way (23,48). Adequate public health responses must take into consideration the local context, by considering the observed mortality risks among different socio-economic categories, such as sex (women vs men), age (younger vs older), and socioeconomical status (e.g., educational level or marital status conditions) (24). This study demonstrated the need to structure simultaneous cold and heat assessments within urban areas, with the objective to assess - on a local base - whether policies during colder periods are also needed in more temperate countries, beside those focusing only on summer. Finally, although the results of this study suggested a general increase of the mortality risk for each analysed subgroup, specific drivers of such a change still need to be identified. For this reason, it is necessary to maintain a continuous and updated research and local management approach.

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Supplementary Materials

S.1] Demographic and socio-economic trends over the time

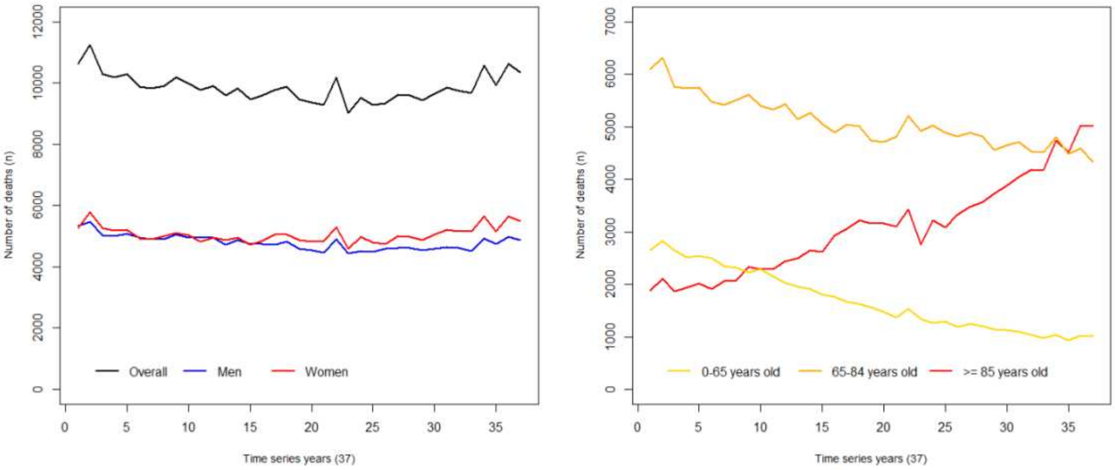


Figure S1 | Demographic changes over time
Evolution of the number of deaths sex (left) and age (right) in Turin, 1982-2018 (37 years of time series)

S.2] Minimum Mortality Temperature: estimates and confidence intervals by all-causes mortality

