Social Science & Medicine xxx (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Social Science & Medicine

journal homepage: www.elsevier.com/locate/socscimed

Exploration of health risks related to air pollution and temperature in three Latin American cities

Patricia Romero-Lankao[b,1], Hua Qin[a,*], Mercy Borbor-Cordova[c]

[a] Department of Environmental Studies, University of Illinois at Springfield, One University Plaza, PAC 307, Springfield, IL 62703, United States
[b] Urban Futures, National Center for Atmospheric Research, United States
[c] Ministry of Environment, Ecuador

ARTICLE INFO

Article history:
Available online 20 January 2013

Keywords:
Risk society
Environmental justice
Urban vulnerability
Health impacts
Air quality and climate
Bogota
Mexico City
Santiago

ABSTRACT

This paper explores whether the health risks related to air pollution and temperature extremes are spatially and socioeconomically differentiated within three Latin American cities: Bogota, Colombia, Mexico City, Mexico, and Santiago, Chile. Based on a theoretical review of three relevant approaches to risk analysis (risk society, environmental justice, and urban vulnerability as impact), we hypothesize that health risks from exposure to air pollution and temperature in these cities do not necessarily depend on socio-economic inequalities. To test this hypothesis, we gathered, validated, and analyzed temperature, air pollution, mortality and socioeconomic vulnerability data from the three study cities. Our results show the association between air pollution levels and socioeconomic vulnerabilities did not always correlate within the study cities. Furthermore, the spatial differences in socioeconomic vulnerabilities within cities do not necessarily correspond with the spatial distribution of health impacts. The present study improves our understanding of the multifaceted nature of health risks and vulnerabilities associated with global environmental change. The findings suggest that health risks from atmospheric conditions and pollutants exist without boundaries or social distinctions, even exhibiting characteristics of a boomerang effect (i.e., affecting rich and poor alike) on a smaller scale such as areas within urban regions. We used human mortality, a severe impact, to measure health risks from air pollution and extreme temperatures. Public health data of better quality (e.g., morbidity, hospital visits) are needed for future research to advance our understanding of the nature of health risks related to climate hazards.

Introduction

Urban populations and activities play a crucial role in the arena of environmental change, not only as sources of atmospheric emissions, but also as epicenters of risks from exposure to such hazards as air pollution and climate variability, which are expected to be further intensified with global climate change. As a result of their concentrations of energy use (Grübler, 2004), urban centers are faced with high levels of air pollutants which, when combined with adverse weather conditions, negatively affect the health of their populations. Severe local weather conditions, such as heat waves caused by climate change, can exacerbate the impact on public health in urban areas. The aggregate of health impacts from air quality and temperature changes becomes especially critical in middle-income countries of Latin America due to such processes as urbanization, urban and territorial governance, and industrial and transportation growth. In fact, Latin America is one of the most urbanized regions in the world, with urbanization levels of 77.8 percent in 2005 (Winchester, 2007), a high level of urban primacy (i.e., a large percentage of a nation's urban population living in a single city), and high levels of socio-spatial segregation and inequality.

Latin American urban areas with their high levels of urbanization and uneven distributions of wealth and resources are, in short, faced with hazards and inequalities that naturally lead to the question of whether the health-risks related to air pollution and temperature are spatially and socio-economically differentiated within and across cities. This question reflects the famous remark by Ulrich Beck that while poverty is hierarchic, risks are ubiquitous, affecting everybody equally, and are, presumably, a matter of concern to everyone (Beck, 1986, 2002). However, other schools of thought call Beck's sweeping statement into question. For example, environmental justice and political ecology scholars have noted that different capacities to cope exist within and across urban

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[*] Corresponding author. Tel.: +1 217 206 8585; fax: +1 217 206 7807.
E-mail addresses: huaqin2@uis.edu (H. Qin), prlankao@ucar.edu (P. Romero-Lankao).
[1] Tel.: +1 303 497 8104; fax: +1 303 497 8401.

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http://dx.doi.org/10.1016/j.socscimed.2013.01.009

Please cite this article in press as: Romero-Lankao, P., et al., Exploration of health risks related to air pollution and temperature in three Latin American cities, *Social Science & Medicine* (2013), http://dx.doi.org/10.1016/j.socscimed.2013.01.009

centers, and that some groups and municipalities within cities are more vulnerable than others because they have higher exposure to environmental hazards and lack the assets and options for risk reduction (Morello-Frosch, Pastor, Porras, & Sadd, 2002; Morello-Frosch, Pastor, & Sadd, 2001; Moser & Satterthwaite, 2010; Mythen, 2005).

This paper explores whether the health risks associated with temperature and air pollution are ubiquitous or spatially and socio-economically differentiated within three Latin American cities: Bogota, Colombia, Mexico City, Mexico, and Santiago, Chile. To achieve this purpose, the paper first discusses three major approaches to risks. It then characterizes the methods and data applied to explore health risks in an integrated way, and describes the climatic, atmospheric and socioeconomic conditions that make these three cities sources of high emissions and hotspots of vulnerability. The findings on the nature and linkages between main dimensions of health risks are presented, and finally the paper closes with remarks and reflections on the implications of the study.

Theoretical foundations

Risk refers to the possibility of loss, injury and other impacts (Thywissen, 2006). However, risk can also be defined as the probability of the occurrence of an adverse event and the probable magnitude of its consequences (Shrader-Frechette, 1982). Although a risk-analysis framework has been widely used by scholars exploring the existing and potential health effects of air pollution and temperature (Makri & Stilianakis, 2008; Peng & Dominici, 2008), risk research is still characterized by inter-disciplinary differences in definition and scope as exemplified by the 25 definitions of risk (Thywissen, 2006). In this paper, we refer to three relevant risk approaches: risk society, environmental justice, and urban vulnerability as impact (see also Romero-Lankao & Qin, 2011) as they relate to the question of whether the health risks associated with temperature and air pollution are ubiquitous or spatially and socio-economically differentiated.

