Review Article

# Links between the Built Environment, Climate and Population Health: Interdisciplinary Environmental Change Research in New York City

Joyce Klein Rosenthal,[1] *MSUP, MPH*, Elliott D Sclar,[1] *PhD*, Patrick L Kinney,[2] *ScD*, Kim Knowlton,[2,3] *DrPH*, Robert Crauderueff,[4] *BA*, Paul W Brandt-Rauf,[2] *MD, ScD, DrPH*

## Abstract

**Global climate change is expected to pose increasing challenges for cities in the following decades, placing greater stress and impacts on multiple social and biophysical systems, including population health, coastal development, urban infrastructure, energy demand, and water supplies. Simultaneously, a strong global trend towards urbanisation of poverty exists, with increased challenges for urban populations and local governance to protect and sustain the well-being of growing cities. In the context of these 2 overarching trends, interdisciplinary research at the city scale is prioritised for understanding the social impacts of climate change and variability and for the evaluation of strategies in the built environment that might serve as adaptive responses to climate change. This article discusses 2 recent initiatives of The Earth Institute at Columbia University (EI) as examples of research that integrates the methods and objectives of several disciplines, including environmental health science and urban planning, to understand the potential public health impacts of global climate change and mitigative measures for the more localised effects of the urban heat island in the New York City metropolitan region. These efforts embody 2 distinct research approaches. The New York Climate & Health Project created a new integrated modeling system to assess the public health impacts of climate and land use change in the metropolitan region. The Cool City Project aims for more applied policy-oriented research that incorporates the local knowledge of community residents to understand the costs and benefits of interventions in the built environment that might serve to mitigate the harmful impacts of climate change and variability, and protect urban populations from health stressors associated with summertime heat. Both types of research are potentially useful for understanding the impacts of environmental change at the urban scale, the policies needed to address these challenges, and to train scholars capable of collaborative approaches across the social and biophysical sciences.**

**Ann Acad Med Singapore 2007;36:834-46**

**Key words: Adaptation, Cities, Planning, Urban heat island**

## Introduction: Global Trends and Local Impacts

This decade marks history's first recognition that a majority of humanity is urbanised – with over 50% of the planet's 6.5 billion people expected to live in urban areas.[1] Within this expanding urbanised population, poverty remains an entrenched and persistent reality for the estimated 1 billion people now living in slum-like conditions, often lacking a roof, secure tenure, sanitation, running water and clean air. Furthermore, cities are expected to absorb virtually all of the growth in global population over the next 25 years – an estimated 2 billion people, in an unprecedented and global shift in population from rural and agrarian to urban lives.[2] Most of this population growth will take place in the cities of the developing world, where slums are expected to shelter at least an additional 1 billion people by 2030, during this time of the "final buildout of humanity," before global population peaks at roughly 10 billion by 2050. The number of cities with over 5 million inhabitants is expected to rapidly increase, growing from 41 at present to a projected 59 in the next 10 years alone, with almost all of the growth in developing countries.[3]

These trends of increasing urbanisation of poverty exist within a changing global environment. An international scientific consensus holds that the global climate is warming,

[1] Urban Planning Program, Graduate School of Architecture, Planning and Preservation (GSAPP), Columbia University, New York, USA
[2] Mailman School of Public Health, Columbia University, New York, USA
[3] Natural Resources Defense Council, New York, USA
[4] Sustainable South Bronx, Bronx, New York, USA
Address for Correspondence: Dr Paul W Brandt-Rauf, Department of Environmental Health Sciences, Mailman School of Public Health, Columbia University; 60 Haven Ave., B-1; New York, NY 10032, USA.
Email: pwb1@columbia.edu

with long-term increases in mean annual surface temperatures of the earth's atmosphere, increased climate variability and projected increases in extreme weather events expressed differentially across the planet.[4] The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report projects that the globally averaged surface temperatures will increase by 1.8°C to 4.0°C (3.2°F to 7.2°F) by 2100. A warming climate over the next 50 years will confront rapidly urbanising populations with a complex array of changes in biological and biophysical systems at every spatial scale, resulting in impacts on urban infrastructure, economic, social and political systems and stressors to human health that also vary regionally.

Urbanisation leads to land use and land cover change, which is a major driver of global environmental change as well. Urbanised land now occupies approximately 3% of total global land surfaces, but with a much larger ecological footprint.[5,6] If consumption of land for development continues to outpace the increase of population, and global urban densities decline as they have in western cities, urbanised areas may occupy over 7% of the earth's land surface in the next couple of decades.[7] Yet, despite projections for rapid urban growth, the interactions between land cover, the atmosphere, human activities and health outcomes are poorly understood in the urban environment.[8]

Increased urbanisation, the presence of urban poor and ecological change are not new. The squalor and inequities of 19$^{th}$-century industrial working class living conditions served as common origins for the new fields of urban planning and public health in crafting policies for addressing environmental problems of the early industrial cities. While the professions and disciplines of urban planning and public health diverged in methods in the past century, the wretched living conditions that led to innovations in these fields are being recreated today, on an even larger scale, in the slums of developing cities.[9] However, the adverse conditions and health challenges created by structural inequities are not confined to the cities of the developing world. In the United States, racial and ethnic groups experience discrimination that in conjunction with "socioeconomic factors (e.g. education, employment, and poverty), lifestyle behaviours (e.g., physical activity and alcohol intake), social environment (e.g., educational and economic opportunities…and neighborhood and work conditions), and access to preventive healthcare services (e.g., cancer screening and vaccination)" contribute to persistent and systemic racial/ethnic health disparities in health status and mortality rates.[10,11]

As Hurricane Katrina made widely visible, cities in developed nations as well need to attend to the interaction of urban poverty and structural inequities of race and income with the dynamics of environmental change. In New Orleans, neighbourhoods with significant flooding "had lower incomes, higher poverty rates and less education."[12] Severe public health consequences following Katrina were disproportionately born by "people in poverty and people of color," and continue to be experienced by thousands of displaced families with limited access to jobs, schools, permanent homes and healthcare.[13]

In the face of ecological change and health disparities at all scales, a renewal of the collaborative approaches between urban planning and public health practice, training and research is necessary to craft adequate collective responses.[3] Towards that end, this article discusses some of the interdisciplinary research undertaken at Columbia University in the city of New York, reviewing recent study on the impacts of climate change on human health; the impacts of urban form on climate and the urban heat island effect; and strategies to enhance urban adaptation to climate change. Our focus on the work of scholars at 1 institution is intended to highlight the ability of cross-cutting initiatives to foster creative interdisciplinary research that aims to develop and apply better theories and models to describe, understand, and predict the interactions between environmental change, population health and the built environment, and to evaluate effective interventions. As scholars in urban planning and environmental health science, we write with an eye towards re-establishing connections in practice between disciplines based in the social and natural sciences.