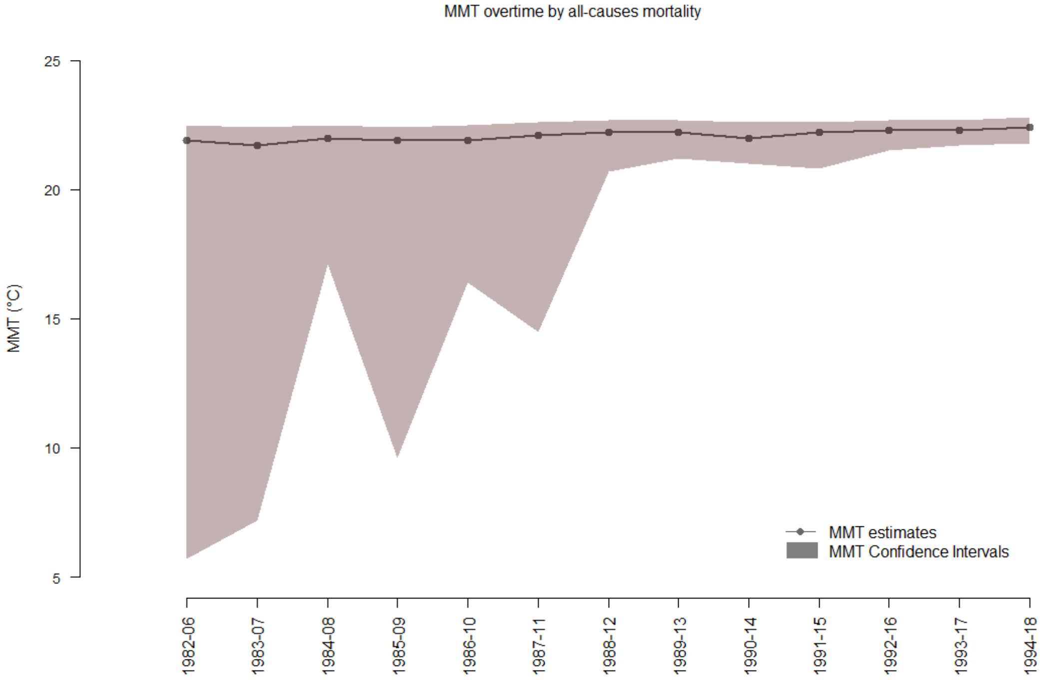


Figure S2 | Minimum Mortality Temperature by all-causes mortality
Minimum Mortality Temperature estimates, trends, and confidence intervals for each of the 13 analysed subperiod

S.3] Sensitivity analysis for modelling choices

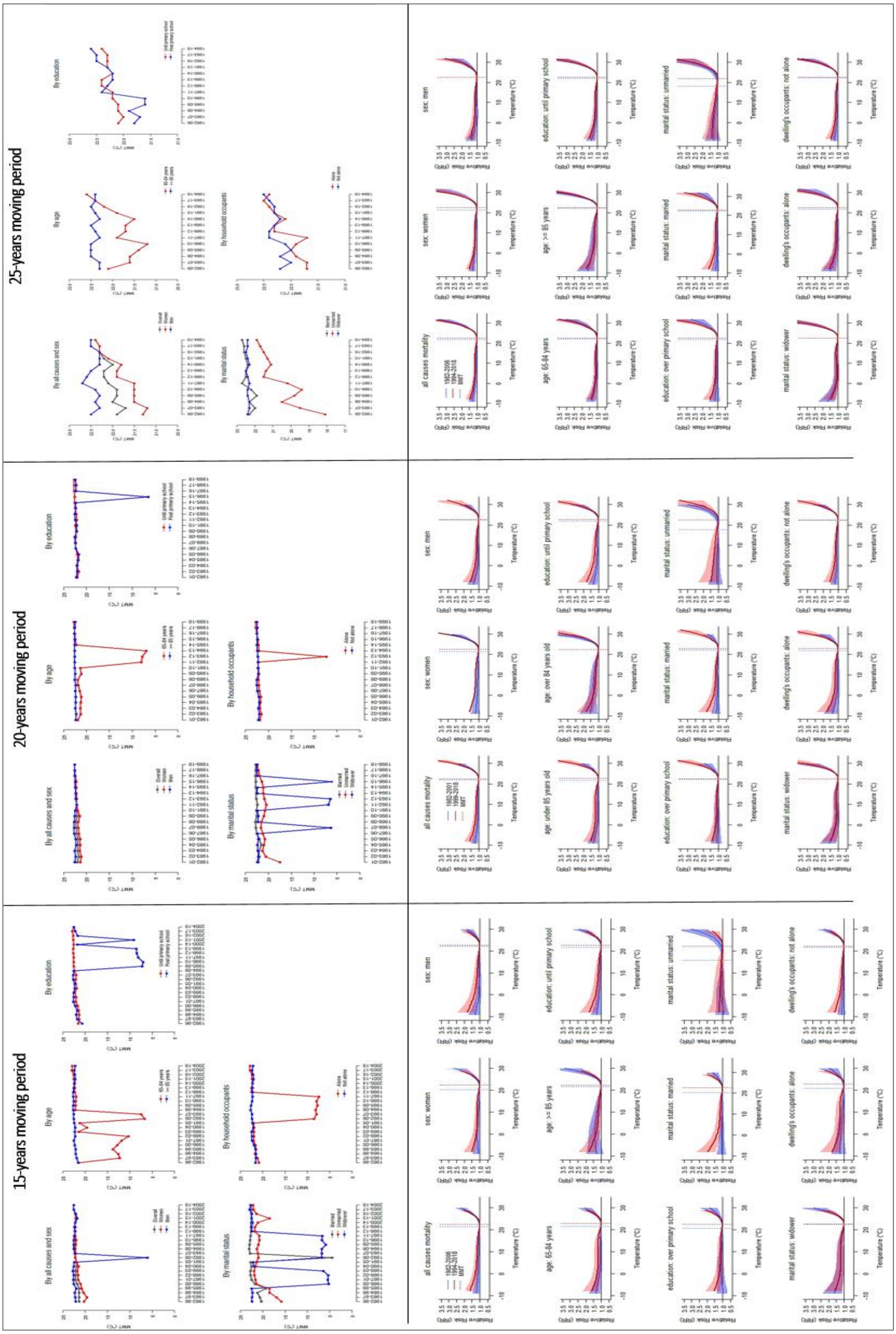


Figure S3.1 | 15-, 20- and 25- years moving periods
Minimum Mortality Temperature trends and Relative Risk curves comparison

