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Urban vulnerability to temperature-related hazards: A meta-analysis and meta-knowledge approach

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ABSTRACT

Research on urban vulnerability has grown considerably during recent years, yet consists primarily of case studies based on conflicting theories and paradigms. Assessing urban vulnerability is also generally considered to be context-dependent. We argue, however, that it is possible to identify some common patterns of vulnerability across urban centers and research paradigms and these commonalities hold potential for the development of a common set of tools to enhance response capacity within multiple contexts. To test this idea we conduct an analysis of 54 papers on urban vulnerability to temperature-related hazards, covering 222 urban areas in all regions of the world. The originality of this effort is in the combination of a standard metaanalysis with a meta-knowledge approach that allows us not only to integrate and summarize *results* across many studies, but also to identify trends in the literature and examine differences in methodology, theoretical frameworks and causation narratives and thereby to compare "apples to oranges." We find that the vast majority of papers examining urban vulnerability to temperature-related hazards come from an *urban vulnerability as impact* approach, and cities from middle and low income countries are understudied. One of the challenges facing scholarship on urban vulnerability is to supplement the emphasis on disciplinary boxes (e.g., temperature–mortality relationships) with an interdisciplinary and integrated approach to adaptive capacity and structural drivers of differences in vulnerability.

1. Introduction

Urban centers are home to a large proportion of the world's population, economic activity, and physical infrastructure that are at risk from the impacts of increased temperatures, extreme cold and heat, heat islands and other hazards climate change is expected to exacerbate. A growing number of studies exists on urban vulnerability; however, existing case studies are based on conflicting theories and paradigms. While some scholars argue that the diversity of approaches is necessary to address the full complexity of the concept, and that a multiplicity of frameworks can be complementary, competing paradigms can also undercut the ability of researchers to find common patterns of causation (Adger, 2006; Birkmann, 2006; Eakin and Luers, 2006; Romero Lankao and Qin, 2011). Another common tenet is that urban vulnerability depends on context (Füssel, 2007). The factors that make the city of Delhi in India vulnerable to climate hazards such as extreme temperatures are not the same as those that make urban areas in nations such as the United States vulnerable. Therefore, one overarching question remains unresolved: Is it possible to go beyond varied case studies and different research traditions to develop an integrated understanding of urban vulnerability by identifying repeated patterns and relationships? We argue that although context matters, it is possible to draw some common patterns of vulnerability across urban centers that may help to develop a common set of tools to enhance response capacity within multiple contexts.

This paper conducts an innovative meta-analysis and "meta-knowledge" exercise aimed at thoroughly and systematically analyzing the state of our knowledge on urban vulnerability to temperature-related hazards. Meta-knowledge, or "knowledge about scientific knowledge" (Evans and Foster, 2011), incorporates and builds on traditional meta-analysis methods by examining not only the *findings* of prior research on a given topic, but also the *disciplinary matrixes*, *research paradigms or research programs* (i.e., research questions, data and methods, see Kuhn, 1962 and Lakatos and Musgrave, 1970) that have been used to generate these findings. In this way, we are better able to identify and highlight what is known about urban vulnerability, as well as what is *not* known. Because urban vulnerability is a broad topic, in this paper

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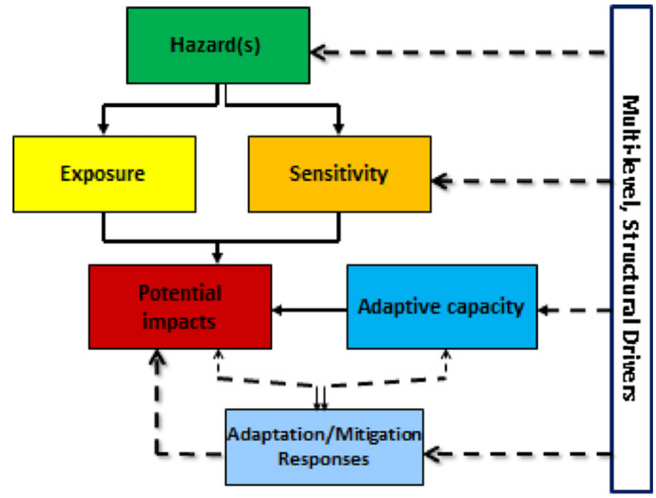
we limit our focus to the impacts and risks associated with temperature-related hazards, the most studied area in the published literature on vulnerability to climate change.

Although some reviews on the health impacts of temperature-related climate hazards have already been conducted (e.g., Basu and Samet, 2002; Reid et al., 2008; Basu, 2009; Gosling et al., 2009), our meta-knowledge approach sets us apart from these other studies. Our analysis uses a comprehensive conceptual framework of urban vulnerability to climate and environmental change which synthesizes the different paradigms that have typically been applied to the study of vulnerability. These paradigms, along with our "meta-framework" are described in Section 2. Using this framework, we systematically reviewed and extracted data from 54 case studies on the relationships between high temperature and human mortality, covering urban areas in all regions of the world. Section 3 details our research methods, which include a vote-counting approach to examining not only previous findings on the determinants of urban mortality associated with high temperature, but also the research questions, methods, and narratives articulating these findings.

We present the main results of our analysis in Sections 4 and 5. Each specific finding (e.g., sensitivity of the elderly to extreme temperatures) is presented in terms of both the amount of empirical evidence available in the literature and the level of agreement across different studies (Mastrandrea et al., 2011). For only one determinant, hazard magnitude, there was a large amount of evidence and a high level of agreement across studies on the relationship between urban vulnerability and temperature. Rather than proving that this determinant is the only one that "matters," however, this was the result of something our meta-knowledge approach in Section 5 illuminates: the dominance of a single research paradigm, *urban vulnerability as impact*, which focuses primarily on the hazards and tends to underemphasize or take a limited view of social and/or structural determinants of vulnerability. Section 6 discusses the implications of these results to help guide future research on this topic that may lead to improved policymaking to reduce vulnerability in urban areas.

2. Conceptual framework

Our approach starts with a meta-framework that synthesizes the diverse lineages of urban vulnerability research into a single, unified model. In this model, which we developed in a previous paper (Romero Lankao and Qin, 2011), urban vulnerability to environmental change describes a complex and dynamic reality comprised of several dimensions (see Fig. 1). Urban vulnerability, or the potential for people in urban areas to be negatively impacted by climate change, is a function of: (a) *hazards*, i.e., probable or looming perturbations and stresses to a system; (b) *exposure*, i.e., the extent to which urban populations are in contact with, or subject to hazards; (c) *sensitivity*, i.e., the degree to which subsets of urban populations are susceptible to hazards with patterns of susceptibility often based on demographic characteristics or medical conditions; and (d) *adaptive capacity*, or the ability to avoid or lessen the negative consequences of climate change based on access to resources, assets and options people draw on to moderate potential damages, to cope with the consequences, or to introduce policy changes to expand the range of variability with which they can cope. Adaptive capacity is different from actual coping and adaptation actions (O'Brien et al., 2004; Birkmann, 2006; Gallopín, 2006; UN/ISDR, 2009; Romero Lankao and Qin, 2011, see Fig. 1). Each of the dimensions of urban vulnerability has different components, determinants or factors. For instance, hazards are defined by such components as their magnitude and frequency, while sensitivity and adaptive capacity are defined by factors such as age, preexisting conditions, income,



Source: Romero-Lankao and Qin (2011).

Fig. 1. A conceptual framework of urban vulnerability to global climate and environmental change.
Source: Romero Lankao and Qin (2011).

dwelling type and quality and access to social networks and health services.

