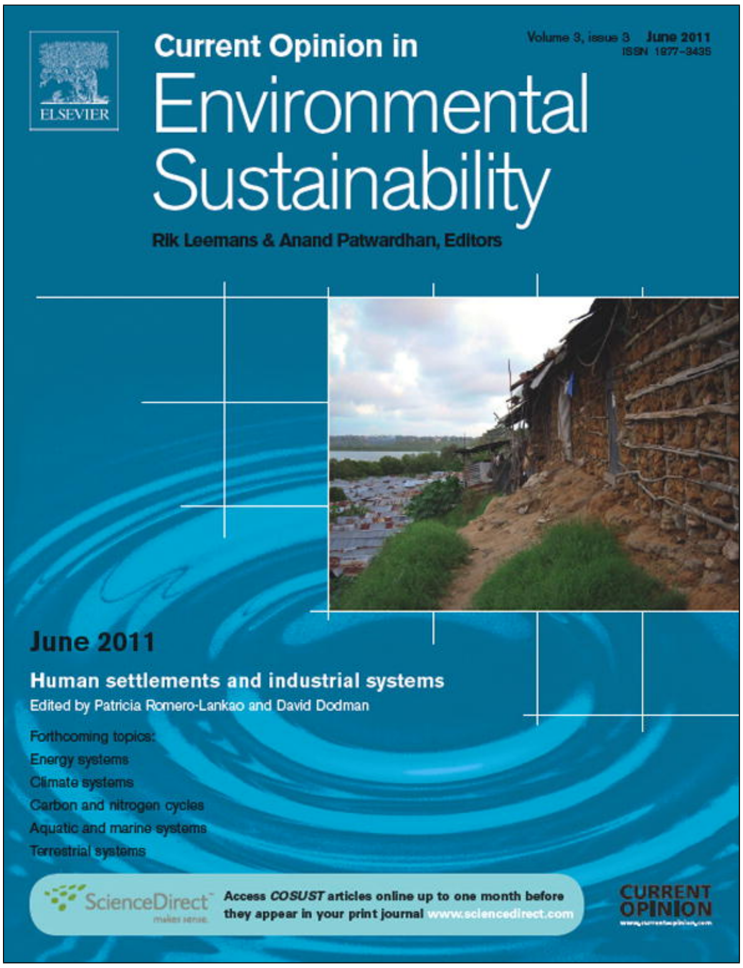
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Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation

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Excess morbidity and mortality related to extremely hot weather and poor air quality are found in cities worldwide. This is a major public health concern for cities now and looking toward the future because the interactions of global climate change, urban heat islands, and air pollution are predicted to place increasing health burdens on cities. The proposed mitigation and adaptation strategies in cities' climate risk management plans may produce health co-benefits by reducing emissions and cooling temperatures through changes in the built environment. There are challenges, however, to implementing the plans and the most widely documented beneficial policy to date is the adoption of heat warning and air quality alert systems to trigger emergency responses.

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Introduction

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) predicted that negative human health impacts will include significant increases in deaths, illnesses, and hardship due to changes in temperature, precipitation, and extreme weather events (direct exposures) and to changes in ecology that extend the ranges of infectious disease and create food and water shortages (indirect exposures) [1]. Future health outcomes will vary across regions and nations, conditioned by specific manifestations of climate change, the vulnerability of particular populations to local social and environmental stressors, and access to health care [2,3]. Since the IPCC Assessment was published, researchers have made significant strides in applying quantitative methodologies to identify types and rates of mortality and morbidity related to weather and in anticipating health outcomes under different climate change scenarios.

Progress is also marked by efforts to mitigate climate change through reduction of greenhouse gas (GHG) emissions and policies designed to increase the adaptive capacity [4,5] of physical and social systems to global change. Many avenues for mitigation and adaptation are appropriate for local initiatives because health outcomes are specific to the circumstances of places and appropriate actions depend in large measure upon local ecologies, economic and social development, available technologies, political capabilities, wealth and age of the population, and public opinion. Local actions can help to reduce human vulnerability by managing health risks, alleviating current health problems, and preventing future catastrophes [6–8].