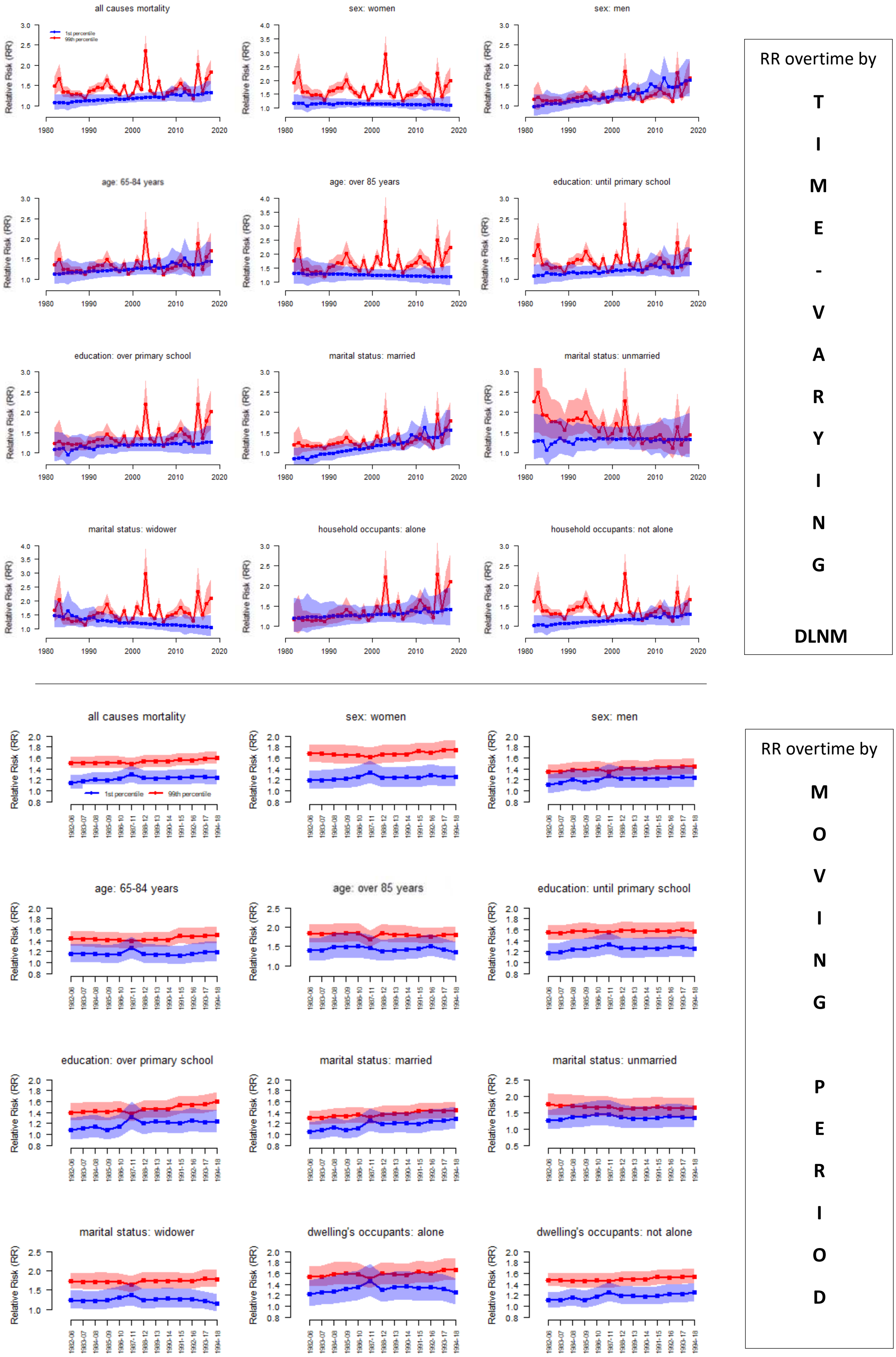
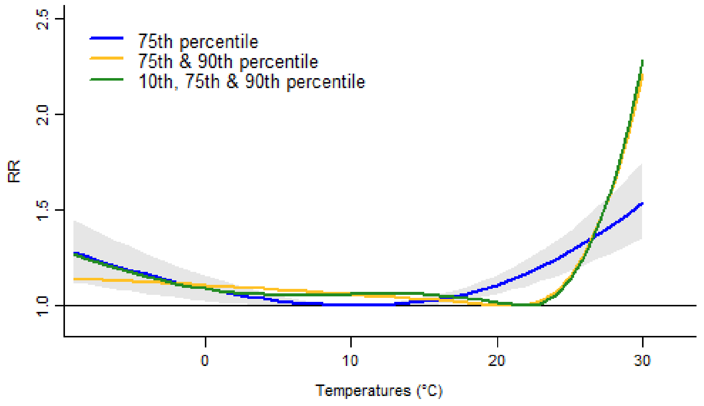