Meanwhile, different research programs on urban vulnerability tend to focus on different subsets of these dimensions. These programs mirror those on vulnerability in the general environmental change context: natural hazards, political economy (or ecology), and ecological resilience.

Coming out of the natural hazards tradition, research on *urban vulnerability as impact* conceives vulnerability as an outcome determined by *exposure* to *hazards* such as temperature, *sensitivity* of urban populations and the resulting or potential *impacts*. There are mainly two types of research within this paradigm. The first explores how changes in parameters such as temperature, air pollution and age relate to such impacts as fluctuations in mortality. The second group, also often called top-down impact assessments, applies a scaled-down version of global climate change scenarios to urban centers to model how parameters such as temperature will evolve in the future. Future climate hazards and their effects are estimated under particular climate change scenarios. In some cases, adaptation options under plausible socioeconomic scenarios are also explored to see how those impacts can be reduced.

Drawing on a political economy approach, a research program on *inherent urban vulnerability* sheds light on *adaptive capacity*, as well as *structural drivers* creating differences in vulnerability among and within urban populations. Important factors include: (a) the demographic and socioeconomic characteristics of urban residents and their available assets; (b) the capacity of urban populations to foresee, resist, react to, recover from, cope with, and take advantage of hazards and stresses; and (c) the way in which governance and policies (e.g., infrastructure provision, health and education) influence those characteristics and adaptive capacities.

An *urban resilience* approach points to the fact that urban populations and economic sectors are not only negatively affected by hazards, but also have the ability to bounce back, recover from and even take advantages of some stresses. It also sheds light on other relevant dimensions, explaining the differentiated nature of climate impacts, namely the dynamics of cities as socio-ecological systems (e.g., with a physical or material dimension given by their built environments and their ecological footprints); urban populations and authorities' flexibility, diversity and capacity for learning and innovation; and some of the mechanisms by which long-term processes and short-term triggers interact to shape the options and constraints to urban adaptation (Leichenko, 2011; Romero Lankao and Qin, 2011).

In this paper, we use our comprehensive conceptual framework to systematically explore not only previous findings on the determinants of urban mortality associated with high temperature, but also the research questions, methods, and narratives articulating these findings. Before we do so, however, we will briefly describe our study methods and design.

3. Methods and study design

A common approach to moving beyond case studies has been to distinguish between specific and generic determinants of vulnerability and to build indicator frameworks (i.e., proxy indicators and indices) that are often aggregated into vulnerability indices at a national, regional or local level within a country (Yohe and Tol, 2002; Brooks et al., 2005; Cutter et al., 2008). Notwithstanding their usefulness and wide application, indicator-based methods face some limitations (Manuel-Navarrete et al., 2007). With some exceptions (e.g., Cutter et al., 2008; Cutter and Finch, 2008), the process of indicator selection often relies on untested assumptions about the determinants of vulnerability. Additionally, lack of data at various scales (especially in low-income countries) can lead to inaccurate calculations. Furthermore, vulnerability is determined by a diversity of dimensions and factors operating at different levels, which may hamper analysts' efforts to find standard indicator frameworks. This suggests the need to look for alternative methods, such as the syndrome approach (Manuel-Navarrete et al., 2007) and model-centered analysis of case studies such as meta-analysis (Young et al., 2006; Rudel, 2008).

The "syndrome" approach refers to identifying a typical co-occurrence of symptoms describing complex and dynamic phenomena. In contrast to causal networks of specific situations, syndromes are "repeatable patterns that can manifest in different parts of the world" (Manuel-Navarrete et al., 2007). Although effective in identifying causal interrelations among vulnerability symptoms of dynamic socio-ecological systems, syndrome analysis is essentially built on descriptive reviews and is limited in terms of the number of case studies that can be included.

Meta-analysis provides another approach for systematically investigating patterns of urban vulnerability. The techniques of meta-analysis can be used to find commonalities within a spectrum of research papers and methods that have grown around questions of global environmental change (Young et al., 2006). They involve the pooling of data that quantitatively examine whether causal relations described in individual papers (e.g., drivers of land use changes, determinants of food insecurity) hold more largely across a broader – or even the entire – literature (Misselhorn, 2005; Young et al., 2006; Rudel, 2008). Therefore, this method can be fruitfully combined with narrative literature reviews to formally synthesize the results of previous research, and is thus most suited to the purpose of this paper.

Although typical meta-analyses synthesize the results of independent empirical case studies, and thus help to address the question of where the scientific light has been shining, this light reflects particular research programs framing urban vulnerability in very particular ways (O'Brien et al., 2007) and leaves some of its dimensions and components in darkness. To shed light on both the well-lit and dark areas, we implement a meta-knowledge approach that deconstructs the research paradigms or programs on urban vulnerability. In other words, we examine the practices defining the dimensions and factors scrutinized and measured; the scientific questions asked; the methods and data applied to answer those questions; the analyses conducted; and the narratives of causation.

3.1. Selection of sample studies

For this project, we were interested in examining the empirical literature on urban vulnerability to climate change. However, since this is an extremely broad topic, we began with a review of studies examining one set of climate-related hazards, namely, temperature-related hazards. We focused on temperature for three main reasons. First, temperature is a major source of climate related mortality. Second, the links between changes in temperature and climate change are more direct and well-documented than other climate-linked hazards such as flooding/precipitation. Finally, the abundance of studies on the effects of temperature-related hazards on urban populations provided sufficient material to conduct a broad-based meta-analysis and meta-knowledge exercise and thus to provide information of relevance for decision making at the local level.

To identify studies to include in our review, we conducted a comprehensive literature search of available databases (Web of Science, BioOne, and Google Scholar) and references of articles selected from these sources. Since urban vulnerability is a relatively new area in climate change research, we focused our review on studies published over the past 21 years (1990–2011). In the first stage, 213 research articles were selected based on a brief review of the titles and abstracts of documents retrieved from a broad keyword search (see Table 1). All these articles explicitly examine determinants of vulnerability to environmental hazards

Table 1
Summary of sample study selection.

Inclusion/exclusion criteria	Selection outcome
Phase 1: Keyword search "vulnerability/mortality/health/adapt/risk/livelihoods/political ecology/resilience/system" AND "climate change/environmental change/hazards/disaster/heat/weather/temperature/flooding/storm" (with one word from each group for every search – e.g., "vulnerability" AND "climate change", "mortality" AND "heat", and "risk" AND "flooding") Only included research articles relating to urban areas and those which explicitly examine influencing factors of urban vulnerability to environmental hazards. Articles focusing only on cold temperature effects on mortality were not included.	213 articles were selected.
Phase 2: Excluded all articles not relating to temperature–mortality relationships.	128 articles remained.
Phase 3: Excluded all single-city studies of the *urban vulnerability as impact* lineage, except for five which cover cities not included in multi-city studies and one that uses remotely sensed data and spatial analysis.	73 articles remained.
Phase 4: Excluded articles only assessing potential changes in temperature-related mortality under climate change scenarios.	47 articles remained for full review.
Phase 5: Added seven relevant articles identified from references sections of the 47 sample studies.	54 articles were finally selected for the meta-analysis.

in urban settings. Studies focusing only on cold temperature effects on mortality were excluded from this research. Second; all articles not relating to temperature–mortality relationships were removed from the selections. Of the articles in the quantitative *urban vulnerability as impact* lineage, we only included multi-city studies in our meta-analysis because we thought their findings were more generalizable than those of single site studies, and because this allowed us to work with a manageable set of articles. However, five single-city studies in this group involve the cities of Beirut; Lebanon [16]; Christchurch; New Zealand [22]; Hong Kong; China [5]; Moscow; Russia [40]; and Shanghai; China [23], which are not covered by the multi-city studies. (*Note*: numbers in square brackets refer to paper IDs in Table 2.) Thus, they were kept in the sample to increase its geographical coverage. Another single-city study [26] from this research tradition was also included because it uses a relatively special type of data and analytic method (remotely sensed data and spatial analysis). The other four single-city studies included represented the *inherent urban vulnerability* or *urban resilience* lineages (since there are only a few studies in these categories).