To explore how interdisciplinary research has sought to examine links between the built environment, global ecosystem change and population health, our focus here is on research in New York City (NYC) and its metropolitan region. The New York metropolitan region is a 31-county, 3-state region including western Connecticut, southern New York, and a portion of northern and coastal New Jersey, with NYC at its core. New York is the largest metropolitan region in the United States, one of the largest of global megacities, and the focus of studies that downscale the impacts of global climate change to the regional and urban scale. This 33,600 square kilometer (13,000 square mile) region is presently home to over 21 million people.[14] The cultural, ethnic, racial and socioeconomic diversity of the region makes it unique among world metropolitan areas. This is mirrored in a complex set of public health vulnerabilities, including extensive areas of poverty, particularly in the inner city; areas of high population density; the constant in-flux of immigrants; an unfiltered municipal water supply; and a sizeable population of immunocompromised persons.[15]

For elucidating the complex relationship and pathways between environmental change and human health, here we rely strongly on the pioneering work by scholars in urban planning and health sciences, especially the joint framework for an urban planning and population health approach developed by Elliott Sclar, an economist and professor of urban planning at Columbia University, and Mary Northridge, an epidemiologist with the Mailman School of Public Health.[16] With a focus on the urban-scale "intermediate factors" of the built environment and society, the Northridge et al[17] conceptual model presents relationships relevant to population health in 3 domains – the natural environment, macrosocial factors (such as political economy and historical conditions), and social and economic inequalities – as containing "the fundamental factors that underlie and influence health and well-being via multiple pathways, through differential access to power, information and resources."

The scale of analysis matters for research on the links between the built environment, environmental change and public health. It is at this intermediate scale of the city and the community, between the global and the individual, where the structures of the **built environment** (land use, transportation systems, services, open space and public institutions and buildings) and the deliberative and decision-making processes of the **social context** (public policies and their enforcement, land use zoning, community capacity and social movements, civic participation and community investment) create patterns of health-relevant exposures and provide opportunities for their amelioration. The intermediate level of the metropolitan region, city and the community is where innovative research has examined the impacts of climate and land use change and air quality on health, where political activities to encourage solutions to these issues have occurred, and where effective interventions that may benefit population health are planned, including "land use strategies based upon densification, land use mixing, and microscale design considerations."[18]

To frame this review, first we define some key terminology relevant to some of the disciplines involved in this research. Next, we briefly overview current concerns on climate change and cities, namely the 2 types of warming experienced in the New York metropolitan region over the past century: that due to global climate change and that from the urban heat island effect. Preliminary findings of the New York Climate & Health Project (NYCHP) on population health impacts in the New York metropolitan region are discussed, as an example of interdisciplinary research based on integrated modeling assessment.

Research on the urban heat island effect and interventions in the built environment for ameliorating the impacts of health-relevant climate extremes on vulnerable urban populations is then discussed. This research seeks to combine the approaches and concerns of urban design, architecture, planning and public health strategies to assess and capture practical benefits for urban communities and enhance adaptive capacity to climate change, variability and extremes. Finally, we conclude with overall suggestions on the characteristics of interdisciplinary problem framing and research on environmental change and cities, and concerns for a normative framework of sustainable development and environment justice to attend to inequities in climate and health outcomes.

## Addressing Global Change and Urban Populations: The Need for Interdisciplinary Research

Interdisciplinary research usually begins with efforts to create a mutual understanding of basic concepts important to collaborating practitioners from different disciplines. In discussion of research on global change and urban populations, we are especially interested in methods that combine research from the social, biophysical and health sciences, in particular urban planning and public health.

*Urban planning* has been defined as a decision/action process that links different forms of knowledge to collective action in the public domain, for societal guidance or social transformation; and as "the process of superseding market forces in guiding the development of the built environment."[3,18] Urban planning activities encompass a range of themes; planning human settlements, interconnections, future orientation, a diversity of social needs, and open participation that seeks to encourage deliberative democracy. Planning works at the interface of technical and scientific knowledge, the built environment, and social systems to generate the physical design of cities and to support inclusive decision-making processes. The *built environment* is used to describe the physical content of cities: urbanised land-cover, converted from natural uses to human settlements; the city and its sum total of buildings, roads, infrastructure, and designed parks, waterfront property and open spaces, which also represent artifice as opposed to nature.[3,19]

*Public health* refers to the health and well-being of human population; according to the World Health Organization, health involves the optimum state of human functioning and is characterised by "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity."[20] The *population health* approach examines the full range of conditions and factors that determine health, and the complex interactions among them, and seeks to improve the health of the entire population and reduce health inequities among population groups.[21]

From the recent National Academy of Sciences report, *Facilitating Interdisciplinary Research*:

*Interdisciplinary research (IDR)* is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from 2 or more disciplines or bodies of specialised knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice.[22]

One methodology potentially useful for integrating knowledge from various scientific disciplines with public input and involvement is *integrated assessments*, or *integrated assessment modeling* (IAM).[23] An integrated model, such as the one developed by the NYCHP, described below, links the mathematical modeling work of researchers based in the natural or physical sciences with scientists using social, economic, or land use data and models to test the response of these systems to changes in inputs or assumptions, often through the use of alternative scenarios. We highlight this method as a means towards integrating research on social, physical, and biological systems in order to test the effects of different assumptions or policy options on environmental and urban health outcomes, to produce insights potentially useful for public decision makers.

IAMs often use a systems approach to examine "how structures, assumptions and policies produce system behaviour and consequences." This methodology can potentially engage public and community stakeholders to help frame research questions and objectives with researchers and modelers, when planned as participatory exercises. However, as a quantitative approach that links complex computer-based models representing different physical, natural and social systems, participatory processes for integrated assessments require a commitment to invest additional time for early, persistent, and sustained efforts at discussion of ideas, disciplinary methods and goals, beyond what many researchers may be accustomed to. Characterising and communicating the uncertainty and assumptions of the modeling system and components with all research partners are a fundamentally important aspect in global change research that seeks to understand the interactions of natural, physical systems and social systems through mathematical modeling.

Another useful method of knowledge production in environmental health and urban planning practice is the *co-production model,* which incorporates and builds on the principles of existing participatory models of research and action, such as "action research, community-based participatory research, popular epidemiology, and joint fact-finding."[24] The co-production model of environmental health research is based on acknowledgement of the interdependence of scientific knowledge and social systems in the creation of expertise. These models aim to strengthen and legitimise research by providing means for local residents to participate fully in the framing of problems and methods of inquiry for studies. Ideally, they include opportunities for residents and lay people to prioritise the scope of research or ensuing policy-making and involve the public in community-improvement interventions. Per Jason Corburn, urban planning faculty at University of California at Berkeley, "scientific knowledge and social order evolve jointly; science is understood as dependent on the natural world, as well as historical events, social practices, material resources and institutions that contribute to the construction, dissemination and use of scientific knowledge." With their potential to enhance the goals of procedural democracy by integrating local knowledge into decision-making, these methods are especially useful for urban environmental change and health research where practical interventions are desired.

**Impacts of Environmental Change: The Urban Heat Island and Global Climate Change in Relation to Public Health**

The increasing complexity, dynamism, diversity, and economic activities of global society have created historically unprecedented changes in biological and physical systems. Global hazards such as climate change are different from those that existed before: they are spatially and temporally diffuse, as they affect future generations and cross national boundaries; there is diffuse responsibility, as it is difficult to hold one single entity directly accountable; and critically for Ulrich Beck's notion of the "risk society" there is no longer any safety net – in the face of widespread and adverse ecological consequences, "it is becoming impossible to compensate those whose lives have been touched by those hazards, as their very calculability becomes problematised."[25] As well, the creation of collective mitigative policies and adaptive capacity in cities has been hampered by what Mike Davis has called uniformitarianism; the denial or ignorance of the accelerating pace of change, the false belief that the rate of current trends will remain the same, and the future will continue much like the past; that the 21st century will be similar to the 20th century, in terms of the biophysical systems that support life.[26]

Human activities influence the atmosphere and climate through air pollution of greenhouse gases and airborne particles, and through land alteration. Anthropogenic emissions of greenhouse gases like carbon dioxide, methane, chloroflourocarbons (CFCs) and nitrous oxide have led to increases in their atmospheric concentration and warming of the lower atmosphere. Among the anticipated impacts of climate change in North America are droughts; diminished and lower quality surface water; a higher incidence of vector-borne diseases; more frequent heat waves in urban centres; and an increase in storm surges in coastal regions.[4,27] Globally, decadal-scale changes in climate are expected to contribute to large-scale, geographically widespread, and potentially adverse changes in the productivity of agricultural systems, fresh water availability, ecosystem stability, and population health.