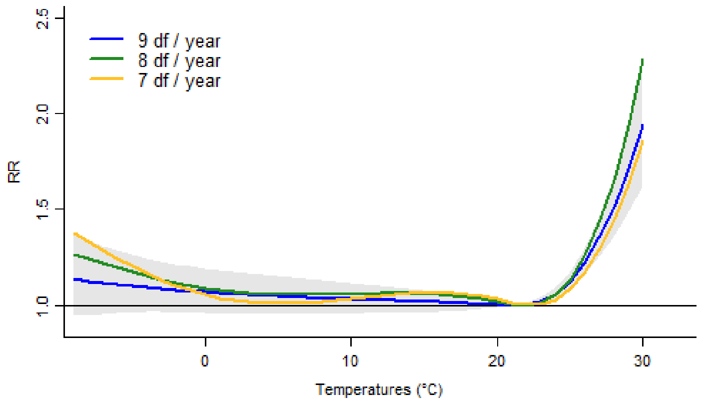
Figure S3.2 | Time-varying DLNM and 25-years moving period
Relative Risk comparison by subgroups and models

S4] Sensitivity analysis for modelling choices

a] Exposure-response function: knots



b] Exposure-response function: degrees of freedom



c] Lag-response function: lag period

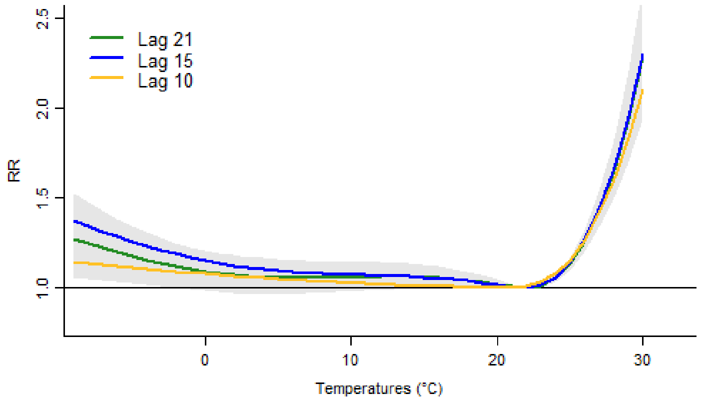


Figure S4.1 | Sensitivity analyses by all-causes mortality looking at knots (a), degrees of freedom (b) and lag period (c)