Studies only assessing potential changes in temperature-related mortality under climate change scenarios were also excluded. This is because rather than on simulations, our focus was on empirical evidence of high-temperature related mortality across diverse case studies and on finding common patterns of determinants of urban health vulnerability to temperature-related hazards. Finally, we crosschecked the references sections of those articles selected for full review, and added seven relevant studies which were not captured in the original literature screening. Table 1 provides a summary of the selection of sample studies. As a result

Table 2
List of studies included in the meta-analysis.

Conceptual framework	ID	Article	Geographical region	Number of cities covered
Urban vulnerability as impacts	1	Almeida et al. (2010)	Europe (Portugal)	2
	2	Baccini et al. (2008)	Europe (multiple countries)	15
	3	Bell et al. (2008)	Latin America (multiple countries)	3
	4	Braga et al. (2002)	North America (USA)	12
	5	Chau et al. (2009)	East Asia (China)	1 (Hong Kong)
	6	Chestnut et al. (1998)	North America (USA)	44
	7	Chung et al. (2009)	East Asia (multiple countries)	4
	8	Conti et al. (2005)	Europe (Italy)	21
	9	Curriero et al. (2002)	North America (USA)	11
	10	D'Ippoliti et al. (2010)	Europe (multiple countries)	9
	11	Davis et al. (2002)	North America (USA)	6
	12	Davis et al. (2003)	North America (USA)	28
	13	Davis et al. (2004)	North America (USA)	28
	14	Dear et al. (2005)	Europe (France)	12
	15	Doyon et al. (2008)	North America (Canada)	3
	16	El-Zein et al. (2004)	Middle East (Lebanon)	1 (Beirut)
	17	Filleul et al. (2006)	Europe (France)	9
	18	Gosling et al. (2007)	North America, Europe, Oceania	6
	19	Guest et al. (1999)	Oceania (Australia)	5
	20	Hajat et al. (2006)	Europe (multiple countries)	3
	21	Hajat and Kosatky (2010)	North America, Europe, Oceania, Asia	64
	22	Hales et al. (2000)	Oceania (New Zealand)	1 (Christchurch)
	23	Huang et al. (2010)	East Asia (China)	1 (Shanghai)
	24	Iñiguez et al. (2010)	Europe (Spain)	13
	25	Ishigami et al. (2008)	Europe (multiple countries)	3
	26	Johnson et al. (2009)	North America (USA)	1 (Philadelphia)
	27	Kim et al. (2006)	East Asia (South Korea)	6
	28	Le Tertre et al. (2006)	Europe (France)	9
	29	Martens (1998)	North America, South America, Europe, Africa, Asia	20
	30	McMichael et al. (2008)	Latin America, Europe, Asia	12
	31	Medina-Ramón and Schwartz (2007)	North America (USA)	50
	32	Medina-Ramón et al. (2006)	North America (USA)	50
	33	Michelozzi et al. (2005)	Europe (Italy)	4
	34	Michelozzi et al. (2006)	Europe (Italy)	4
	35	Nicholls (2009)	North America, Oceania	2
	36	O'Neill et al. (2003)	North America (USA)	7
	37	O'Neill et al. (2005)	North America (USA)	4
	38	Pattenden et al. (2003)	Europe (multiple countries)	2
	39	Ren et al. (2008)	North America (USA)	95
	40	Revich and Shaposhnikov (2008)	Europe (Russia)	1 (Moscow)
	41	Sheridan et al. (2009)	North America (USA)	29
	42	Smoyer et al. (2000a)	North America (USA)	2
	43	Smoyer et al. (2000b)	North America (Canada)	5
	44	Stafoggia et al. (2006)	Europe (Italy)	4
	45	Stafoggia et al. (2008)	Europe (Italy)	4
	46	Stone et al. (2010)	North America (USA)	53
	47	Vandentorren et al. (2004)	Europe (France)	13
	48	Zanobetti and Schwartz (2008)	North America (USA)	9
Inherent urban vulnerability	49	Browning et al. (2006)	North America (USA)	1 (Chicago)
	50	Klinenberg (1999)	North America (USA)	1 (Chicago)
	51	Wolf et al. (2010)	Europe (UK)	2
Urban resilience	52	Harlan et al. (2006) and Harlan et al. (2008)	North America (USA)	1 (Phoenix)
	53	Ruddell et al. (2010)	North America (USA)	1 (Phoenix)
	54	Uejio et al. (2010)	North America (USA)	2

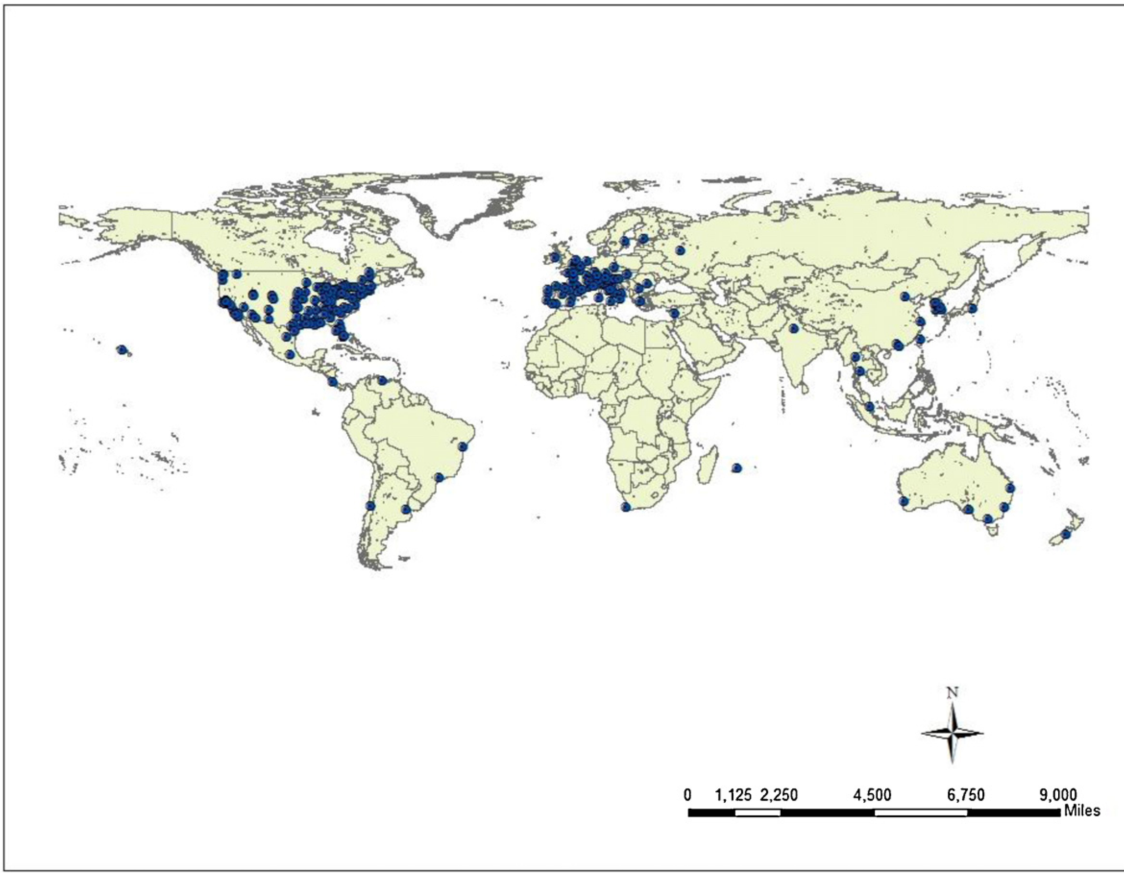


Fig. 2. Cities covered in the meta-analysis.

of this multi-criteria, stepwise selection process, 54 articles specifically addressing the influences of heat waves or elevated temperature on urban human mortality were identified for the systematic review and meta-analysis (see Table 2). Although these studies cover 222 cities on six continents, they are mostly focused on urban centers of Europe and North America (particularly the United States) (Fig. 2: map of study cities).