The development of land to urban uses is another major force driving environmental change. Cities can affect the climate system in a profound variety of ways – altering precipitation patterns, wind speed, cloud cover, humidity and nighttime temperatures, for example. These impacts from urbanised land use are more localised than those caused by global warming. One of the most studied phenomena of the interaction between land use and the atmosphere is the "urban heat island" effect.

Urban areas generally have higher surface and near-surface air temperatures than their surrounding suburban and rural areas, resulting in a hotter urban environment, higher energy demand and accelerated smog formation. These urban heat islands (UHIs) are created principally by man-made surfaces, including dark roofs, asphalt lots and roads, which absorb sunlight and re-radiate energy as heat. The concrete, metal and stone of buildings and street surfaces store and conduct heat and act as multiple reflectors of this energy. Urban streets typically have fewer trees and other vegetation to shade buildings and cool the air by evapotranspiration. As a result, urbanised land cover tends to retain less surface water from precipitation than natural land-cover, and moisture is less available for evaporation and cooling. Other factors proposed as contributing to the heat island effect include: increased storage of heat by urban materials; city morphology, density and size; urban design factors, such as the orientation and form of buildings and roads; the creation of anthropogenic heat; lower heat loss and altered wind patterns in urban canyons.[28,29] Meteorological conditions, such as wind speed, cloud cover and height, can enhance the magnitude of the heat island effect.[30,31]

The urban heat island temperature effect can be measured in terms of the urban canopy layer, the space below the rooftops of buildings, and the mesoscale, which refers to regional temperature measurement in terms of radius.[32] The magnitude of the UHI, in terms of the temperature differential between a city and its surrounding countryside, is greatest during dry, clear, low-wind nights, as the surfaces that comprise the built environment retain and re-radiate more heat into the air at night than vegetation and non-urbanised land cover. The surface geometry and thermal properties of the built environment's non-vegetative surfaces significantly impact the magnitude of the urban heat island.

The long-term development of NYC's urban heat island was examined with temperature data spanning the 20$^{th}$ century.[33] At the turn of the 19$^{th}$ century, parts of Manhattan and Brooklyn were already substantially developed, with materials such as asphalt used for streets and rooftops, and trees and vegetation removed in urbanised neighbourhoods. To assess the development of the NYC's heat island effect over the last century, we looked at average temperature differences of the city centre relative to its surrounding 31-county metropolitan region, comprised of parts of New York State, New Jersey, and Connecticut. Monthly maximum and minimum temperatures for 1900-1997 were obtained from NOAA's National Climatic Data Center, the National Aeronautics and Space Administration (NASA)-Goddard Institute for Space Studies (GISS), and the Lamont-Doherty Earth Observatory of Columbia University for 24 weather stations within the region that are part of the US Historical Climatology Network.

Analysis of annual mean temperatures shows an increasing difference between NYC (the Central Park weather station) and its surrounding region over the 20$^{th}$ century. Analysis of the temperature differences over this period between the New York Central Park station and 23 regional weather stations classified according to distance and level of urbanisation shows a heat island effect existing in NYC, with mean temperatures in the city centre (Central Park weather station) generally higher than the surrounding stations, ranging from 1.2°C (2.2°F) to 3.0°C (5.4°F).[34] A difference of at least 1°C already existed at the beginning of the 20$^{th}$ century between the mean temperature in NYC and its surrounding rural areas, and this difference increased over the 20$^{th}$ century. The difference between NYC and the 23 regional weather stations during the period 1990-1997 averaged 2.35°C (4.2°F). Additionally, a significant decrease in the monthly and seasonal variability of the UHI effect was observed over the century.

NYC is now experiencing 2 types of warming trends; in addition to the urban heat island effect, global climate change has warmed temperatures in the metropolitan region. Over the past century, the 31-country New York metropolitan region warmed about 2ºF (1.1°C), while the worldwide average temperature increased about 1ºF, due to global changes in the atmosphere, according to the *Climate Change and a Global City: An Assessment of the Metropolitan East Coast Region* (MEC) study.[35] The MEC study, released by The Earth Institute (EI) at Columbia University in 2002, documented climate trends and assessed climate change impacts in the metropolitan region as one of the regional components of The US National Assessment of the Potential Consequences of Climate Variability and Change.

These trends are expected to increase in the future. Projections of global and regional climate using meteorological models predict a significant increase in average temperatures in NYC during the next 80 years. The NYCHP, an interdisciplinary assessment of regional climate change impacts led by researchers with Columbia University's Mailman School of Public Health and EI, discussed below, used 2 possible scenarios of future greenhouse gas emissions to model the impact of global climate change on NYC's average daily summer temperatures.[15,36] The climate projections were based on United Nations Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios A2 and B2 greenhouse gas emissions scenarios. Using the A2 scenario of high $CO_2$ emissions of up to 30 gigatons/year by 2100 (compared to an estimated 7 gigatons/year CO2 currently from fossil fuel emissions),[37] projections with the NASA-GISS global climate model predict an increase of 5.4ºF to 6.3ºF (3.0°C to 3.5°C) in average annual temperatures in the city by 2100. Projections using the B2 scenario of medium $CO_2$ emissions of up to 15 gigatons/year by 2100 predict an increase by 3.6ºF to 4.5ºF (2.0°C to 2.5°C) by 2100.[37,38]

### Health Impacts of Climate Change

Air pollution and heat stress are 2 important current public health stressors in many urban areas across the US, and both are strongly affected by temperature and climate variability. Especially, extreme heat events endanger the health and well-being of elderly and poor urban residents.[39,40] The epidemiological literature has identified factors in the built environment and demographic characteristics that can increase the risk of heat-related mortality. Those over 65 years of age and people with pre-existing cardiovascular and/or respiratory illnesses are especially vulnerable populations.[41] Social and place-based factors, such as living alone, in low-income housing and having poor access to public transportation or air-conditioned neighbourhood places led to higher risk of mortality. Similar vulnerabilities exist in NYC's population. High spring and summer temperatures also result in increased heat stress and higher daily mortality rates in NYC.[42] Public health researchers have estimated that there are presently over 300 heat-related excess deaths in NYC during an average summer.[43]

The higher temperatures associated with summertime heat also impact health through increased ambient air pollutants. Higher temperatures accelerate the formation of harmful smog, as ozone precursors combine faster to produce ground-level ozone. This raises concerns about global warming's effect on poor air quality, as the frequency and intensity of high ozone episodes are projected to increase in American cities in future summers.[44,45]

Ozone has been found to exacerbate respiratory symptoms and diseases by damaging lung tissue, reducing lung function, and sensitising the lungs to other irritants.[46-48] Ozone air pollution can trigger or exacerbate asthma attacks, reduce lung growth and function, and "may actually lead to the development of asthma in children, as opposed to simply exacerbating existing disease."[49-51] Elevated ozone conditions have also been shown to increase acute mortality rates, as well as increase hospital admissions for asthma and cardiovascular causes.[46,51,52]