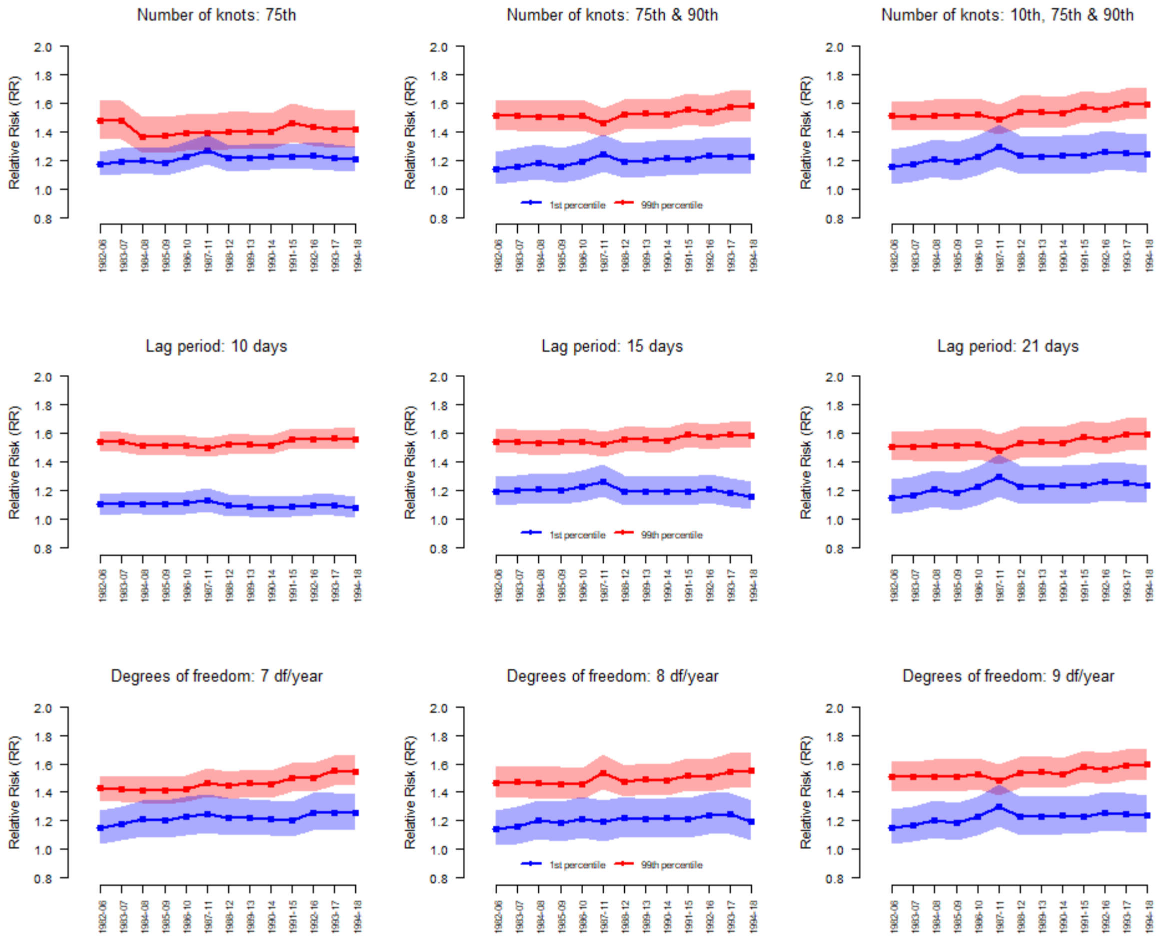


Figure S4.2 | Sensitivity analyses of the trends in Relative Risk, by the number of knots, lag period and degrees of freedom

CHAPTER III

CONCLUSIONS

This section provides the conclusions of the PhD dissertation by summarising the key findings in relation to the literature review [Paper I] and the two empirical studies [Paper II and Paper III]. Their contribution to the state-of-the-art literature is discussed thereof, followed by a series of insights that may be of relevance to health policymakers for the urban case study under investigation. Strengths and limitations are then presented to underline the value of the research as well as its weaknesses. Finally, the section ends with observations on the research article under development [Paper IV], with further routes of advancement for future research.

Final comments

Although there is extensive literature on the impacts of extreme temperatures on human health in urban areas, a persistent research gap remains with reference to the inclusion of social inequalities and built environment characteristics within environmental epidemiology studies. At the micro scale, the aim of this thesis is to explore and advance the knowledge on risk evolution of temperature-mortality associations looking at the nexus between health, social inequality, and the built environment in Turin (Italy). In parallel, at the macro scale, the objective is to define a step-by-step methodology to evaluate - qualitatively and quantitatively - the drivers of cold- and heat- attributable mortality risks in different urban areas, which are in turn characterized by different factors, climates, and drivers of change. Aims and research questions are made explicit in the previous sections, therefore a brief reference to the key takeaways is here outlined.

The initial review investigates how socio-economic factors together with the climate hazard and the urban parameters influence the nexus between extreme temperatures (i.e., heat) and the health outcomes ($\mathbf{Q}_1$ and $\mathbf{O}_1$, Paper I). Overall, findings demonstrate that a detailed identification of elements influencing population sensitivity as well as the consideration of enhanced exposure conditions are necessary to facilitate the comprehension of the context-specific form of the temperature-health nexus and, thereby, to implement effective adaptation measures for the health sector. Identification of the relevant variables within each specific urban system is the first step to determine drivers of inequalities with regards to urban populations, both across and within urban areas. In fact, vulnerability and risks are not a simple outcome of temperatures, but they are produced in and by society.