3.2. Meta-analysis and meta-knowledge methods

Our data extraction and synthesis followed a typical systematic review and meta-analysis approach (Littell et al., 2008). Our conceptual framework of urban vulnerability (Romero Lankao and Qin, 2011) served as a starting point to design and test an article review template and to agree on our own definition of concepts and fields (available upon readers' request). We then used this template to extract data from each of the 54 articles in our sample. First, we classified each article according to the dominant theoretical framework and approach it adopted. Second, each selected article was carefully reviewed by at least two members of our research team to ensure systematic and consistent data extraction. Variables influencing temperature-related impacts (mainly mortality) examined in the selected studies were identified and coded into components of the determinants of urban vulnerability (e.g., hazards, exposure, sensitivity) based on their conceptual relationships to temperature-related mortality.

Similar factors were aggregated into a single concept to combine findings from empirical studies pertaining to different research lineages. Findings for each influencing factor were labeled as positively related, negatively related, or unrelated to vulnerability based on statistical results or qualitative description. We also extracted information on the conceptual and methodological contents of each article, including the research questions and hypotheses, types of methods, types of data, level of analysis, and temporal scale.

Once data extraction for all articles was complete, we applied a vote-counting methodology, which is commonly used in recent applications of meta-analysis (e.g., Misselhorn, 2005; Prokopy et al., 2008). For the analyses focusing on research *findings*, each determinant was examined and its attributes were tallied to synthesize results from the 54 selected studies. Using an approach suggested by the Intergovernmental Panel on Climate Change to qualitatively assess the evidence in a scientific field (Mastrandrea et al., 2011), each determinant was then classified based on the *amount of empirical evidence* available in the literature and the *degree of agreement or consensus* across different studies (see Fig. 3 in Section 4).

Finally, to complete our meta-knowledge exercise, we also tallied and analyzed the theoretical paradigms, research questions, methods, data types, levels of analysis, and temporal scales involved in each study. Taken together, our methodology sheds light on what we know, under which research program (with its methods, questions and data analysis) it has been generated, and which questions remain unanswered in the quest to understand urban vulnerability to temperature-related hazards.

4. Meta-analysis: findings on the determinants of urban vulnerability to temperature-related hazards

The results of the meta-analysis indicate that urban vulnerability to temperature-related hazards has mostly been examined using thirteen factors: hazard magnitude (i.e., temperature level), population density, age, gender, pre-existing medical conditions,

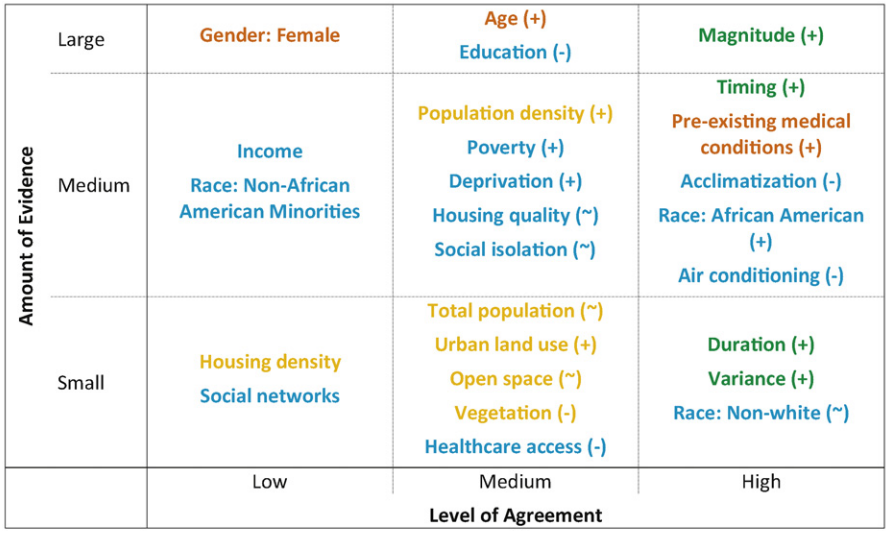


Fig. 3. Determinants of urban vulnerability, levels of evidence and agreement.
Notes: Text color denotes the different categories of vulnerability dimensions. Green = Hazard; Yellow = Exposure; Orange = Sensitivity; Blue = Adaptive capacity/adaptation. Symbols in parentheses denote the direction of the relationship between each particular factor and vulnerability that was identified in the majority of studies, in cases of medium or high level of agreement only. +, positive relationship (increases vulnerability); –, negative relationship (decreases vulnerability); ~, no relationship. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

education, income, poverty, minority status (African American, Non-African American minorities, and non-white), acclimatization, and access to home amenities such as air conditioning and swimming pools (Table 3). These drivers account for 66% of the total tallies of vulnerability determinants. Of these, only one determinant has been extensively studied (i.e., has a large amount of evidence) and shows a high level of agreement in its effects across different studies: hazard magnitude (see Fig. 3), while on the other extreme 19 determinants were explored but only by one paper each (available upon readers' request). Together age and education have abundant evidence but medium level of agreement. Gender, while extensively studied, did not show a consistent relationship with vulnerability across the different studies. Five indicators have medium levels of evidence and high agreement levels: hazard timing, pre-existing medical conditions, acclimatization, African American race, and home amenities. We organize the rest of this discussion around the different dimensions of urban vulnerability (hazards, exposure, sensitivity, adaptive capacity and adaptation) and their determinants.

4.1.1. Hazards

Hazards can be one-off extreme events of short duration (no more than a few minutes, hours or days), often striking with little warning. They can also be slow-onset events (e.g., increasing temperatures) as well as a range of subtle, 'everyday risks' that are the product of a variety of stress mechanisms (e.g., urban heat-island). Most studies find a positive correlation between hazard magnitude (i.e., temperature level) and mortality (Table 3). They confirm that the health effects of temperature do not follow a general linear form, but rather a V- or J-shape relationship, with deaths increasing as temperatures fall below or rise above certain threshold-values. The thresholds are noteworthy since they may be assumed as measures of heat or cold tolerance (Muggeo and Hajat, 2009); or as the 'comfort range' that changes depending on factors such as city location and age (Gosling et al., 2009) and that is expected to be affected by climate change.

Temperature is not the only hazard explored. Nineteen studies assess the influence of air pollutants as confounder or effect modifiers of the temperature–mortality relationship, yet their findings are mixed. Four papers [3, 14, 17, 39] find that air pollution modifies the relationship. Nine studies find that the magnitude of the air pollution impact appears to be considerably less than that of stressful weather or that the relationship is not consistent across the cities [1, 14, 22, 25, 38, 39, 43, 44, 48]. One [22] finds that both hazards are independently associated with increased daily mortality.