Sixty percent of the global population will reside in urban centers by 2030 and an overwhelming majority of urbanization is expected to occur in low-income and middle-income countries [9]. Cities face health challenges from climate change that are similar in some respects to their hinterlands but in other respects are unique because of greater population density and diversity, complexity of the built environment, and dependence on technological systems for survival. Urban residents are more insulated from the natural environment, which leads to a lack of understanding about human effects on environmental systems and negative feedbacks from degraded environments to human health.

This review will summarize epidemiological studies primarily from 2005 to 2010 on mortality and morbidity related to two climate hazards in cities: increasing temperatures and the modifying influence of air pollution. Heat exposure and related illnesses are under intensive investigation worldwide because they affect cities in all types of climate regimes. Air quality, a long-standing environmental issue, has improved in many cities in high-income countries because of government regulations and advances in technology. Nevertheless, respiratory illnesses are still a major global urban health burden.

Many cities are designing and implementing strategic risk management action plans to lessen the impacts of climate change. These plans may have health co-benefits, such as reducing illnesses related to heat and air pollution, as well as other diseases associated with urban lifestyles. This review reports on climate mitigation and adaptation strategies in cities and assesses their potential to improve urban health. Although cities face other risks from climate change, such as flooding and sea level rise [10,11], this review concentrates on climate risks related to rising temperatures and air pollution.

Changes in the climate of cities

Human and natural systems in cities are tightly coupled in synergistic and dynamic relationships embedded within a global environment that is rapidly changing. In urban social–ecological systems, human activities are causing rising temperatures and other climatic changes, which in turn affect human health and well-being. Urban areas, particularly in high income nations, are major sources of carbon dioxide emissions from industrial, transportation, and domestic consumption of fossil fuels that cause global warming [12,13]. During the 20th century, temperatures increased significantly faster in cities compared to nearby rural areas due to the urban heat island (UHI) effect [14,15]. The transformation of native landscapes into dense urban settlements of heat-retaining impervious surfaces and building materials that inhibit night-time cooling [16] is the most significant anthropogenic driver of urban climate change [17] in cities around the world [12].

Warmer baseline temperatures in cities are further elevated by extreme heat events (EHEs) or heat waves, which are projected to strike with increasing frequency and intensity in the 21st century [18,19]. Moreover, meteorology influences air quality, such that elevated temperatures during the summer can contribute to air pollution that exacerbates harmful impacts of heat on human health [1,20••]. Coupled global and regional model simulations show that global warming will probably result in deteriorating urban air quality, including increased surface ozone levels and particulate matter (PM), smoke from wildfires, and some pollens in certain regions of the world [21•,22,23]. The largest effects of climate change on air quality will be experienced in northern mid-latitude cities during high pollution episodes [21•].

Health effects of heat exposure and air pollution in cities

Public health crises in cities pre-date the modern era of climate change by several centuries. Although urban health is improving overall, it is doing so unevenly among nations and rich and poor residents [24]. Outbreaks of infectious diseases, tuberculosis, and respiratory illnesses remain major concerns in cities even as ‘lifestyle’ diseases, such as diabetes, hypertension, coronary diseases, alcoholism, and drug dependence are rapidly increasing. Morbidity and mortality due to extremely hot weather are emergent urban public health problems.

Extreme heat

Studies consistently show a strong relationship between high temperatures and excess all-cause mortality with city-specific thresholds that vary according to latitude and normal average temperatures [25,26••,27]. The range of temperature thresholds indicates variability in human acclimatization and availability of adaptations, such as air conditioning. Moreover, cities on nearly every inhabited continent have experienced EHEs in the 21st century that collectively have resulted in tens, perhaps hundreds, of thousands of excess deaths directly due to heat and its consequences or indirectly due to disease [28•,29,30•,31,32]. In North America, extreme heat is the most common cause of death among all weather-related disasters [33,34]. Additional research is needed on how mortality estimates vary with definitions of heat waves [28•] and whether advance warning systems prevent deaths [35].