The higher temperatures caused by the heat island effect increase demand for cooling energy in commercial and residential buildings in summer, increasing the power plant emissions and peak electrical demand. Other air pollutants generated by power plants, such as particulate matter, carbon monoxide, sulfur dioxide and nitrogen oxides, can also damage lung tissue, irritate lungs, and aggravate breathing problems, respiratory illness and cardiovascular disease.[47,53]

Possible municipal adaptive responses to protect vulnerable populations from heat-health effects have included: access to air conditioned places; emergency planning, and the use of heat and air quality alert systems to communicate increased risk to residents through media and public education; and environmental modifications that can provide a passive approach for reducing the risk of heat stress.[54] Policies to improve the housing conditions of elderly residents and senior's safe access to public places play a central role in reducing urban heat-related mortality. As well, green building techniques such as cool and living roofs may reduce indoor temperatures in residences lacking air conditioners and provide a beneficial intervention for protection of public health from heat health impacts. For example, Philadelphia's Cool Homes Pilot Project, part of the non-profit Energy Coordinating Agency, targets the residences of low-income seniors for cool roof, insulation and ventilation interventions.[55]

Climate variability and extremes influence health through other pathways that raise concern for warming trends. These include contaminated drinking water and water-borne diseases; possible changes in vector habitats and increased incidence of vector-borne diseases; and the direct impacts of flooding and damage to infrastructure and residences. Our focus here is on discussing research on heat and air quality health impacts in the New York metropolitan region.

### Potential Health Impacts of Climate Change in New York City

The NYCHP, an interdisciplinary team of investigators from Columbia and other universities, sought to develop and apply a modeling system to assess potential public health impacts of both climate change and land use change in the New York metropolitan region. This interdisciplinary assessment required the integration of observations and a diverse set of models that attempt to describe behaviour of physical and social systems, including those addressing changes in global climate (General Circulation Models, or

GCMs), land use, regional climate, air quality, demographic projections and human health.[15] A key feature of this work was the downscaling of global climate projections to the regional metropolitan and urban-scale to assess regional climate and air quality under alternative future scenarios of global climate change and regional land use change.[36]

Integrated assessments like the NYCHP pose unique methodological and operational challenges for researchers; assumptions and uncertainty are inherent to every component of the modeling framework. Yet, integrated assessments are especially appropriate for the study of complex problems of global ecological change.[24] More frequently, scientists of different disciplines work separately on research with the tools, techniques and methodologies appropriate to their field in order to answer circumscribed questions and further develop knowledge in their domain. However, efforts to assess the complex pathways of how environmental change interacts with biophysical systems and the built environment to impact human health, encourages if not requires the integration of research across disciplinary boundaries, with research questions and methods developed in collaboration between several disciplinary frameworks. Dr Patrick Kinney of the Mailman School of Public Health conceived of the NYCHP as an opportunity to create and test a framework of linked models and a health risk assessment to evaluate climate and health impacts at urban-scale spatial resolutions, and test the sensitivity of component systems to different parameters. Dr Cynthia Rosenzweig led the team of investigators projecting the future climate in the New York metropolitan region, using the output of a global-scale climate model as initial and boundary conditions for finer-scale simulations by a regional climate model.

The questions driving the NYCHP assessment were: how might health in the region be affected by 2 scenarios of climate and land use change, first considering heat and ozone air pollution effects on mortality? To accomplish these goals, an integrated modeling framework was developed linking the National Aeronautics and Space Administration (NASA-GISS)-Goddard Institute of Space Studies global climate model at 4° x 5° resolution to the Penn State/National Center for Atmospheric Research Mesoscale Model 5 (MM5) and the Community Multiscale Air Quality atmospheric chemistry model at 36 km horizontal grid resolution to simulate hourly regional meteorology and ozone in 5 summers of each decade from 2000-2080 across the metropolitan region.[56] The NYCHP modeling system was run under alternative scenarios of global climate (SRES A2 and B2, discussed below) and regional land use change.

These projections were then used in a quantitative health risk assessment framework to examine mortality impacts of both extreme heat and ozone air quality over the coming century in the New York metropolitan region, with and without assumptions about population growth within the region. The health risk assessment used a range of concentration-response functions from the recent epidemiology literature, and their associated confidence intervals. Future changes in heat and ozone air quality as simulated by the model system were compared relative to conditions in the 1990s across the region, as taken from meteorological observations at the GCM scale or from interpolated CMAQ ozone and/or MM5 temperature simulations at the urban scale.

Climate change projections rely on scenarios of future development. In the face of uncertainty as to the future amount of greenhouse gas emissions and atmospheric concentrations, the IPCC developed alternative GHG emissions scenarios for use in climate change projections. These scenarios characterise potential long-range social, economic, and technological developments, based on storylines of future regional development, and their associated corresponding levels of GHG emissions from sources.[57] To create a unified and consistent framework, the IPCC A2 and B2 emission scenarios were used in the NYCHP integrated model as the basis to characterise other key modeling system parameters; scenarios of land use change, ozone precursor emissions; and population projections. Thus, the characteristics of future land use development patterns and transportation infrastructure in the metropolitan region were defined by geographer William Solecki and his colleagues based on the A2 and B2 emission scenarios, as were projections of population for the 31-county region.[58] Future research with an integrated climate-air quality-health modeling system could take the opposite approach, and project potential levels of air pollutant emissions based on predicted scenarios of land use development and housing patterns.

Columbia's EI and Mailman School of Public Health released preliminary findings of the NYCHP analysis of the health impacts of climate change scenarios in the region in June 2004. Projections with the NYCHP modeling system suggest that public health impacts within the metropolitan region could worsen during the 21$^{st}$ century due to a changing climate. Using the high-growth A2 scenario and temperature projections from the global-scale NASA-GISS climate model, results suggest that heat-related mortalities could increase by more than 55% by the 2020s, and more than double by the 2050s, relative to the 1990s. Using future climate projections at the county level under the A2 and B2 scenarios, increases in summer heat-related premature mortality were projected across the New York metropolitan region by mid-century, with and without acclimatisation effects. The resulting projected 2050s changes in heat-related mortality range from a 38% to a 208% increase, with a mean 70% increase as compared to the 1990s.[59]

Knowlton et al[59] presented the first assessment of ozone public health impacts using global climate change projections downscaled to the metropolitan region. For ozone-related health impacts, the MM5 and the CMAQ models were used to simulate hourly meteorology and ozone in five summers of the 2050s across the 31-country metropolitan region, with input from the NASA-GISS GCM. Changes in ozone-related impacts on summer mortality was assessed for this region in 2 ways: resulting from climate change alone, and with climate change superimposed on future changes in ozone precursor emissions and population growth. In addition to the use of IPCC A2 and B2 scenarios, investigators used a variety of assumptions to enable this assessment. No changes in age structure of future populations were assumed; changes in the temperature-mortality relationship due to acclimatisation or adaptation in future years were not included; and the use of mortality rates from the 1990s does not factor in changes in standards of living or access to or improvement of health care in future decades.

Under these assumptions, considering the effect of climate change alone, there was a median 4.5% increase in summer ozone-related acute mortality across the region in the 2050s. Here, the greatest increases in ozone mortality were found in the urban core counties and in the immediately surrounding suburban counties to the southwest and east of NYC.