Other hazard attributes used in the effect estimation are timing, duration and variance of the hazard. Hazard variance is a measure of dispersion in the statistical distribution of a hazard – that is of how much a set of values deviate from their mean value. Examples would be the standard deviation, variance, or range of a hazard-related variable – e.g., daily summer temperatures. Four studies agree that extremes such as heat waves occurring early in the season have a greater impact on mortality than those of similar intensity occurring later in the season [2, 10, 42, 43]. High temperature hazards of longer duration and larger variance have a higher effect on mortality in most cities [4, 6, 10, 40, 42, 43].

4.1.2. Exposure

Although scholars point to the role of urban density (measured with two indicators, population density or housing density) in exacerbating exposure to such hazards as urban heat-island, there is a medium-to-low level of agreement among the eight studies [6, 21, 26, 31, 49, 52, 53, 54] exploring its influence on the temperature–mortality relation. Three of the four city-level studies find urban density factors to have a negligible influence on exposure to high-temperature [6, 21, 26], yet they do not explore differences in temperature within cities. Meanwhile, all of the neighborhood-level studies [49, 52, 53, 54] find that intra-urban differences in temperature are associated with affluence; in other words, affluent areas are less densely settled, have lower mean temperatures, and thus lower temperature risks. In addition, total population was included in two studies [21, 26] and appears to be unrelated more often than being positively related to temperature-related mortality.

Some studies also explore the weight of factors related to urban land use and land cover on the temperature–mortality relationship. Yet they apply different indicators (e.g., impervious surface,

Table 3
Determinants of urban vulnerability.

Dimension	Determinant	Positively related	Negatively related	Unrelated	Confidence level		Total
					Evidence	Agreement	
Hazard	Magnitude	47	1	4	Large	High	52
	Timing		4	1	Medium	High	5
	Duration	3		1	Small	High	4
	Variance	3	1		Small	High	4
Exposure	Population density	4		3	Medium	Medium	7
	Housing density	1	1	1	Small	Low	3
	Total population	1		2	Small	Medium	3
	Urban land use	2		1	Small	Medium	3
	Amount of open space		1	2	Small	Medium	3
	Vegetation abundance		2	1	Small	Medium	3
Sensitivity	Age	23	4	6	Large	Medium	33
	Gender (females="1"; males="0")	5	3	6	Large	Low	14
	Pre-existing medical conditions (yes="1"; no="0")	6			Medium	High	6
Adaptive Capacity/ Adaptation	Education		7	3	Large	Medium	10
	Income		4	4	Medium	Low	8
	Poverty	4		3	Medium	Medium	7
	Deprivation	3		2	Medium	Medium	5
	African American	7			Medium	High	7
	Non-African American minorities	3	2	3	Medium	Low	8
	Non-white	1		3	Small	High	4
	Acclimatization		8		Medium	High	8
	Home amenity (e.g., air conditioning)		6		Medium	High	6
	Housing quality (dwelling type)		2	3	Medium	Medium	5
	Healthcare access		2	1	Small	Medium	3
	Social isolation (among elderly)	2		3	Medium	Medium	5
	Social network	1	2	1	Small	Low	4

Notes:(1) Amount of evidence: "small" if the total tally for an indicator is less than 5, "medium" if total is between 5 and 9 (inclusive), and "large" if total is 10 or more; (2) Level of agreement: "low" if the result category (positively related, negatively related, or unrelated) with the highest tally accounts for 50% or less of the total, "medium" if the result category with the highest tally accounts for 51–74% of the total, and "high" if the result category with the highest tally accounts for 75% or more of the total.

open space, vegetation abundance), and present mixed results. One study concludes that while vegetation health and the built environment characteristics are not related to heat mortality in Philadelphia, the existence of impervious surface increases heat distress calls in Phoenix [54]. Other studies find that vegetation abundance, which is often associated with affluence, has a significant and negative correlation with temperature and the occurrence of extreme heat events, and thus on health impacts [46, 52]. Also, the amount of open space and housing density were suggested to have different relationships with high temperature risks [6, 25, 52, 54].

4.1.3. Sensitivity

Certain demographic groups (e.g., elderly, very young, and people with pre-existing health impairments) are disproportionately *sensitive* to changes in temperature. Age appears in 33 studies as one of the most important determinants of vulnerability. The elderly are reported in 23 studies as the most sensitive demographic group. Although the influence of gender is also explored in 13 studies, results are mixed. Five of these studies find women to be at higher risk for mortality than men [10, 25, 32, 33, 44], while three show higher risks for men [5, 49, 50] and the others find no significant effect of gender. This lack of consensus across studies on the effects of gender, despite a large amount of evidence, likely indicates that the relationship between gender and vulnerability to heat-related hazards is context-specific. That is, it does not appear to be the case that women (or men) have a universal physiological susceptibility to heat, but rather that social conditions (e.g., occupation, gender equity in access to resources) are responsible for differential effects in some cases and not in others. It is interesting to note, for example, that of the 5 studies that found women to be at higher risk of temperature-related mortality, four used data from Europe (and Italy in particular) [10, 25, 33, 44] while the fifth [32] finds a marginally significant increase in risk of death from cardiovascular disease during extreme heat episodes among women in the United States. In contrast to the apparently culturally dependent role of gender, medical conditions leading to increased risk such as heart disorders, cerebrovascular disease and depression are positively correlated with temperature related mortality in all of the 6 studies examining this factor [2, 7, 10, 32, 44, 45].

4.1.4. Adaptive capacity and adaptation

Many of the studies included in our review examined either the *potential* for people or systems to adapt to the effects of temperature (adaptive capacity), or actual coping and adaptation actions. Since the distinction between adaptive capacity and adaptation is not clearly made in the reviewed studies, we combine these two concepts into a single category of vulnerability determinants in our meta-analysis, although in our conceptual framework we make a clear distinction between the two.

The role of socioeconomic indicators as determinants of adaptive capacity is explored in the studies (Table 3). Seven of the ten studies that consider education find that lower education at the population level increases mortality rates [6, 9, 26, 32, 33, 36, 42]. The results shown when looking at income, poverty and deprivation are also varied. Some studies found these factors had no effect on temperature-stress mortality in all or some cities [4, 6, 19, 25, 42, 44, 45, 54]. Others showed they were significantly related to mortality risk in consistent ways (income: negatively related; poverty and deprivation: positively related) [9, 25, 26, 33, 49, 50, 52, 53]. Undoubtedly, the availability of income and other individual resources (e.g., amenities, health services, and the quality of dwellings) determines people's ability to protect themselves from the consequences of temperature hazards. Yet, a handful of studies point to the importance of neighborhood disadvantage and exclusion in compromising adaptive capacity even above and beyond the compositional effects of individual-level factors such as age, race, and sex [49, 50, 52, 53].

Studies also disagree on the influence of ethnicity on vulnerability, with nine papers showing that minority status was significantly related to temperature caused death and six finding the two were not associated (Table 3). While non-white groups have been identified as having higher temperature related mortality than the white in most cases [26, 32, 36, 37, 49, 50, 52, 53, 54], two studies found non-African American minorities were at relatively lower risk compared to African Americans [50, 54].