The first approach to risk is given by the *risk society theory* (Beck, 1986). Ulrich Beck, its founder, identifies three periods of modernity. In the first stage, simple industrial societies of scarcity were created, where the central issue and key political challenge revolved around the distribution of (scarce) goods (equity). The second is a transitional stage between the first (simple) and the third (reflexive) era. In the reflexive stage, progress in science and technology becomes the central mechanism to increase the production of goods, and thus to reduce material needs. The same scientific and technological developments, however, are the source of “bads”, such as climate change and air pollution, which are the negative byproducts of industrialization, creating risks and dangers of uncertain proportions. Although Beck acknowledges a relationship between the distribution of wealth and the allocation of risk, he also states that with the globalization and intensification of risks in the current – reflexive – era of modernity, the possibilities for wealthy sectors to escape from and compensate for risks diminish or even disappear, and a “boomerang effect” takes place. In other words, the rich cannot escape from the risks of being negatively affected by hazards. Because risks resulting from modernization processes cut through existing class or status boundaries, Beck concludes that while “hunger is hierarchical, smog is democratic” (Beck, 1986, p. 48).

Although compelling, the *risk society theory* has been criticized for having many theoretical and empirical inconsistencies in its interpretation of risk (Atkinson, 2007; Bovenkerk, 2003; Mythen, 2005). Rather than engaging in this debate, however, we will focus here on Beck’s concept of a “boomerang effect,” whereby air pollution, climate change and other “*bads*” that cannot be circumscribed by human boundaries will have an equalizing effect, because they have not been met with coherent policies that could effectively limit their pervasiveness and mobility. Left unchecked, these itinerant threats will inevitably affect previously protected affluent countries and populations, the same populations that have been the primary beneficiaries of the industries and activities that have produced the “bads” and their widespread environmental damage. Beck’s “boomerang” therefore, is this return of the “bads” to affect those who produced them.

In contrast to Beck, the risk paradigm put forward by many *environmental justice*, *political ecology, and livelihoods* scholars underscores the influence of class and social differentiation not only on people’s income, access to goods and services, health and quality of life, but also on their hazard exposure, sensitivity and capacity for managing risks and health outcomes (Atkinson, 2007; Morello-Frosch & Lopez, 2006; Morello-Frosch et al., 2002; Moser & Satterthwaite, 2010). Economic elites of urban areas are able to monopolize the best land, and reap the rewards of local environmental amenities such as clean air, safe fresh water, open space, and tree shade (Bovenkerk, 2003; Morello-Frosch & Lopez, 2006). For instance, intra-urban differences in temperature relate to affluence, and as poorer areas are more densely settled and have a smaller proportion of green spaces, they have higher mean temperatures, and thus, higher temperature risks (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Ruddell, Harlan, Grossman-Clarke, & Buyantuyev, 2010). Furthermore, studies have found that poorer neighborhoods are exposed to higher levels of air pollution (Morello-Frosch et al., 2002) and that the less financial, human, natural or social resources or assets people have, the more vulnerable they generally are to the multiple hazards they face (Moser & Satterthwaite, 2010).

However, as suggested by previous environmental inequality research, at times the relationships between socioeconomic differentiation and risk from exposure to air pollution can be quite unexpected, even when looking at intra-urban differences in exposure and access to assets. A study undertaken in Chicago for instance, has found that “all the rich, most of the poor…almost all of the black…population resides in areas violating primary long-term particulate standards” (Szasz & Meuser, 1997, p. 101). In a more recent study exploring differentiated air pollution exposures in California’s South Coast Air Basin, Marshall (2008) found that for benzene, butadiene, chromium particles, and diesel particles, mean exposures are higher than average for nonwhite, lower-income households inhabiting areas with high population density. Yet, for ozone (a secondary pollutant whose dynamics depend on sunlight), the reverse holds.

From an *urban vulnerability as impact* perspective, risks can be understood as the degree to which exposed populations are susceptible to and unable to cope with adverse effects of global climate and environmental change (Romero-Lankao & Qin, 2011). Risk analysis in vulnerability as impact research relates to a series of analytical concepts and tools used to assess a given or possible health outcome associated with *exposure* to such environmental *hazards* as air pollutants and temperature extremes, particularly in urban areas of North America and Western Europe, and to a much lesser extent in Latin America and other developing regions (Romero-Lankao, Qin, & Dickinson, 2012).

Urban vulnerability as impact studies have found that the risks of adverse health impacts depend on two series of factors. The first relates to the nature of the hazards to which urban populations are exposed, while the second relates to socioeconomic conditions influencing exposure, sensitivity and capacity for responding to risk and health outcomes, which may reflect inequalities in environmental conditions or access to services and welfare systems (e.g., Künzli et al., 2004; Makri & Stilianakis, 2008; O'Neill, Zanobetti, & Schwartz, 2003). Previous studies have found that lower levels of education are associated with higher levels of mortality risk (Medina-Ramón & Schwartz, 2007; Smoyer, Kalkstein, Greene, & Ye, 2000), and that certain demographic groups such as the elderly, the very young and people with pre-existing medical conditions are more sensitive to environmental hazards (Chestnut, Breffle, Smith, & Kalkstein, 1998; Dear, Ranmuthugala, Kjellström, Skinner, & Hanigan, 2005; Pope & Dockery, 2006). However, their results when studying socioeconomic indicators of adaptive capacity as income, poverty and ethnicity are mixed. For instance, while some studies find that poverty, income and deprivation relate with higher risks of mortality from exposure to air pollution and temperature (Johnson, Wilson, & Luber, 2009; O'Neill, Zanobetti, & Schwartz, 2005), other studies find these factors to have no effect (Smoyer et al., 2000; Stafoggia et al., 2006), or inconsistent effects – i.e., sometimes they are positively and others negatively related (D'Ippoliti et al., 2010; Ishigami et al., 2008).

Why is it that both environmental justice and urban vulnerability as impact scholars have produced mixed evidence of the influence of socioeconomic status on health risks associated with environmental hazards? We think that it is problematic to amalgamate hazards as diverse as air pollution, temperature dynamics, toxic waste, and floods without a careful understanding of their nature and dynamics. Because of their physical characteristics, toxic wastes can be dumped in poor neighborhoods with relative ease, but that is not the case with air pollution and temperature. Although wealthy residents live in the more leafy suburbs of a city, farther away from heavy industries and freeways, air pollutants and extreme weather do not know boundaries and do not stop when they reach the limits of wealthy neighborhoods, cities and even countries. Dramatic examples of this are plumes of airborne pollutants that originate in Mexico City and travel to the Gulf of Mexico, or those that originate in Asia and journey to North America (Tie et al., 2009).