Incorporating ozone precursor emission increases along with climate change yielded similar results. When population growth was factored into the projections, absolute impacts increased substantially. With these assumptions, a different geographic pattern emerged, and counties with the highest per cent increases in projected ozone mortality spread beyond the urban core into less densely populated suburban counties.[57]

Time-series analysis has demonstrated that daily mortality has a relationship with local meteorological conditions across the full range of temperatures experienced in the New York metropolitan region; mortality rises with increasingly hot or cold temperatures from an optimum, or threshold, temperature value. Short-term increases in daily mortality rates are experienced both during extreme cold and extreme heat conditions. Although a greater number of people die during the colder winter months, due to higher rates of infectious respiratory disease, in NYC, the temperature-mortality relationship has the strongest association with summertime heat. However, this has led observers to ask if a changing climate would decrease the total number of annual premature temperature-related deaths, due to warmer winters and diminished cold-related morality?

The NYCHP integrated model examined this question. Initial project results using global climate model projections and the A2 emissions scenario suggest that with the combined effects of warmer summers and warmer winters in the 2050s, net annual temperature-related mortality could be 25% greater than in the 1990s. As well, results also suggest that summer heat-related mortality in the 31-county metropolitan region may exceed ozone-related mortality by the 2050s.

This question of overall temperature-related mortality is especially relevant for the urban populations in temperate zone cities, where annual and seasonal climate variability is high and the population more sensitive to extreme heat. Temperate zone cities such as New York, Chicago, and Philadelphia experience cold winters, hot summers, and variable weather within those seasons, and their relationship between high summertime heat and excess mortality is stronger than with residents of tropical cities such as Singapore.[60] Despite the increasing use over the last 30 years of air-conditioning in cities such as New York, the urban population remains more sensitive to adverse health outcomes during extreme heat than populations in cities where the temperature remains high year-round.

In tropical areas, adaptations to year-round warm temperatures include architectural, urban design, cultural, and behavioural measures that serve to acclimatise the population and help them cope with the heat. For example, in Bangkok, called the “Hottest City in the World” by the World Meteorological Organization, traditional housing construction adapts to the climate through use specific design techniques such as high vents in steeply pitched roofs and houses on stilts to maximise cooling indoor ventilation.[61] Lifestyle adaptations in tropical climates, such as loose-fitting and lightweight clothing, and mid-day rest, also can function as climate adaptations.

**Urban Heat Island Mitigation Strategies for New York City: Reshaping the Built Environment**

Communities have planned several types of physical interventions in the built environment, on individual buildings and in urban design, to counter the urban heat island effect and to reduce the impacts of summertime heat on human health and energy consumption. In this section, we discuss NYC-based research on these heat island mitigation techniques, which may hold potential both as climate change mitigation and adaptation measures.

The Cool City Project began in 2000 as a series of proposals from students and faculty in Columbia’s Urban Planning program to bring together researchers and practitioners from the disciplines of public health, urban planning, economics, architecture, landscape architecture and geophysics to evaluate the environmental and health impacts of neighbourhood-based heat island mitigation and energy conservation techniques and identify effective institutional mechanisms and public policies to facilitate the testing and use of effective strategies.

With seed grant funding from Columbia's Institute for Social and Economic Research and Policy (ISERP) the following year, the Cool City Project began research on the NYC heat island effect and the potential benefits of strategies to change the properties of the built environment to mitigate its effect on temperature. These mitigation methods depend primarily on changing 2 properties of the urban environment: increasing urban vegetation and/or increasing the albedo, or reflectivity, of surfaces. Planting street trees that shade buildings from solar radiation is the most common way of increasing vegetation to reduce temperature gain. The use of green roofs, living vegetative systems placed on a building's roof, can also reduce heat gain into a building. As a relatively new technology in the United States, green roof systems have been used less in this country than other forms of UHI mitigation techniques. The currently high installation costs of living roofs, starting at approximately 12 to 25 dollars per square foot in NYC, have limited both their application and research [1) Personal communication with K Bakewell, landscape architect, June 2005; 2) Correspondence with H Taha, staff scientist, Lawrence Berkeley National Laboratories, 3/1/05 and 4/26/06].[62] However, as rooftops occupy an estimated 19% of the city's surface area (11% are flat roofs, the easiest kind on which to construct a green roof), there has been increased interest in the use of vegetated rooftop systems as a heat island mitigation technique.[63,64]

"Cool" highly reflective and emissive roofing materials and "cool" reflective and permeable pavement materials can also reduce near-surface air and surface temperatures. Cool roofing technology is currently better developed than cool pavement technology and more widely used.[65] The cost of cool roof coatings is relatively low, starting at less than $2 per square foot for material and labour.[66] Pilot studies have demonstrated direct energy saving and indirect savings from reduced building heat gain and reduced air temperatures resulting from urban reforestation and use of high-albedo surfaces.[67-70]

The original objectives of the Cool City Project were to:

1) Design and implement pilot demonstration projects with living and cool roofs, focusing first in lower-income neighbourhoods, the communities most in need of the potential benefits. Through pilot projects, evaluate the costs, social function and potential role of vegetation and high albedo (reflective) materials to provide cool roofing. Use of geographic information systems and remotely sensed data to characterise and map the surface heat island effect in NYC, and identify the "hottest" neighbourhoods.

   Researchers approached Columbia University in 2001 to explore options for pilot cool and green rooftop research projects on Columbia-owned buildings, as the University remains one of the largest landlords in NYC.
2) Quantify the potential environmental and public health benefits achieved through use of such measures, including: impacts on building energy usage; the economic costs and benefits, both private and public, of broader application of UHI mitigation strategies in NYC; application of quantitative health-risk assessment to assess the potential impacts of UHI mitigation on the risk of mortality on hot days and during heatwaves.
3) Determine the most effective institutional and organisational channels for encouraging the use of mitigation strategies and disseminating information on beneficial techniques; including economic incentives through utilities, landlords, citizens' organisations, or tax abatements.
4) Make the research results publicly available to facilitate the adoption of cost-effective measures for residential and commercial buildings that hold the potential to mitigate the urban heat island effect and improve air quality in NYC.

With an initial focus on pilot projects in low-income neighbourhoods, the first rooftop demonstration project opened on top of the historic American Banknote Building in the Hunts Point neighbourhood of the South Bronx, in partnership with a community-based environmental justice organisation, Sustainable South Bronx (SSB) in 2005. Hunts Point, a community comprised of low-income Latinos and African-Americans, is heavily burdened with noxious public and industrial uses, including a substantial portion of NYC's waste transfer stations; a facility that transforms the City's sewage sludge into pellets; a large sewage treatment plant; an estimated 15,000 diesel truck trips through local streets each week; and limited access for residents to parks, waterfront or recreational space.[71] Representative of challenged and polluted urban neighbourhoods across the United States and community leaders seek new approaches for sustainable economic development in order to ensure the health and well-being of residents. According to SSB's founder and Executive Director, Majora Carter, the group was conceived to serve as a dedicated mechanism that could address and implement policy and planning in such areas as land use, energy, transportation, water, waste, and sustainable development in the South Bronx, by working to implement the community's visions for sustainable community development. Its programmes are designed to provide tangible and pragmatic projects to support "advocacy for policy decisions that advance the environmental, social and economic rebirth of the South Bronx."[72]

The South Bronx Smart Roof Demonstration Project (SDP) was organised as a partnership between SSB, the EI's Cool City Project, and landscape architects Kathleen Bakewell (Hart Howerton) and Susanne Boyle (The RBA group) to merge community activism, landscape architecture, and scientific and policy research. The SDP's Banknote roof includes over 1000 square feet of extensive and intensive vegetated living roof, and a high albedo cool roof, which reflects over 80% of incoming solar radiation, on a total of 2500 square feet. The Demonstration Project is used extensively by local schools and students, who maintain the living roof and use it as a hands-on learning centre. The ecological design of the living roof includes a comparison, which is monitored by highs school students, of 2 different plant communities: one comprised of widely available commercial varieties, and one comprised of ecologically significant native species. Some of the living rooftop substrate was left unplanted, so that students could monitor which plants and insects establish a new presence on the roof. The SDP is offered as a prototype of community-based sustainable development initiatives that use ecological infrastructure to seek to provide multiple benefits in improved air and water quality, climate protection and energy conservation.