The extent and quality of housing, infrastructure, and public services are potentially important – yet relatively unexplored – components of adaptive capacity, particularly in urban contexts. Although most of the studies addressing the influence of these factors show home amenities (e.g., air conditioning or swimming pools), better housing quality, and healthcare access reduce temperature-related mortality [4, 6, 9, 12, 21, 31, 37, 45, 50, 52], some find little evidence for their influence on heat effects [21, 25, 43, 54].

It has become accepted wisdom within social sciences that the lack of social capital (e.g., individual levels of social trust, participation in networks and family support) is a significant determinant of vulnerability to health hazards and risks (Cutter et al., 2003; Pelling and High, 2005). Notwithstanding this, the reviewed papers exploring the influence of social networks or isolation (i.e., the lack of networks) on health outcomes associated with high temperature present mixed results (Table 3). While some studies suggest that – in some cities – social networks help people withstand heat stresses [50, 52], and that living alone increases health risks associated with high temperature [50, 54], others find no significant effects of these factors [25, 49, 54]. Yet another study finds that strong bonding networks could even potentially exacerbate rather than reduce the vulnerability of elderly people to the effects of heat waves when elderly individuals and their social contacts tend to reinforce one another's low perceptions of vulnerability to heat [51]. These findings are therefore consistent with existing literature stating that rather than being unambiguously positive in reducing vulnerability social capital influences the direction of vulnerability (Pelling and High, 2005).

Some studies [9, 10, 27, 29, 30, 31, 41, 48] evaluated the influence of physiological or behavioral acclimatization on urban vulnerability, and all of them found it to be negatively related to temperature-related mortality. As for physiological acclimatization, urban populations in warmer climates generally have a higher heat threshold (the temperature above which mortality risk clearly begins to the increase), which might reduce their vulnerability to higher temperatures expected from climate change. Conversely, populations residing in colder cities or higher latitudes are expected to be more vulnerable to heat waves. Behavioral acclimatization in some studies relates to existing adaptation measures [11, 29, 41] – i.e., to the proportion of houses with heating systems, central air conditioning and backyard swimming pools that allow populations to cope with the prevalent weather conditions.

The preceding results are based on a meta-analysis tallying method that takes each study and its findings at face value. That is, we have simply reported what the body of literature on temperature–health relationships has found based on a widely varying set of methods. By doing so, we are able to provide an overview of "what we know" (or what we think we know) on this topic. We are careful to note, however, that the validity and robustness of this "knowledge" depends on a number of specific factors related to how each study was carried out and what methods were employed, as well as specific contextual factors. For example, if we were interested in evaluating existing research showing that ethnicity has a causal relationship with temperature-related mortality in a particular urban area, we would need to be assured that all other factors that are likely to covary with ethnicity (such as income, education, housing quality, and residential location in the urban environment) were adequately accounted for in the analyses. Our purpose here is not to present definitive "truth" about each such factor, but rather to provide an overview of what studies have presented as findings to date. The more general point, which we turn to in the next section, is that what we know depends on what questions we ask and what methods we use to answer those questions.

5. From meta-analysis to meta-knowledge: examining how urban vulnerability to temperature-related hazards has been studied in the literature

The diversity of research paradigms on urban vulnerability has been embraced by some scholars (Eakin and Luers, 2006) as necessary in order to address the full complexity of the concept, while for others (O'Brien et al., 2007) these differences not only represent different scientific paradigms, but also result in diverse implications for adaptation policies. This section explores the implications of both assertions by examining the theoretical lineages, research questions, methods, types of data, levels of analysis, and temporal scales coming out of the reviewed studies. As noted earlier, we classified each of the 54 case studies according to the dominant theoretical lineage or paradigm that it represented. The first lineage, *vulnerability as an impact*, is the most represented here (89% of the studies). *Inherent urban vulnerability*, the second lineage, is represented by 3 studies while the remaining 3 studies apply the *urban resilience* paradigm. As Table 4 shows,

Table 4
Research questions and methods used to examine urban vulnerability in the reviewed studies.

	Research paradigm							
	Urban vulnerability as impact		*Inherent urban vulnerability*		*Urban resilience*		All studies	
Number of studies	48		3		3		54	
Research question								
1. What is the relationship between temperature and mortality EXCLUDING additional factors (see question 2)?	15	31%	0	0%	0	0%	15	28%
2. Which additional factors affect the relationship between temperature and human health?	32	67%	2	67%	3	100%	37	69%
a. Which factors make people more sensitive to temperature?	25	52%	2	67%	2	67%	29	54%
b. Which factors influence people's ability to adapt to or cope with temperature?	23	48%	2	67%	3	100%	28	52%
c. What are the structural drivers (e.g., socioeconomic inequality, political power) of vulnerability to temperature-related hazards?	0	0%	2	67%	3	100%	5	9%
3. How does air pollution (or other biophysical factors) affect the temperature-health relationship?	21	44%	0	0%	0	0%	21	39%
4. How does climate change affect temperature-health relationships?	5	10%	0	0%	0	0%	5	9%
5. Which factors influence temperature-related hazards and their distribution (e.g., urban form, land cover, heat islands)?	2	4%	0	0%	2	67%	4	7%
6. How do people perceive vulnerability to temperature-related hazards?	0	0%	1	33%	1	33%	2	4%
7. What are existing and potential adaptation options?	1	2%	0	0%	1	33%	2	4%
Type of methods								
Quantitative	48	100%	2	67%	3	100%	53	98%
-Time series/longitudinal	31	65%	1	33%	0	0%	32	59%
-Cross-sectional	16	33%	0	0%	2	67%	18	33%
-Spatial	1	2%	1	33%	2	67%	4	7%
-Meta-regression (multiple studies)	2	4%	0	0%	0	0%	2	4%
Qualitative	0	0%	2	67%	1	33%	3	6%
Type of data								
Primary	0	0%	2	67%	2	67%	4	7%
Secondary	48	100%	2	67%	3	100%	53	98%
Simulated/modeled	3	6%	0	0%	1	33%	4	7%
Level of analysis								
Individual	6	13%	1	33%	0	0%	7	13%
Neighborhood	1	2%	2	67%	3	100%	6	11%
City	47	98%	0	0%	0	0%	47	87%
Temporal scale								
Single event	8	17%	3	100%	3	100%	14	26%
Short term	26	54%	1	33%	0	0%	27	50%
Medium term	19	40%	0	0%	0	0%	19	35%
Long term	5	11%	0	0%	0	0%	5	9%

Notes: Within each research paradigm, the number of studies and percent of studies in that paradigm using a particular method are presented. For example, the first row tells us that 15 of the 48 *urban vulnerability as impact studies* (or 31% of these studies) addressed the research question, "What is the relationship between temperature and mortality EXCLUDING additional factors?"

there are important differences across these lineages in how urban vulnerability is conceived and studied.