Such vulnerability can change in accordance with the geographical and socio-economic context and may have different meaning in certain places than in others. To demonstrate this theory, the first observational study investigates heat-health risks by sex, age, education, marital status, and household occupants in Turin, reporting overall cumulative associations by each subgroup (**Q_2** and **O_2**, Paper II). By analysing these associations for 37 years, results suggest that the effects of heat on mortality varied by each analysed category, with higher RRs for women, the oldest and for those who lived alone (i.e., unmarried, separated and divorced, widower and alone subgroup). In contrast, in relation to education, risk values are higher for women with relatively lower levels of education, while in men the stronger effects of risk correspond to those with higher education. These differences are probably attributable to local phenomena, such as the influence of the migration pattern from the south of Italy during the city industrialization processes. In terms of new findings, this study provides a more specific understanding on how different drivers of inequalities affected heat stress in a South-European urban context over the last decades.

In addition, understanding how urban populations have adapted locally to cold and hot temperatures over the past decades is needed to guide future city planning. This evidence can provide greater detail and support policymakers in understanding how population risks change over time, and how external policies influence these adaptation processes. With this purpose, the second empirical study, following the second quantitative phase of the step-by-step methodology, contributes to understand the overall temperature-mortality trends, reporting evolution of risks under cold and hot conditions across the last decades, diversified by subperiods and social inequality subgroups (**Q_3** and **O_3**, Paper III). Findings from this research indicate that although extreme temperature events are increasing over time, increases of mortality due to both cold- and heat- temperatures has been observed over the last decades, suggesting an overall maladaptation to ambient temperatures by subperiods and subgroups in Turin. Through the application of this flexible modelling framework, this study demonstrates the need to structure simultaneous cold and heat assessments within urban areas, to evaluate whether policies during colder periods are also needed in more temperate countries besides those focusing only on summer, despite the climate warming. Furthermore, although adaptation measures in place could improve the efficiency of existing health services at the local level, they do not necessarily prevent risks in a homogeneous way.

Finally, further details on how these risks are diversified by sub-urban areas is therefore a necessary step (**Q_4** and **O_4**, Paper IV). This because, to address inequalities in a climate change perspective, adaptation measures require specific insights about the unequal distribution of risks across distinct sub-urban areas as well as on different population subgroups.

Strengths and Limitations

The main strengths of this PhD thesis lie in the following aspects.

Through the analysis of the literature - which includes references on health, socio-economic factors and on indoor and outdoor built environment characteristics - Paper I provides a state-of-the-art understanding on which are nowadays the main aspects that contribute to increase vulnerability of populations to extreme temperatures at the urban scale.

In relation to Paper II and Paper III, several aspects need further attention:

a. the very long daily record-linkage dataset based on mortality registry and municipal census permits to develop the longest environmental epidemiological analyses on social inequalities nowadays available in Italy[35];
b. in order to show that the used climate dataset reproduces well the climatology of the case study (i.e., evaluate the uncertainty), a comparison of the used mean temperature time series with other climate datasets and the local meteorological station has been provided for the whole study period[22];
c. the long exposure-outcome associations on a singular urban scale permits to define the adaptation and evolution of population risks over time by looking at social inequalities differences;
d. the development of a step-by-step methodology based on flexibility guarantees these analyses to be reproduced in different contexts, location, and culture, with different time periods and for a multiplicity of climate change impacts and phenomena (e.g., air pollution).

In parallel, the empirical studies that constitute the core of this PhD thesis share some common limitations that need to be acknowledged. First, an evaluation on specific causes of deaths was not possible due to limitation of available years during the study period, reason why the present research did consider all-causes mortality. Nonetheless, all-cause mortality datasets are often used in these types of research because of both the lack of available data and the absence of a uniform definition of temperature-related death[36,37]. Second, the inclusion of individuals younger than 65 years was not feasible, because of the small number of daily deaths counts recorded for those age ranges, which did not guarantee model convergence and optimal fitting. Third, despite the importance of air pollution (especially PM_{10} in winter and O_3 in summer) and seasonal influenza (in winter), a systemic control in the statistical models has not been explored, due to the lack of data for the reference period. However, available research on the confounding effect of air pollution demonstrates a limited or no modifying effect by environmental factor[38,39], while the role of influenza in the temperature-mortality association is currently under debate[40,41,42]. In addition, these analyses have not made use of combined indices of temperature and relative humidity (i.e., maximum apparent temperature), since it has been proven that the use of these indices do not predict mortality in a more reliable and robust way than single indicators (i.e., mean temperature)[43,44]. Finally, the spatial distributions of social inequalities as well as the specific information on urban design and adaptive measures in place are not included in the presented articles, although these aspects may contribute to understand how susceptible population is distributed within sub-urban areas and how the built environment influence on the improvements in heat- and cold- mortality attributable risks. Details on this investigation are clarified in the next section.