### Discussion and Conclusion

How can educational institutions best foster advances in collaborative research and understanding, framing questions relevant to the usually separate domain of health, biophysical and social sciences? Columbia University created the EI to foster integrated study of the environment and society, building on the core disciplines of the University, in earth sciences, biological sciences, engineering sciences, social sciences and health sciences – stressing cross-disciplinary approaches in research, training and global partnerships. The EI at Columbia University seeks to "mobilise science and technology to advance sustainable development, while placing special emphasis on the needs of the world's poor." As a platform for original research in the climate change field, the EI is a leading academic centre in interdisciplinary study. This article has highlighted only a small portion of a wide range of interdisciplinary climate and society research at the EI, whose scholars are at the forefront of developments in climate modeling and the application of climate forecasts and information for planning purposes.

For example, the International Research Institute for Climate and Society (IRI) helps developing countries use short-term climate forecasts to plan proactively for agricultural, health and economic decisions and risks; IRI research has investigated linkages between infectious diseases, climate variability and land use change in West Africa.[73-75] Climate and society research by scientists with NASA-GISS at Columbia University have examined urban heat island mitigation in the metropolitan region through modeling land cover change.[76] Building on past initiatives, further research results in these areas are forthcoming.

Other research exploring linkages between the built environment and public health at Columbia University includes collaboration between health and social scientists to analyse the impacts of urban design and features in the built environment on physical activity and obesity. Epidemiologists, local government agencies, urban planners and sociologists at Columbia University, led by Dr Andrew Rundle of the Mailman School of Public Health, are collecting and assessing data on land-use mix and characteristics of neighbourhood design, such as density of transit stops, location and condition of parks and recreational facilities, accessibility to food, "even the number of trees on a street and the number of buildings with elevators-that affects a person's diet and activity levels," in order to assess the relationship between body size and the built environment.[77] Measures of urban form such as land-use mix, residential density and street connectivity have been used as evidence to assess the impact of the built environment on physical activity in previous studies.[78] Preliminary results indicate that residents of mixed-use neighbourhoods, with both residential and commercial uses "have lower levels of obesity than people who live in neighbourhoods that are closer to 100 percent residential."[77]

Our focus here on 2 NYC-based efforts is intended to highlight not only research that the authors are directly engaged in, but also 2 fundamentally different approaches: numerically and computationally sophisticated integrated modeling systems, working on statistical analysis of large data sets describing human and biophysical systems; and research applying technical knowledge to create pilot projects in the built environment, where community-based research seeks to co-produce knowledge, integrating knowledge from technical and professional experts and local residents. Some of the issues that arose during these projects are ones common to interdisciplinary research. Researchers have noted that while interdisciplinary research is often encouraged rhetorically in the academy, its actual practice remains small and institutional support is often lacking. A recent National Academy of Sciences study noted that interdisciplinary research often requires a greater time commitment by collaborators, in order to learn the language and fundamental conceptual basis of other disciplines, and recommended that researchers intending to pursue interdisciplinary projects "immerse themselves in the languages, cultures, and knowledge of their collaborators."[22]

One objective in this discussion is to begin to understand the characteristics that have enabled successful research conducted among disciplines in the physical, natural and social sciences. Some suggestions for a joint urban planning-environmental health research framework that emerge from this brief look at 2 types of interdisciplinary research on environmental change in the metropolitan region:

* Global environmental change and the sustainable development paradigm require bringing together separate disciplinary domains in interdisciplinary research; the methodology of integrated assessments involving social and biophysical systems research is one approach that supports this effort, as does community-based research methods;
* The intermediate scale of the city and region is a highly relevant scale of analysis for joint urban planning/ public health/environmental change research;
* In addition to the new formulation of interdisciplinary research agendas in the academy, further attention will be needed on methods and processes for integrating the different objectives and normative frameworks of the social and biophysical sciences.
* Ideally, collaborative research incorporates the perspectives and knowledge of different disciplines and types of people – including local residents, scholars and professional experts in the initial research design and creation of results. Exploration of the roles and uses of expert professional and other forms of knowledge in decision-making processes is a core area of inquiry.

Given critical global trends shaping the future; namely, the globalisation of urban poverty, and the impacts of environmental change as additional stressors for poor populations, more than research and interventions are required to ensure the health of urban residents. What is missing here, and to be discussed in further articles, is a normative framework of sustainable development and environmental justice to enable participatory and deliberative democratic processes and guide policy-making. The distributive and procedural equity criteria embodied by these goals are central to considerations of decision-making for the collective solutions required by these challenges.

***Acknowledgements***

*The authors gratefully acknowledge the collaboration of the team of investigators and practitioners engaged in the New York Climate & Health Project (NYCHP) research, and the Cool City Project and South Bronx Smart Roofs Demonstration Project. NYCHP co-investigators included Cynthia Rosenzweig, Barry Lynn and Richard Goldberg of the NASA-Goddard Institute for Space Studies (GISS) at Columbia University; William Solecki of Hunter College, CUNY; Christopher Small of Columbia University; Michael Ku and Kevin Civerolo of the New York State Department of Environmental Conservation; Tracey Holloway, University of Wisconsin-Madison, and many others who assisted in the research. For the Cool City Project, invaluable support was provided by Kathy Neckerman of ISERP and Julie Touber and Nicole Volavka of the EI's Center for Sustainable Urban Development. The authors are grateful for the thoughtful critical comments and suggestions of Cuz Potter, doctoral candidate in Urban Planning at Columbia University on an earlier draft of this paper, and editing by Stacy Radine, MSUP 2006, Columbia University.*

*The research described in this paper has been funded in part by the NIEHS Center for Environmental Health in Northern Manhattan (P30-ES09089), the United States Environmental Protection Agency (EPA) under the Science to Achieve Results (STAR) Graduate Fellowship Program and the National Center for Environmental Research (NCER) STAR Program Grant R-82873301. EPA has not officially endorsed this publication and the views expressed herein may not reflect the views of the EPA. We gratefully acknowledge the support and encouragement provided by the Earth Institute's Steven Cohen and Louise Rosen. Partial funding for Cool City Project research provided by the Columbia University Institute for Social and Economic Research and Policy (ISERP) and the Earth Institute's Office of Educational Programs.*