The *urban vulnerability as impact* lineage is dominated by epidemiological studies and top-down assessments. (This paper mostly focuses on the former.) A typical study in this lineage is concerned with quantifying the relationship between temperature and mortality, while controlling for factors such as age and gender. Breaking down the results in Table 4, we see that the primary research question in roughly one third of these studies (31%) focused solely on the relationship between the hazard (temperature) and the impacts (mortality) without including other dimensions (sensitivity, adaptive capacity, or structural drivers) in the analysis. Meanwhile, 32 of the 48 studies in this lineage did examine how changes in additional parameters affect the temperature–mortality relationship. Most of these studies examine factors related to sensitivity (particularly age), while indicators of adaptive capacity are also included in 23 of the 48 *urban vulnerability as impact* studies. None of these studies explicitly look at how the structure of society (for example, inequality or determinants of political power) impacts vulnerability to temperature. Rather, these studies tend to view temperature-hazards as a physical phenomenon. As such, 21 of the 48 studies examined the role of a biophysical confounder (mainly, air pollution) in their analysis. Two studies examined the role of non-climate factors such as urban form in shaping the hazard. Quantitative data analysis methods were used in all 48 *urban vulnerability as impact* studies, with most papers (65%) applying time-series or longitudinal methods followed by cross-sectional analysis (Table 4). Case-crossover studies are one subclass of time-series methods employed in five of these studies [3, 31, 44, 45, 48]; in these studies, individuals serve as their own controls, and exposure to temperature on the "case day" (i.e., the day on which the individual died) is compared to exposure on control days (e.g., same days of the week in the month and year in which the death occurred). Only one study employed spatial data analysis methods [26]. Two of the papers performed meta-regressions combining the results of multiple studies [20, 29]. None of the studies used primary data; all studies used secondary data sources (e.g., meteorological data, mortality data), with three studies also employing simulated or modeled data.

All but one study in this lineage conducted analyses at the city level. Of these city-level studies, six also have individual-level data and conduct some analyses at this scale in addition to or as an input into the city-level analysis [3, 25, 31, 44, 45, 48]. Only one conducts neighborhood-level analyses [26]. Finally, most of the studies in this lineage look at short-term (less than 10 year) relationships between temperature and mortality, while another third examine the medium term (10–30 years). The few studies that include a long-term perspective find that notwithstanding statistical increases in temperature, progressive decreases exist in the temperature–mortality link for cold and heat deaths [11, 12, 13, 29], a finding we will come to later in this paper.

The three studies that take an *inherent urban vulnerability* approach differ from the first tradition in several ways. This lineage has evolved from livelihoods, political economy and – later – political ecology (Adger, 2006; Eakin and Luers, 2006). In two of the three studies [49, 50], the main research question revolves around the structural drivers of differences in vulnerability to temperature-related hazards within urban areas, and the interactions among climatic, socioeconomic, and political components of exposure, sensitivity, and adaptive capacity that shape vulnerability. This question results in narratives that differ from those of the urban vulnerability as impact tradition. For instance, urban vulnerability as impacts scholars do not agree on the effect of income, poverty and deprivation on temperature-stress mortality. In contrast *inherent urban vulnerability* scholars state that advanced forms of marginality, such as neighborhood and community commercial degradation, housing crises, and health deterioration, are fundamental factors making certain urban residents (low-income, African-Americans living in more violent neighborhoods) more vulnerable to environmental hazards [49, 50]. The third paper [51], focuses on adaptive capacity and adaptation, addressing how people, specifically the elderly, perceive their own vulnerability to extreme heat and how this perception might influence adaptation. The studies in this lineage apply both qualitative and quantitative methods, and use primary and secondary data sources. Since this tradition is concerned with exploring differentiated vulnerabilities within urban populations, these studies conduct their analyses at the individual or neighborhood level rather than aggregating to the city level. These studies also focus on either single events (such as the 1995 Chicago heat wave) [49, 50] or short-term time horizons (summer 2007) [50].

The three papers representing the *urban resilience* research lineage use more integrated study designs in which cities are viewed as socioecological systems [52–54]. Like the *inherent urban vulnerability* studies, the central research question in all three resilience papers involves structural drivers of vulnerability (question 2c in Table 4). However, in contrast with the *inherent urban vulnerability* tradition frequently dominated by social scientists, these studies bring together experts from both natural and social sciences to understand the dynamics and interactions between "natural" and "human" components of exposure, sensitivity and capacity accounting for intra-urban differences in vulnerability. This, for instance, allows urban resilience scholars to explore the mechanisms by which variations in vegetation and land use patterns across an urbanizing regional landscape produce temperature distributions that are spatially heterogeneous (question 5 in Table 4) and to examine the correlations between this heterogeneity and the social characteristics of urban neighborhoods [52]. It also allows these scholars to examine the alignment of residents' perceptions of temperature and their experience with heat-related illness with simulated air temperatures [53]. These studies combine qualitative and quantitative methods coming from different disciplines. Of the four studies that we identified in this review using spatial data analysis methods, two fell into the resilience tradition. Also reflecting the "mixed methods" tradition is the fact that these papers tend to combine diverse data sources. Two of the three studies we identified employ secondary meteorological and/or sociodemographic data along with primary household survey data [52, 53], and one of these studies [52] also employs simulated weather data. Like the *inherent urban vulnerability* studies, the resilience papers are concerned within the mechanisms by which people and places are affected differently within urban areas; thus, all three of these studies use the neighborhood as the level of analysis. Finally, all three of these papers were single-event studies, using these events to "drill down" and explore the mechanisms influencing vulnerability in a very particular context.

6. Determinants of urban vulnerability: areas of light, shadow and darkness

Our study is certainly not the first to examine vulnerability factors as they influence the relationship between temperature and mortality in urban areas, nor are we the first meta-analysis that has been conducted on this subject. Rather, our innovation is that in addition to integrating and summarizing *results* across many studies, as most meta-analyses do, our use of a meta-framework allows us to examine differences in methodology, theoretical frameworks and causation narratives across a diverse set of studies, and thereby to compare "apples to oranges." That is, by explicitly recognizing that this set of studies includes papers that examine different dimensions of the urban vulnerability complex, we are able to go beyond case studies and, in a more systematic way, to point the way forward for increasing our understanding of urban vulnerability and adaptation.

Using this approach, one of the more striking findings is that the vast majority of papers examining urban vulnerability to temperature-related hazards come from one research paradigm: the *urban vulnerability as impacts* approach (48 papers). This means that our collective knowledge on this subject has shed light on only certain aspects of the problem, while other areas remain in the dark. In particular, existing studies have a lot to say about the quantitative relationship between temperature and mortality. Thanks to this body of work, it is clear that this relationship has a V or J shape, with mortality generally increasing both above and below some temperature threshold. Reviewing studies from different geographical areas, it is also apparent that the precise shape of this relationship varies across urban areas, although the bulk of studies are still concentrated in Europe and North America, a point which we return to later in the discussion. Other questions that have been studied extensively include the role of specific individual- and city-level characteristics in modifying the temperature–mortality relationship; through this work, we are able to say with some confidence that the elderly and people with pre-existing medical conditions are particularly vulnerable to the effects of temperature, and that higher levels of education in a population are associated with decreased risk of mortality. Looking at factors that may be potentially useful in adaptation interventions there is a medium level of evidence and a high degree of agreement on the finding that physiological acclimatization, access to air conditioning and other home amenities can decrease temperature-related mortality. However, such adaptations as an increased use of air conditioning can be seen as mal adaptations because they can lead to higher GHG emissions.

Without downplaying the important contributions that vulnerability as impact studies have made to our understanding of urban vulnerability, it is important to acknowledge the limitations of this paradigm and the questions that are largely ignored in this literature. Our review highlights the fact that many of the questions typically asked by the *inherent urban vulnerability* and urban resilience traditions remain largely unanswered. In particular, one set of questions that emerges from both of these traditions involves the structural drivers and mechanisms determining differences in vulnerability to temperature-related hazards within and across populations in urban areas. Because most urban vulnerability as impact studies take the city as the level of analysis, they are unable to shed sufficient light on these intra-urban inequalities. In contrast, the different paradigms in the *inherent urban vulnerability* and urban resilience studies lead these papers to take individuals or neighborhoods as the level of analysis. As a result, these studies illuminate the role of equity and affluence, the two faces of the urban development coin, in the ability of upper income, white populations to live in low density, greener and cooler neighborhoods and, hence, to be more able to cope with extreme heat. These studies find that intervening mechanisms of structural advantage or disadvantage at the neighborhood level, such as concentrated affluence or commercial decline, play a fundamental role in such health outcomes as heat-wave mortality. Furthermore, the temperature distributions within cities are spatially heterogeneous and correlated with differences in the socioeconomic and environmental characteristics of urban neighborhoods [49, 50, 52, 53].