Therefore, we hypothesize that health risks from air pollution and temperature variation in Latin American cities do not necessarily depend on socio-economic differentiations. If the health risks are indeed nonhierarchical, as proposed by Beck, the differences in vulnerability will not be correlated with these risks; but if the health risks are socio-economically differentiated, the differences in vulnerability will mirror differences in risks. To test this hypothesis, we conceive of health risks as a function of exposure and socioeconomic vulnerability (Birkmann, 2006; Thywissen, 2006; UN/ISDR, 2009). *Exposure* is the extent to which urban populations are in contact with, or subject to temperature change and air pollution (hazards). Vulnerability or the possibility of being harmed depends on a series of societal and environmental conditions besides exposure, namely sensitivity, adaptive capacity, and actual responses (Romero-Lankao & Qin, 2011). The livelihoods approach in climate change research (Moser & Satterthwaite, 2010) also acknowledges the multidimensional nature of vulnerability – the fact that certain demographic groups are particularly vulnerable to hazards not only as a result of age or existing health conditions, but also because of individual/household assets (e.g., income, health services, and education).

Methods and data

Several criteria were used to select the three cities for evaluating the nature of health risks related to air pollution and temperature: each city has a strong weight as a primary center within its national economy; each concentrates populations, economic activities, energy and atmospheric emissions; and lastly, each of these cities is especially affected by two hazards climate change is expected to aggravate: air pollution, and changes in average and extreme temperatures (Magrin et al., 2007). Furthermore, despite the efforts that have been undertaken to curb air pollution in these cities (e.g., the PROAIRE Program to Improve Air Quality in the Valley of Mexico and the Decontamination Plan in Chile), high levels of air pollution remain a serious problem in all of them (Bell et al., 2008; Romero-Lankao, 2007).

Study cities

The climates of the cities range from Mediterranean (Santiago) to subtropical highland (Bogota and Mexico City). While the variations in the average temperatures of any of these cities are not large, there are more seasonal variations in Mexico City and Santiago than in Bogota (Table 1). Health risks in these cities due to changes in temperature are a concern, as are those related to high levels of atmospheric emissions (Bell et al., 2008; O'Neill et al., 2005), particularly because atmospheric and meteorological conditions can be conducive to air pollutant retention and ozone formation in the three cities. Air pollution levels are generally high but with some variations across the three cities. For example, the annual average levels of pollution in coarse particulate matter (PM_{10}) range between 51.6 and 70.2 μg/m^3 in Mexico City and Santiago respectively. Air pollution and changes in mean regional temperatures and other hazards in Latin America will be further intensified with climate change (Magrin et al., 2007). Large changes such as these will tend to affect larger segments of the population and cut across social and economic boundaries. Yet, before we can begin to predict how these cities will be affected by the anticipated impacts of climate change, we still need to understand their current baseline environmental and socioeconomic conditions.

Each of the studied cities is the primary economic hub of its country, with Bogota, Mexico City, and Santiago generating 25, 34, and 43 percent of national GDP, respectively. Besides the possibility that these cities will be negatively impacted, they also have the potential to respond to climate-induced hazards. The ability of urban populations, infrastructures and economic activities to bounce back, recover from, and even take advantages of such climatic and (and also non-climatic) stresses is determined by socioeconomic, political and cultural factors defining urban development.

Urban development shapes the urban populations' vulnerability in many ways (Romero-Lankao & Dodman, 2011). Notwithstanding all their dynamism, high levels of integration in the global economy

Table 1
Environmental and socio-economic features of the study cities.

	Bogota	Mexico City	Santiago
Latitude	4°32 N	9°26 N	33°28 S
Average temp (max temp) in warm seasons (°C)[1]	13.7 (19.1)	17.8 (24.5)	19.8 (26.8)
Average temp (min temp) in cold seasons (°C)[1]	13.6 (8.2)	16.1 (9.9)	12.8 (8.0)
PM_{10} (annual average in μg/m^3)[1]	68.8	51.6	70.2
Ozone (annual average in ppb)[1]	11.6	32.4	29.8
NO_2 (annual average in ppb)[1]	17.3	29.4	18.2
Population[1]	6,776,009	17,946,313	5,392,804
GDP per capita in US $[1]	16,778	9063	17,672
Percentage of people below poverty line[2]	25.4	39.2	10.6
GINI coefficient[2]	0.61	0.55	0.55
Infant mortality rates (per thousand)[2]	13.5	17.8	7.5
Informal employment (% of total workforce)[2]	44.0	45.7	34.0
Slum population (% of inhabitants)[2]	16.8	19.6	2.0
Homicides per 100 thousand population[2]	18.7	17.6	1.6

Sources: 1. ADAPTE's own calculations; 2. Jordán, Rehner, and Samaniego (2010).

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and the presence of a creative middle class, these cities are still faced with high levels of poverty, income inequality, and informality of employment and workforce (Table 1). The patterns of population and economic activities of these cities have changed in recent decades. Although spatial segregation is still a feature, core areas have registered slower growth and in some cases decay; high-income, gated communities have grown in suburban and peri-urban areas; and low-income, often informal settlements have expanded on the periphery. Uneven development and inadequate infrastructure and governance structures constrain the ability of urban populations and authorities to adapt to existing and future hazards. The cities have deficits in key determinants of adaptive capacity such as health (with high infant mortality rates in all three cities), education (with socially segregated school systems), housing (with inadequate housing stock and problems of housing affordability), and informal settlements (an exception being Santiago; see Table 1). Frequently, decaying central areas and peri-urban areas are being inhabited by marginalized populations with inadequate services, a portfolio of precarious livelihood mechanisms, and inappropriate risk-management institutions (Hardoy & Romero-Lankao, 2011). Last but not least, the levels of crime and violence are high in Mexico City and Bogota (Table 1), which prevents the development of social capital (i.e., individual levels of social trust and participation in networks), a key determinant of adaptive capacity.