## REFERENCES

1. Davis M. Planet of slums: urban involution and the informal proletariat. New Left Review 2004;26:5-34.
2. United Nations Human Settlements Programme (UN-HABITAT). Available at: http://www.unhabitat.org/about/challenge.asp. Accessed 14 May 2006.
3. Northridge ME, Sclar E. A joint urban planning and public health framework: contributions to health impact assessment. Am J Public Health 2003;93:118-21.
4. IPCC, 2007. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2007: The Physical Science Basis – Summary for Policymakers. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. WMO/UNEP (February 2007:p12).
5. Columbia Earth Institute, Center for International Earth Science Information Network (CIESIN), Global Rural Urban Mapping Project (GRUMP). Available at: http://www.earthinstitute.columbia.edu/news/2005/story03-07-05.html. Accessed 5 April 2006.
6. Alberti M, Marzluff JM, Shulenberger E, Bradley G, Ryan C, Zumbrunnen G. Integrating humans into ecology: opportunities and challenges for studying urban ecosystems, BioScience 2003;53:1169-79.
7. Emmi P. Coupled Human-Biologic Systems in Urban Areas: Towards an Analytical Framework Using Dynamic Simulation. Presentation at the Twenty-first International System Dynamics Conference, New York City, July 2003. USA: College of Architecture and Planning, University of Utah, 2003.
8. Grimm NB, Grove JM, Pickett TA, Redman CL. Integrated approaches to long-term studies of urban ecological systems. BioScience 2000;50: 571-84.
9. Sclar E, Northridge ME. Slums, slum dwellers, and health. Am J Public Health 2003;93:1381.
10. Health Disparities Experienced by Hispanics – United States. US CDC MMWR Weekly, 15 October 2004. Available at: http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5340a1.htm. Accessed 12 May 2006.
11. Williams DR, Neighbors HW, Jackson JS. Racial/ethnic discrimination and health: findings from community studies. Am J Public Health 2003;93:200-8.
12. NACCHO, 2005. Health Disparities in the Gulf Coast Before and After Katrina: The Public Health Response. Statement of the National Association of County & City Health Officials, 23 September 2005. Available at: http://www.healthandsocietyscholars.org/resources/KatrinaThe PublicHealthResponse.phtml. Accessed 14 May 2006.
13. Redlener I. Orphans of the Storm. The New York Times, 9 May 2006. Available at: http://www.nytimes.com/2006/05/09/opinion/09redlener.html. Accessed 14 May 2006.
14. Kinney PL, Rosenthal J, Rosenzweig C, Hogrefe C, Solecki W, Knowlton K, et al. Assessing the potential public health impacts of changing climate and land use: The New York Climate & Health Project. In: Ruth M, Donaghy K, Kirshen P, editors. Climate Change and Variability: Consequences and Responses. Washington, DC: U.S. Environmental

Protection Agency, 2006.
15. Hamburg M. Emerging and resurgent pathogens in New York City. J Urban Health 1998;75:471-9.
16. Sclar E, Northridge ME, Karpel E. Promoting interdisciplinary curricula and training in transportation, land use, physical activity, and health. TRB Special Report 282: Does the Built Environment Influence Physical Activity? Examining the Evidence, 2005. Paper for the Transportation Research Board and the Institute of Medicine Committee on Physical Activity, Health, Transportation, and Land Use.
17. Northridge M, Sclar E, Biswas P. Sorting out the connections between the built environment and health: a conceptual framework for navigating pathways and planning healthy cities. J Urban Health 2003;80:556-68.
18. Friedmann J. Planning in the Public Domain: From Knowledge to Action. Princeton NJ: Princeton University Press, 1987:38.
19. Lerup L. Toxic Ecology: The struggle between nature and culture in the suburban megacity. Megacities Lecture 2005. Available at: http://www.megacities.nl/lecture_8/11-50Toxicecology.pdf. Accessed 14 March 2006.
20. Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference, New York, 19 June - 22 July 1946; signed on 22 July 1946 by the representatives of 61 States (Official Records of the World Health Organization, no. 2, p. 100) and entered into force on 7 April 1948.
21. Canada Public Health Service. Available at: http://www.phac-aspc.gc.ca/ph-sp/phdd/approach/index.html. Accessed 6 May 2006.
22. National Academy of Sciences. Facilitating interdisciplinary research. Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine; 2004. Executive Summary. Available at: http://www.nap.edu/books/0309094356/html/. Accessed 5 July 2007.
23. Aron JL, Patz JA, editors. Ecosystem Change and Public Health: A Global Perspective. Baltimore: Johns Hopkins University Press, 2001.
24. Corburn J. Street Science: Community Knowledge and Environmental Health Justice. Cambridge MA: MIT Press, 2005.
25. Beck U (translated by Weisz A). Ecological Politics in an Age of Risk. Cambridge, UK: Polity Press, 1995.
26. Davis M. Ecology of Fear: Los Angeles and the Imagination of Disaster. New York: Vintage Books, Random House, 1999.
27. Mehdi B, editor. Adapting to Climate Change: An Introduction for Canadian Municipalities. Canadian Climate Impacts and Adaptation Research Network (C-CIARN), 2006.
28. Chow W, Roth M. Temporal dynamics of the urban heat island of Singapore. Int J Climatol 2006;26:2243-60.
29. Hough M. Cities and Natural Process. New York: Routledge, 2000.
30. Oke TR. City size and the urban heat island. Atmospheric Environment 1973;7:769-79.
31. Gedzelman SD, Austin S, Cermak R, Stefano N, Partridge S, Quesenberry S, et al. Mesoscale aspects of the urban heat island around New York City. Theoretical and Applied Climatology 2003;75,29-42.
32. Voogt JA. Urban heat island. In: Douglas I, editor. Vol. 3. Causes and Consequences of Global Environmental Change in Encyclopedia of Global Environmental Change. Chichester: John Wiley & Sons, 2002: 660-6.
33. Pena Sastre M. The history of the urban heat island effect in New York City [Masters thesis]. Columbia University Graduate School of Architecture, Planning & Preservation, Avery Library, 2003.
34. Rosenthal J, Sastre Pena M, Rosenzweig C, Knowlton K, Goldberg R, Kinney P. One hundred years of New York City's "urban heat island": temperature trends and public health impacts. Eos Trans AGU 2003;84(46), Fall Meet. Suppl., Abstract U32A-0030.
35. Climate Change and a Global City: The Potential Consequences of Climate Variability and Change. Available at: http://metroeast_climate.ciesin.columbia.edu. Columbia Earth Institute (CEI) for the U.S. Global Change Research Program. New York: Columbia Earth Institute, July 2001.
36. Kinney P, Rosenthal J, Knowlton K, Rosenzweig C, Goldberg R, et al. Assessing Potential Public Health and Air Quality Impacts of Changing Climate and Land Use in Metropolitan New York. In: Rosenthal J, Kinney P, Knowlton K, et al, editors. New York Climate & Health Project. New York: Columbia Earth Institute, 2004.
37. Hansen J, Sato M. Greenhouse gas growth rates. Environmental Sciences. Proc Natl Acad Sci U S A 2004;101:16109-14. Published online 2004 November 9. doi: 10.1073/pnas.0406982101. Available at: http://www.pubmedcentral.gov/articlerender.fcgi?artid=526279. Accessed 14 May 2006.
38. Hogrefe C, Ku J-Y, Civerolo K, Lynn B, Werth D, Avissar R, et al. Modeling the impact of global climate and regional land use change on regional climate and air quality over the northeastern United States. In: Borrego C, Incecik S, editors. Air Pollution Modeling and its Application XVI. New York: Kluwer Academic/Plenum, 2004;135-44.
39. Klinenberg E. Heat Wave: A Social Autopsy of Disaster in Chicago. Chicago: The University of Chicago Press, 2002.
40. Buechley R, Van Bruggen, J, Truppi, LE. Heat Island = Death Island? Env Res 1972;5:85-92.
41. Basu R, Samet JM. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiol Rev 2002;24:190-202.
42. Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA. Temperature and mortality in 11 cities of the eastern United States. Am J Epidemiol 2002;155:80-7.
43. Kalkstein LS, Greene JS. An evaluation of climate/mortality relationships in large US cities and the possible impacts of a climate change. Environ Health Perspect 1997;105:84-93.
44. Hogrefe C, Lynn B, Civerolo K, Ku J-Y, Rosenthal J, Rosenzweig C, et al. Simulating changes in regional air pollution over the eastern United States due to changes in global and regional climate and emissions. J Geophys Res 2004;109, D22301, doi:10.1029/2004JD004690.
45. Patz J, Kinney P, et al. Heat Advisory: How global warming creates bad air days. New York: Natural Resources Defense Council (NRDC), July 2004. Available at: http://www.nrdc.org/globalwarming/heatadvisory/contents.asp.
46. Kinney PL. The pulmonary effects of outdoor ozone and particle air pollution, Semin Resp Crit Care Med 1999;20:601-7.
47. Abelsohn A, Stieb D, Sanborn MD, Weir E. Identifying and managing adverse environmental health effects: 2. Outdoor air pollution. Can Med Assoc J 2002;166:1161-7.
48. Patz JA, McGeehin MA, Bernard SM, Ebi KL, Epstein PR, Grambsch A, et al. Potential consequences of climate variability and change for human health in the United States, in Climate Change Impacts on the United States – Foundation Report, National Assessment Synthesis Team, Editor. Cambridge: Cambridge University Press, 2001.
49. Koren HS, Bromberg PA. Respiratory responses of asthmatics to ozone. Int Arch Allergy Immunol 1995;107:236-8.
50. McConnell R, Berhane K, Gilliland F, London SJ, Islam T, Gauderman, WJ, et al. Asthma in exercising children exposed to ozone: a cohort study. Lancet 2002;359:386-91.
51. Thurston GD, Ito K. Epidemiological studies of ozone exposure effects. In: Holgate ST, Samet JM, Koren HS, Maynard RL editors. Air Pollution and Health. San Diego, CA: Academic Press, 1999:485-510.
52. Koken PJM, Piver WT, Ye F, Elixhauser A, Olsen LM, Portier CJ. Temperature, air pollution, and hospitalization for cardiovascular diseases among elderly people in Denver. EHP 2003;111:1312-17.
53. Amdur M, Doull J, Klaassen C, editors. Casarett and Doull's Toxicology: The Basic Science of Poisons. 4th ed. USA: McGraw-Hill, 1991.
54. Smoyer KE, Rainham DB. Beating the heat: development and evaluation of a Canadian hot weather health-response plan. Environ Health Perspect 2001;109:1241-8.
55. Blasnik M. Impact evaluation of the Energy Coordinating Agency of Philadelphia's Cool Homes Pilot Project. Final Report, 5 Nov 2004. Boston, MA: M. Blasnik & Associates. Available at: http://www.ecasavesenergy.org/pdfs/coolhomes_finalimpact_11-04.pdf. Accessed 2 May 2006.
56. Knowlton K, Rosenthal J, Hogrefe C, Lynn B, Gaffin S, Goldberg R, et al. Assessing ozone-related health impacts under a changing climate.