There are fewer studies of the effects of hot weather on hospitalizations and emergency department (ED) visits but heat-related morbidity is an important research area because relatively small increases in rates of illness affect many people and generate large public health costs [36]. Syndromic surveillance systems based on healthcare provider data are also used to activate emergency response measures during EHEs [37•]. Studies have found that several syndromes and diseases associated with excess mortality during EHEs, such as heat-related illnesses (e.g. heat stroke, heat exhaustion, hyperthermia), acute renal failure, and cardiovascular disease, correspond with increased hospital/ED visits during heat waves [36,38]. In addition, visits for malaise [37•], electrolyte imbalance, nephritic syndrome, and diabetes [36] show marked increases. A recent study of a 2006 heat wave covered hospitalization/ED visits in the entire state of California and found thousands of excess cases of heat-related illnesses, even in regions with moderate temperature increases [36]. A review of morbidity studies [25] called for more research because some studies have found significant effects of EHEs on illness rates but other studies have not (e.g. [29,38,39,40]).

Air pollution

The impacts of air quality on urban health outcomes are more complex than temperature impacts, owing to the variable distribution and behavior of a large number of pollutants that affect different disease categories, such as respiratory and cardiovascular illnesses and allergies. Stricter air quality standards have improved health in many high-income countries; for example, between 1970 and 2000, reductions in fine PM accounted for as much as 15 percent of the overall increase in life expectancy in 51 US metropolitan areas [41]. In cities of low-income and middle-income countries, however, air quality continues to deteriorate and to impose increasingly greater health burdens on growing populations that use large amounts of energy to meet domestic and industrial needs [42–44].

At present, there is scientific consensus that extreme heat and air pollution separately cause significant urban health problems and the negative impact of each is expected to intensify with climate change [21•]. There is not consensus, however, on whether air pollution is a modifying influence that interacts with temperature to produce an even larger negative impact on human health. In some studies, air pollution is a significant modifier of high temperature on mortality [20••,45,46] but in others, the interaction effects are negligible [30•,47] or only appear during some heat events [48]. Others find heterogeneity among cities in the magnitude of joint effects and relative contributions of temperature and air quality to mortality rates [49]. More research is required to understand the coupled relationship between emissions and weather in an era of increasing climate change [21•].

Variable health risks within cities

Health risks from extreme heat and air pollution differ *among* cities depending on geography, climate, wealth, and a number of other factors. Owing to a robust research tradition in environmental justice, race, and air pollution in the US [50,51] and advances in socio-spatial analysis of fine-scale social, ecological, and weather data [52••,53], we are beginning to understand the distribution of health risks for urban subpopulations *within* individual cities.

Health risk factors related to climate change include differences in physiological sensitivity to high temperature and air pollution [54], socioeconomic variables that modify exposure levels to hazards [55], and spatial locations that are hazardous living spaces [56,57]. Individuals at risk for increased exposure and susceptibility to extreme heat and air pollution include the elderly, very young, socially isolated, poor, racial/ethnic minorities, and those with pre-existing illnesses or no access to air conditioning [25,36,58,59]. Many recent studies compare the vulnerability of neighorhoods within cities, correlating fine scale measurements of microclimate temperatures or air pollution with neighborhood biophysical and social variables, such as amount of vegetation, open space, and socioeconomic composition of the population [52••,55,60–64,61•]. Several studies reveal spatial variation in intra-urban environmental quality but more studies are needed that include spatial measures of human health.

Potential health co-benefits through mitigation and adaptation

Mitigation strategies are efforts to reduce GHG emissions and increase carbon sequestration in order to slow the rate of climate change, whereas adaptations aim to increase a system's ability to adjust and reduce vulnerability to the effects of climate change [1,65]. Cities may contribute to long-term mitigation of rising temperature and air pollution through policies that reduce energy consumption in transportation, industry, and households [66], improve the built environment [67], or increase carbon sequestration through the preservation or creation of urban forests [68]. Examples of adaptations include improved weather forecasting, heat warning systems, air quality alerts, and emergency preparedness to deal with elderly and institutionalized populations during extreme events [69,70]. Locally integrated frameworks for climate policies that work within specific socio-ecological contexts are imperative [71••].