Data

To examine health risks in the three Latin American cities, we gathered, validated and analyzed local temperature, air pollution, mortality, and socioeconomic vulnerability data. Daily temperature data from the meteorological stations of each city were used to determine maximum, mean, and minimum temperatures. We transformed the temperature data by using a centered moving average (CMA) smoother as a common approach to reduce the noise within the raw data set (e.g., Fouillet et al., 2007). Different CMA ranges (daily, 3, 7, 15, 30, 182 days) were explored whereas a 3-day CMA smoother was found to fit the temperature data best and was subsequently used in the analysis.

Air pollution data registered in the air quality monitoring stations (AQMN) were obtained from each city's environmental agency. We obtained data on three primary criteria pollutants: particulate matter between 2.5 and 10 μm in aerodynamic diameter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and ozone. The monitoring stations used in the study were those having the most complete data sets for the period of analysis for each city (2003–2006 in Bogota, 2000–2004 in Mexico City, and 2001–2005 in Santiago). Missing data points that occasionally occurred in the pollutants' time series were estimated using a multiple linear regression function. We also applied a 3 day CMA smoothing function to the time series data for air pollutants.

A large body of epidemiologic literature has shown mortality rates associated with the effects of temperature and air quality (e.g., Basu, Feng, & Ostro, 2008; Gosling, Lowe, McGregor, Pelling, & Malamud, 2009; Peng & Dominici, 2008; Zanobetti & Schwartz, 2008). We measured health risks related to air pollution and climate variability with the following mortality data from the public health agency of each city: respiratory mortality (International Classification of Diseases, or ICD 10 cause J) and cardiovascular mortality (International Classification of Diseases or ICD 10 cause I) (Peng & Dominici, 2008).[2] The collected data also included information about date of death, age, sex, and geographical location. We stratified the daily death counts into three broad age categories: (1) children, age 0–14 years; (2) adults, age 15–65 years; and (3) elderly, age greater than 65 years. Besides the aggregate data, the elderly sub-group was also specifically analyzed because this age group has been found to be the most vulnerable in prior studies (Bell et al., 2008; Cifuentes, Borja-Aburto, Gouveia, Thurston, & Davis, 2001; Pope & Dockery, 2006).

Socio-demographic data, such as education, poverty, income, age structure and housing condition, were also collected from the study cities' census offices to construct municipality-level measures of vulnerability. Data on Bogota includes 20 municipalities ("localidades"). In Mexico City, 16 delegations of the Federal District and 35 municipalities of the State of Mexico were studied; and in Santiago, 52 "comunas" within the so called "Gran Santiago" region were included. While the temperature and air pollution data of each study city covers a period of years, the data on socioeconomic vulnerability is only for one reference year (2005 for Bogota, 2000 for Mexico, and 2002 for Santiago). In combination, these data were used to capture a snapshot of the risk dynamics operating in the three cities.

We measured socioeconomic vulnerability using a multi-criteria model which is based on four different types of capital generally used in the asset-based framework of deprivation: social, human, physical, and financial capitals (Baud, Pfeffer, Sridharan, & Nainan, 2009; Baud, Sridharan, & Pfeffer, 2008). Each capital was measured by relevant indicators constructed from census data of individual cities. The indicators used for calculating the multi-dimensional vulnerability index (MVI) for each study city are as follows:

> *Social capital*: percentage of houses occupied by owners (all three cities).
> *Human capital*: dependency ratio (ratio of the number of people aged 0–14 and those aged over 64 to the number of people aged 15–64), percentage of population with less than high school education (all three cities).
> *Physical capital*: percentage of households with more than 7 members, number of health care facilities per 10,000 persons (all three cities).
> *Financial capital*: percentages of population living below the food, capacity, and heritage poverty lines (Mexico City); percentages of population living below the poverty line and the misery level (Bogota); percentage of population living below the non-indigent and indigent poverty lines (Santiago).

All of the indicators were first normalized based on the method of the UNDP's Human Development Index (UNDP 2002), which transforms values to a range between 0 and 1 by applying the following formula:

$$\text{Normalized value} = \frac{\text{actual value} - \text{minimum value}}{\text{maximum value} - \text{minimum value}}$$

In the cases of the percentage of houses occupied by owners, per capita income and the number of health care facilities per 10,000 persons, we reversed the index values by using [1 − index value]. This reversal is necessary to ensure that high index values indicate high vulnerability for all indicators. We constructed a sub-index for each of the four dimensions of socioeconomic vulnerability (social, human, physical, and financial) using the average value of relevant normalized indicators (only one in the case of social sub-index). The final index of socioeconomic vulnerability was calculated as the average of the four sub-indices.

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[2] The mortality data sources are the District Department of Health, Bogota; the National Institute of Public Health, Mexico; and the Ministry of Health, Chile.

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Analytic methods

We combined different analytic methods to explore how exposure to temperature change and air pollution hazards and socioeconomic vulnerability influence the mortality risks of urban populations in the three study cities. First, we organized and compared the air quality data of each city with the World Health Organization (WHO) (WHO, 2005) air-quality guidelines that are based on expert evaluation of current scientific evidence on the health impacts of air pollution. We also ran a data decomposition to identify the main temporal patterns (i.e., warm and cold seasons) of health outcomes from the two hazards based on the intrinsic seasonal characteristics of our data set.

We then conducted a time-series approach to evaluate the effects of exposure factors (e.g., temperature and particulate matter) on mortality (similar to Basu et al., 2008; D'Ippoliti et al., 2010; Ishigami et al., 2008). We used generalized linear models (GLMs) with Poisson log-linear distribution to calculate the relative risk of dying from exposure to air pollution or weather at the city level, taking the outcome Y_t to be Poisson with μ_t whereas the log of μ_t is the linear predictor. The linear predictor typically includes terms for the exposure of interest and various potential confounders, i.e., other factors which are not on the causal pathway but correlate with mortality. See Formula 1 as described by Peng and Dominici (2008, p. 70):

Formula 1:

$$\begin{aligned} Y_t &\approx \text{Poisson}(\mu_t) \\ \log \mu_t &= \alpha + \beta x_{t-\ell} + \eta \text{ measured confounders}_t \\ &\quad + \text{unmeasured confounders}_t \end{aligned}$$

With $x_{t-\ell}$ = exposure factors that are included in the model at a lag of ℓ days; β = log-relative risk for $x_{t-\ell}$; η measured confounders$_t$ = confounding effects of factors such as seasonality; unmeasured confounders$_t$ = factors that cannot be directly included in the analysis.