Such spatial differentials, from an *inherent urban vulnerability* perspective, include structural processes by which inequalities in distribution and access to urban infrastructures, health services, and good quality housing are shaped. Other spatially differentiated factors include economic decline and social marginalization of certain neighborhoods; the amount of control, or the lack thereof, that urban dwellers can exert over adaptation choices, options and policies; and people's perception of their own vulnerability (Romero Lankao and Qin, 2011). From an *urban resilience* perspective, key questions include the dynamics of cities as socio-ecological systems, including such localized factors as the long-term and human-induced changes in regional temperatures, such as those brought on by the heat island effect that can create local "riskscapes" [52] that affect urban populations and their built environments. Other factors include flexibility of local urban populations and authorities, diversity and capacity for learning and innovation, and the interactions between long-term processes and short-term triggers that shape the options for and constraints to urban adaptation (Pelling, 2010; Leichenko, 2011; Romero Lankao and Qin, 2011). By leaving these issues in darkness research on urban vulnerability scholars are failing to gain knowledge that is at least as important for adaptation efforts seeking to mitigate the causes of temperature related mortality as are the demographic factors of age, race, and gender traditionally explored by the *urban vulnerability as impact* tradition.

The recognition of spatial–temporal dimensions of urban vulnerability highlights the ways in which scale can influence a study's findings, where scale is defined as the spatial, temporal, quantitative or analytical dimension used by scholars to measure any phenomenon (Gibson et al., 2000). In addition to differences in the spatial scale of different papers discussed above, we also note the importance of different time scales adopted in the studies we reviewed. Independently of research paradigm, most of the studies are limited in their time horizons, examining single events or short time periods (less than 10 years) (Table 4). As we noted previously, the handful of *urban vulnerability as impact* studies that adopt a medium- to long-term perspective find that notwithstanding statistical increases in temperature, progressive decreases exist in the temperature–mortality link for cold and heat deaths. Although several studies include many cities, they often overlook how long term processes such as increasing average temperatures at the city level interact with broader and more subtle socioeconomic trends. Furthermore, they point to two factors explaining this: first, an epidemiologic transition where there was a shift from high to low childhood mortality and towards a predominance of chronic disease mortality at older ages that took place in high income countries during the 20th century (Carson et al., 2006), and, second, the use of air conditioning [11, 12, 29], which we classified as a determinant of adaptive capacity. This helps explain the finding that while average temperatures have increased in many urban centers, vulnerability to cold and heat has decreased, despite the aging of the population and increases in cardiorespiratory disease. Of course, it is possible that after reaching a threshold, the changes in average temperatures and in extremes resulting from climate change might offset the capacity achieved through this transition. However, its importance in enhancing adaptive capacity in urban centers of some nations should not be underestimated. While data limitations are certainly an important factor limiting what is possible in terms of long-term research studies, one potentially fruitful direction for future studies would be to apply the kinds of detailed, multi-layer analyses of the urban resilience tradition to longer time horizons to examine how, for example, changes in land use and economic development over time have shaped patterns of vulnerability within or across urban areas.

While many of the reviewed studies rely on population demographics, and a few studies focus on broader socioeconomic and political processes explaining differences in urban vulnerability, the influence of other factors defining cities as built environments has been overlooked. In particular, it is typical for little or no attention to be paid to the way other critical (built environment) attributes affect the vulnerability of local residents. While some of the reviewed studies quantified the influence of the housing stock (3 studies), of urban infrastructures and services (health care facilities, 3 studies), and of availability of urban and ecologic services (e.g., vegetation abundance, 3 studies; see Table 3), only a couple of them analyzed intra-city variations of these as they relate to differences in urban vulnerability among populations. Furthermore, only one examined the association between urban form at the level of the metropolitan region and the frequency of extreme heat episodes [46].

Cities from middle and low income countries (see Fig. 2) are also understudied. As noted by other scholars (e.g., Lahsen et al., 2010) and the IPCC (Adger et al., 2007), although these countries have been unable to actively pursue research focused on vulnerability issues as part of their overall adaptation responses, it is precisely these cities that are going to be especially exposed and vulnerable to the negative impacts of temperature hazards climate change is expected to aggravate. It is in these cities where many of the determinants of urban vulnerability understudied by the *urban vulnerability as impact* paradigm (e.g., inequities in power and resource distributions) are of particular relevance.

7. Conclusion

The central message of our study is that what we know depends fundamentally on what questions we ask and how we go about answering those questions (i.e., the kind of methods and data we use or have available to us). Our combined meta-analysis and meta-knowledge exercise highlights the fact that while a great deal of research has been done addressing urban vulnerability to temperature-related hazards, the vast majority of studies fall under a single research paradigm – the *urban vulnerability as impacts* approach. Although this paradigm has made important contributions to the understanding of urban vulnerability, it tends to ignore other equally fundamental dimensions and determinants; to produce a set of explanatory variables that are tightly constrained by the availability of data, particularly in developing countries; and it omits any attempt to gain ethnographic knowledge of behavioral norms, social networks and risk perceptions that are equally relevant to understanding urban vulnerability.

The dominance of the *urban vulnerability as impact* paradigm suggests that more studies should be undertaken that apply the *inherent urban vulnerability* and urban resilience approaches. For instance, studies under an *inherent urban vulnerability* paradigm can explore underlying societal processes by which assets and options at the individual, family or community level (e.g., self-help housing or access to social networks) allow urban households to adapt, but can also shed light on why in many cases these personal assets are not enough to reduce urban populations' vulnerability because of the role the state plays in shaping adaptive capacity through such means as promoting economic growth and poverty reduction. Meanwhile, an urban resilience framework holds promise to integrate across disciplines and illuminate a more complete set of drivers of urban vulnerability.

At the same time, we note that despite offering a picture of how direct and underlying socioeconomic and institutional factors of urban vulnerability change over time, *inherent urban vulnerability* studies stop short of providing an entire causal sequence that may show how changing inequities relate to differential impacts and susceptibility over time. To date, the few studies that have adopted the *urban resilience* framework have been limited in their spatial and temporal scales, providing valuable information on a particular context but lacking an ability to move beyond case studies and uncover broader trends in temperature–mortality linkages.

Without a doubt, a more integrated approach to the multiple dimensions and determinants of urban vulnerability is needed. Some efforts within each research paradigm have been undertaken to converge with other traditions. However, as illustrated by this paper, scholars in the area of urban vulnerability tend to be narrowly focused. In order to improve our state of our knowledge, it is fundamental to move beyond disciplinary boxes and create more inclusive efforts aimed at shedding light on areas currently in the shadows and on developing more interdisciplinary and integrated approaches. The central understanding of this integrated approach will be that what each paradigm can shed light on only a small piece of a complex puzzle.

Understanding the nature of urban vulnerability will require novel approaches at integrating the disciplinary threads our science. Our meta-analysis and meta-knowledge method is an attempt to move us towards an understanding of the nature of and the interactions between hazards, and their drivers, exposure, sensitivities, adaptive capacities, actual adaptations and their determinants. The interdisciplinary knowledge that may be gained through studies such as this one, will aid in the design and implementation of more effective adaptation actions in this increasingly urban world.

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