Reducing fossil fuel consumption in cities has significant health co-benefits, especially in developing nations, and the estimated net costs of climate policies would be substantially reduced if the co-benefits of improved air quality were fully valued [72]. In fact, most studies that have quantitatively assessed health co-benefits focus on air pollution, particularly $PM_{2.5}$ and ozone [66]. Using a variety of air pollution and epidemiological models and assumptions about policy scenarios, estimates of co-benefits have been derived for scenarios of reduced GHG emissions in electricity production [73], household energy use [74], and transportation [67,75].

Controlling emissions in cities will also decrease the amount of anthropogenic heat released into the atmosphere, thereby reducing contributions to global warming and the UHI effect, while having the co-benefit of preventing heat-related illnesses and deaths. Cities that promote an energy generation transition from fossil fuels to renewable sources should reap the benefits of a cleaner living environment and restored ecosystems, which will foster co-benefits of a healthier and more active lifestyle for residents. For example, improved air quality will reduce respiratory illnesses [76] and increased physical activity should reduce 'lifestyle' diseases, such as obesity [77], cardiovascular disease [78], and social isolation [79], while also improving mental health [80].

Many cities have developed risk management action plans that include mitigation and adaptation strategies to reduce key vulnerabilities to climate change [81]. If these plans are implemented, positive environmental impacts and health co-benefits that improve the well-being of urban residents are very likely to occur [7,67,82•,83]. We searched the Internet and journal literature to identify cities that have published risk management plans or have reported adopting strategies to deal with the impacts of climate change and we analyzed their major components, environmental impacts, and potential health co-benefits. These cities represent a cross-section of burgeoning to well-established urban centers in high-income and middle-income countries with various climate regimes, population sizes, and demographic profiles. The overarching theme of the plans is to reduce the impact of human activity on the natural environment but cities employ a variety of tactics to achieve their goals. The spectrum of ideas that cities have implemented or are considering for climate mitigation and adaptation are summarized in Table 1. The plans presented in this review are not exhaustive; however, they provide a sample of strategies to address climate

Table 1

Summary of city risk management strategies for climate change mitigation and adaptation with health co-benefits