We explored the impact of time lags on the statistical modeling, assuming that a change in temperature or air pollution on a given day displays its related health impact only after some days in the future (Peng & Dominici, 2008). The analysis tested time lags of 0, 3, 7 and 15 days and of 0, 1, 3 and 7 days respectively for the temperature and air pollution data. A lag of 3 days was finally used for our models because we found it was the most relevant to mortality rates in our analysis. This lag structure is also widely used in the existing literature on associations between temperature and human mortality (Gosling et al., 2009).

We fitted separate models for warm and cold seasons at the city level. To examine whether health risks are spatially and socioeconomically structured within study cities, we further calculated the relative risk factors for mortality associated with air pollution at the municipality level. Because the monitoring stations do not cover the whole metropolitan area of the cities, we could calculate these only for some municipalities within each city. By comparing the relative risk factors with the MVIs, it was possible to explore whether populations in some of the more vulnerable municipalities differ from some of the less vulnerable municipalities in their exposure and sensitivity to a particular hazard. Next, we also tested the statistical correlations between the levels of major air pollutants (PM_{10}, NO_2, and ozone) at monitoring stations and the socioeconomic vulnerability of the municipalities in which these stations were located for each study city.

Finally, to explore whether urban populations with different vulnerabilities at the municipality level can be differentiated with respect to health risks related to air pollution and temperature, we evaluated the correlations between respiratory and cardiovascular mortalities and the MVI at the municipality level in individual study cities. All variables in the analysis were first log transformed to make their distribution more nearly normal and to stabilize the variances. Given the limited numbers of air quality monitoring stations and municipalities in each study city and the nature of the MVI variable, both the Pearson correlation (r) and the Spearman rank correlation (rho) were used in the statistical analysis. Since the data of this study has a spatial dimension, we also contrasted these two standard tests to a spatial bivariate correlation analysis. The statistical and spatial analyses in this study were carried out using the SPSS Statistics 18.0 software and the SpaceStat program version 3.5 respectively. While SpaceStat 3.5 does not have a specific spatial correlation function, its Spatial Regression tool provides a readily available way to assess bivariate correlation with spatial data. Although we assigned variables into the dependent and independent categories in the analysis, we did not assume any causal relationship between them. The spatial regression analysis was only used to account for the spatial dimension of our data while examining bivariate correlations.

Results

To examine whether health risks in the three cities are spatially and socioeconomically unequally distributed, we explored at both the city and the municipality levels some of their key dimensions: hazards, exposure, health outcomes, and social vulnerabilities. Changes in climate at the global and local levels are expected to aggravate existing meteorological and atmospheric conditions of the study cities. Temperature data from these cities suggest a general trend of increasing mean temperature and more intense urban heat. Regarding air pollution hazards, a comparison of our air quality data with the WHO, 2005 air-quality guidelines led us to find that levels of these pollutants are at least three to four times higher than WHO reference standards, and that they exceeded these standards at more than 90 percent of days for PM_{10} and at between 20 and 70 percent of the days for NO_2 during the study periods for the three cities (Fig. 1).

Our quantification of urban populations' likelihood or relative risk (RR) of dying from exposure factors (Table 2) showed there was an increased health risk from higher temperature in cold seasons in Bogota and in warm seasons in Mexico City. A positive correlation was also found between mortality and air pollution levels, but the pattern of the association differs by city and atmospheric condition.

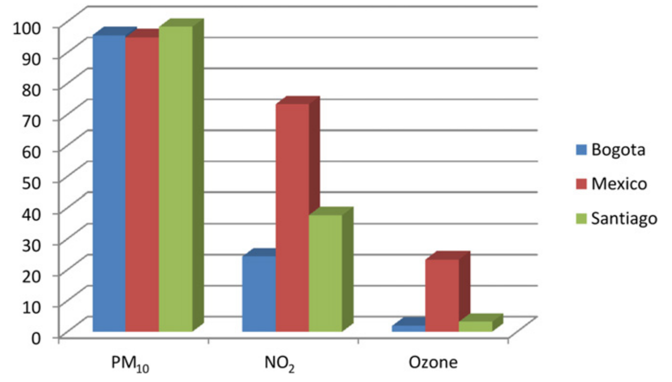

Fig. 1. Non-attainment by criteria pollutant, based on WHO standards. Source: ADAPTE's calculations based on data from cities' AQMN. The WHO reference standards are: for PM_{10}, 20 μg/m^3; for ozone (8-h averages), 50.8 ppm; and for NO_2 (24-h averages), 21.2 ppm.

Please cite this article in press as: Romero-Lankao, P., et al., Exploration of health risks related to air pollution and temperature in three Latin American cities, *Social Science & Medicine* (2013), http://dx.doi.org/10.1016/j.socscimed.2013.01.009

Table 2
Relative risk (RR) of dying from exposure to PM_{10} and average temperature during the warm and cold seasons at the city level.

City	Season	RR: Cardiovascular deaths by temperature	RR: Respiratory deaths by temperature	RR: Cardiovascular deaths by PM_{10}	RR: Respiratory deaths by PM_{10}
Bogota (2003–2006)	Warm	0.950	0.864	**1.001**	0.994
	Cold	**1.002**	0.900	**1.001**	**1.005**
Mexico City (2000–2004)	Warm	**1.015**	**1.001**	**1.001**	**1.015**
	Cold	0.974	0.948	**1.001**	**1.164**
Santiago (2001–2005)	Warm	0.900	0.925	0.950	0.990
	Cold	0.809	0.820	**1.012**	**1.014**

Note: Results included are all statistically significant ($p < 0.05$). The numbers in bold represent an increase in relative risk (RR) related to an increase of 1 °C in average temperature or 10 $\mu g/m^3$ in the level PM_{10}. $100 \times (RR - 1)$ measures the percent increase in mortality per unit increase in the temperature or pollutant. RR data were obtained using the Generalized Linear Model (GLM) with Poisson log-linear distribution.