Environ Health Perspect 2004;112:1557-63.
57. IPCC: Special Report on Emissions Scenarios. Intergovernmental Panel on Climate Change, 2000. Available at: http://www.grida.no/climate/ipcc/emission/. Accessed 5 June 2007.
58. Solecki WD, Oliveri C. Downscaling climate change scenarios in an urban land use change model. J Environ Manage 2004;72:105-15.
59. Knowlton K, Lynn BH, Goldberg R, Rosenzweig C, Hogrefe C, Rosenthal J, et al. Projecting heat-related mortality impacts under a changing climate in the New York City region. Am J Public Health [In print].
60. Kalkstein LS. Biometeorology - Looking at the Links Between Weather, Climate and Health (A speech given to the Executive Council of the WMO, May 25, 2000). World Meteorological Org Bull 2001;50:1-6.
61. Bentley M, Horstmeyer S. Living with Heat. Weatherwise, January/February 2004.
62. Kerr L, Yao D. Reducing New York City's urban heat island effect: Cost-effectiveness calculations for white roofs, green roofs, lighter roadways and trees. New York City: Department of Design and Construction, Unreleased draft, 2004.
63. Rosenzweig, C, Gaffin S, Solecki W, editors. Green Roofs in the New York Metropolitan Region: Research Report. New York: NASA/Goddard Institute for Space Studies, Center for Climate Systems Research of the Earth Institute at Columbia University, Hunter College, CUNY, 2006.
64. Rosenthal J, Crauderueff R, Carter M. Urban Heat Island Mitigation Research and Strategies for New York City. Bronx, New York: Sustainable South Bronx Working Paper, Unreleased draft, 2006.
65. The US EPA Heat Island Reduction Initiative website. Available at: http://www.epa.gov/heatisland/strategies/coolpavement.html. Accessed 14 May 2006.
66. US Environmental Protection Agency. Heat Island Effect: Cool Roof Product Information. Available at: http://www.epa.gov/heatisland/strategies/level3_roofproducts.html. Accessed 12 May 2006.
67. Konopacki S, Akbari H. Energy Savings Calculations for Heat Island Reduction Strategies in Baton Rouge, Sacremento and Salt Lake City. Berkeley, CA: Lawrence Berkeley National Laboratory Report LBNL-42890, 2000.
68. Konopacki S, Akbari, H. Energy Savings of Heat-Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City). Berkeley, CA: Lawrence Berkeley National Laboratory Report LBNL-49638, 2002.
69. Parker DS, Barkaszi SF. Roof solar reflectance and cooling energy use: field research results from Florida. Energy and Buildings 1997;25:105-15.
70. Akbari H, Kurn DM, Bretz SE, Hanford JW. Peak power and cooling energy savings of shade trees. Energy and Buildings 1997;25:139-48.
71. Lena TS, Ochieng V, Carter M, Holguín-Veras J, Kinney PL. Elemental carbon and PM2.5 levels in an urban community heavily impacted by truck traffic. Environ Health Perspect 2002;110:1009-15.
72. Sustainable South Bronx. Available at: www.ssbx.org. Accessed 4 April 2006.
73. Thomson MC, Doblas-Reyes FJ, Mason SJ, Hagedorn R, Connor SJ, Phindela T, et al. Malaria early warnings based on seasonal climate forecasts from multi-model ensembles. Nature 2006;439:576-79.
74. Thomson MC, Connor SJ, Ward N, Molyneux DH. Climate variability and infectious disease in West Africa. Eco Health 2004;1:138-50.
75. Thomson MC, Erickson PJ, Ben Mohammed A, Connor SJ. Land use change and infectious disease in West Africa. In: DeFries R, Asner G, Houghton R, editors. Ecosystems and Land Use Change. Geophysical Monograph. Washington, DC: American Geophysical Union, 2004.
76. Solecki WD, Rosenzweig C, Parshall L, Pope G, Clark M, Cox J, et al. Mitigation of the heat island effect in urban New Jersey. Global Environmental Change Part B: Environmental Hazards 2005;6:39-49.
77. Columbia University Mailman School of Public Health. Does Urban Design Make You Fat? Mailman School Researchers Study Link Between Obesity and the Urban Environment. Available at: http://www.mailman.hs.columbia.edu/news/e-newsletter/AtTheFrontline-vol1no2/rh-obesity.html. Accessed 2 May 2006.
78. Does the built environment influence physical activity? Examining the evidence. TRC Special Report 282. Washington, DC: Transportation Research Board, Institute of Medicine of the National Academies, 2005.