Risk management strategy	Adaptation/mitigation tactic	Environmental outcomes	Human health co-benefits	City examples
Advisory and Prevention	Heat/Health Watch Warning System		Reduce heat-caused and heat-related deaths and illnesses	Shanghai (China) is using a Heat/Health Watch Warning System to monitor regional weather patterns and alert residents of upcoming periods of elevated temperatures [87] (3, 8, 9, 12, 13, 18)
	Air Quality Monitoring and Alert		Reduce respiratory illnesses (e.g. asthma)	New York City, New York (USA) employs an Air Quality Alert system to inform local residents of poor outdoor air quality on days with high emissions (2, 10, 13)
Building Materials and Design	Green roofs	Carbon sequestration, water retention, energy conservation, reduced greenhouse gas emissions, UHI mitigation	Reduce heat-related illnesses and respiratory illnesses, increase thermal comfort	Toronto (Canada) utilizes green roof technologies that help reduce local outdoor temperatures (by sinking carbon) in addition to providing cooling capacity inside buildings (18)
	Increase albedo	Reduce energy use and greenhouse gas emissions, UHI mitigation	Reduce heat-related illnesses and respiratory illnesses, increase thermal comfort	Portland, Oregon (USA) aims to reduce the amount of solar energy urban surfaces absorb by increasing the reflectivity and/or emissivity of building materials [88]
	LEED building compliance	Increase energy efficiency of buildings, reduce energy use and greenhouse gas emissions	Reduce heat-related illnesses and respiratory illnesses, positive aspects of increased natural light in workplace	Cape Town (South Africa), utilizes rating systems and building compliances, such as LEED (Leadership in Energy and Environmental Design) to recognize and reward the impact of environmental building design (1, 3, 4, 6, 8, 15)
	Home insulation	Increase energy efficiency of buildings, reduce energy use and greenhouse gas emissions	Increase thermal comfort, reduce heat-related illnesses and respiratory illnesses	Sao Paulo (Brazil) improves energy efficiency by insulating homes to stay cool in the summer and warm in the winter (1, 6, 9)
Land-use Change	Urban forest	Carbon sequestration, UHI mitigation, storm water retention, improve air quality	Increase shade and thermal comfort, reduce heat-related illnesses, provide recreational green spaces, increase in allergies	Urban Forests policy has been implemented in Chicago Illinois (USA) as a long-term plan designed to improve air quality while mitigating heat stress by increasing vegetation and urban canopy (8, 11, 13)
	Pervious surfaces	Water retention, moisture exchange, surface cooling	Outdoor cooling and thermal comfort, reduce heat-related illnesses, increase green space	Keene, New Hampshire (USA) is replacing asphalt and concrete with pervious surfaces that enable the transmission of moisture, thereby increasing the cooling capacity of urban surfaces (14)
	Community gardens	Carbon sequestration, water retention, improve air quality	Improve nutrition, increase exercise, reduce 'lifestyle' diseases, increase community engagement	Boston, Massachusetts (USA) is using urban gardens that help capture carbon, increase cooling, while producing local fruits and vegetables (1, 4, 14)
Transportation Systems	Public transportation	Reduce energy use and greenhouse gas emissions, reduce mining of fossil fuels, improve air quality	Increase exercise, reduce heat-related illnesses and respiratory illnesses, increase community engagement	Copenhagen (Denmark) reduces dependence on fossil fuels by providing public transportation systems (5, 6, 7, 8, 10, 17)

Table 1 (*Continued*)

Risk management strategy	Adaptation/mitigation tactic	Environmental outcomes	Human health co-benefits	City examples
	Pedestrian-friendly transit, such as bicycle routes and walkable streets	Reduce energy use and greenhouse gas emissions, reduce fossil fuel extraction	Increase exercise, reduce respiratory illnesses, increase community engagement	Rotterdam (The Netherlands) has provided extensive pedestrian-friendly modes of transit (3, 4, 8, 9, 14, 15, 18)
Innovation and Experimentation	Renewable energy transition	Reduce greenhouse gas emissions, harvest natural and sustainable energy sources, reduce mining of fossil fuels, improve air quality	Reduce heat-related illnesses and respiratory illnesses	London (England) is experimenting with biofuels, wind turbines, photovoltaic and solar thermal arrays that simultaneously promote renewable energy generation, economic development opportunities, ecosystem health, and reduced dependence on fossil fuels (4, 5, 6, 9, 13, 15, 16, 18)
	Wind powered cars	Reduce greenhouse gas emissions, harvest natural and sustainable energy sources, reduce mining of fossil fuels, improve air quality	Reduce respiratory illnesses	Copenhagen (Denmark) is harvesting wind as the primary energy source to power electrical and hydrogen-powered cars.
	Community Engagement Program	Reduce greenhouse gas emissions, protect and restore coastal habitats, improve air quality	Expand climate education for city residents, promote green lifestyles	Boston, Massachusetts (USA) has developed a five-point engagement strategy grounded in action, education, and collective responsibility to prepare for the impacts of climate change.