For instance, the adverse impacts of PM_{10} are especially evident during the cold season in Bogota, Mexico City and Santiago. A daily 10 $\mu g/m^3$ increase in the levels of PM_{10} during the cold season has the potential to increase cardiovascular mortality risk by factors of 0.1%, 0.1% and 1.2% in Bogota, Mexico City, and Santiago respectively. It can also lead to an increase in respiratory mortality risk in cold seasons by factors of 0.5%, 16.4% and 1.4% respectively in the three cities. Yet Mexico City and Bogota also showed positive associations between PM_{10} and mortality during warm seasons.

For an entire metropolitan area, however, aggregate analysis cannot capture finer differentiations in the main dimensions of health risks. There are clear spatial variations of air pollution within each study city. For instance, the annual average concentration of PM_{10} oscillated in Mexico City between 40.7 $\mu g/m^3$ at the monitoring station of Plateros in the Southwest zone (SW zone) and 72.6 $\mu g/m^3$ at Nezahualcoyotl in the Northeast zone (NE zone). Within Bogota, the level of PM_{10} ranges from 26.9 $\mu g/m^3$ at the monitoring station of Santo Tomas (NE zone) to 112.96 $\mu g/m^3$ at Puente Aranda (SW zone). And within Santiago the differences range from 52.3 $\mu g/m^3$ at the monitoring station of Las Condes (NE zone) to 91.5 $\mu g/m^3$ at Pudahuel (NW zone).

Differences in some of the socioeconomic factors, as measured by the MVI, can also be observed within each study city. The MVI index ranges from 0.37 to 0.69, 0.06 to 0.76, and 0.33 to 0.62 between the least and the most vulnerable municipalities respectively in Mexico City, Bogota and Santiago. Three municipalities of Mexico City (Coyoacan 0.37, Coacalco de Berriozabal 0.4, and Tlalpan 0.4), three of Bogota (Chapinero 0.06, Teusaquillo 0.10 and Usaquen 0.21), and three of Santiago (La Reina 0.33, Vitacura 0.33, and Providencia 0.35) belong to the relatively least vulnerable within their cities (see Fig. 2). While the most vulnerable municipalities are Nextlalpan (0.69), Chimalhuacán (0.68) and Valle de Chalco in Mexico City, Ciudad Bolivar (0.76) and Sumapaz (0.72) in Bogota, and El Monte (0.61) and Curacaví (0.62) in Santiago (see Fig. 2).

Both the statistical and the spatial analysis (Table 3) show that the annual average concentration of PM_{10} was not correlated with vulnerability conditions for all three cities. Although no significant relationship was found between the NO_2 level and the MVI in Mexico City and Bogota, the spatial correlation analysis suggested the exposure to NO_2 was higher for those more vulnerable districts in Bogota. On the contrary, mean exposures to ozone were found to be negatively related to community vulnerability status for Santiago. While proponents of the environmental justice perspective may expect that spatial differences in environmental hazards overlap with socioeconomic characteristics of human settlement, our results suggest the association between levels of air pollution and social vulnerabilities does not always hold within the study cities. Further analysis also demonstrates that the spatial distribution of health impacts and risks did not correspond with spatial differentiations in socioeconomic vulnerability, mainly in two aspects:

a) Some of the most and the least vulnerable districts in the three cities are at similar relative risk of cardiovascular and respiratory mortality from exposure to PM_{10}. For example, the relative risks of these two types of deaths in Chapinero and Usaquen (RR 1.001 and 1.003), two of the least vulnerable districts in Bogota, are equal to and even higher than those of Rafael Uribe (RR 1.001 and 1.000), a more vulnerable district in the industrial area of Bogota.[3] Likewise, the relative risks of Vitacura, Lo Barnechea and Las Condes (RR 1.003 and 1.002), the three less vulnerable districts of Santiago, are similar to those of Santiago (RR 1.003 and 1.001), a relatively more vulnerable district in Gran Santiago.

b) When we look at the actual mortality outcomes along with the range of vulnerability values within each study city, the variation in respiratory and cardiovascular mortality rates does not coincide with the geographic distribution of the MVI index. For example, Benito Juárez in Mexico City, Fontibon in Bogota, and Providencia in Santiago, three of the least vulnerable districts in the study cities, have some of the highest mortality rates. And vice versa, several of the most vulnerable areas (e.g., Chimalhuacán in Mexico City, Ciudad Bolivar in Bogota, and Padre Hurtado in Santiago) have some of the lowest mortality rates. Overall, the correlation analysis found little evidence for the association between human health risks and social vulnerabilities of urban communities across the three study cities (see Table 3). Only in Mexico City did we find a significant relationship between the cardiovascular mortality rate and the MVI index, but they were negatively correlated. The degree of the correlation reduced when we took the spatial dimension of data into account, but it remained statistically significant. This seemingly counterintuitive relationship suggests the existence of some other complicated mechanisms which increase the health risk of better-off communities.

Discussion

The results above show that major determinants of environmental health risks need to be considered when making assessments of risk and vulnerability in urban populations. Particularly relevant for the purpose of this paper are the key dimensions and the spatial nature of the risk being assessed. Our findings suggest that some risks do indeed act without boundaries or social distinctions and show characteristics of a *boomerang effect*, as did the health risks related to atmospheric conditions and pollutants we studied here. While the ambient air pollution and climate-change-related health

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[3] Since the daily counts of cardiovascular and respiratory deaths of individual municipalities were usually small, we combined some municipalities around the same air quality monitoring stations together in the analysis to better capture the effects of air pollution on mortality.