Future Research and Developments

The findings of this PhD may enable health policymakers to prioritise local adaptation measures based on social inequalities and on evidence related to the built environment characteristics of the urban area under investigation. To further refine the step-by-step methodology, the most vulnerable population subgroups and sub-urban areas need to be geo targeted to plan ad hoc adaptive interventions ($\mathbf{Q}_4$ & $\mathbf{O}_4$, Paper IV). The spatial distributions of vulnerabilities and risks, in fact, help to understand in detail how the sensitive population is distributed within the different areas of a city, by also considering the information of the outdoor (and indoor, if available) urban elements which could contribute to influence the heat- and cold- health associations at the local scale. For this purpose, a spatiotemporal analysis, inclusive of these aspects, is already under development through the adoption of a meta-analysis based on DLNM models, which examine each district (8) and neighbourhood (23) of the city of Turin separately. Figure 2 shows the processes of the analysis (left side), together with the preliminary results from the meta-analysis by neighbourhoods (right side). These predictions will be compared with the estimates obtained from the incorporation of distinct urban parameters in the meta-analyses, to assess whether - and how - the characteristics of the urban environment influence the risks of mortality attributable to cold and heat by demographic and socio-economic subgroups.

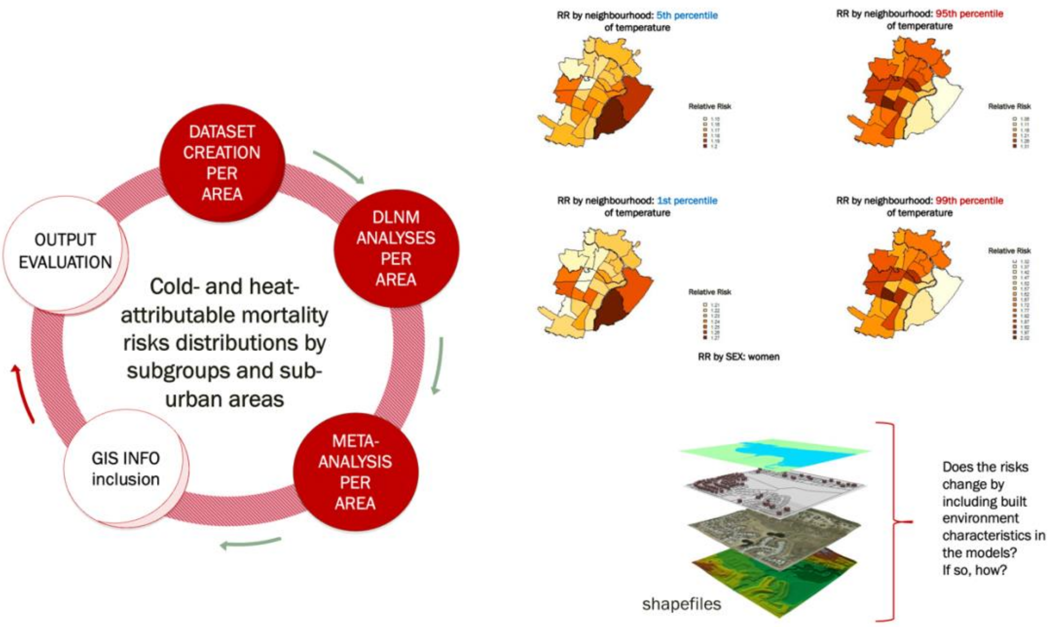


Figure 2 | Paper IV: methods of the analysis (left) and preliminary results (right) by women

Starting from the results of these analyses, a range of activities could be performed. First, a multi-dimensional risk assessment within the city of Turin allows to identify more precisely where to start to implement preventive adaptation measures based on the most affected sub-urban areas and on the most exposed population subgroups. A deep consideration of all the elements related to the climate-urban health-inequality nexus provide several benefits in a view of effective local adaptation action in the short, medium, and long term. In fact, integrating environmental equality issues into urban and infrastructure planning underpins the decision-making process. Some examples of adaptive measures based on the most exposed people and areas could refer to the establishment of neighborhood social programme to enhance the support of the most vulnerable subgroups (i.e., elderly), a reinforced inclusion of environmental and health equality issues in local strategies and plans, or an increased public participation in planning and decision-making processes affecting the local environments of people. Second, an evaluation of the observations could be used as a primary source of information to determine climate change and health anomalies under different Shared Socioeconomic Pathways (SSPs). Moreover, since extreme temperature events do not only influence mortality but also other health outcomes, such as hospital admissions, additional research may be conducted by taking daily hospitalizations as the main object of the analysis. By combining these results with the existing ones, a more complete prospect of the impacts of extreme temperatures on the health of the population of Turin would emerge. Finally, following the change of risk perception since summer 2003, the Civil Protection Department and the Italian Ministry of Health established a national programme for the prevention of heat effects (HHWS). To date, this is the only national adaptation measure in Italy in relation to heat, however, the evaluation of its effectiveness in reducing health outcomes looking at the individual conditions is still inconclusive. In addition, health protection alert systems for winter periods are absent.