Note: Table 1 represents a non-exhaustive summary of risk management tactics and co-benefits from 18 global cities. For each risk management tactic, one city is highlighted as an example and cities employing a similar technique are also listed. The city plans examined in this study are: 1 Boston, Massachusetts (USA); 2 Cape Town (South Africa); 3 Chicago, Illinois (USA); 4 Copenhagen (Denmark); 5 Ho Chi Minh City (Vietnam); 6 Keene, New Hampshire (USA); 7 Seattle, Washington (USA); 8 London (England); 9 Melbourne (Australia); 10 Mexico City (Mexico); 11 New York City, New York (USA); 12 Philadelphia, Pennsylvania (USA); 13 Phoenix, Arizona (USA); 14 Portland, Oregon (USA); 15 Rotterdam (The Netherlands); 16 Santa Cruz, California (USA); 17 Sao Paulo (Brazil), 18 Toronto (Canada).

concerns at the city level. Three key features of the plans are:

1. All action plans utilize targets and benchmarks to reduce vulnerability to climate change. Cities are establishing standards for weather advisory/warning systems, stricter controls on air quality (dust control and carbon emissions), and building codes. They are focused on renewable energy goals, alternative transportation systems (public transit and pedestrian/ bicycle friendly), and new land-use practices that promote accessible parks, open spaces, and urban forests.
2. Action plans call for an integrated framework of top-down and bottom-up (grassroots) approaches to achieve their goals [81]. They also emphasize shared responsibility among local governments, public interest groups, community groups, and individual residents.
3. Additional studies are needed to evaluate the effectiveness of new initiatives, but there could be a number of direct and indirect health co-benefits and positive environmental impacts from pursuing climate adaptation and mitigation strategies. Reduced deaths and illnesses from heat-related causes and air pollution should be expected, as well as indirect benefits from the promotion of active lifestyles.

The development of city action plans is an important step toward reducing human vulnerability to climate change but a number of challenges and tradeoffs are already apparent in the implementation phase. For example, implementing the plans requires an initial financial investment, which many local elected officials and decision-makers are reluctant to make, particularly in a depressed economy. Many cities in developing and industrial countries alike face the difficult choice between pursing economic development in the short-term or reducing environmental degradation and associated public health risks. There are institutional barriers to establishing trust and collaboration between the public and private sectors, grassroots campaigns, and scientific enterprises in order to effectively and equitably carry-out risk management tactics. A serious problem is that many programs do not specifically target marginalized and/or segregated communities in high-income, middle-income, or low-income countries. Neglect of the most vulnerable populations and places will exacerbate uneven development and social inequality at the submetropolitan scale.

Perhaps the biggest challenge to implementing city plans is calculating the cost–benefit ratio of any given climate policy in an urban socio-ecological system that draws on scarce natural resources, as illustrated in examples of urban forests and solar energy. The many benefits of expanding an urban forest need to be evaluated against the costs: increased pollen (allergies), tree maintenance services, and a greater demand on water resources, which is highly problematic in arid environments [84,85]. The use of alternative energy systems such as solar thermal energy (STE) systems is an increasingly popular method for meeting residential and commercial energy needs with reduced GHG emissions but the current systems are highly water-intensive, which must be considered when siting STE plants and allocating water resources [86].

Conclusions

Excessive heat and air pollution increase mortality and morbidity in cities on six continents. Research during the past decade has created a sense of urgency among public health professionals because future scenarios predict warming urban temperatures and increasing frequency and intensity of EHEs due to the interaction of global climate change and UHIs.

Research that identifies the most vulnerable populations and places within cities – heterogeneity of risks – is crucial because health burdens fall disproportionately on urban residents who are physiologically susceptible, socioeconomically disadvantaged, and live in the most degraded environments. The most 'actionable' research findings emerge from studies of specific cities because researchers find so much variation in local meteorology, level of emissions, capabilities of governments, and acclimatization of residents.

City risk management strategies for mitigating and adapting to climate change propose to reduce GHG emissions and cool the city through changes in the built environment, land use, and transportation. Implementing these plans could provide health co-benefits for residents, including reductions in heat-related and respiratory illnesses as well as 'lifestyle' diseases. Many cities have adopted surveillance, warning, and alert systems to trigger emergency responses to EHEs and poor air quality days. However, there is little research to evaluate whether other strategies have been implemented or whether health co-benefits have been realized. There are impediments to implementing costly aspects of city mitigation and adaptation plans under current economic conditions and further research is needed on how much health co-benefits reduce the cost of climate policies.

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