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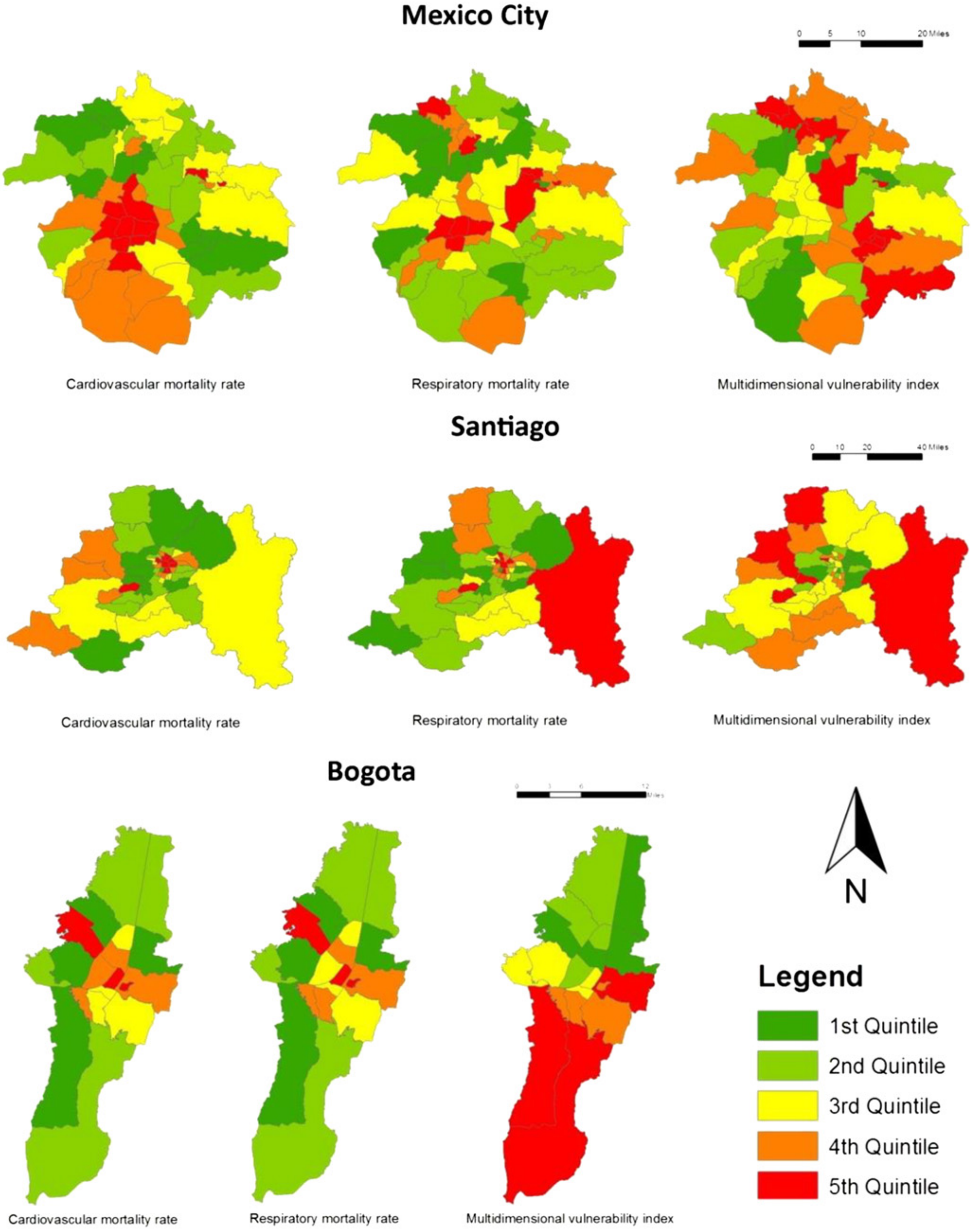

Note: These maps show from left to right the geographic distribution of human mortality rates attributable to cardiovascular and respiratory disease, and the distribution of vulnerable groups as measured by the multidimensional vulnerability index (MVI) in the three cities. Data in the maps are divided into five equal groups. The first quintile contains the lowest 20% of values, while the fifth quintile has the highest 20%.

Fig. 2. Spatial distribution of mortality rates and the multidimensional vulnerability index.

impacts may be spatially and socioeconomically differentiated within or between regions and countries, they may distribute more equally on a smaller scale such as areas within urban regions.

The relationships between some of the key dimensions of health risks explored in this paper are very complex. At the high levels of air pollutants (particularly PM_{10}) found in our studied cities, the health of all local populations is at risk. But the nature of these health risks is quite complex: it varies across cities and with differing weather conditions; and it has different implications for different impacts such as respiratory and cardiovascular mortality. Similarly, a diverse picture emerges when the components of health risks are analyzed at finer spatial levels. As for PM_{10}, the pollution levels at the monitoring stations in the cities were at least three times as high as the WHO standard, but levels could not be correlated with local vulnerability of the municipalities in which the stations were located. The results on exposure to ozone also confirm the finding of previous studies (e.g., Marshall, 2008) that the relationship between environmental hazards and socioeconomic heterogeneities is not always consistent with environmental justice hypotheses. Furthermore, although indicators of socioeconomic vulnerabilities, exposures and impacts differ within and across the three cities, the spatial differences in social vulnerabilities within cities do not necessarily correspond with the spatial distribution of health risks and impacts. This can be seen in at least two ways. First, in the three cities, the populations of communities with different vulnerability levels are at similar relative risk of mortality from exposure to PM_{10}. Second, the

Table 3
Correlations between air pollution levels/mortality rates and multidimensional vulnerability index.

Variables	Mexico City			Bogota			Santiago		
	Pearson's *r*	Spearman's rho	Spatial correlation	Pearson's *r*	Spearman's rho	Spatial correlation	Pearson's *r*	Spearman's rho	Spatial correlation
ln (PM$_{10}$) & ln (MVI)	−0.165	−0.389	−0.346	−0.347	−0.041	−0.376	0.436	0.071	0.431
N	15	15	15	11	11	11	7	7	7
ln (NO$_2$) & ln (MVI)	0.026	0.118	0.106	0.634	0.452	0.687*	–[a]	–	–
N	18	18	18	8	8	8	–	–	–
ln (ozone) & ln (MVI)	−0.281	−0.256	−0.302	–[a]	–	–	−0.855*	−0.821*	−0.873***
N	17	17	17	–	–	–	7	7	7
ln (cardiovascular mortality rate) & ln (MVI)	−0.435**	−0.392**	−0.559*	0.169	0.086	0.227	−0.153	−0.160	−0.297
N	51	51	51	19	19	19	52	52	52
ln (respiratory mortality rate) & ln (MVI)	−0.077	−0.003	−0.200	0.149	0.035	0.206	0.003	−0.020	0.108
N	51	51	51	19	19	19	52	52	52

$^{*} = p < .05$, $^{**} = p < .01$, $^{***} = p < .001$.
[a] No sufficient data for the analysis.

geographic distribution of respiratory and cardiovascular mortality rates does not always coincide with the pattern of the MVI index; at times the relationship found between the two is quite unexpected. We can thus draw the conclusion that, at the high levels of pollution we studied, atmospheric hazards tend to affect both the more and the less socially vulnerable municipalities alike.