An understanding of the risks at the individual and at the community level, together with the involvement of local policymakers is therefore crucial to develop effective preventive measures against climate change impacts at the national, regional, and local scale, reason why this PhD thesis has been developed.

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DEPOSITO ELETTRONICO DELLA TESI DI DOTTORATO

DICHIARAZIONE SOSTITUTIVA DELL'ATTO DI NOTORIETA'
(Art. 47 D.P.R. 445 del 28/12/2000 e relative modifiche)

Io sottoscritto **MARTA ELLENA**
Nata a **TORINO** (prov.**TO**) il **26/09/1991**
residente a **TORINO** in **VIA PIETRO MICCA** n.**1**

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Autore della tesi di dottorato dal titolo:
Extreme temperatures in urban areas:
Assessment of Inequalities looking at High-Resolution Climate Data & Vulnerabilities associated with Socioeconomic Factors and the Built Environment

Dottorato di ricerca in **Science and Management of Climate Change**
(in cotutela con) **/**
Ciclo **33°**
Anno di conseguimento del titolo **2022**

DICHIARO

di essere a conoscenza:
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DICHIARO

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Specificare la motivazione:
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attualmente in fase di revisione presso un giornale peer-review, pertanto richiedo
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Data 18 / 03 / 2022 **Firma** Maria Elena

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Ai sensi dell'art. 13 del D.Lgs. n. 196/03 si informa che il titolare del trattamento dei dati forniti è l'Università Ca' Foscari - Venezia.
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Estratto per riassunto della tesi di dottorato

Studente: **MARTA ELLENA** Matricola: **956340**

Dottorato: **Science and Management of Climate Change**

Ciclo: **33°**

Titolo della tesi: **Extreme temperatures in urban areas. Assessment of inequalities looking at high-resolution climate data and vulnerabilities associated with socioeconomic factors and the built environment**

Abstract:

ITALIANO
Le proiezioni climatiche evidenziano aumenti di temperatura nelle regioni europee, con eventi estremi più intensi e prolungati per le città nel bacino del Mediterraneo. A causa delle emissioni antropogeniche ad effetto serra, la temperatura media annuale in Italia è aumentata di 1,1°C dal 1980. Lo scopo principale di questa tesi è quello di indagare le tendenze del rischio di mortalità da freddo e da caldo in relazione ai fattori socioeconomici, attraverso lo sviluppo di una metodologia flessibile e riproducibile in altri contesti urbani. Il caso studio di questa ricerca è strutturato su una serie temporale di 37 anni della città di Torino (Italia). I risultati mostrano un aumento delle tendenze di rischio sia in condizioni di freddo sia di caldo con associazioni eterogenee tra i diversi fattori che influenzano la vulnerabilità della popolazione allo stress derivante dalle temperature. Una migliore comprensione di come i sottogruppi di popolazione più vulnerabili si siano adattati su scala urbana e sub-urbana è essenziale per prevenire i rischi attraverso l'uso di risposte di salute pubblica mirate in previsione dei futuri eventi di temperatura estrema.

ENGLISH
Severe increases in temperature are projected in European regions, with more intense and prolonged extreme events for cities located in the Mediterranean Basin. Due to anthropogenic greenhouse emissions, the average annual temperature in Italy has increased by 1.1°C since 1980. The scope of this PhD thesis is to investigate trends in cold- and heat- mortality risk and burden by socio-economic factors, through the development of a flexible and reproducible methodology to apply in other urban contexts. The case study used in this research is based on a 37-year time-series of the city of Turin (Italy). Results demonstrated an increase in cold- and heat-attributable risk trends with heterogeneous associations across different factors influencing the population’s vulnerability to extreme burden of temperatures. A better understanding on how the most vulnerable population sub-groups have adapted at the urban and sub- urban scale is essential to prevent risks using targeted public health responses to adapt to future extreme temperature events due to climate change impacts.

Firma dello studente

Marta Ellena