While our results showed that air pollution and climate-related health risks are relatively ubiquitous in these three Latin American cities, the influence of socioeconomic status should not be underestimated as it plays a complex role in driving and explaining health risks, and interacts in intricate ways with the other dimensions of health risks. There is no doubt that uneven development patterns and distribution of wealth in the three studied cities have allowed a minority to disproportionately contribute to the high levels of pollution and health risks there. Although the affluent in these cities do not necessarily receive less of the consequences of poor air quality, they can certainly be given more responsibility for it. It is also true that the populations in the wealthier municipalities may score relatively low in most of the dimensions of vulnerability measured in the MVI index (e.g., have lower levels of overcrowding, higher median housing value, or higher levels of education), while in poorer municipalities, the numbers of high scores in these vulnerability dimensions are generally greater. As a result, the wealthy may have the socioeconomic and political assets, means and options to escape from, or at least to mitigate, many environmental health risks.

In a way, the mixed findings on the socioeconomic differentiation of health risks reflect the multidimensional characteristics of social vulnerability. The findings of this research suggest that the combined effect of social vulnerability factors on health outcomes may be different from the influences of individual socioeconomic factors. One limitation of our analysis is that we used human mortality, a rather severe impact, to measure health risks from air pollution and temperature. Also, the temperature and air pollution data are usually unavailable, or at best incomplete, at lower levels of analysis such as the municipality and the neighborhood. Therefore, public health data of better quality (e.g., morbidity, hospital visits) and the monitoring of air quality and temperature on finer scales should improve understanding of the nature of health risks related to such environmental hazards.

Conclusions

In this paper, we explored the nature of health risks among the populations of Bogota, Mexico City and Santiago through an empirical assessment of the health impacts of air pollution and temperature variation. We asked whether these risks were acting across socio-economic and spatial boundaries (Beck's "risk society thesis") or whether they were unequally distributed along socio-economic or spatial lines ("environmental justice thesis"). We hypothesized that, on the intra-urban scale, health risks related to air pollution and temperature in Latin American cities would not necessarily depend on socio-economic differentiations. Our results bore out our hypothesis, suggesting that health risks from atmospheric conditions and pollutants act without boundaries or social distinctions within urban areas. This highlights the importance of the spatial dimension of risk research and shows how geographic scales and their interactions with the physical characteristics of natural hazards can influence research findings on health risks.

We found that health risks from air pollution and temperature change are of a complex nature that varies across cities and with differing weather conditions, with different implications for different impacts such as respiratory and cardiovascular mortality. For PM$_{10}$, ozone and other criteria pollutants at the high concentration levels found in our study cities, populations in some of the least and the most socioeconomically vulnerable municipalities are at similar risks when simultaneously exposed to air pollution and temperature extremes. These findings are contradictory to what would be normally predicted by the environmental justice literature.

Hazards such as these are examples of environmental threats with no socioeconomic or physical boundaries as suggested by Beck's risk society theory. If the levels of atmospheric pollution in these cities increase far beyond the safe levels established by the WHO, then the *boomerang effect* may hold, with wealthy and poor populations being equally affected. Furthermore, in a plausible future threatened by increasing levels of air pollution interacting with more intense urban heat islands, heat waves and other climate change impacts, what goes around will certainly come around and pose risks to both rich and poor alike.

On a final note, our findings might shed light on a broader debate in the literature on global environmental change: namely, what theories appropriately describe the multifaceted nature of risks and vulnerabilities? Is the focus on underlying social vulnerabilities or on the exposure to hazards enough to understand the complex nature of (health) risks, or do we need more integrated approaches? These findings might also be extrapolated to other areas of inquiry on the effects of climate change: how these effects will be economically and socially differentiated and whether there is a threshold level at which they will begin to be felt by all.

Acknowledgements

This paper is the primary outcome of the project **Adaptation to the Health Impacts of Air Pollution and Climate Extremes in Latin American Cities (**ADAPTE) that investigates the health risks

Please cite this article in press as: Romero-Lankao, P., et al., Exploration of health risks related to air pollution and temperature in three Latin American cities, *Social Science & Medicine* (2013), http://dx.doi.org/10.1016/j.socscimed.2013.01.009

from exposure to climate variability and air pollution in major Latin American cities. ADAPTE has been supported by the Inter American Institute of Global Change Research (IAI) SGP-HD 013 and the National Science Foundation (NSF), and includes the following participants: 1. Patricia Romero-Lankao, Hua Qin, Mercy Borbor-Cordova, Melissa Haeffner, Sara Hughes, Olga Wilhelmi, Steve Sain, Raphael Nawrotzky, Kevin Sampson (*National Center for Atmospheric Research , Boulder, USA*); 2. Eduardo Behrenz, Daniela Parra (*Universidad de los Andes*, *Bogotá, Colombia*); 3. Alejandro Leon, Patricia Matus, Paulina Aldunce, Karla Caneo (*Universidad de Chile, Santiago, Chile*); 4. Laura Dawidowski, Rosana Abrutsky (*Comisión Nacional de Energía Atómica (CNEA), Buenos Aires, Argentina*); 5. Griselda Günther (*Autonomous Metropolitan University (UAM), Mexico City, Mexico*). Any opinions, findings and conclusions, recommendations or omissions expressed are those of the authors and do not necessarily reflect the views of IAI and NSF. We want to thank Daniel Gnatz, Karen Griggs and three anonymous reviewers for their valuable suggestions and inputs to this paper.

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